DYNAMIC FREQUENY CONTROL USING HEAT PUMPS

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Abstract This paper investigates the model of aggregated heat pumps as a source of the flexible load in the Great Britain. A thermal model of a domestic heat pump was presented. A decentralised dynamic frequency control algorithm was developed to regulate the grid frequency. Five case studies were used to identify the suitable number of individual heat pump models that can be aggregated to accurately represent the projected number of heat pumps connected to the 2030 Great Britain power system. The simulation results revealed that an aggregated model of 5,000 individual heat pumps was accurately representing the entire number of heat pumps in the Great Britain power system. Also, two case studies were undertaken to examine the potential of dynamic frequency control algorithm to provide frequency response service. Simulation results showed that the power consumption of aggregated heat pumps was dynamically controlled in response to a frequency deviation. The frequency response behaviour of heat pumps mimics the behaviour of frequency sensitive generators.

1 Introduction

The adversities associated with the increase of the intermittence generations come from the fact that the traditional power systems were designed based on large controllable synchronous generators. The renewable generation could disrupt the operation of conventional method that balances the power generation with the demand. For this reason, new balancing methods should be developed to maintain the generation and supply equal at all the time. At present, the balancing services are mainly provided in the supply side, through different types of services such as primary, secondary, tertiary services [1].

Nowadays, there are much efforts to engage the consumers to the balancing mechanism between generation and demand. Many ways were used to control the energy of consumers. For example, a statistical method was proposed for managing the balance between demand and supply using demand side management [2-4]. Demand Side Response (DSR) is another approach that is used to provide balancing services to the system such as primary frequency control and spinning reserve [5-7]. DSR is used to switch some loads OFF and/or ON or having their power consumption increased/decreased when there is a power mismatch between the generation and the demand [8].

1.1 Brief description of frequency control strategies in the previous work

The mission of this section is to describe the latest strategies that use the demand to provide ancillary services of frequency response so that to continuously balance the supply with demand. Thermostatically Controlled Loads (TCLs), such as fridges, heat pumps, water heaters, bitumen tanks, etc., are also flexible candidate for DSR [9-12]. The normal operation of these appliances can be temporarily interrupted without noticeable effect on the temperature. Because of large number of thermal loads connected to the grid and their thermal storage characteristics, the TCLs could potentially involve significant economic value throughout the provision of various forms of ancillary services [13-15]. For the provision of frequency response service, two main dynamic TCLs frequency control algorithms are noticed, namely centralised and decentralised control. For example, in [16] and [17], a comprehensive DSR strategy based on central load control was developed to regulate the system frequency by controlling the aggregation of electric water heating and air conditioning units. The centralised load control algorithm requires the support of a high-performance communication system between the load and the system operator.

Decentralised control algorithms have been also used for frequency regulation [6, 18]. The decentralised TCLs frequency controller was installed locally without communication with the system operator. The decentralised control strategy used triggering frequency signal with pre-defined frequency deviation ranges.

Another class of the decentralised control system aimed to control the power consumption of TCLs dynamically with the temperature by using dynamic demand control algorithm [11, 12, 19, 20]. The dynamic decentralised controller in [19, 20] controls the power consumption of domestic refrigerators and industrial melting pots linearly with the frequency changes. The controller aims to maintain the primary thermal storage functions of each unit. In [11], the dynamic decentralised controller controls the power consumption of industrial bitumen tanks dynamically in response to frequency deviations by measuring the present and previous frequency samples.

1.2 Research objectives and contribution

The electricity demand is increasing in Great Britain due to the electrification of heat pumps and electric vehicles [21] The aim of this paper is to describe the use of heat pumps to provide ancillary services of frequency response to continuously balance demand with supply in Great Britain. The method that is presented in this research provides a solution to the reduction in system inertia and to the resulting increase of rate of change of frequency. National Grid has stated that the reduction in system inertia is a real problem that could face the future GB power system due to the increase of converter- connected wind generators [22]. The contribution of this study is summarized as the followings:

1. The thermal performance of domestic buildings using heat pumps is modelled.
2. Identify the suitable number of heat pumps that accurately represent the entire number of heat pumps connected to the GB power system according the Element Energy’s 2030 medium uptake scenario.
3. Build a new decentralized dynamic frequency control (DFC) algorithm, enabling the heat pumps to alter their power consumption in response to grid frequency
4. Examines the potential of the DFC algorithm by connecting the aggregated controlled load to the simplified GB power system.

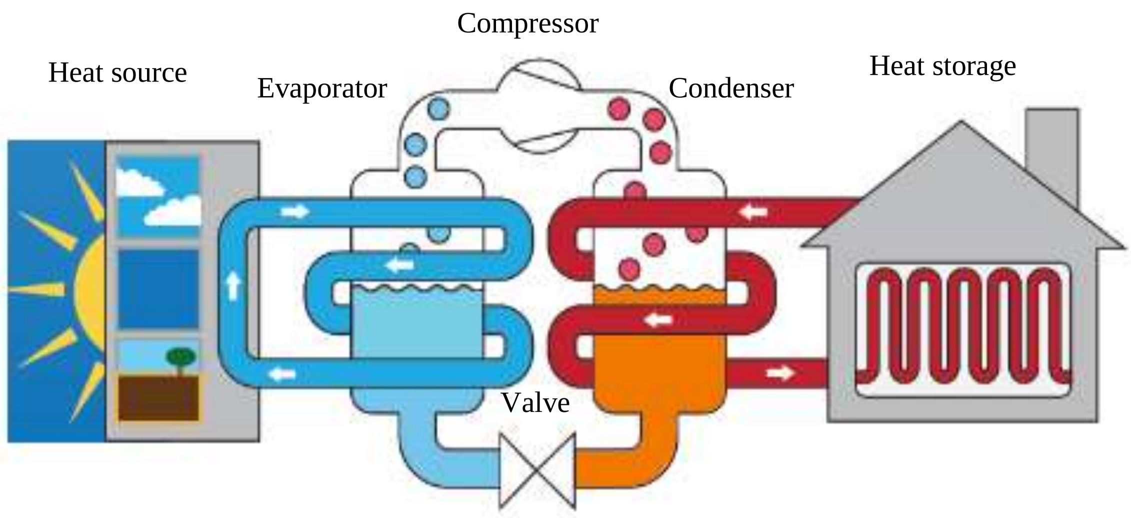

Fig. 1 Diagram of a heat pump operation (modified based on [23])

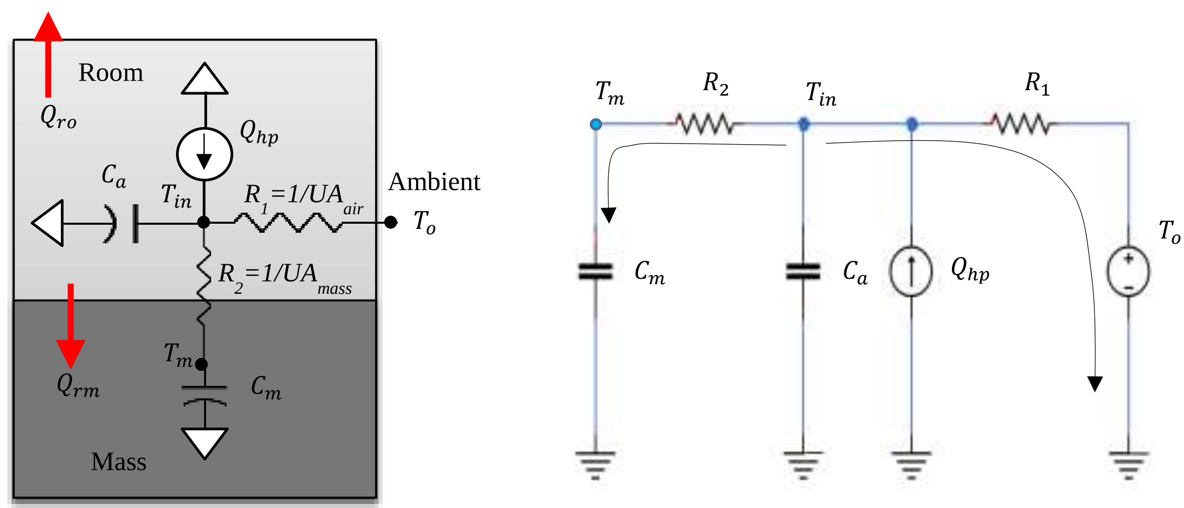

Fig. 2 Equivalent thermal model of a domestic building coupled with a heat pump unit

2 Thermodynamic model of a single heat pump

The diagram of a heat pump is shown in Fig. 1. The heat gain from the environment takes place in the heat pump's evaporator. The liquid refrigerant inside the evaporator is boiled and evaporated even in low-temperature degrees. The resulting gaseous is then compressed through the compressor causing its pressure and temperature to rise. The heated refrigerant passes through the condenser, and the heat is then released to the house. The gaseous is then converted into a hot liquid which goes through an expansion valve causing its temperature to decrease. It can once again absorb the heat from the external environment, and the cycle of the heat pump starts again.

The operation of different types of heat pumps is well detailed in [24, 25]. In this section, a simplified lumped thermal parameters model is introduced as shown in Fig. 2. In this model, C_a(J/^{0}C) and C_m(J/^{0}C) represent the air and mass heat capacity, Q_{hp}(W) is the heat rate flow of heat pump unit, UA_{insl}(W/^{0}C) is the standby heat loss coefficient to the ambient, UA_{mass} (W/^{0}C) is the heat loss coefficient between indoor air and mass, T_o(^{0}C) is the ambient temperature, whilst T_{in}(^{0}C) and T_m(^{0}C) are the house and house mass temperatures respectively [26].

The thermal model can be mathematically modelled by calculating the Ordinary Differential Equations (ODE). The ordinary differential equations descriptions of the model can be found by calculating the variation of the building and building mass temperature. The variation of building temperature is represented by a first order differential equation as shown in equations (1)– (3), where Q_{rm} is the heat transfer between the building and building mass, and Q_{ro} is the heat transfer from the building to the outside ambient.

$$C_a \frac{dT_{in}}{dt} = -Q_{ro} - Q_{rm} + Q_{hp} \tag{1}$$

$$C_a \frac{dT_{in}}{dt} = -\frac{1}{R_1}(T_{in} - T_o) - \frac{1}{R_2}(T_{in} - T_m) + Q_{hp} \tag{2}$$

$$\frac{dT_{in}}{dt} = -\left(\frac{1}{R_1.C_a} + \frac{1}{R_2.C_a}\right) T_{in} + \frac{1}{R_2.C_a} T_m + \frac{1}{R_1.C_a} T_o + \frac{Q_{hp}}{C_a} \tag{3}$$

The balance equation of the building mass is given in (4) and (5).

$$C_m \frac{dT_m}{dt} = Q_{rm} \tag{4}$$

$$\frac{dT_m}{dt} = \frac{1}{R_2.C_m} T_{in} - \frac{1}{R_2.C_m} T_m \tag{5}$$

Typically, the building mass thermal storage C_m and thermal resistance R_2 are large, i.e. the variation of mass temperature dT_{in}/dt is small.

The differential equations in (3) and (5) can be further simplified by neglecting the temperature variation in (5). Thus, the equivalent model that conforms to the measured indoor temperature curve is presented in equation (6).

$$\frac{dT_{in}}{dt} + k_1.T_{in} = k_2 \tag{6}$$

where $k_1 = 1/(R_1.C_a)$ and $k_2 = (UA_{insl}.T_o + Q_{hp})/C_a$. Equation (6) has two possible solutions depending on the heat pump state s_c. For instance, when $s_c = 1$, the heat pump power rate is assumed to be Q_{hp} whilst Q_{hp} is equal to zero when $s_c = 0$. The two solutions of (6) are introduced in (7) and (8).

$$T_{in}^{t+1} = T_o + Q_{hp}.R_1 - \left(T_o + Q_{hp}.R - T_{initial}^{t}\right).e^{-\frac{\Delta t}{R_1 C_a}} \qquad s_c = 1 \tag{7}$$

$$T_{in}^{t+1} = T_o - (T_o - T_{initial}^{t}).e^{-\frac{\Delta t}{R_1 C_a}} \quad s_c = 0 \tag{8}$$

where T_{in}^{t+1} refers to the indoor temperature at the time $t+1$(^{0}C), R_1(^{0}C/W) denotes the thermal resistance, Δt is the step time, s_c is the heat pump's compressor state. The typical ON and OFF periods t_{on} and t_{off} are shown in Fig. 3. For the dwelling insulated to typical UK levels, the heating system ON/OFF setpoint temperature range (T_{min}, T_{max}) is 19–23^{0}C [27]. For this reason, it was assumed that when $s_c = 1$, T_{in} starts from $T_{min} = 19^0$C at $t_{on} = 0$ minute and increases to reach $T_{max} = 23^0$C at $t_{on} = 30$ minute

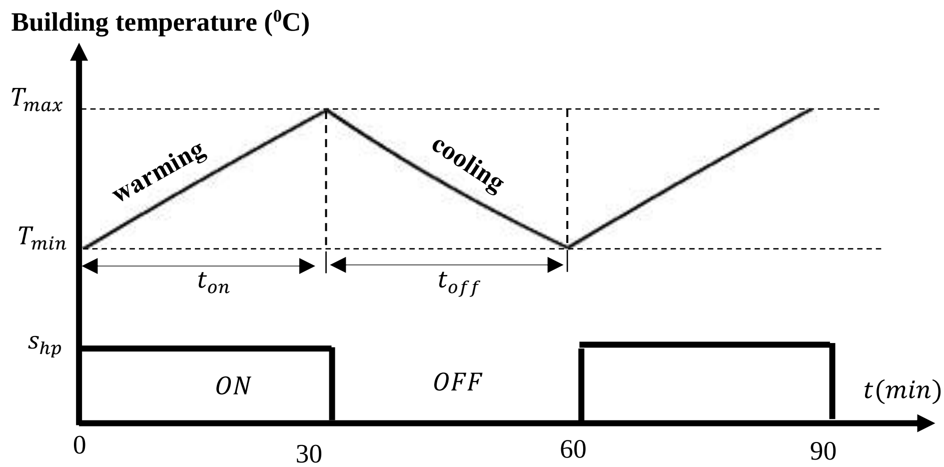

Fig. 3 Temperature control of one heat pump unit

3 Modelling work and simulation results

The thermal model that is given in equations (7) and (8) was simulated using MATLAB. Each heat pump unit has a power rate of 3 kW [12]. There are expected to be around 3.8 million heat pumps in UK houses by 2030 [21].

Using 3.8 million independent heat pump models is infeasible and complex. However, a smaller number of heat pump models can be utilised and then scaled up to represent the total population. The smaller number of heat pump models were considered in five case studies as shown in Table 1. This modelling work was conducted to find the most appropriate case to model the behaviour of all 3.8 million heat pumps.

As shown in Fig. 4, following a drop of power at time 100sec, the power consumption behaviour of five case studies of different numbers of heat pumps in each aggregation were compared. Table 1 gives details for each case study. Fig. 4 shows the power consumption of 100, 1,000, 5,000 and 10,000, 100,000 aggregated heat pump models. The response of the aggregated models with 5,000 and 10,000 heat pumps were more gradual and had a similar power consumption behaviour. The aggregated model, with 5,000 heat pumps multiplied by scaling number 760, was chosen as the best model to represent the entire population of heat pumps based on accuracy and simulation time.

Case Study	Number of individual Heat Pump models	Multiplied Number	Simulation time
1	100	38,000	1 sec
2	1,000	3,800	7 sec
3	5,000	760	45 sec
4	10,000	380	84 sec
5	100,000	38	649 sec

Table 1 Number of aggregated heat pump models

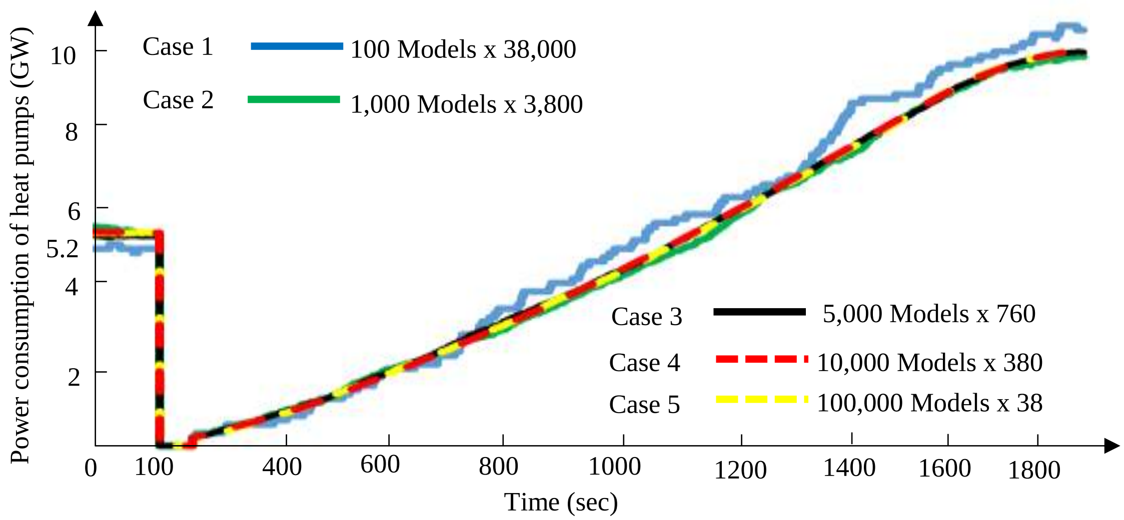

Fig. 4 Total Power Consumption of 3.8 million heat pumps obtained from the thermodynamic model

4 Dynamic Frequency Controller

A control algorithm is developed to switch OFF or ON each heat pump unit in response to a regulation signal. In this paper, the grid frequency $f(t)$ is used as the regulation signal. A decentralized controller that can be applied to the heat pumps is developed as shown in Fig. 5. The Temperature Controller measures the temperature of the buildings, and the Frequency Controller monitors the grid frequency continuously. Each unit is assigned with two trigger frequencies F_{OFF} and F_{ON}. The range of F_{OFF} is 49.5–49.9 Hz and the range of F_{ON} is 50.1–50.5 Hz which is consistent with the steady-state limits of grid frequency in the Great Britain power system. The control algorithm compares $f(t)$ with the trigger frequencies simultaneously. The frequency controller should ensure a smooth switching behaviour and should avoid the high payback that could result from a large number of units recovering at the same time. Therefore, the following techniques are implemented:

- The trigger frequencies of a heat pump Fhp_{OFF} and Fhp_{ON} vary dynamically with the building temperature T_{in}.
- For a frequency drop, heat pumps are switched OFF in descending order starting from the warmest building.
- For a frequency rise, heat pumps are switched ON in ascending order starting from the coldest building.

Fig. 6 shows the flowchart of the control system of the load. The initial temperature T_{in} of a population of buildings is diversified by randomising the starting time using a uniform distribution.

The frequency controller should not undermine the internal temperature (T_{in}). When the temperature exceeds the predefined temperature set-points (typically for a building T_{min}=19 ^{0}C and T_{max}=23 ^{0}C [28]), the Temperature Controller is prioritized and Shp_f follows ST_{in}. In other words, the final switching signal will only respond to the temperature controller but not to the frequency controller even through the time of a frequency incident. However, when the temperature is within the acceptable limit, the frequency controller is prioritized, i.e. Shp_f responds to the frequency controller. If $f(t) \leq Fhp_{OFF}$, this indicates that there is a frequency drop signal and hence the heat pump units are switched OFF in descending order (i.e. $Shp_f = 0$) to decrease the power demand. If $f(t) \geq Fhp_{ON}$, this indicates that there is a frequency rise signal and hence the heat pump units are switched ON in ascending order (i.e. $Shp_f = 1$) to increase the power demand.

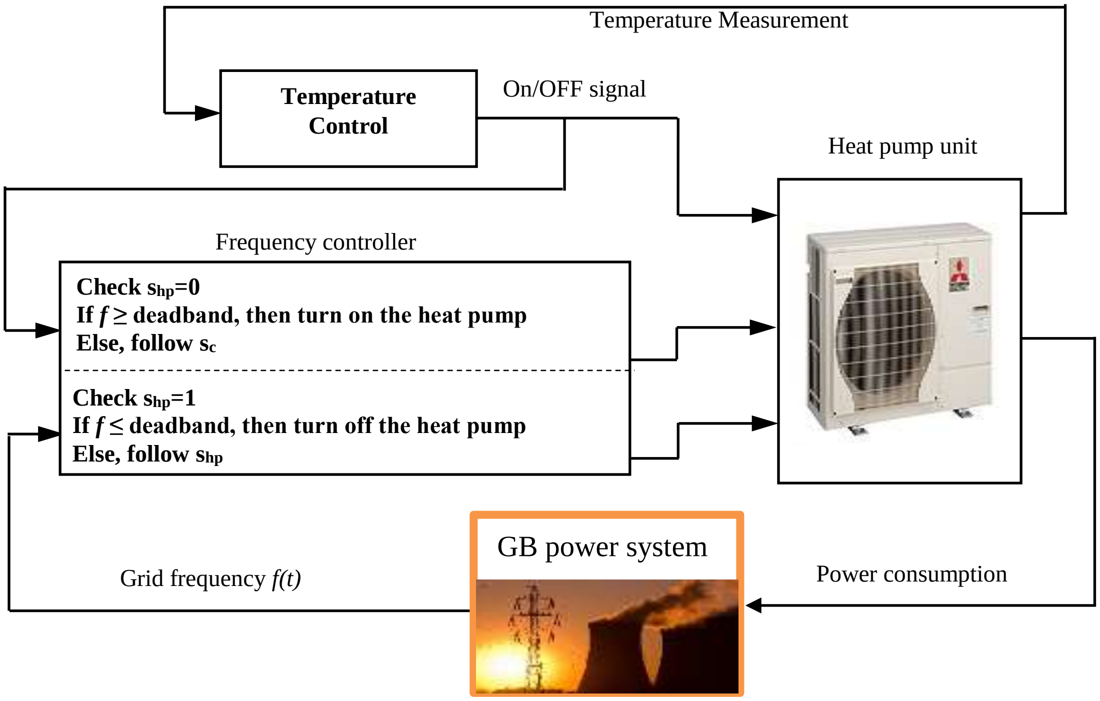

Fig. 5 Decentralised Dynamic Frequency Control algorithm of a heat pump unit

5 Simplified GB power System

In order to investigate fast primary response with the aggregation of the dynamically controlled heat pumps, a simple model representing the governor, inertia and damping of the GB system was used (Fig. 7) [29]. In this study, the system inertia used for the current GB power system is 6.5s and 3.1s when considering the future power system with much generation from wind turbines [11], [30]. For the provision of a primary response, all generators should have a governor droop setting between 3%–5% according to the GB grid code [31]. Some generators are required also to provide secondary frequency control. Therefore, the simplified GB power system are represented by two lumped blocks G1 and G2. G1 represents 20% of the generators that provide primary frequency response, while G2 represents 80% of the generators that provide primary and secondary frequency response as shown in Fig. 7. The provision of secondary response was modelled by the supplement integral control loop with gain K_i. The load frequency dependence was lumped into a damping constant D, which was set to 1pu. The speed governor deadband in blocks G1 and G2 should be no greater than 0.03Hz; however, to increase certainty, it was selected here to be ±0.015Hz [31]. The governor droop is represented by the gain $1/R$ and was set to 20pu in all scenarios. The parameters used in Fig. 7 are given in Table 2, where T_g, T_t, T_{tr}, and T_r are generator-turbine time constants [29].

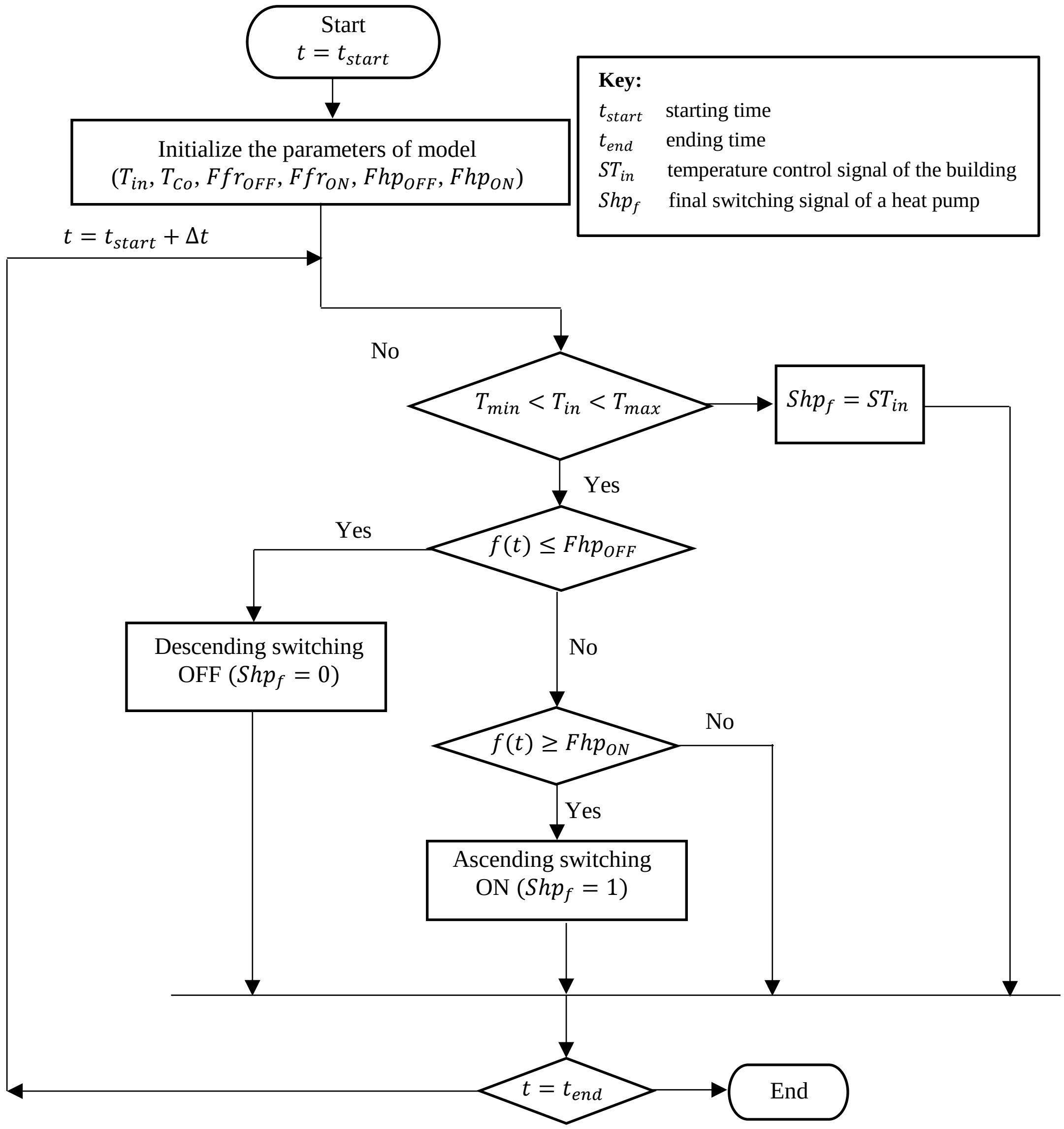

Fig. 6 The flowchart of the aggregated load control system

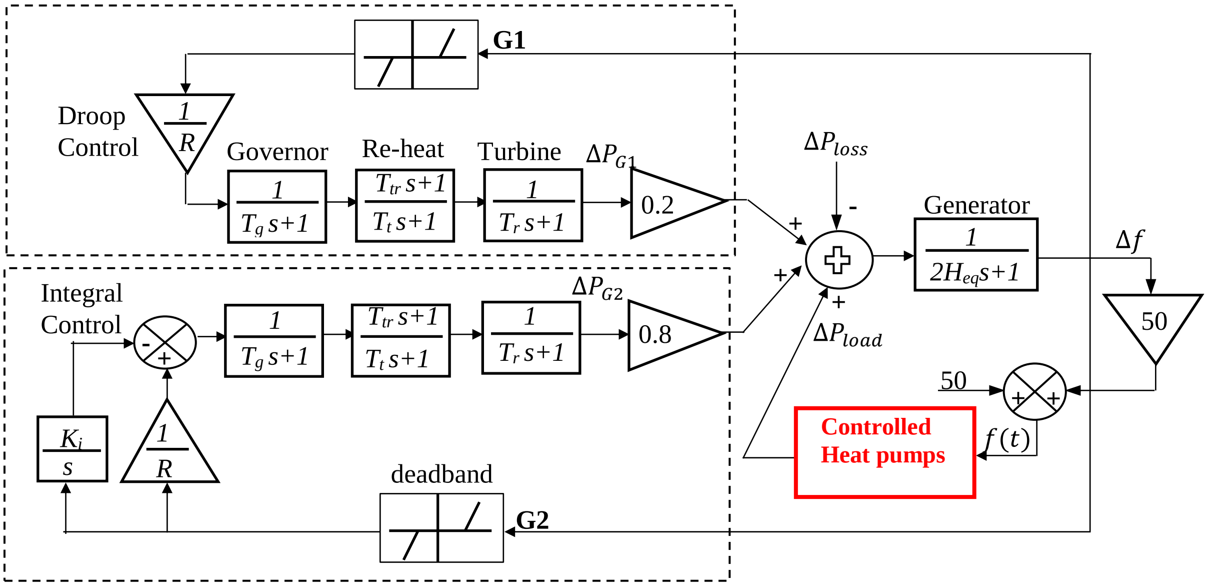

Fig. 7 Simplified Great Britain power system model

Table 2 Parameters of the Simplified Great Britain Power System (System demand=41GW)

1/R	$\boldsymbol{T_g}$	$\boldsymbol{T_{tr}}$	$\boldsymbol{T_t}$	$\boldsymbol{T_r}$	$\boldsymbol{K_i}$
20	0.2	2	20	0.3	0.05

6 Availability of Heat Pumps for Frequency Response

The daily average number of heat pumps in the ON state which are available to be switched OFF in response to a low-frequency response is denoted ONHP. The ONHP was estimated by Element Energy for the 2030 medium uptake scenario of winter months in the Great Britain as shown in Fig. 8. In this study, the ONHP data was used as an input to the model to specify the amount of heat pumps that can provide low-frequency response at each time of the day. The average number of heat pumps that are connected to the grid and are in either the ON and OFF states are denoted NHP. The typical ON and OFF cycles of heat pumps were assumed equal. Therefore, the NHP was assumed as twice as the ONHP.

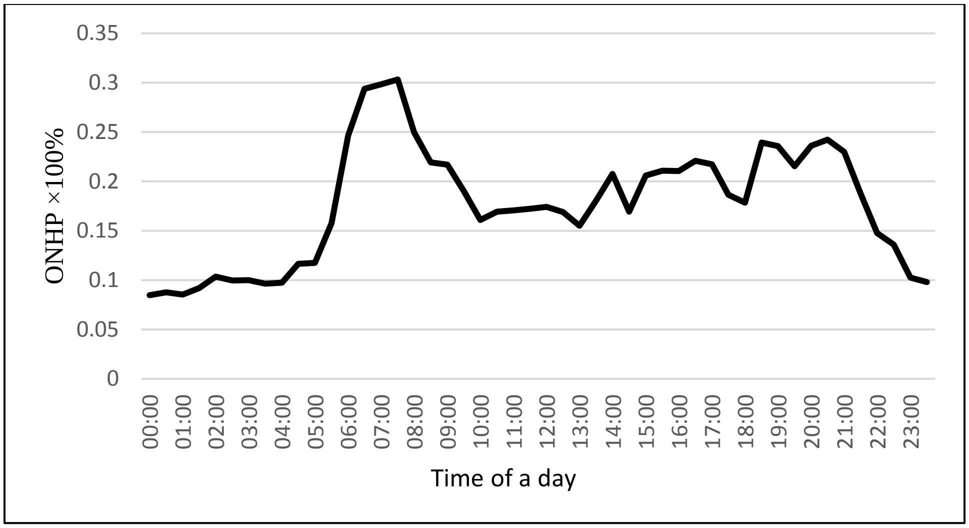

Fig. 8 Diurnal variation in average number of heat pumps (ONHP), 2030 winter medium scenario

7 Case Studies on the Simplified GB Power System

Case studies were undertaken for a population of heat pumps to investigate their capability to provide the low frequency response for a frequency drop. The population of heat pumps connected to the GB power system were represented by 5000-modeled heat pumps multiplied by number (N) as explained in Section 4. Each heat pump model was equipped with the dynamic load control that was described in Section 5.

7.1 Case Study 1

This case study was carried out considering a multiple loss of generations. To generate a frequency incidents similar to the two events which occurred in the GB power system on May 28th 2008 [32], the system parameters shown in Fig. 7 were set as presented in Table 2. These events were caused by the loss of two consecutive generators. The loss of the first generator caused a loss 345MW at time 11:34. Around two minutes later, the loss of the second generator caused additional loss of 1237MW. The system demand was 41MW at that time.

In this case, the first incident (loss of 345MW) was applied to the GB model at time 200 seconds while the second incident (loss of 1237MW) was applied at time 295 seconds.

For reliability, the total low frequency response that can be provided by the heat pumps was chosen to be lower than the ONHP between 11:30-12:00 in Fig. 8. As a result, the total number of heat pumps connected to the GB power system was assumed 1.305 million heat pumps. Considering the accuracy and efficiency of the model that is explained in Section 4, 5000 aggregated heat pump models was simulated. The total power consumption was multiplied by number (N=261) to represent the total 1.305 million heat pumps connected to the GB power system.

Two sets of results during the frequency incident were simulated, with and without controlled heat pumps. Fig. 10 shows the change of power of the heat pumps (see the left axis) and the change of power output of generators (see the right axis). When the first incident occurred, the power consumption of heat pumps reduced to 242MW. After the second incident, the power consumption reduced to a further 787.2MW. The impact of reducing the power consumption of the heat pumps on the frequency drop is shown in Fig. 11. The first frequency drop was reduced from 49.8Hz to 49.92Hz. Following the second incident, the frequency drop was reduced from 49.197Hz to 49.66Hz. Fig. 12 shows that the response from the heat pumps decreased significantly the RoCoF during the earlier sub-seconds following the two events.

Fig. 13 shows the total demand of the heat pumps throughout the event. As can be seen, the dynamically controlled heat pumps effectively deferred 660MW of demand to 30min later. This allowed the system to be restored using stand-by generation (responding after 30min) instead of 1237MW of costly spinning reserve responding in real time.

7.2 Case Study 2

Simulation of the second case study was conducted for low system inertia, i.e., 3.1 second to represent the future GB power system with much generation from wind turbines [30]. Losses of 1800MW, 2000MW, 2500MW, and 3000MW were applied to the model at time 100sec. The system base was assumed 30 GW representing the winter evening. A number of 1.4164 million heat pumps were assumed in this case study. The number of heat pumps were chosen not to exceed the ALFR at the evening time for the future 2030 scenario (see Fig. 9). The simulation results are shown in Figs. 13- 16.

Fig. 13 shows the change of the power of heat pumps with and without the DFC control for a loss of 1.8MW at time 100 sec. It can be seen that after the incident, the power consumption of heat pumps reduced to 0.04 p.u (1.17GW). The reduction of heat pumps energy caused the frequency deviation to decrease from 49.2Hz without DFC control to 49.65Hz with DFC response as shown in Fig. 14.

Figs. 15 and 16 show the average values of the absolute RoCoF between 0.4s to 0.6s and between 0.6s to 0.8s after the time of the incident that would result from imbalance contingencies ranging from 1.8GW to3GW. National Grid aims to keep the threshold level of RoCoF to around 0.125Hz/s [33]. It is clearly observed from Figs. 15 and 16 that the available frequency response from domestic heat pumps reduced the absolute RoCoF significantly at the earlier sub- seconds following the incident, i.e. lowest than 0.125Hz/s.

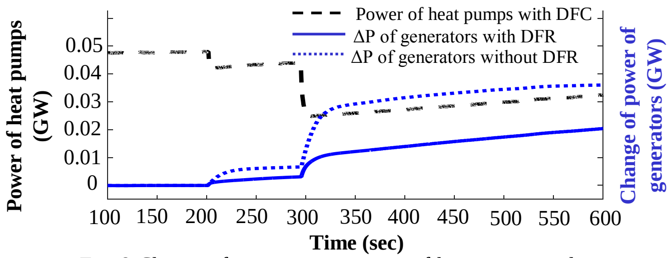

Fig. 9 Change of power consumption of heat pumps and power output of generators (ΔP). H_{eq} =6.5 sec

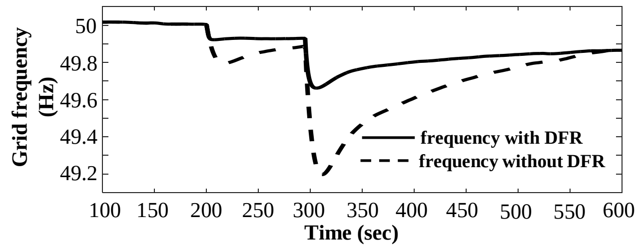

Fig. 10 Variation of system frequency

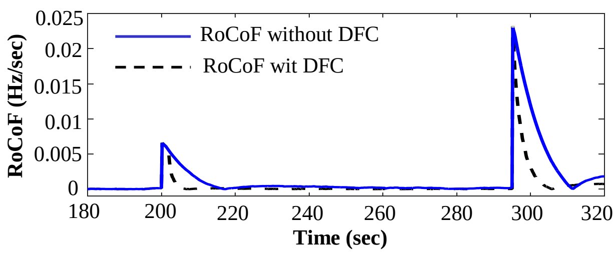

Fig. 11 Grid Rate of Change of Frequency (RoCoF)

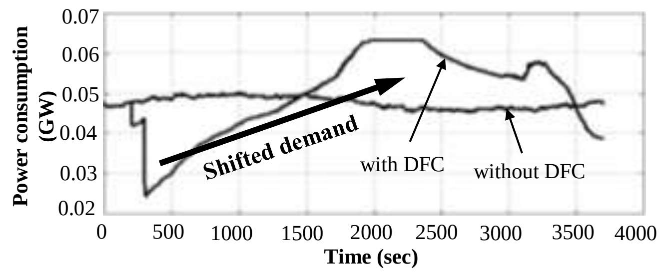

Fig. 12 Total deferred demand of heat pumps to 30 min later

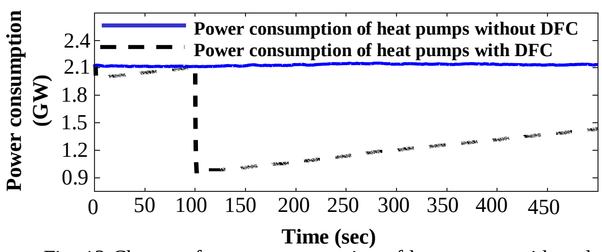

Fig. 13 Change of power consumption of heat pumps with and without frequency control. H_{eq} =3.1 sec

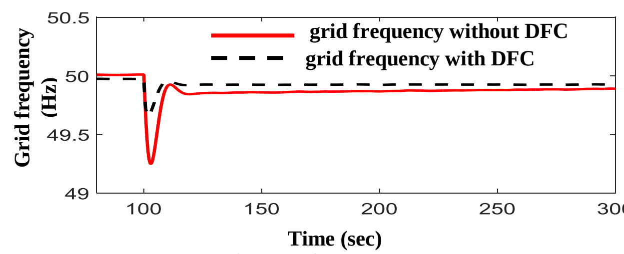

Fig. 14 Variation of system frequency. H_{eq} =3.1 sec

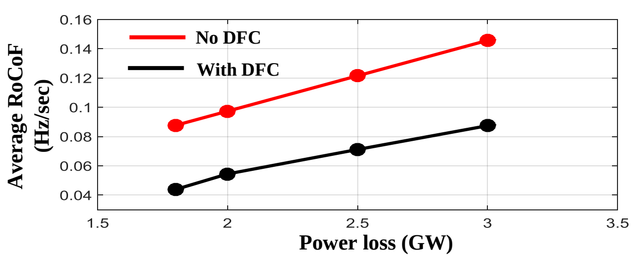

Fig. 15 Average values of absolute RoCoF between 400ms and 600ms following events range from 1.8GW to 3GW. H_{eq}=3.1 sec

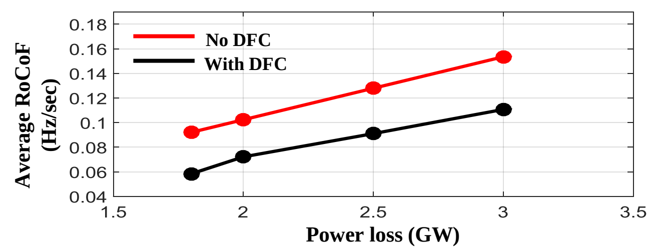

Fig. 16 Average values of absolute RoCoF between 600ms and 800ms following events range from 1.8GW to 3GW. H_{eq}=3.1 sec

8 Conclusion

A decentralized frequency controller for heat pumps was developed to allow the heat pumps alter their power consumption in response to the variation of grid frequency. The dynamic frequency control works without interfering the temperature control function of the buildings.

The heat pump model was then incorporated with the simplified GB power system model. Two highlighted case studies showed that the DFC algorithm has reduced the frequency deviation following a loss of generation. The fast rate of change of frequency, resulted from low system inertia, was halted and maintained within the acceptable threshold limit stated by National Grid.

The contribution of this paper could bring further benefit to the future GB power system in which there is a reduction in system inertia. However, heat pumps cannot sustain their response for long time because their OFF and ON cycles are relatively short. Future work will consider applying the frequency control on appliances with longer ON and OFF states, such as electric vehicles, and water heaters. The future work will also be carried out on a geographic level by integrating the aggregated load control to the detailed Great Britain power system model.

Acknowledgements

The authors would like to thank Element Energy for sharing the heat pumps data which was used in this study. The authors would like to acknowledge Dr. Yun Li and Dr Richard Lerna, the employees at National Grid for facilitating the collaboration visit to National Grid and using the transmission GB power system model.

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