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Decentralized Control of Industrial Heating Loads for Providing Multiple Levels and Types of Primary Frequency Control Service

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Abstract

To keep the real-time balance between electricity supply and demand, i.e. to guarantee the grid frequency within the allowable range, is becoming even challenging because the increasing penetration of renewable energy and decreasing capacity of conventional frequency-sensitive generators. Industrial heating loads are important demand-side resources that can contribute, but the control paradigm needs to be updated to be accommodated with the recent development of electricity markets especially frequency response markets. Accordingly, a decentralized control was proposed for industrial heating loads to provide multiple levels and types of primary frequency control service. Specifically, bitumen tanks and the Firm Frequency Response market in the Great Britain were studied as representatives. Simulation results verified the validity of the proposed control, with the normalized Root Mean Square Errors below 0.08 in all cases.

Keywords: Decentralized control; primary frequency control; industrial heating load; bitumen tank; Firm Frequency Response.

1. Introduction

A fundamental feature of electric power systems is that power supply and demand have to be balanced in real time. This balance is indicated by grid frequency, which is required to be maintained within a certain range to guarantee power quality, e.g. 50±0.5Hz in the Great Britain (GB). Traditionally, frequency control is mainly achieved by partially-loaded frequency-sensitive generators. However, the increasing share of generation from

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renewable energy results in reduced capacity of conventional generators but increased need for flexibility to follow the intermittent and random power output from renewable generation.

Consequently, flexible loads are expected to undertake more responsibility in frequency control. Industrial heating loads, such as bitumen tanks for bitumen storage and melting pots in aluminum factories, are important candidates because of their large power consumption and high automation level. Conventionally, low-frequency relays are installed at contracted large industrial loads to conduct disconnection automatically when the frequency drops to the pre-set value (e.g. 49.7Hz in the GB). In recent years, more delicate control methods have been devised to enable industrial heating loads to dynamically respond to frequency variation. For example, [1] designed a decentralized control for bitumen tanks to provide dynamic frequency service. [2] extended the control method in [1] to melting pots, which have similar but different thermodynamic characteristics.

However, the development of electricity markets especially frequency response markets for demand-side resources requires further improvement of control methods. First of all, there is a trend that frequency control services are divided into more delicate sub-categories with various requirements on response direction and time. Furthermore, a long-term contract (as long as several months or even years) is made between load owners and power system operators through some pre-procurement processes (e.g. the monthly tendering mechanism in the GB), and as a result, flexible loads have to provide contracted level of service in the contracted time frame. Besides, nowadays flexible loads usually need to participate in multiple markets to gather benefits from different value streams. Therefore, control methods need to enable flexible loads to provide different levels of frequency control service, to leave margin for providing other services in other markets.

In order to address the above issues, a decentralized control was proposed for the first time to enable industrial heating loads to provide multiple levels and types of primary frequency control service. Specifically, bitumen tanks and the Firm Frequency Response (FFR) mechanism of the GB were studied as examples for industrial heating loads and frequency response markets respectively. Real data of bitumen tanks and grid frequency in the GB was used to validate the proposed control method.

2. The temperature control and thermodynamic process of bitumen tanks

As a typical type of industrial heating load, bitumen tanks are studied in this paper. They are well-insulated tanks for storing liquid bitumen that is required to be stored within a certain temperature range. Hysteresis control is usually used to control the electric heater of a tank, and the resulting thermodynamic process is illustrated in Fig. 1. It is observed that the temperature increases when the heater remains ON, while decreases due to stand-by heat loss when the heater is OFF. The heater turns OFF when the temperature reaches the upper limit, while turns ON when it reaches the lower limit. The model of this process and control has been well documented, referring to [1].

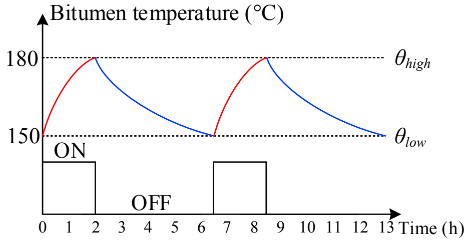

Fig. 1. Hysteresis control and thermodynamic process of a bitumen tank

3. Decentralized control for providing multiple levels and types of primary frequency control service

3.1. Dynamic frequency response in the Firm Frequency Response mechanism of the Great Britain

The FFR mechanism is one of the most profitable routes for flexible loads to provide frequency control service in the GB [3]. In the FFR mechanism, primary frequency control service is further divided into three sub-categories; Primary Response (PR), Secondary Response (SR) and High-frequency Response (HR) [4]. PR and SR are low-frequency service that are called when the frequency is below the normal value (i.e. 50Hz), while HR is high-frequency service for situations with the frequency being higher than the normal value. PR and SR differ from each other in terms of the requirements on response time. For PR, the response is required to be provided within 10 seconds and sustained for further 20 seconds, while for SR the response is required to be provided within 30 seconds and sustained for further 30 minutes. The response of HR is required to be sustained indefinitely.

Load owners submit tenders in advance with response type, capacity, price, time frame and service period proposed. Once a tender is accepted, the contract is made and the loads need to provide contracted level of service throughout the contracted service period (ranging from 1 month to as long as 24 months). Taking PR as an example, if the contracted capacity is V^{PR} (MW), the required response of the load population, $\overline{R}^{PR}$ (MW), is expressed as

$$\overline{R}^{PR} = \begin{cases} -V^{PR} & f < 49.5 \\ V^{PR} \cdot \dfrac{f-50}{0.5} & 49.5 < f < 50 \\ 0 & f \geq 50 \end{cases} \tag{1}$$

where f (Hz) is the real-time grid frequency. The sign of $\overline{R}^{PR}$ represents the direction of the response; negative values mean load reduction while positive ones mean load increase. The actual response of a population of flexible loads, R^{PR} (MW), is calculated as

$$R^{PR} = \sum_{j \in \boldsymbol{J}} p_j - \hat{P} \tag{2}$$

where j is the index of a load; $\boldsymbol{J}$ is the set of all the loads; p (MW) is the actual power consumption of a load; $\hat{P}$ (MW) is the baseline consumption of the load population, which is able to be estimated in a number of ways. In the case study of this paper, it just equals to the average consumption of the load population throughout a day without providing any frequency control service. The required and actual response of SR and HR is able to be calculated in a similar way.

3.2. Decentralized control for providing multiple levels and types of service

This section details the decentralized control proposed for flexible loads for providing multiple levels and types of service. First of all, the control for providing multiple levels of service is described. Then the control of the same load population to provide multiple types of service is described.

1) Control for providing multiple levels of service

Taking the provision of PR as an example, the control for providing multiple levels of service is illustrated in Fig. 2. Each load in the population is equipped with a PR controller that is composed of a frequency trigger module, an activation signal generator, a reset timer and a response timer.

In order to provide required level of response that is consistent with the contracted capacity (as presented by Equation (1)), only a fraction of loads should be active at any time point. The number of active loads, N^{active}, is calculated as

$$N^{active} = N \cdot \frac{V^{PR}}{\sum_{j \in \boldsymbol{J}} P_j} \tag{3}$$

where P (MW) is the rated power of a load.

In the load population, whether a load is active or not depends on the activation signal. In order to ensure the fairness among the loads, the activation signal δ_j (a binary variable with "1" representing for "active" and "0" representing for "inactive") is generated randomly from the local activation signal generator of each load, following the binomial distribution below:

$$q(\delta_j = 1) = \frac{V^{PR}}{\sum_{j \in \boldsymbol{J}} P_j}; \quad q(\delta_j = 0) = 1 - \frac{V^{PR}}{\sum_{j \in \boldsymbol{J}} P_j} \qquad \forall j \in \boldsymbol{J} \tag{4}$$

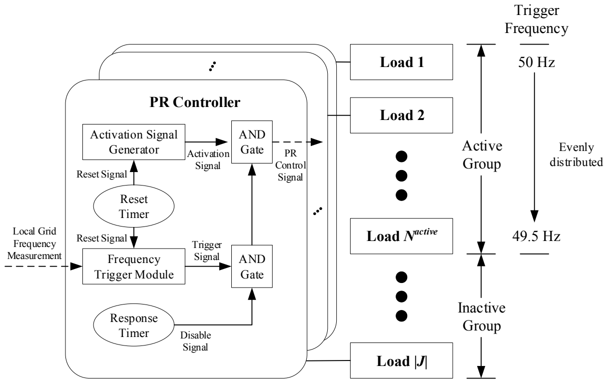

Fig. 2. Decentralized control for flexible loads to provide multiple levels of Primary Response (PR) service

where q represents the probability of an event. Equation (4) guarantees that the required quantity of loads, N^{active}, are active.

The activation signals of all the loads are re-generated at intervals (denoted as T (hour), which is identical for all the loads) to guarantee each load having equal opportunity. This is achieved by the reset timer. The reset timer counts the time elapse. Once it reaches the pre-set threshold T, a reset signal is sent to the activation signal generator to re-generate the activation signal, and at the same time the reset timer is reset and counts from zero again.

The frequency trigger module in each load compares the locally measured grid frequency in real time, f, with the pre-set trigger frequency $\bar{f}_j$ (Hz), and generates the trigger signal, χ_j (a binary variable with "1" representing for "turning OFF" and "0" representing for "keeping the heater state unchanged"). For low-frequency service like PR, the following logic is used:

$$\chi_j = \begin{cases} 1 & if\ f \le \bar{f}_j \\ 0 & if\ f > \bar{f}_j \end{cases}, \forall j \in \boldsymbol{J} \qquad (5)$$

To obtain required level of response from the active group (as presented by Equation (1)), the trigger frequency $\bar{f}_j$ should be set by randomly sampling from the interval [49.5, 50] (Hz) for which a uniform distribution is applied. In this way, from the perspective of the whole load population, the values of trigger frequency evenly range from 49.5Hz to 50Hz, so that the loads that are shut down will be proportional to the deviation of the grid frequency and thus the required response is able to be delivered.

The response timer counts how long the response has been provided. If the response time is within the required time interval (for PR, it is 0-30 seconds), the timer outputs "1" and the active group provides service normally; but if the response time are out of the required interval, the timer outputs "0" to disable the frequency trigger signal to prevent the load from responding to the grid frequency.

The final load control signal of a PR controller is a combination of the signals of its internal modules and timers, as shown in Fig. 2. The load control signal is a binary value, with "1" representing for "turning OFF" and "0" representing "keeping the heater state unchanged".

All the above descriptions are for PR, but it is straightforward to extend the same principles to designing the controllers for providing multiple levels of other service such as SR and HR.

2) Control for providing multiple types of service

Following the methodology described above, controllers are able to be designed for PR, SR and HR separately, according to the respective contracted capacity and requirements on response direction and time. To enable the load population to provide multiple types of service, each load is able to be installed with multiple controllers at the same time. Because of the inherent difference among PR, SR and HR (in terms of response direction or/and time), at most one controller will instruct the load to provide the corresponding type of service, so that the load control signals from different controllers will not contradict each other.

Finally, the load control signals from PR, SR and HR controllers need to be combined with the temperature control signals from the hysteresis controller (as described in Section 2) to generate the signal that decides the ON/FF status of the load at last. When the temperature is within the allowed range, the load control signals have higher priority to the temperature control signal to provide frequency control service. On the other hand, when the temperature is out of the allowed range, the temperature control signal should have higher priority to the load control signals to guarantee the primary function of the load.

4. Case Study

This section validates the proposed decentralized control by using real data of bitumen tanks and grid frequency in the GB. A population of 200 bitumen tanks were used to be equipped with the proposed controllers to provide frequency control service. The parameters of the bitumen tanks were presented in Table 1, which were obtained from the real field tests conducted by Open Energi (a commercial aggregator in the UK) [1]. How to use the parameters to model bitumen tanks in simulation has been detailed in the existing study [1].

Table 1. The parameters of bitumen tanks [1].

Parameter	Description	Value
P	Rated power of a bitumen tank	40 kW
τ_{ON}	ON period of a bitumen tank	42-180 minutes
τ_{OFF}	OFF period of a bitumen tank	60-480 minutes

Two cases have been designed to validate different aspects of the proposed control. Standard testing scenarios defined in *Testing Guidance for Providers of Firm Frequency Response Balancing Service* (abbreviated to "testing guidance" in the rest of this paper) issued by National Grid of the UK were used to conduct the tests [5].

In the first case, the performance of the proposed control to provide multiple levels of service were examined. It was assumed that the tank population provided PR, SR and HR at the same time. The normalized contracted capacity (normalized by the maximum capacity of the corresponding type) of the three types of service were assumed identical, but several values, ranging from 20% to 100%, were examined. The "Test 4 Connection to the Grid Test" in the testing guidance was used for assessment, with the results shown in Table 2 and Fig. 3.

Table 2 presents the resulting performance measured by normalized Root Mean Square Error (*nRMSE*), showing that the proposed control successfully provided multiple levels of response with relatively low *nRMSE*. Fig. 3 illustrates the response of the tanks at a specific contracted capacity (60%) as an example, showing that the actual response followed the frequency change, although with some deviation from the required response.

The second case was designed to further assess whether the proposed control is able to provide different levels of response for different types of service. The tank population was also assumed to be installed with PR, SR and HR controllers at the same time, but the normalized contracted capacity of the three types of service were assumed different from each other, being 50%, 100% and 70% respectively. One of the "Test 2 Frequency Sweep Tests", Test 2.3, in the testing guidance was used for the assessment. The results are shown in Fig. 4.

Table 2. The performance of the proposed control when providing multiple levels of service.

Contracted Capacity	*nRMSE**
20%	0.076
40%	0.037
60%	0.040
80%	0.025
100%	0.020

* The *nRMSE* in this paper is defined as follows:

$$nRMSE = \frac{1}{\max\limits_{i}(V^{i})}\sqrt{\frac{1}{n}\sum_{t=1}^{n}(R_t - \bar{R}_t)}$$

$$i \in \{PR, SR, HR\}$$

where n represents the total number of time points considered.

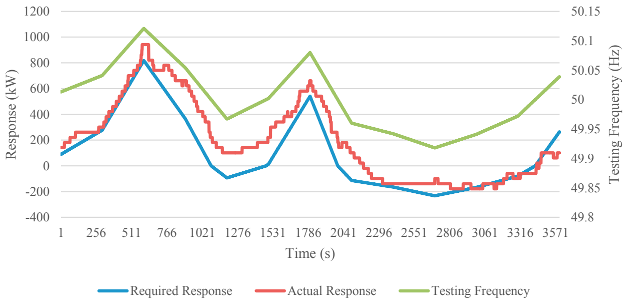

Fig. 3. Response of the tanks with the contracted capacity being 60%.

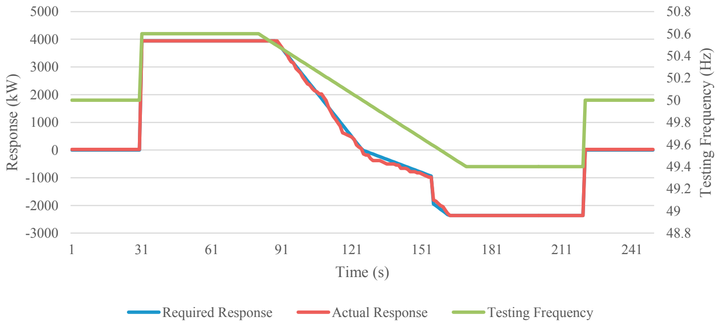

Fig. 4. Performance of the proposed control with different contracted capacity for different types of service

In Fig. 4, it is seen that the difference between the required and actual response was very small (with the *nRMSE* being 0.005), showing that the proposed control performed quite well. Specifically, from the 31st to 120th seconds, the tanks provide required level of HR following the change of the testing frequency. From the 125th to 155th seconds, the tanks provide required level of PR following the frequency decrease. Then it is observed that there was a sudden drop of response at the 156th second, because the low-frequency time exceeded 30 seconds and the type of response that should be provided changed from PR to SR. The contracted capacity of SR is twice as that of PR, so the response volume doubled from -1000kW to -2000kW. After that, the tanks kept providing required level of SR till the 220th second, after which no response was required because the frequency was back to 50Hz.

5. Conclusion

To be accommodated with the development of electricity markets especially frequency response markets, a decentralized control was proposed for industrial heating loads to provide multiple levels and types of primary frequency control service. Specifically, bitumen tanks and the Firm Frequency Response market in the Great Britain were studied as representatives. Simulation results verified the validity of the proposed control, with the normalized Root Mean Square Errors below 0.08 in all cases.

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