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Computer-Aided Design and Optimization of Hybrid Energy Storage Systems

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Abstract

Electricity is the key to the proper functioning of modern human society. Ever-increasing electricity consumption gives rise to recent regulations and significant endeavors to improve the energy efficiency in all kinds of human activity from manufacturing to commerce, from transportation to digital communication, from entertainment to laptops and portable devices. An important technology for helping reduce energy consumption is the ability to store any excess electrical energy for long periods of time and efficiently retrieve the stored energy.

The design and management of electrical energy storage systems is the focus of the present paper, which starts off by reviewing and comparing various types of electrical energy storage elements in terms of various metrics of interest ranging from power and energy density to output power rating and from self-leakage rate to cost per unit of stored energy, and from life cycle of the storage element to the efficiency of the charge/discharge cycle. Next the paper reviews various energy storage systems while motivating the need for a hybrid energy storage system comprised of heterogeneous types of energy storage elements organized in a hierarchical manner so as to hide the weaknesses of each storage element while eliciting their strengths. The paper continues with a detailed explanation of key challenges that one faces when dealing with the optimal design and runtime management of a hybrid energy storage system targeting some specific application scenario; for example, grid-scale energy management, household peak power shaving, mobile platform power saving, and more. A survey of some existing solutions to these problems is also included.

Contents

1

Introduction

Electricity is an integral utility in the modern society, with links to everything from agricultural production to manufacturing, from digital communication to media and internet, and from medical care to living conditions. Electric energy consumption has steadily risen since its industrial introduction in the second half of the nineteenth century. In fact the world's total electrical energy production in 2009 was about 20,000 TWh, which is equivalent to a generated (and consumed) power of around 2.3 TW on average. This level of average power consumption is achieved by a combination of electricity generation stations, including heat engines fueled by chemical combustion or nuclear fission, kinetic energy of flowing water and wind, solar photovoltaics and geothermal processes. Fossil fuels (coal, gas, and oil in that order) account for 67%, renewable energy (mainly hydroelectric, wind, solar, and biomass) for 16%, nuclear power for 13%, and other sources for 3% of all electrical energy produced worldwide. Emissions of pollutants and greenhouse gases from fossil fuel-based electricity generation are responsible for a significant portion of world greenhouse gas emissions. Although Solar PV generation is advertized as environmentally friendly, fabrication of

PV cells utilizes large amounts of water in addition to releasing toxic chemicals such as phosphorus and arsenic.

Reliable supply of electric energy is also an important issue. Power outage is regarded as a public emergency as people take the availability of uninterrupted power supply for granted. Electrical energy consumption in a system changes over time due to changes in the power requirements of load devices as well as the users' behaviors. Load-following power plants (for example, fossil fuel power plants) are intended to handle rapid changes in power demands on the power grid. In addition, the grid requires a certain level of operating reserve, which is made up of spinning and non-spinning reserves, in order to prevent blackouts and brownouts. Spinning reserve denotes the on-line extra generating capacity to deal with the peak power demand that can arise for a short period of time. Non-spinning reserve, on the other hand, refers to the off-line additional generating capacity that can be turned on and connected to the power grid after a short delay. Both the spinning and non-spinning reserves require extra capital investment by the utility companies for their generation facility setup and operation. Reserve power generation is generally more costly than the normal operation on the power grid. Some countries have only small reserve margin during the peak hours, which threatens the power supply and demand match and gives rise to risky operating reserve guard banding. This can be remedied by building extra power plants. However, construction of new power plants requires large capital investment and has social and environmental costs.

To tackle the high demand for electric power and reduce the power plant over-provisioning, electrical energy storage systems (ESS) have been proposed [31]. An ESS performs operating reserve management, which is performed by expensive, environmentally unfriendly load-following power plants. In addition, the ESS effectively enhances the power grid stability as well as the availability of renewable power sources such as windmills and photovoltaic (PV) panels. Renewable power sources have unreliable power generation characteristics; the level of power generation of the renewable power sources, such as PV cells and windmills, is heavily dependent on environmental factors (for example, the solar irradiance level or climate conditions). The ESS also resolves the mismatch between the power generation and power consumption times in case of renewable power sources.

Nevertheless, ESS technologies are not ready for large-scale and widespread deployment. The main reason is that in spite of the large variety of ESS technologies, no technology offers sufficient performance in respect of key figures of merit needed of an electrical energy storage medium. For instance, a high-performance ESS should exhibit high cycle-efficiency, high power and energy storage capacity, low cost, high volumetric and/or graviometric density, and long-cycle life. The ESS technology of choice for many applications (especially those requiring high volumetric and/or graviometric density) is battery storage. Different battery technologies, however, have widely different characteristics. Again no single battery can simultaneously achieve all the desired characteristics of a high-performance ESS. Furthermore, no battery technology is in sight that can achieve these characteristics. So the focus is on finding ways to build ESS that comprise of different battery types so as to hide the weaknesses of each battery type, yet presenting the strongest features of each battery type.

It is a practically promising solution to develop system-level design methodology that enhances storage system performance and lifetime through efficient use of the current energy storage technologies. A hybrid ESS (HESS) consists of multiple heterogeneous energy storage elements so as to exploit the unique advantages of each energy storage element while hiding their unique shortcomings by introducing novel storage system architecture and hierarchy along with sophisticated charge management policy and means [124]. The HESS concept is derived in analogy to the computer memory hierarchy employed in computer systems and used to provide low-latency, yet low-cost, access to program and data storage.

However, designing the optimal HESS is not a trivial problem. Simply mixing different types of energy storage elements does not automatically guarantee to make up a high performance ESS. HESS architectural design is a multi-variable multi-objective optimization, and heterogeneity of the energy storage elements explodes the design complexity. It includes both continuous and discrete design parameters and many complex nonlinear models. Management policies of HESS involves in another highly complicated runtime optimization. Therefore, computer-aided design and optimization is a must for the optimal design and operation of the HESS with reasonable time and efforts.

This paper covers a wide range of topics regarding the computer-aided design and runtime management of HESS. The remainder of the paper is organized as follows.

- Section 2 begins with the introduction and evaluation of various types of energy storage elements. We review some of the performance metrics for energy storage elements and compare these elements in terms of these metrics.
- Section 3 introduces the ESS architecture and components in more detail and provides an overview of research work focusing on the ESS.
- From Section 4, we focus on the HESS. We first explain the HESS architecture in analogy with the computer memory hierarchy. Next we discuss various flavors of HESS architectures focusing on energy storage hybridization.
- Section 5 reviews some of the recent work on the systematic optimization of the HESS, including both design-time and runtime optimization schemes that maximize the benefits of the HESS.
- Section 6 provides a survey of applications of the HESS, including the power grid, electric vehicle (EV)/hybrid electric vehicle (HEV), and low-power embedded systems.
- Section 7 concludes this paper by outlining possible future directions for the HESS research and development.

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