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Stochastic modelling of aggregated thermal loads for impact analysis of demand side frequency regulation in the case of Sardinia in 2020

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ABSTRACT

This paper proposes a model of the thermal dynamics and of the end-use of amics and of the end-use of domestic refrigerators (fridges) and water heaters (boilers) in the foretasted scenario of the Sardinian electric network in 2020. This model is employed to evaluate the potential variations of power demand of the aggregates of fridges and boilers during one year in the considered scenario. The resulting quantities can be considered as a form of power reserves to be used for contributing to the frequency regulation through a proper demand side response strategy. The particular case of the system for frequency control proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E) is then analysed by simulations in order to show advantages and drawbacks.

1. Introduction

The wide installation of renewable energy sources (RES) is drastically changing the modern power system. Differently from conventional generation resources, RES are generally not-programmable and distributed. Moreover, they currently do not provide any control service to the grid, such as frequency or voltage regulation. In order to solve this problem, the Transmission System Operators (TSOs) are proposing new grid codes, which call RESs and customer electric loads (CELs) to actively participate to power system control activities [1,2]. In the case of loads, this approach is referred to as Demand Side Response (DSR).

One of the most promising solutions is the provision of frequency regulation services from thermostatically controlled loads (TCLs), such as domestic refrigerators or water heaters [1,3–5]. The basic idea is to temporarily modify the power demand of TCLs in order to support the frequency recovery. This must be operated without compromising the quality of the customers end use, e.g. the temperature of refrigerators or water.

Several different strategies have been proposed by the scientific literature. A first solution is developed in [6] for freezer-fridges in the Great Britain network. Such a solution consists in a linear modification of the temperature set-points in function of the frequency signal. This technique provides an effective initial response to frequency deviations, but it may cause the synchronization of the fridges cooling cycles [7,8]. In [9–12] a population of TCLs is allowed to track arbitrary power profiles avoiding, in this way, synchronization. Usually these approaches are fully or partially centralized and assumes the availability of a real-time communication infrastructure [13]. A fully decentralized solution is proposed in [14], where an aggregate of fridges responses to severe frequency deviations through suitably defined random on/off switching commands. This allows avoiding synchronization but reduces the response capability.

A recent partially decentralized technique is introduced in [7]. This work proposes control solution for modulating the aggregate power consumption of a large collection of TCLs. Stochastic control is employed to enable an unprecedented range of demand response scenarios, without onerous constraints on the communications system. The potential benefits of this technique on the frequency regulation and from the economical point of view is analyzed in [15,16], in the Great Britain network scenario.

A first attempt of grid code update including DSR by TCLs is proposed by the European Network of Transmission System Operators for Electricity (ENTSO-E) in [17]. The ENTSO-E considers both centralized and distributed control but specifies *simply mandatory* rules only for the fully distributed case. Such a solution is strongly criticized in [18], where the authors argue that this implementation choice results in an unpredictable response that depends

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Nomenclature

α	ENTSO-E DSR gain parameter
Δf	grid frequency deviation from the nominal value
Δf_{db}	ENTSO-E DSR frequency (half) dead-band
ΔP_f	fridge thermal load variation
η_i	portion of thermal energy extracted from the fridge i-th thermal mass by the HP
η	efficiency of the boiler HP
γ	coefficient of performance of the fridge HP
ρ	water density
σ	standard deviation of the aggregated model
$\widetilde{T}_o$	average cold water temperature
$A_{i,j}$	area between the fridge i-th and j-th masses
$c^{\%}$	ACSs equipment percentage
f^{nom}	nominal grid frequency
m_i	fridge i-th thermal mass
N	number of sample loads of the aggregated model
P^{nom}	nominal active power of the HP
P^{nom}_{tot}	total active power of a load aggregate
q	thermostat state
R	maximal percentage of fridge load variation
$R_{1,e}$	boiler thermal resistance
S_i	specific heat capacity of the fridge i-th thermal mass
S_w	water specific heating capacity
T^s_{ACS}	average temperature set-point of houses ACSs
T^s_{AHS}	average temperature set-point of houses AHSs
T_a	external ambient temperature
T_e	room temperature
T_i	temperature of the fridge i-th thermal mass
T_o	cold water temperature
$U(a,b)$	uniform distribution in the interval $[a,b]$
$U_{i,j}$	thermal transmittance between the fridge i-th and j-th masses
V	boiler volume
w	water usage
ACS	air cooling system
AHS	air heating system
HP	heat-pump

strongly on the controller details and, furthermore, it restricts the flexibility to implement advanced controllers that deliver multiple services simultaneously. However, it should be noted that literature does not provide any test of the ENTSO-E rules, which could allow the specific analysis of its potential advantages and drawbacks.

A part of the research on DSR is devoted to the development of suitable models of aggregated TCLs in order to study and/or forecast the behaviour of a large population of heterogeneous devices. Some interesting approaches are presented in [6,19–23]. Most of them propose probabilistic models of TCLs aggregates to be used into any fully or partially centralized DSR strategy.

In this research context, the present paper focuses on the analysis of the impact of the mentioned ENTSO-E demand side strategy for TCLs devices on the particular scenario of the Sardinian electric network in a 2020 forecast horizon [24]. Sardinia is one of the Italian regions with the higher penetration of wind and photovoltaic (PV) generation. Moreover, since it is an island, it may suffer from significant frequency variations more often than continental systems. The study considers the cases of domestic refrigerators (fridge/freezer systems) and domestic water heaters (boilers).

Two proper models are developed for representing the thermal dynamics of these two classes of devices. Particular attention is given to the representation of the end-uses, which strongly influence the power demand, especially in the case of boilers. To this end, a suitable stochastic model, based on statistical data, is proposed and employed to evaluate the potential variation of the active power demanded by the aggregate of residential fridges and boilers in Sardinia during one year. These quantities are of particular interest since they provide the dimension of a sort of *equivalent power reserves* that the thermal loads can provide to any DSR program. The monitoring of the single devices is far from being realizable and only few experimental campaigns are provided by literature. The stochastic simulation scheme proposed in this paper could represent a useful tool for evaluating the potential power reserves of fridges and boilers aggregates.

The thermal models are then integrated in the 2020 Sardinian Network, implemented by a proper system software code. Simulations are finally carried out in order to test the potential impact on the frequency regulation of the ENTSO-E DSR strategy. The results show the advantages and drawbacks of the considered technique. Preliminary analyses in the same scenario of the Sardinian network are presented in [25,26].

The paper is organized as follows. Section 2 introduces the aggregated model for domestic refrigerators and water heaters. Section 3 provides the evaluation of the potential variation of the active power demand of fridges and boilers during one year in Sardinia. The performance analysis of the ENTSO-E DSR strategy is presented in Section 4. Finally, concluding remarks are given in Section 5.

2. Stochastic modelling of aggregated residential thermal loads

2.1. Domestic refrigerators

A domestic refrigeration system, hereafter referred to as *fridge*, is composed by a set of thermally coupled masses, as shown in Fig. 1.

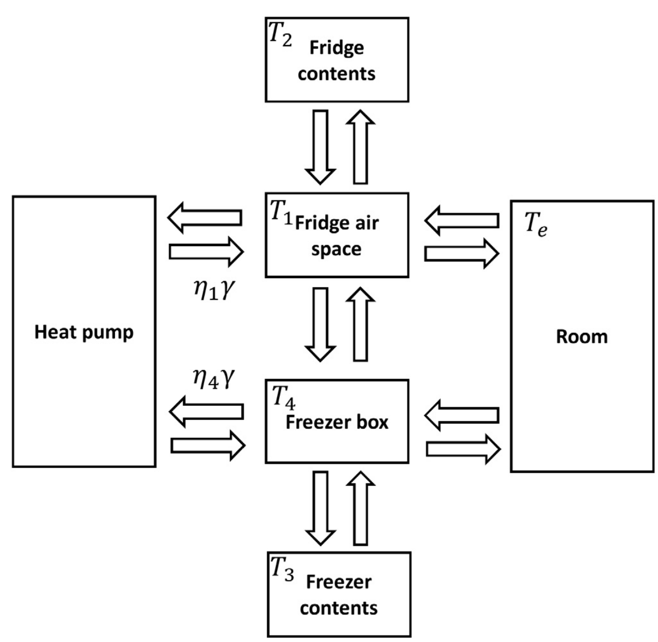

Fig. 1. Simplified thermal model of a refrigerator. Boxes show thermal masses. Arrows show heat flows between the masses.