# A THERMALLY DEPENDENT FUEL CELL MODEL FOR POWER ELECTRONICS DESIGN

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**Abstract—In the dawn of the fuel cell era, it may seem that their development and use would still be immature. However, this is not true – fuel cells are finding use in everything from cell phones to automobiles quite quickly. Regardless of their application, the fuel cell must be accurately modeled in the system it will be used in. Such a model must be simple, easy to use, and fast to simulate. Chemistry, material science, and physics must be transformed into electrical components and systems that work easily in programs like Pspice, Saber, Labview, and the like. Herein, such a model will be presented in its latest form, incorporating dynamic effects of heating and cooling of the stack.**

## I. INTRODUCTION

Fuel cells are becoming more prevalent and the importance of accurately modeling their electrical performance is crucial to the success of any fuel cell based power system development. The governing equations of the electrochemical process, the time constants in mass transport, and the hydration of the membrane are well known and accurately describe the Proton Exchange Membrane (PEM) fuel cell polarization curve. The purpose of this work is not to reiterate or validate these principals – it is to present a thermally dependent electrical model of a commercial fuel cell system. Without such a model, the power electronics circuit designer is forced to rely on experimental verification during the crucial cold start and temperature transient operation of the fuel cell.

The Ballard Nexa 1.2kW PEM fuel cell unit was used for this work, shown in Fig. 1. It is a pressurized stack – the hydrogen fuel is supplied at a constant 7psi – while the oxygen (from ambient air) pressure is maintained by a compressor, with the compressor-driven air supply being the limiting factor during load transients. All data presented herein was captured from this system via a serial data logging connection to Ballard's control board.

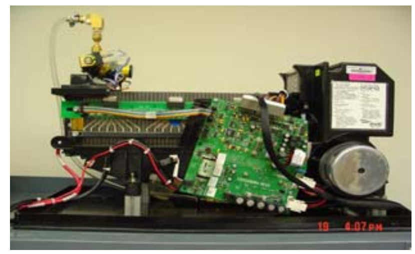

**Fig. 1: Ballard NEXA 1.2kW PEM fuel cell system, including hydrogen pressure regulator, air compressor, and control system with sensors.**

## II. BACKGROUND

Fig. 2 shows a basic system comprised of a fuel cell source, dc-dc converter, dc-ac inverter, and ac load. To accurately design the power electronics and controls, and simulate the system, we need accurate models for each block. The load can be modeled in many different programs, including PSpice, Labview, Saber, and Matlab, as needed. The power electronics are also well modeled in such programs. However, fuel cell models are less mature, in general, and have mechanical and chemical effects not easily added in an electrical simulation program. Some models are available that account for the dozens of factors influencing their behavior, but are complex in nature and take long to simulate, making them poor for electrical design use.

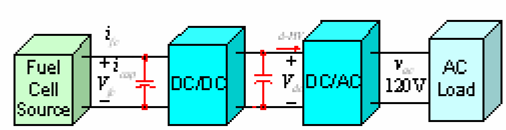


**Fig. 2: Power system driving an ac load, powered by a fuel cell**

Two electrical models developed in 2004 are shown in Fig. 3. The model shown in Fig. 3(a) [1] utilizes one inductor and one capacitor to represent the fuel cell dynamics in electrical circuit format. The model shown in Fig. 3(b) [2] mixes the electrical circuitry representing the static conditions with behavioral models representing the dynamic response of the fuel cell. The models allow for variations of the load being driven, and hence are quite useful.

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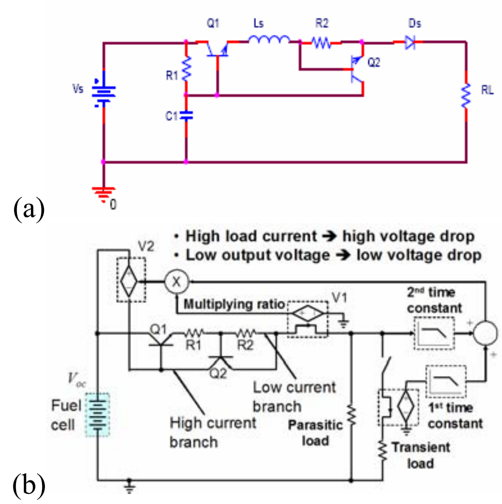


**Fig. 3: PEM fuel cell circuit models developed with (a) pure electrical circuit model [1][1] (b) mix of electrical circuit and behavioral models [2].**

These models can predict fuel cell static and dynamic responses well, but unfortunately do not account for changes caused by heating and cooling of the stack. Over a 2.5V difference can be observed at the output of the stack at full-load, between cold and thermal steady state. Empirical data demonstrating this voltage difference is shown in Fig. 4(a), taken from the Ballard fuel cell stack. This shows a clear need for an improvement in the current fuel cell model, accounting for temperature. Fig. 4(b) shows how the I-V curve is affected by the voltage rise due to temperature, using the linear mathematical relationship established in (a).

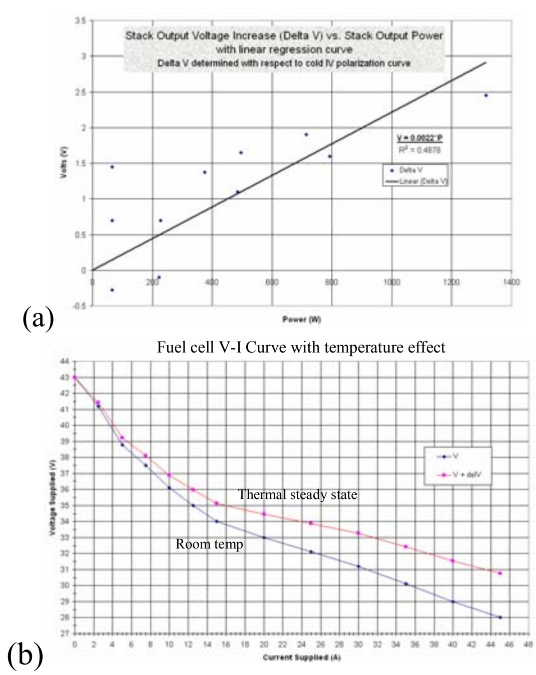


**Fig. 4: Change in stack output voltage from cold to thermal steady state, (a) with experimental data over the power range of the fuel cell and (b) with the mathematical relationship over the I-V curve**

## II. SYSTEM BEHAVIOR

Fig. 5 illustrates load and thermal transients of the Ballard fuel cell stack. Shortly after the load is increased from no-load to full-load in (a), there is a dip in the output voltage (and power) of the stack. This effect is a well known phenomenon called mass transport polarization, and occurs when the fuel cell is deprived of reactants. The deprivation is caused by the slow response of the compressor, which supplies ambient air containing oxygen, the key reactant. As the compressor comes to speed, its effect can be seen as the voltage begins to rise again, eventually settling after about 0.5 seconds of deficiency. The opposite effect can be observed when the load is removed, as well. These dynamic effects are all accounted for by the electrical models proposed in Fig. 3, including charge double layer and stack voltage undershoot. They are critical to the power system designer as they represent the amount of bulk storage necessary to maintain voltage and/or current regulation of the output. Static conditions relate primarily to developing the characteristic I-V curve of the fuel cell, including activation polarization, ohmic (resistive) losses, and mass transportation polarization. The I-V curve has a large effect on the control design.

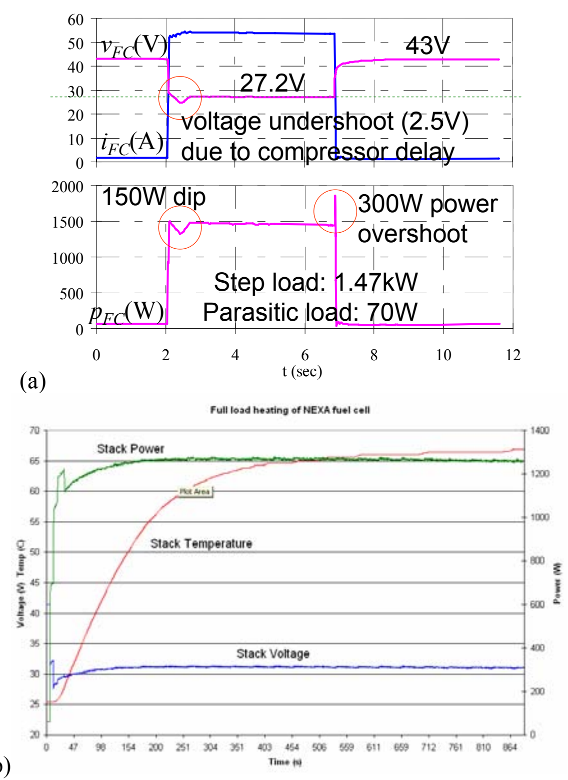


**Fig. 5: (a) Voltage, current, and power load transient behavior and (b) voltage and power thermal transient behavior**

The thermal transient in Fig.5 (b) illustrates the need for improvements in the electrical models. As the load resistance is held constant (negligible load heating occurred), the stack voltage increases as the stack



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temperature increases. From no-load operation (25ºC) to the 68ºC obtained here, the voltage output increased about 2.5V. This can have significant effects on the power electronics design, as the designer may expect the rated 26V at full load, and instead receive 28.5V.

As well, the Ballard fuel cell system has built-in protection while it is in cold-start operation. The exact qualifications for this mode have yet to be uncovered, but the result is an upper limit on the output power of the stack (~300W) during a warm-up period – demanding higher power will result in system shut-down (microcontroller protected). Again, this performance limitation must be considered when designing power electronics that can easily exceed this level.

## III. THERMAL MODEL OPERATION AND FUTURE WORK

### *A. Static model operation*

Since the digest version of this paper was released, the dynamics of the fuel cell have been researched at length. Previous work revealed a model that gave stack voltage and current (and consequently, I-V curve) for a given load after thermal transients had stabilized. This was achieved by feeding stack voltage and current measurements into a multiply block (power), and using a gain block to achieve the linear slope of the power to voltage-increase relationship. This is then fed to a block that provides an increase in voltage at the output of the fuel cell. This circuitry can be observed in Fig. 6 marked "Thermal." For the Ballard fuel cell system tested, we obtained an approximate linear relationship of 2.2 V/kW (see figure 4) – meaning that for every kilowatt of power demanded of the stack, the output voltage will rise 2.2 V above the cold I-V curve, after thermal stability has been reached. The triangular gain block is given a value such that its value is the desired voltage_gain divided by 0.0096. So, for our example, our gain is 0.0022/0.0096 = 0.230.

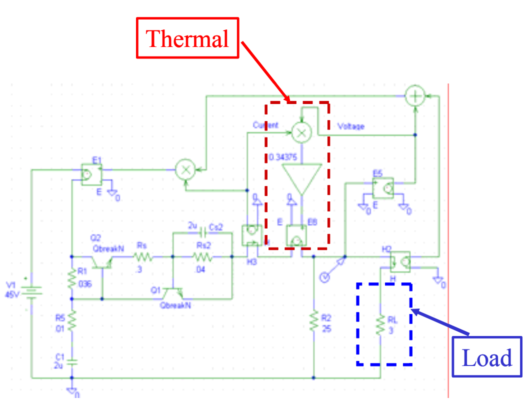


**Fig. 6: Working PSpice fuel cell model incorporating steady state thermal effects**

Since the creation of this model, fuel cell dynamics have been explored by more and more electrical engineers. Most previous information available was written by those focused on the chemical aspect, providing deep insight into the chemistry of the fuel cell operation. However, this must be processed and simplified to be applied to electrical modeling. This paper attempts to build a model that is simple to use, easy to understand, and will simulate quickly. As such, variables like fuel quality, air humidity, oxygen content, etc. are not the focus, but rather the underlying effects of them and polarization, internal resistance, reactivity rate, etc. are studied for their electrical content. From this, we can build a model accurate enough for electrical simulation, yet simple enough for anyone needing such a model to use.

### *B. Theory of Temperature Effects*

Excellent research was documented in June of 2004 in work [3], "A Proton Exchange Membrane Fuel Cell Model." All subsequent information on modeling will be from this work, unless otherwise cited.

First, it is imperative to note that loses in fuel cell operation come in the form of heat, and reflect the general efficiency of the stack. These losses effect the electrical performance in the form of a drop in the stack output voltage (voltage gain due to heating is discussed later). If the open circuit voltage (emf) is noted as E, then the stack output voltage (V) can be given as:

$$V = E + n_{act} + n_{ohmic} + n_{proton} \qquad (1)$$

where each n is its respective overpotential. $n_{act}$ is the activation overpotential, a voltage drop in the electrodes due to an electrochemical effect. It is given by:

$$n_{act} = -A + B*T_s + C*\ln(C_{O2}) - D*\ln(I) \qquad (2)$$

where A through D are coefficients, $T_s$ is the critical temperature, $C_{O2}$ is oxygen concentration, and I is current density. All values are specific to the fuel cell of concern, and were not determined specifically in this paper. Rather, their affect was noted, and incorporated into the net effect on the output.

$n_{ohmic}$ is the loss due purely to internal resistance to electricity flow. It is a direct result of Ohm's Law, and can be represented by:

$$n_{ohmic} = -(I*R_{internal}) \qquad (3)$$

where $R_{internal}$ is related to temperature and current flow by:

$$R_{internal} = F - G*T + H*I \qquad (4)$$

in which F, G, and H vary with the material used.



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$n_{proton}$ is related to proton conductivity through the membrane, and carries a more complex relationship to its variables. Its value is given as

$$n_{proton} = \sigma * I/t_m \qquad (5)$$

where $t_m$ is thickness of the membrane. σ is the conductivity of the membrane, and carries a long equation related to temperature, current, and water vapor activity. This overpotential is relatively negligible up into quite high cell current densities. Since the Ballard Nexa fuel cell system used in this paper was not highly affected by this overpotential, it will not be explored further herein. The reader may see references for additional information.

Bringing these overpotentials back together into equation 1, we should note that they are all negative. This indicates that the effective output voltage will be decreased as each of them are increased. However, the effect of temperature in each of them serves to lessen the overpotential, thereby increasing stack output voltage. This concept was discussed quantitatively earlier in this paper, and has been shown in more detail in this section.

If losses experienced by the fuel cell are converted into heat, the stack temperature will increase and decrease respective to the loss, which is respective to power delivered. This heating can also affect incoming air, and if significant enough, humidity can be altered. Humidity loss in the fuel cell can counteract the benefit of increased temperature, on top of other negative long term effects on the stack, if not corrected.

*C. Building the Dynamic Fuel Cell Model*

From here, empirical data is presented to show how the proposed dynamic fuel cell model can be modified to the user's needs. It should be noted that the model is still work in progress at this point. The current model is the simplest form of a dynamic model that represents the output with good accuracy.

One major problem has kept this model from developing more rapidly into a more accurate version. Thermal effects may have a measurable and quantifiable relationship to power demand of the stack, but the stack's cooling system makes it nearly impossible to observe. Heating curves lose accuracy when the variable speed cooling fan is turning on and off, changing the slew rates of the stack temperature. In our case, the fan is a part of the system; so, it is treated that way. Many different load steps were recorded, and a heating/cooling time constant was chosen carefully to best reflect all possibilities. Larger load steps will always have faster temperature rises, but again, the cooling system will counteract this. From this, the conclusion was drawn that the time constant should be relatively close to this value compared to other test results.

An actual test curve is shown in Fig. 5b (above) from the Ballard Nexa stack. Measuring the time to rise 63% of the way to its final temperature gives 145 seconds. Some additional load tests are shown in Fig. 7 below. From these, time constants were consistently found to be in the range of 160 seconds. Since they were smaller load steps, and in increasing order, they revealed a good upper bound to the time constant.

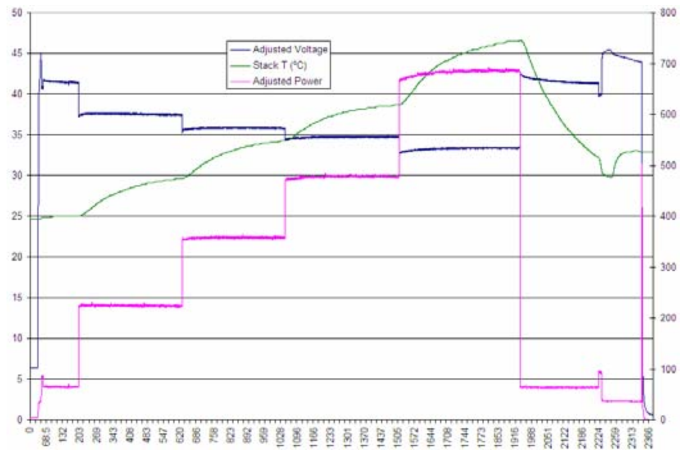


**Fig. 7: Four upward load steps used in determining temperature time constant. The right scale is power, left is temperature and voltage.**

After obtaining thermal data, finding a representative time constant, and finding a linear voltage-power relationship, the dynamic model is ready to be set up.

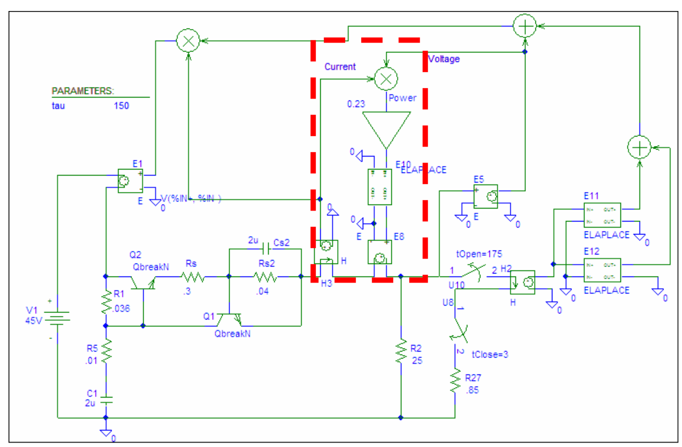


**Fig. 8: Current dynamic fuel cell model PSpice model. Red box indicates thermal section, as in Fig. 6.**

Fig. 8 shows the static model updated for dynamic effects. The thermal effect is still modeled as a voltage gain on the stack output. However, an "ELAPLACE" block has been added to represent the delay in output voltage swing, due to heating and cooling. As such, this block uses the temperature time constant obtained to control the voltage swing. It is entered in LaPlace form, which is 1/(1+s*tau),



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the transform of the exponential time function. The additional LaPlace blocks on the right side of the model are used to represent the time constants of the fuel cell response and air compressor response, which are discussed in section 2 of this paper, and shown in Fig. 5a.

### *D. Model Simulation Results*

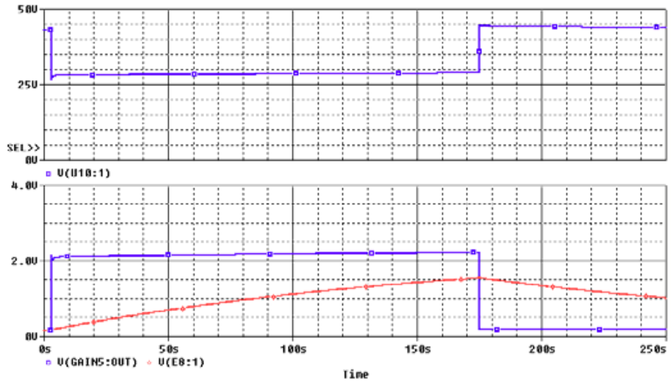


**Fig. 9: Dynamic simulation of fuel cell output voltage. Full load step up and down are shown. Lower curves show thermal static and dynamic effects over time.**

The result of the model being assembled and simulated is shown in Fig. 9. The top curve shows the output voltage of the stack. Note first the dip after the initial transient – this is the compressor delay effect. This transient typically settles out in less than a second. In the time following, a subtle rise in output voltage can be observed, as the fuel cell is heating up. The lower curves show the input and output of the "ELAPLACE" block, which is creating this voltage rise. At 175s, the load switch is opened, and the stack voltage rises up very high. At this point, the stack is hot, so the voltage can be observed falling as cooling occurs.

This model does represent the heating and cooling of the stack well. However, it is not as accurate in tracking the voltage increase due to temperature after a load change. When the load step occurs at 175s, the voltage increase afterwards should fall to the blue trace and fall exponentially from there. This indicates the need for future work – instead of using a voltage block to show the effect of temperature, make the temperature modify the internal resistances of the model.

As well, additional future work is planned for modeling SOFC, MCFC, and DMFC systems. The ultimate goal would to have one model that can closely represent all of these, with only a few quick parameter changes to reflect the operation of each.

## IV. CONCLUSIONS

This paper has presented a modified electrical model to account for thermal variations in the fuel cell stack. Starting with a simple linear approximation to steady state temperature effects, the model can give stack voltage at a given load condition. This voltage can differ from the cold operation point by as much as 2.5V – a difference of nearly 10%. As well, this model allows the power electronics designer to simulate the following fuel cell phenomenon: activation losses (static I-V curve), stack voltage undershoot (dynamic load transients), and stack variations due to temperature, steady state thermal voltage effects, and dynamic thermal conditions. This is, of course, a summary of a long list of fuel cell characteristics that are incorporated underneath the equations.

This model is especially important to power electronics designers, as they need a representative electrical model for the fuel cell system. Here we have presented a model for a specific system – the Ballard NEXA 1.2kW PEM fuel cell stack. This model could be easily modified for use with another system, simply by changing component values and time constants in the model. A series of tests could be performed on the stack, and with the given results, a working, accurate, and simplistic fuel cell electrical model can be built. When complete, the designer can utilize the proposed model as a black box, and design their system with confidence.

Any losses experienced in power electronics will also cause more demand on the fuel cell, further increasing its losses. Consequently, if we can improve the efficiency of the power electronics downstream, it has been said that less of the very expensive catalyst platinum is required, in addition to reducing the load on the fuel cell. Since cost is such a large factor, we should not forget that the benefits of improving system efficiency fall into many categories.

Given that digital controllers are being used more and more for power electronics, this model will be essential for testing the cold operation and control algorithms implemented. The more accurately the model represents the fuel cell's operation, while still maintaining its simplicity, the more valuable it is to the designer. Value, in this case, translates into less modeling time, and more design time, then ultimately a well designed fuel cell system.

## ACKNOWLEDGMENT


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