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OPTIMAL CAPACITY TENDERING OF INDUSTRIAL ELECTRIC HEATING LOADS IN THE FREQUENCY RESPONSE MARKET OF GREAT BRITAIN

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ABSTRACT

With the increasing penetration of renewable power generation and decreasing share of conventional frequency-sensitive generating units, demand-side response is playing an increasingly important role in balancing the real-time supply and demand of electric power systems. Industrial electric heating loads are critical demand-side resources because of their significant electric power consumption, large thermal energy storage capability and high automation level. In this paper, an optimal tendering method was proposed to decide the baseline load and response capacity of a group of bitumen tanks to provide the Firm Frequency Response service in the context of Great Britain. Simulation studies were conducted based on field test data of bitumen tanks and practical market data of Great Britain. The results show that the proposed method is able to minimize the net cost the tank group, considering both the energy cost in the electricity retail market and the remuneration from providing the frequency response service.

Keywords: industrial electric heating loads, optimal scheduling, bidding strategy, frequency response, demand response

1. INTRODUCTION

In the low-carbon transition process to fight against climate change, there is an increasing penetration of renewable power generation and a decreasing share of conventional frequency-sensitive generating units in electric power systems. As a result, demand-side response (DSR) becomes even more important to help power systems maintain the real-time supply and demand balance. In this context, a significant number of studies have been conducted to utilize various types of demand-side resources, such as battery energy storage systems (BESSs), electric vehicles (EVs), residential and commercial thermostatically controlled loads (TCLs), to provide frequency response services for power systems.

Besides these demand-side resources, industrial electric heating loads (IEHLs) also play a critical role, because of their significant electric power consumption, large thermal energy storage capability and high automation level. For decades, IEHLs such as steelworks have been participating in under frequency load shedding schemes of power systems, where they are set to be disconnected automatically at a predefined low frequency. Some recent studies also developed decentralized control methods to enable IEHLs, such as bitumen tanks and melting pots, to provide dynamic frequency response services for power systems [1], [2].

In this paper, a further step has been made to study the optimal tendering strategy for IEHLs to participate in the frequency response market. Specifically, the tendering capacity was optimized for bitumen tanks to provide frequency response services in the context of Great Britain (GB). Compared to the existing studies, this paper has the following contributions:

- To the best of our knowledge, regarding the capacity tendering of demand-side resources for providing frequency response services, the existing studies are around other types of demand-side resources, such as BESSs [3], EVs [4], and residential/commercial TCLs [5], but not IEHLs which have unique features.
- The Firm Frequency Response (FFR) scheme of the UK considered in this paper further divides the primary frequency control service into three sub-categories and has complicated remuneration rules,

which have not been studied in the existing studies but are important trends for future frequency response services [4], [5].

2. METHODOLOGY

2.1 Bitumen Tank Modelling

Bitumen tanks are considered in this paper, as a typical type of IEHL, to provide frequency response services. Bitumen tanks are well-insulated tanks for storing liquid bitumen. The internal temperature of a tank is maintained within a predefined range (usually 150°C-180°C) by a hysteresis control. The temperature dynamics within a bitumen tank can be expressed as

$$\theta_{t+1} = a_{\mathrm{ON}} + b \cdot \theta_t , \qquad (1)$$

$$\theta_{t+1} = a_{\mathrm{OFF}} + b \cdot \theta_t , \qquad (2)$$

where θ (°C) is the bitumen temperature; a (°C) and b are coefficients named as "temperature addition" "temperature gain". Subscript t is the time step index. Equation (1) describes the thermodynamics when the heater of the tank is ON, while Equation (2) is for the situation where the heater is OFF.

2.2 Market Models in GB

The optimal capacity to be tendered for the tank group depends on the expected energy cost in the electricity retail market and the expected remuneration from the frequency response market.

2.2.1 Retail Market in GB: Economy 7 and Economy 10

Time-of-use pricing is widely applied for industrial and residential users in GB. Economy 7 (E7) and Economy 10 (E10) are two popular time-of-use pricing schemes at present. An example is shown in Table 1.

Table 1 Tariff structures for Economy 7 and Economy 10

Tariff	Rate (pence/kWh)		Period	
Type	Standard	Off-Peak	Standard	Off-Peak
E7	18.30	7.88	7:00-24:00	0:00-7:00
E10	18.68	10.07	5:00-13:00 16:00-20:00 22:00-24:00	0:00-5:00 13:00-16:00 20:00-22:00

2.2.2 Frequency Response Market in GB: Firm Frequency Response

Aggregated flexible loads participate in the GB frequency response market through the FFR scheme. In this scheme, the primary frequency control service is further divided into three sub-services: Primary Response (PR), Secondary Response (SR) and High-Frequency Response (HR). PR and SR are under-frequency services. In PR, service providers are required to deliver a decrease in active power demand within 10 seconds after a frequency drop incident and can be sustained for a further 20 seconds. In SR, the demand decrease should be delivered within 30 seconds and sustained for 30 minutes. HR is an over-frequency service, and a demand increase is required to be delivered within 10 seconds and sustained indefinitely.

Service providers procure their qualification to provide frequency response services for future months through a monthly electronic tender process. The GB power system operator, National Grid, will assess the quality, quantity and the nature of the services and accept the most economical tenders. An example tender is shown in Table 2.

Table 2 A part of a practical FFR tender [6]

Tendered Unit Name	SHOS-1	Primary Response (MW)	24
Tendered Service Period	01.01.14-31.01.14 (single month)	Secondary Response (MW)	75
Tendered Time Frame	All days, 23:00 to 23:00	High Frequency Response (MW)	24
Availability Fee (£/h)	910	Nomination Fee (£/h)	790

In Table 2, it is seen that the capacity for different types of frequency response services need to be presented in the tender for future months. The prices for the services need to be presented as well. However, in this paper, only the capacity tendering is studied. The prices tendered are simply assumed to be the average value of the historical prices, and able to enable the tender to be accepted by the system operator.

From Table 2, it is seen that the service providers are remunerated through availability and nomination fees. The availability fee is for the hours in which a provider has tendered to make the service available for, while the nomination fee is a holding fee for each hour utilized within FFR nominated windows. How to divide the fees in the tender for different types of services (i.e. for PR, SR and HR) refers to [7].

2.3 Optimization of Baseline Load and Tendering Capacity for Bitumen Tanks

The baseline load and the associated tendering capacity of the tank group need to be optimized to achieve the lowest net cost, considering both the energy cost in the electricity retail market and the remuneration from the FFR scheme. Although the service period to be tendered is as long as several months, only the daily baseline load is optimized, considering the operation of tanks is not significantly affected by ambient environment and thus the daily results are able to represent the whole service period.

The objective function is expressed as follows:

$$\min(COST_{\text{eng}} - REVENUE_{\text{frq}}) \tag{3}$$

where $COST_{\text{eng}}$ (£) represents the daily electricity cost of the tank group in the retail market and $REVENUE_{\text{frq}}$ (£) represents the revenue obtained in the frequency response market. Thus, (3) is to minimize the net cost.

$COST_{\text{eng}}$ is calculated by

$$COST_{\text{eng}} = \sum_{t\in \boldsymbol{N}} \sum_{j\in \boldsymbol{J}} r_t \cdot P_j \cdot u_{j,t} \cdot \Delta t \tag{4}$$

where $\boldsymbol{N}$ is the set of all the time steps during the scheduling horizon (one day); $\boldsymbol{J}$ is the set of all the bitumen tanks; r (£/kWh) is the retail price; P (kW) is the rated power of the tank; u represents the heater state (ON/OFF, represented by 0/1); Δt (h) is the length of a time step; subscript j is the index for tanks.

$REVENUE_{\text{frq}}$ is calculated by

$$\begin{aligned} REVENUE_{\text{frq}} = &|\boldsymbol{N}|\Delta t(p_{a1} + \xi_1 p_{n1}) \cdot C_1 \\ &+ |\boldsymbol{N}|\Delta t(p_{a2} + \xi_2 p_{n2}) \cdot C_2 \\ &+ |\boldsymbol{N}|\Delta t(p_{ah} + \xi_h p_{nh}) \cdot C_h \end{aligned} \tag{5}$$

where C_1 (kW), C_2 (kW) and C_{h} (kW) are the tendering capacity of the tank group for PR, SR and HR, and are calculated by

$$C_1 = C_2 = \min_{t\in \boldsymbol{N}} \sum_{j\in \boldsymbol{J}} P_j u_{j,t}, \tag{6}$$

$$C_{\text{h}} = \sum_{j\in \boldsymbol{J}} P_j - \max_{t\in \boldsymbol{N}} \sum_{j\in \boldsymbol{J}} P_j u_{j,t}. \tag{7}$$

In (5)-(7), p (£/kWh) represents the response price for the tank group; subscripts 1, 2 and h represent response types, to be PR, SR and HR; subscripts a and n represent the availability fee and nomination fee respectively. The utilization rate ξ represents the proportion of a day during which the available frequency response capacity is utilized.

The constraints of the load scheduling problem are formulated below. First of all, temperature of all tanks throughout the scheduling horizon is required to be maintained within a certain range, that is

$$\forall j \in \boldsymbol{J}, t \in \boldsymbol{N} \qquad \theta_{j,t}^{\text{low}} \le \theta_{j,t} \le \theta_{j,t}^{\text{up}}, \tag{8}$$

where based on (1) and (2) there is

$$\begin{aligned} \theta_{j,t+1} = &u_{j,t}(a_{j,\text{ON}} + b_j \theta_{j,t}) \\ &+ (1-u_{j,t})(a_{j,\text{OFF}} + b_j \theta_{j,t}) \end{aligned}. \tag{9}$$

In addition, considering that the daily load schedules need to be applicable for tens of days within the tendered service period, it is required that the bitumen temperature at the end of a day equals to that at the beginning of the day,

$$\forall j \in \boldsymbol{J} \qquad |\theta_{j,|\boldsymbol{N}|} - \theta_{j,0}| \le \varepsilon, \tag{10}$$

where ε (°C) is a small positive number predefined to relax the constraint to tolerable errors.

Summarizing the above formulation, the optimization problem is composed of the objective function (3) and constraints (8)-(10). The decision variables are the ON/OFF states for each tank throughout the scheduling horizon, $u_{j,t}$, which are binary variables. Therefore, mathematically, the optimization problem is a binary linear programming problem which can be solved by existing tools.

Based on the obtained $u_{j,t}$ for each tank at each time step, the baseline load for each time step is able to be calculated by adding up the active power of all the tanks, and the tendering capacity for the tank group is able to be calculated by (6) and (7).

3. CASE STUDY

Bitumen tanks to provide frequency response services in the FFR scheme of the GB were studied to verify the performance of the proposed optimal tendering method.

The parameters of bitumen tanks were measured by Open Energi from field tests, with the typical values listed in Table 3. A homogeneous population of 1000 bitumen tanks were considered in the case study.

The electricity prices in the retail market were assumed as those in Table 1. The historical data of the FFR scheme in 2014 was used as the frequency response market data [6].

Table 3 Typical parameters of bitumen tanks in GB

Parameter	Description	Typical Value
P	Rated power of a bitumen tank	40 kW
a_{ON}	Temperature addition (heater ON)	1.3195 °C
a_{OFF}	Temperature addition (heater OFF)	0.9688 °C
b	Temperature gain	0.9933
θ^{low}	Lower temperature limit	150 °C
θ^{up}	Upper temperature limit	180 °C

Two reference methods were used to be compared with the proposed tendering method. In the first method (named as 'Hysteresis Control'), the aggregated load of bitumen tanks with the conventional hysteresis control was used as the baseline load based on which the tendering capacity was decided. In the second method (named as 'Energy Cost Minimization'), the baseline load was decided by running an optimization to minimize the energy cost in the retail market, and then the tendering capacity was decided. The baseline loads with different methods are shown in Figs. 1 and 2. Based on these results, the associated tendering capacity was calculated by (6) and (7), and the expected annual revenues/costs of the tank group were calculated by taking the product of 365 and the daily values obtained by (3)-(5), as listed in Tables 4 and 5.

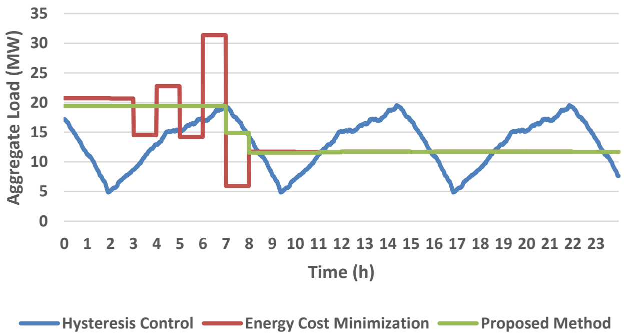

Fig 1 Baseline loads under the E7 with different methods adopted

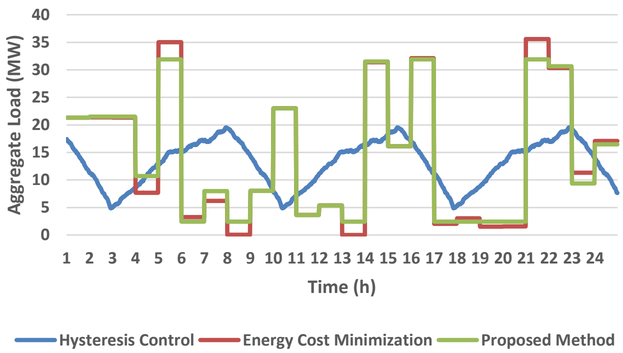

Fig 2 Baseline loads under the E10 with different methods adopted

Table 4 Expected annual revenues/costs of the tank group (1000 tanks) in the FFR scheme of GB with the E7 as the retail pricing scheme

Method	Revenue in the FFR Scheme (million £)	Energy Cost in the Retail Market (million £)	Net Cost (Cost-Revenue) (million £)
Hysteresis Control	2.05	17.60	15.55
Energy Cost Minimization	1.64	17.08	15.44
Proposed Method	3.39	17.37	13.98

Table 5 Expected annual revenues/costs of the tank group (1000 tanks) in the FFR scheme of GB with the E10 as the retail pricing scheme

Method	Revenue in the FFR Scheme (million £)	Energy Cost in the Retail Market (million £)	Net Cost (Cost-Revenue) (million £)
Hysteresis Control	2.05	17.05	15.00
Energy Cost Minimization	0.24	15.14	14.90
Proposed Method	0.91	15.32	14.41

From Tables 4 and 5, it is seen that with the baseline loads and tendering capacity decided by the proposed method, higher revenues in the FFR scheme and lower net costs were obtained, compared to the two reference methods in both the E7 and E10 situations, showing the superiority of the proposed tendering method.

4. CONCLUSION

In this paper, an optimal tendering method was proposed to decide the baseline load and response capacity of a group of bitumen tanks to provide the Firm Frequency Response service in the context of Great Britain. In different retail pricing schemes, the proposed tendering method was able to result in higher revenues from the frequency response market and lower net costs compared to the reference methods.

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