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Equivalent electricity storage capacity of domestic thermostatically controlled loads

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ABSTRACT

A method to quantify the equivalent storage capacity inherent the operation of thermostatically controlled loads (TCLs) is developed. Equivalent storage capacity is defined as the amount of power and electricity consumption which can be deferred or anticipated in time with respect to the baseline consumption (i.e. when no demand side event occurs) without violating temperature limits. The analysis is carried out for 4 common domestic TCLs: an electric space heating system, freezer, fridge, and electric water heater. They are simulated by applying grey-box thermal models identified from measurements. They describe the heat transfer of the considered TCLs as a function of the electric power consumption and environment conditions. To represent typical TCLs operating conditions, Monte Carlo simulations are developed, where models inputs and parameters are sampled from relevant statistical distributions. The analysis provides a way to compare flexible demand against competitive storage technologies. It is intended as a tool for system planners to assess the TCLs potential to support electrical grid operation. In the paper, a comparison of the storage capacity per unit of capital investment cost is performed considering the selected TCLs and two grid-connected battery storage systems (a 720 kVA/500 kWh lithium-ion unit and 15 kVA/120 kWh Vanadium flow redox) is performed.

1. Introduction

Thermostatically controlled loads (TCLs), like electric space heating, air conditioning, water heating, and refrigeration systems, are characterized by a certain level of flexibility in the consumption thanks to their thermal mass, which allows anticipating or deferring their electricity demand without quick alterations of the temperature to regulate. Although the contribution of a single TCL is negligible, the aggregated and coordinated contribution from a large number of units might have relevant size and be able to impact power system operation.

Achieving nondisruptive controllability (i.e., while respecting consumer comfort) of TCLs has often been advocated in the existing technical literature as a way to provide ancillary services to the electrical grid and tackle the challenge of restoring an adequate level of controllability after the displacement of conventional generation in favor of production from renewables. E.g., in Refs. [1–3], TCLs are used to support primary frequency regulation, for voltage regulations in local distribution systems [4], balancing power provision [5,6], peak shaving and self-consumption [7–11].

Despite the blooming of applications for flexible demand, the current literature does not address the problem of defining specific metrics to quantify the intrinsic flexibility of TCLs. This aspect is of fundamental importance for electric power systems planning because it allows designing response programs for TCLs and quantifying the support they can provide to power system ancillary services. On the contrary for grid-connected electrochemical storage devices (like batteries or fuel-cell/electrolyzer systems), the power and energy capacity ratings allows for a straightforward interpretation of the inherent flexibility and enabled the development of advanced planning strategies (see e.g. Refs. [12,13]) as well as quantification of economic pay-back times ([14]). The development of similar metrics for the case of TCLs would allow extending existing technical and economic evaluations to the case of flexible demand as well.

The purpose of this paper is presenting a methodology to quantify the equivalent storage capacity of TLCs as if they were conventional grid-connected storage devices. In general, TCLs and conventional storage devices, besides being based on different technologies, do not have equivalent capabilities: whereas the former requires a baseline consumption to guarantee a minimal consumer comfort, the latter does not, and it can even back-feed

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Nomenclature and abbreviations

Δt	Model simulation sample time (s)
BESS	Battery Energy Storage System
SOC	State of charge
TCL	Thermostatically controlled loads
θ	Set of state-space model parameters
A	Continuous time state-space system matrix
B	Continuous time state-space input matrix
C	Continuous time state-space output matrix
$E^{\downarrow}$	Decrease in electricity consumption with respect to the baseline that a TCL can sustain without violation thermostat bounds (kWh)
$E^{\uparrow}$	Increase in electricity consumption with respect to the baseline that a TCL can sustain without violation thermostat bounds (kWh)
h	Thermostatic control deadband (°C)
i	Discretized time index
P	Nominal TCL power consumption (kW)
$P^{\downarrow}$	Decrease in power consumption that a TCL can achieve (kW)
$P^{\uparrow}$	Increase in power consumption that a TCL can achieve (kW)
Q	Hot water demand (Ls^{-1})
s	Thermostat state
T	(Air or water) TCL Temperature (°C)
T^*	Thermostatic set-point (°C)
T^o	Outside air temperature (°C)
T^r	Room air temperature (°C)
T^w	Inlet water temperature (°C)
$t_i^{\downarrow}$	Time taken by the TCL to pass from T_i to $T^* - h$
$t_i^{\uparrow}$	Time taken by the TCL to pass from T_i to $T^* + h$
u	Continuous time state-space input vector
x	Continuous time state-space vector state

power if enough charge is available (an important characteristics if considering e.g. power systems restoration procedures). Nevertheless, in certain operational contexts, such as implementation of peak shaving strategies or provision of regulating power, their behavior is comparable: in the same way as storage devices achieve to store electricity for later use, flexible demand can postpone the consumption, thus indirectly achieving the same target, even if for a limited amount of time.[1] Therefore, the idea of quantifying the capacity of flexible demand in terms of electricity they can store (equivalent storage capacity) arises naturally in this context, as also considered in Ref. [16].

We contribute to the literature by proposing a methodology to evaluate the equivalent storage capacity of common domestic TCLs. The proposed method is applied to evaluate the flexibility intrinsic the operation of four common domestic TCLs (an electric space heating system, electric water heater, freezer and fridge) thanks to thermal models identified from experimental measurements and Montecarlo simulations to reproduce realistic typical operating conditions. The proposed analysis is a valuable tool for system planners to assess the potential of TCLs to support power system operation, allowing for a straightforward comparison with competitive storage technologies, and understanding the amount of flexibility it is possible to harvest from populations of TCLs in given portion of the networks.

The paper is organized as follows: Section 2 introduce the notation, Section 3 states the operational definition of equivalent storage capacity of TCLs, distinguishing among the cases where TCLs are requested to decrease or increase the consumption, Section 4 describes the modelling approach and Montecarlo simulations, Section 5 is for results and discussion, and finally Section 6 states the conclusions.

2. Preliminaries and notation

As known, a TCL is a device where the state of the active element (like resistors for radiators, or compressors for heat-pump-based loads) can assume two values, *on* or *off*. The thermostat state $s(t)$ at a given time t is determined by a feedback control loop with hysteresis that enables or disables the power consumption when the temperature to regulate falls outside an established dead-band. E.g., for a building space heating TCL, the control law is:

$$s(t) = \begin{cases} \text{on}, & T(t) \leq T^* + h \\ \text{off}, & T(t) > T^* - h \\ s(t - \delta t), & \text{otherwise} \end{cases} \quad (1)$$

where $T(t)$ is the building air temperature, T^* temperature set-point, h temperature hysteresis, and $s(t - \delta t)$ denotes the thermostat previous activation state. Fig. E.1 exemplifies the temperature dynamics of a TCL and is to introduce the notation used in the following formulation. For convenience in the explanation, we assume that Fig. E.1 refers to a TCL for heating application (e.g., space heating), so that the temperature raises when the heating element is active, and vice-versa. Two data points in Fig. E.1 are of special interest and are identified by the Cartesian coordinates (t_x, T_x) and (t_z, T_z):

- Fig. E.1, coordinate (t_x, T_x): the time that the temperature takes to reach the upper thermostatic bound in the case the heater element is kept in the *on* state is denoted by $t_x^{\uparrow}$. Conversely, $t_x^{\downarrow}$ is the time that the temperature takes to reach the lower thermostatic bound if the heating element is switched off. The latter temperature evolution is denoted by the blue dashed line.
- Fig. E.1, coordinate (t_z, T_z): the time that the temperature takes to reach the lower thermostatic bound in the case the heater element is kept in *off* state is denoted by $t_z^{\downarrow}$, whereas $t_z^{\uparrow}$ is the time that the temperature takes to reach the upper thermostatic bound if the heating element is switched on. The latter temperature trend is denoted by the red dotted line.

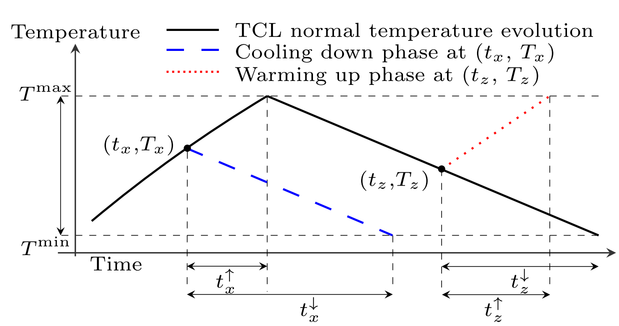

Fig. E.1. Temperature evolution of a TCL, where the notation used in the text is introduced.

[1] An additional concern related to the use of flexible demand is the loss of load diversity after a prolonged demand response event, which causes oscillations of the aggregated power consumption, as e.g. shown in Ref. [15].