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Provision of secondary frequency control via demand response activation on thermostatically controlled loads: Solutions and experiences from Denmark

Venkatachalam Lakshmanan, Mattia Marinelli *, Junjie Hu, Henrik W. Bindner

Centre for Electric Power and Energy, Technical University of Denmark, Risø Campus, Roskilde, Denmark

HIGHLIGHTS

- Field experiment with refrigerators to study frequency control by demand response.
- Response time and ramp rate of a population of refrigerators during the control.
- Hybrid experimental setup to verify refrigerators response in an islanded system.
- Ramp rates are compared with Danish grid code for conventional power plants.

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ABSTRACT

This paper studies the provision of secondary frequency control in electric power systems based on demand response (DR) activation on thermostatically controlled loads (TCLs) and quantifies the computation resource constraints for the control of large TCL population. Since TCLs are fast responsive loads, they represent a suitable alternative to conventional sources for providing such control. An experimental investigation with domestic fridges representing the TCLs was conducted in an islanded power system to evaluate the secondary frequency control. The investigation quantifies the flexibility of household fridge performance in terms of response time and ramp-up rate, as well as the impact on fridge temperature and behaviour after the control period. The experimental results show that TCLs are fast responsive loads for DR activation, with the average control signal response time of 24 s and an equivalent ramping rate of 63% per minute, which could also comply with the requirements for primary frequency control.

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1. Introduction

In electric power systems, frequency control relies on the balance between generation and demand. Frequency must always be maintained within the admissible range of its nominal value [1], since it affects the performance and life expectancy of the power system components. For example, the frequency has a direct impact on the speed of asynchronous machines at the demand side and causes a reduction in their efficiency and life span. In modern power systems, electricity production follows demand, and frequency stability is achieved by controlling the generation. As an electric power network grows in capacity and area, its operation is managed by multiple parties: power production by different power plant owners, power distribution by distribution system operators (DSOs), and power system balance by transmission system operators (TSOs). Frequency control in a conventional electric grid can be classified into primary, secondary and tertiary components. Primary control is achieved via the droop control of the generators [2]. Power plants are responsible for providing primary control as per the response time specified by the TSOs' grid code. As any additional demand must be supplied immediately in order to arrest further frequency deviation, the primary frequency control acts typically within seconds [2,3]. Secondary frequency control restores the frequency to nominal system frequency, i.e. the steady state error in the frequency is eliminated. Secondary frequency control is achieved by TSOs through automatic generation control (AGC) [4]. The TSO establishes contracts for secondary frequency control with balance responsible parties (BRP), who must then obey the TSO's AGC signal. Each BRP's production facility must also comply with the ramp rate specifications of the grid code provided by the TSO. An illustration of frequency deviation and frequency control by different reserves is shown in Fig. 1 [5]. As shown in the figure, secondary reserves are activated in minutes

* Corresponding author.
E-mail address: matm@elektro.dtu.dk (M. Marinelli).

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Abbreviations

AGC	automatic generation control
BRP	balance responsible party
COP	coefficient of performance
DR	demand response
DSO	distribution system operator
EWH	electric water heaters
HVAC	heating ventilation and air conditioning
ICT	information and communications technology
RES	renewable energy sources
SLA	service level agreement
TCL	thermostatically controlled load
TSO	transmission system operator
V2G	vehicle to grid

to upregulate the frequency to the nominal frequency. Once the system frequency is restored to the nominal operating frequency by the secondary reserves, the primary reserves are restored and the system operator plans new power dispatch schedule as per the latest power system operating conditions [6]. The tertiary control, activated manually and centrally at the TSO control center, aims to restore the operating reserve, or to anticipate on expected imbalances. Typically, the activation time is from 15 min up to several hours [7]. The tertiary reserves are activated in the new schedule to restore the secondary reserves. The power system operator has the freedom to decide when the tertiary reserves have to be activated [6].

In recent years, the adverse impact of greenhouse gases on the environment has created an awareness to reduce carbon footprints in every part of the world. For example, Denmark has the goal of fossil-free energy usage in every sector, including transportation, by the year 2050 [8]. As energy industries are being pushed to reduce carbon footprints, the focus for energy sources is shifting towards green and environmentally friendly renewable energies. Future power systems will thus have to cope with the high penetration and participation of renewable energy sources (RESs). RESs such as solar and wind are ephemeral due to their nature and this is reflected in their production [9]. Ref. [10] discusses the power system frequency response due to the combined effect of high penetration of wind and solar energy sources in the power system. One very obvious option is to balance RES fluctuations via the use of conventional generation units using AGC. The other option would be to adjust the demand side to match production. Demand response (DR) is typically employed to improve power system efficiency in such scenarios [11], with the end consumer motivated to adjust their demand in response to a signal, such as control/price signal.

DR programs mainly focus on three sectors: industrial, commercial and domestic [11–13]. In the industrial and commercial sectors, the demand that could be adjusted by a single entity is very large in comparison to that in the residential sector [14]. The focus in the industrial sector is placed on improving efficiency and energy shift from one time of day to another [11]. For power system stability control via DR, a requirement for load reduction may occur at any time and thus loads must respond sufficiently rapidly to meet the control time requirements. Here the residential sector could provide support; although the demand adjusted in a single household is very small, the total aggregated demand from multiple households will be large [15–18]. For power system operators such as TSOs, it is a challenge to aggregate small loads from multiple consumers and to remain in control. A new type of business entity known as an aggregator can act as a bridge between power system operators and consumers [19–21] by installing the required infrastructure for appliance control at the consumer premises, and trade the available capacity with the TSO. Aggregator consumer commitments are covered by a service level agreement (SLA) between two parties [22,23], with the aggregators delivering the service provided by the BRP by reducing the load based on the application of DR on consumer controllable loads. An illustration of aggregators playing the role of BRPs is shown in Fig. 2, which represents a simplified scenario of power system set-up with demand side management as presented in [24].

The service offered by appliances to consumers should not be affected even if their operation is interrupted by power system stability control processes, such as secondary frequency control. Thermostatic controlled loads (TCLs) such as heating ventilation and cooling (HVAC) and electric water heaters (EWH) are considered highly suitable for such applications [25,26] due to their fast response [27] and their thermal inertia property. Chillers in both

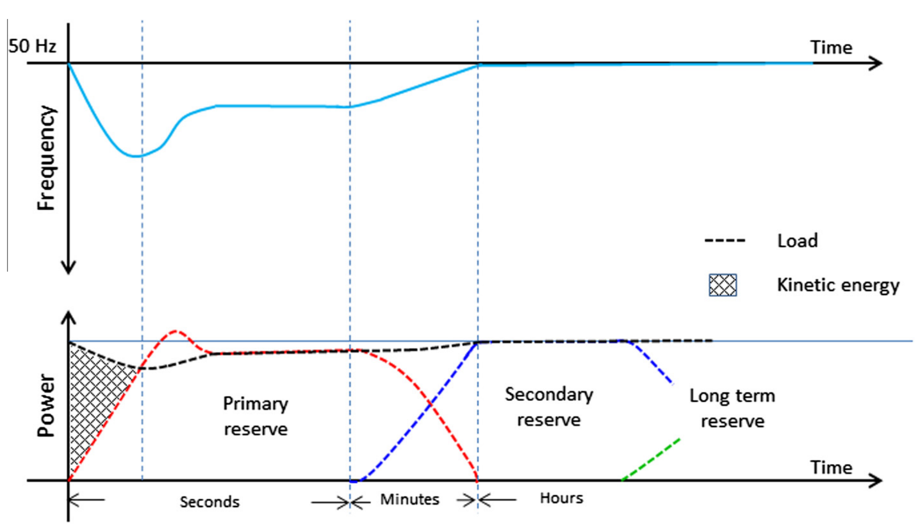

Fig. 1. Primary and secondary frequency control and their response times.

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