

Fuelcell power supply system – modelling and optimization

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Abstract— The paper presents an analytical model for sizing supercapacitors as part of a hybrid power supply. The load is assumed to be modeled by its power over time requirements. Approximating the theoretical curve as combinations of constant and linearly increasing power segments equations are obtained for the supercapacitor current as a function of its initial and final voltage. This allows for sizing the supercapacitor for wide variety of application. The model is verified by means of simulation and experimental results.

Keywords— energy storage, fuel cell, supercapacitor, high efficiency, synchronous dc-dc converter.

I. INTRODUCTION

The fuel cell is a very attractive power source for powering next generation vehicles simultaneously lowering emissions and achieving long drive range [1]. This can be done only if the fuel cell is loaded properly as it achieves optimal conversion efficiency only in a narrow range of load currents [2]. The power required for the propulsion of the vehicle can have regions with sharp transitions leading to high current stress on the fuel cell ultimately leading to lower efficiency. For this reason usually a hybrid system is proposed consisting of both a fuel cell and a second element that can provide the energy during the high power requirements of the load. Many topologies including batteries, supercapacitors or both have been considered, each with its own advantages and disadvantages [3], [4].

The design of such a system naturally requires sizing the value of the supercapacitor and this can be done with simulation [5]. However, an analytical approach is highly desired as it allows for optimization without significant computational resources. This paper presents such an analytical approach to sizing the capacitor in such a system. It models the supercapacitor as a combination of elementary cells, while abstracting the load by its power requirements over time. This data is easily obtained for the vehicle. Formulas are obtained for two cases with practical significance – linearly increasing power demand (typical for vehicle acceleration mode) and constant power. This can be positive (propulsion) or negative (recuperation) but this is not significant in the analysis. The obtained model is verified by means of simulation and experimental results.

The paper is structured as follows: In the next section shows the block diagram of the hybrid system and introduces the approximations used during the mathematical analysis. It obtains equations for the supercapacitor current for two common practical cases. The obtained formulas are then

verified with simulation results in section III. Section IV presents experimental results and compares them with simulation. Section V comments on the use of the obtained equations and presents practical formulas for choosing the supercapacitor in a hybrid system. Section VI summarizes the paper.

II. DESIGNED SYSTEM

The block diagram of the system under consideration is presented in fig. 1. The system consists of a fuel cell as the main energy storage element, a dc/dc converter that transfers its energy to a supercapacitor, and a second dc/dc converter that regulates the load voltage. The supercapacitor handles the peak power requirements of the load, which is modelled by its power profile over time.

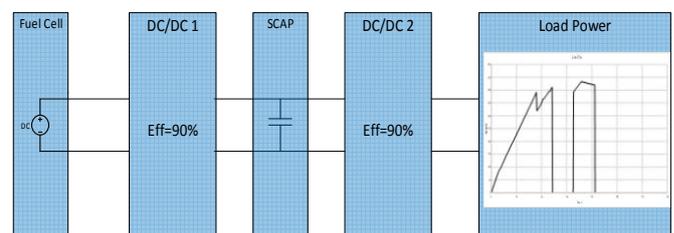


Figure 1. Block-diagram of the energy storage system.

The first dc/dc converter charges the supercapacitor by a constant current, thus loading the fuel cell optimally. The second dc/dc converter regulates the voltage on the load at 48V. This voltage is the input of a BDC motor driving the vehicle. As the modeling of the mechanical system is complicated a much easier alternative is presented here, where the whole load is modeled as a combination of constant (including zero) and ramp segments of power consumption. Combining these two cases almost any load profile can be modeled. The designer of the system usually specifies the required minimum value of the supercapacitor voltage during discharge, its initial value at the start of the race and needs an equation that links its current to the power demand of the load. Having such an equation allows for plotting the supercapacitor voltage over time and ultimately choosing the optimal value for the specified requirements. The maximum supercapacitor current also sets the semiconductor device stress.

In order to obtain a model that couples the above requirements the following assumptions have been made during the analysis:

- The first dc/dc converter charges the supercapacitor with constant current, thus can be modeled as a constant current source I_{ch} .

- The second dc/dc converter acts to keep the load voltage constant.

- The required power consumption is known and can be obtained as a combination of constant (including zero) and ramp segments.

- The supercapacitor is modeled as a series combination of many cells. Each cell includes only the equivalent series resistance (ESR) of the supercapacitor. All cells are assumed to be equal for the analysis. Also, it is assumed to be linear and time invariant.

Based on the above assumptions the analyzed circuit is shown in fig. 2. For the circuit using Kirchoff's equations the following differential equation can be written:

$$I_L I_{Sc} \frac{dV_{sc}}{dt} + P_L \frac{dI_{Sc}}{dt} = I_L I_{ch} \frac{dV_{sc}}{dt} - I_L \frac{dV_{sc}}{R_{in}} - I_L \frac{dP_L}{dt} \quad (1)$$

The equation for the supercapacitor voltage can be obtained as:

$$\frac{dV_{sc}}{dt} = \frac{dI_{Sc}}{dt} (R_{esr} + R_{esr1} + R_{esr2}) + \left(\frac{1}{C_{Scap}} + \frac{1}{C_{Scap1}} + \frac{1}{C_{Scap2}} \right) I_{sc} \quad (2)$$

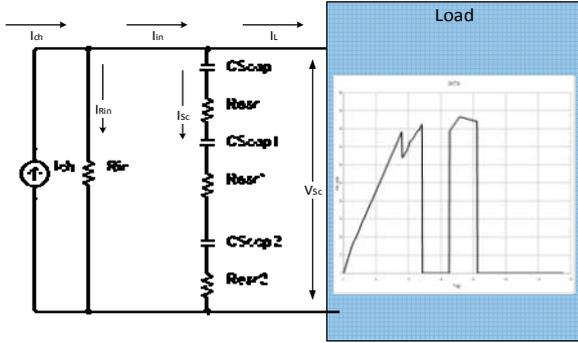


Figure 2. Analyzed System

Assuming that the capacitor cells are equal and substituting from Eqn. 2 in Eqn. 1, eliminating the load current and the nonlinear terms the following differential equation is obtained:

$$\begin{aligned} & \frac{dI_{Sc}}{dt} (P_L + (I_{ch} - I_{sc})(I_{sc} - I_{ch})R_{esreq}) \\ & + (I_{ch} - I_{sc})(I_{sc} - I_{ch}) \left(\frac{1}{C_{Scapeq}} I_{sc} + \frac{dP_L}{dt} \right) \approx 0 \end{aligned} \quad (3)$$

Further, if we assume that the ESR is zero:

$$P_L(t) \frac{dI_{Sc}}{dt} - \frac{I_{Sc}^3}{C} - I_{Sc} \frac{dP_L}{dt} = 0 \quad (4)$$

This equation can be solved for two very important practical cases.

A. Consnant load power

In this case $P_L(t) = P_L$ and its derivative is zero.

If we set the initial condition for the load current to be

$$I_L(0) = \frac{P_L}{V_{sc}(0)} \quad \text{than the solution is obtained as:}$$

$$I_L(t) = \frac{P_L}{V_{sc}(0)} \frac{\sqrt{CV_{sc}^2(0)}}{\sqrt{CV_{sc}^2(0) - 2tP_L^2}} \quad (5)$$

In the above equation $V_{sc}(0)$ is the initial supercapacitor voltage.

B. Linearly changing load power

In this case $P_L(t) = kt$ and its derivative is k . Assuming an initial condition leads to a singular solution, so alternatively an end condition is specified as

$$I_L(t_{end}) = \frac{P_L(t_{end})}{V_{sc}(t_{end})} = \frac{P_{Lmax}}{V_{Scmin}} \quad . \quad \text{It should be noted that}$$

maximum current stress occurs at minimum supercapacitor value and this is an important design parameter for the system.

In this case the assuming $P_{Lmax} = kt_{end}$ the solution can be obtained as:

$$I_L(t) = \frac{k\sqrt{Ct}}{\sqrt{k(t_{end}^2 - t^2) + CV_{Scmin}^2}} \quad (6)$$

As the supercapacitor also has a maximum allowed voltage, specifying both sets the amount of energy that can be stored.

III. SIMULATIONAL RESULTS

Based on the block diagram presented in fig. 1 a model of the system is constructed in Matlab/Simulink – presented in fig. 3. The supercapacitor is charged by a consnant current source I_{ch} . The power load demand is shown in figure 4 (thick line). The PL constant current source is controlled by dividing the required power (set in the repeating sequence block) by the current supercapacitor voltage. This way the load current is set by the power block.

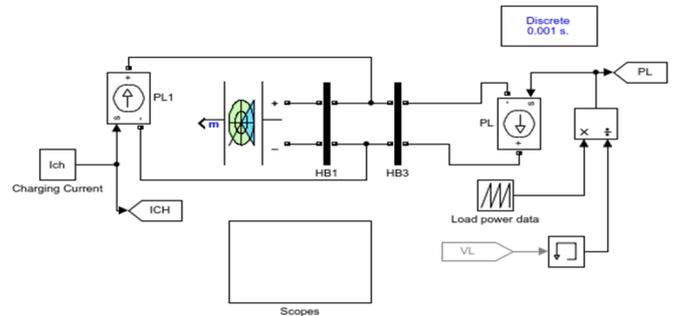


Figure 3. Simulation Circuit

The parameters are summarized in table I, and the used fuel cell in table II. The load power used for the test is shown in figure 4, along with the one approximated for the model. It consist of three segments

- Linearly increasing power for $t=[0s - 38s]$
- Constant power $t=[65s-80s]$
- Zero power in the remaining time.

TABLE I. CIRCUIT PARAMETERS

Value	Parameter	
	Description	Name
4	Charge Current [A]	I _{ch}
58	Supercapacitor value [F]	C _{Scap}
38	Supercapacitor initial voltage[V]	V _{init}
433	Maximum power during phase 1 [W]	P _{max}

TABLE II. FUEL CELL (HORIZON H-1000XP).

Cell Type	Rated Power, kW	Rated Current, A	Rated Voltage, V	Nominal Operating Current, A	Operating Voltage, V	Composition, %	Max. temperature, °C	stack Weight, kg
PEM50	1	33	48	0.5	99.99% H ₂	65	6.8	

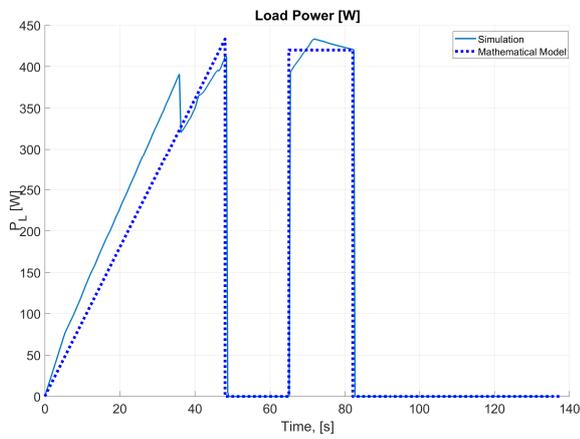


Figure 4. Load Power (real) and used for the model

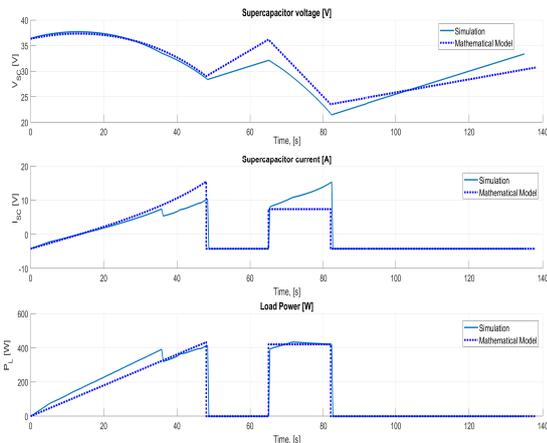


Figure 5. Comparison between experimental model and simulation

IV. EXPERIMENTAL RESULTS

The setup for the experimental results is shown in fig. 6. It consists of a buck-boost converter connected between the fuel cell and the supercapacitor. The supercapacitor is loaded by a resistive load. The control of the converter and the two switches are also shown. First, the supercapacitor is charged through the converter from the fuel cell by closing switch 1 and enabling the converter. When the supercapacitor reaches a certain value, switch 1 is opened and the supercapacitor is discharged by a resistance connected to a load. The presented model in the last section is modified in order to compare the voltages and currents and it is shown in fig. 7. First the fuel cell is simulated as a constant power source. The moment that the load is turned on depends on when the load current data reaches a certain threshold point, closing the load switch.

The results for the experimental data for the voltages, currents and power for the load supercapacitor and fuel cell are shown in fig. 8, 9 and 10 respectively.

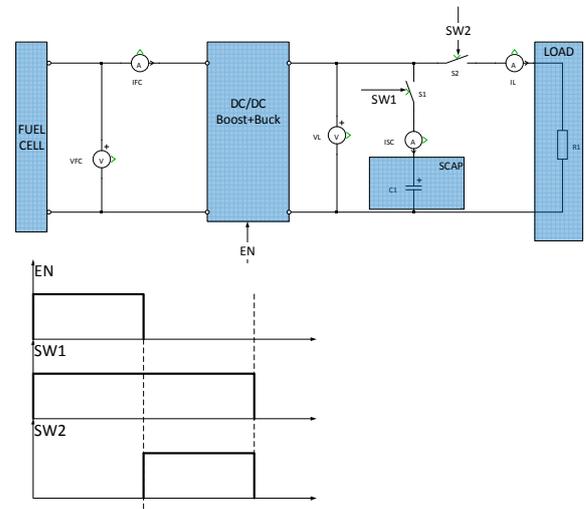


Figure 6. Comparison between experimental model and simulation

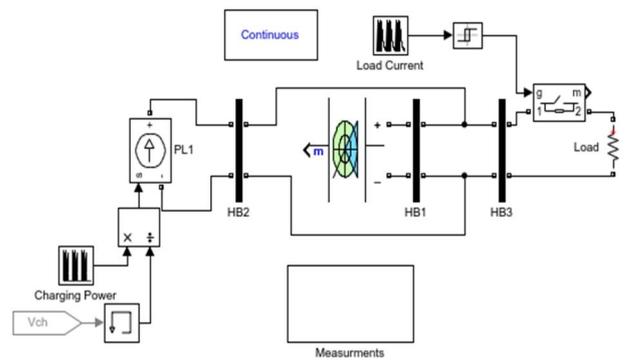


Figure 7. Simulation Model

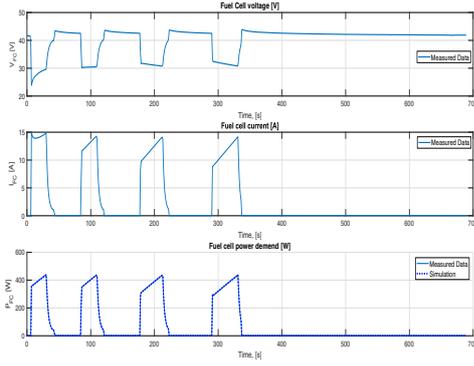


Figure 8. Comparison between experimental model for the fuel cell

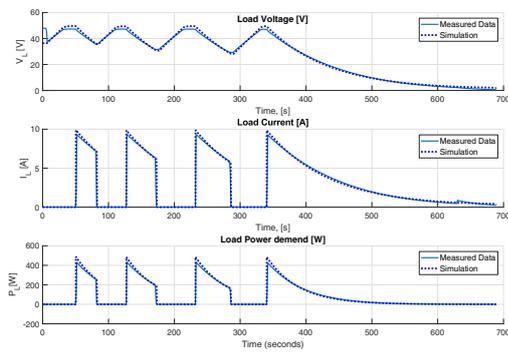


Figure 9. Comparison between experimental model for the load voltage

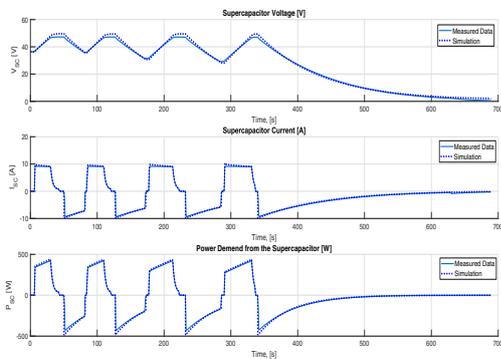


Figure 10. Comparison between experimental model for the supercapacitor

V. COMMENTS

The obtained formulas can be used for first order guidelines for choosing the size of the supercapacitor and also the maximum current stress on the semiconductor devices.

Depending on specific subcase two useful results can be obtained:

For the constant power case we can find the following useful practical case:

- Find the minimum capacitor C_{min} needed in order to supply constant power P_L for specified time t_p

by fixing the maximum current stress I_{Lmax} . This can be obtained by manipulating Eqn. (5) into:

$$C_{min} = \frac{2I_{Lmax}^2 t_p P_L^2}{V_{Sc0}^2 I_{Lmax}^2 - P_L^2} \quad (7)$$

For the linearly increasing power case we can find the following useful practical case:

- Find the minimum capacitor C_{min} that has E_{cmin} for linearly increasing power load with P_{Lmax} , while the maximum current stress is I_{Lmax} :

$$C_{min} = \frac{I_{Lmax}^2 E_{cmin}}{P_{Lmax}} \quad (8)$$

VI. CONCLUSION

The paper presented a mathematical model of a hybrid energy source combining a fuel cell and a supercapacitor. The load is defined by its power over time requirement combining sections with constant power and ramping power. Using this approximation formulas are obtained for the current through the supercapacitor both for both cases. Using these formulas the system designer can optimize the capacitor size by specifying its minimal and maximum voltage during operation are specified. The obtained formulas are also useful in obtaining the maximum current stress on the semiconductor devices used in the converters. The obtained equations are verified by simulation and experimental results.

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