Design Optimization and Simplification of PEM Fuel Cell Systems for Back Up Power Applications

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Introduction

The widespread growth of the telecommunication and wireless industry has led to a need for reliable energy storage and uninterruptible power supply in both remote locations and in areas that are currently served by electric utility grids. Currently in most of these applications the back-up power sources are usually batteries and diesel/gasoline generators. Although these commercial technologies have existed over a significant period of time, the end-users have had to live with several drawbacks such as frequent maintenance, replacement and reliability issues (resulting in high costs), noise etc. There is therefore a growing need for alternative energy solutions. A Regenerative Fuel Cell (RFC) system (Figure 1) is a device that stores electrical energy in the form of hydrogen produced by electrolysis of water and then converts the hydrogen to electricity in a PEM fuel cell when the power is needed. Thus it operates alternately as an electrolyzer and a fuel cell. Although the electrolyzer and fuel cell functions can be integrated into a single stack to operate reversibly, this paper focuses on the option of using two separate or discrete stacks referred to as Discrete Regenerative Fuel Cell System (DRFC). The DRFC has the potential to overcome several drawbacks of conventional energy generation and storage technologies listed above and offer other advantages as well. It provides greater flexibility and offers favorable scale-up and scale-down in design because unlike batteries it separates charging time, energy storage, and power generation. Charging time can be varied by the size of the electrolyzer, storage by the size of hydrogen storage capacity, and power generation by the size of fuel cell system. In addition, these systems are virtually silent and offer 100% pollution-free operation using water as the only fuel source.

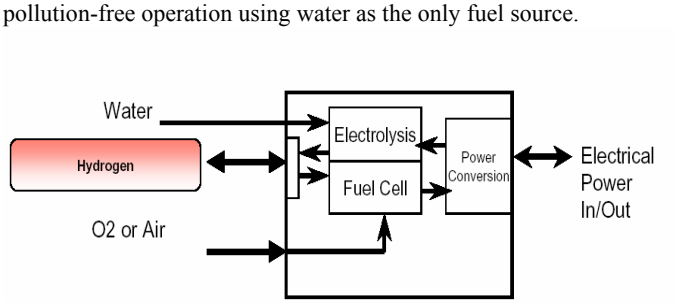

Figure 1. Regenerative Fuel Cell Functional Block Diagram

Design Trade-Offs and Optimization

There are several trade-offs that need to be considered during design of a PEM fuel cell sub-system and its subsequent integration with the electrolyzer for such applications, based on performance and cost. The key input parameters for the system are electrical power output and voltage, limitations on water requirements and reasonable efficiency. Due to the nature of this application, efficiency of the system is not as critical as in automotive and residential fuel cell systems. Key system design parameters include selection of operating temperature and pressure, water and thermal management and quick startup. Design variables for the stack include number of cells in the stack, cell active area, and selection of nominal cell voltage. This paper provides a general overview on the selection of the "right" combination of the above variables/parameters that will result in the most optimal and economical DRFC system.

Operating Pressure and Temperature. The PEM fuel cell may be operated from pressures near ambient to about 6 atm, and at temperatures between 50 and 90°C. It is well known that the fuel cell operates better at higher pressures. Higher power densities are achievable associated with a voltage gain at higher pressures as shown in Figure 2. However higher pressure necessitates the use of a compressor which requires additional power thereby decreasing the overall system efficiency. Figure 3 shows the additional power needed for compression as a function of the stoichiometric ratio and at several nominal cell voltages. At 300 kPa the compressor may consume between 15 to 30% of the stack power output, while at lower pressures it may consume as low as 2%.

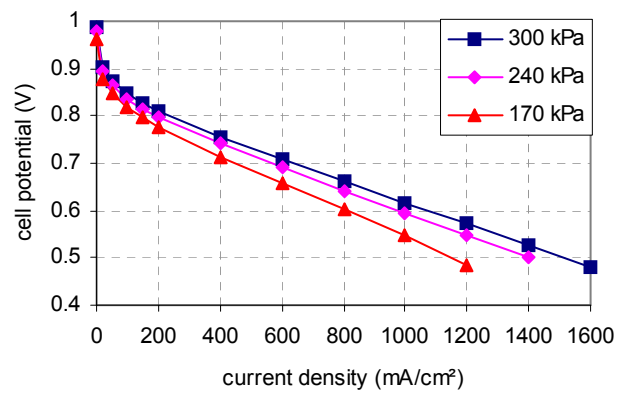

Figure 2. Effect of Operating Pressure on Performance of a Typical PEM Fuel Cell Stack.

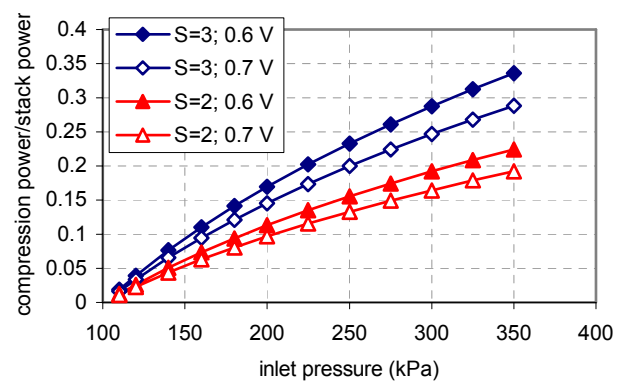

Figure 3. Effect of Operating Pressure on Compression Power.

Thus power needed to run the compressor may offset the voltage gain. Furthermore a low-pressure (slightly above ambient) system will most likely utilize an off-the-shelf blower thus simplifying the overall system and reducing costs. It may thus seem that there is no significant advantage by selecting a higher pressure. However other factors such as humidification and water balance (which are functions of both temperature and pressure) must be taken into consideration thus adding complexity to the above analysis.

Humidification. A PEM fuel cell stack with Nafion membrane requires water to conduct protons across. Both reactant gases

(hydrogen and air) typically need to be humidified at the inlet in order to prevent the membrane from drying out. The vapor pressure of water in gas is an exponentially increasing function of temperature. Also the amount of water and heat required for humidification is higher at lower pressures. Therefore water management in the system might pose a significant challenge particularly under these conditions. However with a clever stack design and wise selection of operating temperature and pressure humidification requirements might be relaxed or even eliminated. Figure 4 shows the minimum level of humidification needed of the cathode inlet air in order to maintain at least a saturated gas at the cathode exit. Percent wetness is defined as the ratio of the amount of liquid water to the total water content in the cathode exhaust gas. It can thus be seen that at temperatures at or below 60°C theoretically no humidification of air is required; the product water is sufficient to completely saturate the exhaust gas. Higher temperatures require some amount of humidification, for example, for a stack operating at 65°C the inlet air must be humidified to at least 70% RH in order to maintain a minimal amount of wetness in the cathode exhaust. Thus a wise selection of operating temperature and pressure may relax humidification requirements and simplify the overall system.

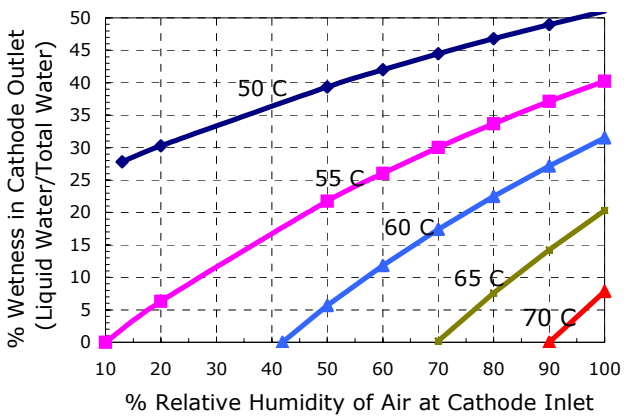

Figure 4. Effect of Humidification of Air at Cathode Inlet on the Wetness of Gas at Cathode Outlet at various fuel cell temperatures.

Although this may seem straightforward the water balance in the stack is further complicated by water crossover: from anode to cathode due to the electro-osmotic drag, and from cathode to anode due to back-diffusion caused by concentration gradients. With thin membranes this can be overcome, but this is also a function of cell design, temperature distribution in the fuel cell, and properties of gas diffusion layer and MEA.

Water Management. Water is consumed in the electrolysis process for hydrogen production. The hydrogen and oxygen gases generated during electrolysis are fully saturated with water vapor. Prior to storage hydrogen is dried and water is recovered. Since oxygen is a by-product it is simply vented and therefore a small amount of water is lost during this purge. The same amount of water that was consumed in the electrolysis process is theoretically produced in the fuel cell. The fuel cell also needs water for humidification of reactant gases. Depending on the operating conditions of the fuel cell water may exit the stack as vapor only or as a mixture of vapor and liquid. Water that exits the fuel cell as liquid can directly be separated and recovered from the cathode exhaust gas in simple knock-out water separators. However depending on the cathode exhaust gas conditions, a significant amount of water may escape in the form of vapor and a condenser might be required to cool the exhaust gas and recover the water. Although neutral water balance is not as critical for backup power applications as compared to automotive it is essential to minimize water losses so as to have sufficient water available for the complete duration of operation of the DRFC system. A typical duration of a 2 kW DRFC system is about 200 hours a year with annual maintenance.

Figure 5 shows the effect of the fuel cell operating temperature on the water balance of the fuel cell subsystem and the overall DRFC subsystem. It can be seen that at temperatures at or below 55°C there is a positive water balance maintained in the fuel cell subsystem. This is because at this low temperature most of the product water in the fuel cell exists as liquid droplets and can be directly recovered without additional cooling. At higher temperatures the cathode exhaust gas has greater capacity of retaining moisture and carries greater amounts of water vapor as it exits the fuel cell stack resulting in a negative water balance in the system. It can also be seen that water balance worsens with higher humidification requirements particularly at higher temperatures and an exhaust gas condenser may be needed to minimize the water loss. It is important to note however that there is always some water loss in the overall DRFC system even at the low temperatures that may not be completely recovered even with an exhaust condenser. However as mentioned before water balance requirements for backup power applications are not as critical as compared to automotive systems, and can be minimized by proper sizing of the water reservoir and by operating the system at relatively lower temperatures or by cooling the exhaust gas.

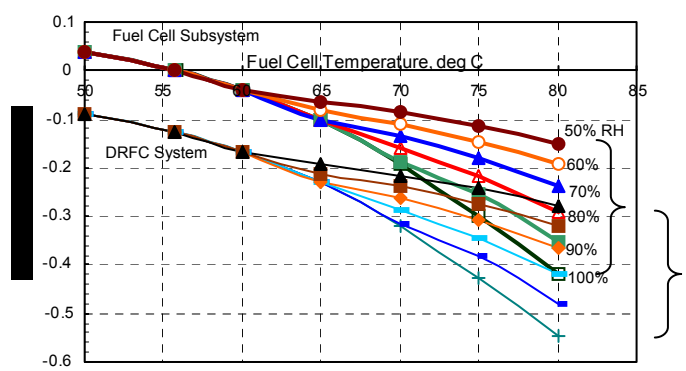

Figure 5. Effect of Fuel Cell Temperature on System Water Balance at Different Humidification Levels, Without Using An Exhaust Gas Condenser.

Nominal Cell Voltage and Stack Size. The selection of nominal operating point has a direct impact on the fuel cell stack and efficiency. It can be selected on any point along the polarization curve of Figure 2. The power density (which is the product of cell voltage and current density) is higher at lower cell voltages resulting in a smaller stack size and vice versa at higher cell voltages. Figure 6 shows the effect of nominal cell voltage on the size of the stack. It is evident from above that a stack designed to operate at a nominal cell voltage of 0.7 V would require twice the active area as that sized to operate at 0.5 V per cell thus increasing the equipment cost. However a higher cell voltage results in a higher efficiency and decreases fuel consumption.

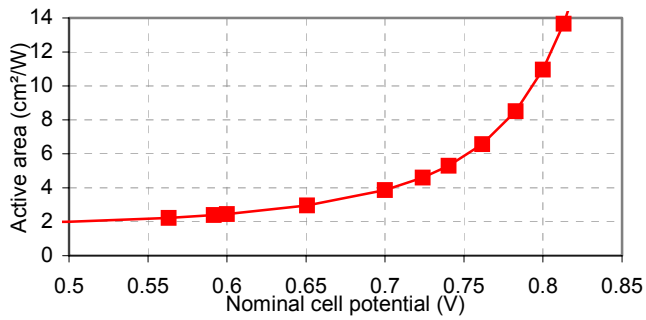

Figure 6. Effect of Nominal Cell Voltage on Fuel Cell Stack Size

But selection of optimum cell voltage at nominal power must be made based on the lowest cost of generated electricity. Therefore it must collectively take into account factors such as cost of the stack, cost of fuel consumed, load profile and capacity factor, lifetime, etc. Figure 7 compares the efficiency of three stacks each sized at different nominal cell voltages over the entire power range. It is evident that the largest stack (with a nominal cell voltage of 0.8 V) results in the highest efficiency at the peak power. But if the stack were to be operated at or below 20% of nominal power most of the time, higher selected nominal cell voltage does not offer the high efficiency advantage at this point.

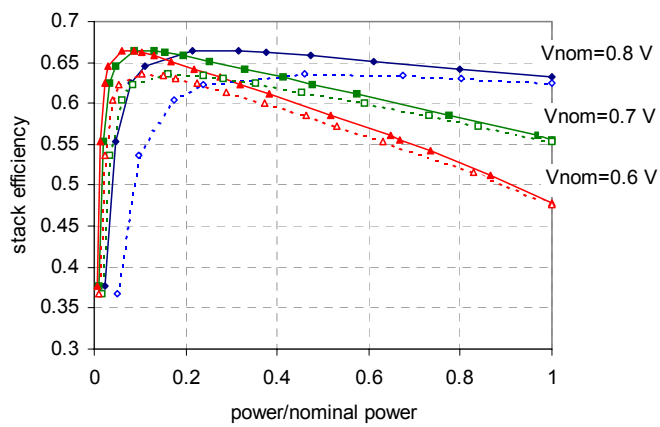

Figure 7. Stack efficiency vs. power output for different selected nominal cell voltages.

Conclusions

The objective of this paper is to provide a general overview on optimizing a PEM fuel cell system for backup power applications based on a set of key input and design parameters such as temperature, pressure, humidification, water management, and cell voltage. Low temperature and low pressure is beneficial for system simplicity and efficiency. It is possible to relax water management and humidification requirements at low pressures by selecting low operating temperatures. Higher selected nominal cell voltage does not necessarily mean higher operating efficiency particularly if the stack is operated at partial loads most of the time. So selection of nominal cell voltage must be based collectively on factors such as cost of the stack, cost of fuel consumed, load profile and capacity factor, lifetime, etc.

References

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