Battery Energy Storage for a Low-Voltage DC Microgrid System

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Abstract

As part of an ongoing collaborative project with local industry, an advanced lead-acid battery energy storage system was designed and installed into an existing 24VDC microgrid power system. A small rooftop solar array is used to provide energy for the lighting load in a laboratory and classroom space. A building grid-powered AC-DC power supply provides supplemental energy when the solar array cannot meet the demand of the load. The energy is distributed throughout the space to the load via a two-conductor microgrid network embedded in the ceiling tile support framework. This ceiling grid energy distribution technology is available as a commercial product and was installed as part of an earlier collaboration with the manufacturer. In this latest phase of the project, advanced lead-acid batteries were added to the system to store surplus solar energy for later use. A PLC-based control system provides supervisory monitoring and control of the charging and discharging of the batteries. The installed energy storage system serves as a testbed for similar projects under development by the industry partner. This paper provides a brief overview of the 24VDC microgrid system. The battery energy storage system motivation, design goals, and tradeoffs are also described. System hardware and software are presented and discussed. A simple system model developed to predict performance is also presented. Preliminary energy storage system performance data is discussed. Ongoing system improvements and lessons learned are also presented.

Introduction

An emerging technology in building power distribution involves the use of a room ceiling tile support grid to create a low voltage "microgrid" network. With this network, 24VDC power is routed throughout the room via conductors embedded in the drop-ceiling support structure. Users can then tap into the low voltage supply from any location in the room. The microgrid effort is organized by a consortium of industry and university partners called the Emerge Alliance [1]. The Emerge Alliance promotes the use of low voltage DC indoor power distribution for a variety of commercial, industrial and residential applications. An example of applications on the load side includes lighting and ventilation devices. Input power for the microgrid can be derived from many sources including standard building AC power and alternative sources such as solar. A 24VDC ceiling system was installed in one room of the engineering building at Penn State Berks. The room serves as both laboratory and classroom space. Students in the engineering technology programs have been involved with designing and fabricating devices to use and/or control power derived from the 24VDC microgrid system. Devices include room lighting control and portable device charging stations. The low voltage microgrid provides a relatively safe environment in which to experiment with new devices for occupied space environmental control [2].

The 24VDC microgrid receives its energy from multiple sources. During periods of sunshine, the microgrid load energy is supplied primarily by a rooftop-mounted solar array. The system also contains an AC-DC power supply to maintain the 24VDC bus voltage regulation during times when no other sources are available. The utility of the 24VDC microgrid has been further enhanced by incorporating battery energy storage into the system. A simplified system diagram is shown in Figure 1.

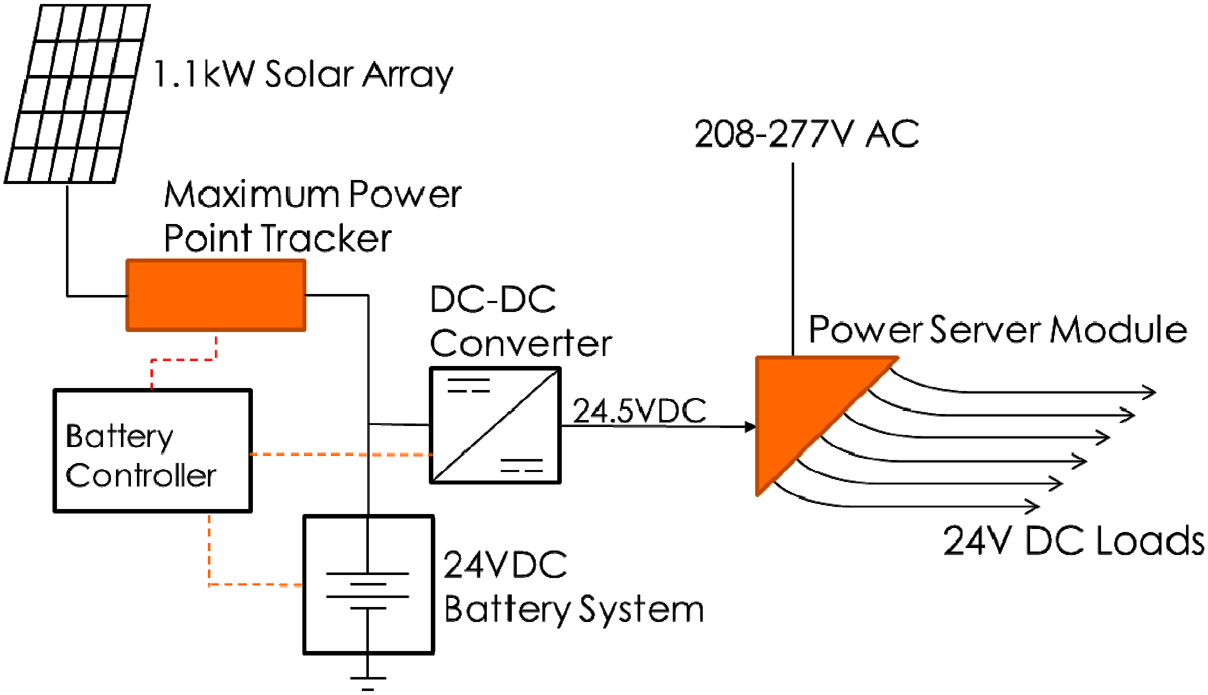

Figure 1. Simplified 24VDC microgrid system diagram

Due to the intermittent occupancy of the room during daylight hours, there is significant opportunity to store otherwise unused energy collected by the solar array. The stored energy can then be used by the microgrid to supply the room load as needed. Together with industry partner, Ecoult, an advanced lead-acid battery technology, UltraBattery®, energy storage system has been developed and installed as part of the 24VDC microgrid. The UltraBattery® operates very efficiently in continuous Partial State of Charge (PSoC) use without frequent overcharge maintenance cycles. It can be utilized to continually manage energy intermittencies, smooth power, and shift energy, using a band of charge that is neither totally full nor totally empty [3]. The UltraBattery was developed by the CSIRO in Australia and taken to market by Ecoult [4]. The installed system is substantially similar to that already commissioned in Australia to power remotely-located cellular telephone tower equipment [5].

As shown in Figure 1, energy from the solar array (five Canadian Solar 235W panels) is processed by the maximum power point tracker (MPPT) unit (MidNite Solar Classic 250). The DC-DC converter (Vicor MegaPAC, 1600 Watts) provides a regulated 24.5VDC output voltage while the battery voltage varies depending on its State of Charge (SoC). The control algorithm of the battery controller provides control signals to the MPPT and DC-DC converter based on the SoC of the battery. When the battery SoC is in the range where it could accept charge, the MPPT is enabled. Likewise, when the SoC of the battery is in a suitable range for providing energy (discharging), the DC-DC converter is enabled. When the DC-DC converter is enabled, its 24.5VDC output voltage overrides the 24VDC produced by the AC-DC converter in the Power Server Module. Thus no energy is drawn from the AC line to supply the bus loads, it is all provided by the battery via the DC-DC converter.

Battery Selection and Sizing

The intermittent nature of solar energy and the sporadic demand profile of the room lighting load align well with the performance capability of the UltraBattery. As shown in Figure 2, the UltraBattery's construction incorporates a traditional lead-acid battery in parallel with a supercapacitor structure. This combination produces an energy storage package that performs very well under partial state of charge conditions as are typically experienced in this type of application.

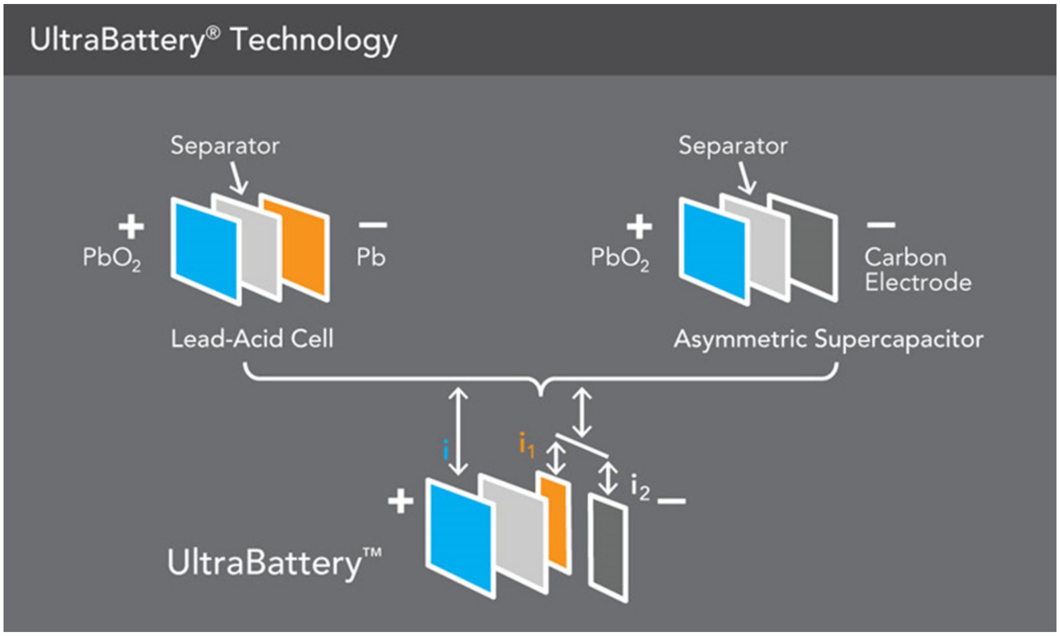

Figure 2. UltraBattery construction diagram

The laboratory/classroom space is lit by ceiling fluorescent lighting fixtures. These fixtures are equipped with electronic dimming ballasts designed for 24VDC input voltage. The ballasts receive their input voltage from the microgrid with a total power of about 850W at full brightness. The initial design used this load power and a goal of providing enough energy to sustain this load for two hours (the typical duration of an evening laboratory class session). Therefore the battery was sized at a nominal energy rating of 2kWh. The battery arrangement is then four, 12V battery units configured as two parallel strings of two batteries each.

Each of the four batteries in the energy storage system is equipped with battery monitoring electronics mounted directly on the positive and negative terminals as shown in Figure 3. The monitoring hardware and software continuously measures key parameters of voltage, current and cell temperature and can also be configured to monitor ambient temperature and gas concentrations for enhanced safety and performance.

Figure 3. Battery monitor mounted on an UltraBattery.

The batteries are housed in an industrial battery cabinet as shown in Figure 4. Each battery monitor is connected to the main monitoring and control electronics via infrared link to provide galvanic isolation and eliminate grounding issues. Remote monitoring and control of the entire battery system is accomplished with a web-enabled PC contained within the battery cabinet control compartment. This arrangement also provides a means for remote software updates and system troubleshooting. For the system installed on campus, a wired LAN connection is used, however, a cellular connection has also been used for previous similar systems installed in remote locations.

Figure 4. Battery cabinet and control/monitoring electronics enclosure.

Control System Architecture

The battery controller is implemented using a Programmable Logic Controller (PLC). The primary function of the PLC is to monitor the batteries and protect them from over-charging or over-discharging. This function is accomplished by controlling the MPPT (the battery charging component) and the DC-DC converter (the battery discharging component). A simple discrete enable/disable signal is sent from the PLC to the MPPT and the DC-DC converter based on the current SoC of the battery. A diagram of these control signals is shown in Figure 5. A small bit of hysteresis is added to each signal to minimize excessive system cycling near the extremes of the SoC.

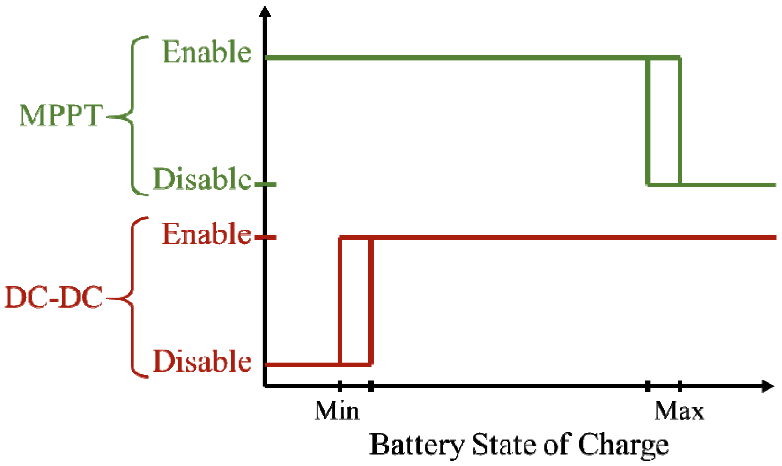

Figure 5. Battery charge and discharge enable signal hysteresis curves

System Modelling

To get a first-order estimate of expected system performance, a simple discretized system model was developed to describe the battery state of charge for various solar array power and DC bus load power profiles. A simplified linear model (constant) for the battery SoC was used.

$$K_{SoC} = \frac{SoC_{Max} - SoC_{Min}}{\text{Wh capacity}} \quad \%/\text{Wh} \tag{1}$$

A discrete time step of 1 minute was used for the simulation. The change in stored energy during each time step can be calculated as follows using a Coulomb-counting method [6]:

$$\Delta E = [(P_{Solar})(Eff_{MPPT}) - (P_{Load})/Eff_{DC\text{-}DC}]/60 \quad \text{Wh} \tag{2}$$

Where,

P_{Solar} is the output power of the solar array
Eff_{MPPT} is the input-output efficiency of the MPPT unit
P_{Load} is the power consumed by the room lighting load
$Eff_{DC\text{-}DC}$ is the input-output efficiency of the DC-DC converter

The model was implemented in Matlab however generic pseudocode is shown in Table 1.

Table 1. Listing of system model pseudocode

```
Loop{
$\Delta E = ((P_{Solar})*(Eff_{MPPT}) - (P_{Load})/(Eff_{DC-DC}))/60$
if (($\Delta E$ > 0 AND OK2Chrg = True) OR ($\Delta E$ < 0 AND OK2Dischrg = True))
   SoC = SoC + $K_{SoC}$*($\Delta E$)
if ((SoC < Max AND OK2Chrg = True) OR (SoC < (Max - Hyst))
   OK2Chrg = True
else
```

```
   OK2Chrg = False
if ((SoC > Min AND OK2Dischrg = True) OR (SoC > Min + Hyst))
   OK2Dischrg = True
   $V_{Bus}$ = 24.5
else
   OK2Dischrg = False
   $V_{Bus}$ = 24.0
}
```

Using this simple system model, various profiles for available solar energy (P_{Solar}) and room lighting load (P_{Load}) could be explored to see the effects on the SoC profile. In the actual Matlab code, the P_{Solar} and P_{Load} arrays were contained in spreadsheet files which were imported when the simulation was run. Figure 6 shows the simulation results for typical solar array power (~900W) and room lighting load (~ 850W) profiles. Efficiencies used for the MPPT and DC-DC converter were 90% and 80% respectively. The SoC limits were SoC_{Min} = 30% and SoC_{Max} = 80%.

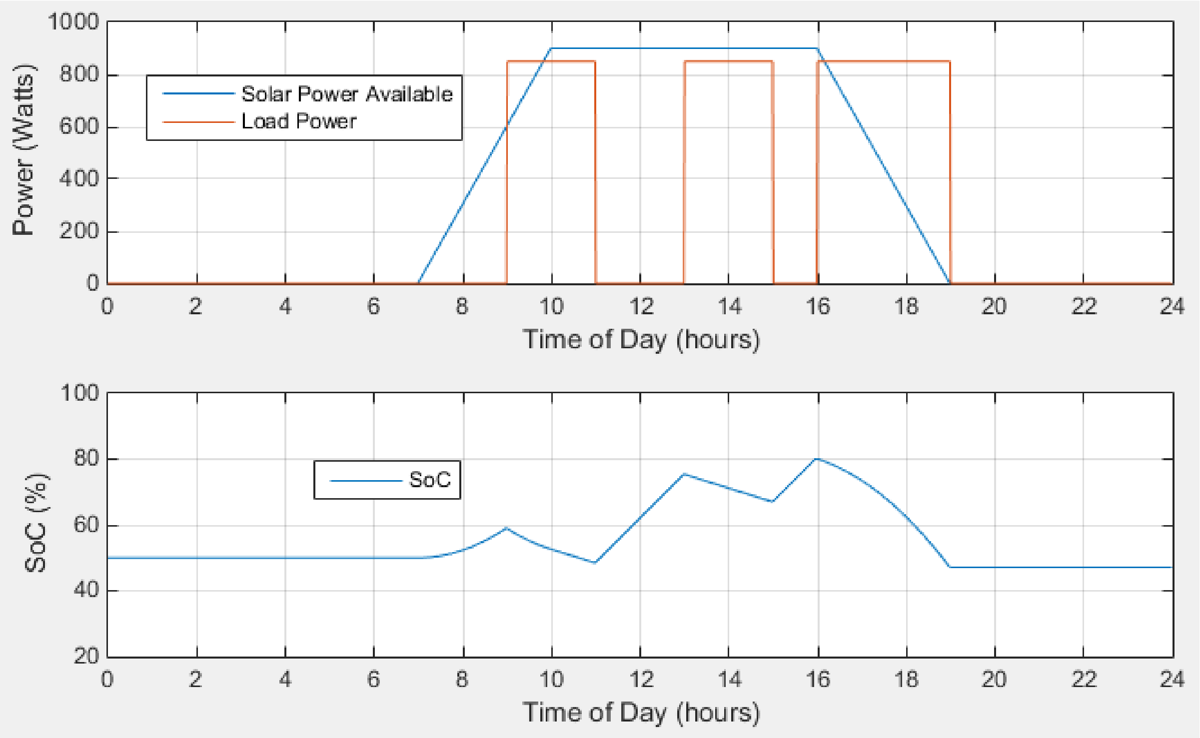

Figure 6. First example of system simulation results

As shown in Figure 6, the SoC begins at a random initial value (energy leftover from the previous day) and begins to increase when solar power becomes available at sunrise. The intermittent use of the room is indicated by the rectangular load power profile. Due to the inefficiency of the MPPT and the DC-DC converter, the solar array is not quite able to supply the entire lighting load, therefore a slight discharge occurs during those intervals.

However, during times when the room is unoccupied, significant charging occurs. The net change in the SoC for the day is slightly negative for this profile combination.

Figure 7 shows the simulation results for a different load profile. In this example, the solar power input profile is the same as the first example. The load profile shows some periods of reduced demand (only some of the room lighting turned on) as would typically be experienced in the actual room. In this scenario, the net change in the SoC for the day is positive.

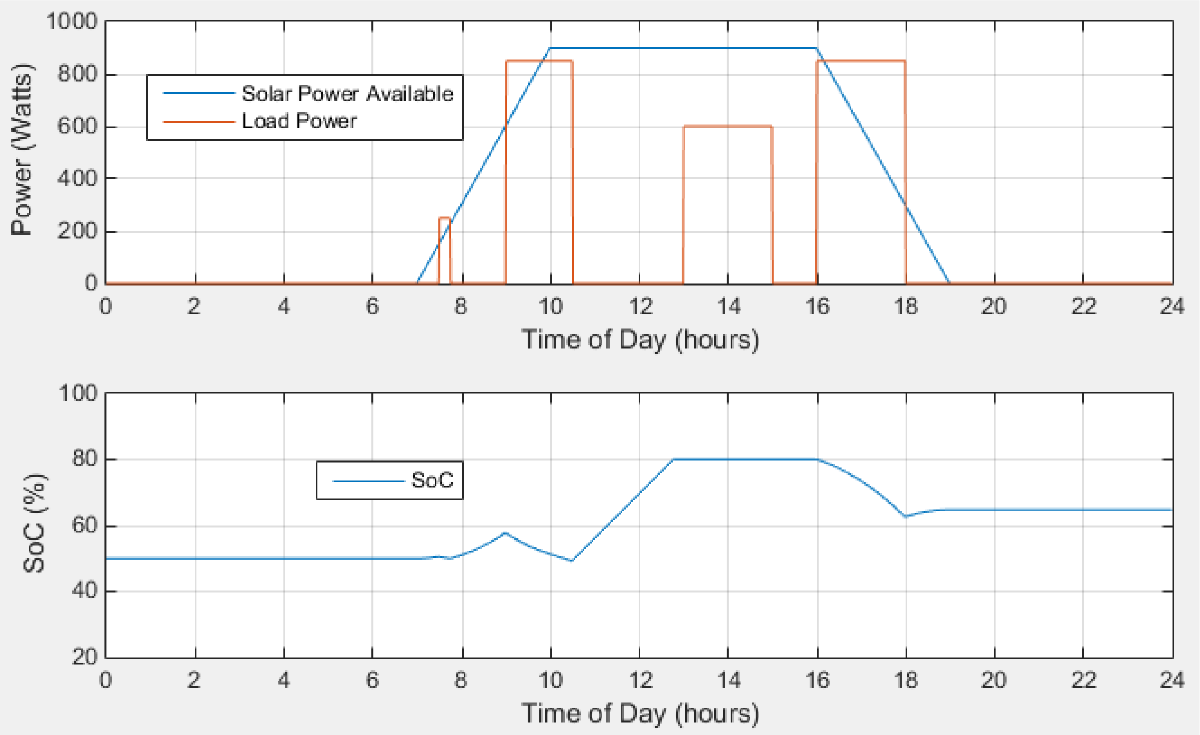

Figure 7. Second example of system simulation results

System Data

Battery data is collected and stored by the system's PC at a sampling rate of about one sample each 10 seconds. Each battery monitor unit measures and reports the battery's voltage, current and temperature. State of charge is calculated using a proprietary algorithm. Data for an early spring day with significant sunshine and typical room lighting profile is plotted in Figure 8. For the day shown, the battery begins with a significant SoC and ends the day nearly exhausted. On the subsequent day, a lighter load would allow for a substantial recharge of the battery thus producing an overall reduction in grid power used by the room lighting load when averaged over several days.

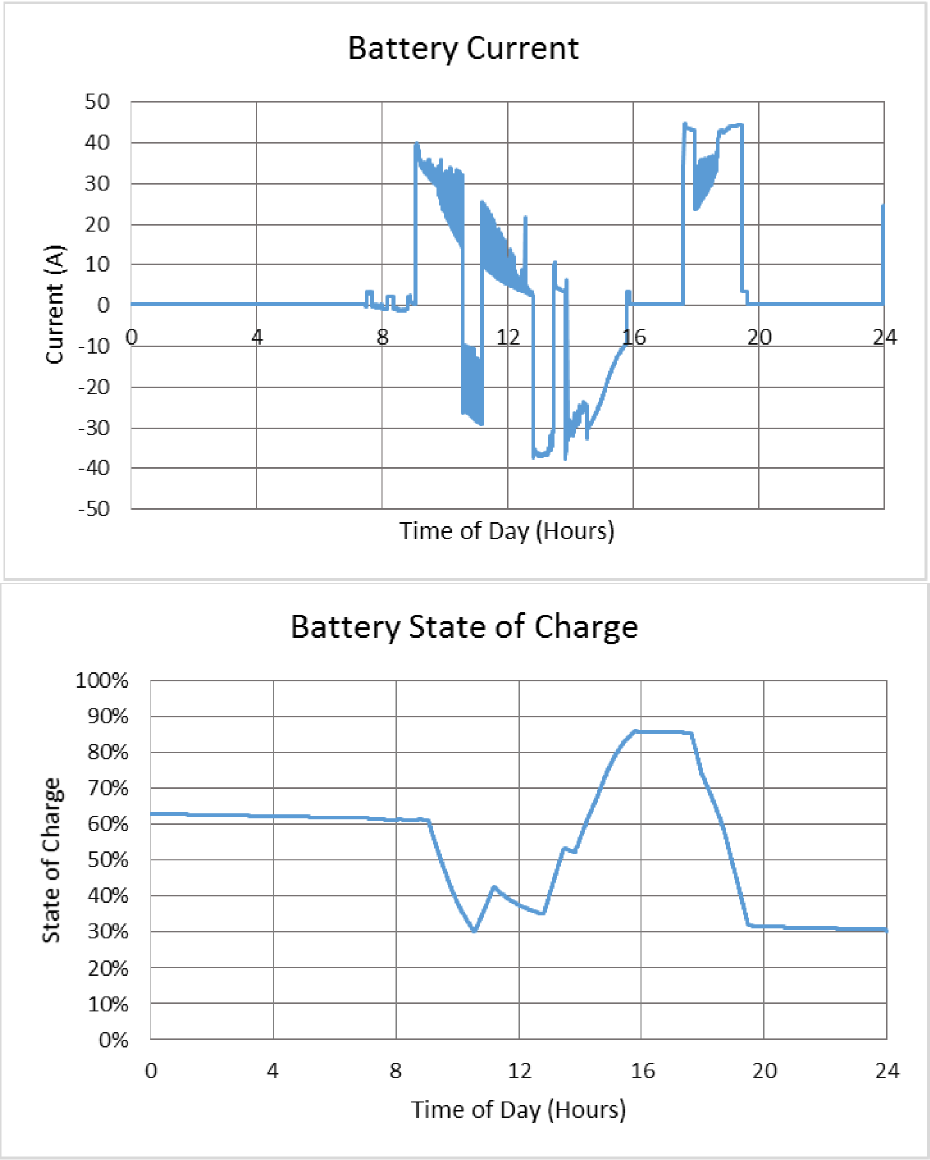

Figure 8. System data for a sunny day with typical room load profile.

Ongoing Work

The 24VDC microgrid installation continues to evolve. Efficiency improvement changes on both the distribution and consumption of the microgrid energy were underway at the time of the writing of this paper. A grant has also been received to help support research to develop better system models for this type of application.

The DC-DC converter consumes a large amount of quiescent energy from its input side just to power the cooling fan and other supervisory electronics even when the unit is disabled. This energy is taken from the batteries and during periods of sustained cloudiness, can cause the SoC to drop below the design minimum. A change is being developed to provide a solid state switch disconnect between the battery and the DC-DC converter. A similar switch will also be installed on the output side of the DC-DC converter to minimize quiescent loading on the 24VDC bus. On the load side, the consumed power can be reduced by managing the light level in the room rather than just allowing users to turn the lights on or off. The installed fluorescent ballasts are dimmable so this change could be implemented with minimal hardware changes.

The current model for the battery state of charge as a function of input/output power is very simplistic. Although many parameters would be needed to completely model the energy system behavior, significant improvement can be achieved by including a few key parameters in a new empirical behavioral model. Performance data will be used to help develop this model. Also, as more data is obtained on the UltraBattery, the SoC limits may be able to be widened to make use of even more stored energy for a given battery size.

Conclusion

The 24VDC microgrid is an evolving technology. Low voltage DC allows for more experimentation and faster development of technology than higher voltages which impose more safety and regulatory restrictions. Energy storage and alternative energy sources can easily be added to the 24VDC microgrid. Although in this work energy storage has been added at the top level (the main 24V bus), energy could be injected into or stored in any of the 96 Watt, class 2 partitions of the microgrid. With proper modelling, the energy storage system can be appropriately sized to meet the load requirements. Proper sizing will also help to ensure that the system uses minimal energy from the AC grid.

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Biographies

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NICHOLAS BATT leads the Application Engineering team at Australian energy storage provider Ecoult. His team works across kW and MW systems. The team seeks out new applications that can benefit from the Ecoult UltraBattery, invented by CSIRO in Melbourne Australia. Nicholas has over 10 years of experience as a Power and Control engineer and has focused on renewable energy and smart grids.

JASON HOFFMAN is a Senior Engineer with Ecoult. He is focused primarily on managing the design and implementation of large scale grid connected energy storage systems. He received his B.S from Bucknell University, and his M.S. from Penn State University both in electrical engineering. Following his education, he has been working in the power industry, primarily in the renewable energy and energy storage areas.