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Performance of industrial melting pots in the provision of dynamic frequency response in the Great Britain power system

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HIGHLIGHTS

- Thermodynamics of Melting Pot (MP) loads is modeled based on field measurements.
- Power consumption of MPs is controlled to keep varying with grid frequency changes.
- Frequency response (FR) of MPs is similar but faster than that of generators.
- FR provided by loads can mitigate the impact of reduced system inertia.
- Firm FR in the GB power system is most beneficial for load aggregators to tender.

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ABSTRACT

As a result of the increasing integration of Renewable Energy Source (RES), maintenance of the balance between supply and demand in the power system is more challenging because of RES's intermittency and uncontrollability. The smart control of demand is able to contribute to the balance by providing the grid frequency response. This paper uses the industrial Melting Pot (MP) loads as an example. A thermodynamic model depicting the physical characteristics of MPs was firstly developed based on field measurements carried out by Open Energi. A distributed control was applied to each MP which dynamically changes the aggregated power consumption of MPs in proportion to changes in grid frequency while maintaining the primary heating function of each MP. An aggregation of individual MP models equipped with the control was integrated with the Great Britain (GB) power system models. Case studies verified that the aggregated MPs are able to provide frequency response to the power system. The response from MPs is similar but faster than the conventional generators and therefore contributes to the reduction of carbon emissions by replacing the spinning reserve capacity of fossil-fuel generators. Through the reviews of the present balancing services in the GB power system, with the proposed frequency control strategy, the Firm Frequency Response service is most beneficial at present for demand aggregators to tender for. All studies have been conducted in partnership between Cardiff University, Open Energi London – Demand Aggregator, and National Grid – System Operator in GB to ensure the quality and compliance of results.

1. Introduction

The increasing integration of Renewable Energy Source (RES) will reduce the capacity of fossil-fuel generators and therefore reduce the Green House Gas (GHG) emissions. However, the intermittency of RES causes power quality issues [1] including voltage and frequency fluctuations and harmonics that will affect power system planning, operation and evaluation [2]. The uncertainties in the power supply challenge the real-time power balance between generation and demand of the entire system and consequently lead to the stability issue of grid frequency. Furthermore, the integration of RES through power electronics reduces the system inertia. This will cause even greater and faster frequency variations in case of any imbalances between supply and demand.

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The conventional solution of regulating grid frequency mainly relies on the spinning reserve of frequency-sensitive generators. In order to increase or decrease the power output in response to frequency deviations, the generators are required to be partly-loaded which results in considerable opportunity costs [3]. Also, running at reduced power output means running at reduced fuel efficiency for most generation technologies [3]. There are also the costs of wear-and-tear of generators caused by the continually changing outputs [3]. As reported by the Great Britain (GB) System Operator – National Grid, the cost of the procurement of frequency response only in July 2014 was £14.27 million [4]. The cost will be increased further because the uncertain supply from RES requires more capacity of frequency response. In addition, the frequency-sensitive generators are mainly large fossil-fuel generators and therefore aggravate the GHG emissions. One alternative low carbon solution is the use of Energy Storage System (ESS), such as the flywheel energy storage system and the battery energy storage system, when a large amount of variability exists in the system. Ref. [5] reports that several projects have been carried out which validated the control of BESS charging/discharging and the power converters can support grid frequency regulation and to enhance the power quality. However, most grid-scale ESS is still considered as a high cost technology [6].

Recent research shows the potential of managing the existing network assets – flexible loads in the power system, to mitigate the risks caused by the integration of RES and to reduce the overall operational costs of the power system [7]. Through measurements, quantifications and estimations on the flexibility of flexible loads, the loads can be scheduled to provide peak shaving and load shifting [8–10]. This reduces the congestions in the electric network during the peak demand period, facilitates the integration of RES and also reduces the requirements of the costly peak power plants. Demand is also able to be controlled to change the power consumption in response to regulation signals for different applications. For example, as illustrated in [11], demand response was coordinated with the battery energy storage to provide tie-line smoothing of a Microgrid. Furthermore, as compared in [12], demand response is able to provide a greater reduction in the electricity bill in the residential sector compared with the battery energy storage, in the context of the installation of self-consumed photovoltaic systems. Ref. [13] developed an event-driven smart home controller on the smart appliances to respond to the Time of Use tariff which reduces the customer bills.

As demand can provide response to the aforementioned regulation signals, demand is also considered to be controlled to change the power consumption in order to provide balancing services and to gain benefits from the System Operator.

The GB System Operator at present procures balancing services including the frequency response services and the reserve services [14] in order to balance the supply and demand and to maintain the grid frequency at 50 Hz. Among the services, demand mainly participates through the Frequency Control by Demand Management (**FCDM**) and the Short Term Operating Reserve (**STOR**) services.

FCDM [15] is a static response to severe frequency drops and mainly procured from industrial loads such as steelworks and smelting aluminum. Demand needs to be switched off in 2 s when frequency falls below pre-set set-points, e.g. at 49.7 Hz, and remain off for 30 min. **STOR** [16] is a service for the provision of additional active power from generation and/or demand reduction. It is needed, at certain times of the day, to deal with actual demand being greater than forecast demand and/or plant unavailability. Demand is required to deliver the power reduction in 240 min from receiving instructions from National Grid, and to sustain the demand reduction for at least 2 h when instructed.

However, both services aim at switching off loads for the lack of generation in the power system. The services are considered as the static or non-dynamic frequency response which usually is a discrete service triggered at a defined frequency deviation [17]. In the future, with the uncertainty from RES generation, there will possibly be redundant generation in the system. Therefore, it is expected that demand can be regulated to increase the power consumption when the system needs, for instance, in response to the increase in grid frequency. A dynamic frequency response is therefore expected which is a continuously provided service to manage the normal second by second power changes on the system [17]. At present, such dynamic frequency response is mainly provided by conventional generators through the droop control.

Time-flexible loads, e.g. thermostatically controlled loads such as domestic water heaters and domestic refrigerators, were considered to be suitable for the provision of grid frequency response [18,19]. The power consumption of the loads can be shifted in time as long as their temperature stays within the pre-set set-points. However, these domestic loads usually have small power consumption (e.g. 4.5 kW for water heaters and 0.1 kW for refrigerators) and hence require an aggregation of great numbers of loads in order to provide a notable response in the context of the GB power system with a minimum demand of approx. 20 GW. This makes the investment process rather long and costly. In addition, the temperature set-points of water heaters and refrigerators (e.g. 5.6 °C and 1 °C) are narrow which will cause unexpected synchronization in their operating status especially during a severe frequency drop [20] which switches all available loads off. After the frequency incident, these loads will then be switched on simultaneously which leads to a second disturbance in grid frequency. Furthermore, as illustrated in [19], variations of temperature set-points of thermal loads in order to provide frequency control sometimes cause the internal temperature of a load to be outside the normal operating range.

To minimize the adverse impacts of using demand for grid frequency response, this paper utilizes the industrial heating loads – Melting Pots (MPs) as an example, to dynamically provide grid frequency response both upwards and downwards without undermining the primary heating function of the loads. The loss of diversity amongst loads is reduced which alleviates the impact of synchronization of loads after the provision of frequency response. A thermodynamic model of individual MPs was developed and validated based on the field measurements carried out by Open Energi. The model can be a generic model and be applied to the modelling of different types of thermal loads. The only required parameters for the model are the temperature variations and power consumption of the loads which can be easily measured, and there is no need for the physical thermal parameters such as the specific heat capacity of the materials or the area of thermal contacts. Case studies were undertaken to show the performance of the controlled MPs on the GB power system models that are used by National Grid at present. The potential benefits of demand to participate in the balancing services based on the present operational practice of the GB power system were also discussed and compared.

2. Model of melting pot loads and validation

The industrial Melting Pots (MPs) are electrically heated loads which are used for storing molten metal in readiness for casting. Inherently, a hysteresis temperature control is used in each MP to control the On/Off state and maintains the molten metal at the specified temperature. The specified temperature is usually high, for example, the molten aluminum is required to be maintained at around 730 ± 25 °C. The power consumption of a MP is typically 30 kW when it is at On-state. Normally, MPs are switched off outside operating hours as shown in Fig. 1 (see before 0 h) which depicts the field measurements on a MP. The model and control of MPs in this paper only consider the hours when a MP is operating within the specified temperature set-points (see the zoomed figure in Fig. 1).

2.1. Thermodynamics in a melting pot

In order to ensure that any extra controls on the MPs will not undermine the inherent temperature performance, a thermodynamic model depicting the temperature variations of each MP was developed. Although the entire industrial process of MPs is complicated, for simplicity, each MP was depicted by a heat transfer process and represented by a first order differential equation as shown in (1) which was analysed and obtained based on [21].

$$\frac{d\mathrm{T}_{\mathrm{MP}}}{dt} = \frac{P \times s_{\mathrm{MP}}}{c_v \times m} - \frac{U \times A \times (\mathrm{T}_{\mathrm{MP}} - \mathrm{T}_{\mathrm{Amb}})}{c_v \times m} \quad (1)$$

where T_{MP} (°C) is the temperature inside a MP, P (W) is the power consumption of a MP, c_v (Jkg^{-1} °C^{-1}) is the specific heat capacity of a MP, m (kg) is the thermal mass, U (W m^{-2} °C^{-1}) is the overall heat transfer coefficient, A (m^2) is the contact area of heat transfer, $\mathrm{T}_{\mathrm{Amb}}$ (°C) is the surrounding temperature, s_{MP} is a binary number (0/1) representing the On-state (s_{MP} = 1) or Off-state (s_{MP} = 0).

The variations of MP's temperature can be obtained by solving (1) depending on the On/Off state s_{MP}. However, in real conditions, it is difficult to obtain the physical parameters for each MP, e.g. U, c_v etc. Instead, it is much simpler to measure the On and Off period of each MP and the form of the temperature variations. Therefore, a simplified curve-fit model of the MPs was developed in the following subsections based on field measurements and the simplified model can accurately depict the thermodynamics, i.e. variations of temperature with time.

2.2. Definition of t_{ON} and t_{OFF} of a Melting Pot

As depicted by the zoomed figure in Fig. 1, the increase and decrease of temperature with time show nearly linear variations with time. A schematic diagram of heating and cooling of a MP is plotted in Fig. 2. Please note temperature is denoted as 'T' while the On/Off period of a MP is denoted as italic 'T'. The MP is switched On at $\mathrm{T}_{\mathrm{low}}$ (point A) and the MP temperature T_{MP} follows the curve AB. Conversely, the MP is switched Off at $\mathrm{T}_{\mathrm{high}}$ (point B) and T_{MP} follows the curve BC. However, when a MP is used for frequency control, the On/Off state of a MP will be interrupted by frequency violations. The MP can therefore be switched On/Off at an intermediate temperature, i.e. any temperatures between $\mathrm{T}_{\mathrm{low}}$ and $\mathrm{T}_{\mathrm{high}}$. For example, as shown in Fig. 2(a), MP is On at D. If the heater remains On, temperature will follow the curve DB for a time t_{ON} until $\mathrm{T}_{\mathrm{high}}$ is reached at B. However, if the heater is switched Off at D, temperature will follow the curve DE for a time t_{OFF} until $\mathrm{T}_{\mathrm{low}}$ is reached at E. A similar process applies as shown in Fig. 2(b) when a MP is initially Off at the point M.

The minimum possible value of t_{ON} is zero and occurs when temperature reaches $\mathrm{T}_{\mathrm{high}}$. The maximum possible value of t_{ON} is the On-period T_{ON} when temperature is at $\mathrm{T}_{\mathrm{low}}$. Similarly, the range of t_{OFF} is from zero to T_{OFF}.

t_{ON} and t_{OFF} were measured on two 32 kW and two 44 kW real MPs at different times of several days. At different temperatures of a MP, a pair of t_{ON} and t_{OFF} were taken by recording the time of the MP to remain On and remain Off. As illustrated in Fig. 3, the temperature data varying with time can firstly be recorded by the field measurements. For a given temperature T, the relevant time when temperature equals to T is obtained, i.e. t_{D}, t_{F} in Fig. 3. The acquisition of t_{ON} and t_{OFF} are therefore obtained as shown in Fig. 3. The measured pair of t_{ON} and t_{OFF} at each temperature is therefore obtained and depicted by a cross in Fig. 4.

The analytical expression of the relationship between t_{ON} and t_{OFF} in Fig. 4 was derived by the curve fitting toolbox (cftool) of Matlab and is shown by (2) and (3).

$$t_{\mathrm{ON}} = -\frac{t_{\mathrm{OFF}} \times T_{\mathrm{ON}}}{T_{\mathrm{OFF}}} + T_{\mathrm{ON}} \quad (2)$$

$$t_{\mathrm{OFF}} = -\frac{t_{\mathrm{ON}} \times T_{\mathrm{OFF}}}{T_{\mathrm{ON}}} + T_{\mathrm{OFF}} \quad (3)$$

The curve fitting method based on field measurements provides a generic way to obtain the relationship between t_{ON} and t_{OFF} for different types of thermal loads with various shapes of temperature variations with time. The modelling method is therefore able to be applied to different thermal loads and even load types with on/off cycles.

2.3. Simplified curve-fit model of a melting pot

A simplified curve-fit model of each Melting Pot (MP) was developed in Matlab/Simulink based on the relationship of t_{ON} and t_{OFF} as shown in Fig. 4. Thermodynamics of a MP, i.e. variations of the MP temperature over time, were modelled using variations of t_{ON} and t_{OFF} over time as illustrated by Fig. 2.

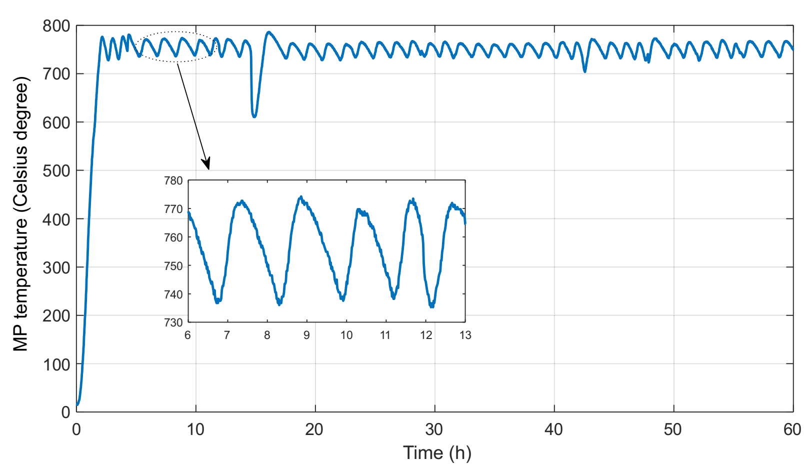

Fig. 1. Field measurements of temperature of a MP from GB demand aggregator, Open Energi.

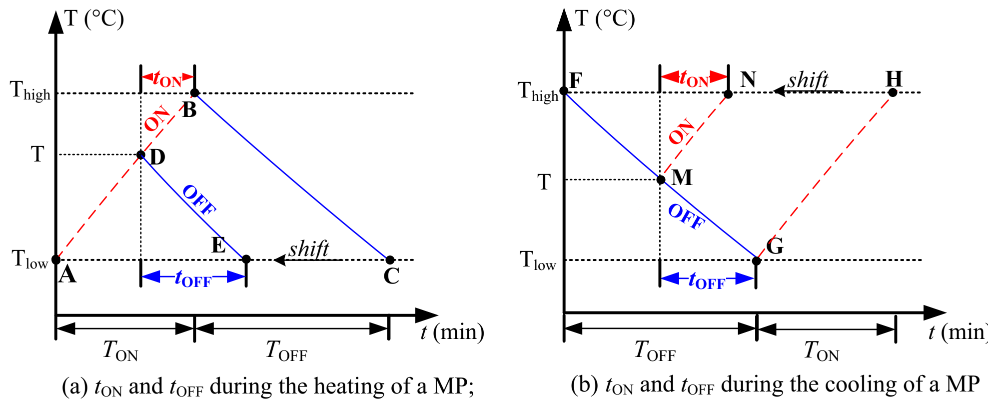

Fig. 2. (a) t_{ON} and t_{OFF} during the heating of a MP; (b) t_{ON} and t_{OFF} during the cooling of a MP.

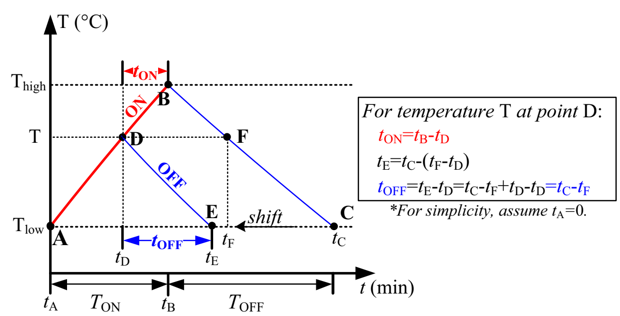

Fig. 3. Acquisition of t_{ON} and t_{OFF} from the field measurements.

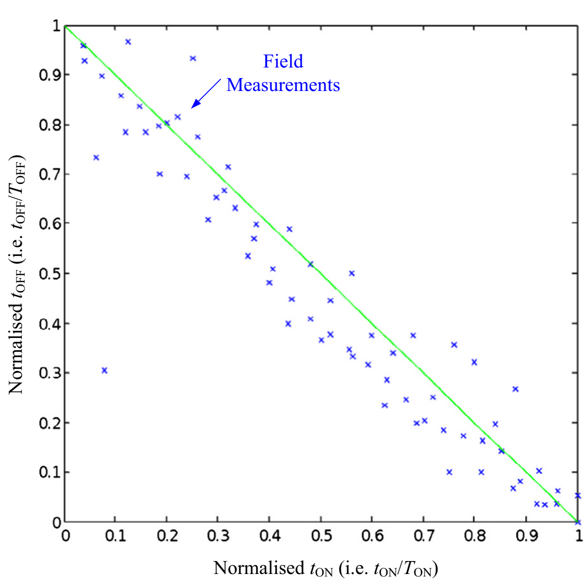

Fig. 4. Relationship of t_{ON} and t_{OFF} of a MP from field measurements and the curve fitting result (t_{ON} is normalized with maximum t_{ON} (i.e. T_{ON}) and t_{OFF} is normalized with maximum t_{OFF} (i.e. T_{OFF})).

[Table 1](#) is used to model the variations of t_{ON} and t_{OFF} for all possible thermal status (see 1st column). Δt is the time step (e.g. 10 ms in simulations). Eq. (5) was based on (3) and Eq. (6) was based on (2).

MPs were assigned different initial t_{ON} and t_{OFF} in order to reflect the diversity amongst MPs. t_{ON} was assigned randomly in the range of 0 to T_{ON}. t_{OFF} was assigned randomly in the range of 0 to T_{OFF}. The value of T_{ON} was distributed randomly within the range of 6–41 min, which was obtained from the field measurements on different MPs. Similarly, T_{OFF} was distributed randomly within the range 19–69 min.

Table 1
t_{ON} and t_{OFF} of a MP model.

On/Off of a MP	Variations of t_{ON} and t_{OFF}	
Remain On at t	$t_{ON}(t+\Delta t) = t_{ON}(t) - \Delta t$	(4)
Switched On at t	$t_{OFF}(t+\Delta t) = T_{OFF} \times \left(-\frac{t_{ON}(t)-\Delta t}{T_{ON}} + 1\right)$	(5)
Remain Off at t	$t_{ON}(t+\Delta t) = T_{ON} \times \left(-\frac{t_{OFF}(t)-\Delta t}{T_{OFF}} + 1\right)$	(6)
Switched Off at t	$t_{OFF}(t+\Delta t) = t_{OFF}(t) - \Delta t$	(7)

Take a MP from the site measurements with the following parameters of On-period of approx. 21 min and Off-period of 37 min, high and low temperature set-points of 747.5 °C and 731 °C as an example to validate the simplified curve-fit model. A thermodynamic model of the MP depicting the variations of temperature with time [22] was also developed for the MP for comparison as shown in (8) and (9).

$$s_{MP} = 1: \ T_{MP}(t) = 731 + 26.1026(1 - e^{-t/21}) \tag{8}$$

$$s_{MP} = 0: \ T_{MP}(t) = 747.5 - 26.1026(1 - e^{-(t-21)/37}) \tag{9}$$

Fig. 5 shows the temperature variations obtained from the curve-fit model, the thermal model and the field measurements. The temperature variations and On/Off cycles of the three nearly match each other. The simplified curve-fit model was validated to represent the thermodynamics of MPs and showed a high computational efficiency for the studies of the performance of grid-scale MP loads.

3. Control of melting pots for frequency response

Fig. 6 briefly depicts the control strategy of a Melting Pot (MP) for frequency response. The inherent hysteresis temperature control constantly measures temperature (T_{MP}) and compares with the specified temperature set-points (T_{high} and T_{low}) in order to determine the On/Off state of the MP.

A dynamic controller for frequency control is added on each MP as shown in Fig. 6 which constantly measures the grid frequency (f), compares it with a pair of frequency set-points (F_{ON} and F_{OFF}) of each MP, and then determines to switch On/Off the MP. F_{ON} and F_{OFF} are randomly distributed within the range of 49.5–50 Hz and of 50–50.5 Hz. If frequency drops lower than F_{OFF} ($f < F_{OFF}$), the MP is switched Off in order to respond to the drop in frequency.

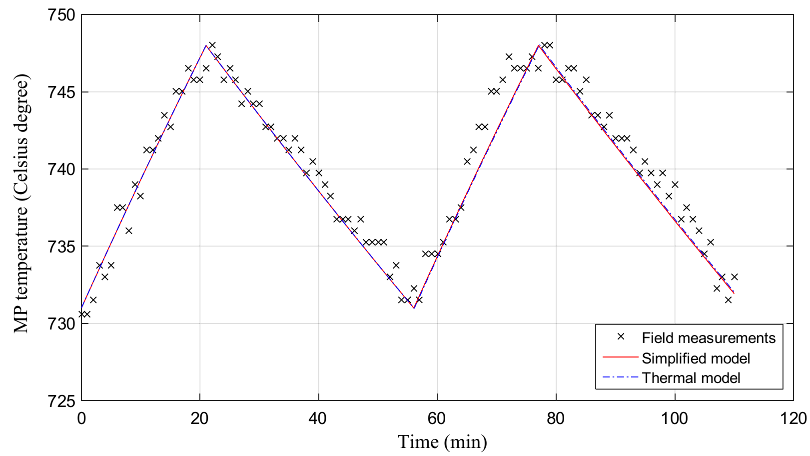

Fig. 5. Comparison of temperature of a MP in the site measurement, thermal model and simplified model.

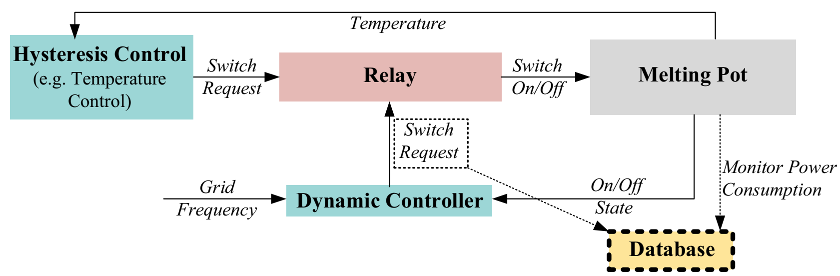

Fig. 6. Control strategy of one melting pot for frequency response.

Alternatively, if frequency increases higher than F_{ON} ($f > F_{ON}$), the MP is switched On in order to respond to the increase in frequency. Therefore, once frequency varies outside the dead-band between F_{ON} and F_{OFF}, the dynamic control will override the hysteresis temperature control and turn On/Off the MP.

However, if temperature in the MP is outside the temperature set-points, the MP will be switched according to temperature control regardless of any frequency changes. This process was depicted by the flowchart shown in Fig. 7 which ensures that the extra dynamic controller will not undermine the temperature performance of the MP.

Specifically, as the shaded diagram in the flowchart marked in Fig. 7, it makes the decision whether it is the responsive period ('Y'), i.e. frequency is deviating from nominal 50 Hz, or it is in the recovery period ('N'), i.e. frequency is returning to nominal 50 Hz. During the responsive period, as aforementioned, MPs will be switched according to the comparison between the frequency and its set-points. While during the recovery period, F_{ON} or F_{OFF} of each MP are updated following the frequency recovery in order to revert back to the previous MP's state before the occurrence of the frequency incident. The updates of F_{ON} and F_{OFF} are illustrated below:

- If $f < 50$ Hz, and f is moving towards 50 Hz (i.e. $f(t) < 50$ Hz & $f(t) > f(t - \Delta t)$); F_{OFF} will be updated according to (10) which moves F_{OFF} towards 50 Hz. Until F_{OFF} reaches 50 Hz; F_{OFF} is re-assigned to be the minimum value at 49.5 Hz, and is therefore smaller than f. This switches the MP back to On-state as $f > F_{OFF}$.

$$F_{OFF}(t) = F_{OFF}(t - \Delta t) + f(t) - f(t - \Delta t) \quad (10)$$

- If $f > 50$ Hz, and f is moving towards 50 Hz (i.e. $f(t) > 50$ Hz & $f(t) < f(t - \Delta t)$); F_{ON} will be updated according to (11) which moves F_{ON} towards 50 Hz. Until F_{ON} reaches 50 Hz; F_{ON} is re-assigned to be the maximum value at 50.5 Hz, and is therefore greater than f. This switches the MP back to Off-state as $f < F_{ON}$.

$$F_{ON}(t) = F_{ON}(t - \Delta t) + f(t) - f(t - \Delta t) \quad (11)$$

In summary, by aggregating a population of MPs, the proposed dynamic control of MPs provides a linear response to frequency changes which is similar to the droop control of the conventional generators. MPs are guaranteed to share equal opportunity to be switched in response to frequency deviations. The continuous updates of frequency set-points recover the power consumption of MPs dynamically following the frequency recovery. The MP that responded first will be the first to revert back to the pre-event state. The control of each MP takes the temperature control as a priority which will not undermine the primary function of heating. The control strategy can be a generic method and applied to other loads such as other heating loads and small-size water pumping loads. In addition, the control strategy can also be applied to distributed small-size storage units for frequency response such as domestic battery energy storage units. Following the frequency deviations, rather than all the units start charging/discharging, the number of responding units can be designed to vary in linear with frequency deviations. The method can reduce the number of charging and discharging of each energy storage unit and hence prolong the lifetime of the energy storage units.

4. Case studies and discussions

Four case studies were undertaken in order to test the performance of the dynamic frequency control of Melting Pots (MPs). Discussions on the service provision from demand and the participation of such controlled loads in the frequency response services based on the present operational practice in the GB power system are given in Section 4.5.

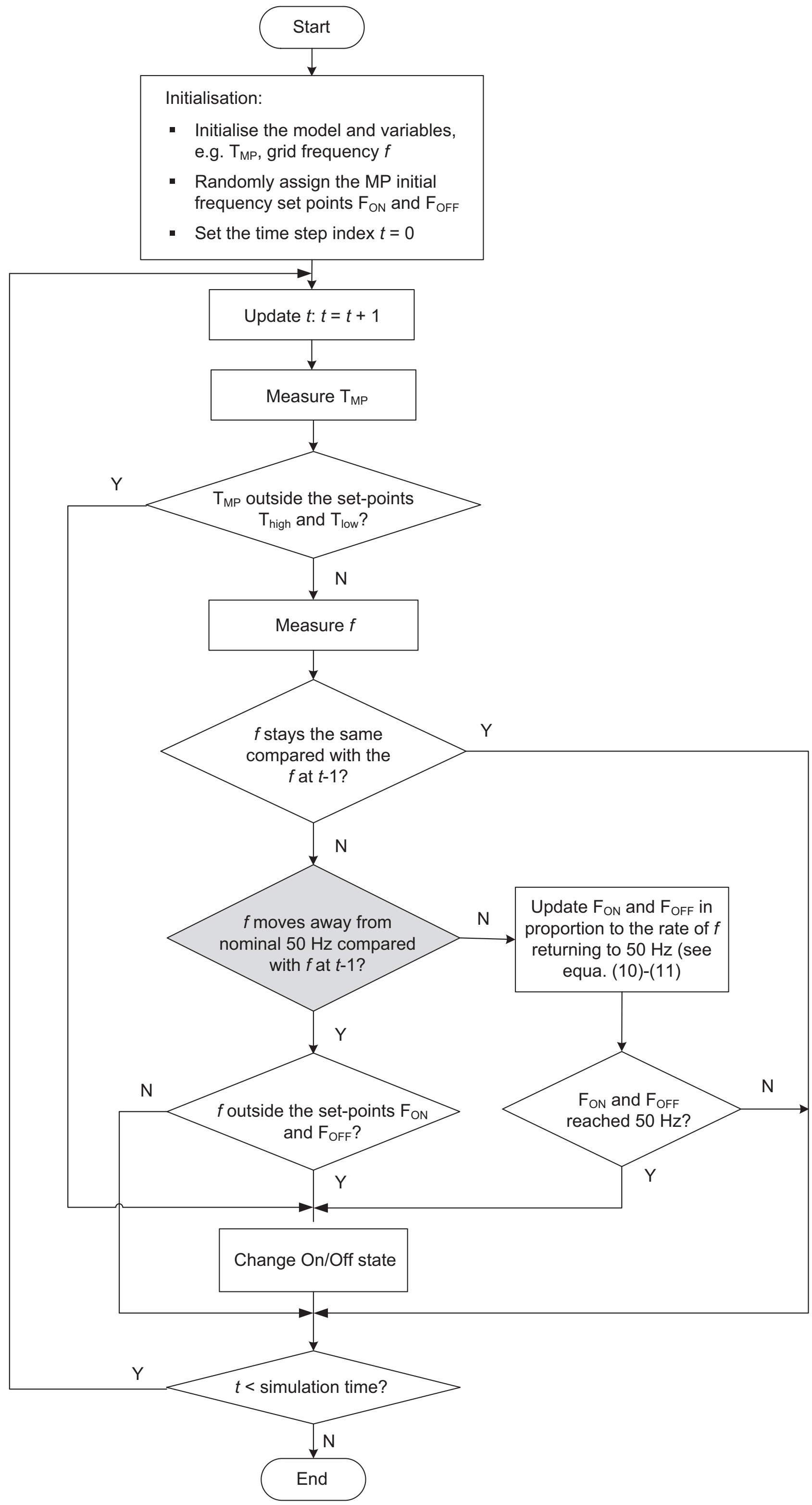

Fig. 7. Flow chart of the control algorithm at one step for each melting pot.

4.1. Mps' response following continuous normal frequency variations

A one-hour frequency profile (second-by-second frequency data) from National Grid [23] recording the period 15:15–16:15 on 9th Jan 2015 was selected and injected into an aggregation of 50,000 models of MPs (30 kW per MP) with the dynamic frequency control. The profile includes a frequency drop to 49.7 Hz as shown in Fig. 8 (see the 1st subplot). The power consumption of MPs was depicted in the 2nd subplot of Fig. 8. It can be seen, the power consumption of MPs continuously changing in proportion to frequency deviations.

The temperature curve of one MP was recorded in the 3rd subplot of Fig. 8 during the one-hour as an example. Because the MP was originally at Off-state (i.e. MP temperature was decreasing), the MP was unable to be switched Off in response to the severe frequency drop at around 40 min. However, the MP temperature reached its low set-point at 715 °C and was switched On at approx. 48 min. It was then switched Off at 50.5 min in response to the frequency drop. It can be seen, the extra frequency control does not interfere the inherent temperature performance of MPs. Under normal frequency variations, the required response from each MP is short. According to Open Energi's site measurements and statistical analysis [24], 90% of switches caused by the dynamic frequency control last less than 5 min. Compared with the On/Off cycles of most MPs, the '⩽5-min' response period is small and hence the normal operation of MPs is guaranteed.

4.2. Mps' response following abnormal frequency incidents

According to the GB power system frequency control requirements as depicted by Fig. 9, there will possibly be (but rarely happen) abnormal frequency incidents caused by unexpected trips of large generators. The largest infeed loss that the transmission system must be able to sustain is 1.8 GW and the maximum grid frequency changes is limited to −0.8 Hz. The grid frequency is required to return to 49.5 Hz within 1 min [25].

In order to investigate the performance of MPs during the abnormal frequency incidents, the aggregated 50,000 MP models with the frequency control was connected with a one-bus GB power system model from National Grid. The schematic diagram of the model is depicted by Fig. 10.

The system model was developed in PowerFactory and set to simulate an extreme system condition with a low system demand of 20 GW and quite low system inertia of 1 s representing the future power system with high integration of RES.

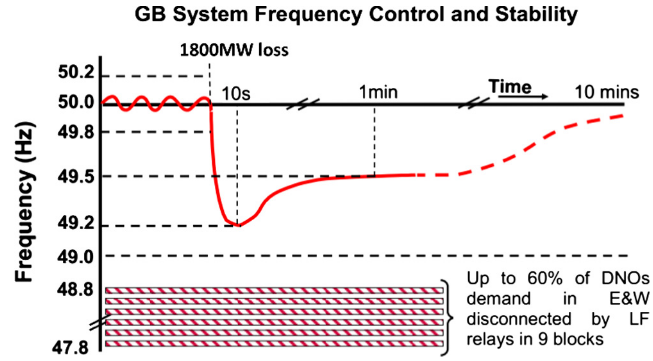

Fig. 9. Frequency control and stability of the GB power system (modified figure based on [25,26]).

4.2.1. Apply a loss of generation

The maximum infeed loss of 1.8 GW was applied to the power system at 2 s in Fig. 10 which led to a severe frequency drop. Simulation results are shown in Fig. 11.

The 1st subplot of Fig. 11 compares the variations in grid frequency after the infeed loss with and without the response of MPs. The 2nd subplot compares the rate of change of frequency with and without the response of MPs based on [27]. The 3rd subplot shows the total response of approx. 500 MW from all MPs connected when frequency drops to 49.38 Hz.

It can be seen, with the response of MPs, the drop of grid frequency was reduced by approx. 0.18 Hz. The decrease in the rate of change of frequency indicates that the MPs provided a faster response (within 1 s) compared with the response of frequency-sensitive generators. According to the measurements of Open Energi, the delivery of response from such controlled demand can be on average of 0.7 s.

4.2.2. Apply a loss of demand

A loss of 1 GW of demand was applied to the power system at 2 s in Fig. 10 which led to a severe frequency increase. Simulation results are shown in Fig. 12.

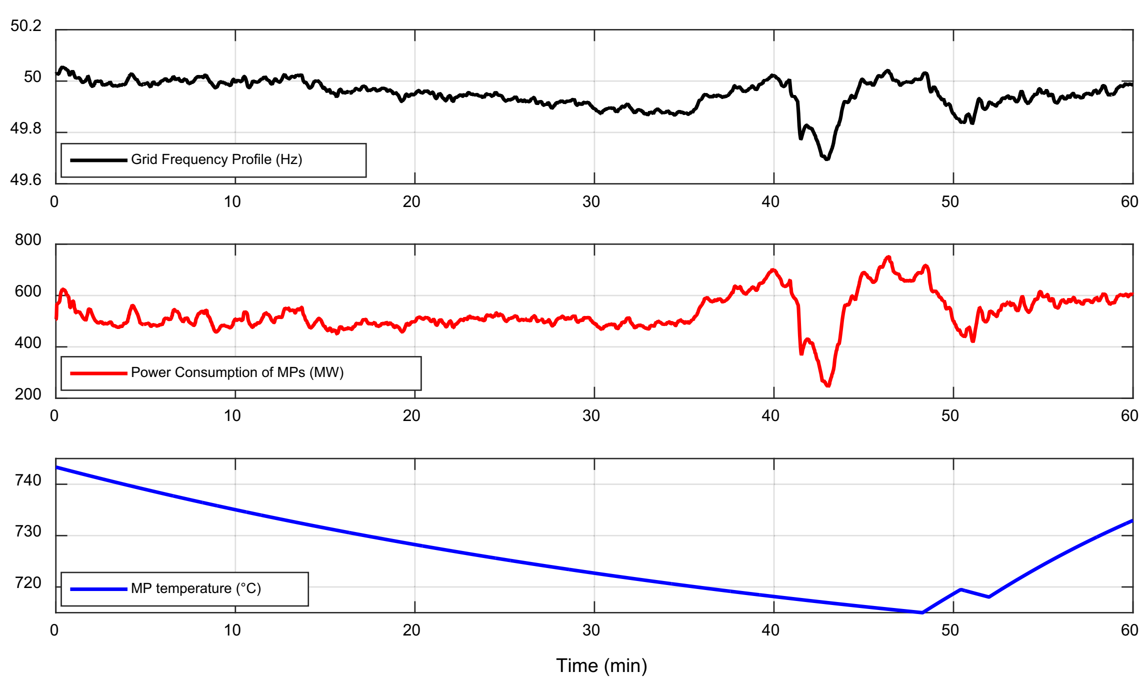

Fig. 8. Power consumption of aggregated response of 50,000 MPs in response to normal frequency variations.

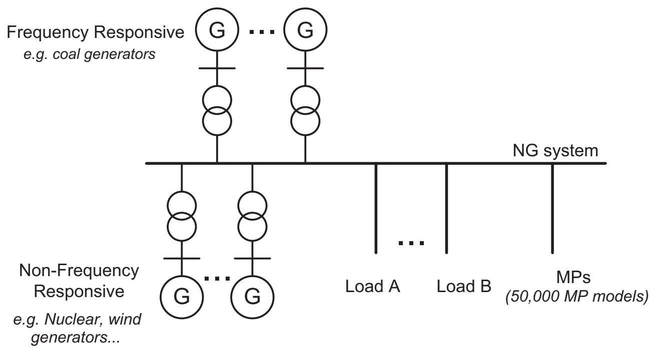

Fig. 10. Schematic diagram of the one-bus GB power system model provided by National Grid.

Similar to Fig. 11, the 1st subplot of Fig. 12 compares the variations in grid frequency after the loss of demand with and without the response of MPs. The 3rd subplot shows the total response of approx. 772 MW from all MPs connected. With the response of MPs, the increase of grid frequency was reduced by approx. 0.2 Hz. The 2nd subplot shows the decrease in the rate of change of frequency with the response of MPs.

Comparing the results shown in Figs. 11 and 12, MPs provide more response following the frequency increase than following the frequency drop. The contribution to reducing frequency deviations following the demand loss is also greater than following the generation loss. This is because the Off-period of a MP is usually longer than the On-period. At a given time, more MPs stay Off than On. When there is an increase in frequency, more MPs will be available to be switched On to respond to the frequency increase compared with the alternative case when there is a frequency drop, the MPs will be switched Off. Therefore, after the loss of demand, MPs provide a greater change in power consumption (772 MW in Fig. 12) and contribute more to reducing a frequency increase than a frequency drop. When the load aggregator tenders for the provision of frequency response, they can tender for frequency drop events, for frequency rise events and for both with different amounts of MW.

4.3. Mps' response from different locations

To investigate the impact of location on the response provided by MPs, a case study was carried out using the master dynamic GB power system model in National Grid which is at present used by the system operator for network studies. The model containing 11,792 buses represents the present GB transmission network connecting with 12 Distribution Network Operator (DNO) areas as illustrated in [28]. Table 2 shows the DNO numbers and the relevant DNO. In each DNO area, an aggregation of different numbers of MPs was connected to one 33 kV bus. The numbers of MPs in each DNO area are also shown in Table 2 which was determined based on the proportion of power consumption of demand in each DNO area.

The system condition was set to represent the summer minimum load scenario in 2014. The system demand was approx. 22 GW. The system inertia was 4.9 s.

A loss of generation of a total of 1.2 GW was applied to the GB power system model at 4 s. Simulation results are shown in Figs. 13 and 14.

The 1st subplot of Fig. 13 shows the frequency measurements at each bus that was connected with MPs model. The frequency measurements at each bus were not exactly similar to each other across the entire network at the first few seconds. This indicates that the rate of frequency changes immediately after the sudden changes in generation/demand across the network is slightly different. The 2nd subplot shows the response of MPs at each bus in different areas. The response of MPs shows that there is little locational impact on the provision of frequency response. MPs in all different areas provide immediate response in proportional to changes in grid frequency.

The 1st subplot of Fig. 14 compares the grid frequency variations with and without MPs after the loss of generation. The 2nd subplot shows the total reduction in power consumption of MPs of approx. 310 MW. The response of MPs assists to reduce the maximum frequency drop by 0.09 Hz from 49.49 Hz to 49.58 Hz.

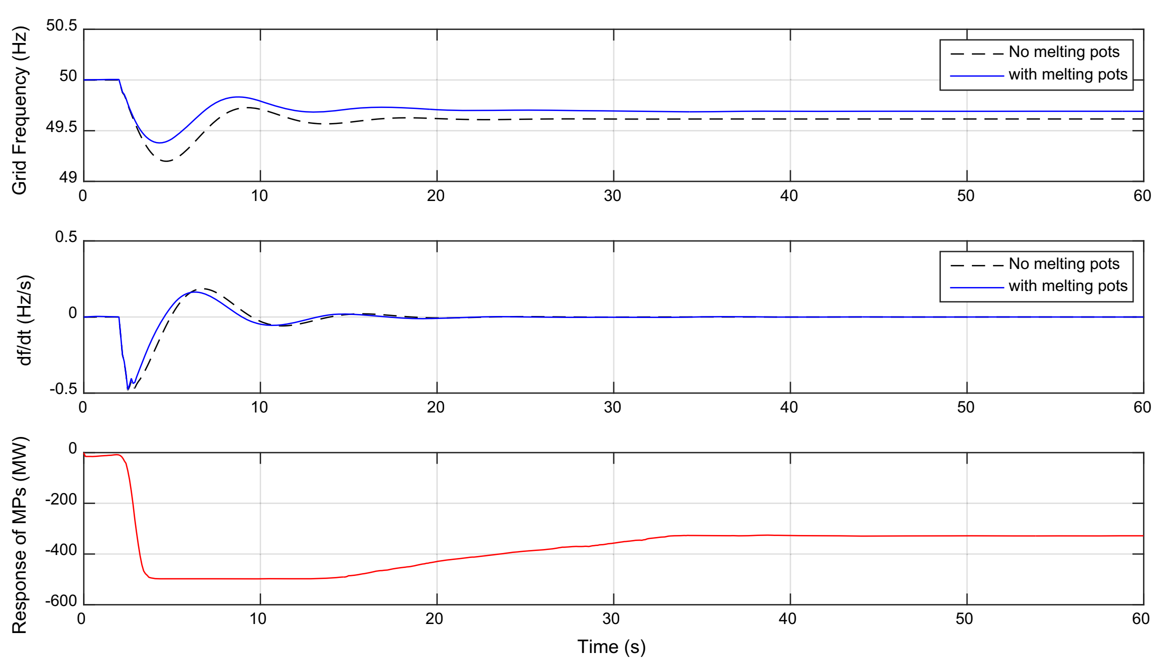

Fig. 11. Response of MPs after the infeed loss, and comparisons of grid frequency and rate of change of frequency with and without MPs' response.

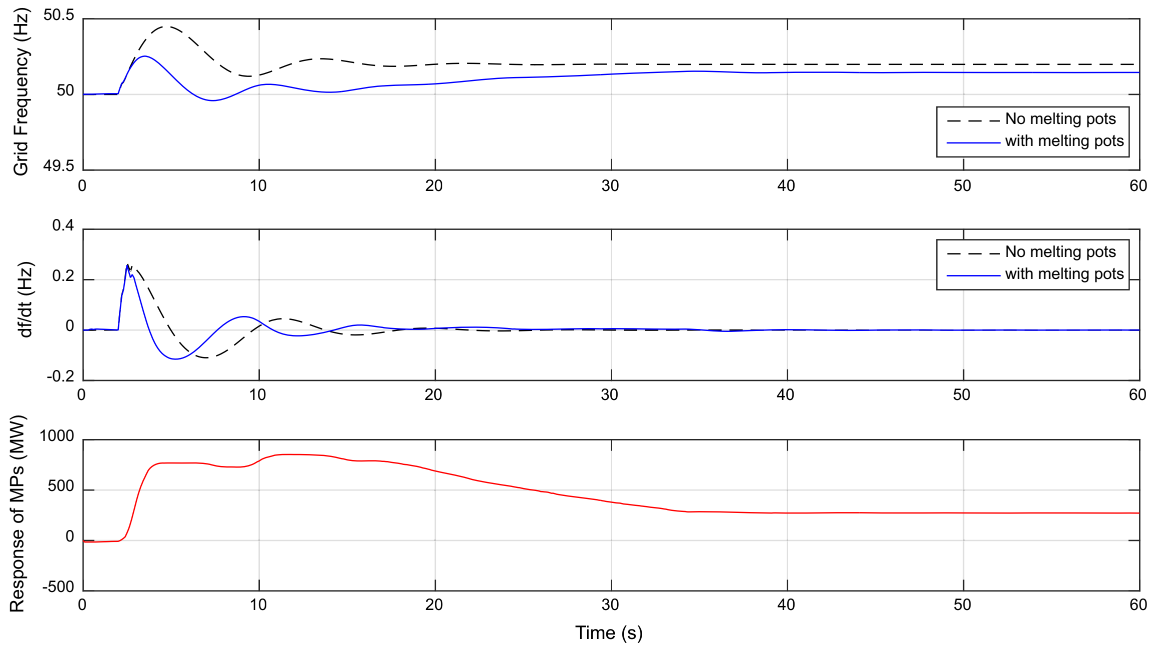

Fig. 12. Response of MPs after the loss of demand and the comparison of grid frequency and rate of change of frequency with and without MPs' response.

Table 2
DNOs in different areas and the number of MPs connected in each DNO area.

DNO numbers	DNO in the area	Number of DD of each load category
01	UK Power Network LPN	5000
02	UK Power Network SEPN	2151
03	SSE Southern	3749
04	WPD South West	1995
05	UK Power Networks Eastern	3980
06	WPD East Midlands	3087
07	WPD West Midlands	2980
08	WPD South Wales	1820
09	SP MANWEB (Scottish Power)	2093
10	NPG-Y (Northern Power Grid)	2931
11	NPG-NE (Northern Power Grid)	1779
12	ENW (Electric North-West)	2363

4.4. Expected MPs' response under the May 2008 frequency incident

A frequency profile recording the frequency incident that occurred on 27 May 2008 (see 1st subplot of Fig. 15) was injected to an aggregation of 50,000 MP models. The frequency incident was quite uncommon which were caused by consecutive trips of two generators (345 MW and 1237 MW)) leading the frequency to drop to 48.8 Hz. The expected performance of MPs was simulated as shown in Fig. 15.

The 2nd subplot shows the response of MPs. It can be seen, following the consecutive drops of frequency, the power consumption of MPs is reduced almost immediately in proportion to the changes in frequency. Therefore, the dynamic frequency control is able to allow demand to provide continuous and repetitive

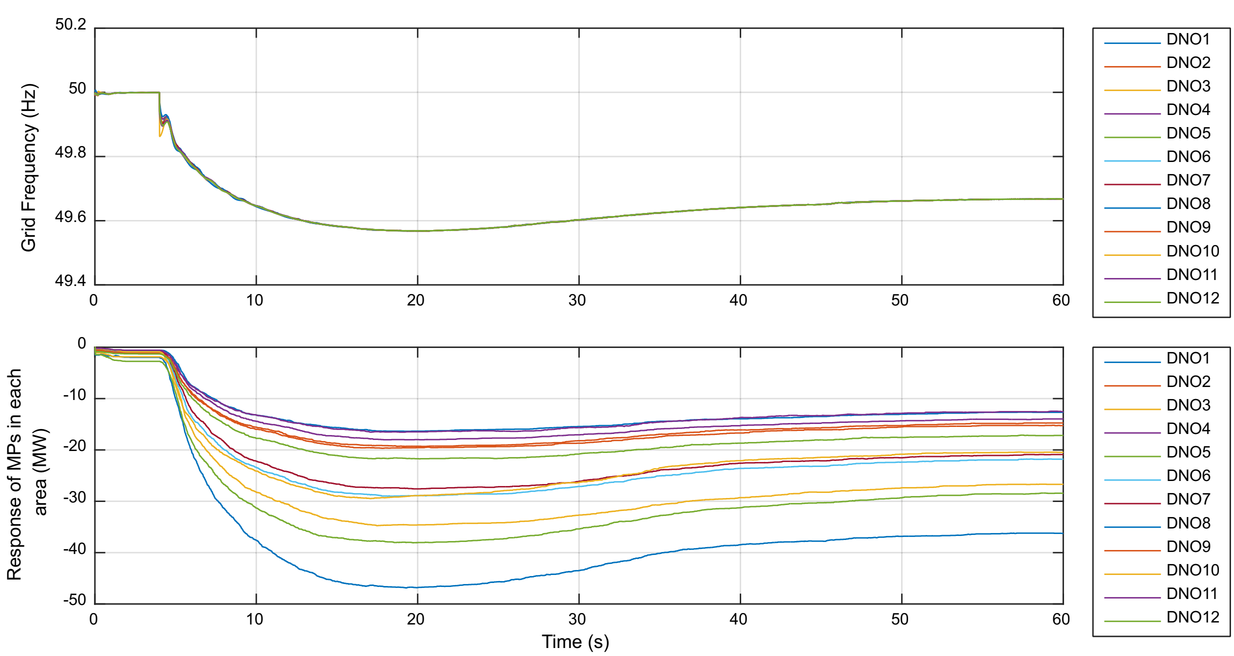

Fig. 13. Grid frequency measured at different bus connecting with MPs model and response of MPs in each DNO area.

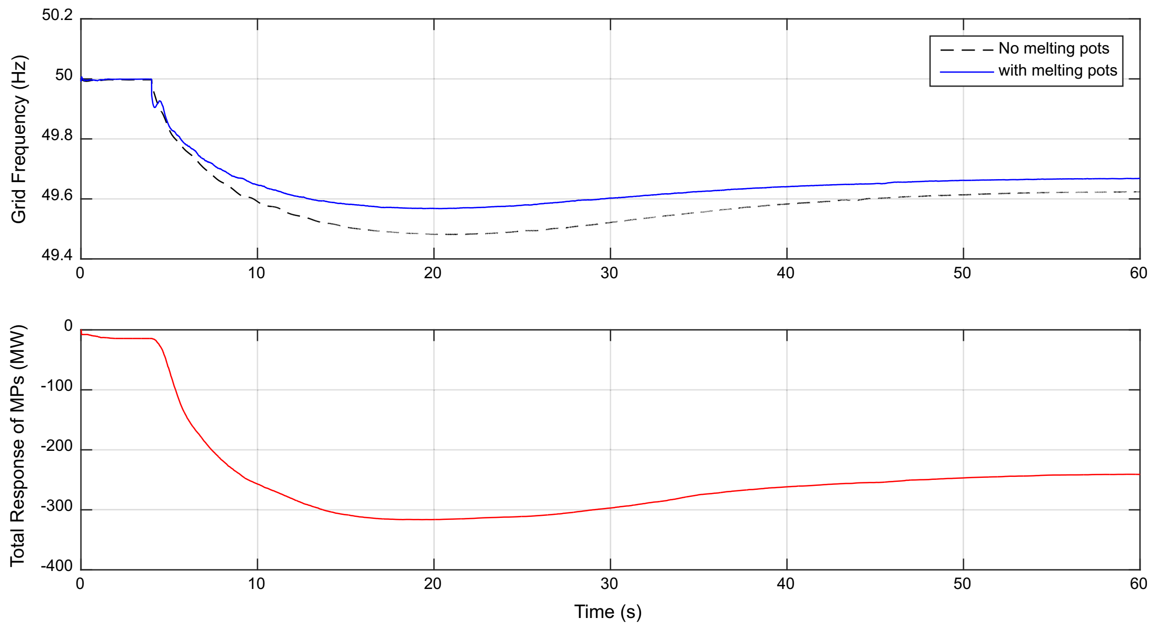

Fig. 14. Grid frequency with and without MPs and the total response of MPs.

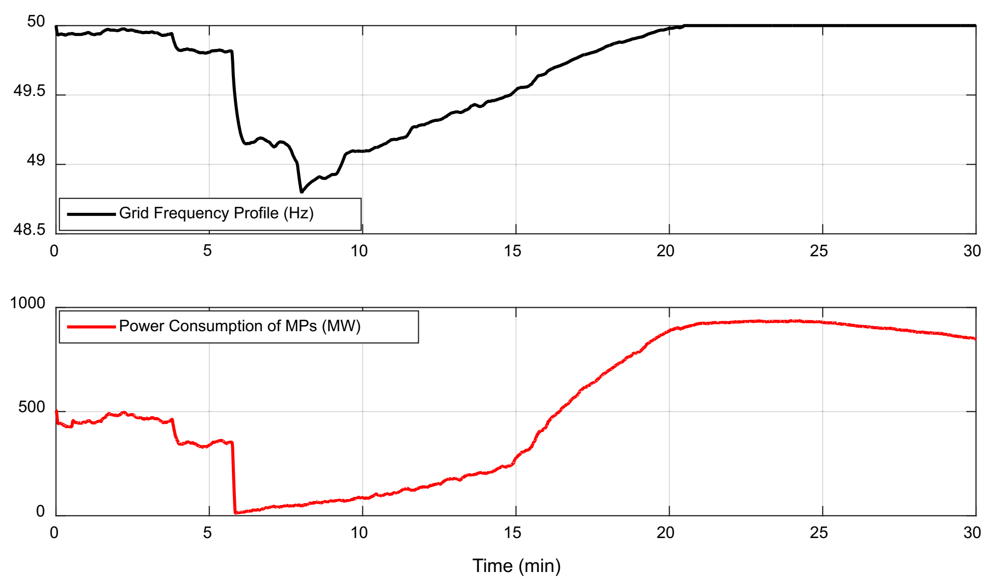

Fig. 15. Grid frequency with and without MPs and the power consumption of MPs.

response to frequency deviations. However, it can be seen, the power consumption of MPs start to recover several minutes after the provision of frequency response. This was because the On and Off-periods of MPs (average approx. 23.5 min and 44 min) is not sufficiently long. Furthermore, most of them are interrupted from an intermediate point of an On/Off cycle rather than the start of the cycle. The time to remain On/Off is even less than the On/Off periods. After the severe frequency incident, MPs start to gradually reconnect to compensate for the loss of electricity and to meet the temperature requirements. Specifically at around 15 min, the frequency has recovered to be above the minimum frequency setpoint (F_{OFF}) at 49.5 Hz. This indicates the requirement of frequency response is reducing and the dynamic frequency control allows more MPs to recover following the frequency recovery. This causes an increase in the power consumption when frequency returns to the normal range. However, it is believed the back-up reserve is able to be called online in 10 min to recover the frequency and also to restore the lost energy for fast frequency response.

Therefore, the On/Off period of loads is a key factor in determining the capability of one type of loads to sustain the delivery of frequency response. Loads with longer On and Off periods, e.g. industrial bitumen tanks, small-size water pumps, are able to sustain the delivery of frequency response over a longer period.

4.5. Discussions on demand for balancing services based on the GB present operational practice

As reviewed in Section 1, at present, the GB System Operator procures the balancing services from demand mainly through the FCDM and STOR. Considering the dynamic frequency response of

Table 3
Comparison of services provided by demand.

	FCDM	STOR	FFR
Response time	2 s	5–20 min (tendered parameter)	2 s
Trigger	Frequency fall below 49.7 Hz	Instruction issued by National Grid	Any variations in frequency
Upward or downward regulation	Downward	Downward	Both
Average event duration	20 min	1.5 h	5 min
Max event duration	30 min	4 h	30 min
Amount utilized	30 times per year	60 h per year	Continuously
How to participate	Bilateral negotiations	Tender	Tender
Availability payment	Yes	Yes	Yes
Utilization payment	No	Yes	No
Value (£/MW/year)	£22,000–£26,000	£10,000–£15,000	£85,000

demand in this paper, such controlled demand is able to participate through the FFR [29] which is the firm provision of dynamic or non-dynamic response to changes in frequency.

The characteristics and value of the aforementioned three services are compared by Open Energi [30] as shown in Table 3. It can be seen, amongst the services, demand will gain more benefits by providing dynamic response via the FFR service. This is because the dynamic frequency control presented in this paper is able to provide an automated service with full time utilization. It offers a service with the capability of responding to both frequency falls and frequency rises which therefore commands a relatively premium price.

In summary, the dynamic control method in the paper is the first time to be applied to an aggregation of MPs for the provision of grid frequency response. It is a unique method which can provide an autonomous and dynamic response proportionally following grid frequency changes without undermining the inherent functions of loads. The response is similar to the automatic droop control of conventional frequency-sensitive generators and hence the required capacity of spinning reserve of the generators can be reduced.

Comparing with other methods providing a static frequency response that simply switch off loads when required by the System Operator or a pre-defined set-point, and then recovers following the instructions from the System Operator, this method is more effective by providing a response similar to the frequency-sensitive generators and allows the loads to participate in the Firm Frequency Response (FFR) market (According to the GB System Operator in [31], '*FFR is one of the most valuable balancing services to National Grid. It is also one of the more technically challenging services to provide, and remuneration reflects this*').

5. Conclusions

To facilitate the integration of RES while maintaining the balance of supply and demand, the paper uses the industrial Melting Pots (MPs) to provide grid frequency response dynamically. A generic thermodynamic model was developed for individual MPs based on field measurements in order to ensure that the temperature performance of each MP will not be interrupted by the additional frequency control. The dynamic frequency control is a decentralized control which dynamically and autonomously changes power consumption of MPs.

Case studies were undertaken to quantify the benefits of MPs' response for frequency control. Results showed that MPs are able to provide dynamic frequency response in a manner similar to but faster than the frequency-sensitive generators. This will also contributes to smoothing the supply fluctuations of RES.

Discussion and reviews were carried out to show the benefits of using demand with the dynamic frequency control to participate in the present frequency response services in the GB power system. The demand with the dynamic frequency control proposed in this paper is able to provide frequency response through the Firm Frequency Response service which shows outstanding benefits compared with the response through other services.

Because of the relatively short On and Off periods of MPs, it shows that MPs are able to provide fast response with less capability of sustaining the delivery of response for a long period. Future work will be carried out by applying the dynamic frequency control to other loads with longer On and Off periods, e.g. small-size water pumps, industrial bitumen tanks. Coordination amongst these load types for the provision of frequency response will be investigated in order to deliver a fast and more sustainable frequency response. In addition to using flexible demand, there are also methods that can be applied to other network assets, such as the generators and energy storage for the provision of frequency response. Future work will be carried out to compare the performance of different network assets in terms of technical and economic views.

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