Abstract—This paper presents a novel system design for a fuel-cell-powered battery-charging station. This battery charging station allows multiple batteries to be charged simultaneously. Three baseline static charging algorithms are proposed to coordinate the power distribution among the battery branches. The control strategies include equal rate charging, proportional rate charging and pulse current charging. These charging algorithms are then realized in MATLAB/Simulink, and the current and voltage regulations are implemented using the classical proportional-integral approach. The system simulation is conducted in VTB by embedding Simulink objects and cosimulating with MATLAB. The experimental tests are performed by compiling Simulink codes and downloading onto the DSpace platform. The simulation and experimental results are also given.

Keywords—charging algorithm; fuel cell; battery; charging station; Simulink; dSPACE; VTB

I. INTRODUCTION

Rechargeable batteries, such as lithium ion cells, are playing an increasingly significant role in the utilization of portable electronic devices such as portable computers, cellular phones and camcorders [1]. Their limited usable time makes it necessary to develop some kind of portable battery charging system. The field application of a portable charging system may be far away from the utility power. In this case, the fuel cell, which is emerging as one of the most promising technologies for the future power sources [2-3], may provide a good solution for powering the portable charging station. However, the characteristics that the fuel cell has the limited power supply and that both fuel cells and lithium ion batteries are strongly nonlinear present a lot of difficulties for the system design [4-7]. Power converters are thus needed in this fuel cell/battery system and should be controlled properly for the best system efficiency.

In general, the battery charging station should allow multiple batteries to be charged simultaneously. In order to meet the simultaneous requirements of multiple users, power converters are connected in parallel, each for one battery pack. The initial states of the batteries may be different. A battery with lower initial state-of-charge may require larger charging current or otherwise longer charging time. Furthermore, when charging advanced technology batteries such as Li-Ion cells, it is hazardous to exceed certain current or voltage limits. Therefore, the power from the fuel cells should be distributed efficiently among these charging branches and the power converters should be regulated appropriately. The power distribution from a nonlinear and current-limited power source presents a lot of challenges for control algorithm design. Obvious difficulty also arises from the controller design of power converter because the source and load of the power converter are strongly nonlinear and dynamic.

This paper presents a novel system design for a fuel-cell-powered battery-charging station. Three baseline static charging algorithms are developed to coordinate the power distribution among the battery branches. The charging controllers are designed based on these proposed charging algorithms and implemented in MATLAB/Simulink for both system simulation and experimental tests. The simulation and experimental results are finally given.

II. SYSTEM ARCHITECTURE DESIGN

Since the battery charging station is configured for multiple batteries to be charged simultaneously, a lot of individual charging channels can be built in the charging station. For convenience of analysis, a typical case of three charging channels is studied in this paper, which can represent the general solution of many charging channels. Assume here that all the batteries are put in the charger. The case that some batteries are inserted or retrieved during charging is investigated in another paper [8].

The system block diagram of the proposed fuel-cell-powered battery-charging station and its development environment is shown in Figure 1. A fuel cell stack, which is the power generation system, is used to charge up to three lithium ion battery packs each through a buck converter. Each battery contains four series-connected cells. These three buck converters are connected in parallel. They have the same power source but different loads. All the batteries share the power from the fuel cells. The sum of the power to each battery is restricted by the fuel cell power limit and should be less than this limit. In practice, this requirement can be implemented by limiting the current from the fuel cells within an appropriate range. Considering the variations of the voltages of the fuel cells and batteries are not too large, the duty cycle will vary within a limited small range. Based on this assumption, the sum of the charging currents for three batteries should be less than some
value that can be calculated according to the power limit of the fuel cell stack. In this paper, this is an important design criterion for the control strategy.

The charging control algorithms reside on a general-purpose dSPACE real-time controller board, which also houses the hardware interface consisting of multi-channel A/D and D/A converters. The control algorithms are designed and implemented using MATLAB/Simulink, and the codes are then compiled and dropped onto a dSPACE DS1103 PPC controller board for rapid prototyping. The controller algorithms will be migrated to an inexpensive dedicated controller IC for the final production system.

The charging currents and battery voltages are monitored and input to the dSPACE controller board through the A/D converters mounted on it. The power source bus voltage is also an input variable. The real-time controller provides the switch duty commands to each power converter. The circuit protection function is also implemented with the software that is executed on the DSP. For example, the dSpace board can output the command signals of the switches for soft startup or shutdown when fault is detected.

**III. CHARGING ALGORITHM DESIGN**

The users may have different requirements for charging their batteries according to their own needs. Some people may require that the batteries be fully charged within the shortest period of time, while others need a better life expectation for their batteries. In order to discover the appropriate control schemes for the various requirements, three baseline static charging algorithms are investigated to coordinate the power distribution among the battery branches. These strategies include equal rate charging, proportional rate charging and pulse charging.

Among these power distribution algorithms, two charging protocols are used. They are constant current-constant voltage (CC-CV) charging and pulse current charging. CC-CV charging protocol can help to protect the battery from overcharging. Under this protocol, the battery is charged to an end potential using a constant current. The potential is then held constant after this potential is reached, and the charging current will taper gradually. Charging stops when the current reaches a preset small value during the constant voltage mode. Under pulse charging protocol, a pulse current with a period of $T$ and on-time of $T_{on}$ is applied to the battery. Pulse current charging has been shown to enhance charging rate capability and also prevent the increase of internal impedance of the battery, thus reducing the total charging time [7].

A direct method for charging all the batteries is to distribute the charging current equally among them. Due to the difference in the initial states of the batteries, some batteries may reach the reference voltage earlier than others. When one battery reaches its voltage limit, the voltage will be kept constant and its charging current tapers. The rest of the total available current will be distributed equally between other two batteries. And then the same scheme is followed for the remaining batteries till all the batteries move to constant voltage mode. This control strategy is illustrated in Figure 2-a. This algorithm is easily implemented but it may take a relatively long time for all batteries to become fully charged when the initial states of charge of the batteries are widely disparate.

A more time-efficient method can take into consideration the fact that the charge that the battery will need to become fully charged is proportional to its depth of discharge where the depth of discharge is defined as unity minus the state of charge. If DC currents of the same magnitude are applied to charge different batteries, the charging times will be approximately proportional to the depth of discharge (neglecting nonlinearity of the batteries). On the other hand, if we want all the batteries to become fully charged during the same period of time, the charging current can be proportional to the fraction of the depth of discharge of each battery, which can be calculated according to Eq. (1)

$$I_i = I_{lim} \frac{1 - SOC_i}{\sum_{i=1}^{3} (1 - SOC_i)}, i = 1,2,3$$

where $I_i$ is the charging current of the $i$th battery, $I_{lim}$ is the total available charging current, and $SOC_i$ is the initial state of charge of the $i$th battery.

This control strategy is called proportional rate charging, which is shown in Figure 2-b. Under this algorithm, the batteries may become fully charged almost simultaneously. But it is difficult to estimate the state of charge. For Li-Ion batteries, an approximate relationship between the state of charge (SOC) and open circuit voltage can be found when the SOC is not within the extreme range, i.e., if the SOC is between 0.1 and 0.9. Therefore, the initial SOC can be estimated by measuring the battery open circuit voltage. In this paper, the estimation of initial battery state of charge is obtained by linearly fitting the open circuit voltage to the state of charge. As we will show, even this simple approximation is sufficient for defining the current sharing.
Besides the DC charging, the third method is pulse current charging. Three pulse currents with the same period of $T$ and different ON-times are applied to three batteries alternatively. The sum of the ON-time of each pulse is equal to the period. The illustration of this control strategy is given in Figure 2-c. A similar strategy as the proportional rate charging can be found for pulse charging. The duty cycle of each pulse charging current can be proportional to the fraction of the depth of discharge of this battery, which can be estimated according to the following equation.

$$d_i = \frac{1 - SOC_i}{3} \cdot i = 1, 2, 3$$

where $d_i$ is the duty cycle of the charging current of the $i$th battery.

Under this algorithm, the charging current can be relatively large because only one battery draws this current at any time. With this algorithm, it is also possible for all the batteries to become fully charged almost simultaneously. But the disadvantage is that it is difficult to implement because of the high dynamics of the algorithm itself.

![Image](image.png)

**Figure 2. Illustration of the proposed charging algorithms**

The detail of implementing the proposed three charging algorithms as shown in Figure 2 is explained as follows. For the convenience of demonstration, assume that initially $V1 > V2 > V3$ where $V1$, $V2$, $V3$ are the voltages of three batteries respectively. In these algorithms, $I_{lim}$ is the limit of total charging current. $V_{ref}$ is battery end potential, which is usually 4.2V for each cell. $I_1$, $I_2$, $I_3$ are the charging currents of three batteries respectively. (Here we assume that the maximum current available from the fuel cell, $I_{lim}$ is less than the sum of the maximum safe charging current for the batteries.)

### A. Algorithm 1: Equal rate charging

- If $V_i < V_{ref}$, $I_{ref} = I_{ref, i} = I_{lim}$
- If $V_i = V_{ref}$, $I_1$ tapering, $I_{ref} = I_{ref, i} = (I_{lim} - I_1)/2$
- If $V_i = V_{ref}$, $I_2$ tapering, $I_{ref} = I_{lim} - I_1 - I_2$
- If $V_i = V_{ref}$, $I_3$ tapering
- If $I_i < 0.1 \times I_{lim}/3$, $I_{ref} = 0$, where $i=1, 2, 3$

### B. Algorithm 2: Proportional rate charging

- $I_{ref} = I_{lim} \cdot (1-SOC) / [(1-SOC_1) + (1-SOC_2) + (1-SOC_3)]$, $i=1, 2, 3$
- If $V_i = V_{ref}$, $I_1$ tapering
- If $V_i = V_{ref}$, $I_2$ tapering
- If $V_i = V_{ref}$, $I_3$ tapering
- If $I_i < 0.1 \times I_{ref}, I_{ref}, i = 0$, where $i=1, 2, 3$

### C. Algorithm 3: Pulse current charging

- $I_{ref, i} = I_{lim}$, $I_{low, i} = I_{lim} \times 1\%$
- $D_{ref} = (1-SOC)/[(1-SOC_1) + (1-SOC_2) + (1-SOC_3)]$
- If $V_{low} \geq V_{ref}$, $I_{ref} = 0$, $i=1, 2, 3$

**IV. SYNTHESIS AND IMPLEMENTATION OF CHARGE CONTROLLER**

The charging controllers were designed and implemented in MATLAB/Simulink for the convenience of system simulation and experimental tests. The system simulations were conducted in VTB by embedding Simulink object of the controllers and cosimulating interactively. The experimental tests were performed by compiling Simulink codes of the controllers and downloading onto the DSpace platform to control the real hardware.

The Simulink models of the charge controllers for the proposed fuel-cell-powered battery-charging station are shown in Figure 3 for DC charging (3-a) and pulse current charging (3-b) respectively. Both equal rate charging and proportional rate charging can be implemented in the controller shown in Figure 3-a. Pulse current charging is implemented in the controller shown in Figure 3-b. The main functional blocks in the controllers are the charging current strategy module, current regulation module, voltage regulation module, and charging termination decision module. The charging current strategy module is to calculate the reference charging currents according to the measured battery voltages and currents and it is developed based on each of the proposed three charging algorithms. The current and voltage regulation modules are used to compute the duty cycles to the buck converters according to the reference currents from the charging current strategy module and the
reference voltages respectively. The charging termination decision module can determine when the charging stops and output a signal to the corresponding power converter.

\[ d = d_{old} + k_p (I_{ref} - I) + k_i \int (I_{ref} - I) dt \]  
\[ d = d_{old} + k_p (V_{ref} - V) + k_i \int (V_{ref} - V) dt \]

where \( V, I \) are the sampled voltage and current of the battery, \( d \) and \( d_{old} \) are the current and previous duty cycles used to control the buck converter, both of which are values between 0.05 and 0.95, \( V_{ref} \) and \( I_{ref} \) are the reference end voltage and reference charging current of the battery, \( k_p, k_i \), and \( k_{pv}, k_{iv} \) are proportional and integral gains for current and voltage regulations respectively.

V. SIMULATION RESULTS

In order to investigate the performance of the proposed charging algorithms, simulation studies were first conducted in the VTB [9]. Figure 4 shows the VTB schematic view of the system shown in Figure 1. The power source is a 25-cell PEM fuel cell stack. Each battery is 4X1 (in series by parallel connection) lithium ion cells. The capacity of each battery is 1500mAh. The initial states of charge of the batteries are 0.60, 0.50, and 0.40 respectively.

The controller is implemented in the Simulink models as shown in Figure 3. It is embedded in VTB through a VTB-Simulink interface and it can co-simulate with VTB interactively. The charging currents and battery voltages are sensed and fed to the controller. The controller outputs three duty cycles to the power converters and three commands for the switches. In the studied charging algorithms, the sum of the charging currents is limited to 2 Amperes. Each power converter is implemented by a switching-average buck converter model in series with a low pass filter. This system is simulated with the proposed three different charging algorithms for 2 hours (7200 seconds). The simulated charging currents and states of charge of the batteries under three charging algorithms are shown in Figures 5-a, b, 5-c, d, and 5-e, f respectively.

The classical proportional-integral approach is used to regulate the charging currents and voltages. The current and voltage regulations are formulated in Eqs. (3) and (4) respectively.
From the simulation results, the following conclusions can be drawn for the proposed three charging algorithms.

1) The battery with the highest initial SOC can become full fastest under equal rate charging algorithm. But the total charging time may be the longest. It takes about 4500 and 6000 seconds for the first and last batteries to become full respectively.

2) With pulse current charging, the total charging time is minimum because the individual charging current is relatively large. It takes about 4500 seconds for all the batteries to become full, about 1500 seconds faster than the equal rate charging algorithm and 1200 seconds faster than proportional rate charging algorithm.

3) All the batteries can become fully charged almost simultaneously when they are charged with appropriate proportional-rate currents or pulse currents.
Since the charging currents are determined at the very beginning with the proportional rate charging algorithm and do not change any way, a real-time charging strategy that adjusts the charging currents according to the estimated SOCs of the batteries would be desired. This is the work being done for the next step [10].

VI. EXPERIMENTAL RESULTS

Next, the performances of the proposed charging algorithms were validated with real hardware. A prototype of the proposed fuel-cell-powered battery-charging station was built using an H Power D35 PEM fuel cell stack as the power source. This stack has a nominal power capacity of 35W and nominal 24V open circuit voltage. Three 4-cell Panasonic lithium ion batteries were used. The controller designed in Simulink was migrated to a dSpace-based platform to control the real hardware. The switching of each power converter was controlled by commands from the dSpace controller board.

The experimental testing was conducted using the proportional rate charging algorithm. The total charging current was scaled down to 1 Ampere. The initial open circuit voltages of the batteries were 16.20V, 16.05V, and 15.95V for batteries #1 though #3 respectively. According to the estimates of initial states of charge of the batteries, the charging currents were selected by the controller as 0.28A, 0.33A, and 0.39A for batteries #1 though #3 respectively. The measured battery voltages and charging currents are shown in Figure 6.

From Figure 6, it is seen that the battery with the lowest initial voltage (and thus the least initial charge) was charged with the highest current, and its voltage increased more rapidly than others. This is also predicted by the simulation (Figure 5-d) where the state of charge of the battery with the least initial charge increased fastest because the simulation models are very complete and accurate. This battery reached the constant voltage a little earlier than others, and then its current tapered. A little while later, the other two batteries reached the constant voltage. It is seen from the experiment results that all three batteries became fully charged almost simultaneously.

VII. CONCLUSIONS

This paper presents an effective design for a fuel-cell-powered battery-charging station. Three baseline static charging algorithms are developed to handle the power sharing among multiple battery branches. The charging controllers are implemented in MATLAB/Simulink for both system simulation and experimental tests. Simulation results have shown that the battery with the highest initial SOC can become full fastest but the total charging time may be the longest under equal rate charging algorithm, that the total charging time is minimum with pulse current charging, and that it is possible for all the batteries to become full almost simultaneously when they are charged with appropriate proportional-rate currents or pulse currents. The experiment tests validated the control design.

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