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Maximizing the revenues of data centers in regulation market by coordinating with electric vehicles☆

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ABSTRACT

Frequency regulation is a major market service to reduce the undesired imbalance between power supply and demand in the power market. In order to participate in the regulation market, both the supply and demand sides need to be capable of flexibly adjusting their power generation and consumption, respectively. As the scale of Internet data centers is increasing rapidly, their significant power consumption has enabled them to become an important player in the regulation market for maximized profits and thus minimized operating expenses. On the other side, Plug-in Hybrid Electric Vehicles (PHEVs) have also recently been identified as a major participant in the regulation market, due to their large power demand for battery charging.

In this paper, we propose a novel power management scheme that jointly leverages a data center and its employees' PHEVs to (1) maximize the revenues that the data center receives from the regulation market and (2) get the PHEVs charged at no expense to their owners. Our scheme features a two-level hierarchical power control design. At the first level, our scheme interacts with the regulation market to provide information about the data center power consumption on an hourly basis. At the second level, the scheme decides the power budgets for the servers and UPS in the data center, as well as PHEVs, in real time, to follow the given regulation signal. In addition, we show how to leverage the thermal energy storage (TES) tanks available in many data centers to adapt the cooling power consumption for better management of the data center power demand and further increased regulation revenues. We evaluate the proposed scheme with real-world workload and regulation traces. The results show that our scheme performs a high-quality regulation service. As a result, the proposed scheme outperforms several commonly used baselines by having higher regulation revenues, and so lower operating expenses, for the data center. Finally, we analyze the cost savings of the PHEV owners, throughout the lifetime of the PHEVs, by getting their batteries charged at no expense.

1. Introduction

Frequency regulation is a major market service [1] to reduce the undesired imbalance between power supply and demand in the power market. In order to participate in the regulation market, both the supply and demand sides need to be capable of flexibly adjusting their power generation and consumption, respectively. Every few seconds the regulation market sends a regulation signal to the regulation assets according to an agreed regulation capacity [2,3]. Based on capacity range and tracking performance of the signal, participants receive compensation from the market [4–6]. Internet data centers [7,8] and Plug-in Hybrid Electric Vehicles (PHEVs) [9–11] have been recently identified as eligible participants in the regulation market. However, existing work does not consider the possibility to join data centers and PHEVs to maximize frequency regulation profits.

Modern data centers can participate in the regulation market thanks to their ability to flexibly change power consumption. For example, they can (1) change server power consumption with Dynamic Voltage Frequency Scaling (DVFS) [12], (2) manage charge and discharge cycles of Uninterruptible Power Supply (UPS) batteries [13], and (3) turn on/off servers via dynamic capacity provisioning [14]. Moreover, data centers account for 1.5% of total energy demand in US [15]. The percentage is expected to grow up to 8% by 2020 [16]. As the scale of Internet data centers is increasing rapidly, their significant power consumption has enabled them to become an important player in the regulation

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market for maximized profits and thus minimized Operating Expenses (OpEx).

Another way to mitigate the imbalance in the power grid, is offered by electric vehicles. The introduction of these cars is mainly driven by the price increase and by the limited quantity of fossil fuel. PHEVs can play an important role to maintain frequency stability, due to their large power demand for battery charging [10,9]. These cars are typically equipped with a 2–10 kWh battery capacity. For example, if 50 vehicles are charging at the same time and in the same place, there are up to 500 kWh to use for regulation. Assume that in a remote future everyone owns an electric car. A data center's parking lot may have potentially 50–200 small batteries to exploit for frequency regulation [17,18]. The contribution of electric cars, is useful for data centers to further widen the regulation capacity and track the regulation signal. In addition, employees have the opportunity to receive a free charge of their vehicles. In this paper, we propose a novel two level hierarchical power management scheme that jointly leverages a data center and its employees' PHEVs to (1) maximize the revenues that the data center receives from the regulation market, and (2) get the PHEVs charged at no expense to their owners. At the first level, our scheme interacts with the regulation market to provide information about regulation capacity and baseload on an hourly basis. At the second level, the scheme decides the power budgets for servers, UPS, and PHEVs, in real time, to follow the given regulation signal. Our algorithm (1) ensures 24 h of regulation for maximized revenues, (2) respects response time of workload and battery lifetime constraints, (3) ensures an acceptable final state of charge for the vehicles, and (4) offers high quality regulation service. In addition, because the cooling system today represents a big portion of data center power demand, we study how thermal energy storage (TES) devices equipped in many data centers, such as ice tanks or water tanks, can be integrated in the power management scheme to further increase regulation revenues.

The rest of the paper is organized as follow: Section 2 discusses the related work. Section 3 gives some background about regulation market and PHEVs. Section 4 describes our control architecture. Section 5 gives insights about its different components. Section 6 describes how to exploit thermal energy storage in the regulation problem. Section 7 describes the trace files and the baselines used in our simulations. Section 8 shows the results and Section 9 concludes the paper.

2. Related work

Numerous approaches for data center power management have been explored in literature. Lefurgy et al. [19], Wang and Chen [20], and Wang et al. [12] explore the potential of DVFS to accurately track a desired power consumption at server, cluster, and data center level, respectively. Ahmad and Vijaykumar [21] choose which servers to turn on in order to optimize the temperature within a data center. Liu et al. [14] adjust the number of active servers to minimize OpEx. Kontorinis et al. [13] study UPS batteries in different configurations to track a desired power budget at data center level. Urgaonkar et al. [22] charge and discharge batteries according to fluctuation of energy price to minimize OpEx. Different from these papers, we propose to exploit knobs of data centers jointly with PHEVs, to participate in the regulation market.

Regulation market is a service to maintain the instantaneous balance between demand and generation to ensure power grid reliability. Traditionally this service is mainly provided by coal fired generators that come with heavy cost associated with degraded heat rate. Moreover, generators lose opportunities in producing electricity. Some non-traditional resource is also proposed in literature as for example commercial buildings [23] and aggregated residential loads [24]. However, the long response time of commercial buildings limits the potential of these structures as a regulation resource. In addition, the control of residential loads requires expensive metering and communication infrastructures; the expenses of these advanced instruments leave the regulation effort unrewarded. Our paper instead, explores the potentialities to integrate modern data center and electric cars for regulation service.

Few other studies attempt to involve data centers in the regulation market. Wang et al. [7] explore the integration of multiple data centers in the demand response market by migrating virtual machines. Aikema et al. [8] study how a data center can provide different services of the ancillary market with DVFS to reduce costs. Different from existing work, our solution exploits multiple knobs (e.g., DVFS, UPS, and capacity provisioning) of the data center jointly with PHEVs charging rate, to provide high quality regulation service.

Other research projects use PHEVs to minimize frequency imbalance. Tuffner and Kintner-Meyer [10] and Li et al. [25] schedule a smart charge of PHEV batteries to minimize the fluctuations of wind energy. Kempton et al. [9] equip PHEVs with a special mechanism called V2G. This mechanism, besides simply charging batteries, allows the grid to discharge them. However, wind energy is not the only cause of frequency fluctuations and not all the electric cars are equipped with the V2G. Different from previous work, our algorithm directly interacts with regulation market to offer regulation service. Additionally, we only charge the PHEV cars once per day to preserve battery lifetime and to refer to a more common case.

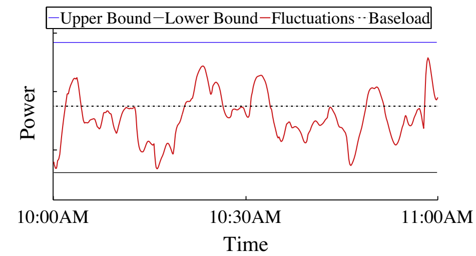

Fig. 1. The regulation signal leads to fluctuations of power consumption around the power baseload.

3. Background

3.1. Regulation market

Regulation market is a kind of ancillary service [26]. It has been created to stabilize the grid frequency (around 60 Hz) when an imbalance between generation and demand occurs. At the beginning of each operation hour, the regulation assets send the baseload power and regulation capacity to the market to characterize the agreed regulation capacity range. Fig. 1 illustrates power baseload and bounds. Regulation capacity is the absolute difference between baseload and higher (or lower) bound. Within each operation hour, participants in regulation service, receive from the market the regulation signal with time step between 2 s and 60 s. This signal is normalized between −1 and 1 and is then elaborated by the assets. For example, if an asset commits 0.1 MW capacity with baseload 1 MW, then a regulation signal with value 0.8 means that the asset has to consume or generate 1.08 MW of power.

Data centers are eligible assets for regulation service because of their high power flexibility and their growing power consumption. Our work shows how to decrease data center's OpEx with frequency regulation without any loss in reliability and performance.