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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.

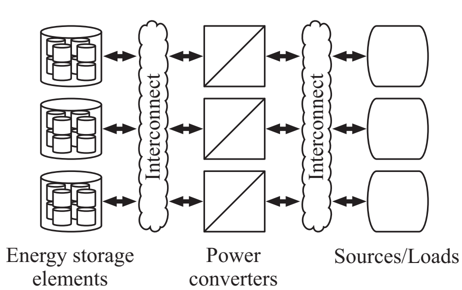

Fig. 1. General components of an ESS.

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