IN-SITU ELECTRICAL TERMINAL CHARACTERIZATION
OF FUEL CELL STACKS

by

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Eric Matthew Seger

January, 2010
I dedicate this thesis to Charlene and Caitlynn.
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This thesis demonstrates in-situ characterization of a 5kW solid oxide fuel cell (SOFC) stack and a 165W proton exchange membrane fuel cell (PEMFC) stack at the electrical terminals, using impedance spectroscopy and time-domain modeling. The SOFC experiments are performed using excitation from the power electronic ripple current and exogenous excitation generated from several different sources including a hybrid system which uses a secondary power source for the generation of the small-signal currents. The PEMFC experiments are performed using exogenous excitation from a boost converter. In contrast to typical off-line analysis using specialized instrumentation, the measurements are made as the stacks deliver power to their respective loads. The power electronic switching waveform is used as a source of excitation. This technique could be implemented on-line for continuous condition assessment of the stack. The results show typical data from the stack, comparison of model predictions and measured data, and whole-stack impedance spectroscopy results.
INTRODUCTION

Fuel cells promise to be an important technology for chemical to electrical energy conversion because of their low emissions, scalability, and high efficiency [2]. Fuel cells achieve their efficiency advantage relative to conventional heat-engines by partitioning the overall oxidation of the fuel source so that the electrons involved are directed through an external circuit. In contrast, traditional thermal plants burn fuel to produce thermal energy, use a heat engine to convert thermal to mechanical energy, and finally a generator to produce electricity from the rotation of a shaft. Also unlike thermal plants, fuel cells can achieve good efficiency relatively independent of their scale. This has led to a wide range of envisioned and emerging applications, including portable electronics, large stationary electric power, distributed power, backup power, auxiliary and propulsive power for UAVs, and auxiliary power for space vehicles. Many of these applications are “high-end”, in the sense that they are either technology demonstration projects or niche areas where high cost and frequent replacement are tolerable. However, there is an increasing realization that the commercial viability of fuel cells depends on enhanced reliability and durability [3, 4]. Much of the effort in this area is appropriately focused on materials development using traditional materials science methodologies, e.g. single cell or even single component testing in controlled environments thought to be similar to the conditions inside a stack. However, there is also interest in understanding degradation phenomena that can occur as fuel cells are integrated into real systems. As an example, in [5], Ramschak et al. provide a method to detect the failure of a single cell within a stack by analyzing the harmonic distortion of the stack voltage. Similarly, in [6] Gemmen et al. study the impact of inverter load dynamics on a fuel cell, with the conclusion that stack / inverter
interaction is significant in the operating conditions and long term behavior of the stack.

*In-situ* Fuel Cell Stack Characterization

*In-situ* whole stack characterization of fuel cells has not been widely reported upon in literature. This thesis demonstrates *in-situ* characterization of both an SOFC stack and a PEMFC stack at their electrical terminals. This method requires minimal instrumentation only at the stack electrical terminals, and in many cases can be integrated with the controls of existing power electronics to provide non-invasive, low cost stack prognostics. Furthermore, *In-situ* characterization can be performed without interfering with the overall operation of the stack and without disturbing the load, and it could ultimately be integrated with fuel cell systems in the field to provide feedback on how these systems perform in real-world circumstances. The underlying motivation of this work, not directly addressed in this thesis, is that it may ultimately be able to improve reliability, implement on-line stack prognostics, and mitigate materials challenges through controls at the electrical terminals that are richly informed of the state of the stack.

In this thesis several techniques are demonstrated that can be applied to the electrical terminals to measure the state of the fuel cell stack. Calculations of whole stack impedance spectroscopy is used to obtain a non-parametric characterization of the stack, and a time-domain analysis is performed resulting in a parametric model of the stack. These characterizations use both the switching waveform of the power electronics connected to the stacks and an exogenous excitation. The SOFC stack characterization is performed while the stack is delivering power to the grid and
under control of power electronics, and the characterization of the PEMFC stack is performed while under control of a power electronic boost converter.

Three sets of experiments were performed using the SOFC, and then a final set of experiments was performed using the PEMFC. The excitation used in the first set of experiments with the SOFC was composed only of the ripple from the existing power electronics. This demonstrated a minimal instrumentation approach to perform whole stack characterization, using only the stack current and voltage waveforms. However, this approach will not support models containing slower dynamics, since the frequencies present in this excitation consists only of the power electronics switching frequency and harmonics. Additionally, the power electronics for the Alpha 8 SOFC switches at 12.3 kHz and the magnitude of the ripple current is nearly 20% of the DC value. It is expected that the power electronics of future fuel cell systems will switch at a significantly higher frequency and contain a lower magnitude ripple current, thereby limiting the usefulness of using only the ripple current from the power electronics.

An exogenous test signal was introduced to the SOFC stack, and a second set of experiments was performed. The exogenous test signal contained frequencies lower than the power electronics switching frequency, so lower frequency dynamics could be observed.

A third set of experiments was performed with a hybrid power electronics system providing the exogenous excitation for the SOFC. The hybrid system contains a second power source allowing informative experiments to be done on the SOFC stack independent of the load and without interfering with the operation of the fuel cell. Typical fuel cell power electronics include a secondary power source allowing low-cost, non-invasive, in-situ characterization of fuel cell stacks without the addition of external test equipment.
Since significant power electronics ripple current was present for all tests using the Alpha 8 SOFC, a PEMFC stack with a simple boost converter was used for the final set of experiments. The boost converter switching frequency was high enough such that the ripple current was not used for the identification of the PEMFC stack. The operating point of the PEMFC is established by the set point of the boost converter duty cycle, and the dither of the duty cycle introduces the test signal. This experiment illustrates that a test system fully integrated with the stack power electronics can be implemented with a simple circuit and simple control.

**Thesis Organization**

The thesis begins with an overview of SOFCs and PEMFCs and a discussion of electrochemical impedance spectroscopy (EIS) and associated system identification considerations in chapter 2. Also in chapter 2 a lumped parameter, time-domain model and identification procedure for the small signal response of the stack is suggested. The SOFC experimental setup and results are described in chapters 3 and 4, and the PEMFC experimental setup and results are described in chapter 5. The thesis concludes in chapter 6 with a summary of the results and a discussion as to how the implementation of this work could lead to an increase in the life-cycle and cost-effectiveness of fuel cell systems.
FUEL CELL MODELING

Fuel Cells

A fuel cell is an electrochemical device which converts fuel directly to electricity through a two-part chemical reaction. The oxidation half reaction occurs at the anode where electrons are removed from the fuel, and the reduction half reaction occurs at the cathode where electrons are added to the oxidant. A non-conductive electrolyte separates the anode and cathode, so the electrons must flow through an external circuit from the anode to the cathode. Ions are produced by one half reaction and then consumed by the other half reaction. Depending on the type of fuel cell these ions conduct through the electrolyte either from the anode to the cathode or from the cathode to the anode. In this way, electricity will be generated as long as the fuel cell is continually supplied with fuel and oxidant [7]. Figures 2.1(a) and 2.1(b) are schematic representations of a SOFC and a PEMFC, respectively.

The current produced by the fuel cell is proportional to the reaction surface area, so the electrodes are made to be porous in order to increase the surface area. The porous electrodes also allows good access of the reactants to the site where the reaction occurs. A catalyst is used to improve the efficiency of the reactions, and the electrolyte is made as thin as possible in order to minimize the resistive loss due to the ionic transport through the electrolyte [7].

Fuel cells are typically classified by the type of electrolyte they use [8, 7, 9, 10], and the electrolyte type determines the direction of the ionic flow, the operating temperature of the fuel cell, and type of fuel which can be used in the fuel cell. In this thesis experiments were conducted with a SOFC as well as a PEMFC. SOFCs use a ceramic-type metal oxide electrolyte, typically yttria-stabilized zirconia. At high
Figure 2.1: Schematic representation of a solid oxide fuel cell and a proton exchange membrane fuel cell.
temperatures (600 – 1000°C), these electrolytes are good conductors of \( O^{2-} \) ions. Because of its high operating temperature and \( O^{2-} \) conduction mechanism, SOFCs can use hydrocarbon fuel as well as hydrogen [10]. The Siemens Alpha 8 SOFC used in these experiments uses natural gas, which consists primarily of methane, as its fuel. Equations (2.1,2.2,2.3) describe the reactions when an SOFC utilizes hydrogen as its fuel [10].

\[
\begin{align*}
H_2 + O^{2-} & \rightarrow H_2O + 2e^- \quad \text{(anode reaction)} \quad (2.1) \\
\frac{1}{2}O_2 + 2e^- & \rightarrow O^{2-} \quad \text{(cathode reaction)} \quad (2.2) \\
H_2 + \frac{1}{2}O_2 & \rightarrow H_2O \quad \text{(overall reaction)} \quad (2.3)
\end{align*}
\]

When methane is used as the fuel in an SOFC the direct electrochemical reaction of methane at the anode is negligible [11]; however, because of the high temperature of the SOFC and the presence of water vapor at the anode, it is likely the methane is internally reformed before it reaches the reaction site. Equations (2.4,2.5) describes one process by which this occurs. In (2.4) the methane reacts with steam to produce carbon monoxide and hydrogen. Some of the carbon monoxide is directly oxidized at the anode according to (2.6,2.7,2.8); however, most of the carbon monoxide further reacts with steam to form carbon dioxide and hydrogen according to the water-gas shift reaction (2.5) [11]. External reforming of methane is also possible.

\[
\begin{align*}
CH_4 + H_2O & \rightarrow CO + 3H_2 \quad \text{(steam methane reforming reaction)} \quad (2.4) \\
CO + H_2O & \rightarrow CO_2 + H_2 \quad \text{(water–gas shift reaction)} \quad (2.5) \\
CO + O^{2-} & \rightarrow CO_2 + 2e^- \quad \text{(anode reaction)} \quad (2.6) \\
\frac{1}{2}O_2 + 2e^- & \rightarrow O^{2-} \quad \text{(cathode reaction)} \quad (2.7) \\
CO + \frac{1}{2}O_2 & \rightarrow CO_2 \quad \text{(overall reaction)} \quad (2.8)
\end{align*}
\]
PEMFCs utilize a thin polymer membrane electrolyte which is a good conductor of $H^+$ ions [10]. The low operating temperature ($60 - 80^\circ C$) and catalyst of the PEMFC causes it to be sensitive to poisoning by fuel impurities, e.g. CO [9, 10]. Poisoning occurs when an impurity like CO aggregates onto the catalyst. The catalyst is deactivated by the blocking of reaction sites [7]. Equations (2.9,2.10,2.11) describe the PEMFC reactions [10].

\[
H_2 \Rightarrow 2H^+ + 2e^- \text{ (anode reaction)} \quad (2.9)
\]

\[
\frac{1}{2}O_2 + 2H^+ + 2e^- \Rightarrow H_2O \text{ (cathode reaction)} \quad (2.10)
\]

\[
H_2 + \frac{1}{2}O_2 \Rightarrow H_2O \text{ (overall reaction)} \quad (2.11)
\]

According to [7], there are three major types of fuel cell losses. Activation losses are due to reaction kinetics and they are the dominant loss at low currents. At high currents concentration losses are dominant. Concentration losses are due to byproduct counterflow and the mass transport of the fuel and oxidant, e.g. in the PEMFC the formation of $H_2O$ at the cathode impedes the flow of the oxidant to the reaction site. Ohmic losses are due to ionic and electronic conduction, and they are most apparent in the middle part of the $I - V$ curve. These three loss types are shown in the fuel cell $I - V$ curve of Fig. 2.2. The fuel cell output voltage can thereby be written as

\[
V = E \cdot n_{\text{cells}} - v_{\text{act}} - v_{\text{ohm}} - v_{\text{conc}} \quad (2.12)
\]

where $V$ is the actual output voltage of the fuel cell stack, $E$ is the ideal cell output voltage, $n_{\text{cells}}$ is the number of cells in the stack, $v_{\text{act}}$ are the activation losses, $v_{\text{ohm}}$ are the ohmic losses, and $v_{\text{conc}}$ are the concentration losses [7]. The ideal fuel cell output voltage $E$ is given by the Nernst equation

\[
E = E^0 + \frac{RT}{2F} \ln \left( \frac{P_{H_2} \cdot P_{\frac{1}{2}O_2}}{P_{H_2O}} \right) \quad (2.13)
\]
where $E^0$ is the ideal cell voltage at standard pressure, $R$ is the gas constant, $T$ is the temperature, $F$ is Faraday’s constant, and $P_{H_2}$, $P_{O_2}$, and $P_{H_2O}$ are the partial pressures of $H_2$, $O_2$, and $H_2O$, respectively.

**Fuel Cell Equivalent Circuit**

Equivalent circuit models are widely used in the study of fuel cells, and numerous fuel cell equivalent circuit models have been reported in literature [4, 10, 12, 13, 14]. The equivalent circuit model is attractive since each circuit element has a corresponding physical or chemical meaning [4]. Figure 2.3 shows the three equivalent circuit models used in this thesis.

Figure 2.3(a) is the simplest model and is derived from the straight line approximation of the ohmic region of the fuel cell $I-V$ curve. In this model $R$ is the ohmic resistance, $L$ is the internal inductance of the fuel cell, and $V_o$ is the stack voltage at bias point $I_o$. The equivalent circuit model in Fig. 2.3(b) is derived from the model...
Figure 2.3: Equivalent circuit models for solid oxide and proton exchange membrane fuel cells.
proposed by Nehrir et al. in [10]. This model adds the parallel combination of \( R_1 \) and \( C_1 \). According to [7], the impedance behavior of an electrode-electrolyte interface can be modeled as the parallel combination of a resistor and capacitor. Here, \( C_1 \) is the *double-layer capacitance* which models the capacitive behavior of the interface, and \( R_1 \) is the *Faradaic resistance* which models the kinetics of the electrochemical reaction. In this model the cathode and anode impedances are lumped together; however, in [12], Wagner et al. show that the cathode and anode impedances can both be determined. The equivalent circuit model in 2.3(c) adds the parallel combination of \( R_2 \) and \( C_2 \). Here, \( C_1 \) and \( R_1 \) are the *double-layer capacitance* and the *Faradaic resistance* associated with one of the electrodes, and \( C_2 \) and \( R_2 \) are those same quantities associated with the opposite electrode. With this model the dynamics, in principle, for each electrode can be determined.

**Fuel Cell Impedance Spectroscopy**

Electrochemical impedance spectroscopy models the AC electrical terminal response of a fuel cell (or other electrochemical system) as an impedance, i.e.

\[
V(j\omega) = I(j\omega)Z(j\omega).
\]  

(2.14)

In this equation, \( V(j\omega) \) is the AC cell voltage in the frequency domain, \( I(j\omega) \) is the cell current and \( Z(j\omega) \) is the cell impedance. Electrochemical impedance spectroscopy experiments are often performed under a DC bias current corresponding to a nominal operating point. In the time domain, the electrical terminal quantities are

\[
v_c(t) = V_o + v(t)
\]

(2.15)

\[
i_c(t) = I_o + i(t)
\]

(2.16)
where $v(t)$ is $V(j\omega)$ in the time domain, $V_o$ is the cell voltage at the bias point $I_o$, and $v_c(t)$ and $i_c(t)$ are the cell terminal voltage and current. Use of this model presumes that the cell responds linearly over the range of excitation in the vicinity of the bias point, i.e. that excitation at a single frequency produces a response at that frequency. For this assumption to hold it is necessary for the cell to be operating in the ohmic region.

An estimate of the impedance response, $\hat{Z}(j\omega)$, can be extracted from measurements of the terminal voltage and current under sufficiently rich excitation. In particular, an impedance estimate is

$$\hat{Z}(j\omega) = \frac{V_c(j\omega)}{I_c(j\omega)}, \quad |\omega| > 0 \quad (2.17)$$

where $V_c(j\omega)$ and $I_c(j\omega)$ are estimates of the frequency domain representations from measured electrical terminal responses $v_c(t)$ and $i_c(t)$. The process of estimating spectral content of signals using sampled data and discrete-time Fourier transform techniques, including windowing and other considerations, is reviewed in [15] among others. Significantly, note that the excitation $i_c(t)$ imposed at the electrical terminals must be broadly exciting, i.e. if $I_c(j\omega)$ lacks content at some frequency, or is dominated by noise, the variance in $\hat{Z}(j\omega)$ can be large. Rich excitation can be achieved with broad band excitation, or with a series of narrow band signals, such as a sinusoid. Alternatively, a practical measure is to restrict evaluation of $\hat{Z}(j\omega)$ to frequencies where there is sufficient excitation. Sinusoidal excitation has the advantage of revealing whether the system response comprises more than the single excitation frequency, providing the information needed to check the implicit assumption of linearity.

Impedance spectroscopy is a standard technique for characterization of electrochemical systems, including fuel cells. Typical examples include the analysis of a PEM cell in [16] and the application to an SOFC cell in [12]. Specialized test equip-
ment, using sinusoidal excitation, is generally used to obtain impedance spectroscopy results. A frequency range of 0.01Hz to 1MHz is typical for studying SOFC systems [4]. Impedance spectroscopy results are generally displayed using a Nyquist plot showing real and complex parts of the impedance with frequency as an implicit argument. An electrochemist can recognize the characteristic shapes of typical processes in the Nyquist diagram [17]. From the system identification point of view, this kind of characterization is a non-parametric analysis. However, practitioners often propose lumped parameter circuit models for impedance spectroscopy results, and in some cases correlate physical processes with individual circuit elements. In [12], a parameterized impedance spectroscopy model is used to synthesize an equivalent circuit of an SOFC. For a survey of impedance spectroscopy in fuel cells, see [18].

With the Siemens Alpha 8 SOFC stack, and in many similar fuel cell applications, it is not feasible to characterize the stack using specialized instrumentation because the stack can not be removed from service. However, given sufficiently rich measurements of $i_c(t)$ and $v_c(t)$, it should be possible to estimate the impedance of the stack. To this end, the electrical terminal current and voltage is measured under a composite excitation consisting of the power management system ripple current and test signals injected using programmable loads.

**Time-domain Modeling and Identification**

In addition to impedance spectroscopy, there are several examples where fuel cell behavior is modeled directly using a differential equation model. Hall [19] develops a transient model of a tubular SOFC which includes electrochemical, thermal, and mass flow elements. Wang et al. [13] develop a dynamic model for a PEMFC using electrical circuit elements, and Pasricha et al. [20] provide a dynamic electrical terminal model
of a PEMFC. Like impedance spectroscopy, the richness of the data determines the number of model elements that can be supported.

The three-parameter ohmic model in 2.3(a) can be written as

\[ v(t) = V_o - Ri(t) - Ls i(t), \]  

(2.18)

where \( v(t) \) is the stack voltage, \( i(t) \) is the stack current, \( V_o \) is the nominal stack voltage, \( R \) is the resistance, \( L \) is the inductance, and \( s \) is the \( \frac{d}{dt} \) operator. With an abuse of notation, \( s \) may be thought of as the independent variable of the Laplace transform.

To obtain estimates for the parameters of (2.18), it is necessary to evaluate the derivative \( s i(t) \). This presents a variety of practical problems, particularly when \( i(t) \) is available as a set of noise-corrupted measurements. To avoid these difficulties, a model transformation technique [15] is used with the operator

\[ \lambda = \frac{1}{1 + s\tau}. \]  

(2.19)

Isolating \( s \) yields

\[ s = \frac{1 - \lambda}{\lambda\tau}. \]  

(2.20)

Substituting \( s \) into (2.18) and rearranging to avoid \( \lambda \) in the denominator, results in the transformed model

\[ \lambda\tau V_o - \tau\lambda i(t)R + (\lambda - 1)i(t)L = \tau\lambda v(t). \]  

(2.21)

This is appealing because \( \lambda\tau \), \( \lambda i(t) \), and \( \lambda v(t) \) can be evaluated using a discrete-time implementation of \( \lambda \), which is a low pass filter. In the analysis, the \( \lambda \) operator is applied to large data sets and the transient portion corresponding to zero initial conditions is eliminated. Also, \( \lambda \) must be selected with some consideration to the
time constants apparent in the data. Setting $\lambda \tau V_o$ to the final value forms the least squares tableau

$$
\begin{pmatrix}
\tau & -\tau \lambda i[1] & (\lambda - 1)i[1] \\
\tau & -\tau \lambda i[2] & (\lambda - 1)i[2] \\
\vdots & \vdots & \vdots \\
\tau & -\tau \lambda i[n] & (\lambda - 1)i[n]
\end{pmatrix}
\begin{pmatrix}
V_o \\
R \\
L
\end{pmatrix}
= 
\begin{pmatrix}
\tau \lambda v[1] \\
\tau \lambda v[2] \\
\vdots \\
\tau \lambda v[n]
\end{pmatrix}
$$

(2.22)

which can be solved to obtain estimates for the parameters $V_o$, $R$, and $L$. In (2.22), the notation $\lambda i[n]$ indicates the $n$’th sample of the result of applying a discrete-time implementation of $\lambda$ to the sampled input signal $i[k] = i(kT)$. 
SOFC EXPERIMENTS

Some figures in this section were obtained from "In-situ Electrical Terminal Characterization of a 5 kW Solid Oxide Fuel Cell Stack" which was submitted for publication in *IEEE Transactions on Energy Conversion* [21].

**Experimental Setup**

**Instruments**

Figure 3.1 shows a photograph of the Siemens Alpha 8 5kW SOFC, which uses city natural gas for fuel. Figure 3.2 shows an overall schematic of the Siemens 5kW stack, connections to the built-in power electronics and storage, and the locations of the measurements. Under steady-state operation, the unit is configured to regulate current from the stack with a front-end boost converter connected to an array of batteries. A three-phase inverter is then controlled to transfer power to the grid. The stack current is measured using a Tektronix A6303 current probe, while the voltage is measured using an isolated, differential Tektronix 5205 probe. Signals from both probes are recorded using a National Instruments data acquisition system with a PXI-5122 14-bit analog to digital converter. Sampling was conducted at a minimum of 2MS/s to avoid under-sampling issues.

**Test Procedure**

Two types of experiments were conducted with one using only the stack ripple current as the excitation, and the other using an exogenous excitation in addition to the stack ripple current. For the experiments without the exogenous excitation data was collected at 10MS/s for a duration of 10ms, which provided over 100 cycles of the stack ripple current. For experiments using the exogenous excitation, a pro-
Figure 3.1: Siemens Alpha 8 5kW Solid Oxide Fuel Cell.

Figure 3.2: Schematic illustration of stack, power electronics, and measurements. Components within the dashed line are part of the Siemens Alpha 8 system.
grammable electronic load was configured, as in Fig. 3.2, to introduce an auxiliary current in addition to that supplied by the stack power electronics. When using this exogenous source, the Agilent N3302A was configured to a DC level of 2.5A, and introduced a 4A peak-to-peak waveform in addition to the DC level. In this manner, the N3302A is assured to absorb power and remain within the range of operation where full performance can be maintained. The N3302A was used to introduce auxiliary test signals from 4.6Hz to 21.6kHz. For these experiments sampling was conducted at 2MS/s, but the number of samples collected was adjusted to provide a minimum of 80 cycles of the exogenous excitation.

Results

Ripple Current Excitation Experiments

Figure 3.3 shows typical data collected from the test setup in Fig. 3.2 under steady state operating conditions. The current and voltage levels in Fig. 3.3, nominally 100A and 28V, were typical of the stack load during testing and show the substantial ripple current excitation due to the power electronic control system. The measured stack current in Fig. 3.3(a) is represented by data points, which have been decimated for clarity.

Figure 3.4 shows a magnitude and phase representation of the impedance of the stack as a function of frequency, using the ripple current excitation shown in Fig. 3.3. Data points show the non-parametric representation of stack impedance as calculated by the ratio of voltage and current spectral content of the measured waveforms, while the line shows the response of model in (2.18) with parameters $V_o = 34.7V$, $R = 0.0677\Omega$, and $L = 0.471\mu H$, which were derived using the model transformation technique described in chapter 2. The identification of the three-parameter model
Figure 3.3: Stack current and voltage, measured as indicated in Fig. 3.2. The triangle current waveform in 3.3(a) is due to the operation of the DC/DC converter in the system. The corresponding voltage of the stack appears in 3.3(b).
from 2.3(a) is appropriate here since the frequency spectra of the excitation contains only the fundamental switching frequency and several of its harmonics. The line in Fig. 3.3(a) shows the time-domain current predictions of the parameterized model. In Fig. 3.4, only selected data points in the non-parametric response are shown. Plotted data points correspond to frequencies where the magnitude of the current excitation exceeds a user-selected threshold. This effectively constrains the plot to fundamental and harmonic frequencies of the power electronic ripple. The noise associated with impedance estimates with little or no supporting excitation would otherwise obscure the results.

In addition to fitting models to individual data sets, stack current and voltage waveforms were captured each week over a period of nine months to track the degradation of the system. Fig. 3.5 summarizes this data by showing the trend in the resistance parameter $R$, nominal stack voltage parameter $V_o$, and inductance parameter $L$ obtained by fitting (2.18) to the data, minimizing voltage predictions in the least squared sense. The perturbation in resistance between October and November 2008 corresponds to an adjustment in operating conditions that resulted in a 15°C increase in stack temperature. Similarly, the spike between March and April corresponds to a data set that was collected when there was a temporary reduction of 17A in the operating point. Parameters $V_o$ and $L$ in (2.18) did not change significantly; however, they both exhibit the spike between March and April. It’s surmised that the increasing resistance trend reflects the degradation of one or more cells in the stack.

**Exogenous Excitation Experiments**

The power electronic ripple current provides excitation of the stack at and above the fundamental switching frequency of roughly 12kHz. An exogenous test signal was introduced using an active load (Fig. 3.2) to explore performance for frequencies
Figure 3.4: Stack impedance, $Z(j\omega)$, derived from the stack ripple current and voltage measurements. Results are shown for both the non-parametric and parametric models. (a) shows the magnitude of $Z(j\omega)$, and (b) shows the phase of $Z(j\omega)$. 
Figure 3.5: Nine month trend of (a) the resistance parameter, $R$, (b) the nominal stack voltage parameter, $V_o$, and (c) the inductance parameter, $L$, for the stack model in (2.18). Time period is summer 2008 to Spring 2009.
ranging from 4.6Hz to 21.6kHz. Both sine wave and square wave excitation was used. Figure 3.6 shows typical magnitude and phase responses for these experiments. The data in Fig. 3.6 can be compared to the result in Fig. 3.4, which shows magnitude and phase obtained from the ripple current waveforms. Note that Fig. 3.6 presents the impedance as a function of frequency with a log scale that emphasizes the behavior between DC and the power electronic switching frequency. Figure 3.7 shows Nyquist plots of $Z(j\omega)$, prepared according to the conventions for impedance spectroscopy, for the data obtained with exogenous excitation and ripple. The plots in Fig. 3.7(a) and Fig. 3.7(b) were obtained using square-wave excitation. Fig. 3.7(b) shows the low frequency portion corresponding to the exogenous excitation, while Fig. 3.7(a) shows a composite of the ripple current and exogenous excitation. Similarly, Fig. 3.7(d) shows low frequency sine wave results, while Fig. 3.7(c) shows a composite of exogenous and ripple current. The square-wave excitation results are more densely populated because each test probes the stack at the fundamental and harmonics of the test signal. The arc shape of the curve for low frequencies is characteristic of parallel $RC$ elements which is found in numerous equivalent circuit models of fuel cells. In the composite impedance spectroscopy results in Fig. 3.7(a) and Fig. 3.7(c), the data obtained from ripple current excitation is represented by discrete clusters – these correspond to the fundamental and harmonics of the power electronic switching waveform. As the magnitude of the harmonics decrease, the variance of each cluster increases.
Figure 3.6: Stack impedance, $Z(j\omega)$, derived from the exogenous excitation experiments. Results are shown for both the sine wave excitation and the square wave excitation. (a) shows the magnitude of $Z(j\omega)$, and (b) shows the phase of $Z(j\omega)$. 
Figure 3.7: Whole stack impedance spectroscopy results for various excitation types. (a) Square wave and ripple current result. (b) Low frequency portion due to square wave excitation. (c) Sine wave and ripple current result. (d) Low frequency portion due to sine wave excitation.
SOFC EXPERIMENTS WITH HYBRID POWER ELECTRONICS

Some figures in this section were obtained from ”Characterization of a 5 kW Solid Oxide Fuel Cell Stack using Power Electronic Excitation” which was submitted for publication in *Proceedings of IEEE Applied Power Electronics Conference* [1].

**Experimental Setup**

John Cooley, Massachusetts Institute of Technology Ph.D. candidate, developed a hybrid power electronics system consisting of two commercial power supplies and a secondary power source. This system generates small-signal currents at the fuel cell terminals without disturbing the load current. The exogenous excitation experiments in chapter 3 were repeated except this hybrid power system was used for the exogenous excitation. Figure 4.1 is a simplified schematic of the hybrid power system. A detailed description of the design of the hybrid power system is found in [1].

**Instruments**

Figure 4.2 shows an overall schematic of the Siemens 5kW stack, connections to the built-in power electronics, the hybrid power system, and the locations of the measurements. The hybrid power system is connected to the stack terminals as indicated in Fig. 4.2. An HP 6010A power supply was used as the secondary power supply, and a Tektronix CFG250 function generator supplied the control signal to the hybrid power system. The stack current is measured using a Tektronix A6303 current probe, while the voltage is measured using an isolated, differential Tektronix 5205 probe. Signals from both probes are recorded using a National Instruments data acquisition system with a PXI-5122 14-bit analog to digital converter. Sampling was conducted at a minimum of 2MS/s to avoid under-sampling issues.
Figure 4.1: A hybrid power system with EIS functionality built from off-the-shelf components [1].
Test Procedure

The hybrid power system load was configured, as in Fig. 4.2, to introduce an auxiliary current in addition to that supplied by the stack power electronics. When using this exogenous source, the hybrid power system was configured to introduce into the stack a 3.4A DC current with a 2A peak-to-peak waveform riding on top of the DC level. In this manner, it is assured that the hybrid power system absorbs power and remains within the range of operation where full performance can be maintained. The hybrid power system was used to introduce auxiliary test signals from 1.0Hz to 10.0kHz. For these experiments sampling was conducted at a minimum of 2MS/s. Fig. 4.3 shows typical data collected from the test setup in Fig. 4.2 when excited by the hybrid power system. Figure 4.4 is an oscilloscope screen shot showing the battery and stack currents when the hybrid power system was supplying a 100Hz exogenous current to the stack.
Figure 4.3: Stack current and voltage, measured as indicated in Fig. 4.2. The triangle current waveform in (a) is due to the operation of the DC/DC converter in the system. The corresponding voltage of the stack appears in (b).
Figure 4.4: An oscilloscope screen shot showing the battery and fuel cell currents during run-time EIS (≈ 100Hz). Top to bottom: load voltage (ch2), fuel cell current (ch3), battery current (ch4), control signal (ch1). The excitation current flows out of the battery terminals and into the fuel cell terminals while the load voltage is largely unaffected by the run-time EIS measurement [1].
Results

The power electronic ripple current provides excitation of the stack at and above the fundamental switching frequency of roughly 12kHz. An exogenous test signal was introduced using the hybrid power system load (Fig. 4.2) to explore performance for frequencies ranging from 1.0Hz to 10.0kHz. Figure 4.5 shows Nyquist plots of $Z(j\omega)$, prepared according to the conventions for impedance spectroscopy, for the data obtained with exogenous excitation and ripple. Figure 4.5(b) shows the low frequency portion corresponding to the exogenous excitation, while Fig. 4.5(a) shows a composite of the ripple current and exogenous excitation. The arc shape of the curve for low frequencies is characteristic of parallel $RC$ elements which is found in numerous equivalent circuit models of fuel cells. In the composite impedance spectroscopy results in Fig. 4.5(a), the data obtained from ripple current excitation is represented by discrete clusters – these correspond to the fundamental and harmonics of the power electronic switching waveform. As the magnitude of the harmonics decrease, the variance of each cluster increases.

The stack current and voltage waveforms obtained from the 1kHz power electronic excitation were used to identify the parameters in (2.18), and the resulting estimates were $V_o = 34.1V$, $R = 0.0677\Omega$, and $L = 0.471\mu H$. This experiment was performed in May, 2009, and these values are comparable to the values in Fig. 3.5 corresponding to May, 2009. A cross-validation was performed by simulating (2.18) using the estimated parameters $V_o$, $R$, and $L$ and the stack voltage waveform obtained from the 5.4kHz excitation. Figure 4 shows the measured and predicted 5.4kHz current waveforms.
Figure 4.5: Whole stack impedance spectroscopy results. (a) Stack response to ripple current and power electronic test signal. (b) Low-frequency portion of stack response showing response to power electronic test signal.
Figure 4.6: Measured and predicted stack current as a function of time.
PEMFC EXPERIMENTS

Experimental Setup

PEMFC Fuel Cell Stack

The PEMFC stack used for these experiments was constructed from four series connected PEMFC modules which were removed from an Avista Labs 500W SR-12 PEMFC stack. Each of the four PEMFC modules contained two 2-cell stacks. All 16 cells were electrically connected in series as shown in fig. 5.2. The output capacity of this stack is approximately 165W. Additionally, each PEMFC module had a hydrogen gas input as well as an exhaust output. Figure 5.1 shows a photograph of this PEMFC 16-cell stack.

Hydrogen Supply

Each PEMFC module was connected to the 99.95% pure hydrogen supply through a 0 to 30 PSI regulator, and was exhausted through a needle valve into a flask of water providing visual indication of hydrogen flow. This allowed static control of the hydrogen pressure and flow rate; however, dynamic control was not possible. Also, forced air flow through the modules was not provided.

PEMFC Load

The PEMFC load was provided by a DC-DC boost converter. The PEMFC stack was connected to the boost converter input, and the boost converter output was connected to a Chroma 63112 DC load. The boost converter was operated open-loop with its duty cycle controlled by a Tektronix AFG 3022B function generator. In this manner the current drawn from the PEMFC stack was indirectly controlled by the boost converter duty cycle, $D_1$. 
Figure 5.1: PEMFC Fuel Cell Stack.

Figure 5.2: Schematic illustration of PEMFC stack, power electronics, and measurements.
Data Collection

The stack current is measured using a Tektronix TCP202 current probe, while the stack and two cell voltages are measured using Tektronix P6139A voltage probes. Signals from the four probes are recorded using a National Instruments data acquisition system with two PXI-5122 14-bit analog to digital converters. Sampling was conducted at a minimum of 1MS/s to avoid under-sampling issues.

Boost Converter

Operation

Figure 5.3 is a schematic of a typical boost converter. When switch S₁ turns on, energy is transferred into the inductor, L, from the boost converter input, resulting in an increase in inductor current, $i_L(t)$. When switch S₁ turns off, energy is transferred from L through diode, D, to the output capacitor, $C_{out}$, and to the boost converter output, resulting in a decrease of $i_L(t)$. The decreasing $i_L(t)$ induces a negative $v_L(t)$ forcing the output voltage, $V_{out}$, higher than the input voltage, $V_{in}$. In steady state operation the energy gained by L when S₁ is on must equal the energy lost by L when S₁ is off which results in a constant ripple current in L. $C_{out}$ sinks current from L when S₁ is off and sources current to the boost converter output when S₁ is
The input capacitor, $C_{in}$, reduces the ripple current seen at $V_{in}$. To reduce the losses in $D$, $S_2$ can be turned on whenever $S_1$ is off. For an ideal boost converter the relationships between $V_{in}$, $V_{out}$, $I_{in}$ and $I_{out}$ can be expressed as

$$V_{out} = \frac{V_{in}}{1 - D_1}, \tag{5.1}$$

and

$$\frac{V_{in}}{V_{out}} = \frac{I_{out}}{I_{in}} = D_2 \tag{5.2}$$

where $D_1$ is the duty cycle of $S_1$, $D_2$ is the duty cycle of $D$ (or $S_2$), $0 \leq D_1 < 1$, and $D_2 = 1 - D_1$ [22]. Equations 5.1 and 5.2 guarantee that $V_{out} > V_{in}$ and $I_{in} > I_{out}$.

**Design**

The output voltage of a fuel cell varies significantly with the output current, and since the boost converter would be supplied by a stack of fuel cells it was necessary to choose the component values to allow efficient operation over a wide input voltage range. The input voltage was assumed to be a maximum of 18V allowing operation with a 21 cell SOFC stack. The 16 cell PEMFC stack has an output voltage of approximately 8V when loaded at 8A, so operation at 8V was also necessary. Selecting an output voltage of 20V results in a realizable maximum voltage gain of 2.5 when $V_{in} = 8V$. The 47$\mu$H, 10A inductor chosen for this application coupled with the 100kHz switching frequency, limits the current ripple to about 20% over the intended operating range of the boost converter. The 100$\mu$F, 160V capacitors used for both $C_{in}$ and $C_{out}$ were chosen for their high ripple current capacity. MOSFET’s $S_1$ and $S_2$ are rated for 100V and 36A with an on resistance of 26.5$m\Omega$, and diode $D$, is a Schottky type rated at 10A and 60V. MOSFET $S_2$, which is in parallel with $D$, is used to increase the efficiency of the boost circuit. MOSFET $S_2$ is turned on whenever $S_1$ is off. Since $S_2$ will have a lower voltage drop across it than $D$, the
current will flow through $S_2$ rather than $D$ thereby reducing the losses. The diode is kept in the circuit since its reverse recovery characteristics are better than those of the intrinsic body diode of $S_2$, which helps tame the switching transients when $S_1$ is turned on. The half-bridge driver used to drive $S_1$ and $S_2$ is designed for synchronous operation. The built-in deadtime prevents $S_1$ and $S_2$ from conducting simultaneously.

Figures 5.4(a) and 5.4(b) show the top side and bottom side of the boost converter, respectively. Care was taken in the parts placement to minimize parasitic inductance. In particular, $S_1$ and $D$ were placed back to back to allow the shortest possible path
between them. This is the most critical node in terms of keeping switching transients low.

**Verification**

Figure 5.5(a) shows the input voltage, output voltage, switching waveform, and inductor current when the converter was operating with an output power of 80W. With the input voltage was set to 16.0V and the output voltage was clamped at 20.0V, the mean inductor current was measured at 5.0A, and the output current was measured at 4.05A. Figures 5.5(b) and 5.5(c) show the same waveforms but with the time scale adjusted to show the *turn-on* and *turn-off* transients. With an output power of 40W the efficiency was greater than 97%, and with an output power of 100W the power loss in the converter was still less than 7W.

Static tests were conducted to see how the PEMFC stack would perform with the boost converter as its load. For these tests the boost converter output was clamped to 20V using the Chroma electronic load. The duty cycle was varied from 49% to 68.8% and the stack voltage, cell voltages, and stack current were recorded. Figure 5.6(a) shows the stack voltage and output power as a function of current, and Fig. 5.6(b) shows the cell voltages as a function of stack current. In Fig. 5.6(a) the stack voltage decreases linearly as the stack current increases which is a good indication that the PEMFC is operating in the ohmic region. Figure 5.7 shows the stack current as a function of boost converter duty cycle. Here it can be seen that this relationship is nearly linear. This allows the stack current to be controlled by modulating the boost converter duty cycle with the resulting stack current waveform being proportional to modulating waveform.
(a) Boost converter switching waveforms.

(b) Boost converter turn on.

(c) Boost converter turn off.

Figure 5.5: Boost converter switching waveforms.
(a) PEMFC stack voltage and power as a function of stack current.

(b) PEMFC cell voltage as a function of stack current.

Figure 5.6: PEMFC voltage vs current and power vs current.
Figure 5.7: PEMFC stack current as a function of boost converter duty cycle. The boost converter output was clamped at 20V.

Test Procedure

The hydrogen supply was turned on and the regulator was adjusted to the desired pressure. The needle valve was adjusted such that a steady stream of bubbles was present in the water. The Chroma DC load was configured to clamp the boost converter output voltage to 20V. The Agilent function generator was configured to output a 60% duty cycle, 100kHz pulse, causing the boost converter to draw 5A from the PEMFC stack. After allowing the PEMFC to warm up for 13 minutes, the boost converter duty cycle was modulated by a sinusoid that was swept from 0.3Hz to 30kHz over a 50s period. The magnitude of the modulation was adjusted to produce the desired magnitude of AC stack current excitation. Using the NI PXI 5122 data acquisition system, the Tektronix current probe, and three Tektronix voltage probes, the stack current, stack voltage, voltage at the negative terminal of cell 1A, and voltage at the positive terminal of cell 1B were recorded. In order to avoid aliasing, the sample rate was 1MS/s. Typical stack current, stack voltage, and cell voltage waveforms are shown in Figs. 5.8(a), 5.8(b), and 5.8(c).
Figure 5.8: PEMFC voltage and current.

(a) Typical PEMFC stack current as a function of time.

(b) Typical PEMFC stack voltage as a function of time.

(c) Typical PEMFC cell voltage as a function of time.
Results

The current and voltage waveforms were analyzed first, in the frequency domain in order to obtain an impedance estimate. Then a time domain analysis was used to identify the parameters of several PEMFC equivalent circuit models.

Data Preprocessing

The current and voltage waveforms were recorded over a 50s period at a sampling rate of 1MS/s resulting in $5 \times 10^7$ data points for each waveform. Working with waveforms of this size can be problematic, so each waveform was lowpass filtered at 13.33kHz and then decimated by a factor of 30, which reduced the data to $1.67 \times 10^6$ data points per waveform. Even though the waveforms contained frequencies up to several harmonics of the 100kHz switching frequency, the magnitudes were small resulting in a poor signal to noise ratio, so filtering at 13.33kHz did not result in the loss of meaningful data.

Impedance Estimation

Since the stack excitation current was a swept sinusoid, applying a window to the full time domain waveforms would result in poor signal to noise ratio at both the low and high frequencies. So the time domain waveforms were analyzed in the frequency domain using a moving window FFT. First, a Blackman window was constructed with a width spanning a fraction of a decade in frequency. Starting at the beginning of the waveform, this window was applied multiple times; however, each successive time the window was shifted higher in frequency. An FFT was performed on each set of windowed data. Since the waveforms were of a swept sinusoid, the bandwidth of the windowed data was narrow and the resulting FFT contained a single, well defined peak. The value of the FFT at the frequency of the peak was recorded for
each set of windowed data. This process was repeated for each waveform, and the
impedance estimate at each of these frequencies was calculated by dividing the FFT
of the voltage waveform by the FFT of the current waveform. Figure 5.9(a) is a
Nyquist plot of the stack impedance estimate of the PEMFC over several different
operating points, and Figs. 5.9(b), and 5.9(c) are plots of the impedances of cell 1A
and cell 1B, respectively, over the same operating points.

**Time Domain Parameter Estimation**

The time domain waveforms were also used to identify the parameters for the
PEMFC model. The number of identifiable parameters largely depends on the fre-
quency content of the current waveform used to excite the PEMFC stack. In order to
determine the expected number of parameters which are identifiable with the stack
current and voltage waveforms, the time-domain data was fit to ARX models of
several different orders. The ARX model family is described by

\[
A(q)y(t) = B(q)u(t) + e(t),
\]

where \(y(t)\) is the output, \(u(t)\) is the input, and \(e(t)\) is noise. The function \(A(q)\)
describes the autoregressive behavior of the output, and \(B(q)\) describes the treatment
of the exogenous input, \(u(t)\). For the ARX model, \(e(t)\) is simply added to the equation.

Solving for \(y(t)\) results in

\[
y(t) = \frac{B(q)}{A(q)}u(t) + \frac{1}{A(q)}e(t).
\]

So in the ARX model the error, \(e(t)\), is acted upon by the poles of the system; however,
it is likely that in the true system \(e(t)\) is not acted upon by the system poles.

Figure 5.10 shows the loss functions corresponding to the different ARX model
orders used to fit the time-domain data. In this plot \(na\) is the number of poles of
the model, \(nb\) is the number of zeros of the model plus one, and \(nk\) is the number
(a) PEMFC stack impedance plots at several different hydrogen pressures.

(b) PEMFC Cell1A impedance plots at several different hydrogen pressures.

(c) PEMFC Cell1B impedance plots at several different hydrogen pressures.

Figure 5.9: PEMFC Impedance
of input samples that occur before the input affects the output. The sum \( na + nb \) is the total number of unknown parameters in the corresponding model. The loss function describes how well the data fits the model, where a lower number reflects a better fit. For a simple model the loss function is expected to be high, as there would be dynamics not captured in the model. As additional parameters are added to the model, more of these dynamics are captured by the model and the loss function will decrease. There is a point, however, where adding additional parameters to the model will not significantly decrease the loss function. In Fig. 5.10 it is apparent that the lowest loss functions occurs for \( nk = 0 \). Furthermore, the loss function does not decrease significantly for models with more than six parameters. The specific ARX model order suggested by Fig. 5.10 is \( na = 3 \), \( nb = 3 \), and \( nk = 0 \). Figure 5.11(a) shows the measured output and the simulated output for an ARX model with \( na = 3 \), \( nb = 3 \), and \( nk = 0 \) (3 poles and 2 zeros). The fit for this model is 81.13\%, which is unsatisfactory.

The output error model family (OE) is described by

\[
y(t) = \frac{B(q)}{F(q)} u(t) + e(t)
\]  

(5.5)
[23] where \( y(t) \) is the output, \( u(t) \) is the input, and \( e(t) \) is noise. Here, the error is added in a more realistic way, as it is not acted upon by the system poles as in the ARX model. Figure 5.11(c) shows the measured output and the simulated output for an OE model with \( nb = 3, nf = 3 \), and \( nk = 0 \) (3 poles and 2 zeros). The fit is 96.04% which is significantly better than the ARX model. For comparison, the measured output and the simulated output for the OE model with \( nb = 2, nf = 2 \), and \( nk = 0 \) (2 poles and 1 zeros) is shown in Fig. 5.11(b). The fit for this model is 93.73%, which is considerably better than the higher order ARX model.

**Equivalent Circuit Component Calculation**

The impedance transfer function, \( \hat{Z}(s) \), corresponding to the 6-parameter equivalent circuit model in 2.3(c) is

\[
\hat{Z}(s) = \frac{f_1 s^3 + f_2 s^2 + f_3 s + f_4}{b_1 s^2 + b_2 s + b_3}
\]  

(5.6)

where \( b_1 = \frac{1}{L} \), \( b_2 = \frac{1}{L} \left( \frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} \right) \), \( b_3 = \frac{1}{LC_2 R_2 C_1 R_1} \), \( f_1 = 1 \), \( f_2 = \frac{R}{L} + \frac{1}{C_1 R_1} + \frac{1}{C_2 R_2} \), \( f_3 = \frac{1}{LC_2} + \frac{1}{LC_1} + \frac{R}{LC_1 R_1} + \frac{R}{LC_2 R_2} + \frac{1}{C_2 R_2 C_1 R_1} \), and \( f_4 = \frac{R_2 + R_1 + R}{LC_2 R_2 C_1 R_1} \). This is an improper transfer function, so it is inverted to form the admittance transfer function, \( \hat{Y}(s) \),

\[
\hat{Y}(s) = \frac{b_1 s^2 + b_2 s + b_3}{f_1 s^3 + f_2 s^2 + f_3 s + f_4},
\]

(5.7)

which has the model order suggested by the loss function study. Using the MATLAB \( oe() \) and \( d2c() \) functions to fit the time-domain data and then convert from discrete time to continuous time results in parameter values \( b_1 = 7.75 \times 10^5 \), \( b_2 = 2.50 \times 10^9 \), \( b_3 = 7.12 \times 10^{10} \), \( f_2 = 5.18 \times 10^4 \), \( f_3 = 1.94 \times 10^8 \), and \( f_4 = 2.75 \times 10^{10} \). Solving for the component values of the equivalent circuit model in Fig. 2.3(c) results in \( L = 1.29 \mu H \), \( R = 0.0626 \Omega \), \( C_1 = 112 mF \), \( C_2 = 26.1 mF \), \( R_1 = 0.312 \Omega \), and \( R_2 = 0.0120 \Omega \). Figure 5.12(b) shows the measured impedance and the output of 5.6 when using the component values obtained above. For comparison, component values
(a) Output error for an ARX model with 2 zeros and 3 poles.

(b) Output error for an Output Error model with 1 zero and 2 poles.

(c) Output error for an Output Error model with 2 zeros and 3 poles.

Figure 5.11: Output error for various models.
of the 4-parameter equivalent circuit model in Fig. 2.3(b) were estimated with the resulting impedances plotted in Fig. 5.12(a). The 6-parameter model has a better fit throughout most of the frequency range, and it captures the shape of the higher frequency arc. The measured impedance and the output of the 6-parameter model compare favorably except at the highest and lowest frequencies. At high frequencies the magnitude of the impedance from the model increases more quickly than it does with the measured data. This would be the result if the estimated value for $L$ was greater than the true value. As the frequency approaches DC, the magnitude of the measured impedance increases more quickly than it does with the model. A better fit at low frequencies could potentially be obtained by modeling the dynamics corresponding to the mass transfer process, which according to [7] can be accomplished by using the *porous bounded Warburg* model of a *Warburg* circuit element.
Figure 5.12: Comparison between measured data and model.

(a) Impedance plots for the measured data and the 4-parameter model.

(b) Impedance plots for the measured data and the 6-parameter model.
DISCUSSION

This thesis demonstrates novel in-situ measurements and signal processing on data obtained from a multi-kW SOFC stack and a sub-kW PEMFC stack to extract time-domain models, as well as parametric and non-parametric impedance spectroscopy results. The results suggest that the kind of information that can be inferred from an electrochemical impedance spectroscopy plot can also be obtained at the terminals of an entire stack, without removing the stack from service. Results were obtained using excitation from both power electronic ripple in the energy management electronics and exogenous low-frequency waveforms injected using test equipment. The results were essentially consistent across analysis methods and excitation. Furthermore, trending of the parameterized model of the stack supported by ripple current shows a long term degradation in performance.

The characterizations of the whole stack and of a single cell under essentially the same operating conditions was done and the results were compared. More detail was seen in the characterization of the whole stack than was observed by looking at a single cell. Perhaps increasing the signal-to-noise ratio would reveal more detail in the single cell characterization; however, it does appear that under essentially the same conditions there is a little more sensitivity with respect to the high frequency behavior of the stack than there is for a single cell. There are relatively few results available for the whole stack characterization and essentially none under operating conditions.

The techniques described in this thesis involve low-cost, non-invasive electrical terminal measurements that could be added to a variety of fuel cell systems. This was demonstrated by a hybrid power system that utilized a secondary power source such that the low-frequency excitation was made essentially independent of the load
power requirements. This is a secondary use of the hybridization, in addition to the primary role of enhancing system load following and disturbance rejection capability. Furthermore, the test equipment could be replaced with appropriately controlled power electronics in a fully integrated system as demonstrated by the PEMFC with the boost converter load. This kind of integrated control and characterization of the stack may ultimately increase the overall life-cycle and cost-effectiveness of fuel cell systems. Although not covered in this thesis, these *in-situ* characterization techniques could be implemented in parallel with a current interrupt measurement, which measures the voltage response to the sudden interruption of current and is useful in determining the ohmic component of the fuel cell loss. The current interrupt technique is presented in more detail in [7].

Several applications of *in-situ* characterization of fuel cell stacks are envisioned. For example, stack diagnostics can be used to inform system level controls of changes in operating conditions that may mitigate degradation.

Reports from the field indicate that stack degradation is often significantly faster than what would be expected from the extrapolation from single cell testing in the laboratory, therefore condition based maintenance will be an essential component of making fuel cell systems reliable. By performing *in-situ* characterization of the fuel cell stack, it may be possible to predict ahead of time when the system is going to fail, and with that knowledge maintenance can be performed in order to avoid the unscheduled shutdown or failure of the system.

Finally, *in-situ* characterization of the fuel cell stack provides the results needed to understand degradation and performance issues under field conditions. If the characterization of fuel cells consists only of analyzing single cells in the laboratory, and the results in the field are inconsistent with the single cell laboratory results, then there is no real mechanism of performing experiments or informing the design
of new stacks to avoid the conditions observed in the field. Fuel cell stacks have several degradation mechanisms which are not present with a single cell, e.g. seal leakage and interconnects within the stack. Now, with in-situ characterization, the progression of degradation in the field can be measured, and the time history of the impedance spectroscopy result of the stack in the field under operating conditions can be obtained by looking at the terminals and performing diagnostics.
REFERENCES CITED


