Fuel Cell Powered UPS Systems: Design Considerations

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Abstract: **In this paper a 1-kVA fuel cell powered line-interactive UPS system employing modular (fuel cell & power converter) blocks is introduced. Two commercially available PEMFC Fuel Cell (25-39V, 500W) modules along with suitable DC/DC and DC/AC power electronic converter modules are employed. A Supercapacitor module is also employed to compensate for the instantaneous power fluctuations and overcome the slow dynamics of the fuel processor such as reformers. Further energy stored in the supercapacitor is also utilized to handle a momentary overload such as 200% for a short duration. Due to the absence of batteries, the system satisfies the demand for an environmentally friendly clean source of energy. A complete design example illustrating the amount of hydrogen storage required for 1hr power outage, and sizing of supercapacitors for transient load demand is presented for a 1kVA UPS. Simulation and experimental results show the validity and feasibility of the 1kVA fuel cell power plant.**

I. INTRODUCTION

Conventional uninterruptible power supply systems (UPS) employ engine generators and/or batteries as their main power sources to provide the electric power for critical functions or loads when the normal supply, i.e. utility power, is not available [1][5]. Typical UPS systems consist of rechargeable batteries such as sealed lead-acid (SSLA) or nickel cadmium (Ni-Cd). However, these batteries contain toxic heavy metals such as cadmium, mercury, and lead and may cause serious environmental problems if they are discarded without special care [8].

Fuel cells are emerging as an attractive power source by virtue of their inherently clean, efficient and reliable service [2][4]. As the demand for various applications such as remote generation, backup power generation and distributed generation increases, their use is spreading widely. Accordingly, their prices are steadily reducing and this is further accelerating their penetration into market [5]. Among various kinds of fuel cells, PEMFCs (Proton Exchange Membrane Fuel Cells) are compact and lightweight; provide a high output power density at room temperature, plus ease of start-up and shut down in system operation [4]. Further, unlike batteries, fuel cells can continuously provide power as long as the reactants are supplied. This feature is especially useful under the condition where the duration of the power outage is uncertain.

It is important for the UPS system to be able to immediately take over the full load at the power outage or out-of-tolerance situation to avoid any data loss, uncontrolled system shutdown or malfunctioning of the devices. Some critical applications do not allow even several tens of millisecond power interruption. As is well known, fuel processors have a delay as much as several tens of seconds, and fuel cell cannot take over the full load if its membrane is not properly conditioned. For this reason, a supercapacitor module is employed to compensate for these response delays by supplying the required instantaneous energy, which is stored during the normal operation. This energy can be used to handle overload conditions as well.

In this paper, design considerations of a 1-kVA fuel cell powered line-interactive UPS system employing modular (fuel cell & power converter) blocks is discussed (Fig. 1). A design example for the DC/DC boost converter and sizing of the supercapacitor as well as fuel calculations are presented and the validity of the design is verified through the simulation.

II. PROPOSED FUEL CELL POWERED UPS SYTEM ARCHITECTURE

Fig. 1 shows the block diagram of the proposed approach. The approach consists of two boost converters with fuel cells and one bi-directional converter with a supercapacitor. Normally, the utility power is transferred to the load through the static switch SSM. At the initial start, fuel cells charge the supercapacitor through the bi-directional converter, and then supply 10% of the rated load along with the utility. In the event of power outage or out-of-tolerance, however, the controller turns the SSM off, thereby the fuel cell and their power converter modules start to power the full load alone.

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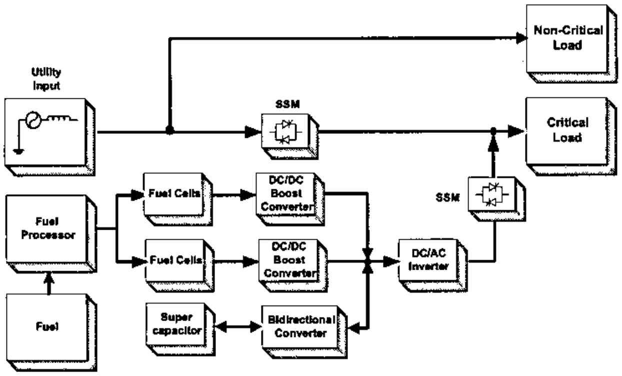

Fig. 1 Proposed Fuel Cell Powered Linc-Interactive Uninterruptible Power Supply System

At the moment of the transition from the normal mode to fuel cell powering mode, the system is not able to take over the full load due to the slow dynamics of the fuel processor. This proposed topology overcomes this drawback by placing the supercapacitor and bi-directional converter module in parallel with the fuel cell and power converter modules. This module transfers the energy that was stored in the supercapacitor during the normal mode operation, to the load at the initial start to make up the instantaneous power shortage. This stored energy can also be used to handle the transient power shortage due to load step changes and/or overload conditions for a short time. When the transient situation is over, the fuel cells supply the minimum power to the load and at the same time recharges the supercapacitor. The control circuit monitors the utility and the fuel cells status continuously. When the system detects a utility disturbance condition, it controls the fuel cell and power converter modules to supply more power. After the disturbance, the controller connects the utility to the load through the synchronization process. The advantages of the proposed approach over conventional UPS systems are as follows:

1. Due to the absence of batteries and an engine generator, it is environmentally friendly, clean and quiet.
2. In the proposed fuel cell powered UPS, the amount of power availability is a function of Hydrogen availability. This is an advantage compared to the battery based UPS whose state-of-charge (SOC) is not always precisely known.
3. No delay time is required to take over the full load when the power disturbance occurs due to fast discharging characteristics of the supercapacitor.
4. The system possesses good overload handling capability with the supercapacitor.
5. Continuous power generation is possible as long as the reactant gases are supplied to the fuel cells.

Fig. 2 shows the detailed circuit of the proposed Architecture. The DC/DC conversion stage of this architecture consists of two fuel cells employing boost converters, a supercapacitor employing bi-directional buck-boost converter and a low voltage DC bus capacitor. An additional DC/DC converter and a high frequency isolation transformer are employed to form the high voltage DC link. At the initial start-up, two fuel cells charge the supercapacitor through the MOSFET S3 and DC bus capacitor as well. Under normal operating conditions, two boost converters supply 10% of the rated power to the load. However, when the load changes suddenly, the UPS system is not able to respond promptly to the power demand change due to its delay time for fuel flow rates to adjust. In this situation, the system controls the switch S4 to supply the DC bus by the boost operation. This control topology is also useful for handling the instantaneous overload situation. If the load demands more than the rated power momentarily, the stored energy in the supercapacitor can be utilized to supply the load, thereby preventing the fuel cell from being overloaded. It is obvious that system delay or voltage drop is unavoidable without this auxiliary power system in the condition of sudden load change and/or overload. The DC/AC conversion stage of this architecture consists of a DC/AC IGBT inverter and produces the high quality sinusoidal 120/240V output voltage based on the neutral point produced by the switch S5 and S6 in a controlled manner or 3-phase AC output.

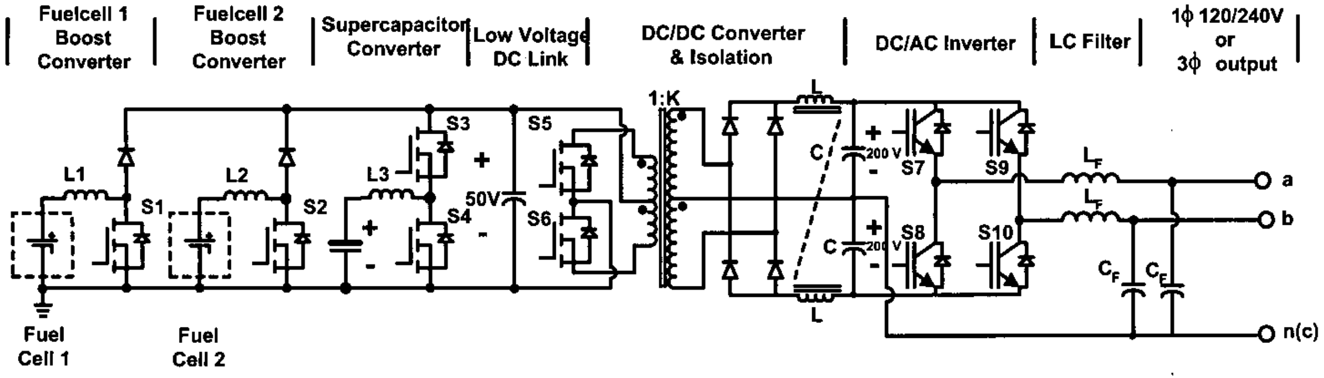

Fig 2. Circuit Topology of the Proposed Fuel Cell Powered UPS System.

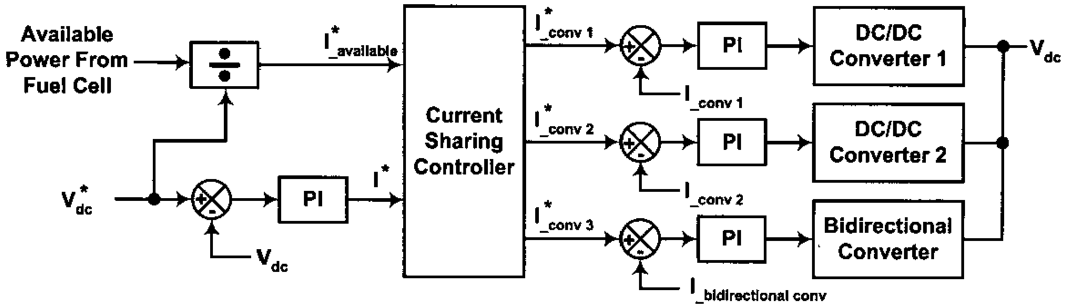

Fig 3. Block diagram of the parallel DC-DC converter control scheme

In this architecture, though the additional DC converter stage results in a reduced system efficiency, it is attractive in that this approach does not require a low frequency transformer, which is bulky and heavy.

III. DC-BUS CONTROL SCHEME

Figure 3 shows the block diagram of the parallel DC-DC boost converter control scheme. In the figure DC/DC converters 1 and 2 are combined with fuel cells 1 and 2, and DC/DC converter 3 is combined with a supercapacitor. The control scheme is composed of one voltage control loop and three independent current control loops and the DC bus voltage is controlled by a PI controller to generate the system current command. Power available signal from the fuel cell indicates the available power from the fuel cell at the moment and thereby available current command is calculated. In the situation of a power shortage or instantaneous overload current sharing controller calculates the appropriate current command values for each converter and sends it to them.

IV. SIMULATION RESULTS

Fig.4 shows the simulation results for the DC/DC converters incorporated with the fuel cells and supercapacitor when the power outage occurs. Initially, the DC/DC converter and fuel cell modules are powering the 10% of the load and then load changes suddenly from 10% to 100%. In this condition, the system is not able to respond fast enough to supply the load. The top trace is the 'power available signal' indicating the amount of power available from the fuel cells. In this simulation, it is assumed for convenience that the reformer and fuel cell stack have 6-second response delay. Therefore, it takes 6 seconds for the fuel cell and associated reformer to produce enough power to supply 100% load from the moment of a power outage. The second and third traces show inductor (L1 and L2) current waveforms for boost converters 1and 2. Each converter is sharing the load equally in the range of the available power. The fourth trace is the inductor (L3) current waveform showing that power from the supercapacitor is making up for the power shortage during the transient. The supercapacitor is discharging to supply the load. The bottom trace shows the DC bus voltage being maintained stable during the transient. After the transient, the supercapacitor is recharged. Fig 5. shows the simulation results when the load changes from 100% to 200% for a short time. At the

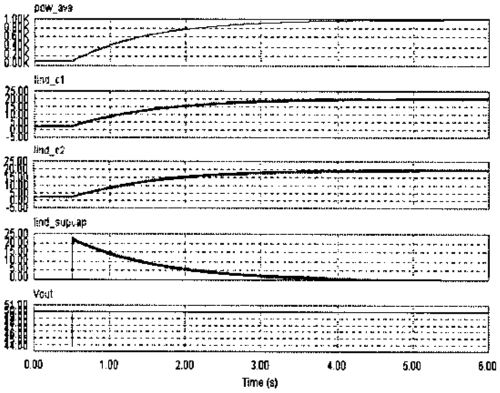

Fig. 4 Simulation results: (a) Power available signal form the fuel cell (b) Inductor current of converter 1 (c) Inductor current of converter 2 (d) Inductor current of bi-directional converter (e) DC bus voltage

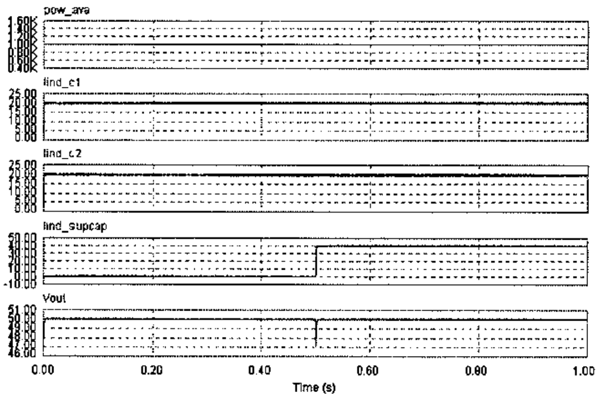

Fig 5. Simulation results: (a) Power available signal form the fuel cell (b) Inductor current of converter 1 (c) Inductor current of converter 2 (d) Inductor current of bi-directional converter (e) DC bus voltage

beginning, two converters are powering the 100% load equally and the load increased to 200% in 0.5 second. In this condition, the supercapacitor is discharging its stored energy to supply the overloaded portion. The first and second traces show that the two boost converters 1 and 2 are not overloaded.

V. DESIGN EXAMPLE

V-1 Specification of proposed fuel cell powered UPS

- Rated Power: 1 KVA
- Normal Output Power: 10% rated power with utility power available
- Fuel Reformer Time Constant: < 20 sec
- Output Voltage: 120VAC ± 5%
- Output Voltage Frequency: 60HZ ± 0.1%
- THD (Total Harmonic Distortion): < 2%
- Overload Rating: 200% for 10 sec.

In this design example, all the calculations are done based on a PEMFC (Proton Exchange Membrane Fuel Cell).

V-2. Required Fuel Calculation for 1-hr Power Outage and Normal Mode Operation [4][9]

In this section Hydrogen consumption is calculated for the 1kW PEMFC stack.

The basic chemical equation for a fuel cell reaction can be expressed as,

$$2H_2 + O_2 = 2H_2O \qquad (1)$$

The rate of Hydrogen fuel usage in a single cell is related to current by,

$$Q_{\_H_2} = \frac{I}{Z \cdot F} \text{ [moles / sec]} \qquad (2)$$

where,

$Q_{\_H2}$: Hydrogen flow rate
F: Faraday constant 96485[coulombs/mole]
Z: Number of electrons participating in the reaction

Thus, the Hydrogen flow rate required to generate 1 ampere for one cell can be calculated by,

$$Q_{U\_H_2} = \frac{I}{Z * F * I * K} = \frac{1[\frac{\text{coulomb}}{\text{sec}}] * 60[\frac{\text{sec}}{\text{min}}] * 22.4[\frac{\text{SL}}{\text{mol}}]}{2 * 96485[\frac{\text{coulombs}}{\text{mol}}] * 1[\text{A}] * 1[\text{cell}]}$$

$$= 0.007[\frac{\text{SLM}}{\text{A} \cdot \text{Cell}}] \qquad (3)$$

where,

K: Number of cells
SLM: Standard liter per minute

For the parasitic power to run the control system of the fuel cell, it is estimated that the fuel cell is required to generate about 10% more power than needed. Thus, the hydrogen flow rate needed for 1kW fuel cell stack can be calculated as follows.

$$Q_{T\_H2} = Q_{U\_H_2} * \frac{P * 1.1}{V_{cell}} * N * S = 0.007 * \frac{1000 * 1.1}{25} * 48 * 1.05 = 15.5[\text{SLM}]$$

(4)

where,

$Q_{\_T\_H2}$: Hydrogen flow rate needed to generate total power
V_{cell}: Fuel cell output voltage at the rated load
N: Number of cells
S: Stoichiometry

Therefore, the total amount of Hydrogen to be consumed for a 1kVA UPS system during a 1-hour power outage can be calculated as,

$$Q_{T\_H2}[\text{SLM}] * 60[\text{min}] = 15.5 * 60 = 931[\text{L}] \qquad (5)$$

If the Hydrogen is stored in the cylinder as a compressed gas at 25°C (298.15[K]), its weight and volume at 150 atm (2205 [psi]) can be calculated as follows. The weight of Hydrogen is given by,

$$\frac{931[\text{L}] * 2[\frac{\text{g}}{\text{mole}}]}{22.4[\frac{\text{L}}{\text{mole}}]} = 83[\text{g}] \qquad (6)$$

Since Hydrogen gas normally takes up 3 weight percent when it is contained in a cylinder as a compressed gas, the total weight of the compressed Hydrogen gas and its cylinder is

$$\frac{83[\text{g}]}{3[\text{wt\%}]} = 2766[\text{g}] \qquad (7)$$

The volume of the Hydrogen at 150[atm] can be calculated by eq. (8-10) The number of moles of Hydrogen in a certain volume (931[L] in this case) can be calculated as

$$n = \frac{P \cdot V}{R \cdot T} = \frac{1[\text{atm}] * 931[\text{L}] * 10^3[\text{cm}^3 / \text{L}]}{82.06[\frac{\text{cm3} \cdot \text{atm}}{\text{mol} \cdot \text{K}}] * 298.15[\text{K}]} = 38[\text{moles}] \qquad (8)$$

where,

n: Number of moles
P: Pressure [atm]
V: Volume of the gas [cm^3]
R: Gas constant
T: Temperature [K]

The volume of one mole of Hydrogen at 150[atm] can be calculated from the virial equation [9-10] as

$$V_{\_U} = \frac{R \cdot T}{P} + B = \frac{82.06[\frac{\text{cm3} \cdot \text{atm}}{\text{mol} \cdot \text{K}}] * 298.15[\text{K}]}{150[\text{atm}]} + 15.4[\frac{\text{cm3}}{\text{mol}}] = 178.5[\frac{\text{cm}^3}{\text{mole}}]$$

(9)

where,
$V_{\_U}$: Volume of one mole of Hydrogen at a certain pressure
B: Virial constant at 298.15[K]

Thus, the total volume of the Hydrogen at 25[°C] at 150 [atm] is

$$V_{\_U} * n = 178.5[\frac{cm^3}{mole}] * 38[mole] * 10^{-3}[\frac{L}{cm^3}] = 6.78[L] \quad (10)$$

The proposed line-interactive UPS system is assumed to supply 10% of the rated load. Thus the Hydrogen needed for normal mode operation is 93-Liters per hour.

V-3. DC/DC Converter Design

The DC/DC converter is designed according to the following calculations [7]:

Switching frequency (Fs)= 100 [kHz]
Critical load (I_out_crit) = Po/Vo*0.1= 1[A];
10% of the full load for continuous current mode
Output voltage ripple (Vr) = Vo*0.01 = 0.5 [V];
1% output voltage ripple
Output power of each converter (Po) = 500 [W]
Input voltage (Vs) = 25-39 [V] ;
Output voltage (Vo) = 50 [V]
Maximum output voltage / Input voltage ratio(M)=50/25=2
Output current(Io)=Po/Vo=10 [A]
Maximum input current (Is) = 500/25 =20 [A]
Minimum inductance
Lc=Vo*(M-1)/(Iout_crit*Fs*2*M^3) = 32.15 [uH]
Worst-case peak current
Ipk = Io*(M((+M-1)/(2*Io*Lc*Fs/Vo*M^2)))=22 [A]
Output dc capacitance
Co = (Ipk^2 *Lc) / (2*Vr*(Vo-Vs)) = 600 [uF]

V-4. Sizing the Supercapacitor

The energy stored in a supercapacitor is given by:

$$W_j = \frac{1}{2} CV^2 \quad (11)$$

Since the energy stored in a supercapacitor is directly proportional to the square of the voltage, a drop in 30% of its voltage (1pu to 0.7pu) represents the release of 50% of the stored energy. Further, losses in the DC/DC boost converter powering the supercapacitor along with the internal losses due to the equivalent series resistance (ESR) also need to be accounted for. Adopting this discharge strategy, the following equation can be written:

$$\frac{1}{2}[CV_{sup}^2 - C(0.7V_{sup})^2] * k = P_{shortage} * t \quad (12)$$

where, C is the required capacitance of the supercapacitor, k is the efficiency, which is less than 1 due to loss. $P_{shortage}$ is the amount of power shortage (watts) due to the system delay or overload and "t" is the specified duration for those events. In the proposed approach, the fuel cell and associated reformer are assumed to have 20 seconds of response delay. Therefore, as shown in the simulation (Fig. 4), supercapacitor needs to make up for the power shortage, which is the power difference between the required power for the load and available power from the fuel cells. For the proposed system, we have $P_{shortage}$=500[W]; t=20[seconds] and let k=0.9. Assuming a supercapacitor of 40[V] rating, the required capacitance value can be calculated by substituting these values in Eqn. (12), and

$$C = \frac{4 \cdot P_{shortage} \cdot t}{k * V_{sup}^2} = \frac{4 \cdot 500 \cdot 20}{0.9 * 40^2} = 27.8[F] \quad (13)$$

This can be achieved by connecting 16 of commercially available supercapacitors (450F, 2.5V) in series. Detailed specification for the supercapacitor is presented in the appendix B.

VI. FUEL CELL SYSTEM SETUP

Fig. 6 shows the experimental setup installed in the Power Electronics & Clean Power Research Laboratory of the Texas A&M University. Hydrogen is stored in the two cylinders at high pressure (2200psia). The pressure regulator and indicator are installed at the top of the cylinder. The regulator controls outgoing pressure of the gas and the pressure indicator shows the pressure of the cylinder as well as the outgoing gas. When the cylinder valve is open, hydrogen gas comes out through the in-line filter to meet the necessary purity (99.95%) for the fuel cells. Hydrogen velocity fuses and flame arrestor is installed for safety. The former blocks the Hydrogen flow when the flow rate exceeds a preset value and the latter quenches any flame that may occur inside the Hydrogen pipe. An electronic flow meter indicates the flow rate of the gas and it generates an electric signal for the monitoring system. A second pressure regulator is placed to step down the pressure further. Two-way ball valves are connected to make it possible to control the gas flow manually. Finally, Hydrogen gas is supplied to each fuel cell at the pressure of 7.5psig (55 Kpa-g). Electronic mass flow meter monitors the Hydrogen flow rate to the fuel cell stack. Detailed specification for the fuel cell stack is presented in the appendix A. Fig 7 shows the V-I characteristics of the SR-12 fuel cell stack and Fig 8 shows its power versus current curve.

VII. CONCLUSION

A fuel cell powered, line-interactive UPS system has been discussed in detail. The approach provides stable power to the load when the utility is interrupted. Also, this approach verifies the possibility that the fuel cell can replace conventional UPS power sources such as engine generators, batteries and flywheels. A supercapacitor module is incorporated to overcome the transients such as instantaneous power fluctuations, slow dynamics of the fuel preprocessor and overload conditions. In conclusion, an environmentally friendly and clean power back-up system has been proposed and its validity and feasibility has been verified through the simulation.

Fig. 6 Fuel Cell System Installed in the Power Electronics & Clean Power Research Laboratory of Texas A&M University.

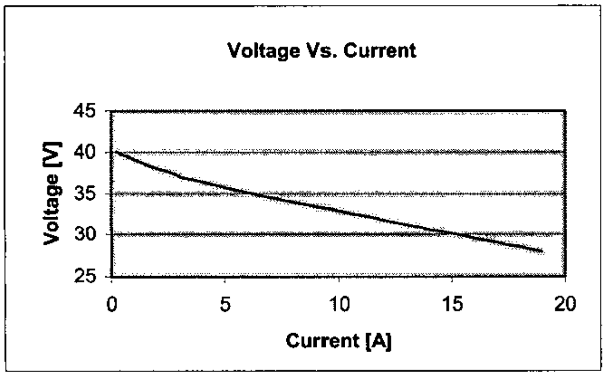

Fig. 7 Voltage versus Current Curve for the SR-12 Fuel Cell Stack

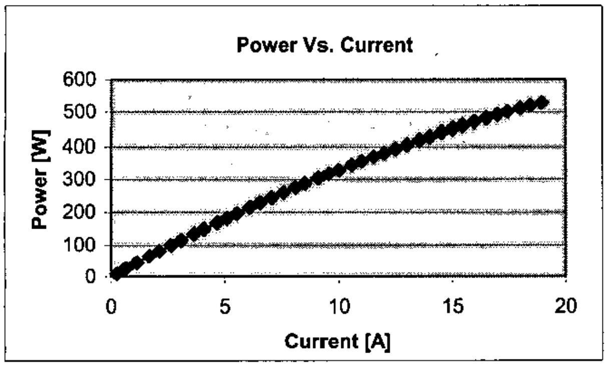

Fig. 8 Power versus Current Curve for the SR-12 Fuel Cell Stack

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APPENDIX

Appendix A. Specification of 500W PEM Fuel Cell Stack, SR-12 (available from Avista Labs)

Power Output (Cont.)	500 W
Output Voltage	25-39 VDC
Fuel Source	Hydrogen
Fuel Consumption	7.0L/min 500W (<1.0L/min @ no load)
System Start Time	7 minutes @room temperature
Turndown Ratio	500W to no load, infinity
Operating Temperature	5°C to 35°C
Dimension(W x D x H)	22.3" x 24.2" x 13.6"
Weight	44kg w/cartridge

Appendix B. Specification of Supercapacitor, BCAP0013 (available from Maxwell Technologies)

Capacitance	450 Farads (±20%)
Maximum Series Resistance ESR(25°C)	2.4 mohms
Specific Power Density	3400 (W/kg)
Voltage(Cont.)	2.5 V
Voltage(Peak)	2.8 V
Maximum current	180 A
Dimensions	50 x 97 mm
Weight	190 g
Volume	.15 L
Temperature (Operating & Storage)	-35°C to 65°C
Leakage Current (12 hours, 25°C)	3 mA