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Incremental Cost Consensus Algorithm for On/Off Loads to Enhance the Frequency Response of the Power System

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ABSTRACT Flexible loads, most of which are on/off appliances, are playing an important role in keeping the balance between power generation and demand. In this paper, a distributed consensus-based control strategy is proposed for the economic load dispatch in the frequency regulation. In order to avoid the complexity caused by the discrete cost characteristics, the continuous cost function of each user is fitted by the least squares method in advance. To minimize the overall load dispatching costs during the frequency regulation, Incremental Cost Consensus (ICC) algorithm is proposed in the load control. The economic load dispatch is realized through the convergence of the Incremental Cost (IC) of users. Case studies are provided to verify the effectiveness of the proposed method, with comparisons of different discretization methods.

INDEX TERMS On/off loads, load control, economic load dispatch, incremental cost consensus algorithm, frequency response.

NOMENCLATURE

K_I	Integral gain of the secondary frequency control
s	Laplace operator
P_{sp}	Power setpoint calculated by the secondary frequency control
R	Speed droop parameter
T_g	Speed governor time constant
ΔY	Gate position deviation
T_r	Reheat time constant
F_{HP}	Power fraction of the HP turbine section
ΔP_r	Thermal power deviation of reheated turbines
T_t	Turbine time constant
ΔP_m	Mechanical power deviation of generators
H	Generator inertia
D	Load-damping factor
Δf	Frequency deviation
i, j	Index of users (nodes)
P_i	Response power of user i
ΔP_d	Disturbance power ($\Delta P_d > 0$ for a sudden increase in load and $\Delta P_d < 0$ for a sudden increase in generation).
P_{syst}	Feedback power required by the system
k_p	Proportional gain of the controller
k_d	Differential gain of the controller
t	Index of time periods
σ	Index of loads
s_σ	Cost for switching load σ
d_σ	Compensation price for load σ
p_σ	Response power of load σ
m	Number of interruptible loads
g	Number of loads involved in the frequency control
P_{D_g}	Response power of g loads
C_{D_g}	Cost of g loads
$C(P)$	Quadratic function for fitting the continuous cost function
P	Response power for fitting the continuous cost function
α, β, γ	Coefficients of the quadratic cost function
r_g	Residual for the gth data point
I	Summed square of r_g
G	An undirected graph
V	Set of vertices
E	Set of edges
A	Adjacency matrix
Δ	Degree matrix
L	Laplacian matrix

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a_{ij}	Elements in A
l_{ij}	Elements in L
x_i	State variable of node i
k	Discrete-time index
δ_{ij}	Coefficient determined by the matrix L
C_i	Continuous cost function of user i
P_i	Response power of user i
$\alpha_i, \beta_i, \gamma_i$	Coefficients of the continuous cost function C_i
C_{total}	Total load dispatching costs
n	Number of users
$P_{i\_\min}, P_{i\_\max}$	Minimum and maximum values of the response power of user i
IC_i	Incremental cost of user i
λ_i	Consensus variable of user i
ε	Convergence coefficient
ΔP	Difference between the power supply and the system demand

I. INTRODUCTION

A. MOTIVATION

Renewable Energy Generation (REG) has been integrated into power systems on a large scale, which greatly relieves the pressure on the environment and the shortage of non-renewable resources [1]–[3]. However, fluctuations of REG would result in the unbalance between power generation and demand, making it difficult to maintain the system frequency stability [4]–[6]. To address this issue, reliable and economic approaches must be utilized to deal with the frequency oscillations caused by the high penetration of REG. As considerable researches have demonstrated the effectiveness of demand side load control in this respect, this paper aims to realize the economic load dispatch for distributed flexible loads which participate in the frequency regulation.

B. LITERATURE REVIEW

With the rapid development of Demand Response (DR) technologies, flexible load management plays an important role in smoothing fluctuations caused by REG [7]–[10]. Focusing on the frequency control problems by DR, reference [11] shows the role of Thermostatically Controlled Loads (TCLs) in enhancing the frequency stability. An intelligent DR strategy is introduced in [12] to cooperate with the secondary frequency control of the multi-area power system. By monitoring tie-line power variations, the magnitude and the location of the disturbance can be accurately acquired. A novel hierarchical demand-side load control strategy is proposed in [13] to provide the primary frequency control. It improves the inter-area oscillation damping and enhances the dynamic performance of the power system. Reference [14] develops a frequency control strategy of DR for an interconnected multi-area power system. The frequency deviation and the tie-line power are both adopted as the input signal of DR, and the optimal performance of the system is achieved by the genetic algorithm. In [15], a progressive control strategy of TCLs, which considers the comfort of customers and the influence of frequent switching of loads, is proposed to provide a fast and smooth frequency support. Reference [16] proposes a robust control strategy for air conditioner loads to support the primary frequency control of the power system. Integrated with Battery Energy Storage System (BESS), flexible loads are employed in [17] to improve the frequency stability of the power system.

In the above-mentioned papers, costs of DR for frequency control are not taken into consideration. Given the circumstance, a battery-assisted Load Frequency Control (LFC) strategy which considers the economic load dispatch is presented in [18]. It only considers the total fuel cost, giving little attention to the compensation for loads involved in the frequency regulation. Reference [19] gives a resources planning model which contains interruptible loads and shiftable loads. It takes the overall planning cost into account, but the compensation for load interruption is not discussed separately. Reference [20] proposes a distributed economic model predictive control strategy. In the same way, the cost of LFC is included in the general economic cost function without separate and detailed discussion.

Although economic factors are taken into account in the works above, the distributed control for flexible loads has not received enough attention. To sum up, few researches focus on the economic dispatch of loads which participate in the frequency control in the distributed framework. To address this issue, ICC algorithm is proposed in this paper to minimize the load dispatching costs in the frequency control. According to the equal incremental principle, the economic load dispatch can be realized by achieving the agreement among the IC of each user. With the rapid development of wireless communication and sensor network technology, it is possible to realize the distributed consensus-based control. In our previous work [21], ICC algorithm is applied to BESS which participates in the frequency control. It is proved effective in saving the total life-loss cost of BESS. The ICC control strategy is also employed in [22] and [23] to minimize the dispatching costs of electric vehicles and on/off loads, respectively. In terms of Economic Dispatch Problems (EDPs), reference [24]–[26] also make use of ICC algorithm to realize the optimal power allocation.

C. CONTRIBUTIONS

Considering the superiority of ICC algorithm in the economic load dispatch, it is proposed in this paper for distributed on/off appliances to enhance the frequency response. In addition, the proportional-differential controller is adopted in this paper to provide a fast and smooth frequency support [27].

Compared with existing studies, the main contributions of this paper can be summed up as follows:

- On/off appliances are sorted in ascending order of their cost, making sure the load with less compensation will be switched off preferentially. By accumulating their response power and cost, the discrete cost data can be obtained. Then, the continuous cost function is fitted by the least squares method, making preparations for ICC algorithm.

- ICC algorithm is employed to control the widely distributed on/off loads. By selecting IC of each user as the consensus variable, the overall load dispatching costs can be minimized. Compared with the method proposed in [28], ICC-based control strategy performs better in saving the total load dispatching costs.

D. ORGANIZATION

The paper is organized as follows. In Section 2, the test system is introduced and then the fitting method is utilized to obtain the continuous cost function. Section 3 provides the graph-theory-based ICC algorithm for on/off loads. In Section 4, numerical results are presented to evaluate the performance of the proposed method. Conclusions are summarized in Section 5.

II. MODEL DESCRIPTION

In this section, a single area power system is established to evaluate the performance of the proposed method. In addition, many of the flexible loads participating in the frequency response are on/off appliances, whose output power cannot be continuously regulated like batteries and generators. It directly results in the discrete characteristics of the cost function, making it a challenge to address the economic load dispatch problem. On the one hand, it is complicated to process discrete cost data without a unified expression in the load frequency control. On the other hand, the ICC control strategy proposed in this paper requires a continuous cost function to ensure the natural convergence of the consensus variables. Accordingly, the least squares fitting method is employed to obtain the continuous cost function.

A. TEST SYSTEM DESCRIPTION

A single area frequency response model is illustrated in Fig. 1. Each user provides several on/off appliances to support the frequency control, and the proposed load control strategy is introduced in the next section.

A proportional-differential controller is designed for on/off loads to participate in the frequency control. P_{syst} is the feedback power required by the system, which can be calculated by

$$P_{syst} = k_p \Delta f + k_d \frac{d\Delta f}{dt} \quad (1)$$

The feedback power includes two terms. The first term is the proportional control, which represents the primary frequency regulation. The second term performs as the virtual inertial control, which can quickly respond to the frequency deviation. By involving the two terms in the controller, the responding speed and the dynamic performance of the system can be enhanced.

The model of the power system can be described by the following state-space equations, which are realized by Euler

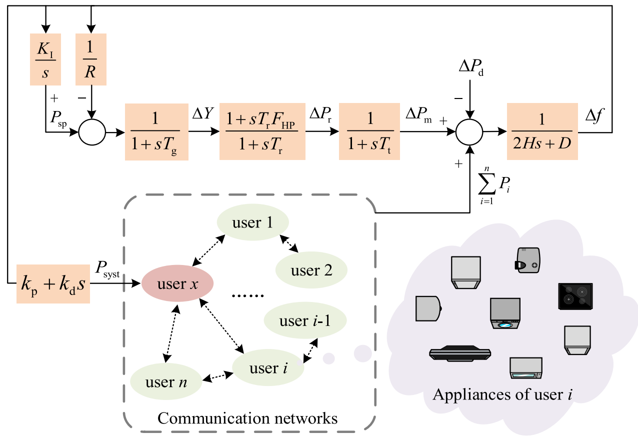

FIGURE 1. A single area frequency response model with on/off loads.

method.

$$\begin{cases} \dot{\boldsymbol{X}} = \boldsymbol{J}\boldsymbol{X} + \boldsymbol{K}\boldsymbol{U} + \boldsymbol{R}\Delta P_d \\ \boldsymbol{Y} = \boldsymbol{C}\boldsymbol{X} \end{cases} \quad (2)$$

where

$$\boldsymbol{X} = [P_{sp} \quad \Delta Y \quad \Delta P_r \quad \Delta P_m \quad \Delta f]^T$$

$$\boldsymbol{K} = \left[0\ 0\ 0\ 0\ \frac{1}{2H}\right]^T \quad \boldsymbol{R} = \left[0\ 0\ 0\ 0\ -\frac{1}{2H}\right]^T$$

$$\boldsymbol{C} = [0 \quad 0 \quad 0 \quad 0 \quad 1] \quad \boldsymbol{U} = \sum_{i=1}^{n} P_i$$

$$\boldsymbol{J} = \begin{bmatrix} 0 & 0 & 0 & 0 & -K_I \\ \frac{1}{T_g} & -\frac{1}{T_g} & 0 & 0 & -\frac{1}{T_g R} \\ \frac{F_{HP}}{T_g} & \frac{1}{T_r} - \frac{F_{HP}}{T_g} & -\frac{1}{T_r} & 0 & -\frac{F_{HP}}{T_g R} \\ 0 & 0 & \frac{1}{T_t} & -\frac{1}{T_t} & 0 \\ 0 & 0 & 0 & \frac{1}{2H} & -\frac{D}{2H} \end{bmatrix}$$

B. ACQUISITION OF THE CONTINUOUS COST FUNCTION

The cost of load control depends on the compensation for each load. It can be calculated as follows:

$$s_\sigma = d_\sigma p_\sigma \quad (3)$$

When a disturbance occurs in the power system, flexible loads will respond in ascending order of cost, which means the load with less compensation will be switched off preferentially. The order is as following:

$$s_1 \leq s_2 \leq \cdots \leq s_\sigma \leq \cdots \leq s_m \quad 1 \leq \sigma \leq m \quad (4)$$

By accumulating the response power and cost of these loads, a series of scattered points are obtained. Assuming that there are g loads involved in the frequency control, the response power P_{D_g} and the cost C_{D_g} can be calculated

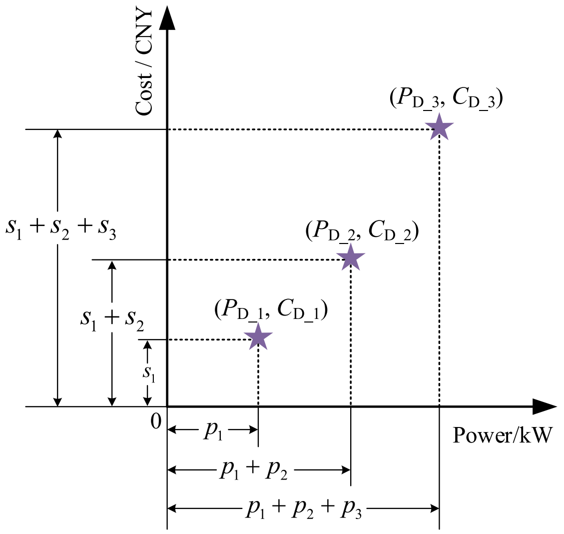

FIGURE 2. Method of finding discrete cost data.

by:

$$P_{D\_g} = \sum_{\sigma=1}^{g} p_\sigma \tag{5}$$

$$C_{D\_g} = \sum_{\sigma=1}^{g} s_\sigma \tag{6}$$

Fig. 2 gives the example of three loads to describe the method of finding the discrete cost data. When participating in the frequency response of the power system, load 1, load 2 and load 3 will be switched off in order.

The distribution of these discrete points is similar to the trajectory of the quadratic function which is used in this paper to describe the relationship between the cost and the power:

$$C(P) = \alpha P^2 + \beta P + \gamma \tag{7}$$

Coefficients of polynomials are fixed by the least squares fitting method. The residual r_g for the gth data point is defined as the error between the actual value C_{D_g} and the fitted value $C(P_{D\_g})$:

$$r_g = C_{D\_g} - C(P_{D\_g}) \tag{8}$$

The summed square of residuals is given by

$$I = \sum_{g=1}^{m} r_g^2 = \sum_{g=1}^{m} \left[C_{D\_g} - (\alpha P_{D\_g}^2 + \beta P_{D\_g} + \gamma)\right]^2 \tag{9}$$

Because the least squares fitting process minimizes the summed square of the residuals, the coefficients are determined by differentiating I with respect to each parameter, and setting the result equal to zero.

III. APPLICATION OF ICC ALGORITHM

In this section, an ICC-based distributed control strategy is proposed to minimize the total dispatching costs of the load control. Graph theory and the consensus algorithm are introduced as preparations for ICC formulations. Details about the power limit are considered.

A. GRAPH-THEORY-BASED DESCRIPTION OF COMMUNICATION NETWORKS

An undirected graph $G = (V, E)$ is employed to represent the topology of the communication networks. V is the set of vertices and the node inside is labeled by $v_i \in V$. E is the set of edges, where the edge between v_i and v_j is denoted by $(v_i, v_j) \in E$. Each node stands for a user and the edge represents the communication link for information exchange between users.

For a graph G on n vertices, the adjacency matrix A is a $n \times n$ matrix whose diagonal elements are all 0. Its off-diagonal element a_{ij} is determined by

$$a_{ij} = \begin{cases} 1, & \text{if } (v_i, v_j) \in E \\ 0, & \text{otherwise} \end{cases} \tag{10}$$

The degree of v_i is the number of its neighbors. Hence, the degree matrix is defined as

$$\Delta = \begin{cases} \sum_{j=1}^{n} a_{ij}, & i = j \\ 0, & i \neq j \end{cases} \tag{11}$$

Then, the laplacian matrix L can be obtained by

$$L = \Delta - A = \begin{cases} \sum_{j=1}^{n} a_{ij}, & i = j \\ -a_{ij}, & i \neq j \end{cases} \tag{12}$$

L is a symmetric positive-semidefinite matrix, and all the row sums of it are 0. It can be used to find many useful properties of a graph.

B. FIRST-ORDER CONSENSUS ALGORITHM

Let x_i be the state variable of node i. If the state of (13) is satisfied, it can be said that the consensus of the system is achieved.

$$x_1 = x_2 = \cdots = x_n \tag{13}$$

The linear first-order consensus algorithm is defined as

$$\dot{x}_i = \sum_{j=1}^{n} a_{ij}(x_j - x_i) \quad i = 1, 2, 3, \cdots, n \tag{14}$$

Combined with (12), the matrix form of (14) can be given by

$$\dot{\boldsymbol{x}} = -\boldsymbol{L}\boldsymbol{x} \tag{15}$$

where $x = [x_1, x_2, x_3, \ldots, x_n]^{\mathrm{T}}$.

If it takes a fixed interval to exchange information between neighbors, the algorithm can be transferred into a discrete-time form:

$$x_i(k+1) = \sum_{j=1}^{n} \delta_{ij} x_j(k) \quad i = 1, 2, 3, \cdots, n \tag{16}$$

$$\delta_{ij} = \frac{|l_{ij}|}{\sum\limits_{j=1}^{n} |l_{ij}|} \quad i = 1, 2, 3, \cdots, n \tag{17}$$

C. ICC FORMULATIONS

The continuous cost function can be expressed by equation (7), of which parameters are calculated by (8)-(9). For ith user, the cost function can be written by

$$C_i(P_i) = \alpha_i P_i^2 + \beta_i P_i + \gamma_i \tag{18}$$

The dispatch of responsive DR loads is aimed at minimizing the total costs of users during the load control process, which can be represented by the following expression:

$$\text{Min } C_{\text{total}} = \sum_{i=1}^{n} C_i(P_i) \tag{19}$$

The power balance and the limit constraint should be satisfied:

$$P_{\text{syst}} - \sum_{i=1}^{n} P_i = 0 \tag{20}$$

$$P_{i\_\min} \leq P_i \leq P_{i\_\max} \tag{21}$$

In the ICC algorithm, IC of each user is selected as the consensus variable. As the information exchanged among nodes, it is defined as

$$\text{IC}_i = \frac{\partial C_i}{\partial P_i} = \lambda_i \quad i = 1, 2, 3, \ldots, n \tag{22}$$

According to (16) and (17), the updating rule for user i is given by

$$\lambda_i(k+1) = \sum_{j=1}^{n} \delta_{ij}\lambda_j(k) \quad i = 1, 2, 3, \cdots, n \tag{23}$$

The user with the most neighbors is selected as the leader unit to receive the dispatching information. It should decide to increase or decrease the group IC according to the unbalance between power supply and demand. Then, the control signal will be transmitted to all nodes through communication networks. The updating rule for the leader node is modified as follows:

$$\lambda_i(k+1) = \sum_{j=1}^{n} \delta_{ij}\lambda_j(k) + \varepsilon\Delta P \tag{24}$$

$$\Delta P = P_{\text{syst}} - \sum_{i=1}^{n} P_i \tag{25}$$

Based on (18) and (22), the response power of user i can be expressed by

$$P_i = \frac{\lambda_i - \beta_i}{2\alpha_i} \tag{26}$$

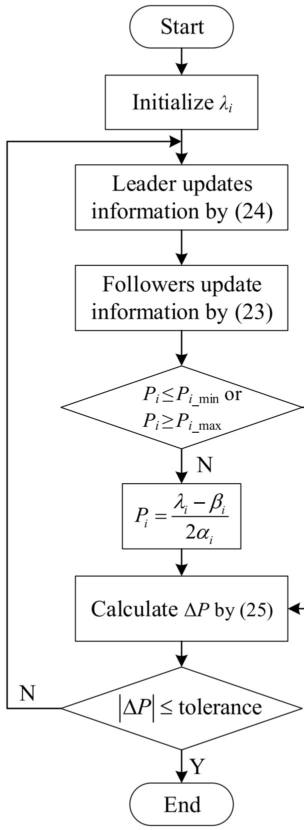

FIGURE 3. Flowchart of ICC algorithm.

Taking the power constraints into consideration, the response power can be modified as

$$P_i = \begin{cases} P_{i\_\min}, & \dfrac{\lambda_i - \beta_i}{2\alpha_i} \leq P_{i\_\min} \\ \dfrac{\lambda_i - \beta_i}{2\alpha_i}, & P_{i\_\min} \leq \dfrac{\lambda_i - \beta_i}{2\alpha_i} \leq P_{i\_\max} \\ P_{i\_\max}, & \dfrac{\lambda_i - \beta_i}{2\alpha_i} \geq P_{i\_\max} \end{cases} \tag{27}$$

Equations (23)-(27) are main mathematical expressions involved in the ICC-based control strategy. The flowchart is presented in Fig. 3.

IV. RESULTS AND DISCUSSION

Compared with the capacity of a microgrid, the total response power provided by a single user is very small. If each user is regarded as a node, there will be thousands of nodes in the communication topologies, making it difficult for computers to run. Moreover, a complex building can provide considerable loads, and a certain number of complex buildings are sufficient to provide the frequency support for a microgrid.

Considering a microgrid system of 20MW, 20 buildings are selected as users to participate in the frequency control. The communication network is provided in Fig. 4. Considering the limited coverage of Wi-Fi, communication links should be established between adjacent buildings as much as possible. Each building represents a node, with the communication

FIGURE 4. Communication topologies of the system with 20 buildings.

topology depicted in yellow. Building 8 with the most neighbors is selected as the leader node. Experiments are carried out in Matlab under the condition of reliable and ideal communication.

In this section, firstly, the validity of the least squares fitting method is shown. Secondly, costs of different control methods are compared to find the most economic one. Finally, since subjects in this paper are on/off loads, different discretization methods of continuous response characteristics are also analyzed.

A. RESULTS OF LEAST SQUARES FITTING

According to their importance, appliances in each building are classified into 9 groups, and appliances in a group are compensated at the same price. The data of power and price are listed in Appendix A. The continuous cost function of each building can be obtained according to the least squares fitting method introduced in Section 2. Fitting results of building 4 is presented in Fig. 5 as an example. It can be seen that the fitted continuous cost curve is highly coincident with the discrete points. All fitting coefficients of the 20 buildings are listed in Appendix B.

B. COMPARISONS OF DIFFERENT CONTROL METHODS

In this subsection, the proposed ICC control strategy is compared with the method of [28] in the respect of frequency response and total dispatching costs. The following three cases are considered to evaluate the performance of the ICC method. The cost function in equation (18) is adopted.

Case 1: There is no on/off load involved in the frequency control.

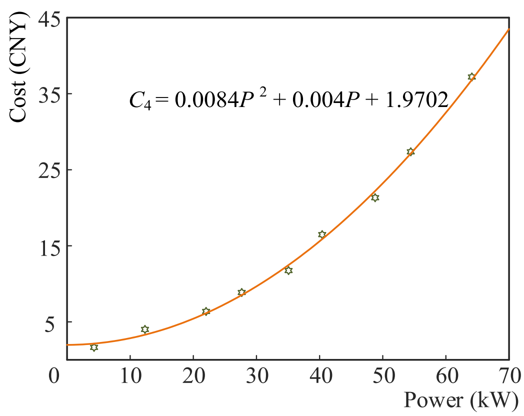

FIGURE 5. The cost function of building 4.

Case 2: The method proposed in [28] is adopted for on/off loads to participate in the frequency control.

Case 3: ICC algorithm is adopted for on/off loads to participate in the frequency control.

Parameters of the system in Fig. 1 are listed in Appendix C. Considering 0.03p.u. step disturbance at 1s, simulation results are presented in Fig. 6-8, with quantitative indicators provided in Table 1.

- Fig. 6 presents the frequency deviations of three cases. It can be seen that the participation of on/off loads can effectively curtail the frequency fluctuations caused by the sudden disturbance. According to the data in Table 1, the maximum frequency deviation of Case 2 and Case 3 are apparently smaller than that of Case 1.
- Fig. 7 shows the response power of Case 2 and Case 3. Combing Fig.7 (a) and Fig. 6, it can be found that

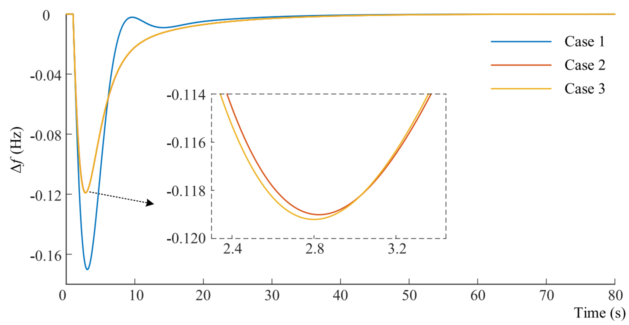

FIGURE 6. **Frequency deviations of three cases.**

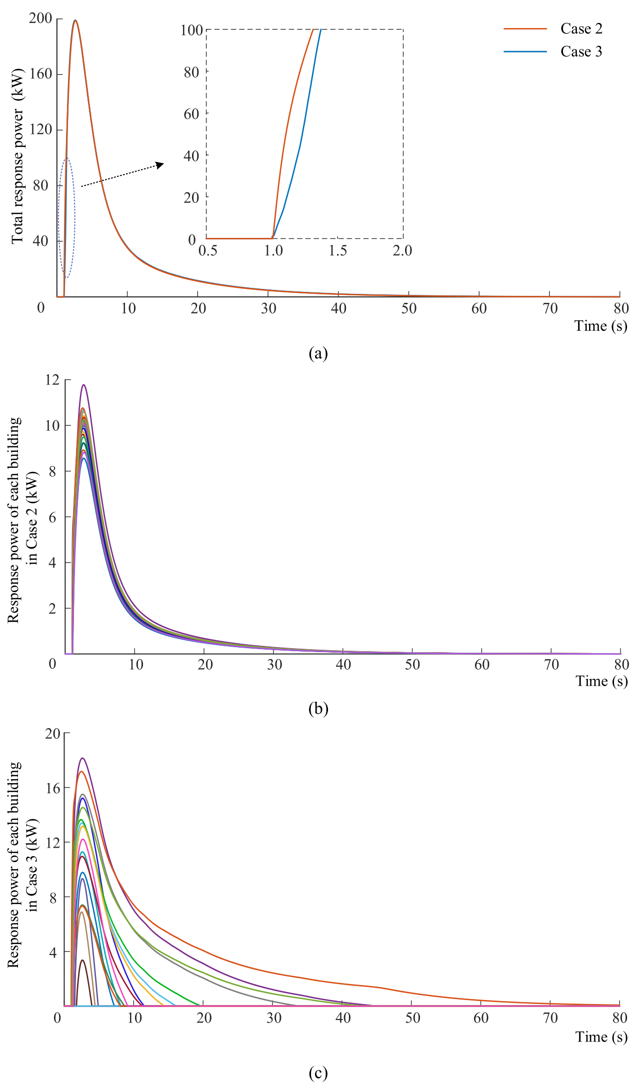

FIGURE 7. **Response power of two cases: (a) total response power of the two cases; (b) response power of each building in Case 2; (c) response power of each building in Case 3.**

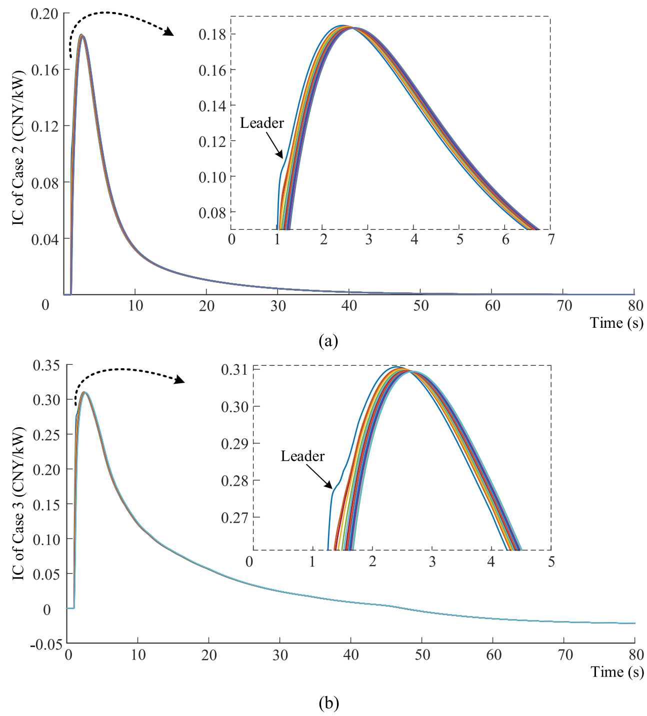

FIGURE 8. **Incremental cost of Case 2 and Case 3: (a) IC of Case 2; (b) IC of Case 3.**

TABLE 1. **Results of the maximum frequency deviation and total dispatching costs.**

Case No.	Maximum frequency deviation (Hz)	Total dispatching costs (CNY)
Case 1	0.1702	
Case 2	0.1190	65.9255
Case 3	0.1192	62.5832

TABLE 2. **Results of the maximum frequency deviation and total dispatching costs.**

Method No.	Maximum frequency deviation (Hz)	Total dispatching costs (CNY)
Method 1	0.1320	54.5278
Method 2	0.1036	91.0472
Method 3	0.1200	72.7581

under the circumstance of similar total response power, the frequency response of Case 2 and Case 3 do not differ a lot. Nevertheless, costs in Table 1 indicate that the ICC method (Case 3) costs less than the method of [28] (Case 2). Additionally, it can be observed that the method in Case 2 responds a little faster than ICC control strategy (Case 3), leading to its slightly better performance in reducing the maximum frequency deviation.

- IC of the 20 nodes are depicted in Fig. 8. The leader node (Building 8) changes first immediately after the disturbance, followed by follower nodes. After a few iterations, IC of all nodes converge to be equal, which means the consensus of the system is achieved.

From the analysis above, it can be concluded that the involvement of on/off loads can improve the frequency

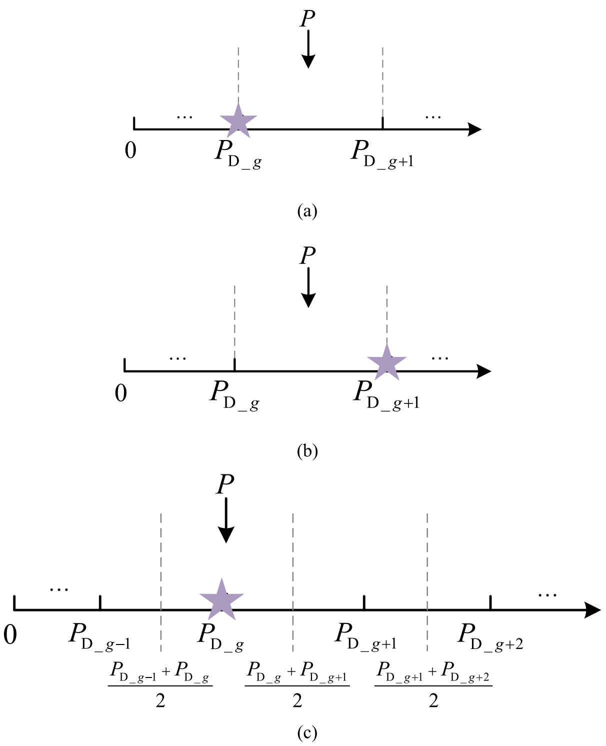

FIGURE 9. Diagram explanations of the three methods: (a) Method 1; (b) Method 2; (c) Method 3.

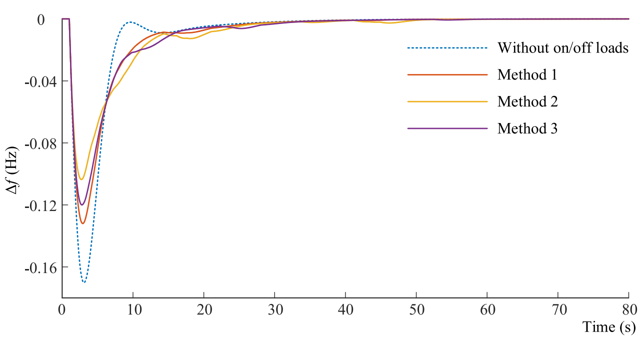

FIGURE 10. Frequency deviations of three methods.

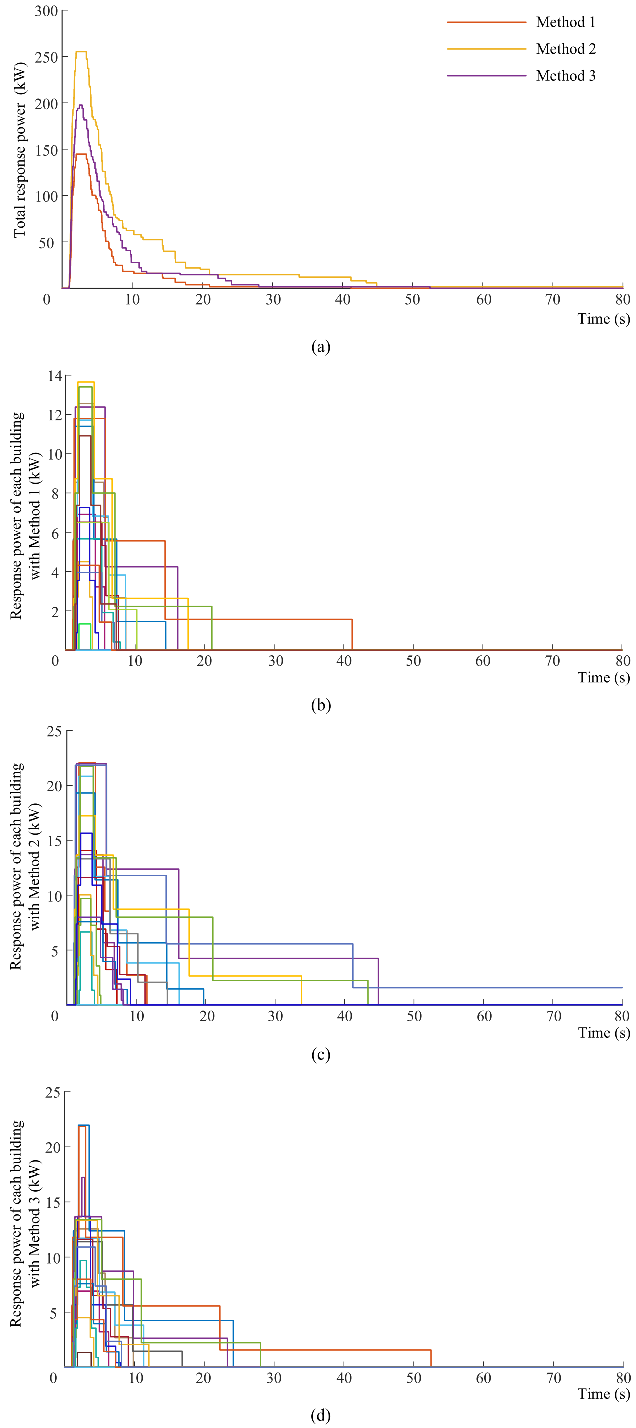

FIGURE 11. Response power of three methods: (a) total response power of the three methods; (b) response power of each building with Method 1; (c) response power of each building with Method 2; (d) response power of each building with Method 3.

response of the power system. Moreover, the ICC-based control strategy can minimize the total load dispatching costs in the frequency control.

C. COMPARISONS OF DIFFERENT DISCRETIZATION METHODS

The discretization of the response power is based on the continuous characteristics obtained in the previous subsection. In this subsection, three methods are designed to discretize the continuous characteristics, with the details as follows:

$$\text{Method 1: } P = \begin{cases} 0, & 0 \le P < P_{D\_1} \\ P_{D\_g}, & P_{D\_g} \le P < P_{D\_g+1} \\ P_{D\_m}, & P = P_{D\_m} \end{cases} \tag{28}$$

$$\text{Method 2: } P = \begin{cases} P_{D\_1}, & 0 < P \le P_{D\_1} \\ P_{D\_g+1}, & P_{D\_g} < P \le P_{D\_g+1} \end{cases} \tag{29}$$

$$\text{Method 3: } P = \begin{cases} 0, & 0 \le P < \dfrac{P_{D\_1}}{2} \\ P_{D\_g}, & \dfrac{P_{D\_g-1}+P_{D\_g}}{2} \le P < \dfrac{P_{D\_g}+P_{D\_g+1}}{2} \\ P_{D\_m}, & \dfrac{P_{D\_m-1}+P_{D\_m}}{2} \le P \le P_{D\_m} \end{cases} \tag{30}$$

TABLE 3. The power capacity of appliances in 9 groups (kW).

Group No.	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Building 1	7.1547	1.9852	4.6067	7.8883	3.6925	8.7031	3.2200	8.9565	8.1928
Building 2	9.5109	1.7752	4.0061	2.6782	8.7234	8.3398	10.0996	6.5317	4.0922
Building 3	1.3335	8.9159	8.0381	5.3123	6.1453	3.2676	10.5490	3.6848	9.5375
Building 4	9.5907	9.8070	8.3496	7.3402	5.7722	5.5496	8.1368	5.3893	4.2413
Building 5	6.6395	7.1267	1.9621	9.3548	9.6306	1.7395	8.5820	4.2189	1.0129
Building 6	3.8241	7.9562	5.1422	10.0723	3.0016	6.3210	9.1210	7.7980	4.8860
Building 7	7.1239	7.8029	4.6788	1.5456	7.9506	2.7615	7.8869	2.5193	9.8917
Building 8	5.7421	4.1181	6.7865	1.4553	7.9142	6.8677	4.1979	8.2950	10.0394
Building 9	10.0541	6.8824	7.4480	1.5673	3.9949	7.2366	6.2286	5.4313	9.5396
Building 10	10.1311	1.7976	7.9240	2.7041	5.9619	7.8554	8.4007	2.5193	5.5279
Building 11	3.7548	0.4137	9.8980	8.8277	1.4966	5.4306	8.0297	4.3813	9.4654
Building 12	10.1913	2.4339	7.1372	2.6698	8.2663	0.8799	9.5620	5.4215	3.7079
Building 13	10.0506	2.9078	6.8782	8.5498	5.5734	2.4045	1.9096	9.4787	8.6226
Building 14	5.0967	1.1851	8.7073	2.5571	8.1816	9.5900	2.7699	9.9204	5.7617
Building 15	1.4028	8.0199	4.7495	9.7573	2.8070	8.6002	3.6281	5.1541	2.5515
Building 16	2.8896	8.6464	5.2325	3.6750	8.3643	8.6709	1.4287	5.1373	4.5745
Building 17	4.4282	7.2954	10.0772	2.0643	5.9724	5.6525	9.1273	3.5462	6.8159
Building 18	9.6152	3.3292	3.5742	2.6362	4.9287	10.4594	6.0872	9.4507	7.6832
Building 19	8.3181	9.9771	6.1453	6.4687	2.2253	7.8211	5.7736	3.8773	5.4012
Building 20	10.0744	1.7619	2.3499	7.7693	3.5399	4.6480	5.0218	8.1676	4.7348

TABLE 4. The compensation price for each group.

Group No.	Group 1	Group 2	Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Compensation (CNY/kW)	0.2546	1.0041	0.5915	0.3941	0.4257	1.0705	0.2912	0.8701	0.3712

TABLE 5. Coefficients of 20 buildings.

Building No.	α_i (CNY/kW^2)	β_i (CNY/kW)	γ_i (CNY)	Building No.	α_i (CNY/kW^2)	β_i (CNY/kW)	γ_i (CNY)
1	0.0072	0.1694	0.9845	11	0.0071	0.1503	0.6739
2	0.0066	0.1072	2.2656	12	0.0035	0.2441	1.4916
3	0.0047	0.2777	0.2664	13	0.0034	0.3200	0.1527
4	0.0084	0.0040	1.9702	14	0.0092	0.1090	1.2532
5	0.0035	0.3191	0.3632	15	0.0113	0.1419	0.5836
6	0.0088	0.0748	1.2425	16	0.0108	0.1513	0.4607
7	0.0033	0.3415	-0.1020	17	0.0085	0.0850	1.1593
8	0.0093	0.0570	1.0563	18	0.0094	0.0179	2.0660
9	0.0097	-0.0230	1.8196	19	0.0105	0.0055	1.6046
10	0.0038	0.2571	1.7180	20	0.0071	0.1353	1.7501

Diagram explanations of the three methods are provided in Fig. 9.

Based on results of the ICC control strategy (Case 3 of the previous subsection), the performance of these discretization

TABLE 6. Parameters of the single area system.

Parameter	Value	Parameter	Value
K_{I}	1.91	R	0.05
T_{g}	0.2	T_{r}	7
F_{HP}	0.3	T_{t}	0.3
H	5	D	1
k_{p}	-1650	k_{d}	-400
ε	0.0006	Simulation time-step-size	0.005

methods is presented in Fig. 10-11, with quantitative indicators listed in Table 2.

- Fig. 11 illustrates the response power of three methods. As shown in Fig. 11 (a), three methods vary in the total response power. The total response power of Method 1 and Method 2 is the minimum and the maximum, respectively, and that of Method 3 is in between.
- Fig. 10 shows the frequency response of three methods. Combing with Table 2 where the total dispatching costs are provided, it is observed that the method which provides more response power gives better results in reducing the maximum frequency deviation. However, it inevitably costs more due to the increasing response amount. If it regards the performance of the frequency control as the most important issue rather than the dispatching costs, Method 2 is the best. Conversely, Method 1 is the best. If the two factors are both taken into account, Method 3 is the optimum.

From the analysis above, it can be seen that different discretization methods would result in the differences in the total response power of on/off loads. The method with more response power performs better in stabilizing the system frequency, yet its dispatching costs are higher.

V. CONCLUSION

In this paper, an economical distributed control strategy is designed for on/off loads to enhance the frequency stability of the power system. These loads are sorted and summed as preparations for the continuous cost function which is obtained by the least squares fitting method. Considering the overall dispatching costs of loads involved in the frequency control, the ICC-based control strategy is proposed. Compared with the existing studies, the main contributions of this paper can be summarized as following:

- Least squares fitting method is employed in this paper to achieve the continuous cost function of the on/off loads. It greatly simplifies the load frequency control process which considers the load dispatching costs.
- In order to minimize the total load dispatching costs, the ICC algorithm is proposed for distributed on/off loads to participate in the frequency control. Compared with the method proposed in [28], the ICC control strategy performs better in saving the overall load dispatching costs.

In the future work, we will focus on establishing a comprehensive cost model of TCLs (e.g. air-conditioners) considering thermodynamic characteristics. We will try to apply ICC algorithm to the economic dispatch of TCLs which participate in the frequency control.

APPENDIXES

APPENDIX A

Table 3, and 4.

APPENDIX B

Table 5.

APPENDIX C

Table 6.

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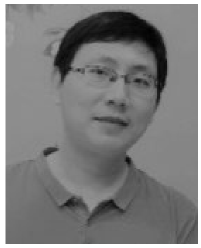

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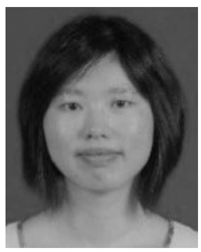

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