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Harvesting-aware charge management in embedded systems equipped with a hybrid electrical energy storage[☆]

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ABSTRACT

A sustainable energy supply trend for portable embedded devices is energy harvesting, although its variability necessitates having energy storage systems (ESSs) besides. Requirements like energy and power capacities motivate the using of two or more complementary ESSs (e.g. battery and supercapacitor) in the form of a hybrid ESS (HESS). The capacity of most ESSs is divided into two instantly available charge (IAC) and instantly unavailable charge (IUC) parts. This paper first defines the concept of effective power as the sum of external applied power and internal charge migration power between IAC and IUC. It then proposes an adaptive charge/discharge management method, aware of energy harvesting, to use the possibilities of storing the surplus harvested energy into the HESS IUC part and extracting that stored energy to face with energy shortage. Simulation results show up to 20% improvements in the system lifetime in comparison to the state-of-the-art HESS charge management policies.

1. Introduction

Emerging technologies like Internet of Things (IoT) provide the possibility of connecting billions of small-scale autonomous devices, for which eternity is a major need. Recent studies [1] emphasize that ambient energy harvesting is a promising strategy to achieve sustainability. Energy harvesting is the conversion of ambient energies from different sources, such as light, radio-frequency, thermal gradients, etc. to the electrical energy. However, the increased power consumption of today's powerful embedded systems, along with the limited capacity and non-idealness of energy storages, as well as the varying nature of environmental energy sources raise major service predictability challenges; further, due to the size and weight constraints [2], using larger energy storages is not a perdurable solution to the issue; therefore, this paper focuses on energy storage management methods.

Variety of IoT application domains need both energy harvesting and subtle energy storage management. A self-powered camera [3] can be used in a monitoring application to periodically take pictures, needing appropriate usage of stored energy to survive in the aforementioned unsafe conditions of energy harvesting. The aim of this study is to extend the lifetime of such systems in the presence of variability in energy harvesting and power load profile.

An accepted approach is to employ one or more energy storage systems (ESSs) to store excessive energy for further use. No energy storage type is ideal for all metrics [4]; rather, each ESS type is suitable for a specific category of applications, depending on the target performance metric, e.g. cycle efficiency, cost per unit capacity, energy density, power density and cycle life. Different ESSs with various characteristics include li-ion batteries, lead acid batteries, fuel cell batteries, capacitors, and supercapacitors. For example, li-

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ion batteries have high energy density, low power density and low cycle life (suitable for electric cars); supercapacitors have low energy density, high power density, and high cycle life (appropriate for street lights) [5]. The hybrid energy storage system (HESS) tries to use a few ESS types to exploit their complementary benefits by considering the application [4]. This motivates to have an appropriate HESS charge management policy to determine the charge/discharge periods of individual EESs.

Considering battery and supercapacitor as two ESSs, their capacity is usually modeled by two separate parts: instantly available charge (IAC) and instantly unavailable charge (IUC) [6,7]. The latter is the part of the ESS charge that cannot be used directly to store charge or to supply the load. The IUC part can be up to 35% of the total ESS capacity [8]. The ESS charge flows between the IAC and IUC parts based on their relative status.

All previous charge management policies try to maximize IAC [9,10], which fail in specific scenarios. Consider a solar energy source under good harvesting conditions, e.g. when it is noon. If IAC is maximized, this part rapidly becomes full and the extra arriving energy is lost. However, if the policy could store the energy in IUC, by accepting that it might not be usable in the short-term, more energy could be stored in the whole ESS, and the IUC part could be used for later usage, e.g. at night. Additional information, including the HESS status, the harvesting condition, and the workload power consumption trace, would be beneficial for making an optimal decision on extending the system lifetime (i.e. the duration with no energy breakdown).

In this paper, we investigate the impact of the charge/discharge scheduling policy on the system lifetime for an embedded system that is equipped with an energy harvester and a HESS. The charge management problem is divided into two sub-problems:

1. **Charge allocation:** when there is excessive harvested energy, how the HESS elements contribute for storing the extra energy?
2. **Charge replacement:** when the harvesting energy is insufficient, how the HESS elements contribute for charge provisioning?

Overall, when a charge/discharge power is applied to the HESS, the proposed charge management policy first determines whether IAC or IUC should be maximized based on the HESS status and energy harvesting prediction. Then, the applied power to the HESS is divided appropriately between the HESS elements. In addition, in the current study, we use relatively accurate battery and supercapacitor models, namely, the kinetic battery model (KiBaM) [6] and the variable leakage resistance (VLR) model [7]. (The current literature on HESS charge management policies assumes ideal [10] or simple [9,11,12] ESS models.) The contributions of this paper can be summarized as follows:

1. Formulating the charge flow power between IAC and IUC of individual ESSs as well as the whole HESS;
2. Proposing the concept of effective power, both for individual EESs and the HESS, as the summation of external applied power and internal charge flow power;
3. Giving the idea of using IUC of each EES as a buffer to store the surplus harvested energy, and use it when the system faces with energy shortage;
4. Maximizing the system lifetime through IAC/IUC charge/discharge management based on the effective power concept, energy harvesting pattern, power consumption trace, and instantaneous HESS status;
5. Adapting the existing state of the art charge/discharge allocation methods with more accurate battery and supercapacitor models (the IAC Maximization method) to be used as comparison baselines in the simulations.

The rest of this paper is organized as follows. Section 2 describes the most related studies to this work. The system model and problem statement are described in Section 3. Section 4 presents the proposed method. Simulation results and the corresponding discussions are presented in Section 5. Finally, the conclusions are drawn in Section 6.

2. Related work

In this section, we review the most closely related works in three categories: 1) efficient charge extraction, 2) harvester-aware energy consumption, and 3) hybrid energy storage systems. Then, we discuss how the current study differs from them.

2.1. Efficient charge extraction

To maximize the extracted charge from the energy storage, the authors of [13] prove that the optimal workload scheduling with regard to the battery is the sequence of tasks in non-increasing order of power usage. Likewise, it is proved in [10] that similar policies work for supercapacitors; they suggest to always execute the highest-power task first. While some researchers use task scheduling to address the non-linear battery characteristics, others suggest battery scheduling [14] when the system consists of multiple batteries. In [15], however, the simultaneous use of task and battery scheduling is proposed. This paper, in addition to ESS scheduling for maximizing the extracted energy from the HESS when it is required, aims at using the IUC part for a second objective, namely for saving the extra harvested energy for future use.

2.2. Harvester-aware energy consumption

Most papers on harvesting-aware energy consumption perform workload scheduling by simultaneous consideration of the load trace and the harvesting pattern. Moser et al. [16] proposed a reward maximization algorithm for executing tasks with some given energy constraints. The Lazy scheduling algorithm [17] additionally accounts for constraints that arise from the time domain. In [7],