Power Converters for Micro Fuel Cells

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Consideration of power conversion requirements during fuel cell design enables optimization of the energy density, power, size and cost for the complete micro fuel cell system.

Micro fuel cells have made tremendous strides in the past few years. New materials and fuel-delivery mechanisms have enabled energy density surpassing lithium ion (Li-ion) batteries, the de facto standard energy storage medium for portable electronics. Fuel cell-powered cellular phones have been demonstrated.[1] Soon, the marketplace will see the results of the research efforts of the past decade.

Fuel cell research and development has primarily emphasized the chemical plant, delivering fuel to the cell and converting it efficiently into electricity. As power electronics designers, the electrochemistry is less important than the terminal characteristics of this new source. A cursory review of common characteristics will reveal a serious need for power conversion and possibly energy storage.

Fuel cell terminal voltage can range as much as ±50%, depending on load and fuel delivery. Micro fuel cells suffer some of the system sluggishness of their larger cousins, limiting the slew rate of the load current imposed on the fuel cell itself. Portable electronics have been designed around the energy density limits of Li-ion batteries by taking advantage of the relatively high power density available from modern batteries. Either the loads need to be redesigned to accommodate the limitations of fuel cells, or sophisticated power electronics are required to give battery-like characteristics to the fuel cells.

Cell Phone Fuel Cell Conversion

Cellular phones require high power density and high energy density in a given form factor. A typical fuel cell-based battery replacement apportions only a small percentage of the available volume to the power converter. This power converter must boost whatever voltage is available from the fuel cell to a voltage high enough to operate the phone. Load can range from a high of more than 3 W

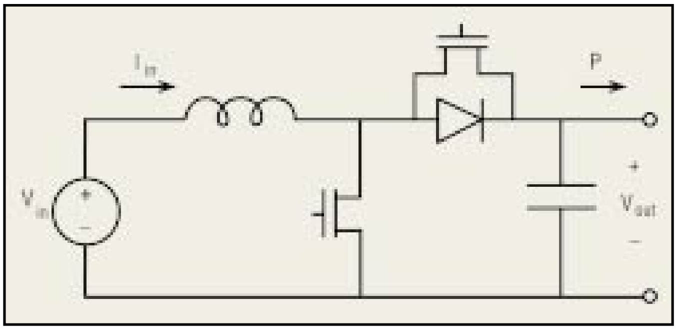

Fig. 1. *Synchronous boost converter.*

(during analog operation of a dual-mode phone) to a few megawatts (while the phone is idle). Power converter efficiency at heavy load and standby current at light load are both necessary to achieve talk time that exceeds Li-ion batteries.

A typical fuel cell generates approximately 0.2 V to 0.4 V, depending on the fuel cell type and load. From the fuel cell maker's standpoint, a single-cell solution is ideal, because it eliminates many problems associated with stacking of series cells, including seals, fuel distribution and other packaging issues. From a power conversion standpoint, such a system is a designer's nightmare.

The power converter is characterized by several parameters. There is some power required for the logic and gate drive, P_{ov}, generally small but a significant factor at light load. P_{ov} is a constant loss factor. A MOSFET switching loss factor is:

$$K = \frac{fV_{out}t_{switch}}{2} \qquad (1)$$

The factor, K, has units of volts and is multiplied by the input current to get switching loss, so this loss term increases linearly with load. Similarly, losses in the equivalent series resistance of the output capacitor, r_C, increase linearly with load. Most significantly, total resistance, *R*, causes losses to increase quadratically with input current. *R* includes fuel cell parasitic resistance, inductor resistance, MOSFET on-state resistance and PCB trace resistance.

Input current can be determined by solving the following equation:

$$RI_{in}^2 + \left(K + r_C\frac{P_{out}}{V_{out}} - V_{in}\right)I_{in} + P_{ov} + P_{out} - r_C\left(\frac{P_{out}}{V_{out}}\right)^2 = 0 \quad (2)$$

Knowing input current, the efficiency is:

$$\eta = \frac{P_{out}}{V_{in}I_{in}} \quad (3)$$

Taking these equations together, it becomes clear that efficiency drops dramatically with input voltage (see reference 2 for more details). Resistance, *R*, dominates practical converter designs. To generate 3.3-V output at 2 W with an input of 0.3 V and an efficiency of 90%, neglecting other loss mechanisms, requires total resistance of 4.05 mΩ.

For perspective, this resistance is equivalent to a 22 AWG wire that is 2.4-in. long, or a 50 mil trace in 2 oz. copper 1-in. long. With this total resistance, the power designer needs to build an inductor, buy two MOSFETs and wire them all together on a PCB. Given that there are other loss mechanisms in addition to resistance, the problem appears to be intractable. For example, both *K* and P_{ov} increase for larger MOSFETs that have lower on-state resistance.

Fig. 2. *Photograph of sample boost converter.*

Fig. 2 shows a sample converter constructed to verify the above equations. Fig. 3 shows the efficiency versus load for various input voltages. For an input of 1 V and a load of 1 W, efficiency is greater than 85%. For an input of 0.4 V at the same load, efficiency is only 67%. Reduced efficiency in the power converter affects the fuel cell system in a variety of ways. The fuel cell needs to be larger in order to generate enough power to carry the load. The system also can reach a point of voltage collapse, just over 1.5 W at 0.4-V input in the sample converter.

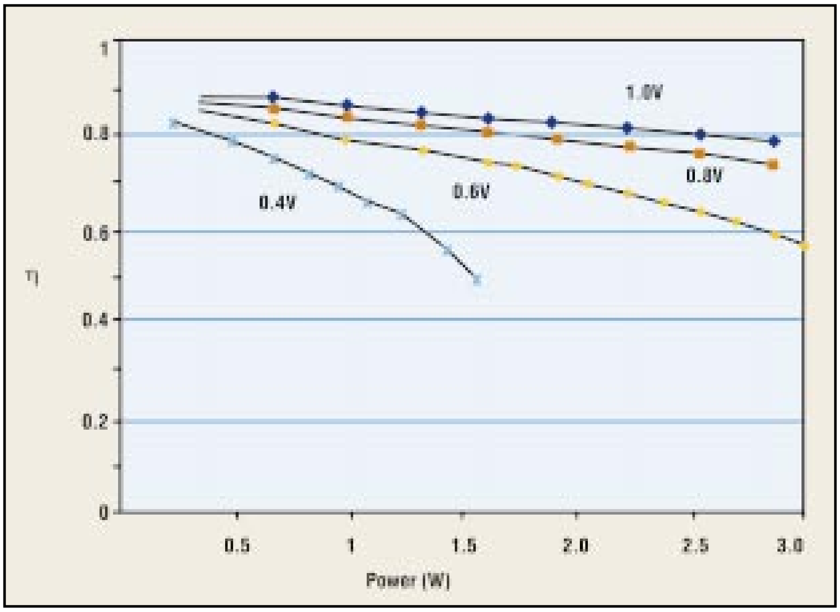

Fig. 3. *The measured efficiency of the power converter at various input voltages varies as a function of load. Output voltage is fixed at 3.3 V.*

Voltage collapse is a phenomenon seen in many power applications. In the high-voltage power transmission grid, when the losses exceed 50% at any point, localized blackouts occur. In a boost converter, controllers assume that increasing duty cycle increases the boost ratio. As efficiency drops, a point is reached where increasing duty cycle instead decreases the boost ratio by increasing losses in the inductor and low-side switch. The controller quickly reaches maximum duty cycle, dropping the load and possibly damaging the fuel cell or the converter.

The best solution is to design the fuel cell stack so that the boost ratio (the ratio between the desired output voltage and the actual input voltage) is as close to 1 as possible. Typical fuel cell characteristics will mandate that the boost ratio varies significantly with load, and the converter designer must consider all operating points carefully.

Raising the input voltage simplifies another important operation: starting the power converter. Surveying commercially available dc-dc converter ICs reveals that few are guaranteed to start below 1-V input. Those that can start from below 1 V must start into a light load, well below rated output power. If the no-load fuel cell voltage is increased by stacking several cells in series to reduce the boost ratio, many dc-dc converter ICs can be found that will start without any problems.

Laptop Computer Power Conversion

A laptop computer is a much different system than a cell phone. Space is still at a premium, but geometries are large enough that the designer has the flexibility to optimize each element of the system and the system as a whole. Battery voltage is generally higher, up to 18.5 V, as is power, on the order of 100 W.

Research is currently under way to determine the ideal fuel cell system solution for a laptop. A likely candidate, topology resembles a stationary fuel cell system at a greatly reduced scale. Fuel cell energy density exceeds that of Li-ion batteries, but fuel cell power density can be substantially lower.

Laptops are designed to minimize energy use by powering down peripherals that are not being used, stopping the hard drive and so forth. When these devices are powered back up, the resulting power demand can exceed the power available from a reasonably sized fuel cell. Stationary fuel cells handle varying loads by using a battery. A novel power buffer was demonstrated in for stationary fuel cells.[3] This method, or other similar methods, can be used to provide the high power density of a battery combined with the high energy density of a fuel cell.

Again, voltage levels must be chosen carefully. With a 4-V input and a 12-V output at 100 W, a boost converter efficiency of 90% requires a total resistance of 14 mΩ. Although much more achievable than the 0.3-V to 3.3-V design proposed above, proper design requires strict attention to detail. Power converter design is simplified with appropriately chosen voltages, minimizing the boost ratio necessary.

Advances in fuel cell technology require similar advances in power converter technology. By considering power conversion design parameters early in the system design, a small, inexpensive converter can be built to accompany a reasonably sized fuel cell for high system power and energy density. **PETech**

References

1. *www.engology.com/artfuelcells.htm*.

2. *Kimball, J.W.; Flowers, T.L.; Chapman, P.L. "Issues with Low-Input-Voltage Boost Converter Design,"* Record of the Power Electronics Specialists Conference, *2004, pp. 2152-2156.*

3. *Krein, P.T.; Balog, R. "Low Cost Inverter Suitable for Medium-Power Fuel Cell Sources,"* Record of the Power Electronics Specialists Conference, *2002, pp. 321-326.*

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