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Thermostat Controlled Loads Flexibility Assessment for Enabling Load Shifting – An Experimental Proof in a Low Voltage Grid

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Abstract— **This paper investigates the usability of thermostat controlled domestic appliances for load shift in LV distribution grids. The proposed method uses refrigerators for the demonstration of adaptive load prediction to estimate its flexibility and perform scheduling based on load threshold limit. Two 1-week long experiments with real-time fridge measurements from 10 real households are conducted to observe the usability of domestic thermostat controlled loads in solving issues by load shift. The experimental results show that the total threshold crossing time is reduced by 37.48% with energy reduction by 17 kWh and an increase in the average cold chamber temperature by 1.7°C. The control flexibility of loads increases from 22.5% to 54% by bypassing their thermostat. Based on the results, we can conclude that thermostat controlled appliances can be used for load shifting without compromising the user comfort expressed by the temperature limits.**

Index Terms-- **Demand response, Flexibility, Load shifting, Refrigerators, Smart grid, Thermostat controlled loads.**

I. INTRODUCTION

As the energy demand increases and inflexible renewable sources are added to the electric power system, demand response becomes an inevitable method to manage power balance. Power balance is nowadays influenced more and more by a large number of distributed fluctuating productions, new consumption units, such as electric vehicles and heat pumps, and new load patterns. The increasing number of production and consumption units in the distribution grid can produce new peaks and create congestion problems. The demand response paradigm is suggesting addressing power system stability issues with control of the demand side rather than production side [1]-[3]. This paper investigates a method for scheduling domestic appliances to target load shift in the distribution grid.

In Nordic countries consumption form residential buildings accounts for 26% of the total consumption. The household appliances consume around 17% of this amount [4]. In the future demand response (DR) last mile devices will be deployed in residential houses in several locations of the low voltage grid. Thermostat controlled appliances commonly found in households are space heaters, heat pumps, air conditioners, fridges and freezers. All of these devices have a potential for load shifting, because of the periodical operation and availability of high thermal capacity. Among the thermostat controlled appliances, fridge availability in most residential houses and the ease of their control are also advantages for demand response field study. Additionally fridge's most important objective: keeping a low temperature, can be easily measured with a simple temperature sensor. The results obtained can be scaled up to the similar thermostat controlled appliances.

Demand response with fridges has been considered for several smart grid applications [5]-[9]. An algorithm presented in [5] uses simulation of 1000 fridges to regulate frequency in distribution grid. Authors in [8] recommend fridges for flexibility shift for power balancing. Authors in [9] propose including domestic appliances in congestion management and recommend refrigerators and freezers as suitable for load shifting.

The aim of this work is to investigate refrigerators usability for load shifting in a low voltage grid. The purpose of this investigation is to estimate the actual flexibility of fridges used in real houses over one week. An experimental investigation with domestic fridges used by real customers is conducted taking in account the unknown users' behaviour. The presented scheduling method uses the adaptive fridge model presented in [6] to predict the behaviour of a fridge. A laboratory setup is constructed using real-time measurements from Danish household refrigerators and emulating them in an experimental distribution grid in order to measure the effectiveness of the controller for load shift.

The rest of this paper is organized as follows: in Section II the principle of the estimation method and problem outline are introduced, and the control strategy adopted for energy reduction and, the experiment platform, hardware devices used for control and measurement and their configuration are briefly presented. Section III discusses about the control strategy, practical limitations and safety constraints in detail. The results of the experiments are discussed in section IV and the conclusions and future work are reported in section V.

II. METHODOLOGY AND EXPERIMENTAL PROCEDURE

A. *Methodology*

This section presents the principle of the flexibility estimation method and the control strategy adopted for load shift proposed in this paper. In order to schedule the load shift, an algorithm needs to calculate the available thermal capacity and estimate the thermostatic cycles. There are many modelling techniques available to estimate the available thermal capacity of the refrigerator [10]-[11]. The black box model presented in [6] is used in the work presented here due to its simplicity and less number of measurements from the refrigerator in the field. The model presented in [6] requires only two measurements namely the refrigerator power consumption and the refrigerator cool chamber temperature to predict cool chamber temperature close to actual when the dynamics of the system is not changing. It is also a generalized model suitable for other thermostat controlled loads. Such model is suitable for experiments with large number of refrigerators, where the number of parameters measured is limited.

The proposed method manages the load shift by controlling the refrigerators operation without violating their temperature limits T_{max} and T_{min}. In the presented control architecture, a central controller for refrigerators collects the temperature measurements and power consumptions from all refrigerators. The central controller predicts the temperature of fridges and the duration for which they can be switched OFF or ON with use of a black box model given in [6]. To manage the load shift, the controller executes an algorithm with two parallel procedures presented in Listing. 1.

```
define variables:
    var fridge_list (array of all available fridges)
    var fridge_activation_list (list of fridges to be activated)
    struct: scheduling_queue (order of fridges to be activated, highest off-time first)
initialize variables:
    fridge_list ←not active for service
    scheduling_queue ← empty
function schedule_fridges(fridge):
  fridge_temp ← fridge.getTemperature()
  lower_temp ← fridge.getMaxTemperature()
  upper_temp← fridge.getMinTemperature()
    if fridge in fridge_activation_list{
      if fridge_temp <= upper_temp {
        fridge.turnOff()
      }
      else{
        fridge_activation_list.remove(fridge)
      }
    }
    else{
      scheduling_queue.add(fridge)
      scheduling_queue.sortBy(off_time)
    }
function activate_fridges():
 total_consumption ← 0
 for fridge in fridge_list{
  total_consumption ← total_consumption + fridge.getPower()
 }
 while total_consumption > power_limit{
  scheduling_queue.get(1)
  fridge_activation_list.add(fridge)
  total_consumption<- total_consumption-fridge.getPower()
 }
```

Listing. 1. Control algorithm for load shift.

In the proposed algorithm the fridge flexibility is measured with the duration for which the refrigerator can be switched OFF. The refrigerators with longer OFF time are selected first for the load shifting.

B. *Experimental setup*

The aim of the experiment is to study the load shift in the low voltage network by controlling refrigerators power consumption. Conducting the experiment in a real low voltage network has the following problems: 1. Lack of sufficient electric measurements at different section of the LV network under study, 2. Availability of sufficient number of refrigerators to participate in the experiment, 3. Other unknown parameters that may influence the experimental results. In order to avoid these challenges we have decided to conduct the experiment in a laboratory setting where the parameters are under control and the threshold crossing load flows can be intentionally created. The experiment is conducted in low voltage grid formed at the SYSLAB facility in Technical University of Denmark (DTU) with vanadium battery bank and controllable resistive load connected to a 200 kVA distribution transformer. The vanadium battery is used to emulate power consumption of the refrigerators in the houses. Fig. 1 shows the network configuration diagram. SYSLAB is equipped with Class 0.2 Multi-instrument; MIC-2 which is interfaced with the SYSLAB SCADA for all grid parameters measurement. Each measurement in SYSLAB is recorded every second.

C. *Refrigerator emulation*

In order to emulate the power consumption and control of refrigerators, the refrigerators participating in the Project INCAP (INducing Consumer Adoption of automated reaction technology for dynamic Power pricing tariffs) are used. INCAP project has established the information and communication technologies (ICT) infrastructure for the real-time measurement and control of Danish household fridges for a field experiment. The block diagram of experimental set-up is shown in the Fig. 1.

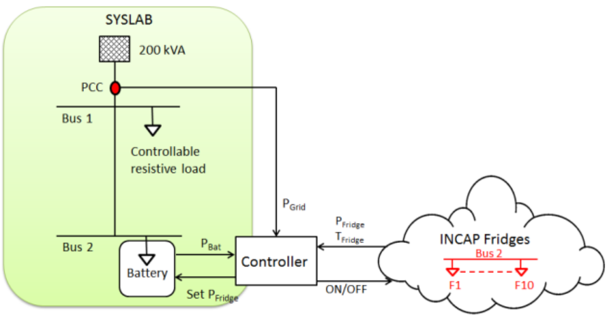

Fig. 1. SYSLAB experimental setup.

D. INCAP fridge data and control access

The block diagram in Fig. 2 shows the devices installed in each household participating in project INCAP. The devices used for control and data collection are (as shown in the Fig. 2):

1. Zigbee - relay unit to switch the fridge ON and OFF in response to a remote command from the remote server with facility to measure the power consumption of the refrigerator with 1 Watt resolution in every10 seconds interval.

2. Battery powered temperature sensor to measure temperature inside the fridge cool chamber in every 2 minutes interval with an accuracy of ±0.5 °C.

3. A user interface device with red and green lights and two push to ON switches to communicate with user.

4. A Zigbee- Ethernet gateway device to enable interaction of these devices with the central server through home internet connection.

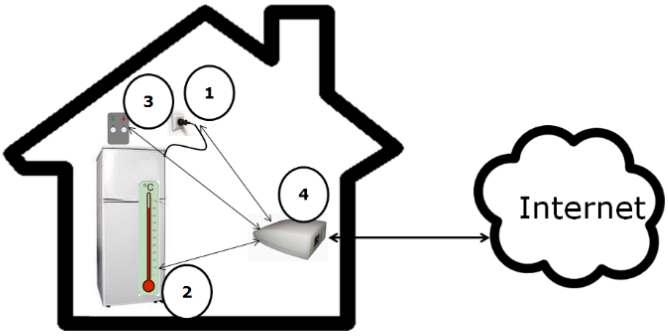

Fig. 2. Refrigerator control device installation in single house.

III. CONTROLLER DESCRIPTION

A. Controller architecture

The controller has the following objectives: predict fridge switch OFF time using the fridge model described in [6] and activates load shift by controlling the fridges. The communication interface between the controller and the fridges are provided by a software 'Smart AMM server' which is hosted in central server of DTU. All of the devices connected to the fridge in the household communicate and send data to the Zigbee-Ethernet gateway device. The Zigbee-Ethernet gateway device sends the data to the Smart AMM server in the form of short messages through the internet connection. Smart AMM server can send a copy of received messages from the fridges to the central controller and send the commands from the central controller to the fridges. Fig. 3 shows the overview of communication between the controller and the fridges in the houses. The central controller is a Java program executed in a Windows computer. This program connects to Smart AMM server to receive temperature and power measurements from the fridges and to the SYSLAB SCADA for grid and battery measurements.

As the model described in [6] requires the temperatures of the previous heating cycle and cooling cycle, the control software stores those temperature values corresponding to previous cycles (heating and cooling) locally. The heating and cooling cycles are identified by the compressor power consumption. During cooling the compressor is active and consumes power and during heating, there is no power consumption by the compressor. Some of the fridges have few watts power consumption for their internal electronic components and for light bulb illumination while the fridge door is opened. A 30 watt threshold is used to separate the compressor power consumption and the power consumption by the light bulb and other components.

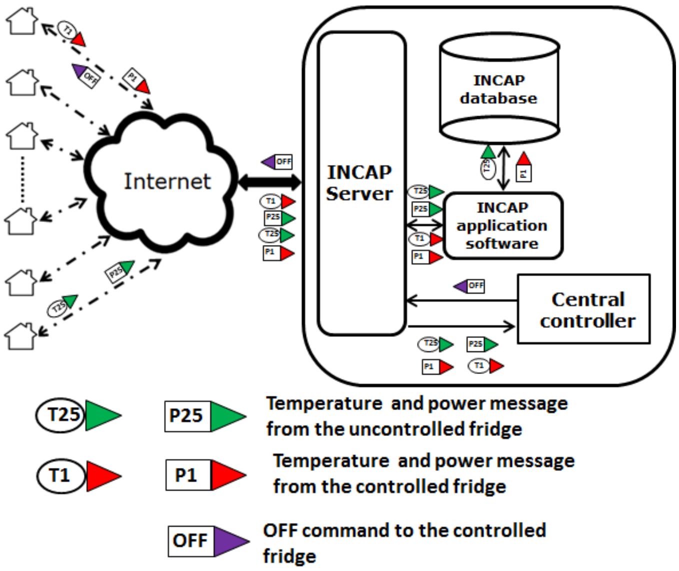

Fig. 3. Data flow from the fridges to the controller. [12]

B. Control task timings

The switch OFF time for the active fridges (in which the compressor is ON) is calculated using the fridge model [6] on every temperature update from the fridges. The fridges are sorted in an order based on their switch OFF time, the fridge that would otherwise turn off the soonest would be the first priority. Though the fridge power is measured every 10 seconds, the battery charging set-point is varied once in a minute with latest cumulative power of the fridges to avoid stress on the vanadium battery due to rapid change in charging current. The time delay to sense a change in power from the fridges is 10 seconds. As the battery set-point is changed once in a minute, the correction for load shift is also done once in a minute.

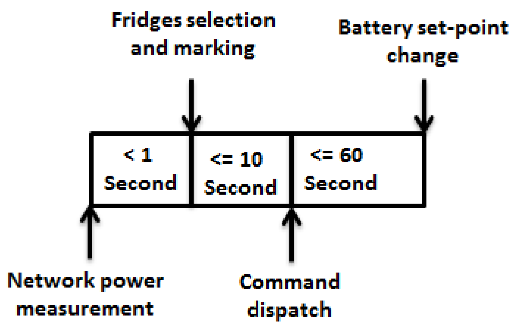

Fig. 4. Control event sequence and their timing during control.

On load shift correction, the fridges which have to be switched OFF to limit the power in the network are marked internally in the software. If the temperature of the fridge reaches its T_{max}, then the corresponding fridge is removed from the control list. The maximum delay in the load shift correction is 60 seconds, as the power measurement is once in 10 seconds and the load shift correction is once in 1 minute. The control event sequence and their timing during the control are shown in the Fig. 4.

IV. EXPERIMENTAL RESULTS

A. *Scenario definition*

The experiment is conducted with 10 fridges for 2 full weeks. On the first week of experiment, the controller for load shift is not enabled and on the second week, load shift is enabled. The two scenarios are compared. The controllable resistive load is set to consume 2.5 kW to enable a base load in the network. The total power rating of all 10 fridges is 0.8 kW. By assuming 50% of the fridges operational at any point of time, the power threshold limit is set at 2.9 kW. The experimental results are presented in 2 scenarios:

- Scenario 1: Load shift controller not enabled.
- Scenario 2: Load shift controller enabled.

B. *Scenario 1: Load shift controller not enabled*

Fridges' temperatures and grid power measurements for the week when the load shift controller is not enabled are reported in Fig. 5. The 2.9 kW threshold limit is marked in red in the upper plot, whereas the lower plot reports the 10 fridges individual temperatures. The average temperature of the refrigerator population is 3.9 °C.

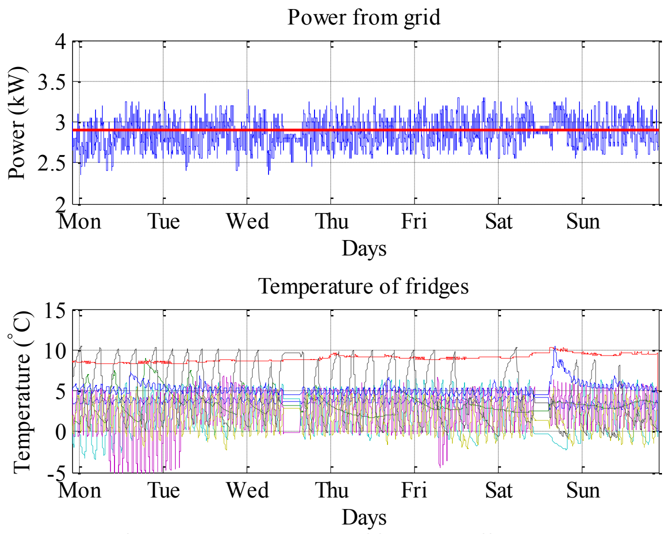

Fig. 5. Power from grid and temperature of fridges in different colors without fridge control. (1 second sampling)

C. *Scenario2: Load shift controller enabled*

Similar to the previous scenario, fridges' temperatures and grid power measurements for the week when load shift is enabled are reported in Fig. 6. The 2.9 kW threshold limit is marked in red in the upper plot of Fig. 6. The lower plot reports the 10 fridges individual temperatures. The average temperature of the refrigerator population is 5.6 °C.

D. *Result analysis*

TABLE I reports the main numerical results for the studied scenarios: fridges' temperatures averages, grid power average, total energy consumption, threshold crossing duration and the percentage of threshold crossing duration for the two weeks with and without load shift. The load flow above threshold is clearly visible from Fig. 5, when there is no control enabled on the refrigerators. It is also visible from Fig. 6, that the assumption about the 50% of the population of fridges operational at any point of time is valid.

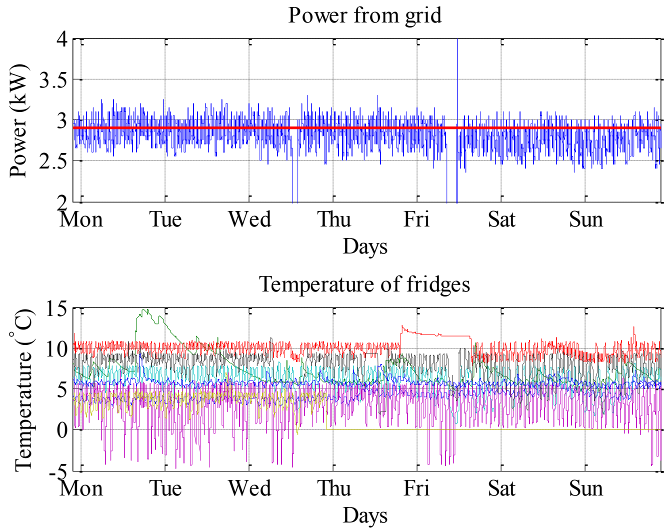

Fig. 6. Power from grid and temperature of fridges in different colors with fridge control. (1 second sampling)

TABLE I
Effect of Control on Fridge and Grid Parameters

Parameter		Control OFF	Control ON
Experiment duration		7 days	7 days
Average temperature (°C)		3.9	5.6
Average grid power (kW)		2.85	2.75
Total energy consumption (kWh)		475	458
Available flexibility (%)		22.5	54.0
Fridges energy consumption (kWh)		55	38
1 Second Sampling	Threshold crossing duration (h)	54.5	22.3
	Duration in percentage (%)	32.8	13.4
1 Minute average	Threshold crossing duration (h)	67.9	31.5
	Duration in percentage (%)	40.9	19.0
10 Minutes average	Threshold crossing duration (h)	63.2	23.7
	Duration in percentage (%)	38.1	14.3

The proposed method reduces the threshold crossing duration from 32.8% to 13.4%. The average temperature of the fridges increases from 3.9 °C to 5.6 °C when the load shift control is enabled. This may affect the quality of service provided by the fridges. As the T_{max} of every individual fridge is not exceeded, the food quality may not suffer. The average power consumption from the grid reduced from 2.85 kW to 2.75 kW once the load shift control is enabled. The general data logging of the measured parameters in substations is on 10 minutes basics, 1 minute and 10 minutes average of the power measurement at PCC are respectively shown in Fig. 7 and Fig. 8. In Fig. 8, it is clearly visible that the power flow is well maintained below the threshold limit by load shifting.

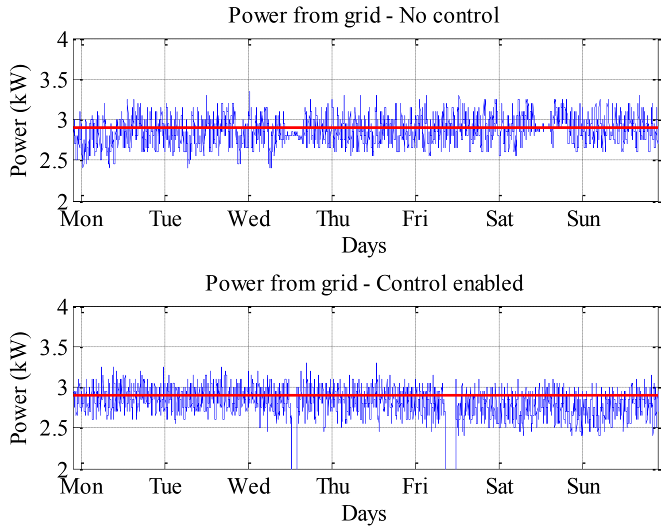

Fig. 7. PCC power average over 1 minute.

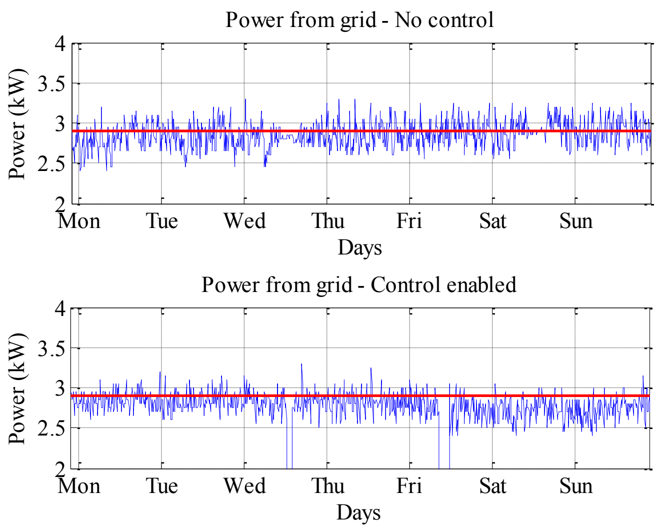

Fig. 8. PCC power average over 10 minutes.

E. Refrigerator flexibility

The refrigerator's flexibility can be defined from their thermostatic cycles as shown in the Fig. 9 [13]. At the beginning of the cooling cycle, the temperature of the cool chamber is close to T_{max} and the refrigerator is not flexible to participate in load shift. We can say that the flexibility is 0%. At the end of the cooling cycle, the refrigerator is fully charged to its thermal capacity. Therefore, the flexibility is 100%. The thermostat of the refrigerator disconnects the compressor from the network, once the temperature reaches the value T_{min} and the refrigerator is not available for external control. Therefore, the flexibility drops abruptly to 0% from 100% at the end of cooling cycle.

The flexibility at any temperature T in between the two temperature limits T_{max} and T_{min} can be calculated using the formula (1) given below, provided the thermostat is not OFF.

$$\text{Flexibility (f) \%} = \frac{(T - Tmin)}{(Tmax - Tmin)} \times 100 \qquad (1)$$

The heating time interval of the refrigerator can be defined as the time that it takes to reach the temperature T_{max} from T_{min} during the heat cycle as shown in the Fig. 9. The average weighted heating time interval to reach T_{max} with the compressor power rating of the refrigerator population is 80.5 minutes. Similarly, the cooling time interval of the refrigerator can be defined as the time that it takes to reach the temperature T_{min} from T_{max} during the heat cycle as shown in the Fig. 9. The average weighted cooling time interval to reach T_{min} with the compressor power rating of the refrigerator population is 35.4 minutes.

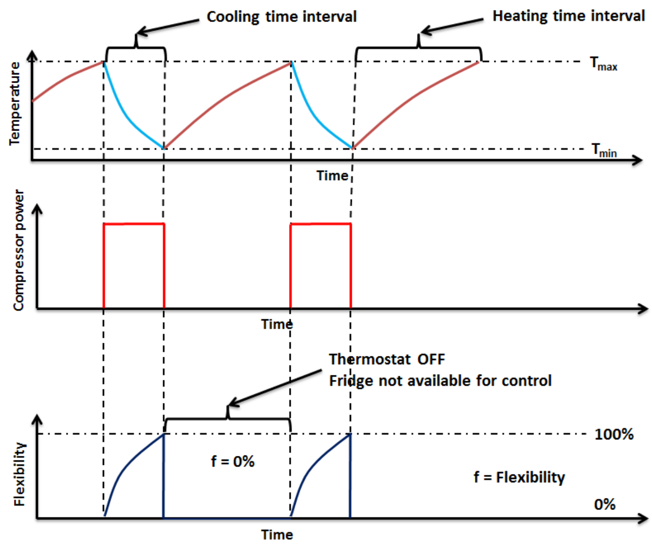

Fig. 9. Refrigerator flexibility definition. [13]

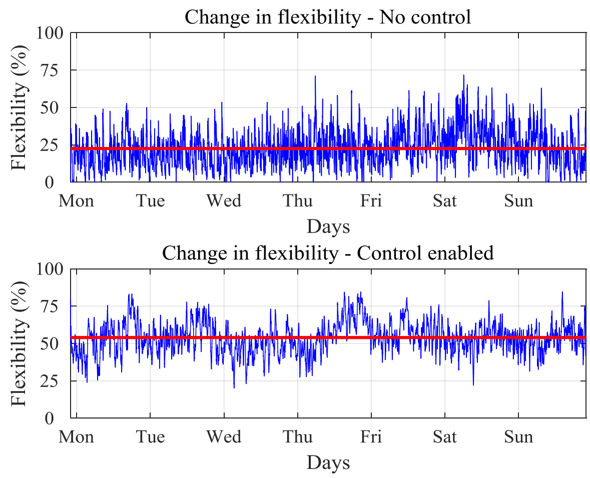

Fig. 10. Change in flexibility with and without load shift.

The change in flexibility on controlling the refrigerators for load shift is analyzed. When the controller for load shift is not enabled, the average available flexibility of the population of refrigerators is 22.5%. The available flexibility increases to 54.0% when the load shift controller is enabled. During the control period, the refrigerator is switched OFF before the temperature reaches Tmin. The refrigerator is available for control even if the compressor is OFF, as the thermostat is not OFF. Therefore, the flexibility increases as the thermal capacity is included during the heating period. The upper plot in the Fig. 10 shows the change in flexibility during the period when the load shift is not enabled. The lower plot in the Fig. 10 shows the change in flexibility on enabling the load shift control. The red line both plots indicates the average available flexibility in the respective scenarios.

V. CONCLUSION AND FUTURE WORK

This paper investigated the load shift in the low voltage network using centrally controlled thermostat controlled devices using a demonstration with domestic refrigerators. The experiment results showed that the load shift of refrigerators is possible without violating the temperature limits of the participating refrigerators to power system services. The reduction in aggregated energy of all refrigerators was 30.90% over one week duration. The weighted average heating time interval to reach T_{max} for the refrigerator population is 80.5 minutes. The weighted average cooling time interval to reach T_{min} for the refrigerator population is 35.4 minutes The refrigerator flexibility during normal operation was 22.5%. The flexibility increased to 54.0% when the refrigerators were controlled, as the flexibility during the heating cycle is utilized by the controller by overriding the internal thermostat of the refrigerator. In refrigerators controlled by two state (ON/OFF) thermostats, the energy required to maintain the refrigerator cool chamber temperature was inversely proportional to the average cool chamber temperature provided the variations in the other parameters like thermal mass, insulation and ambient temperature were negligibly small. As the temperature was maintained close to the T_{max} of the refrigerators, the aggregated power consumption showed a reduction and thus the aggregated energy.

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