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Load Aggregation over a Time of Day to provide Frequency Response in the Great Britain Power System

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Abstract

In the traditional power system, most of the frequency response services are provided from expensive large synchronous generators. However, demand is an effective element to provide frequency response with less expenditure. This paper discusses the availability of domestic heat pumps and fridges load to provide frequency response service to the Great Britain power system. The data of the low and high-frequency response from heat pumps is supplied by Element Energy while Open Energi provides data of the availability of fridges over the time of day. The potential of frequency response from the aggregation of heat pumps and fridges without undermining the inherent function of the load was estimated at a time of day. The combination of both loads to provide Firm Frequency Response (FFR) service was also investigated. Frequency control was developed to alter the power consumption of the aggregated load in response to a frequency signal. Simulation results showed that the aggregation of the load is an effective way to provide a dynamic frequency response over a day.

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Keywords: Heat pump; Fridge; Load aggregation; Dynamic frequency control; Smart grid

1. Introduction

In a traditional power system, balancing the power supply between generation and demand is mainly provided by the generation side. Moving toward a low-carbon power system will add more variable generation resources to the network, especially wind and solar generation. For this reason, the importance of Demand Side Response (DSR) is becoming more significant in the GB power system. DSR is defined as the changing of end-users demand pattern in response to an external signal [1].

When modelling DSR, it is important to identify the flexible loads that are required to be used as a source of DSR. Flexible loads are defined as those appliances that can operate with a degree of independence from the consumer, such

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as thermal loads. Thermal loads are time-flexible loads that can be interrupted without affecting the consumer comfort.

Previous research have investigated several demand control approaches to control the demand of the thermal loads in response to grid frequency. Some of these approaches have considered the use of centralised control algorithm which requires a two-way communication between the loads and the system operator [2]. Other approaches use a decentralised control algorithm that do not require a complex communication [3]. In [2], a comprehensive DSR strategy based on central direct load control was developed to balance the power mismatch between generation and demand. Another load control algorithm was presented in [4] to regulate the system frequency by controlling the aggregation of small loads such as electric water heating and air conditioning units. The system operator operates the central controller which monitors the ON/OFF state conditions of all thermostats and decides to turn them ON or OFF in response to a regulation signal.

A decentralised control approach was introduced in [3] which used a triggering control algorithm at different frequency deviation ranges. The frequency controller triggered the loads ON or OFF only when the frequency deviation went through these deviation ranges. However, the power consumption of each domestic unit is usually small, and hence the aggregation of different type of small units should be considered. Also, to provide a frequency response services such as Firm Frequency Response (FFR), each system aggregator must adopt a certain amount of load aggregation to provide at least 10MW of load power for frequency control [5]. Reference [6] has considered the combination of domestic refrigerators and industrial bitumen tanks loads to provide frequency control over the day.

This paper investigated the potential of two domestic appliances, such as heat pumps and fridges to provide low and high-frequency response independently. The paper also examined the availability of frequency response that was obtained from the aggregation of both heat pumps and fridges over the time of day. The combination of certain numbers of both loads to provide FFR service was also calculated.

2. Comparison of heat pumps and fridges

Fridge consists of Cooler and Freezer compartments. Cooler compartment is usually large and is used to store the food at a cool temperature. The freezer compartment is generally smaller and is used to make ice and store food below a freezing point. When the fridge's compressor is switched ON, the refrigerant material flows through the pipes. The refrigerant goes through the evaporator, and the warm temperature is transferred to the ambient causing the temperature inside the fridge to drop. The thermodynamic model of the Cooler and Freezer was presented in [6].

The heat pump has a reverse operation to the fridge. It transfers heat from a source of heat to the buildings' indoor. The heat gain is absorbed from the environment through the heat pump's evaporator. The refrigerant inside the evaporator is compressed through a compressor which causes its temperature to rise. The hot temperature is then transferred to the building through a heat exchanger. The thermodynamic model of a domestic building equipped with a heat pump was presented in [7].

The ON/OFF cycles and temperature behaviour of a fridge and heat pump are shown in Fig. 1. The heat pump has a longer ON and shorter OFF cycles than the fridge has. The typical ON and OFF cycles of a heat pump in a typical building having a range of temperature between (19^0C to 23^0C) is ≥30min [7]. The ON and OFF cycles of a fridge are 15min to 45 min [6]. This means that the heat pumps are more eligible to provide low-frequency response because they have longer ON cycle, while fridges are more eligible to provide a high-frequency response because they have longer OFF cycle.

The temperature difference between the low and high temperature set-points (T_{min}, T_{max}) of a typical domestic building is ≥4 ^{0}C which is higher than that of the fridge (typically 1-2 ^{0}C). This means that the variation of internal temperature (T_{in}) of a building has a wider range than the change of Cooler temperature (T_{Co}) of a fridge.

2.1. Availability of heat pumps at different time of day

Availability of load is defined as the fraction of load that is available to provide low and high-frequency response without undermining the inherent load function. In real life, only part of the load has ON-state and is available to be switched OFF and only part of load has OFF-state and is available to be switched ON in response to system frequency. Therefore, system operator needs to be notified about the amount of load that is available to respond to the grid frequency at each time of the day.

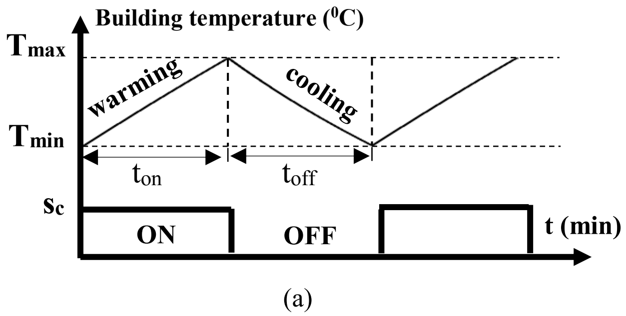

Fig. 1. Conventional control(a) heat pump; (b) fridge.

In this paper, the Availability of Low Response (*ALR*) is defined as the percentage of load that is available to be switched OFF (provide a low-frequency response). The Availability of High Response (*AHR*) is the percentage of load that is available to be switched ON (provide a high-frequency response). For heat pumps, data of average ALR_{hp} and AHR_{hp} are gathered and estimated for the Element Energy's medium uptake scenario for the year 2030 [8]. The ALR_{hp} and AHR_{hp} are half hour data over a day and are averaged for the winter months in the Great Britain (GB), as presented in Fig. 2. It is shown that response is highest at 06:30 and is lowest between 23:00 and 04:00.

The response from heat pumps is extremely seasonal. Heat pumps use less power in summer than in winter due to lower heating demand. The seasonal effect on the energy consumption of heat pumps over the year is obtained from [8] as shown in Fig. 3. The seasonal availability of low-frequency response in winter and summer months are denoted SAL_{winter} and SAL_{summer}. For a high-frequency response, the seasonal availability is denoted SAH_{winter} and SAH_{summer}.

Based on the $ALR_{hp}(winter)$, $AHR_{hp}(winter)$ and the seasonal availability, the ALR_{hp} and AHR_{hp} over a summer day ($ALR_{hp}(summer)$ and $AHR_{hp}(summer)$) were calculated by using equations (1) and (2). Fig. 4 shows the $ALR_{hp}(summer)$ and $AHR_{hp}(summer)$ that are averaged between April to September.

$$ALR_{hp}^{summer} = ALR_{hp}^{winter} x \frac{SAL_{summer}}{SAL_{winter}} \quad (1)$$

$$AHR_{hp}^{summer} = AHR_{hp}^{winter} x \frac{SAH_{winter}}{SAH_{summer}} \quad (2)$$

2.2. Availability of fridges at different time of day

For fridges, field test to measure the ALR_{fr} and AHR_{fr} were undertaken for winter months in 2011/2012 [6]. The investigations were carried out on 1,000 fridges in UK homes including diverse types of Coolers/Freezers covering almost 80% of the UK market. The average ALR_{fr} and AHR_{fr} in the summer and winter at each hour of the day are given in [6]. The availability of fridges is nearly constant over the day because fridges are usually engaged to the consumers' use.

2.3. Potential response from all heat pumps and fridges

According to the 2030 medium uptake scenario of Element Energy presented in [8], there are expected to be 3.8 million heat pumps in GB dwellings by 2030. Also, the average number of fridges per household in the GB is two [9], which means there will be an approximately 60 million fridges in the GB by 2030. Each heat pump has a typical power consumption of 3kW [8] and each fridge has a typical power consumption of 0.1kW [6]. The total availability response from all the heat pumps and fridges over the whole day is calculated using equations (3) and (4).

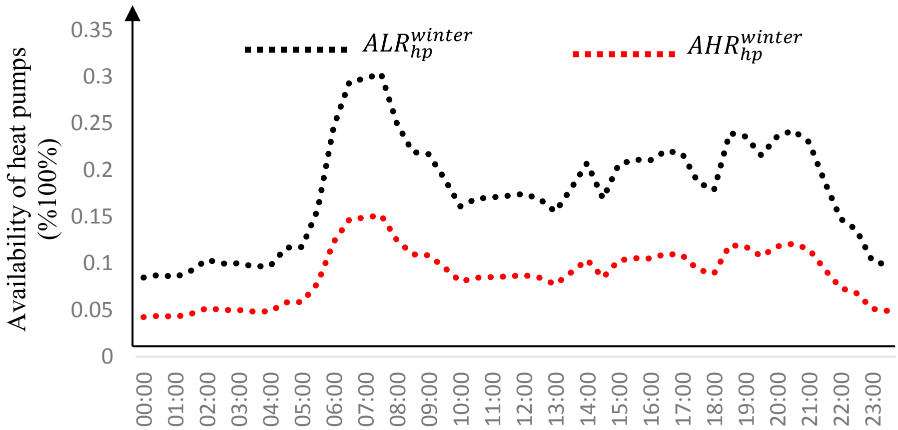

Fig. 2. Availability of heat pumps over a Winter day

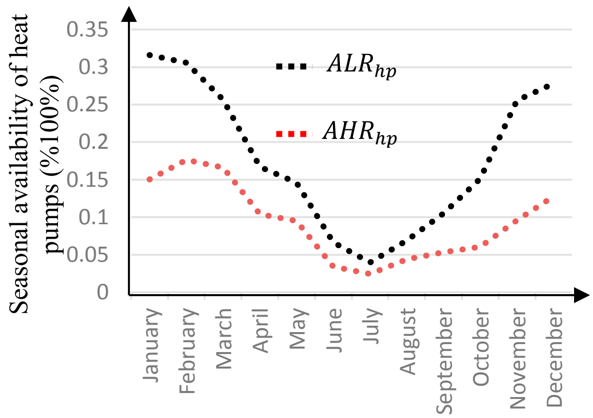

Fig. 3 Seasonal Availability (SA) of heat pumps obtained from Element Energy

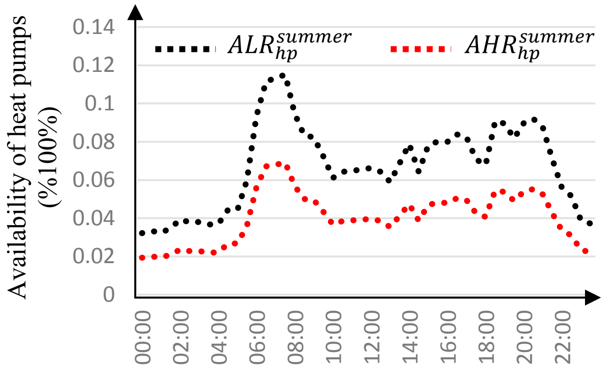

Fig. 4 Availability of heat pumps over a Summer day

$$ALR_{total}(t) = \frac{(NALR_{hp} \times NFR)+(NALR_{fr} \times NHP)}{NHP \times NFR} \times 100\% \quad (3)$$

$$AHR_{total}(t) = \frac{(NAHR_{hp} \times NFR)+(NAHR_{fr} \times NHP)}{NHP \times NFR} \times 100\% \quad (4)$$

where $NALR_{hp}$ and $NAHR_{hp}$ are the numbers of heat pumps that have ON and OFF states respectively and achieve $T_{min}<T_{in}<T_{max}$. Similarly, $NALR_{fr}$ and $NAHR_{fr}$ are the number of fridges that have ON and OFF states respectively, and satisfy $T_{min}<T_{Co}<T_{max}$. NHP and NFR are the total numbers of heat pumps and fridges respectively.

Fig. 5 shows the entire availability of load change at different time of the day. As shown in Fig. 5, the potential of frequency response from aggregated heat pumps and fridges is considerable, especially in the winter. On the GB's peak demand time (17:00-20:00), the heat pumps and fridges are available to provide a minimum of 3,500MW load decrease in winter and drop to 2,450MW in summer. On the lowest GB system demand between (00:00-06:00), the load aggregation is able to provide a minimum of 3,640MW increase in winter and 2,320MW in summer. It can be observed that the availability of frequency response is always higher in the winter due to lower heat pumps demand in the summer.

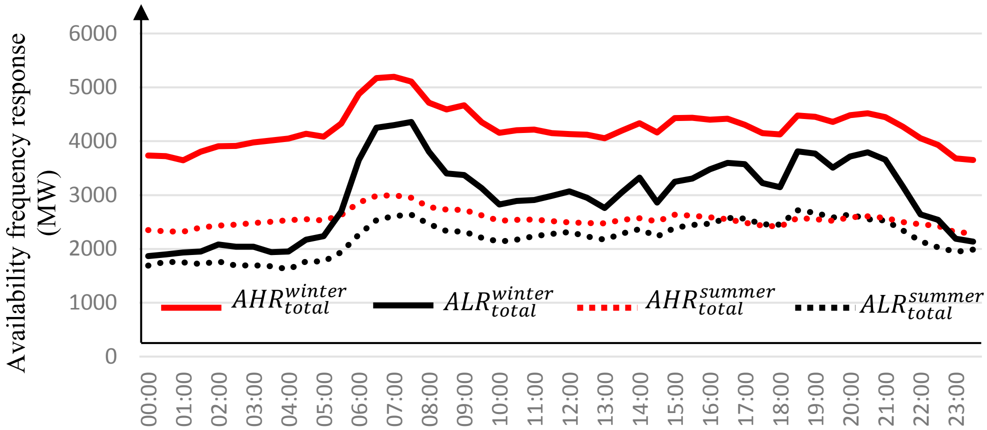

Fig. 5 Available frequency response from all heat pumps and fridges over a day

2.4. Load aggregation to provide Firm Frequency Response(FFR)

FFR is one of the most valuable balancing services in the GB. Aggregators or suppliers must be able to provide a minimum of 10MW to the grid within 30 seconds of a frequency event, such as a power station tripping out. The aggregation of certain numbers from both heat pumps and fridges to provide a minimum power of 10MW to the grid is calculated over the time (14:00-21:00).

3. Simulation Results

A dynamic frequency controller was developed to control the power consumption of the load in response to system frequency [10]. It was assumed that each heat pump and fridge were equipped with a frequency controller. The controller has two inputs; the internal temperature input *T(t)* and system frequency *f(t)*. The system frequency was compared with a low frequency (49.5-49.9) Hz and a high frequency (50.1-50.5) Hz set-point signals. If the system frequency drops lower than the low-frequency setpoint, the controller turns the load OFF. Similarly, when the system frequency rises higher than the high-frequency setpoint, the controller turns the load ON. The frequency control only works when the internal temperature is within the pre-defined range (T_{min}, T_{max}). A case study was conducted for the aggregation of 8,000 heat pumps with 30,5396 fridges which was estimated over the time (14:00-21:00). Fig. 6 shows the frequency profile that was injected to the system. The frequency drop at time 470 sec was considered to test the capability of the aggregated controllable loads to reduce their power consumption offering a FFR service. Fig. 7 shows the behaviour of the power consumption drawn by dynamically controlled loads during the frequency event. Heat pumps and fridges were switched OFF in a very fast manner and provided a reduction of their power consumption of about 10 MW in proportional to the frequency drop. It can be concluded that each aggregator must adopt at least 8,000 controlled heat pumps and 30,5396 controlled fridges to participate in the FFR service.

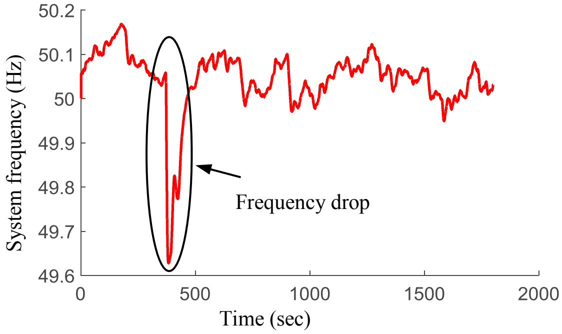

Fig. 6 Injected grid frequency profile

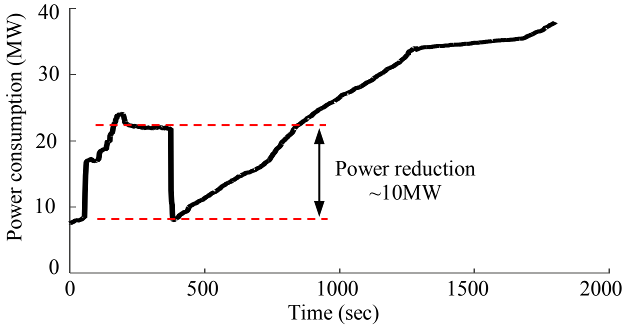

Fig. 7 Power reduction from aggregated heat pumps and fridges to provide 10MW

Conclusion

The availability of heat pumps and fridges at the time of day was presented. Aggregation of the low and high-frequency response from all heat pumps and fridges was calculated for the Great Britain power system at different time of winter and summer days. Also, the number of heat pumps and fridges to provide FFR service was estimated over the time (14:00-21:00). It was shown that the aggregation of 8,000 heat pumps with 30,5396 fridges is able to provide at least 10 MW of power demand reduction over the time (14:00-21:00).

Each load was equipped with a dynamic frequency controller to control the load power in response to system frequency. Simulation results showed that controlled aggregation load is an effective way to provide dynamic frequency control service.

In the future, simulations will be carried out by connecting the dynamically controlled loads to the regional Great Britain generation and transmission system model.

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