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# A scalable and flexible hybrid energy storage system design and implementation

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## HIGHLIGHTS

- System architecture and control method for scalability and flexibility.
- Detailed description on implementation of hybrid energy storage system prototype.
- Power conversion efficiency and energy storage element characteristics considered.

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## ABSTRACT

Energy storage systems (ESS) are becoming one of the most important components that noticeably change overall system performance in various applications, ranging from the power grid infrastructure to electric vehicles (EV) and portable electronics. However, a homogeneous ESS is subject to limited characteristics in terms of cost, efficiency, lifetime, etc., by the energy storage technology that comprises the ESS. On the other hand, hybrid ESS (HESS) are a viable solution for a practical ESS with currently available technologies as they have potential to overcome such limitations by exploiting only advantages of heterogeneous energy storage technologies while hiding their drawbacks.

However, the HESS concept basically mandates sophisticated design and control to actually make the benefits happen. The HESS architecture should be able to provide controllability of many parts, which are often fixed in homogeneous ESS, and novel management policies should be able to utilize the control features. This paper introduces a complete design practice of a HESS prototype to demonstrate scalability, flexibility, and energy efficiency. It is composed of three heterogenous energy storage elements: lead-acid batteries, lithium-ion batteries, and supercapacitors. We demonstrate a novel system control methodology and enhanced energy efficiency through this design practice.



## 1. Introduction

As people rely more on electrical energy in daily life, it is very critical to supply electricity in a more reliable and economical way. Reliable electricity supply should be free from frequency and voltage fluctuation regardless of sudden load change, load misprediction, power plant malfunction, ground fault, etc. A brute-force way to secure higher reserve margin is building more power plants. As renewable power plants are limited to environmental condition, the higher reserve margin is often achieved by building more traditional nuclear and fossil power plants. This incurs not only cost issues but lots of environmental and social issues.

Adopting energy storage systems (ESS) for storing excess electrical energy and compensating the energy shortage prevents over-investment for the power generation facilities by reducing costly spinning reserve requirement and leveling the load fluctuation. A large, power grid-scale ESS can be positioned [1] in parallel with traditional power plants and seen as a power plant to the transmission system. Alternatively, a small, residential-scale ESS can be positioned more closer to the load side to perform fine-grained power management [2]. ESS also effectively enhance the power

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grid stability as well as availability of renewable power sources such as windmills and solar panels. Aside from the power grid, demand for standalone (off-grid) ESS increases rapidly for electric vehicles (EV) and hybrid EV (HEV).

Nevertheless, ESS technologies are not still commercially and/or practically attractive in many aspects, which discourage its wide deployment yet. There have been active research activities to improve ESS over decades, and previous researches mostly have focused on development of new battery technology aiming at high-performance energy storage systems. For example, enhancing the energy capacity or power capacity of traditional batteries or supercapacitors by use of advanced electrodes or electrolytes is an active research direction. Recent researches introduce orders-of-magnitude higher power and energy capacities compared with traditional batteries and supercapacitors by use of advanced materials such as carbon nanotubes [3], silicon nanowires [4], and so forth. Other electrochemical energy storage technologies such as zinc–bromine battery [5] and vanadium redox battery [6] generally have advantages of long cycle life, environmental friendliness, quick charging by electrolyte replacement, and so on. Improving performance of individual energy storage technology is fundamental and indispensable for developing practical ESS. However, in spite of significant improvements from active researches, an ultimate all-round energy storage technology that beats any other in all aspects—cost, efficiency, power/energy capacity, weight/volume, cycle life, etc—is not likely to appear in a near future.

A hybrid ESS (HESS), on the other hand, consists of multiple, heterogeneous energy storage elements and take advantages of the electrical storage elements while hiding their weaknesses and make them operate at the most efficient condition [7–11]. HESS is a viable solution in that it utilizes system-level design methodology to enhance ESS performance even without fundamental progress of the storage technology through efficient use of the current energy storages. For instance, supercapacitors, which have advantages of a long cycle life, high cycle efficiency, and high power capacity, can be used to compensate limitations of conventional batteries [8,12–16].

This paper introduces a HESS design practice covering consideration of the storage technology characterization, power converter electronics, implementation of the charge management software, and complete integration of the prototype. Although the hybrid approach is also applicable for advanced energy storage technologies such as fuel cells [17] or flow batteries [18], we select mature technologies to focus on the system-level design. The prototype is composed of three types of energy storage technologies for demonstration purpose: 163 Wh lead-acid batteries, 115 Wh lithium-ion batteries, and 6.5 Wh supercapacitors, but the design methodology is not limited to those particular storage technologies nor to the number of storage banks.

The architecture, scale, and control methods of the HESS are designed for load leveling for an average household, which is similar to Ref [2] in scale and application. We discuss details on these decisions taking various practical considerations into account, including scalability, flexibility (controllability), observability (system status monitoring capability) and energy efficiency. Experimental results verify the functionality of the control method for the load-leveling application.

This paper is organized as follows. In Section 2, we first give an overview of previous research on ESS and HESS and discuss their limitations. We describe our design considerations in Section 3 and implementation details in Section 4 focusing on overcoming such limitations. More detailed discussion on the power converter and controller is given in Section 5. Section 6 shows some experimental results, and finally, Section 7 concludes this paper.

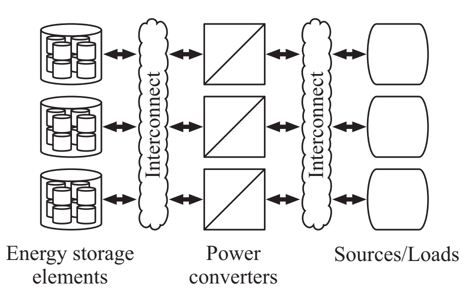



**Fig. 1.** General components of an ESS.

## 2. Energy storage systems

An ESS is a system composed of energy storage elements, input/output power converters, and a system controller. Fig. 1 shows a conceptual structure of an ESS. In order to provide a desired amount of energy and power capacity, multiple energy storage elements are aggregated to build a larger storage. For example, Tesla Roadster (Fig. 2(a)) is equipped with 6831 of lithium-ion battery cells, and the ESS operated by Golden Valley Electric Association in Alaska (Fig. 2(b)) has 13,760 nickel–cadmium battery cells. Applications of the ESS include a wide range of scales from portable devices (a few Wh or smaller), household appliances and electrical vehicles (a few kWh), to power grid (hundreds of kWh or larger).

Input power from the power sources (e.g., solar panels or wind turbines) are not generally compatible with the energy storage elements in terms of voltage level, current magnitude, AC/DC, and so on. The voltage level or AC/DC that the load devices require may be different from that the energy storage elements provide. The power converters are required to resolve such mismatches among the energy storage elements, power sources, and load devices.

### 2.1. Homogeneous energy storage systems

A typical ESS consists of a single type of energy storage elements. This is natural because homogeneity offers ease of implementation, control and maintenance. System-level design consideration of a homogeneous ESS include the bank array dimension, number of banks, distributed or centralized input and output power converters, etc. In reality, the mainstream of the homogeneous energy storage system development is energy storage technology evolution, e.g., developing a new battery technology. As can be seen in Fig. 1, homogeneous ESS architecture is rather straightforward. Typical EV/HEV mainly focused on management of battery-based homogeneous ESS [19–22]. There are grid-scale ESS actually deployed with a single-type of energy storage technology such as lead-acid batteries, nickel–cadmium batteries, and lithium-ion batteries [23–25].

### 2.2. Hybrid energy storage systems

As briefly mentioned in Section 1, each energy storage technology has its own strengths and weaknesses. A homogeneous ESS is naturally subject to the limitations of the energy storage elements that comprise the ESS. HESS, on the other hand, exploit distinct advantages of multiple heterogeneous energy storage technologies and hide their drawbacks instead of relying on a single type of energy storage technology. It is similar to the computer memory hierarchy that is composed of heterogeneous memory devices, which have different characteristics in density, cost, latency, volatility, and so on [26].

A general HESS is of any number of multiple (may be more than two) energy storage elements. Conventional research on HESS

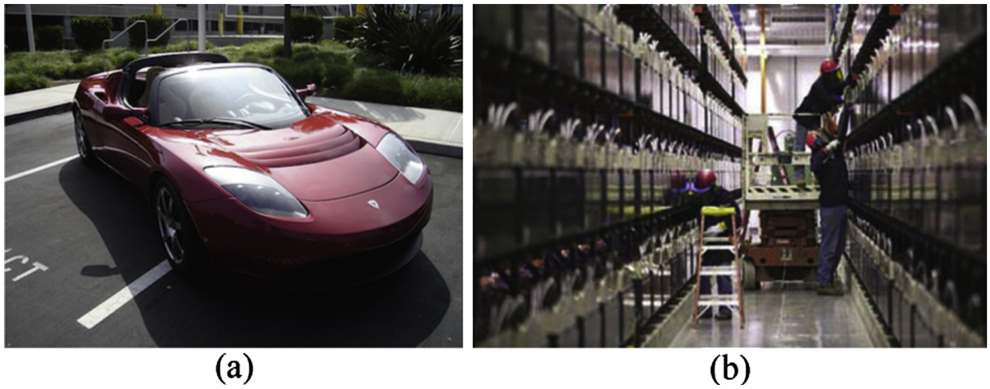



**Fig. 2.** Examples of battery-based homogeneous ESS. (a) Tesla Roadster, a 53 kWh lithium-ion battery-based EV. (a) Golden Valley Electric Association ESS, Fairbanks, AK, a 27 MW nickel–cadmium battery ESS.

includes diverse scales such as sensor networks, EV/HEV, and residential-scale applications. Out of various energy storage technologies, battery-supercapacitor HESS have been most actively investigated. Battery lifetime is a critical issue for low-power sensor nodes because replacing the batteries is not practical after deployment. Therefore, they employ a battery-supercapacitor hybrid to prolong the battery lifetime [12,27]. Use of supercapacitors in a complementary manner with batteries is also beneficial for EV/HEV in many aspect [8,28,13,14,29,30]. EV/HEV have noticeable benefits for regenerative braking. Conventional batteries have limited rate capability especially during charging, and thus significant power loss occurs during regenerative braking that produces enormous amount of power. Use of supercapacitors can significantly reduce the power loss during regenerative braking [31]. Battery-supercapacitor HESS has been investigated for grid-level systems as well. The supercapacitor reduces strain of deep discharge and high power rating for wind turbine generator [32] and solar power generator [33].

### 2.3. Hybridization architectures and storage sizing

Hybridization architecture in a HESS has a significant impact on the energy management policy and various performance such as scalability, energy efficiency, and so on. A more general architecture allows higher degree of freedom in control and management, and it provide higher potential of improved performance at expense of complexity and cost. Most previous hybridization architectures have been tailored for particular control and management policies.

Fig. 3 shows HESS architectures proposed in previous literature. Fig. 3(a) is the passive parallel connection of two energy storage elements without any power conversion circuit between them. This simple hybridization effectively reduces the internal resistance the primary energy storage (e.g., battery) and with low internal resistance energy storage (e.g., supercapacitor) [35]. The ultra-battery in Fig. 4(a) falls in this category [34,36]. Its capacitor electrode and the lead-acid negative plate are connected in parallel inside sharing the same lead-acid positive plate in one unit cell. Most of all, the passive parallel connection is more serious in lack of controllability of the state-of-charge (SoC), current distribution, state-of-health (SoH), and so forth. For instance, energy capacity of the supercapacitor is not fully utilized because the supercapacitor voltage, which changes linearly proportional to its SoC, is coupled to the battery voltage, which is relatively constant regardless of the SoC. In addition, the passive parallel connection architecture has limited scalability because it cannot directly connect unlimitedly many elements in parallel.

Cascaded converter architecture shown in Fig. 3(b) enables active energy management by use of additional power converter between two energy storage elements [15,16]. Fig. 4(b) is an example of this architecture based on a constant-current charger that effectively smoothes battery current fluctuations that cause the rate-capacity effect. This architecture allows independent management of SoC and open-circuit voltage (OCV), and thus SoH. However, one of the most distinct disadvantages of this architecture is lack of freedom in the control policy. The cascaded converter architecture is also limited in scalability because it suffers from more conversion losses as the number of power conversion steps increases.

The single shared bus architecture in Fig. 3(c) is more general in that all the energy storages are connected to a DC bus forming a physically flat topology. This architecture shows certainly a higher degree of freedom in the energy flow comparing with the above mentioned two architectures. It is more scalable because the number of power conversion steps between any energy storage and source/load is always two, and the power conversion loss does not increase as the heterogeneity increases. A typical control policy for this architecture is that one of the energy storages is used for maintain the DC bus voltage at a fixed voltage, and the other energy storages inject designated current into the DC bus. One control

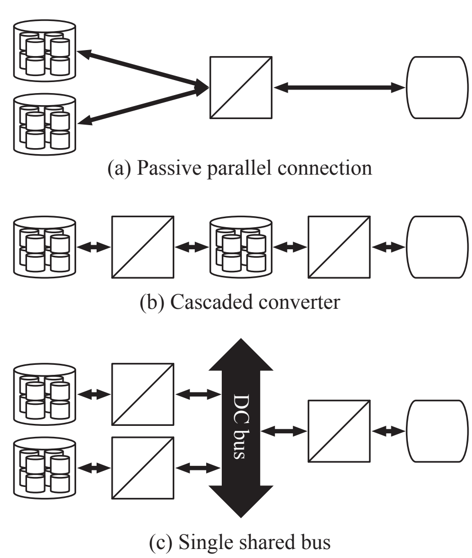
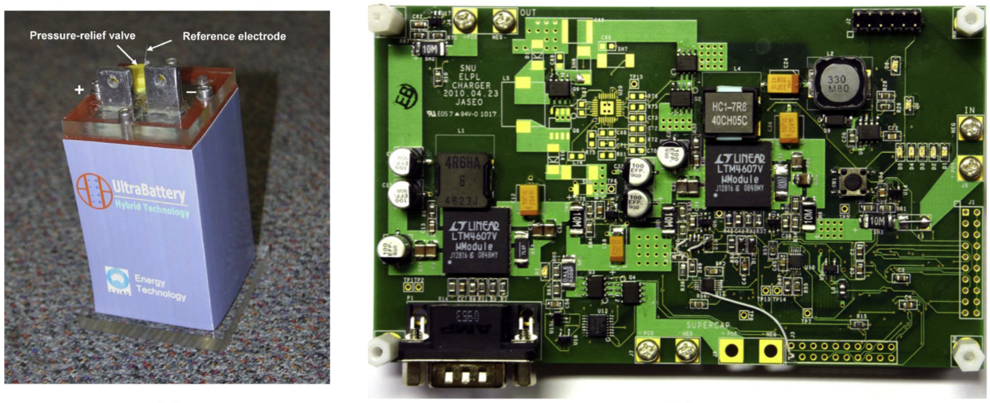



**Fig. 3.** Hybridization architectures for HESS.




(a) (b)

**Fig. 4.** Examples of battery-supercapacitor HESS. (a) Ultra-battery, combination of a supercapacitor and a lead-acid battery in one unit cell [34]. (b) Constant-current regulator-based battery-supercapacitor HESS [16].

method for this architecture regulates the voltage of a fast-responding energy storage element with the current of a slow-responding energy storage element [28,37]. Another DC bus-based HESS proposes a control method that increases the supercapacitor current as the battery current increases [38].

In addition to the hybridization architecture, determination of capacity of the energy storages is one of the most critical design decision for the HESS. It is not a trivial task not only due to the heterogeneous characteristics of different energy storages, but also due to the multi-objective nature of the ESS design. Considerable research efforts have been directed towards optimization of the energy storage capacity balance to maximize the benefits of the HESS. A sizing optimization method in Ref. [39] aims at finding a cost-optimal combination of photovoltaic power generation module, fuel cell, and battery for a stand-alone photovoltaic power system. In Refs. [40,41], they maximize the amortized annual profit under a monetary budget constraint and a voltage constraint considering. On the other hands, optimization objective in Refs. [15,16] is volumetric energy density of a battery-supercapacitor HESS for portable applications that exhibit high current fluctuation. In this paper, however, we limit our focus on system architecture and control method, but not the capacity determination.

### 2.4. Control system for high-level management

The HESS requires sophisticated management policies than conventional ESS does because of the heterogeneity of energy storage technologies. Using multiple different energy storage technologies does not guarantee improved energy efficiency. It is mandatory to devise high-level management policies in order for maximizing the benefits of the HESS in energy efficiency, lifetime, etc, by exploiting its heterogeneity, which have not been considered for the conventional homogeneous ESS. Specifically, it is necessary to select particular energy storage banks to charge or discharge, determine the current, and determine the voltage of the interconnect during HESS operation. Also, stored energy may need to migrate to another energy storage bank within a HESS in order to mitigate self-discharge or to prepare for expected future demand for energy/power capacity. We recently proposed novel charge management policies for HESS, which include i) charge allocation for charging energy storage banks [42], ii) charge replacement for discharging energy storage banks [43], and iii) charge migration for moving energy between energy storage banks [44,45]. Characteristics of the energy storage elements, power converter efficiency, input or output power variations, and time constraint are considered to obtain the energy storage banks and amount of current that achieves the energy-optimal charge transfers.

These sophisticated management policies require optimized determination of each storage bank as well as high-level controllability in order to take account the above-mentioned factors. For example, a simple management policy may determine the current from each energy storage bank directly from the voltage or current of another energy storage bank [28,37,38] or speed of the EV [13]. However, considering non-linear and time-varying characteristics such as power converter efficiency, rate capability, and cycle life requires a more elaborate control system. Such a control system induces a considerable amount of control data transfer through a communication network for collecting information from many energy storage banks, power sources, and load devices and sending commands to them. Therefore, the communication network should be designed considering the high-speed requirement and should be scalable for many nodes.

## 3. HESS design considerations

While the proposed a HESS architecture is scalable, we still need to focus on a particular application when we actually implement a HESS prototype. In this paper, we derive the system specification of the HESS aiming at peak shaving and load leveling of household AC electrical appliances powered by the AC power grid. Power demand fluctuation is a major cause that hinders cost-effective and reliable power supply. Load-following power plants operated during the peak hours consumes much expensive fuel than base load power plants (e.g., nuclear power plants) do. In some countries, accelerated climate change and unexpected power outages are resulting in low reserve margin and unreliable power supply. South Korea experiences difficulty to keep a safe reserve margin during the peak hours primarily due to air-conditioning and heating in summer and winter, respectively. The reserve margin in South Korea is below 10% [46,47]. Japan is also suffering from low reserve margin (only a few percent) after Fukushima nuclear power plant shutdown [48]. The International Energy Agency recommends 20–30% of reserve margin [49].

### 3.1. System power input and output

Both the input and output of the HESS is 120 V AC. The proposed HESS is transparent to both the power grid and load devices; it is seen as an ordinary AC-powered appliance to the power grid while it is an AC power outlet to the load devices. DC power sources or DC load devices are not considered in this paper. However, the DC power sources and DC load devices may be adopted as easily as AC power sources and AC load devices by use of DC power converters instead of AC power converters while the basic architecture remains the same.

### 3.2. Power and energy capacity

Power capacity is the key requirement to consider when designing power converter circuit of a HESS, which is the maximum instantaneous power that the power converter circuit can handle. On the other hand, energy capacity is important factor for commercialization that determines the size and cost of the HESS. The power and energy capacities are derived based on the load profile. Fig. 5 is an hourly average residential load profile [50], and it shows the power consumption largely changes over time in range of 450–1000 W. This fluctuation may be significantly reduced to 650–800 kW when a HESS provides just 200 W charging/discharging capability. The amount of energy charged during off-peak hours is about 1 kWh, and the amount energy discharged during peak hours is about 0.6 kWh. As we focus on a proof-of-concept HESS rather than commercialization, the power capacity is set to be 300 W, which is sufficiently large. Each energy storage bank should be able to solely supply at least 300 W to the load device. On the other hand, the total energy capacity of the HESS is set as small as 300 Wh to shorten time of charging and discharging the system for mainly experimental purpose. Otherwise, charging and discharging experiments would take too long time. However, it is easy to increase the energy capacity by simply extending the energy storage array and/or adding more energy storage banks. Power capacity increase requires electronics subsystem revision (power converters) on the other hand.

### 3.3. Subcomponents voltage level

Subcomponents, such as power converters and energy storage arrays, should be designed with proper operating voltage level to maximize the power converter efficiency. A high voltage level incurs large switching power loss while a low voltage level incurs large conduction loss due to increased current. We refer to commercial power converters for the appropriate voltage level and to secure the voltage compatibility. Typical power converters with a few hundred watts power capacity are designed with a DC voltage range of 12–24 V. Commercial DC–DC converters have similar input and output voltage levels, and AC–DC rectifiers and DC–AC inverters also have similar voltage level for the DC side while the AC side has the voltage level of the power grid. In order to cover the voltage variation of the supercapacitor, we design the HESS to handle a wide range of voltage, 6–36 V.

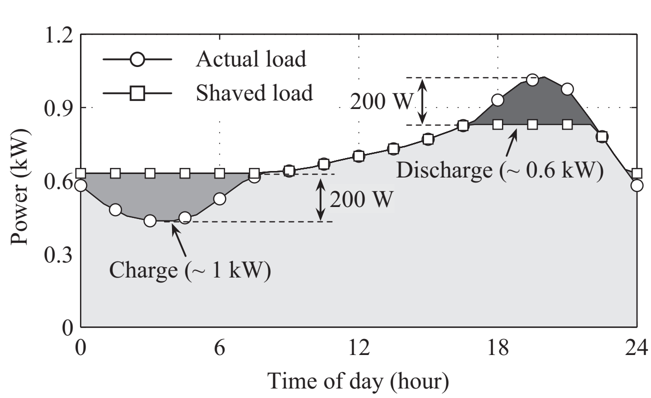



**Fig. 5.** Hourly average residential load profile (Southern California Edison territory) [50].

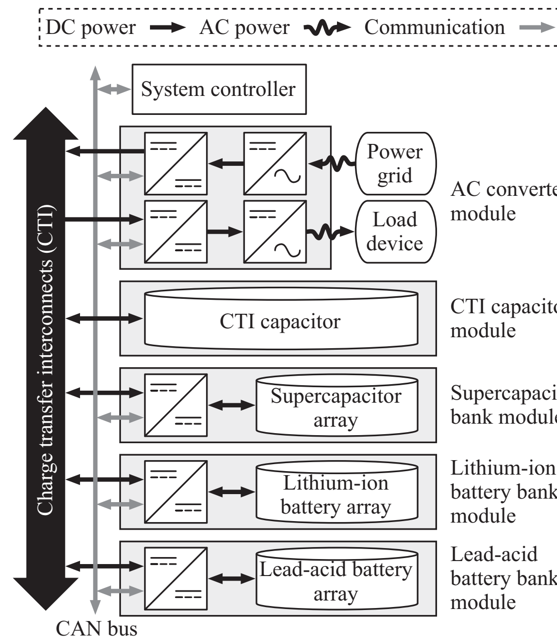



**Fig. 6.** Architecture of the proposed HESS.

### 3.4. Energy storage technologies

We use three types of energy storage technologies in the proposed HESS: supercapacitor, lithium-ion battery and lead-acid battery. The supercapacitor has advantages in power capacity cycle life, and cycle efficiency, while the lead-acid battery has advantages in cost. The lithium-ion battery has moderately good characteristics all round, except for the cost. We do not consider other types of energy storage elements such as kinetic or thermal storages. The proposed HESS does not restrict types of energy storage technologies fundamentally.

We design the HESS for proof-of-concept purpose. To utilize the HESS to develop and verify various HESS design methodologies and management policies, the following features should be considered for implementation.

- *Flexibility* to adopt various types of energy storage technologies, power sources, and load devices with a high degree of controllability.
- *Scalability* to accommodate many energy storages without degradation of performance.
- *Modularity* to easily remove or add energy storages, and change individual energy storages without significant modification to the system.

High degree of flexibility and scalability are required to compose the HESS with any types and numbers of energy storages, power sources, and load devices without performance degradation. High modularity is important to efficiently find and verify the right design of the system. Surely, there are more features that a practical HESS should consider, e.g., economic feasibility, volume and weight, manufacturability, etc., but we emphasize the above three features for the prototype implementation.

## 4. Module design and implementation

We discuss design and implementation of the HESS in this and next sections. This section explains the system architecture and module-level design, and the next section explains the controller and power converter circuit design. We justify that the proposed HESS satisfies the specifications and features discussed in Section 3.

### 4.1. System architecture

Fig. 6 shows the architecture of the proposed HESS. It is composed of five modules: three energy storage bank modules, AC converter module, and bulk capacitor module. These five modules are connected through two networks; one is the charge transfer interconnect (CTI) for energy transfer, and the other is control area network (CAN) for communication.

We employ a single shared DC bus CTI, which is reasonable for this number of modules, among several hybridization architectures discussed in Section 2.3. The single shared bus CTI offers relatively higher scalability. In addition to that, the novel control method for the CTI achieves high energy efficiency and flexibility of the system. (We discuss the CTI control method in detail in the next section.) The goal of high modularity of the HESS is accomplished by implementing components in five separate modules as shown in Fig. 6. Each module has the uniform interface to the CTI and the CAN bus. Adding another energy storage bank to increase power/energy capacity of the HESS or removing one for energy storage element replacement or maintenance is easily done with simple connection of the standard interface. The following subsections discuss design and implementation of each module.

The HESS is connected to the system controller through the CAN bus, which performs a high-level system control and management. The system controller is in charge of determining the CTI voltage and current of each energy storage banks and power sources based on the load current and energy storage bank status such as SoC and SoH. While the system controller makes such high-level decisions with a system-level control loop, the power converters in each bank maintain designated CTI voltage and input/output current with a circuit-level control loop. The system-level control loop continuously updates the voltage/current set points to maximize the system efficiency by the use of system-level management policies.

### 4.2. AC converter module

The AC converter module is composed of AC-to-DC and DC-to-AC converters. The proposed HESS receives AC power from the power grid and supplies AC power to the load devices. On the other hand, batteries and supercapacitors are all DC energy storages. Therefore, AC power converters are necessary to perform power conversion between AC and DC for charging and discharging. These AC power converters do not need to be bidirectional because the proposed HESS does not supply power back to the power grid.

In our HESS, commercial high-efficiency AC converters are adopted rather than designing custom AC converters. Mean Well SE-600, a 600 W AC–DC rectifier [51] generates a 36 V fixed output voltage while we need an adjustable output voltage in order to dynamically change the CTI voltage. Between the AC–DC rectifier and the CTI, a DC–DC converter performs wide-range output voltage adjustment from the 36 V fixed input voltage. For DC-to-AC conversion, we use the Samlex PST-100S-24A, a 1 kW pure sine wave DC–AC inverter [52]. In contrast to the AC–DC rectifier, the

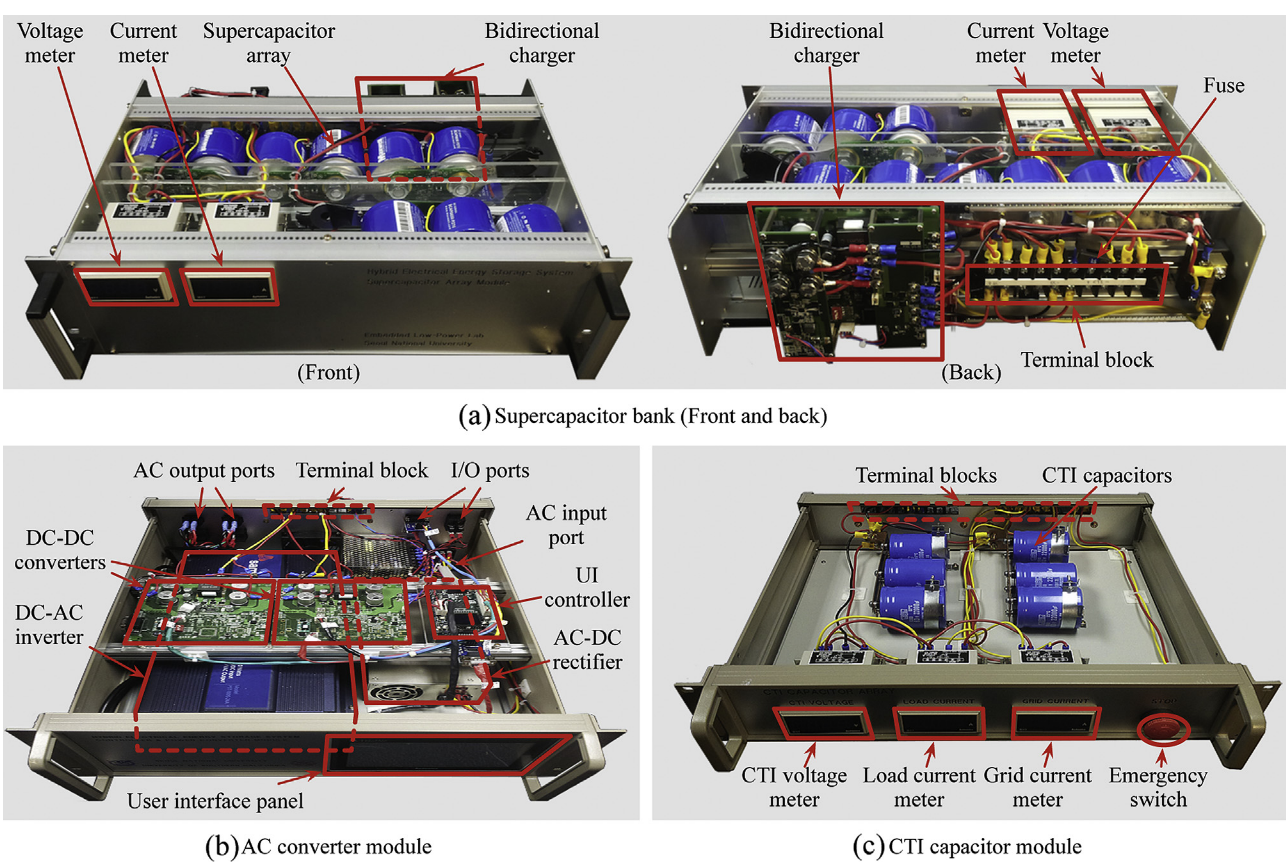



**Fig. 7.** Modules of the proposed HESS.

DC–AC inverter is required to accept wide input voltage of 6–36 V from the CTI, but typical commercial inverters designed for batteries do not support such a wide input range. The PST-100S-24A is operational only for 21.4–33 V input, and the nominal input voltage is 24 V. Therefore, similar to the AC–DC rectifier, we implement a DC–DC converter which accepts 6–36 V input voltage and generates 24 V fixed output voltage.

Fig. 7(b) is a photo of the AC converter module. It shows the AC–DC rectifier, DC–AC inverter, and two DC–DC converters inside. The back panel of this module is populated with AC and DC power ports and digital I/O ports (RS232, CAN, user switches, etc.).

### 4.3. Bank modules

An energy storage bank module is composed of a homogeneous energy storage array and a bidirectional charger. For bank-level hybridization, all the energy storage elements in a bank are homogeneous, but each bank is composed of different energy storage elements. The energy storage array is a set of multiple homogeneous energy storage elements that are connected in series and/or parallel forming a regular array structure. In this paper, only a regular array structure is considered in order to maintain the same SoC and SoH of all the elements in the array. The dimension of the energy storage array is determined by the power and energy capacity, and the maximum voltage rating of the energy storage bank. Also, external cell balancing circuits are implemented because even though all the energy storage elements are of the same type, manufacturing variation in practice may result in imbalance of characteristics such as capacity and internal resistance that causes imbalanced SoC during operation and even damage to the elements [53].

The bidirectional charger is the interface for the bank module to be integrated into the HESS; it has compatibility of the terminal voltage range and the communication network protocol. The charger performs current regulation between the CTI and energy storage array, which is necessary for charging or discharging the array. It is also able to perform voltage regulation for maintaining a constant CTI voltage when discharging the array. The bidirectional charger is connected to the system controller through the CAN bus. When the power is on, the system controller identifies the bank characteristics such as the type of energy storage bank, maximum charging/discharging current, SoC, SoH, array terminal voltage, temperature of the cells, etc. The bidirectional charger continues reporting the voltage, current, temperature, and so on to the system controller during operation.

The proposed HESS has three energy storage banks: a supercapacitor bank, a lithium-ion battery bank, and a lead-acid battery bank. We implement the energy storage bank modules in 19-inch rack cases for scalability and modularity as a prototype. Due to the uniformity of the power and communication port, changing the configuration of an energy storage bank module or adding/removing a module is simple and has limited influence to the whole system. Fig. 7(a) shows the supercapacitor bank module viewed from the front and back assembled in a 19-inch rack case. There is an energy storage array composed of 18 supercapacitors inside the rack case, and a bidirectional charger is attached to the back of the module together with terminal blocks. The voltage and current meters on the front panel display the voltage and current of the energy storage array. We put a fuse to prevent excess current flow between the bank and CTI that may cause damage to the array or charger. The lithium-ion battery module bank and the lead-acid battery bank module also have a similar structure. Composition each energy storage bank module is summarized in Table 1. Detailed implementation of each energy storage bank is described below.

**Table 1**
Composition of energy storage banks.

| Parameter | | Supercapacitor | Lithium-ion battery | Lead-acid battery |
|---|---|---|---|---|
| Unit cell | Cell | Maxwell BCAP0650 | Samsung ICR18650-26F | Panasonic LC-R123R4P |
| | Voltage | 2.7 V (max) | 3.7 V | 12 V |
| | Capacity | 650 F | 2600 mAh | 3400 mAh |
| | Energy | 0.66 Wh | 9.6 Wh | 40.8 Wh |
| | Cost | $69/Wh | $3/Wh | $1/Wh |
| Configuration | Series | 18 | 6 | 2 |
| | Parallel | 1 | 2 | 2 |
| Bank | Voltage | 48.6 V (max) | 22.2 V | 24.0 V |
| | Energy | 6.3 Wh | 115 Wh | 163 Wh |

#### 4.3.1. Supercapacitor bank

We use 18 cells of Maxwell BCAP0650 supercapacitor connected in series to compose the supercapacitor bank [54]. Each cell has 650 F capacity with maximum voltage of 2.7 V, and so 18-series connection makes a 36 F supercapacitor array of maximum voltage of 48.6 V. The primary advantage of the supercapacitors is the extra long cycle life. The datasheet states that it has a cycle life of 1,000,000 cycles. The maximum energy stored in the supercapacitor array is 11.8 Wh when the charged to 48.6 V. Actual maximum energy capacity utilized is 6.3 Wh because we limit the terminal voltage of the supercapacitor array within 6–36 V as specified in Section 3. Cost per energy of the supercapacitor is about $69/Wh based on the retail price for purchasing single cell, which is much more costly than that of batteries by an order of magnitude.

#### 4.3.2. Lithium-ion battery bank

We compose the lithium-ion battery bank with 12 cells of Samsung ICR18650-26F [55]. Each cell has 2600 mAh capacity and nominal voltage of 3.7 V. We arrange the 12 cells into a 6-by-2 array which give us 22.2 V nominal voltage and 115 Wh energy capacity. The number of series connection is determined to make the nominal voltage be placed in the middle of voltage range of 6–36 V in order to mitigate power efficiency degradation which may be caused by voltage difference between the battery array and CTI. The total energy capacity is chosen to be small so as to shorten the time for experiments as we mentioned in Section 3. In fact, the rack case has a plenty of room for additional batteries.

#### 4.3.3. Lead-acid battery bank

The lead-acid battery bank consists of four Panasonic LC-R123R4P batteries [56]. Each battery is composed of six series cells which make nominal voltage of 12.0 V. We make a 2-by-2 array to obtain a terminal voltage of 24.0 V. The lead-acid battery bank has the largest energy capacity thanks to its low cost, which is only $1/Wh based on the retail price for purchasing a single battery. The total energy capacity of the lead-acid battery bank is also set small for fast experiments.

### 4.4. CTI capacitor module

The CTI is the input or output of the bidirectional chargers, and so a sufficient amount of bulk capacitors is required to prevent voltage fluctuation. The power converters have limited capability to deal with sudden changes of the load current, which may result in rapid changes of the CTI voltage unless the CTI has enough energy buffer. Severe CTI voltage drop may violate the minimum input voltage requirement of the bidirectional chargers and result in system failure.

We implement the energy buffer for the CTI with an array of large-capacitance aluminum capacitors. Fig. 7(c) is a photo of the CTI capacitor module. We connect six of United Chemi-Con

22,000 μF aluminum capacitors in parallel to compose the CTI capacitor array. The total 132,000 μF capacitance is proven by experiments to be sufficient to maintain a stable voltage against 300 W load increase when charged over 25 V. The system controller determines the CTI voltage level with considerations on the energy efficiency of the charge transfers and predicted load demand. The CTI capacitor module has one voltage meter and two current meters on the front panel to show the CTI voltage, current from CTI to the load devices, and current from the power grid to the CTI. The emergency switch is also placed on the front panel to cut off the main power to inactivate all the power paths manually in case of emergency.

### 4.5. Module assembly

Fig. 8 shows the front and back views of the HESS assembled in a 19-inch rack. Dimension of the whole system is 60 (W) × 65 (L) × 96 (H) cm (23.6 × 25.6 × 37.8 inch). Fig. 8(a) shows the AC converter module, CTI capacitor module, supercapacitor bank module, lithium-ion battery bank module, and lead-acid battery bank module from top to bottom. The standard 19-inch rack makes it easier to change the system configuration and develop the modules independently. The modules are reusable for other HESS. Heat generated from the energy storage elements and circuits is removed from the rack by four cooling fans installed on the back (not shown in the figure).

## 5. Bidirectional charger and controller design

### 5.1. Bidirectional charger

The charger design is a key for the HESS to achieve high efficiency and high reliability. It has integrated functionalities of a DC–DC converter, battery charger, battery monitor, and so on. This is similar to conventional battery management systems, but provides more high-level controllability for the HESS management by being integrated with the system controller and other chargers. Specifically, the bidirectional charger implemented for the proposed HESS has the following features:

- *Bidirectional conversion* for charging the energy storage array from the CTI, as well as discharging the energy storage array to the CTI.
- *Voltage and current regulation* for generating either regulated voltage or regulated current. When it is charging an energy storage array, this is necessary to perform the constant-current and constant-voltage (CC–CV) charging. When it is discharging an energy storage array, this is necessary either for maintaining the CTI voltage or injecting designated amount of current into the CTI. Also, the output voltage and current should be adjustable depending on the charging or discharging conditions and the high-level management policies.
- *Wide operational range* to cope with wide variation of energy storage array terminal voltage and CTI voltage. The terminal voltage of the energy storage arrays changes depending on their SoC and load current, especially for supercapacitor whose array terminal voltage is linearly proportional to its SoC. The CTI voltage also changes in a wide range for energy efficiency and reliability. Therefore, the charger requires a wide input and output voltage range of 6–36 V as specified in Section 3.
- *Board-to-board communication* for reporting the current status of the bank to the system controller and receiving operational commands from the system controller through the CAN bus.

Fig. 9(a) shows the charger implemented for the proposed HESS. The charger is composed of three parts: controller, power converter, and power path controller. The power converter performs unidirectional, adjustable voltage or current regulation with wide input/output voltage (6–36 V) and high-current (up to 10 A). The converter circuit uses a combination of the LTC3789 DC–DC converter [57] and the LTC4000 power management IC [58] from Linear Technology. The LTC4000 is originally designed to generate a

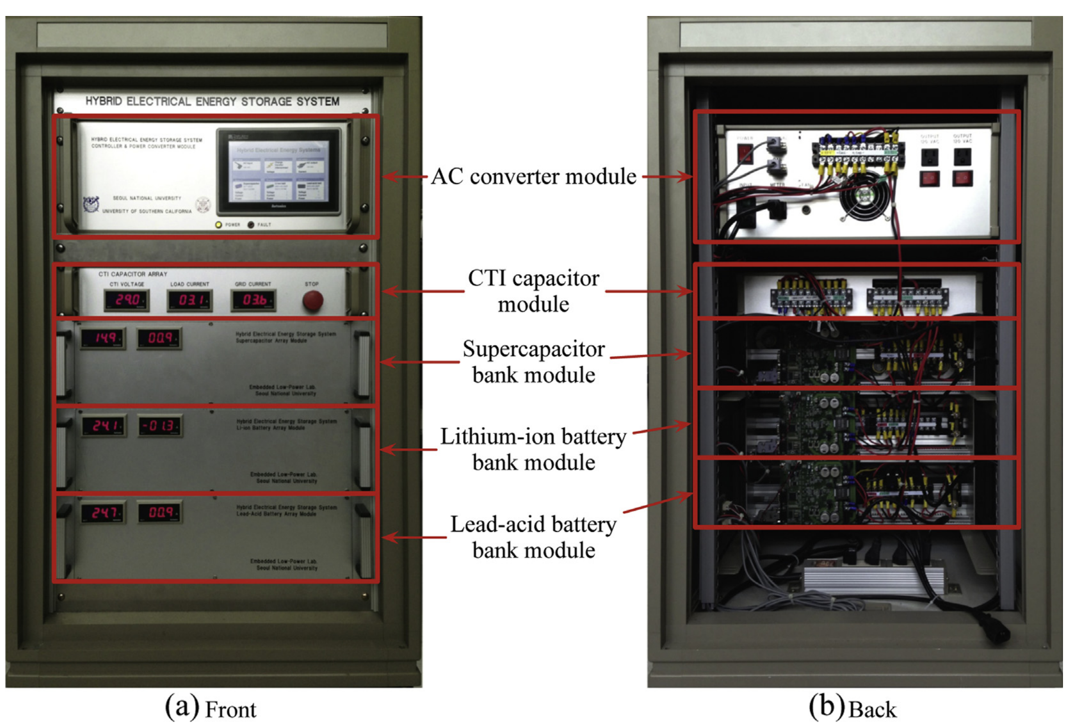



**Fig. 8.** Front and back views of the assembled HESS.

fixed voltage or fixed current for charging battery from the wall power. We modify the voltage and current feedback loops with digital potentiometers to make them dynamically adjustable by a microcontroller in the controller part.

The power path controller interchanges the input and output ports of the power converter as needed for bidirectional power conversion. When charging the energy storage bank, the input is the CTI and the output is the energy storage array; and when discharging the energy storage bank, it is the opposite. We use four solid-state relays made of a pair of MOSFET switches to dynamically change the input and output as shown in Fig. 9(b). Two solid-state relays are coupled as a pair and opened or closed together, and the two pairs are exclusively closed. For example, the microcontroller closes SW1 and SW2 are closed and opens SW3 and SW4 as shown in Fig. 9(b) when charging. We implement a hardware protection circuit on the power path controller to prevent short circuit from the CTI and energy storage array by control flaws or signal glitches.

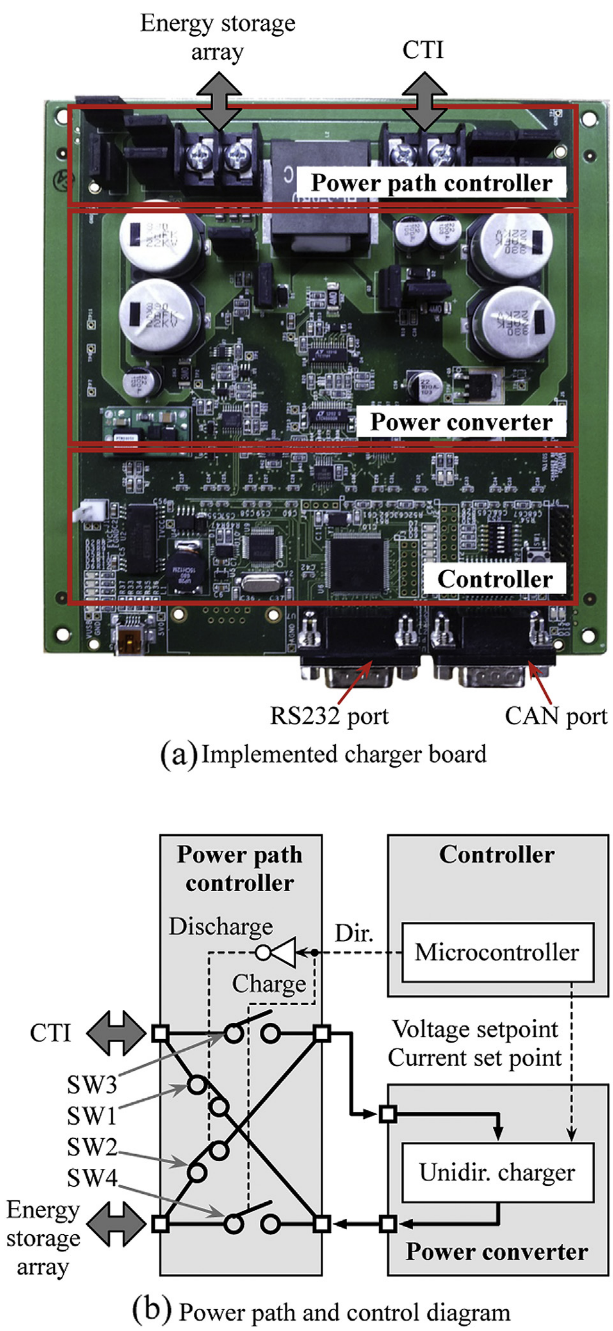



**Fig. 9.** Implemented charger board and the power path of the charger.

### 5.2. Control system design

The control system for the proposed HESS is composed i) the bidirectional chargers in each bank and ii) the system controller. The chargers perform individual control of the energy storage bank as directed by the system controller, which makes decisions for the high-level management. Fig. 10 shows the block diagram of the control system. The chargers and system controller are connected through the CAN bus together with the system controller in order to perform high-level management of the HESS as mentioned in Section 2.4.

The chargers run real-time control tasks on top of the μ C-OS II real-time operating system at 1 kHz frequency on the Texas Instruments LM3S2965 microcontroller. Each task has a different scheduling priority depending on its impact on the system. Emergency management task, which has the highest priority, detects abnormal status and shuts down all power paths and power converters in the system. Measurement task, charger control task, and CAN communication task are the next high priority tier tasks. The measurement task periodically collects the voltage/current values of the input/output of the power converter, and the charger control task sets the voltage and current regulation set points and input/output direction. The set points and direction are mainly given by the system controller, but may be locally overridden for safety or manual control. The CAN communication task collects messages from other tasks and deliver them over the CAN network periodically or on demand. Critical messages related with the system controller's decision (e.g., measured voltage/current and control commands) are delivered periodically at the task execution rate, while slowly changing values (e.g., SoC and SoH) are delivered upon request. Console task and SoC/SoH estimation task have a lower priority. The console task is for communication with the user for monitoring and manual control interface. The SoC/SoH estimation task calculates the SoC and SoH based on the measured voltage and current profiles.

The system controller is in charge of determining the CTI voltage and current of each energy storage bank for high energy efficiency and reliability. We implement the charge management task in the system controller to determine the optimal values [42–45]. The decision is made based on many parameters including voltage, current and SoC of the energy storage banks and load demand prediction. We do not cover the optimization methods in detail in this paper.

### 5.3. CTI voltage and current control method

Control of the CTI voltage is critical to energy-efficient and reliable operation of the HESS. Net current (sum of inflow currents and outflow currents) of the CTI should be zero in steady state in order to keep the CTI voltage at the desired level. In an ideal case, all power converters may operate in the current-regulating mode and adjust the output current immediately responding to CTI voltage variation. However, the capacitance of the CTI capacitor is not very large in practice, and thus the voltage changes very rapidly even with a slight mismatch between inflow and outflow currents. The software-based control offers high-level controllability, but may not be fast enough to detect the CTI voltage variation and re-determine the current of energy storage banks in time. This is especially critical when experiencing a sudden increase of the load current but the system fails to increase the discharging current in time, resulting in an under-voltage failure.

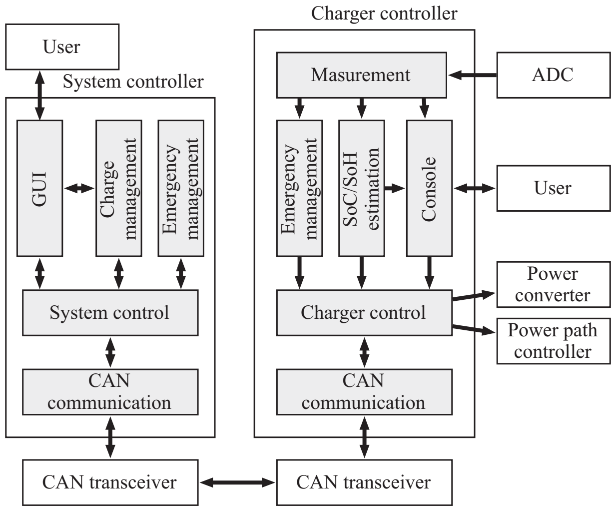



**Fig. 10.** Control system block diagram.

We employ a cascade control loop to overcome the CTI voltage reliability problem as illustrated in Fig. 11. We operate AC–DC rectifier from the power grid to the CTI in the voltage-regulating mode so that it maintains the CTI voltage with a hardware feedback control loop. The voltage regulation performed by the hardware voltage feedback control loop of the converter is fast enough to keep the CTI voltage at the desired level against the fluctuation of the input and output current of the CTI. Other current-regulating power converters extract or inject a designated amount of current from or to the CTI. Current supplied by the voltage-regulating power converter is consequently determined to the amount that makes the net current of the CTI zero. Choosing the voltage-regulating converter is an important decision though any of chargers of discharging energy storage banks and power converters from power sources can take this role. It is related to reliability because the it may have to solely maintain the CTI voltage during transient periods. We designate the DC–DC converter from the power grid as the voltage-regulating converter for reliability because the power grid has virtually unlimited power capacity and energy capacity. Consequently, the bidirectional chargers in the energy storage banks are in current-regulating mode. Our control method provides more flexibility and a higher degree of freedom for energy-efficient control by allowing

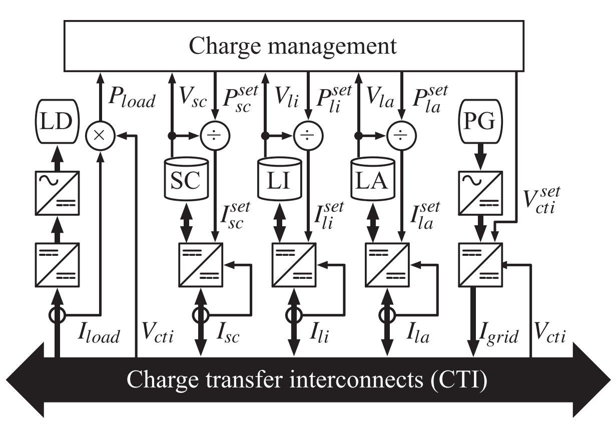



**Fig. 11.** Control system design. (LD: load devices, SC: supercapacitor, LI: lithium-ion battery, LA: lead-acid battery, PG: power grid.)

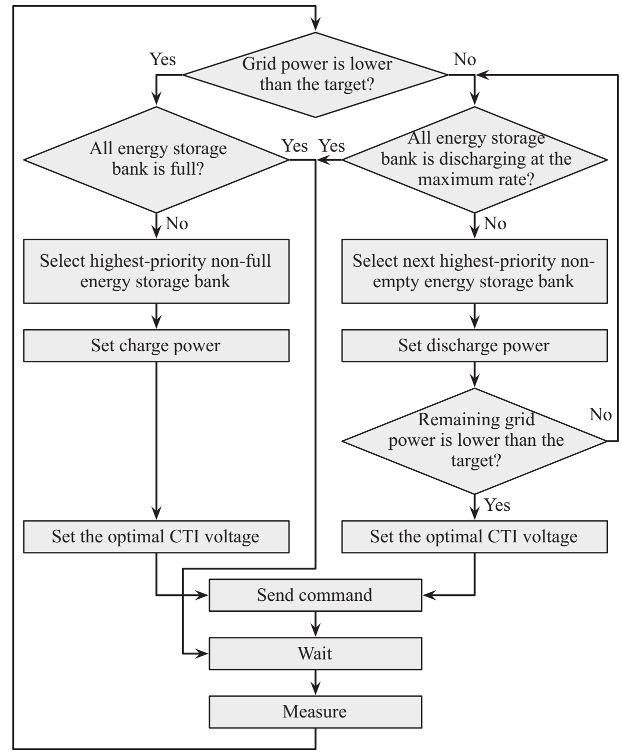



**Fig. 12.** Charge management policy.

arbitrary current for each energy storage banks as well as variable CTI voltage.

For validation of our control method, we implement a charge management policy as shown in Fig. 12. The objective of this policy is load leveling; it maintains the power consumption from the power grid to a constant level by dynamically charging or discharging the HESS. Power distribution during charging and discharging is priority-based considering the cycle efficiency, cycle life, and power converter efficiency. The supercapacitor bank, which has the highest cycle efficiency and cycle life, has the highest priority. The lithium-ion battery bank has the second priority. The lead-acid battery bank, which is vulnerable to frequent cycling, has the lowest priority. We calculate the optimal CTI voltage level that minimizes the power loss using a power converter efficiency map. This high-level policy is more complicated than other simple hardware-based policies, for example, maintaining constant voltage for each bank. The high degree of flexibility of the proposed control method enables such high complexity policies for higher energy efficiency. Although this policy may be improved further by considering energy storage element cost for reducing return of investment (ROI) and electricity cost, it is sufficient for validation of the proposed control method.

## 6. Experimental results

### 6.1. Bidirectional charger efficiency

We first show the power converter efficiency of the implemented charger. The power converter efficiency is derived from measured input/output voltage and current of the power converter circuit of the charger. Fig. 13(a) and (b) shows the efficiency over a wide range of input and output voltages when the output current is 0.5 A and 1.5 A, respectively. Generally speaking, it shows a good

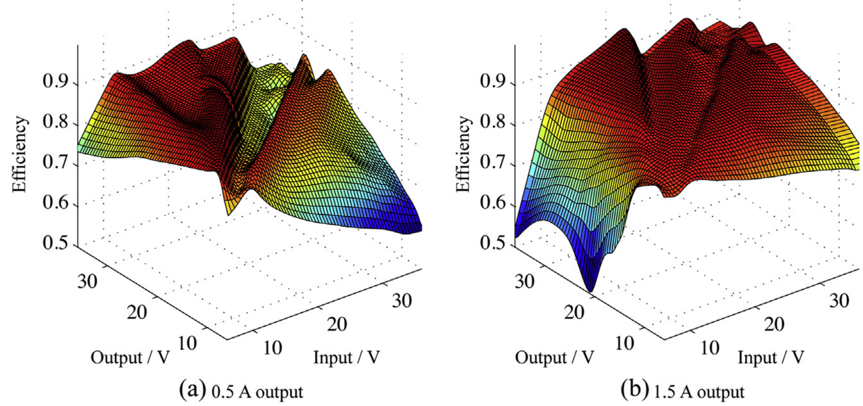



**Fig. 13.** Power converter efficiency of the bidirectional charger.

efficiency when the input and output voltage are similar. As the voltage difference between the input and output becomes larger, the efficiency drops. The measured result is close to the efficiency depicted in the datasheet of the LTC3789 [57].

### 6.2. Charge management

We show the measurement result of the system while running by the charge management policies introduced in Section 5.3

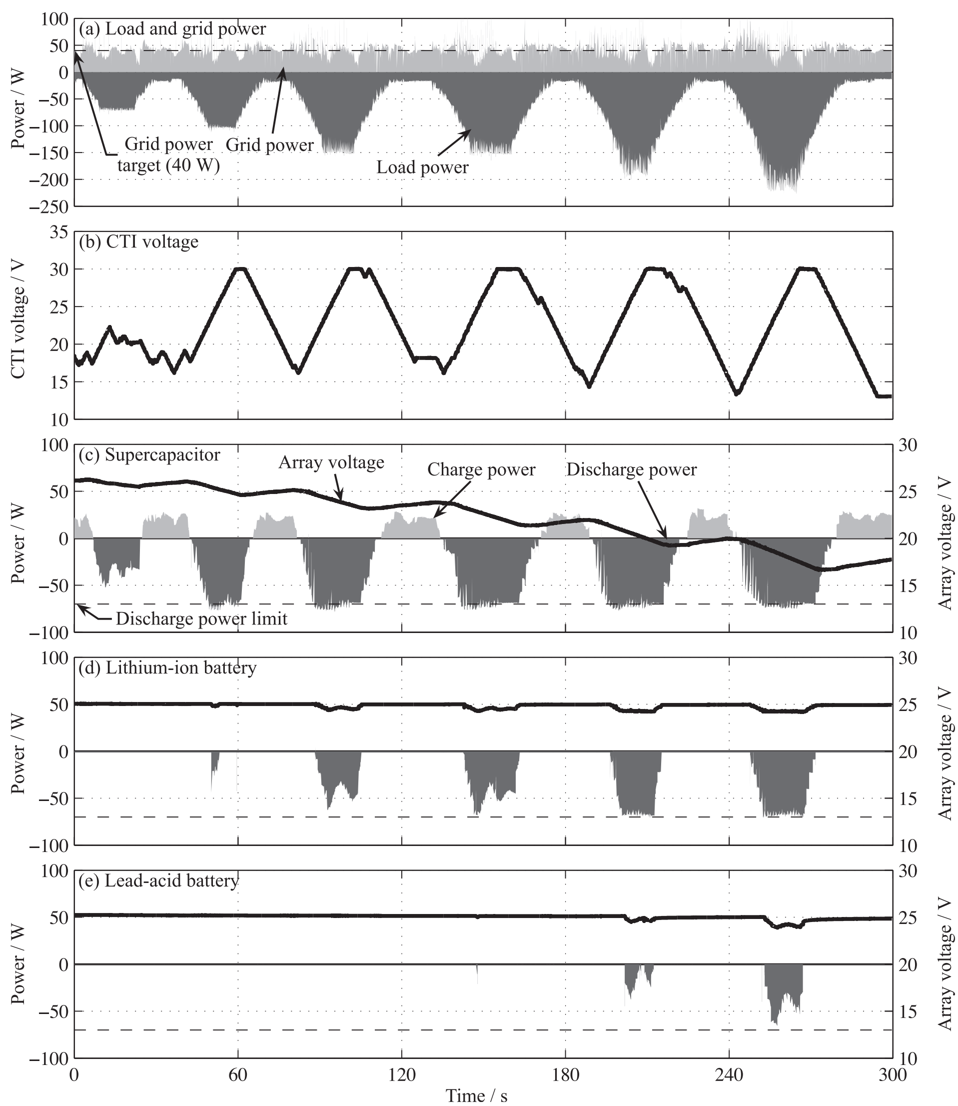



**Fig. 14.** CTI voltage and current of nodes measured while increasing and decreasing the load current. (a) load and grid power, (b) CTI voltage, (c) supercapacitor voltage and current, (d) lithium-ion battery voltage and current, and (e) lead-acid battery voltage and current.

(Fig. 12). We set the grid power target to 40 W and maintain the grid power to the target regardless of the load power variation. Fig. 14 shows voltage, current, and power measured from various points while the load power significantly changes over time. Fig. 14(a) shows the load power (discharged from the HESS) and grid power (charged to the HESS). The dashed line is the grid power target, which is 40 W. The grid power stays near the target level even the load power changes between 15 W and 220 W. As the load power increases, a higher CTI voltage becomes more beneficial to reduce conductance loss in the converter circuit. As a result, the CTI voltage changes in a wide range to achieve the best conversion efficiency as shown in Fig. 14(b). Fig. 14(c)–(e) shows power and voltage variation of the supercapacitor array, lithium-ion battery array, and lead-acid battery array, respectively. While the grid power is lower than the target, the supercapacitor bank is charged first. The array voltage of the supercapacitor bank increases or decreases as it is charged or discharged. The lithium-ion battery bank and lead-acid battery bank consecutively start to discharge as the load power becomes heavier. This experimental result demonstrates the capability of operating high-level system management policies, which is enabled by the proposed control method.

## 7. Conclusions

Energy storage systems (ESS) are expected to play key roles to improve efficiency and reliability in various applications. Hybrid energy storage system (HESS) is an emerging system-level design technique to build a high-performance ESS in a cost-performance way by complementary use of heterogeneous energy storage technologies available today. This work demonstrated a 300 W HESS prototype composed of three types of energy storage technologies: 6.3 Wh supercapacitors, 115 Wh lithium-ion batteries, and 163 Wh lead-acid batteries. We introduced a novel control method with customized voltage- and current-regulating power converter. The power converter enables high energy efficiency by controllable regulation mode and output value. The high-level management performs load-leveling functionality taking the power converter efficiency and cycle efficiency of each energy storage into account for the control decision. The experimental results showed the effectiveness of the proposed control method for load-leveling; the input power from the grid is maintained to a fixed level 40 W, independent to the load power fluctuation between 15 W and 220 W, with dynamic adjustment of the charge transfer interconnect (CTI) voltage in 6–36 V range.

## Acknowledgment

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## References


[1] M. Świerczyński, D. Stroe, A.-I. Stan, R. Teodorescu, D. Sauer, IEEE Trans. Sustain. Energy PP (99) (2013) 1–12.
[2] Y. Wang, X. Lin, M. Pedram, in: Proceedings of the IEEE Green Technologies Conference, 2013, pp. 28–34.
[3] X.-M. Liu, Z. dong Huang, S. woon Oh, B. Zhang, P.-C. Ma, M.M. Yuen, J.-K. Kim, Compos. Sci. Technol. 72 (2) (2012) 121–144.
[4] M. Ge, J. Rong, X. Fang, C. Zhou, Nano Lett. 12 (5) (2012) 2318–2323.
[5] P. Lex, B. Jonshagen, Power Eng. J. 13 (3) (1999) 142–148.
[6] C. Fabjan, J. Garche, B. Harrer, L. Jörissen, C. Kolbeck, F. Philippi, G. Tomazic, F. Wagner, Electrochim. Acta 47 (5) (2001) 825–831.
[7] S. Vosen, J. Keller, Int. J. Hydrogen Energy 24 (12) (1999) 1139–1156.
[8] S. Lukic, S. Wirasingha, F. Rodriguez, J. Cao, A. Emadi, in: Proceedings of the Vehicle Power and Propulsion Conference (VPPC), 2006, pp. 1–6.
[9] J.D. Maclay, J. Brouwer, G.S. Samuelsen, J. Power Sources 163 (2) (2007) 916–925.
[10] M. Pedram, N. Chang, Y. Kim, Y. Wang, in: Proceedings of the International Symposium on Low Power Electronics and Design (ISLPED), 2010, pp. 363–368.
[11] F. Koushanfar, in: Proceedings of the Design Automation Conference (DAC), 2010, pp. 629–630.
[12] X. Jiang, J. Polastre, D. Culler, in: Proceedings of the International Symposium on Information Processing in Sensor Networks (IPSN), 2005, pp. 463–468.
[13] J. Moreno, M. Ortuzar, J. Dixon, IEEE Trans. Ind. Electron. 53 (2) (2006) 614–623.
[14] B. Frenzel, P. Kurzweil, H. Rönnebeck, J. Power Sources 196 (12) (2011) 5364–5376.
[15] D. Shin, Y. Wang, Y. Kim, J. Seo, M. Pedram, N. Chang, in: Proceedings of the Design, Automation & Test in Europe Conference & Exhibition (DATE), 2011, pp. 1–4.
[16] D. Shin, Y. Kim, Y. Wang, N. Chang, M. Pedram, J. Power Sources 205 (2012) 516–524.
[17] W. Gao, IEEE Trans. Veh. Technol. 54 (3) (2005) 846–855.
[18] J. Hongxin, F. Yang, Z. Yu, H. Weiguo, in: Proceedings of the Asia-Pacific Power and Energy Engineering Conference (APPEEC), 2010, pp. 1–6.
[19] M. M. Thackeray, C. Wolverton, E. D. Isaacs, Energy Environ. Sci.
[20] A. Xu, S. Xie, X. Liu, IEEE Trans. Veh. Technol. 58 (8) (2009) 3981–3987.
[21] S.J. Moura, D.S. Callaway, H.K. Fathy, J.L. Stein, J. Power Sources 195 (9) (2010) 2979–2988.
[22] S. Bashash, S.J. Moura, J.C. Forman, H.K. Fathy, J. Power Sources 196 (1) (2011) 541–549.
[23] K. Divya, J. Østergaard, Electr. Power Syst. Res. 79 (4) (2009) 511–520.
[24] D.H. Doughty, P.C. Butler, A.A. Akhil, N.H. Clark, J.D. Boyes, Batteries for Large-scale Stationary Electrical Energy Storage, The Electrochemical Society Interface, 2010, pp. 49–53.
[25] K. Yoshimoto, T. Nanahara, G. Koshimizu, in: Power Systems Conference and Exposition (PSCE), 2006, pp. 1244–1251.
[26] S.A. Przybylski, Cache and Memory Hierarchy Design: A Performance Directed Approach, Morgan Kaufmann, 1990.
[27] C. Park, P. Chou, in: Proceedings of the Communications Society Conference on Sensor, Mesh and Ad Hoc Communications and Networks, 2006, pp. 168–177.
[28] P. Thounthong, S. Rael, B. Davat, J. Power Sources 193 (1) (2009) 376–385.
[29] M. Masih-Tehrani, M.-R. Ha'iri-Yazdi, V. Esfahanian, A. Safaei, J. Power Sources 244 (2013) 2–10.
[30] S. Fiorenti, J. Guanetti, Y. Guezennec, S. Onori, J. Power Sources 241 (2013) 112–120.
[31] S. Park, Y. Kim, N. Chang, in: Proceedings of the Design Automation Conference (DAC), 2013, 97:1–97:6.
[32] W. Li, G. Joos, J. Belanger, IEEE Trans. Ind. Electron. 57 (4) (2010) 1137–1145.
[33] M. Glavin, P. Chan, S. Armstrong, W. Hurley, in: Proceedings of the Power Electronics and Motion Control Conference (PEMC), 2008, pp. 1688–1695.
[34] R. Dougal, S. Liu, R. White, IEEE Trans. Compon. Packag. Technol. 25 (1) (2002) 120–131.
[35] L. Lam, R. Louey, J. Power Sources 158 (2) (2006) 1140–1148.
[36] J. Furukawa, T. Takada, D. Monma, L. Lam, J. Power Sources 195 (4) (2010) 1241–1245.
[37] P. Thounthong, V. Chunkag, P. Sethakul, S. Sikkabut, S. Pierfederici, B. Davat, J. Power Sources 196 (1) (2011) 313–324.
[38] Y. Zhang, Z. Jiang, X. Yu, in: Proceedings of the Energy 2030 Conference, 2008, pp. 1–6.
[39] C.-H. Li, X.-J. Zhu, G.-Y. Cao, S. Sui, M.-R. Hu, Renew. Energy 34 (3) (2009) 815–826.
[40] D. Zhu, Y. Wang, S. Yue, Q. Xie, N. Chang, M. Pedram, in: Proceedings of Asia and South Pacific Design Automation Conference (ASP-DAC), 2013.
[41] D. Zhu, S. Yue, Y. Wang, Y. Kim, N. Chang, M. Pedram, in: Proceedings of the International Conference on Hardware/Software Codesign and System Synthesis (CODES+ISSS), 2013, pp. 1–9.
[42] Q. Xie, Y. Wang, Y. Kim, N. Chang, M. Pedram, in: Proceedings of the International Conference on Hardware/Software Codesign and System Synthesis (CODES+ISSS), 2011, pp. 277–284.
[43] Q. Xie, Y. Wang, Y. Kim, D. Shin, N. Chang, M. Pedram, in: Proceedings of the Asia and South Pacific Design Automation Conference (ASP-DAC), 2012, pp. 627–632.
[44] Y. Wang, Y. Kim, Q. Xie, N. Chang, M. Pedram, in: Proceedings of the International Symposium on Low Power Electronics and Design (ISLPED), 2011, pp. 103–108.
[45] Y. Wang, Q. Xie, M. Pedram, Y. Kim, N. Chang, M. Poncino, in: Proceedings of the Design, Automation & Test in Europe Conference & Exhibition (DATE), 2012, pp. 169–174.
[46] Tech. rep., Fact Sheet: Generating Capacity & Reserve Margin, CLP Group, 2012
[47] M. Lee, Energy Policy 63 (0) (2013) 1217–1223.
[48] Electricity Supply-demand Outlook & Measures for the Summer of FY2013, Agency for Natural Resources and Energy Ministry of Economy, Trade and Industry, Japan, 2013.
[49] F. Nguyen, U. Stridbaek, Tackling Investment Challenges in Power Generation, Tech. rep., International Energy Agency, 2007
[50] J. Wiehagen, D. Harrell, Review of Residential Electrical Energy Use Data, Tech. rep., NAHB Research Center, Inc., 2001

[51] Mean Well, 600W Single Output Power Supply: SE-600 Series, 2011.
[52] Samlex, 1000W DC–AC inverter pure since wave.
[53] Y. Barsukov, Battery Cell Balancing: What to Balance and How, Tech. rep., Texas Instruments, 2009
[54] Maxwell Technologies, K2 series ultracapacitors.
[55] Samsung SDI, Specification of Product for Lithium-ion Rechargeable Cell Model ICR18650-26F, 2009.
[56] Panasonic, Value-regulated Lead Acid Batteries: Individual Data Sheet: LC-R123R4P, 2005.
[57] Linear Technology, LTC3789: High Efficiency, Synchronous, 4-switch Buck-boost Controller.
[58] Linear Technology, LTC4000: High Voltage High Current Controller for Battery Charging and Power management.