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Fuel-cell powered uninterruptible power supply systems: Design considerations

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Abstract

A 1-kVA fuel cell powered, line-interactive uninterruptible power supply (UPS) system that employs modular (fuel cell and power converter) blocks is introduced. Two commercially available proton-exchange membrane fuel cell (25–39 V, 500 W) modules together with suitable dc–dc and dc–ac power electronic converter modules are employed. A supercapacitor module is also used to compensate for the instantaneous power fluctuations and to overcome the slow dynamics of the fuel processor (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 clean source of energy. A complete design that defines the amount of hydrogen storage required for a power outage of 1 h, and the sizing of the supercapacitors for transient load demand is presented for a 1-kVA UPS.

Keywords: Proton-exchange membrane; Fuel cell; Line-interactive uninterruptible power supply; Supercapacitor; Reformer; Fuel calculation

1. Introduction

Conventional uninterruptible power supply systems (UPSs) 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 [1,2]. Typical UPS systems consist of rechargeable batteries such as valve-regulated lead-acid (VRLA) or nickel–cadmium (Ni–Cd). These batteries, however contain toxic heavy metals such as cadmium, mercury, and lead and may cause serious environmental problems if they are discarded without special care [3].

Fuel cells are emerging as an attractive power source by virtue of their inherently clean, efficient and reliable service [4]. As the demand for various applications such as remote generation, back-up power generation and distributed generation increases, the use of fuel cell is spreading widely. Accordingly, their prices are steadily reducing and this is further accelerating their penetration into market. Among the various kinds of fuel cells, proton exchange membrane fuel cells (PEMFCs) are compact and lightweight. They also provide a high output power density at room temperature, plus ease of start-up and shut-down in system operation [6]. Further, unlike batteries, fuel cells can continuously provide power as long as the reactants are supplied. This feature is especially useful in situations where the duration of the power outage is uncertain.

It is important for the UPS system to be able to take over immediately the full load in power outage or out-of-tolerance situations to avoid any data loss, uncontrolled system shutdown or malfunctioning of the devices. Some critical applications do not even allow power interruptions of only several tens of milliseconds. As is well known, fuel processors have

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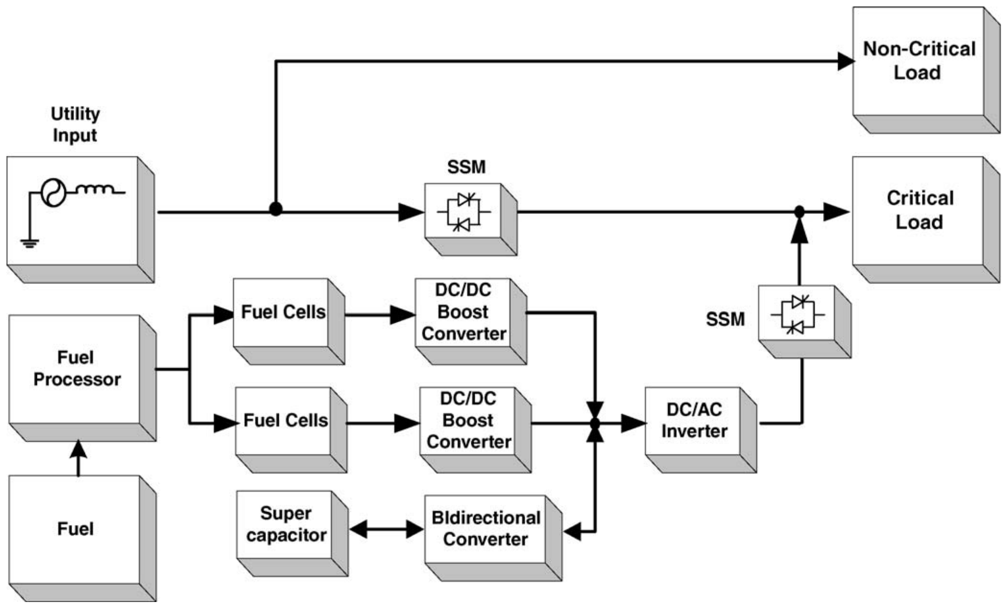

Fig. 1. Proposed fuel-cell powered line-interactive uninterruptible power supply system.

a delay as much as several tens of seconds, and a fuel cell cannot take over the full load if its membrane is not properly humidified. For this reason, a supercapacitor module is employed to compensate for these response delays by supplying the required instantaneous energy, which is stored during normal operation. This energy can also be used to handle overload conditions.

In this paper, the design of a 1-kVA, fuel-cell powered line-interactive UPS system that employs modular (fuel cell and 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 calculation, is presented and the validity of the design is verified through simulation.

2. Architecture of proposed fuel-cell powered UPS system

A block diagram of the proposed approach is given in Fig. 1. The design 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 conditions, however, the controller turns the SSM off, thereby the fuel cell and their power converter modules start to power the full load alone.

At the moment of the transition from the normal mode to the fuel-cell powering mode, the system is not able to take over the full load due to the slow dynamics of the fuel processor. The 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 allows transfer of the energy stored in the supercapacitor during the normal mode operation to the load at the initial start to make up the instantaneous power shortage. The stored energy can also be used to handle transient power shortages 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 recharge the supercapacitor. The control circuit monitors continuously the status of the utility and the fuel cells. When the system detects a utility disturbance, it commands the fuel cell and power converter modules to supply more power. After the disturbance, the controller connects the utility to the load through a synchronization process. The advantages of the proposed approach over conventional UPS systems are as follows:

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

The detailed circuit of the proposed architecture is given in Fig. 2. The dc–dc conversion stage of this architecture

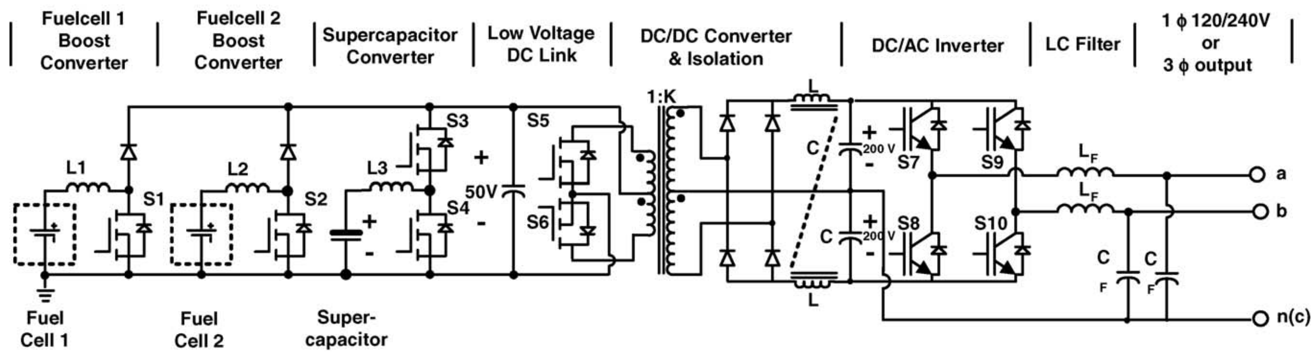

Fig. 2. Circuit topology of the proposed fuel cell powered UPS system.

consists of two fuel cells employing boost converters, a supercapacitor employing a 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. Under normal operating conditions, the two boost converters supply 10% of the rated power to the load. When the load changes suddenly, however, the UPS system is not able to respond promptly to the change in power demand due to the delay time required 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 situations. If the load demands more than the rated power momentarily, the stored energy in the supercapacitor can be utilized to supply the load, and thereby prevent the fuel cell from being overloaded. It is obvious that system delay or voltage drop is unavoidable without this auxiliary power system under conditions 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 120/240 V output voltage based on the neutral point produced by the switch S5 and S6 in a controlled manner or a three-phase ac output. Though the additional dc converter stage results in reduced system efficiency, this approach is attractive in that it does not require a low-frequency transformer, which is bulky and heavy.

3. DC-Bus control scheme

A block diagram of the parallel dc–dc boost converter control scheme is presented in Fig. 3. The dc–dc converters 1 and 2 are combined with fuel cells 1 and 2, and a bi-directional converter is combined with a supercapacitor module. The control scheme is composed of one voltage control loop and three independent current control loops. The dc bus voltage is controlled by a PI controller to generate the system current command. A signal from the fuel cell indicates the available power from the fuel cell and thereby the available current command is calculated. Under steady-state operation, this command is evenly distributed to each converter and the supercapacitor is charged. In a transient state, such as a load step change or overload, the system current command becomes larger than the available current command due to the slow dynamics of the fuel processor. In this case, a current-sharing controller calculates the difference between the system current command and the available current command and sends it to the bi-directional converter to discharge the stored energy in the supercapacitor.

4. Simulation results

Simulation results are shown in Fig. 4 for the dc–dc converters incorporated with the fuel cells and supercapacitor when a power outage occurs. Initially, the dc–dc converter

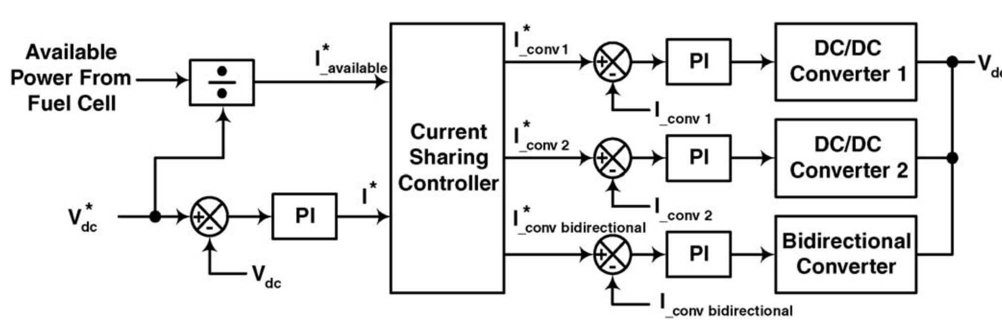

Fig. 3. Block diagram of the parallel dc–dc converter control scheme.

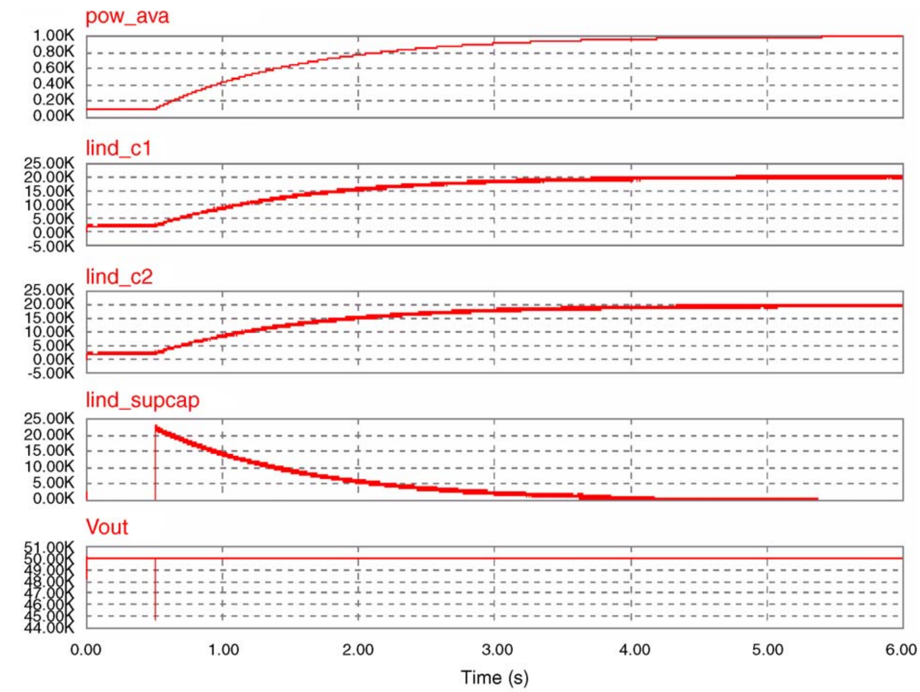

Fig. 4. Simulation results: (a) power available signal from fuel cell; (b) inductor current of converter 1; (c) inductor current of converter 2; (d) inductor current of bi-directional converter; (e) dc bus voltage.

and fuel cell modules power 10% of the load and then the 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", which indicates 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 a 6-s response delay. Therefore, it takes 6 s for the fuel cell and associated reformer to produce sufficient 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 1 and 2. The two converters are sharing the load equally in the range of the available power. The fourth trace is the inductor (L3) current waveform. This shows that power from the supercapacitor is making up for the power shortage during the transient. The supercapacitor discharges to supply the load. The bottom

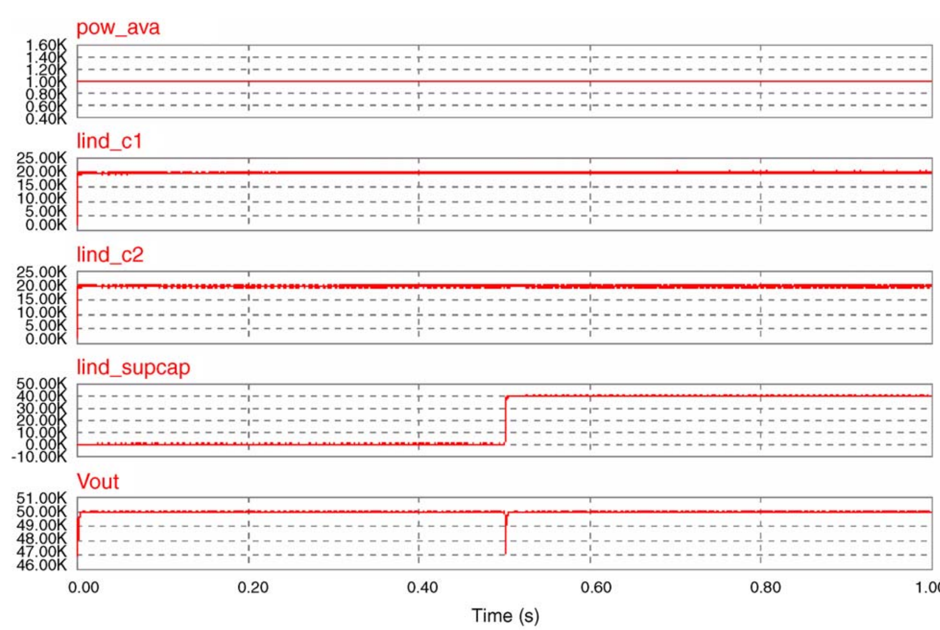

Fig. 5. Simulation results: (a) power available signal form fuel cell; (b) inductor current of converter 1; (c) inductor current of converter 2; (d) inductor current of bi-directional converter; (e) dc bus voltage.

trace shows that the dc bus voltage remains stable during the transient. After the transient, the supercapacitor is recharged. The simulation results for when the load changes from 100 to 200% for a short time are shown in Fig. 5. At the beginning the two converters power the 100% load equally and the load increase to 200% at 0.5 s. In this condition, the supercapacitor discharges 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.

5. Design example

5.1. 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 s,
- output voltage: 120 Vac ± 5%,
- output voltage frequency: 60 Hz ± 0.1%,
- total harmonic distortion (THD): <2%,
- overload rating: 200% for 10 s.

In this design example, all the calculations are based on a PEMFC manufactured by Avistalabs (Appendix A).

5.2. Required fuel calculation for 1-h power outage and normal mode operation

In this section, hydrogen consumption is calculated for a 1-kW PEMFC stack. The basic chemical equation for a fuel cell reaction can be expressed as [5–7]:

$$2H_2 + O_2 = 2H_2O \tag{1}$$

The rate of hydrogen fuel usage in a single cell is related to the current by

$$Q_{\_H_2} = \frac{I}{ZF}(\text{mol s}^{-1}) \tag{2}$$

where $Q_{\_H_2}$ is the hydrogen flow rate, F the Faraday constant 96 485 C mol^{-1}, and Z the number of electrons participating in the reaction.

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

$$Q_{U\_H_2} = \frac{I}{ZFK} = \frac{1\,\text{C s}^{-1} \times 60\,\text{s min}^{-1} \times 22.4\,\text{SL mol}^{-1}}{2 \times 96\,485\,\text{C mol}^{-1} \times 1\,\text{cell}} = 0.007\,\text{SLM A cell} \tag{3}$$

where K is the number of cells and SLM is the 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 a 1 kW fuel-cell stack can be calculated as follows:

$$Q_{T\_H_2} = Q_{U\_H_2} \times \frac{P \times 1.1}{V_{\text{cell}}} \times N \times S = 0.007 \times \frac{1000 \times 1.1}{25} \times 48 \times 1.05 = 15.5\,\text{SLM} \tag{4}$$

where $Q_{T\_H_2}$ is the hydrogen flow rate needed to generate total power, V_{cell} the fuel cell output voltage at rated load, N the number of cells, and S is the stoichiometry.

Therefore, the total amount of hydrogen consumed by a 1-kVA UPS system during a 1-h power outage can be calculated as

$$Q_{T\_H_2}(\text{SLM}) \times 60\text{ min} = 15.5 \times 60 = 931\,\text{L} \tag{5}$$

If the hydrogen is stored in a cylinder as 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 (G_{H_2}) is given by

$$G_{H_2} = \frac{931\,\text{L} \times 2\,\text{g mol}^{-1}}{22.4\,\text{L mol}^{-1}} = 83\,\text{g} \tag{6}$$

Since hydrogen gas normally takes up 3 wt.% when it is contained in a cylinder as a compressed gas, the total weight of the compressed hydrogen gas and its cylinder is

$$G_{H_2\_\text{total}} = \frac{83\,\text{g}}{3\,\text{wt.\%}} = 2766\,\text{g} \tag{7}$$

The volume of the hydrogen at 150 atm can be calculated by using Eqs. (8)–(10). The number of moles of hydrogen in a certain volume (931 L in this case) can be calculated as

$$n = \frac{PV}{RT} = \frac{1\,\text{atm} \times 931\,\text{L} \times 10^3\,\text{cm}^3\,\text{L}^{-1}}{82.06\,\text{cm}^3\,\text{atm mol K}^{-1} \times 298.15\,\text{K}} = 38\,\text{mol} \tag{8}$$

where n is the number of moles of hydrogen, P the pressure (atm), V the volume of the gas (cm^3), R the gas constant, and T is the temperature (K).

The volume of 1 mol of hydrogen at 150 atm can be calculated from the virial Eqs. (9) and (10) as [8]

$$V_{U\_H_2} = \frac{RT}{P} + B = \frac{82.06\,\text{cm}^3\,\text{atm mol K}^{-1} \times 298.15\,\text{K}}{150\,\text{atm}} + 15.4\,\text{cm}^3\,\text{mol}^{-1} = 178.5\,\text{cm}^3\,\text{mol}^{-1} \tag{9}$$

where $V_{\_U}$ is the volume of 1 mol of hydrogen at a certain pressure and B is the Virial constant at 298.15 K.

Thus, the total volume of hydrogen at 25 °C at 150 atm is

$$V_{\_U} \times n = 178.5\,\text{cm}^3\,\text{mol}^{-1} \times 38\,\text{mol} \times 10^{-3}\,\text{L cm}^3 = 6.78\,\text{L} \tag{10}$$

The proposed line-interactive UPS system is assumed to supply 10% of the rated load. Thus, the hydrogen required for normal mode operation is $93.1\,\mathrm{L\,h^{-1}}$.

5.3. dc–dc Boost converter design

The dc–dc boost converter is designed according to the following calculations Eqs. (11)–(17). The rated output power of each converter is 500 W and the input voltage varies from 25 to 39 V. The output voltage of the converter is 50 V and the switching frequency is chosen as 100 kHz. Since the fuel cell and power converter module supply 10% of the load in normal operation, the minimum inductance can be calculated based on this value to guarantee the continuous current-mode operation of the converter during normal operation of the UPS as in Eq. (14). Expressions for the peak current and voltage of the switch are written for switch selection as in Eqs. (15) and (16). When the output voltage ripple is limited to 1%, minimum capacitance value can be decided as in Eq. (17) [9]:

$$\text{maximum voltage conversion ratio}: M = \frac{50}{25} = 2 \tag{11}$$

$$\text{maximum output current}: I_0 = \frac{P_0}{V_0} = 10\,\mathrm{A} \tag{12}$$

$$\text{maximum input current}: (I_{\text{in\_peak}}) = \frac{500}{25} = 20\,\mathrm{A} \tag{13}$$

$$L_C = \frac{V_0 \times (M-1)}{(I_0 \times 0.1) \times F_S \times 2 \times M^3} = 32.15\,\mu\mathrm{H} \tag{14}$$

$$I_{\text{sw\_peak}} = I_0 \times \left[M + \left(\frac{V_0}{2 \times F_S \times I_0 \times L_C}\right) \times \left(\frac{M-1}{M^3}\right)\right] = 22\,\mathrm{A} \tag{15}$$

$$V_{\text{sw\_peak}} = V_{\text{in\_max}} + V_{\text{out}} = 39 + 50 = 89\,\mathrm{V} \tag{16}$$

$$C_0 = \frac{I^2_{\text{sw\_peak}} \times L_C}{2 \times \Delta V_0 \times (V_0 - V_{\text{in\_min}})} = 600\,\mu\mathrm{F} \tag{17}$$

5.4. Sizing of the supercapacitor

The energy stored in a supercapacitor is given by

$$W_j = \tfrac{1}{2} C V^2 \tag{18}$$

Since the energy stored in a supercapacitor is directly proportional to the square of the voltage, a drop of 30% of the voltage (1–0.7 pu) represents a 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 taken into account. Adopting this discharge strategy, the following equation can be written:

$$\tfrac{1}{2}[C V^2_{\text{sup}} - C(0.7 V_{\text{sup}})^2] \times k = P_{\text{shortage}} t \tag{19}$$

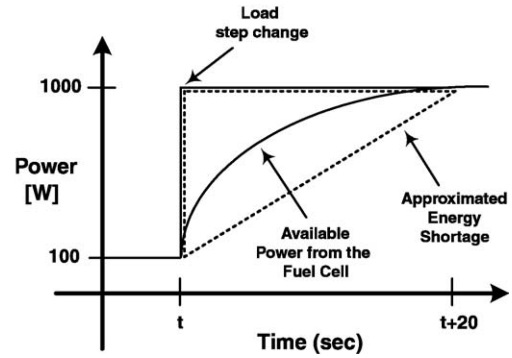

Fig. 6. Required energy calculation for sizing the supercapacitor.

where C is the required capacitance of the supercapacitor, k the efficiency, which is less than 1 due to loss, and P_{shortage} is the amount of power shortage (W) due to the system delay or overload and t is the specified duration for these events. In the proposed approach, the fuel cell and associated reformer are assumed to have 20 s of response delay. Therefore, as shown in Fig. 6 the supercapacitor needs to make up for the power shortage, which is the power difference between the required power for the load and the available power from the fuel cells.

For the proposed system, $P_{\text{shortage}} = 500\,\mathrm{W}$; $t = 20\,\mathrm{s}$ and $k = 0.9$. Assuming a supercapacitor of 40 V rating, the required capacitance value can be calculated by substituting these values in Eq. (19), and

$$C = \frac{4 P_{\text{shortage}} t}{k \times V^2_{\text{sup}}} = \frac{4 \times 500 \times 20}{0.9 \times 40^2} = 27.8\,\mathrm{F} \tag{20}$$

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

6. Conclusions

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 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 simulation.

Acknowledgement

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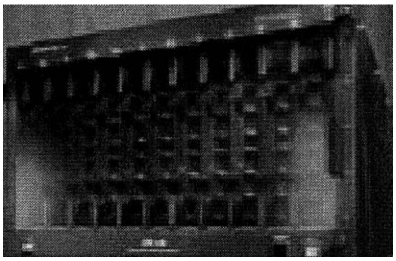
Appendix A. [10]

Specification of 500-W PEMFC stack, SR-12 (available from Avista Labs)



Power output (control)	500 W
Output voltage	25–39 Vdc
Fuel source	Hydrogen
Fuel consumption	7.0 L min^{-1} 500 W (<1.0 L min^{-1} at no load)
System start time	7 min at room temperature
Turndown ratio	500 W to no load, infinity
Operating temperature	5–35 °C
Dimension ($W \times D \times H$)	22.3 in. × 24.2 in. × 13.6 in.
Weight	44 kgw $cartridge^{-1}$

Appendix B

Specification of supercapacitor, BCAP0013 (available from Maxwell Technologies)

Capacitance	450 Farads (±20%)
Maximum series resistance ESR (25 °C)	2.4 MΩ
Specific power density	3400 (W kg^{-1})
Voltage (control)	2.5 V
Voltage (peak)	2.8 V
Maximum current	180 A
Dimensions	50 mm × 97 mm
Weight	190 g
Volume	0.15 L
Temperature (operating and storage)	−35 to 65 °C
Leakage current (12 h, 25 °C)	3 mA

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