

Control Strategies for Power Quantized Solid Oxide Fuel Cell Hybrid Powertrains: In Mobile Robot Applications

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ABSTRACT

This paper addresses scheduling of quantized power levels (including part load operation and startup/shutdown periods) for a propane powered solid oxide fuel cell (SOFC) hybridized with a lithium-ion battery for a tracked mobile robot. The military requires silent operation and long duration missions, which cannot be met by batteries alone due to low energy density or with combustion engines due to noise. To meet this need we consider an SOFC operated at a few discrete power levels where maximum system efficiency can be achieved. The fuel efficiency decreases during transients and resulting thermal gradients lead to stress and degradation of the stack; therefore switching power levels should be minimized. Excess generated energy is used to charge the battery, but when it's fully charged the SOFC should be turned off to conserve fuel. However, startup and shutdown phases consume both battery and fuel energy and induce stack degradation, and therefore should be scheduled as infrequently as possible. Simple models of the battery and SOFC are used to evaluate the optimal scheduling strategy using Dynamic Programming. Representative cycles are generated from random sampling of measured power data for specific tasks. Finally a rule-based control strategy is developed and compared with the optimal one, considering battery degradation, fuel efficiency as well as design robustness. The application to military tracked robots for surveillance is considered as an example using power profiles from an instrumented PackBot; however the methodology can be applied broadly to hybrid power systems for transportation which have large turn on/off penalties.

CITATION: Wang, Y., Siegel, J., and Stefanopoulou, A., "Control Strategies for Power Quantized Solid Oxide Fuel Cell Hybrid Powertrains: In Mobile Robot Applications," *SAE Int. J. Alt. Power.* 5(1):2016, doi:10.4271/2016-01-0317.

INTRODUCTION

Currently almost all robotic vehicles are powered by Li-ion batteries. However, increasingly demanding mission duration requirements are unlikely to be met with batteries alone due to their limited energy density (190 Wh/Kg, 306 Wh/L), and there arises a need for alternative energy storage. Fuel cells are an ideal choice for augmenting battery storage, as they are more efficient than combustion engines and operate silently.

A hybrid power system combining batteries with a small propane fueled solid oxide fuel cell (SOFC) for a mobile robot has been simulated using an Ultra Electronics AMI 200 Watt fuel cell and a high energy BB2590 battery pack [1]. The SOFC power plant has a quantized on/off behavior characterized by the following properties (1) the fuel cell lacks load-following ability [1] and therefore operates most of the time at a constant power output; (2) each SOFC startup and shutdown event takes several minutes and consumes significant battery power 6.5/5.3 Wh respectively. This SOFC achieves optimum fuel utilization at full load, since the fuel flow rate is constant, and part loading is very inefficient. Therefore it is preferred to operate the FC stack in an on/off manner, however determining when to turn on and off the fuel cell to optimize fuel utilization is not trivial. While the conventional continuously operated hybrid systems [4]-[7] have been heavily studied, the quantized FC-battery hybrid has not been

studied except the hybridization with a gas turbine [11]-[12]. New systematic methodologies are needed to get optimum power and endurance from this system.

This paper addresses the power split of an energy dense solid oxide fuel cell power source, hybridized with a lithium ion battery pack. The resulting power splits are tested with cycles generated from random sampling of measured power data from a PackBot while performing specific tasks [2]. Fuel cell sizing, dynamic performance (ability to change loads), and efficiency (as a function of output power) have a large impact on the performance and fuel economy of the overall system. The power split and scheduling of shutdowns are investigated via optimization (minimization of fuel consumption) using Dynamic Programming (DP) and a simulation model of hybridized battery and fuel cell system.

ENERGY REQUIREMENTS

The iRobot PackBot, which is a tracked robot, is considered for this study. The PackBot weighs 11kg without batteries or manipulator arm and is typically powered by 2 BB-2590/U lithium ion battery packs which provide more than 4 hours of continuous runtime and up to 16 kilometers of travel according to the manufacturer. Our goal is to extend the operating time beyond 10 hours, which would require 1130 Wh of energy or roughly 3x the number of batteries.

Table 1. Sample Profile Statistics

Sample Profile	Mean (W)	Standard deviation (W)	Max (W)
Pea gravel	110.7	27.0	159.5
Sand	108.7	35.9	166.4
Crushed concrete	124.7	35.0	170.7
Hill climb and decent	88.0	66.2	236.3
Obstacle	155.8	44.5	240.1
Manipulator	90.2	29.2	151.0
Synthetic	97.8	46.3	240.1

Overall hybrid system fuel efficiency (FE) will be evaluated using load profiles measured with an instrumented PackBot [2]. These scenarios represent typical tasks the robot is expected to perform during a mission. Various power profiles are combined in sequence to construct a “real-world” driving cycle from each of the shorter tasks.

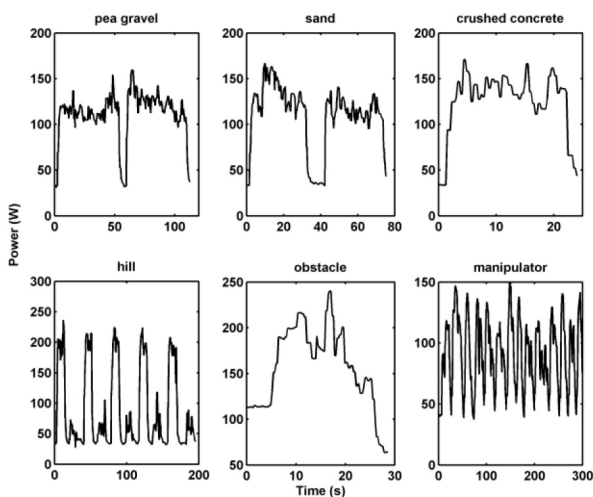


Figure 1. Power profiles sampled for typical terrain/operations at normal speed.

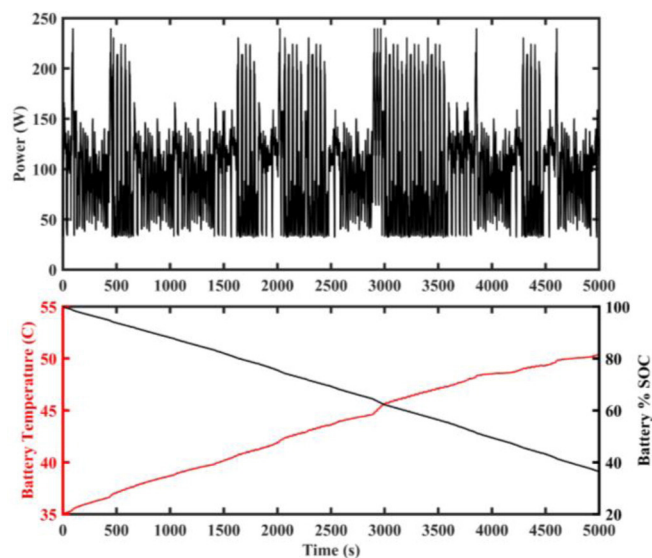


Figure 2. Synthetic power profile randomly generated by uniform sampling of the six mission profiles (top), and battery temperature (bottom) for case where robot is supported by only one BB2590.

As shown in Table 1 and Figure 1, load profiles are sampled for traversing typical terrains including pea gravel, sand, crushed concrete and operations such as climbing hill, travelling over an obstacle or using the manipulator. It should be noted that power profiles vary greatly even for identical terrain or operation, depending on vehicle speed, weight and environmental conditions. For a 10-hour mission, the cycle to cycle difference could also be significant due to varying mix of different scenarios. In order to evaluate system performance consistently, a Synthetic power profile is constructed. The measured power from six short duration task profiles are randomly sampled, assuming a uniform probability, and stacked to build longer mission profile as shown in Figure 2. For this 10 hour cycle, the average power draw is 98 W, the maximum power draw is 240 W and the standard deviation is 46 W.

ARCHITECTURE AND MODELS

There are two common options for hybridizing the fuel cell with a battery, either direct parallel connection of battery and fuel cell with a diode (to prevent back feeding current into the fuel cell), or use of DC/DC converter with the load either connected to the FC or battery as shown in Fig. 3. Other variations combining the above schemes may also be considered such as utilizing a small buck converter for optimum efficiency point operation with direct connection for high power (thus enabling operation with smaller DC/DC converter rating) [18], [20].

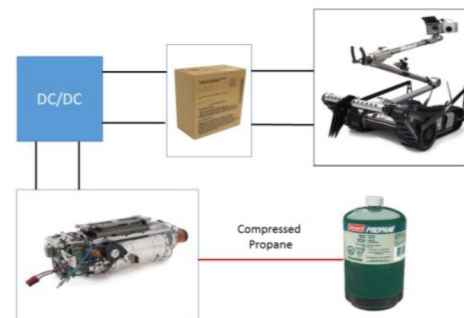


Figure 3. SOFC hybrid with DC/DC converter and high energy BB pack [2]

A DC/DC converter is connected between the battery and SOFC stack as shown in Fig. 3. Fuel cell auxiliaries are assumed to be powered by the battery pack to avoid issues of directly connecting unregulated loads to the fuel cell [19]. The SOFC is paired with a single low power high energy density BB-2590 pack because the SOFC can also provide high power, but has extended transitional phases (startup/shutdown) requiring significant energy to be provided from the battery.

Battery

The standard PackBot configuration uses 2 BB2590U packs storing 6.8 Ah each. Inside each ruggedized plastic container are 24 18650 cells packaged with electronics to perform battery management, protection, and cell balancing. The cells are connected 3 each in parallel and then 8 in series (3P8S) arrangement. Due to the packaging and sealed plastic waterproof container there is limited

heat rejection from the battery pack and temperature rise during operation is a concern for battery only operation [13], as shown by the 15 degree temperature rise in a few hours in Fig. 2.

The Battery pack can be modeled using a 4-state electro-thermal model of the cylindrical cell [15]. The model consists of two R-C equivalent circuits and state of charge (SOC) plus one thermal state. For the purpose of DP the battery model can be further reduced to 2 states (V_1 and SOC), when the battery temperature is well regulated, with little loss in fidelity. The reduced model consists of a single R-C equivalent circuit with series resistance and state of charge, appropriate for the low C-rate ($<1C$) operation of the battery [14]. The battery current is related to the battery power and load demand from the drive cycle by the following equation.

$$\begin{aligned} P_{batt} &= P_{dmd} + P_{aux} - P_{fc} \\ &= V_1 I_{batt} = (V_{OCV}(SOC) - V_1 - I_{batt} R_{int}) I_{batt} \end{aligned} \quad (1)$$

The open circuit voltage V_{OCV} is a function of the battery SOC, and the battery resistances R_l and R_{int} depend strongly on temperature when cold, but remain relatively constant for the temperature range of interest here. The battery charging current is limited to 4.8A, with a manufacture recommended value of 3A. The charging current should be further reduced when the battery is near full charge such that the terminal voltage V_t does not exceed 33.6V. Therefore we limit the charging current to 3A during simulation of the hybrid system even if the FC is producing excess power.

$$\begin{aligned} I_{batt} &= \max(-3, I_{bc}) \\ I_{bc} &= \frac{(V_{OCV} - V_1) + \sqrt{(V_1 - V_{OCV})^2 - 4R_{int}(P_{dmd} + P_{aux} - P_{fc})}}{2R_{int}} \end{aligned} \quad (2)$$

The battery state of charge can be calculated from the battery current using the following equation

$$\frac{dSOC}{dt} = -\frac{I_{batt}}{Q_{cap}} \quad (3)$$

where Q_{cap} is the battery capacity. The voltage V_1 represents the capacitor voltage in the R-C branch of the equivalent circuit model.

$$\frac{dV_1}{dt} = \frac{I_{batt}}{C_1} - \frac{V_1}{C_1 R_1} \quad (4)$$

Finally the battery temperature, T_{batt} , is given by the following dynamic state equation,

$$m_{batt} C_p \frac{dT_{batt}}{dt} = h \cdot A \cdot (T_{batt} - T_{amb}) + Q_{gen}(P_{batt}, V_1, SOC), \quad (5)$$

where m_{batt} and C_p are the battery mass and heat capacity. The convective heat transfer is proportional to the temperature difference between the battery and ambient air and $h \cdot A$ is the surface area times the heat transfer coefficient given in Table 2. Battery heat generation Q_{gen} is a combination of ohmic heat and entropic heat; the effects of enthalpy-of-mixing, phase-change, and heat capacity are neglected for simplicity [15].

Table 2. Battery model parameters

Parameter	Value (from [15])	Parameter	Value (from [22])
Q_{cap}	7.11, Ah	a	$8.61e-6, 1/Ah \cdot K^2$
R_{int}	0.18, Ohm	b	$-5.13e-3, 1/Ah \cdot K$
A	$5.76e-2, m^2$	c	$7.63e-1, 1/Ah$
h	$5, W/(m^2 \cdot K)$	d	$-6.7e-3, 1/K(C-rate)$
m_{batt}	1.4, Kg	e	$2.35, 1/(C-rate)$
C_p	617, J/(Kg·K)	f	$14876, 1/day^{(1/2)}$
$V_{OCV}(0.2/0.8)$	29.68/31.86, V	E_a	24.5, KJ/mol
R_l	6.79E-2		
C_l	3246 Farads	T_{amb}	35°C

To predict capacity fade of the battery, a semi-empirical model from [22] is adopted taking into consideration both calendar-life and cycle-life loss.

$$Q_{loss, \%} = Q_{loss, calendar} + Q_{loss, cycle} \quad (6)$$

Where, the cycle loss and calendar losses are given by,

$$Q_{loss, calendar} = f t^{0.5} \exp(-E_a / RT) \quad (7)$$

$$Q_{loss, cycle} = (aT_{batt}^2 + bT_{batt} + c) \exp((dT_{batt} + e)I_{rate}) Ah_{throughput} \quad (8)$$

The former is modelled using a square root of time relation to account for the diffusion limited capacity loss and an Arrhenius correlation to capture the influence of temperature. The latter depends linearly on charge throughput while exponentially on current rate. The parameters of the capacity fade model and BB2590 electro-thermal model in Table 2 are experimentally derived in [22] and [16] respectively.

Solid Oxide Fuel Cell

The Ultra-AMI SOFC runs on readily available commercial propane cylinders, each containing about 0.5kg of propane. The fuel flow rate is pre-determined so as to maintain the delicate thermal balance within the stack and provide power for auxiliaries. Shutting down the fuel cell at low power demand is thus preferable to idling, because partial load operation is highly inefficient. However, the SOFC has an extended startup procedure requiring a significant amount of energy to heat up before power can be generated as explained in [1]. Similarly the shutdown procedure consumes battery energy to run the cooling fans. Therefore the SOFC must be paired with a relatively large energy storage battery (BB2590 pack).