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

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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.

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

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Abbreviations

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

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

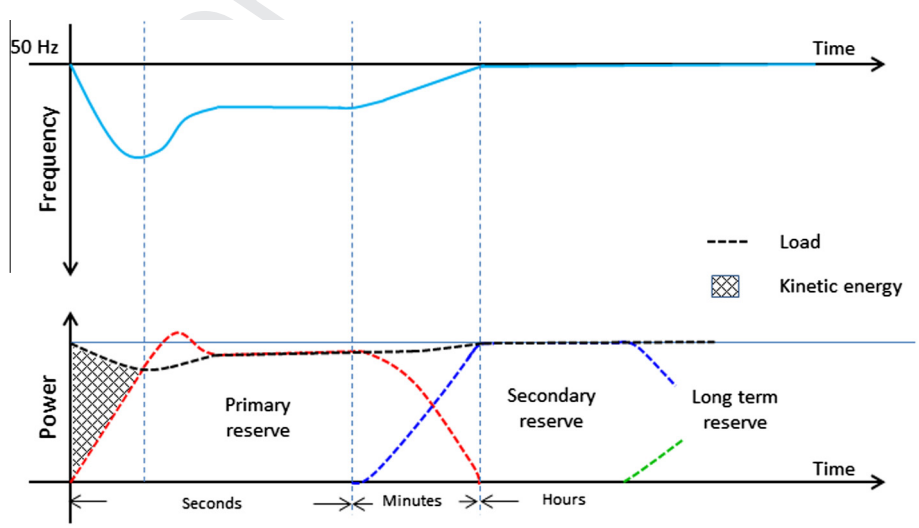

Fig. 1. Primary and secondary frequency control and their response times.

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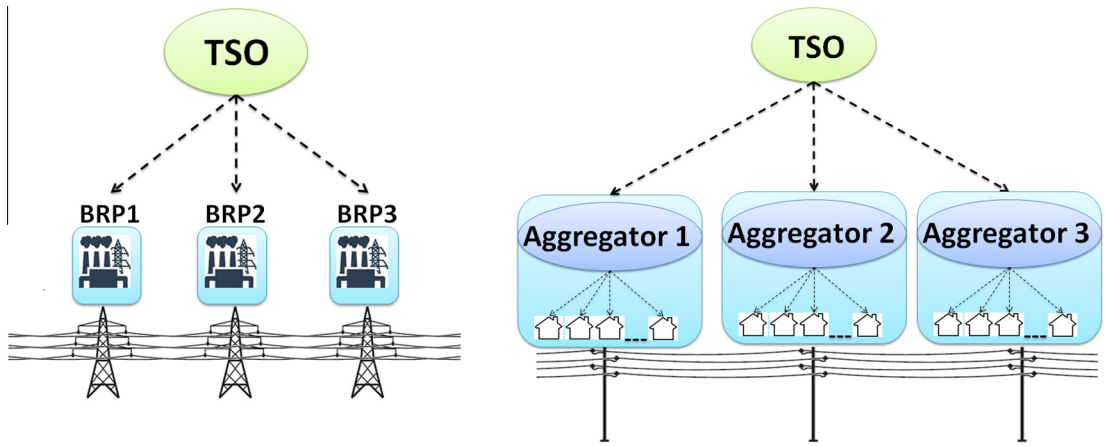

Fig. 2. Secondary frequency control with AGC of BRP units and with DR activation by different aggregators.

commercial and residential buildings are examined for use in smart grid DR application in [28], while refrigerators are easy to work with in order to analyse and validate TCL DR application for smart grid purposes [29–35]. The thermal resistance of the refrigerators ranges from 1.3 to 1.98 K/W [35,36] and the thermal capacity ranges from 1 to 5 Wh/K [35] depending on their size (50–350 L), capacity, amount of food inside and the material used for the refrigerator walls. Therefore the thermal time constant of the refrigerator is in the range of 1.3–9.9 h. In terms of Danish electricity demand, refrigerators and freezers contribute 18% of total domestic electricity demand and are regarded as important demand responses in the smart grid [37]. A black-box model [30] and a grey-box model [35] of refrigerators have been developed for smart grid application and their flexibility for DR application are analysed in [31,35]. Simulation studies investigating grid frequency stability with respect to residential TCL appliance demand response are presented in [29]. In a simulation study presented in [33,34], refrigerators are considered for the management of RES supply fluctuation.

The aim of the present work was to investigate the potential of secondary frequency control via DR activation on TCLs, using domestic refrigerators as an example. The investigation expected to quantify the flexibility of household TCL performance in terms of response time and ramp up rate, as well as the impact on TCL temperature and behaviour after a control period. An experimental investigation with domestic fridges used by real customers was conducted, taking into account the unknown users' behaviour, with the adaptive fridge model presented in [30] used to predict fridge behaviour for their selection and subsequent control.

The rest of this paper is organised as follows. Section 2 introduces the developed method of secondary frequency control and an outline of the studied problem. Section 3 presents the experimental platform, the hardware devices used for control and measurement, and their configuration. Section 4 provides a detailed discussion of the control strategy, practical limitations and safety constraints. The results of the experiments are reported in Section 5 and discussed in Section 6, and conclusions and future work are reported in Section 7.

2. Methodology

A refrigerator is essentially a climate – (in this case temperature) – controlled box containing a thermally insulated chamber (cool chamber) fitted with a compressor to pump heat and a thermostat to control compressor operation. The thermostat maintains the temperature inside the cool chamber between two limits, namely T_{max} and T_{min}. When the temperature is above T_{max}, the thermostat switches the compressor ON; the compressor then pumps heat from the cool chamber to the ambient and the temperature inside the cool chamber is reduced. As the temperature decreases to T_{min}, the thermostat switches the compressor OFF; the temperature inside the cool chamber then starts to increase due to heat flow from the ambient into the cool chamber through the walls and during refrigerator door opening for food exchange. The duration of these thermostatic cycles for heating and cooling depends on many parameters. For example, the cooling cycle length required to reach T_{min} from T_{max} depends on compressor power and its coefficient of performance (COP), ambient temperature, the refrigerator wall's thermal insulation, and the thermal mass of the cool chamber's content. The duration of heating required to reach T_{max} from T_{min} depends on the same parameters as above with the exception of those related to the compressor. As a refrigerator has the ability to store the temperature effect with its thermal inertia, this can be used to provide secondary frequency control.

The method described here introduces load disturbance into a balanced islanded system in order to create steady state frequency error, as shown in Fig. 3. The frequency controller reduces the load by switching the refrigerators OFF to perform secondary frequency control and thus bring system frequency back to the nominal value. The time required for the frequency to attain its nominal value depends on the inertia of the power system and the load imbalance, with the greater the load reduction, the smaller the amount of time required to restore the frequency. The proposed method reduces the load in steps. In order to sustain the effect of load reduction, refrigerator selection is based on their ability to stay OFF for longer. Refrigerator OFF time is calculated using the black box model described in [30], which considers the temperature curves of the thermostatic cycles as piece-wise linear, and uses the slopes of temperature curves from previous thermostatic cycles to predict the present cycle's OFF time. The black box model is a generalised model for any TCL and has been validated for different types of refrigerator [30], with model prediction errors within 5% under normal conditions [31].

3. Experimental procedure

The experimental setup used for secondary frequency control is explained in this section, including details of the test grid formed, a description of the information and communication technology (ICT) infrastructure supporting the experiment, and a description of the collected measurements.

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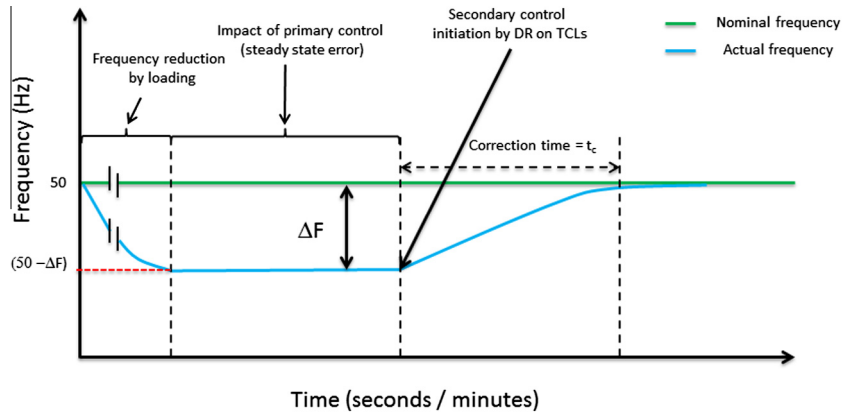

Fig. 3. Illustration of secondary frequency control via DR activation.

3.1. Experimental setup

The experiment was designed to study secondary frequency control by controlling refrigerators. Regarding frequency deviations, especially for those toward low frequencies, balance responsible parties were asked by the TSO to provide the additional power required to bring the frequency back to the normal value. The power flow in the Nordic synchronous zone, of which Denmark is a part, is close to 45 GW [38], with the DK1 region (Western Denmark) possessing a generation capacity close to 6000 MW and a power regulation capacity close to 750 MW [39]. The regulation capacity available for the refrigerators participating in the experiment was 1.25 kW, which is negligibly low in comparison to the DK1 power grid capacity and thus it was not feasible to visualise the frequency restoration process with the refrigerator control if the experiment was conducted using the grid connection. Therefore, the experiment was conducted in an islanded grid with a capacity of 12 kW, which is comparable to the available refrigerator regulating power of 1.25 kW. The experiment was conducted in an islanded LV network in the SYSLAB facility at the Technical University of Denmark (DTU), with a vanadium battery bank as the load and a 48 kW/60 kVA diesel generator as the source. A network configuration block diagram is shown in Fig. 4. The SYSLAB islanded low voltage grid is formed by connecting two busbars in series to a 200 kVA distribution transformer through a circuit breaker, which is opened in order to island the system. Busbar 1 has the diesel generator and the 200 kVA transformer, while busbar 2 has a vanadium battery in order to emulate refrigerator consumption and to provide base load and load variations. The information gathered from every house is fridge temperature and power, regardless the fridge is controlled or not. The temperature, power and control messages exchange between the controller and the houses are shown in Fig. 4.

3.2. Refrigerator emulation in the SYSLAB LV islanded network

In project INCAP, an ICT infrastructure for the real-time measurement and control of the temperature and power of domestic fridges located in real households in Denmark is implemented. INCAP (Inducing consumer adoption of automated reaction tech-

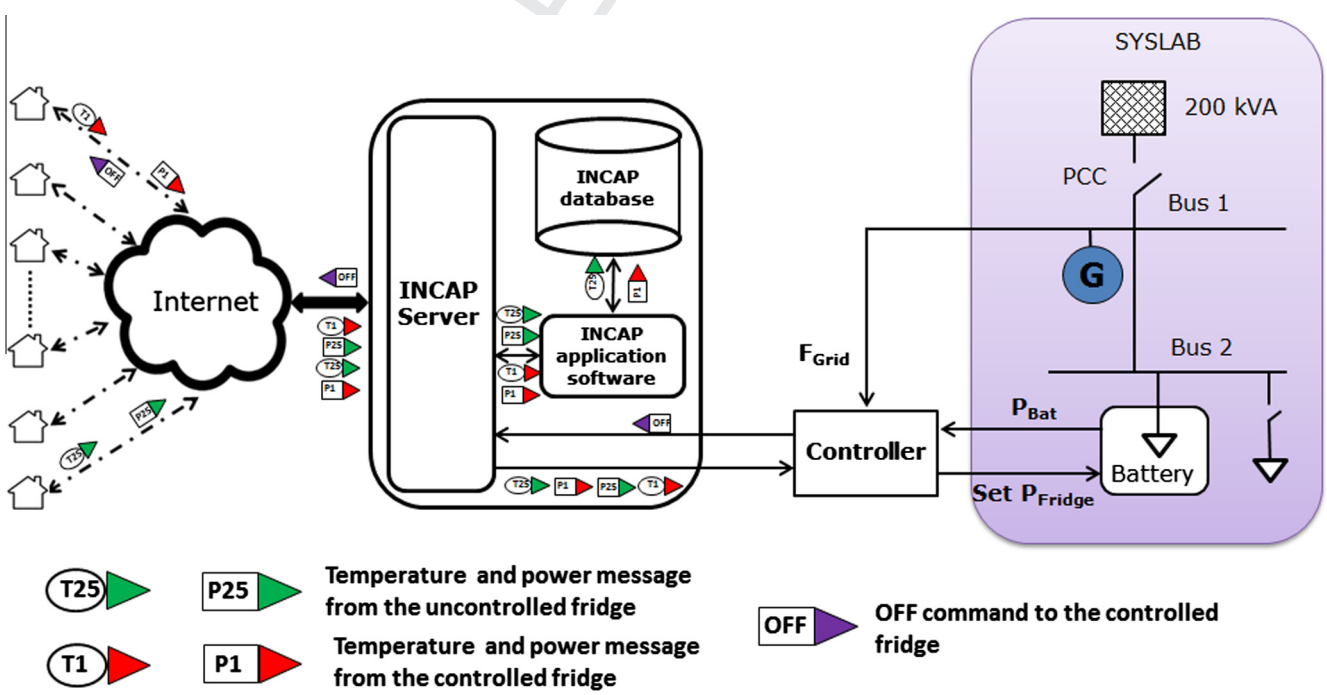

Fig. 4. Block diagram of the experimental setup.

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nology for dynamic power pricing tariffs), is a research project funded by Danish Council for Strategic Research. The main objective of the project is to analyse user behaviour in relation to flexible power demand at domestic household level. Domestic refrigerator is selected for control in this project, as it is commonly available in every household and it is cyclic operation makes it available all day for control. As the real time measurement and control of fridges is viable, those fridges can be emulated in the SYSLAB LV grid by the vanadium battery. Refrigerator emulation is carried out by changing the vanadium battery charging set point with the aggregated power consumption of all refrigerators, with the latter value calculated by summing the active power measurements sent via relay unit to the INCAP server. Data flow from every household participating in the INCAP project to the INCAP server is shown in Fig. 4.

3.3. INCAP fridge data and control access

The devices connected to each refrigerator participating in the INCAP project are shown in the block diagram presented in Fig. 5, with the control, measurement and user interface devices listed as follows:

1. *Control device:* A 'relay unit' with a power measurement function is used to control the refrigerator. The relay unit not only switches the refrigerator ON and OFF in response to the respective command from the remote computer, but also has the ability to measure and transmit active power, voltage and current.
2. *Sensor:* A temperature sensor is used to measure the temperature of the fridge cool chamber.
3. *User interface:* A user interface device with red and green lights and two buttons is used to communicate with the user.
4. *Communication device:* All of the above devices use Zigbee wireless protocol for communication. A Zigbee Ethernet gateway device enables interaction between these devices and the remote server.

All of the above devices are commercially available from Develco Products A/S, one of the official partners of project INCAP. An ADSL home Internet connection is used to establish communication with the control server. Two of the devices, namely the temperature sensor and the user interface device, are battery powered, while the other two are mains supply powered. Device installation is simple and can be carried out by the refrigerator owner. Upon installation, devices identify the control centre server and obtain authorisation to join the Zigbee network.

3.4. Measurement parameters and sampling rate

As the temperature sensor is battery operated, the manufacturer preconfigured the transmission rate. The temperature sensor is configured to transmit temperature measurements at 2-min intervals, which is considered sufficient as refrigerator temperature changes very slowly due to thermal inertia. The temperature sensor has an accuracy of ±0.5 °C. Active power consumption by the refrigerator is measured by the relay unit at 1 watt resolution every 10 s.

SYSLAB grid power measurements: SYSLAB is equipped with the multi-instrument MIC-2 (DEIF A/S) for all grid parameter measurements. MIC-2 has a standard Ethernet interface, which is here connected to the SYSLAB SCADA system, and is classified as belonging to accuracy class 0.2. SYSLAB SCADA can be polled for power measurements of the diesel generator and vanadium battery bank, as well as the frequency of the islanded network. Each measurement in SYSLAB is recorded every second.

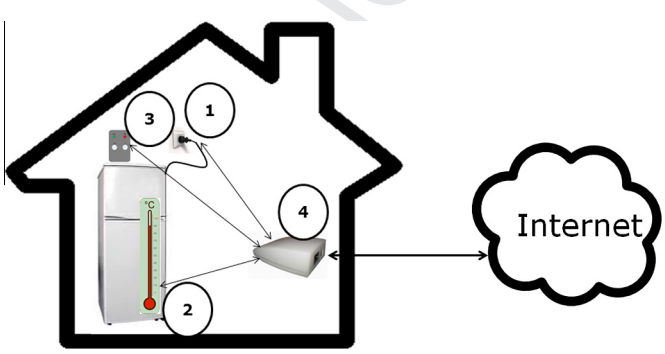

Fig. 5. Refrigerator control device installation in a house.

4. System set up description

4.1. Islanded system set up

The balanced islanded network comprises a diesel generator running in fixed power mode and with the loads matching the power production. Initial system balance is achieved via the following steps:

1. The SYSLAB LV network is connected to the external grid.
2. The loads are configured for a total consumption of 11.7 kW and by considering 0.3 kW line losses, that leads to an overall power consumption of 12.0 kW.
3. The generator is started, with a fixed power output set point of 12.0 kW.
4. Islanding – Once the generator is stabilised with the configured power production, the circuit breaker to the external grid is opened to form the islanded network.

In order to study secondary frequency control based on TCLs, the frequency must drop and stabilise at a lower value due to additional load in the network. It is assumed that the primary frequency control manages to supply additional power to stabilise the frequency at a lower value without allowing any further frequency drop. Primary control can be realised by limiting the additional load duration until the frequency is lowered to the required value. Other than the additional load serving a disturbance, the system must be in balance.

The aggregated power from the refrigerators varies as the status of individual refrigerators changes with their temperature and thermostat status. Considering the small population of refrigerators in the system, the change in aggregated power is sufficient to disturb system stability. Therefore, a base load with variations is added to keep the total load value constant. The base load is retained with the last value before the secondary frequency controller is started. The reason for balancing the system with a flat battery profile is to create the same initial conditions for all the series of experiments. In this way the results of each trial can be systematically compared.

4.2. Controller description

The controller has two functions: (1) Refrigerator emulation as described in Section 3.2. (2) System balance and frequency restoration. The frequency correction loop of the controller runs at 30-s intervals. During frequency correction, the controller calculates the difference between system frequency and nominal frequency (50 Hz). If the former is less than 49.5 Hz, load reduction is initiated. For load reduction, the controller switches off the refrigerators one by one until the specified reduction limit is reached. The

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order of refrigerator selection is based on their ability to stay OFF without violating the temperature limit, with that able to remain OFF for the longest time being selected first. The length of time a refrigerator can stay OFF is predicted by using the refrigerator model described in [30].

The model uses the slopes of the temperature curves when the compressor is ON and OFF to predict the length of OFF time. These slopes are derived from the most recent compressor cycles, which are identified based on power consumption. Unlike the compressor, the refrigerator light bulb and electronic controllers consume only a few watts of power; as a result a 30-watt threshold is used to separate compressor power consumption from that of the refrigerator auxiliaries.

The control procedure for secondary frequency control is given in the following Algorithm 1.

Algorithm 1. Frequency control algorithm

```
Initialisation:
  mark all fridges not active for service
  create an empty scheduling queue
Procedure 1:
  for all fridges{
    get fridge cool chamber temperature
    if fridge is activated for service{
      if temperature above T_max{
        turn the fridge ON
      }
      else{
        turn the fridge OFF
      }
    }
    else{
      put the fridge into the scheduling queue
      sort scheduling queue descending by length of OFF time
    }
  }
Procedure 2:
if frequency is lower than the 50 Hz{
  mark power reduction of 300 W
  while power reduction is smaller than 300 W{
    get the first fridge from the scheduling queue
    mark the fridge to be activated for service
    subtract the fridge power from the power reduction
  }
}
```

The controller runs two procedures in parallel: Procedure 1 manages refrigerator operation and procedure 2 manages the frequency control by selecting fridges to be turned off in order to deliver the power reduction.

4.3. Control task timings

During the first 10 min after initiation, the controller program executes those tasks related to refrigerator emulation, base charging value adjustment for system balance, OFF time calculation for active refrigerators, and resource queue preparation. These first 10 min are required in order to prepare the islanded network, to lower the system frequency, and to collect refrigerator temperature and power data. The battery charge set point is adjusted every second with the aggregated value of power measurements received from the refrigerators. The OFF time calculation for active refrigerators is carried out for every temperature measurement update received from each refrigerator. After the 10 min have elapsed, frequency control is activated, with the estimated maximum time delay for control action being 20 s, and 30 s (t_W) allowed for the power system to respond to the load change. Therefore, frequency correction is carried out at 50-s intervals.

5. Experimental results

The experiment was conducted using 25 refrigerators with a total compressor power consumption capacity of 2500 W. Due to their thermostatic cycles, some of the refrigerators were OFF. Average power consumption was around 1250 W, with power reduction planned in steps of 300 W, or around 25% of the available load for control. Before starting the experiment, refrigerator temperatures and power consumption were recorded until at least one thermostatic cycle of all refrigerators was completed. This observation was necessary in order for the black box model to calculate the switch OFF time for each refrigerator upon receiving the temperature measurement from the corresponding refrigerator. The vanadium battery and controllable resistive load were then connected to the SYSLAB network, with the controller program initiated to emulate refrigerator consumption by changing the vanadium battery's charging set point. The diesel generator was configured to produce fixed power at 25% of generator nominal capacity of 48 kW, or 12 kW, and was connected to the network for synchronisation to the nominal power system frequency of 50 Hz. As the aggregated power consumption of the refrigerators was close to 10% of the generator set point (i.e., 1.2 kW), a base, constant charging value was added. After the synchronisation of the generator with the grid frequency, the SYSLAB network was islanded from the external grid.

5.1. Controlled frequency reduction

Once the network was islanded, the system frequency was brought down via additional loading, with the controllable resistive load set to consume 1 kW for 60 s. Based on a fixed power set point, the generator droop controller was disabled, causing the frequency to drop. In the power system, as the load increases, the system frequency starts to decrease. The primary reserves produce the additional power on load variations and thus the system frequency stabilises at a lower value rather than reducing further. In the experimental set up, there was no primary reserve. Therefore, the controllable load was manually disabled as soon as the system frequency reached 49 Hz. At this instant the system was in power balance in terms of production and consumption, and the system frequency was stable at the lower value.

5.2. Secondary frequency control

The control action for secondary frequency control was initiated after 600 s, with the controller checking the difference between system frequency and nominal frequency (50 Hz). If the difference was greater than 0.5 Hz, a 300 W load reduction was scheduled. Fridges were prioritised according to their OFF time, with the longer the OFF time the higher the priority. Those refrigerators corresponding to the power limit of 300 W were marked OFF, and the switch off command sent in response to the reception of power measurement data. The maximum round trip delay in sending the command, receiving the updated power measurement value and the change in battery charge power set point value was 20 s. After the load reduction, a 30-s response time was allowed for the system to respond to the frequency control. The frequency control loop was executed at 50-s intervals.

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5.3. System response

The power system parameters during the experiment are shown in Fig. 6, in which plot – (a) shows the system frequency, plot – (b) refrigerator power consumption during the experiment, and plot – (c) the power flow in the network. At between 480 and 540 s, the system was loaded with an additional load of 1 kW, as seen in plot – (c) (Power flow in the network) of Fig. 7. System frequency decreased, with the length of time required for a decrease of 1 Hz being 60 s.

Frequency correction took place in two steps, as shown in Fig. 7. In the first iteration, although the target power reduction was 300 W, the actual reduction, P_{R1}, was 360 W due to the granularity of the aggregated power. This granularity was, however, limited to the last refrigerator compressor power capacity selected for load reduction in each frequency correction iteration. The round trip control delay or response time for the first correction iteration is marked as t_R1 in Fig. 7, and was here equal to 23 s. As the frequency did not reach the threshold limit after the delay of 30 s t_W as shown in the Fig. 7, the second correction iteration was initiated. The second iteration is effective after a total delay of 56 s (i.e., $t_w + t_{R2}$) at 650th second. The power reduced, P_{R2}, after the second iteration was 360 W, with the round trip control delay or response time for the second correction iteration marked as t_R2 in Fig. 7 and equal to 26 s. The total time required for the system to restore a nominal system frequency of 50 Hz was 117 s, shown in Fig. 7 as f_{ct}.

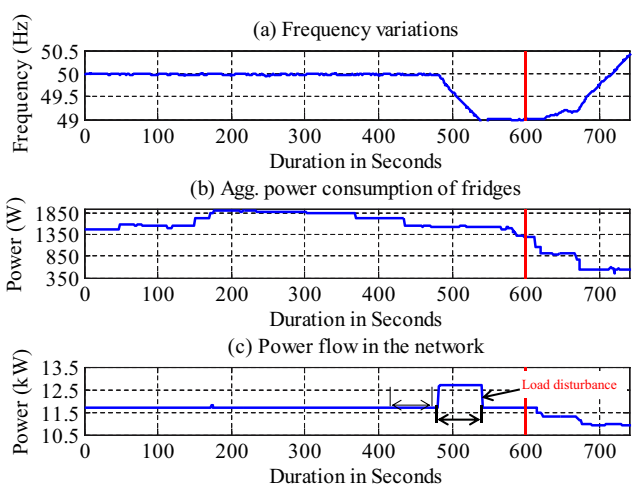

Fig. 6. System frequency, aggregated fridge power, and power flow in the network.

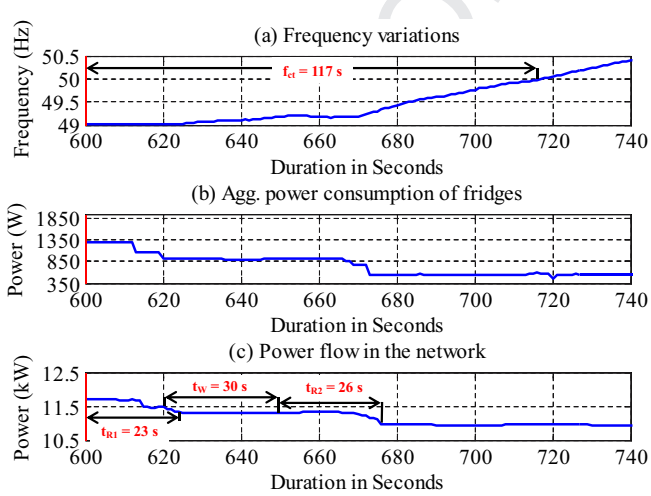

Fig. 7. Close-up view of the secondary frequency control period.

6. Discussion

6.1. Response time

The response time is calculated as a total time in seconds between the time instants of the control action initiation and the time instant when the vanadium battery power consumption reaches the stable value after power reduction as marked in the plot – (b) of Fig. 7. The response time can be broken into three parts as a. Controller delay, b. Command dispatch delay and communication delay over internet, and c. Status update delay and.

6.1.1. Controller delay

The frequency controller compares the measured frequency value with the nominal value and marks the refrigerators to be switched off in the scheduling queue maintained in the controller. The switch-off commands are dispatched to the individual refrigerators as a response to their power measurement message.

6.1.2. Command dispatch delay

The switch off command is sent to the individual refrigerators as a response to the power measurement message from the corresponding refrigerator. Here the power measurement information is used as flag for assessing the status of the refrigerator. The maximum delay in command dispatch is 10 s in the INCAP measurement setup. The communication delay over internet is within 1 s.

6.1.3. Status update delay

The status update delay has two components: refrigerator response time and islanded system response time.

6.1.3.1. Refrigerator response time. The refrigerator response time is the time between the command dispatch and the latest power measurement from the refrigerator after the command dispatch. In INCAP measurement setup, this delay is 10 s.

6.1.3.2. Islanded system response time. The islanded system response time is the response time of the battery and other related communication components in SYSLAB to change the set point of the battery charging power.

In real system, with the present INCAP setup, the status update delay will not appear. Therefore, the response time will solely depend on the command dispatch delay which is in the range of 0–10 s. The experiments are repeated for 8 times to evaluate the consistency of the frequency recovery and the refrigerators behaviour. The system response is shown in the Fig. 8. The result from each trial of the experiment is given in the Table 1.

The power reductions during some of the trials are less than 300 W. The refrigerator compressor power consumption varies depending on the temperature difference between the cool chamber and the ambient (more precisely the temperature around evaporator and the condenser). Fig. 9 shows temperature and power consumption for two cooling cycles recorded from a domestic refrigerator in seconds time scale. From the measurements, it is evident that the variations in the power consumption are up to 30% from the nominal compressor rating. The algorithm used in the experiment uses the nominal rating of the compressor when the load reduction is scheduled. In the reality the actual power consumption by the compressor could be less than the nominal consumption. Therefore there is a difference in the scheduled and actual power reduction (see Table 2).

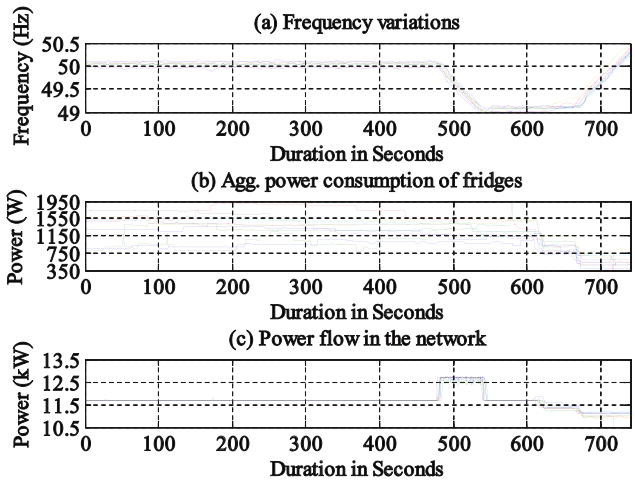

Fig. 8. System response for 8 iterations.

Table 1
Response times and power reduction.

Trial	t_{R1} (s)	P_{R1} (W)	t_{R2} (s)	P_{R2} (W)	Total response time (S)
1	23	360	26	360	117
2	25	300	25	320	121
3	24	250	26	370	121
4	23	270	23	270	127
5	18	230	20	250	120
6	22	400	26	310	109
7	26	340	26	310	124
8	25	400	23	250	122

6.2. DR resource upscaling

When the system is used with higher population of refrigerators, the performance of the temperature prediction algorithm and the resource sorting algorithm will decrease with the number of refrigerators. A simulation study with different large number of refrigerator populations are carried out and the performances are mentioned in the following Table 3. The refrigerators' temperature cycle length is assumed with a maximum value of 60 min to calculate the performance of temperature prediction algorithm. The resource sorting method used here a simple method to sort an array of number corresponding to the number of refrigerators. The maximum sorting time is simulated by reversing the array with ascending numbers representing the resource flexibility (switch-off time). Though the computational power of the computer used is a major factor for computational delay, the calculated times will give an indicative representation.

The time required for sorting the resources is increasing with the increase in the number of refrigerators. Therefore, the sorting technique used and the number of times the resource sorting is carried out in a scenario of large population of refrigerators will be one of the major factors determining the performance.

Table 2
Computational delays.

Number of fridges	Time for temperature prediction (ms)	Time for resource sorting (ms)
1,000	1	5
10,000	2	80
100,000	5	7609
1,000,000	21	906,146

Table 3
Effect of control on aggregated refrigerator power.

Parameter	Secondary frequency control	
	Experimental values	Grid code for DK1 [7]
Average control response time (s)	24	900
Ramp rate (%/min)	63	10 (Gas 20–100%) 20 (Diesel 20–100%)

6.3. Control impact on fridge temperature and population

Fig. 10 displays, along with the frequency variations, the number of refrigerators active during the experiment and the instantaneous temperature average of all 25 refrigerators.

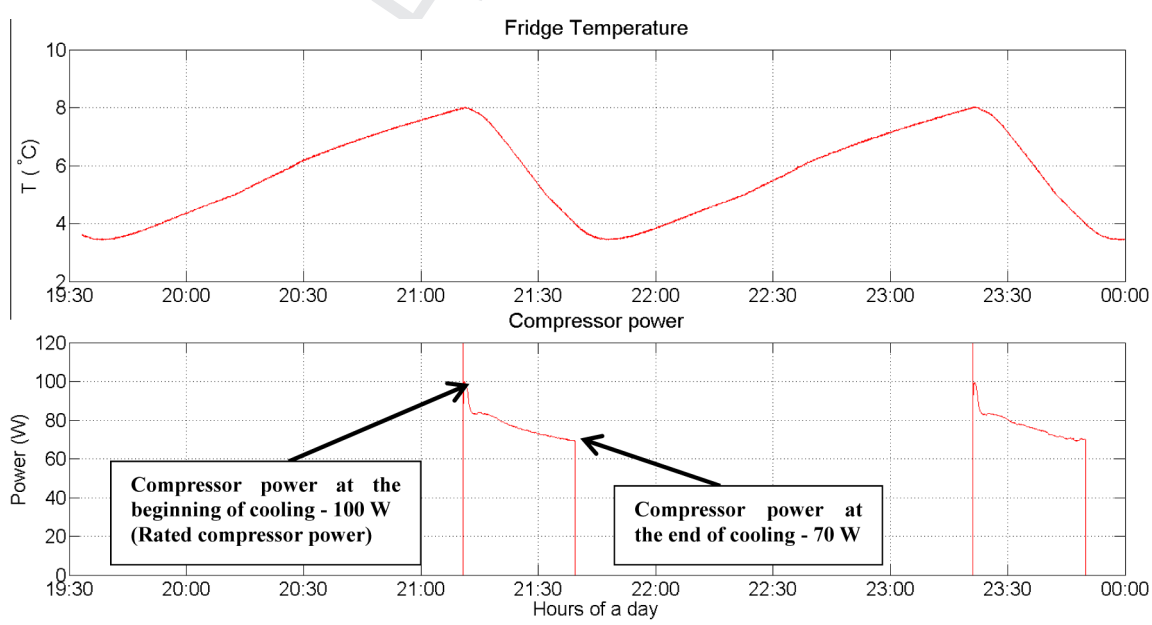

Fig. 9. Refrigerator power consumption and temperature.

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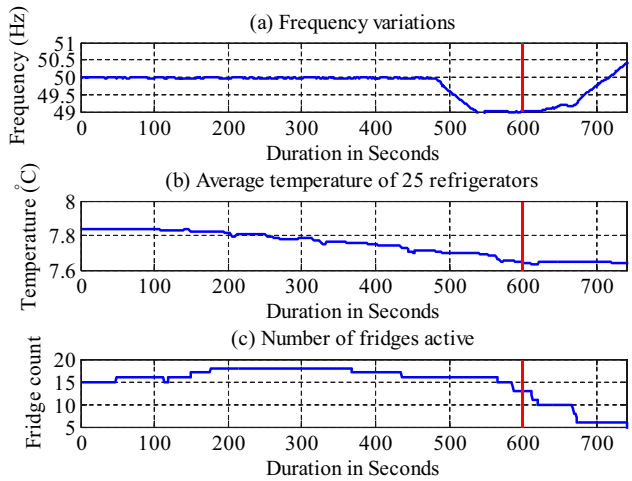

Fig. 10. System frequency, instantaneous temperature average, and number of active fridges.

As shown in plot – (c) of Figs. 10 and 13 refrigerators were active during the experiment, and 3 were switched OFF upon the first iteration of power reduction during frequency correction. At the second iteration, 4 more refrigerators were switched OFF. The instantaneous temperature average of all refrigerators, shown in plot – (b), continued to follow the trend of decreasing temperature. The cool chamber temperatures of all refrigerators participating in the experiment are shown in Fig. 11, in which the controller activation time is marked by the red vertical line and cool chamber temperatures shown 200 s after the control period. As the control period was very short, refrigerator cool chamber temperatures did not show any appreciable change due to the thermal mass and thermal inertia of the refrigerator contents. Therefore, the trend in the instantaneous temperature average also did not vary.

6.4. Ramp rate performance and gird code requirements

Table 3 lists the performance parameters of the secondary frequency control experiment, as well as the secondary frequency control requirements for the western Denmark power system (DK1).

The average control response time of the two power reduction iterations of 24 s is comparable to primary frequency control parameters. Primary frequency control in the Danish power system (DK1) requires production to be increased by 50% in 15 s, with 100% capacity reached in 30 s in the scenario of up-regulation. Although the power reduction obtained in the conducted experiment was 25% for each correction step, it is possible to achieve 100% reduction within the same response time. The ramp rate required for secondary frequency control by different fuel-based steam power plants is in the range of 2–4% per minute for a power capacity range of 20–100%, with the highest requirement associated with diesel engines at 20% per minute for a power capacity range of 20–100%. The ramp rate requirement for gas fuel-based power plants (gas turbines, gas engines and gas fired combined cycles) is 10% per minute for a power capacity range of 20–100%. During secondary frequency control, the average power reduction is 312 W which is 25% of the available power (i.e., 1250 W). The average control response time is 24 s. Therefore the ramp rate obtained is 63% per minute. Note that different ramping rates could be defined for different percentage of load reduction.

The Danish TSO EnergyNet.DK receives bids from the balance responsible parties (BRPs) till 15 min before every hour and activates the qualified bids as and when required in the consecutive hour [7]. In principle the service has to be provided for at least 1 h until the bids are received in the next hour, accepted and activated. The experimental analysis of impact of demand response activation on refrigerators shows that, load reduction to 25% of total compressor capacity for 3 h is possible with 4.25% over all integral square error [40]. The number of refrigerators involved and the power reduced are similar to the one used in [40].

The refrigerators require a switch ON delay during a power cycle in order for the back pressure in the evaporator to be dis-

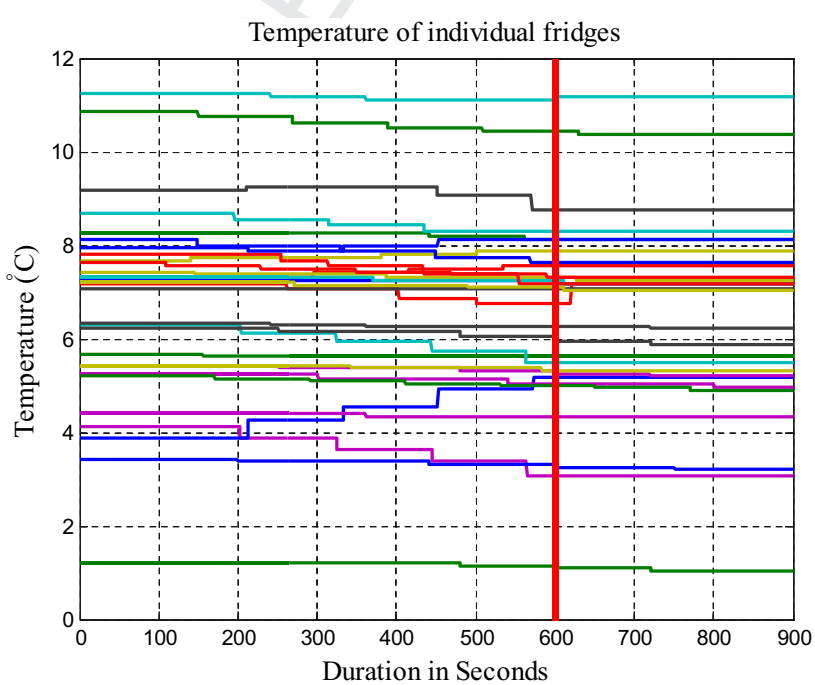

Fig. 11. Temperature of each refrigerator, as represented by the different coloured lines.

charged, with the duration of this delay ranging from 5 to 15 min depending on the size of the refrigerator unit. In this experiment, the ON command is sent to the refrigerators as soon as the system frequency reached 50 Hz. Though the control plug is activated, not all the refrigerators are switched ON. Some of the refrigerators have electronic controllers for compressor switching. The reason for all the refrigerators that are not switching ON is due to the delay provided by these in-built controllers. If the compressor start-up delay is not maintained, the compressor will consume a high startup current for a longer duration due to the compressor split phase asynchronous motor construction and the high startup torque requirement. Such high startup current may cause long-term motor winding damage due to overheating. This scenario creates limitations on control signal withdrawal after the system frequency reaches the nominal value; primary frequency control in the generation units should thus possess down regulation capability in such situations. The compressor motor consumes inrush current, which is typically 5 times maximum load current, for several seconds when it is switched ON. Therefore, compressor switch ON synchronisation should be avoided after control signal withdrawal, as their aggregated impact may produce unwanted transients in the power system. The synchronisation of the refrigerators' operation can be avoided by providing a delay between each refrigerator while switching them ON, at the end of the control period as suggested in [40].

7. Conclusions and future work

This paper studied secondary frequency control via DR activation on TCLs using an experiment involving refrigerators in real domestic households as an example. The results revealed that the average control signal response time was 24 s, considerably lower for secondary frequency control and comparable to that for primary frequency control. The ramp rate achieved was 63% per minute, or almost twice that of diesel engine power plants, which are considered to have the highest ramp rate of any power plant type. The obtained response time and ramp rate values demonstrate that TCLs can be considered rapid responsive loads for DR activation and can be utilised for power system control operations. Because of the minimum switch-off time requirement of the running TCL compressor, it is disadvantageous to switch it ON immediately after frequency restoration. In large populations of compressor-operated TCLs, the minimum switch-off time requirement can be solved using a better control algorithm. Such a problem will not arise with resistive loads such as space heaters and water heaters. The temperature prediction method is best suited even for a large population of TCLs. But the sorting method has to be optimised for the large population of TCLs. Further investigations will focus on the combined study of primary and secondary frequency control, including the analysis of vehicle to grid (V2G) electric vehicles and DR activation on TCLs.

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