PRIMARY FREQUENCY RESPONSE IN THE GREAT BRITAIN POWER SYSTEM FROM DYNAMICALLY CONTROLLED REFRIGERATORS

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ABSTRACT

Primary frequency response from dynamically controlled refrigerators was investigated. A control algorithm was applied to a model of refrigerators to regulate their power consumption according to the deviation of system frequency. A model of a population of refrigerators equipped with such control was implemented in PowerFactory. A simplified Great Britain (GB) power system model was used to investigate primary frequency response from the refrigerators. Simulation results show that the refrigerators react effectively to the frequency variations by varying their power consumption.

INTRODUCTION

System frequency indicates the balance of generation and demand in a power system. The GB power system requires the frequency to be maintained at 50Hz ±1% except in exceptional circumstances [1]. Conventionally, this power system relies mainly on partly-loaded, fossil fuel generators to maintain the system frequency. These generators provide primary frequency response by regulating their output power and reacting to frequency variations within 10 seconds and adjusting their power output for 30 seconds. According to the National Grid ‘Gone Green Scenario’ [2], the limit of generation in-feed loss in the GB power system will increase from 1320MW to 1800MW. Additional response will be required to cater for a larger in-feed loss in the power system. However, primary frequency response from conventional generators is not efficient because the generators need to be partly-loaded and this will cause more CO_2 emissions. Thus, apart from using generation, changes in demand are useful for supporting the frequency. Electrical loads which are time-flexible [3] can be interrupted for a certain period of time. Such appliances are able to participate in primary frequency response.

There are several control methods to manage the behaviour of load according to system frequency. Direct Load Control (DLC) of the domestic loads to provide primary frequency response using smart meters was investigated in [4]. Temperature-dependent appliances such as refrigerators were used in [5, 6] to respond to the variation of system frequency. The temperature set-points of the appliances were defined to vary linearly with the frequency deviation to decide when to switch off.

This paper investigates a control algorithm for refrigerators to respond to the deviation of system frequency. A model of the dynamically controlled refrigerators was integrated into a simplified GB power system model. Different from most of the load controls which tend to disturb the natural diversity of loads [7], load diversity is maintained by the proposed method.

MODELLING

GB power system model

Figure 1 shows the simplified GB power system model. The characteristics of the generators in the system and damping from the frequency dependent loads are represented through the system inertia $\boldsymbol{H_{eq}}$ (9 seconds) and damping constant $\boldsymbol{D}$ (1.0 p.u.) [8]. The synchronous generators respond to a drop of frequency by increasing their power output. Primary frequency response is achieved by the governor droop control with the equivalent gain $\boldsymbol{R_{eq}}$, which is a combination of droops of all the generator speed governors in the power system. $1/\boldsymbol{R_{eq}}$ is set as -11(p.u./Hz) in the simulation. The typical time constant of governor $\boldsymbol{T_g}$ is 0.2 seconds. A lead-lag transfer function with time constants $\boldsymbol{T_1}$ (2 seconds) and $\boldsymbol{T_2}$ (12 seconds) is placed between governor and turbine to ensure stable performance of the speed control. The mechanical output power is obtained following the turbine time constant $\boldsymbol{T_t}$ (0.3 seconds). The parameters of the model were adjusted based on the frequency event that occurred in GB on May 27th, 2008. The parameters provide a good fit of the frequency curve on that day [4].

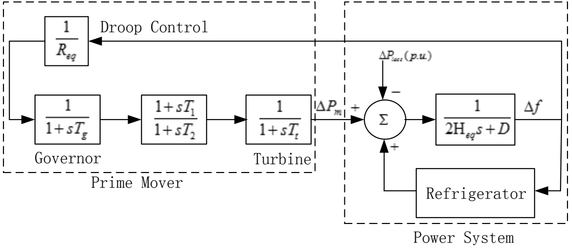

Figure 1. The GB power system model

Dynamically controlled refrigerator model

Refrigerators typically have a switching-ON/OFF cycle of 15 minutes to 1 hour. Switching actions caused by primary frequency response which lasts for around 30 seconds should not disturb the normal operation of a refrigerator [5]. Refrigerators are in service in all seasons, thus they are able to participate in the frequency regulation all the year round [5].

Figure 2 shows a simplified refrigerator comprising a cavity box and an evaporator box. The cavity box stores food. Temperature in the cavity box are measured by a temperature sensor. This temperature ($\boldsymbol{T}$) determines the

ON/OFF state of a refrigerator by comparing the current temperature with the pre-set temperature set-points. For the normal operation of a refrigerator, if temperature is below the low temperature set-point (***T_low***), the refrigerator should switch off; and if the temperature is above the high temperature set-point (***T_high***), the refrigerator should switch on. The cavity box is in thermal contact with both the evaporator and the room. The evaporator is used to pump out heat to the room by a compressor, i.e. work is done by the compressor to release heat to the room. For simplification, the refrigerator model in this paper assumed that no thermal contact between the evaporator and the room is accounted for and all heat leakage occurs from the cavity box, as shown in Figure 2.

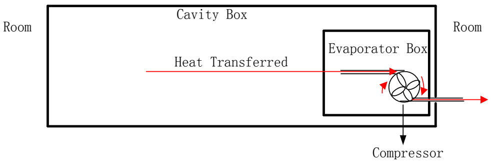

Figure 2. Diagram of a simplified refrigerator

The model of a dynamically controlled refrigerator is illustrated in Figure 3. The input to the model is the grid frequency. The output is the power consumption of the refrigerators.

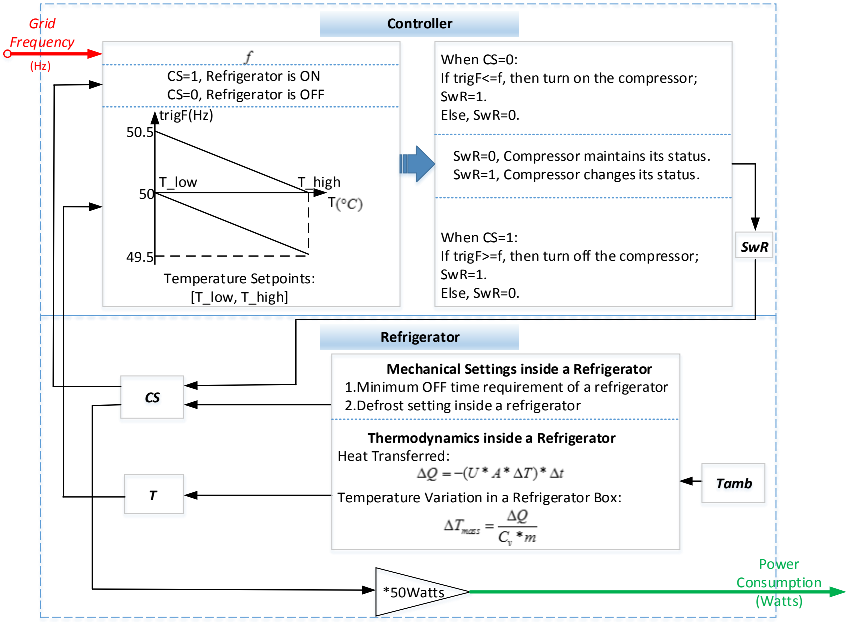

Figure 3. Model of a single dynamically controlled refrigerator

Controller

The first part of the model in Figure 3 is the controller. There are three inputs to the controller: grid frequency (***f***) of the power system, the compressor status (***CS***) and temperature (***T***) of a refrigerator. ***CS*** represents the ON/OFF of a refrigerator. The controller needs to consider the ***CS*** because when frequency drops, only the ON-refrigerators are able to respond and switch off. When frequency rises, only the OFF-refrigerators are able to respond and switch on. The temperature inside a refrigerator is required to decide when to switch on/off a refrigerator. The highest temperature is always the first to switch on, while the lowest temperature is always the first to switch off.

Trigger frequency (***trigF***) is defined as a linear function of temperature (***T***). It is the calculated frequency at which the compressor status of a refrigerator will be changed. The linear function is defined so that when the frequency drops, the refrigerators will be triggered to switch off from the lowest to the highest temperature. When the frequency rises, the refrigerators will switch on to absorb the extra power from the highest to lowest temperature. This rule gives the order to switch the refrigerators.

In the case of frequency-drop, if ***f*** drops lower than ***trigF***, this refrigerator will switch off and vice versa, as illustrated in Figure 3. The switch recommendation (***SwR***) is the output of the controller. It informs the refrigerator whether to change its status or not.

To guarantee the load diversity of a population of refrigerators, ***trigF*** of each individual refrigerator is set in a diverse way by introducing a random element to the linear relationship in Figure 3. Over a population of refrigerators, this random element still preserves the linear relationship on average. The random ***trigF*** of each refrigerator is calculated at every sampling time, which maintains the load diversity of refrigerators.

A special period defined as the 'recovery period' is considered when most refrigerators need to recover after responding to a frequency event. In the case of a frequency-drop event, the refrigerators which switch off need to switch on to recover as they reach the limit of their inside temperature set-points. A simultaneous switching-on action of most refrigerators will cause a second frequency-drop in the power system. To prevent the second frequency-drop due to the simultaneous recovery, the recovery of OFF-state refrigerators will take place before the system frequency recovers to 50Hz. The OFF-state refrigerators are switched on starting from the one with the highest temperature.

Refrigerator Model

The second part of the model in Figure 3 is the refrigerator. The input to the refrigerator is the switching recommendation (***SwR***) received from the controller and the ambient room temperature ($\boldsymbol{T_{amb}}$). Ambient room temperature influences the refrigeration loads. Winter load can be two thirds of that in summer [5].

Two thermal equations are used as shown in Figure 3. One is the heat transfer function, the other is the temperature variation in a body. $\boldsymbol{\Delta Q}$ is the amount of heat transferred (J), $\boldsymbol{A}$ is the area of thermal contact (m^2), $\boldsymbol{U}$ is the U-value which is the overall heat transfer coefficient of the thermal contact ($Jm^{-2}K^{-1}s^{-1}$), $\boldsymbol{\Delta T}$ is the temperature difference between the two sides of a thermal contact (K), $\boldsymbol{\Delta T_{mass}}$ is the variation of temperature at a body of mass m (kg) such as the mass of the cavity box, $\boldsymbol{C_v}$ is the specific heat capacity of the mass ($Jkg^{-1}K^{-1}$). Based on the two thermal equations, the thermodynamics inside a refrigerator are considered in the cavity and the evaporator box separately as depicted in Figure 2.

In the cavity box, there is heat transferred through both of its thermal contacts with the evaporator and ambient room. This causes the variation of temperature in the cavity box which is written as a first order differential equation as shown in Equation (1):

$$\frac{\Delta \mathrm{T}^{\mathrm{Ca}}_{mass}}{\Delta t} = -\frac{U^{CaEv} * A^{CaEv}}{C_v^{Ca} * m^{Ca}} * \Delta T^{CaEv} - \frac{U^{CaEv} * A^{CaAmb}}{C_v^{Ca} * m^{Ca}} * \Delta T^{CaAmb} \quad (1)$$

where *'Ca'*, *'Ev'* and *'Amb'* are cavity, evaporator and ambient room respectively.

Similarly in the evaporator box, there is heat transferred at the thermal contact with the cavity. Work done by the compressor influences the temperature in the evaporator. The temperature variation in the evaporator box is described by Equation (2):

$$\frac{\Delta \mathrm{T}^{\mathrm{Ev}}_{mass}}{\Delta t} = -\frac{U^{CaEv} * A^{CaEv}}{C_v^{Ev} * m^{Ev}} * \Delta T^{CaEv} - \frac{Q_m}{C_v^{Ev} * m^{Ev}} \quad (2)$$

where $\boldsymbol{Q_m}$ is the power consumption of the compressor in *Watts*.

To model a population of refrigerators separately, the parameters and initial value of the variables of each refrigerator are selected within a typical range randomly using a Monte Carlo simulation.

The mechanical settings which influence the ON/OFF cycles of a refrigerator are considered as shown in Figure 3. The minimum OFF time between compressor cycles is to allow the pressure in the cooling circuit to drop before switching on the compressor again. The defrost setting also influences the ON/OFF status as if frost occurs, the refrigerator needs to be OFF until the frost melted.

SIMULATION RESULTS

A model of a number of individual refrigerators with dynamic control was integrated to the GB power system model in PowerFactory as shown in Figure 1. A sudden loss of generation of 1320MW (with a base of 25GW) was applied to the system at t=10 second. Case studies were carried out with different numbers of refrigerators aggregated as shown in Table 1. The number of refrigerators in each case is scaled up by multiplying a coefficient to represent the total number of refrigerators in GB, i.e. 40 million. The simulation results are shown in Figures 4-7.

Table 1: Number of refrigerators aggregated in a model

Classification	Case0	Case1	Case2	Case3
Number of refrigerators	0	100	1,000	10,000

Figure 4 compares the variation of system frequency of the four cases. At t=10 second, there is an obvious frequency-drop due to the sudden loss of generation. In the cases containing frequency responsive refrigerators, the drop of frequency is less severe than the case without refrigerators. Figure 5 compares the power consumption of refrigerators. The power consumption of the model in Case2 almost coincides with that of the model in Case3. The power consumption of the model in Case1 deviates from that of the model in Case2 and Case3 significantly. Figure 6 compares the primary frequency response of conventional generators in the four cases. The amount of primary frequency response from conventional generator in the case of no refrigerators is larger than the cases with refrigerators. This indicates that the refrigerators can help reduce the requirements on conventional generators in a frequency event. Figure 7 compares the power consumption of refrigerators in the four cases in a long timeframe. This period includes the time when most refrigerators are in the recovery period and start to consume power to satisfy their internal temperature. The power consumption in Case2 is close to that in Case3, while the power consumption in Case1 is different from that in Case3 significantly.

According to Figure 5 and Figure 7, it is shown that a model of 1,000 refrigerators aggregated should be suitable to represent all the refrigertors in the GB power system and provide a compromise between accuracy and simulation speed. A model of 100 refrigerators aggregated gives low accuracy while 10,000 refrigerators aggregated takes too much simulation time.

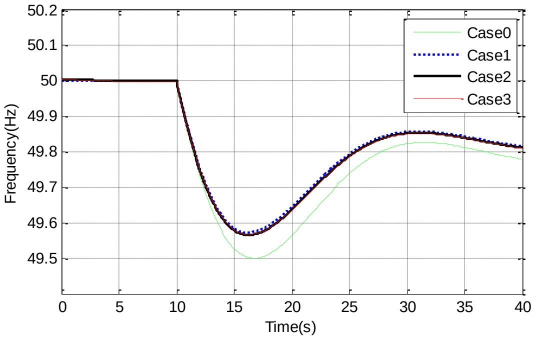

Figure 4. System frequency variation in the primary frequency response timeframe

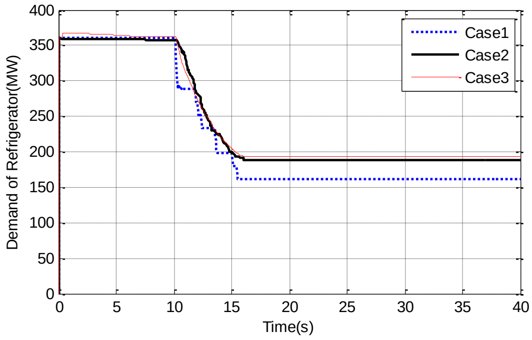

Figure 5. Response from dynamic refrigerators in the primary frequency response timeframe

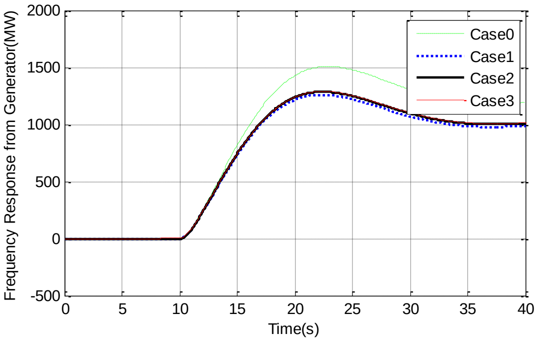

Figure 6. Response from conventional generators in the primary frequency response timeframe

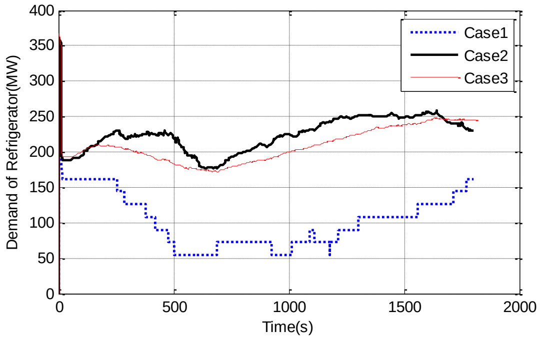

Figure 7. Power consumption of dynamic refrigerators after providing the primary frequency response

Figure 7 also shows that when the refrigerators are switching on to recover, the control helps avoid the sudden simultaneous switching-on of refrigerators. The diversity of the refrigerators is still maintained in this period.

CONCLUSION

A refrigerator model with dynamic control was developed in the software PowerFactory. An aggregated model of large numbers of the dynamically controlled refrigerators was integrated to the GB power system model. Simulation results show that the dynamically controlled refrigerators provide fast primary frequency response without major impacts on the normal operation of refrigerators. The refrigerators help regulate the system frequency and thus reduce the regulation requirements of conventional generators. The load diversity is maintained during and after a frequency event.

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