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Potentials and economics of residential thermal loads providing regulation reserve

He Hao [a,*], Borhan M. Sanandaji [a], Kameshwar Poolla [a], Tyrone L. Vincent [b]

[a] *Electrical Engineering and Computer Sciences, University of California, Berkeley, CA 94720, USA*
[b] *Electrical Engineering and Computer Science, Colorado School of Mines, Golden, CO 80401, USA*

HIGHLIGHTS

- We estimate the potential of residential thermal loads for regulation service.
- The potential exceeds regulation needs in the CAISO electricity market.
- We estimate cost and revenue of residential loads providing regulation reserve.
- Regulation reserve using thermal loads is cheaper than other storage technologies.
- We discuss necessary policy changes and customer incentive methods.

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ABSTRACT

Residential Thermostatically Controlled Load (TCLs) such as Air Conditioners (ACs), heat pumps, water heaters, and refrigerators have an enormous thermal storage potential for providing regulation reserve to the grid. In this paper, we study the potential resource and economic analysis of TCLs providing frequency regulation service. In particular, we show that the potential resource of TCLs in California is more than enough for both current and predicted near-future regulation requirements for the California power system. Moreover, we estimate the cost and revenue of TCLs, discuss the qualification requirements, recommended policy changes, and participation incentive methods, and compare TCLs with other energy storage technologies. We show that TCLs are potentially more cost-effective than other energy storage technologies such as flywheels, Li-ion, advanced lead acid, and Zinc Bromide batteries.

1. Introduction

The reliability and stability of the power grid requires continuous balance between supply and demand on a second-to-second basis, which otherwise will result in catastrophic consequences. Ancillary services such as frequency regulation and load following play an important role in achieving this power balance under normal operating conditions. While load following handles more predictable and slower changes in load, frequency regulation mitigates faster changes in system load and corrects unintended fluctuations in generation (Kirby, 2007). Frequency regulation has been traditionally provided by relatively fast-responding generators. However, the ramping rate of these generators is generally slower than that of the regulation signal, which results in poor power quality and high regulation procurement (Kirby, 2007; Texas Energy Storage Alliance,). The regulation requirement can be lowered if faster responding resources are available (Vu et al., 2009). It has been shown if California Independent System Operator (CAISO) dispatched fast responding regulation resources, it could reduce its regulation procurement by as much as 40% (Makarov et al., 2008). This issue has been recognized in the power system community. The recently issued FERC orders 784 and 755 require considering the speed and accuracy of regulation resources when procuring regulation service.

In accordance to FERC order 755, CAISO has introduced a mileage product to provide compensation for faster and more accurate regulation resources (CAISO,). Moreover, CAISO's definition of a Non-Generator Resource (NGR) with Regulation Energy Management (REM) allows NGRs with limited energy capacities, such as batteries and flywheels, to competitively bid in the regulation market. REM resources can bid to provide power based on their 15-minute energy capacity into the day-ahead ancillary service market, and CAISO will dispatch these resources so that their

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[*] Corresponding author.
E-mail address: haohe.cn@gmail.com (H. Hao).

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State of Charge (SoC) limits are respected (CAISO storage,). These regulatory developments have roused a growing interest in tapping the potentials of fast-responding and accurate regulation resources.

In this paper, we show that Thermostatically Controlled Load (TCLs) have a great potential for providing fast regulation service, due to their large population size and the ability of being turned ON/OFF simultaneously. The proof of concept of using TCLs to provide regulation reserve and load following has been reported in Lu (2012), Mathieu et al. (2013a), Kundu et al. (2011), Zhang et al. (2013), and Bashash and Fathy (2013). Other related work include study of commercial HVAC (Heating, Ventilation, and Air-Conditioning) systems, residential pool pumps, and electric vehicles to provide ancillary services to the grid (Lin et al., 2013; Hao et al., 2014a; Oldewurtel et al., 2013; Meyn et al., 2013; Hao and Chen, 2015; Barooah et al., 2015; Kempton et al., 2008; Nayyar et al., 2013). In our recent work (Hao et al., 2013, 2015), we have shown that the aggregate flexibility offered by a collection of TCLs can be succinctly modeled as a generalized battery with dissipation. A similar work that models TCLs as a battery (without dissipation) is given in Mathieu et al. (2013b). Moreover, we analytically characterized the power limits and energy capacity of this battery model in terms of the TCL parameters and exogenous variables such as ambient temperature and user-specified set-points. Based on this battery model, in this paper we estimate the potential of TCLs in California for regulation service provision. We show that conservative estimate of the available power is larger than twice of the current maximum regulation procurement (600 MW). Additionally, it is larger than the predicted maximum regulation requirement of CAISO with 33% of renewable penetration (1.3 GW) (Helman, 2010). Moreover, conservative estimate of the available energy capacity is much larger than the maximum energy requirement for regulation with both the 600 MW and 1.3 GW power procurements. The potential of TCLs in California is more than enough for provision of regulation service for now and the near future.

We further estimate the cost and revenue of TCLs for providing regulation service to the grid. Due to the stringent telemetry and metering requirements of CAISO, the real-time power measurement of each individual TCL is required to be reported to the ISO every 4 s. This requirement imposes a non-trivial cost on each unit to satisfy the qualification requirements. Moreover, CAISO currently requires the minimum resource size to be 0.5 MW, and no aggregation of loads is allowed. We comment that these rules must be changed in order to allow an aggregator to profitably provide regulation service using TCLs in the California regulation market. We also estimate the cost of instrumentation to enable TCLs to provide regulation service, and recommend new policies to integrate power measurement, external control, and communication capabilities into appliance standards to reduce their capital cost. Additionally, we show that the annual revenue per TCL is not very attractive if the total revenue is split evenly to each unit. Therefore, a fair and attractive incentive method needs to be designed to encourage customer participation. Moreover, we compare TCLs with other energy storage technologies that are suitable for frequency regulation. We show that TCLs are more competitive than other storage technologies such as flywheels, Li-ion, advanced lead acid, and Zinc Bromide batteries. However, large scale implementations need to be conducted to showcase the feasibility of this method.

The work of Mathieu et al. (2012), Hao et al. (2014b), MacDonald et al. (2012) is closely related to the present paper. In Mathieu et al. (2012), Hao et al. (2014b), the authors estimated the potential and revenue of TCLs for providing frequency regulation and/or load following services. Different from the work in Mathieu et al. (2012), Hao et al. (2014b) that estimate the revenue based on "pay-by-capacity" scheme in the regulation market, we estimate the potential of TCLs for regulation provision based on the "pay-for-performance" scheme using historic data of CAISO. In MacDonald et al. (2012), the authors reviewed the historic ancillary service price, market size, and discussed the ancillary service qualification requirements for various ISOs in the United States. In this paper, we focus on the regulation market in California, and give more details on the qualification requirements in CAISO for regulation service provision, and recommend certain policy changes to enable TCLs to participate in the CAISO regulation market.

The remainder of the paper unfolds as follows. In Section 2, we present a method of characterizing the aggregate flexibility of TCLs using a generalized battery model. On the basis of this generalized battery model, we study in Section 3 the potential and revenue of TCLs for regulation service provision in California. In Section 4, we estimate the capital cost of TCLs for regulation service provision, discuss the customer incentive methods and qualification requirements, and compare TCLs with other energy storage technologies. In Section 5, we give conclusions and future work, and recommend certain policy changes in order to enable TCLs to participate in the CAISO regulation market.

2. Methods

In this section, we present a method of characterizing the aggregate flexibility of a large collection of TCLs. The central idea is a generalized battery model, which provides a simple, compact, and meaningful representation of the flexibility offered by TCLs. This generalized battery model is the foundation for studying the potential and revenue of TCLs for regulation service provision in the California power system.

2.1. Individual model of TCLs

In this paper, we consider a large collection of Thermostatically Controlled Loads (TCLs). The temperature dynamics of each TCL are described by a standard hybrid-system model:

$$\dot{\theta}(t) = \begin{cases} a(\theta_a - \theta(t)) - bP_m + w, & \text{ON state}, \quad q(t) = 1, \\ a(\theta_a - \theta(t)) + w, & \text{OFF state}, \quad q(t) = 0, \end{cases} \tag{1}$$

where θ is the TCL temperature, θ_a is the ambient temperature, P_m is the rated power, and $a = 1/CR$, $b = \eta/C$ are given in terms of the thermal capacitance C, thermal resistance R, and coefficient of performance η. The term w accounts for external disturbances from occupancy, appliances, and so on. Each TCL has a temperature setpoint θ_r with a hysteretic ON/OFF local control within a temperature band $[\theta_r - \Delta, \theta_r + \Delta]$. The operating state $q(t)$ evolves as

$$\lim_{\epsilon \to 0} q(t+\epsilon) = \begin{cases} q(t), & |\theta(t) - \theta_r| < \Delta, \\ 1 - q(t), & |\theta(t) - \theta_r| = \Delta. \end{cases}$$

The parameters that specify this TCL model are $\chi = (a, b, \theta_a, \theta_r, \Delta, P_m)$. We consider four types of TCLs: AC, heat pump, water heater and refrigerator. Table 1 describes the parameters and their typical values (Mathieu et al., 2012).

The average power consumed by a TCL over a cycle is

$$P_o = \frac{P_m T_{\mathrm{ON}}}{T_{\mathrm{ON}} + T_{\mathrm{OFF}}}, \tag{2}$$

where T_{ON} and T_{OFF} are respectively the time it spends in the ON and OFF states per ON/OFF cycle. For a large collection of TCLs that is uncoordinated, the steady-state power draw will be very close to the summation of their average power consumption, because at