

Event-Triggered Distributed Hybrid Control Scheme for the Integrated Energy System

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Abstract—For the integrated energy system (IES) formed by a cluster of energy hubs (EHs), the outputs of EHs and system parameters, which greatly influence the security performance, should be properly adjusted. In this article, an event-triggered distributed hybrid control scheme is proposed to achieve security and economic operation for the IES. First, the EH output control is designed based on the features of energy networks as well as the containment and consensus algorithms. According to the control of outputs, the electricity and heat load power can be accurately shared without knowing the network parameters. Second, the pressure is bounded within an acceptable range, and the frequency is reverted to the reference value by implementing the proposed control method. Third, an event-triggered communication strategy is employed to design the corresponding protocols, resulting in reduced communication cost. Finally, the control of devices based on the equal incremental principle is proposed to achieve the minimal economic cost for each EH with considering energy prices. The results of numerical case studies are presented to validate the performance of the proposed control method.

Index Terms—Distributed hybrid control (DHC), economic cost, energy hub (EH), event-triggered mechanism, integrated energy system (IES), parameter restoration, power sharing.

I. INTRODUCTION

WITH the increasing concern for the environment, the shortage of fossil fuels, and the development of key technologies related to energy coupling, the energy system structures integrating multienergy carriers have gained wide attention in recent years [1], [2]. To better analyze the relationship among different kinds of energy, the project named “Vision of Future Energy Networks” introduces the concept of energy hub (EH). As a primary unit of the integrated energy system (IES), the EH

possesses the ability to convert, transform, and store multiple kinds of energy [3].

Recently, most studies about EH have been focused on the modeling and scheduling problems [4]. In light of detailed situations, different kinds of EH models were investigated in [5]–[8]. New formulations of the EH model that considered the efficiencies and limitations during operation were presented in [5]. Moghaddam *et al.* [6] proposed a comprehensive model of an EH, in which the possible connections between devices were analyzed. Barmayoon *et al.* [7] modeled a renewable residential EH and also assessed the usage of storage in the model in detail. An urban-level EH was modeled to integrate the decentralized energy systems in [8]. Numerous research works paid attention to the scheduling of EH since the operation of EH can determine performance of the IES [9]–[11]. Sheikhi *et al.* [9] formulated a noncooperative game between EHs in the IES. Dolatabadi *et al.* [10] represented a short-term scheduling method, which simultaneously considered the uncertainties of energy prices, wind power, and load. In [11], the energy management of the IES was realized under uncertainties of data and demand response. The reliability-based optimal problem was investigated in [12]–[14]. Zhang and Che [12] utilized the minimal cut-maximal flow algorithm to resolve the reliability-based optimal planning problem for the IES. The network reliability was extended as the constraint for optimal planning in [13]. Shahmohammadi and Moradi-Dalvand [14] proposed a linearized optimal model considering reliability constraints. Important indices such as maximum allowable loss of load probability and adequacy indices are also checked. In the optimization process, different reliability indices are introduced to meet the requirement of reliability.

Besides the modeling and optimal scheduling, the underlying control method is also important, which is the essential requirement of the energy system. However, such research works were mostly focused on the electric power system. Several approaches such as droop control methods [15], [16] and distributed coordination control methods [17]–[20] were proposed to realize accurate power sharing. The droop control method that imitated the feature of the synchronous generator can achieve the “plug-and-play” of distributed generation units. Nevertheless, poor reactive power sharing is typically resulted by utilizing the method in practical situations since the impedance of different lines are generally mismatched. The deviations of frequency and voltage are also caused by the droop control. To ensure the reactive power sharing and keep the desired voltage and frequency values simultaneously, distributed control methods based on

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TABLE I
COMPARISON OF RELEVANT WORKS PROPOSED IN THE LITERATURE AND THE METHOD PROPOSED IN THIS ARTICLE

Reference	Method	Energy type	Optimal operation	Power sharing	Parameter restorations	Distribution mode	Communication mechanism
[15]	Droop control	Electricity	-	✓	-	Decentralized	-
[19]	Consensus-based droop control	Electricity	-	✓	✓	Distributed	Time-triggered
[24]	Consensus-based droop control	Electricity	-	✓	-	Distributed	Event-triggered
[25]	Multi-energy droop control	Multi-energy	✓	✓	-	Decentralized	-
Proposed	Multi-energy consensus control/IEIP	Multi-energy	✓	✓	✓	Distributed	Event-triggered

multiagent theory were investigated. The authors of [17] and [18] proposed consensus-based control approaches to share the active power accurately. In [19] and [20], the distributed secondary controls were presented to achieve not only power sharing but also the regulations for voltage and frequency. By utilizing the distributed method, communication between agents is necessary. As a popular used method to reduce the communication transmission, event-triggered communication has been studied by many researchers. A delay-tolerant predictive power compensation control method was proposed in [21] for voltage regulation. Moreover, the maximum tolerable communication delay can be estimated, and the accurate prediction can be achieved by utilizing the method proposed in [21]. Peng *et al.* [22] proposed a higher energy-efficient mixed sampling scheme to improve the energy efficiency in energy-constrained wireless networked control systems. According to the method, the idle-listening period of wireless sensor nodes can be increased, and the number of transmitted packets can be reduced. An event-based distributed method with some desirable features was proposed in [23] to solve the optimal operation issue in a fully distributed fashion. Fan *et al.* [24] proposed an event-based distributed control for accurate reactive power sharing.

Though the control methods for the electric power system and communication mechanisms have been widely studied, the corresponding method for power sharing and parameters restoration of the IES is still lacked. The IES is more flexible compared with the power system due to the multienergy carriers and energy conversions. However, flexibility causes multiple possible results for a certain case and makes the operation of the IES more complex. It is hard to utilize the aforementioned methods in the IES due to the different characters of different energy resources and the energy coupling feature. In previous work [25], a control approach that can proportionally allocate the outputs of EHs was presented to achieve power sharing of the IES. Table I summarizes the taxonomy of the proposed methodologies. However, several critical problems still exist.

- 1) In order to achieve power sharing, network parameters such as line resistances are indispensable for the approach. However, the parameters are different for different networks. It is also difficult to accurately measure and expediently access the parameters.
- 2) The method will cause frequency and pressure to deviate from corresponding nominal values. It is also hard to restore the pressure to the nominal value due to the influence of branch. Since the system parameters have strict requirements for the security operation of the system, the deviations of corresponding parameters will highly impact the performance of the IES.

- 3) In the IES, different energy networks share different time scales. Some networks such as heat network have slower response speed. Therefore, the periodic communication mechanism is unnecessary for the IES, and lots of communication may be redundant. A proper sampling strategy should be designed to reduce the communication cost considering the multi-time-scale feature.
- 4) While realizing power sharing, how to adjust the operation of devices in the EH and enhance economic performance by the control method still need further research.

To tackle those challenges, an event-triggered distributed hybrid control (DHC) scheme is proposed. By implementing the proposed scheme containing the EH output control and device control, the EHs and the system parameters can be adjusted appropriately. The major contributions of this article are summarized as follows.

- 1) The control of EH outputs based on the containment algorithm and the consensus algorithm is proposed. With this effort, the outputs of electricity and heat power of EHs can be accurately allocated by using the control method without the network parameters, which are acquired with difficulty.
- 2) The restoration of parameters is investigated to regulate the system parameters of the IES, such as frequency and pressure. The control of output can constrain the pressure in an acceptable range and restore the frequency to eliminate the influence of parameter deviation. As a consequence, the security operation of the IES can be guaranteed.
- 3) The event-triggered mechanism is embedded in the proposed DHC scheme to reduce communication interaction among EHs. By designing the sampling strategy properly, the event-triggered control approach can dramatically reduce the amount of communication without affecting the achievement and fit well with multi-time-scale characteristic of the IES.
- 4) With considerations of the energy coupling characteristics and energy prices, the control of devices based on the equal incremental principle (EIP) is proposed to realize the appropriate regulation of devices in EHs and reduce economic cost for each EH.

The rest of this article is organized as follows. Section II presents the structure of the IES. Section III proposes the event-triggered DHC scheme that achieves both security operation and economic benefit. Section IV introduces several cases to verify the DHC scheme applied to a simulated IES. Finally, Section V concludes this article.

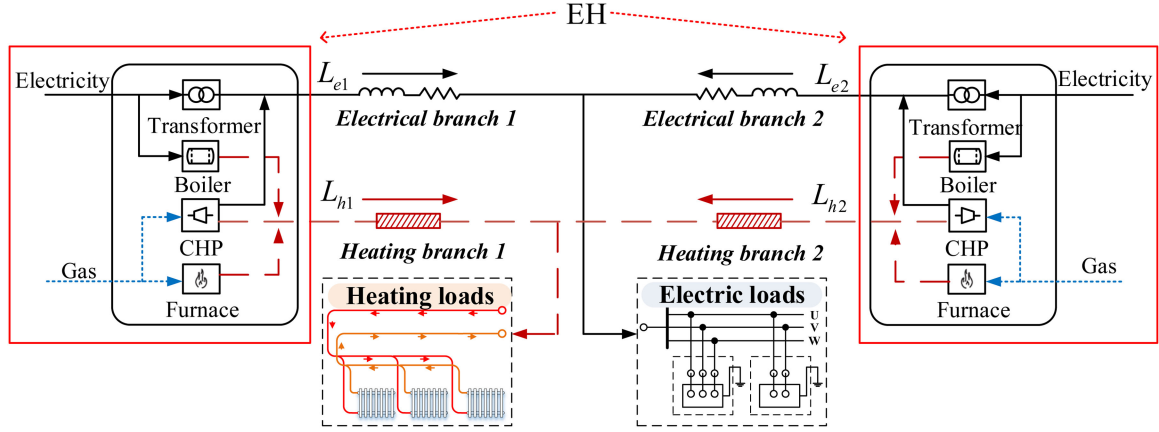


Fig. 1. Architecture of the IES.

II. STRUCTURE OF THE SYSTEM AND THE PROPOSED CONTROL METHOD

A. Structure of the System

A possible layout of the IES is described in Fig. 1, where several EHs are utilized to satisfy the loads in the system. The EH model in this article is a basic model, and each EH has its own devices to dispose multiple energy carriers [5], [25]. A basic EH with the furnace, the combined heat and power (CHP), the boiler, and the transformer is also expressed in Fig. 1. Based on the devices, an EH can convert, transform, or store energy. In order to resolve the issue of power sharing and regulate the system parameters of the IES, the outputs of EHs are necessary to be appropriately adjusted. The controller structure used in the IES is designed based on a multiagent system, and each EH is controlled by different agents. The loads and EHs are interconnected through corresponding networks, as shown in Fig. 1. The dynamic model of the IES in this article is the general model based on [26] and [27]. The dynamic heat network model can be expressed as

$$\left(\rho \bar{C}_p \bar{A}_{\tilde{i}} \frac{\partial T_{\tilde{i}}^{\text{pipe}}(x, t)}{\partial t} + \bar{m}_{\tilde{i}}^{\text{pipe}}(x, t) \bar{C}_p \frac{\partial T_{\tilde{i}}^{\text{pipe}}(x, t)}{\partial x} \right) = \frac{T_{\tilde{i}}^{\text{area}} - T_{\tilde{i}}^{\text{pipe}}(x, t)}{\bar{R}_{\tilde{i}}}. \quad (1)$$

In (1), $T_{\tilde{i}}^{\text{pipe}}(x, t)$ is the pipe temperature at time t and distance x for pipe $\tilde{i}$. Similarly, $\bar{m}_{\tilde{i}}^{\text{pipe}}(x, t)$ is the mass flow for the corresponding pipe. Density and capacity of water can be expressed by ρ and $\bar{C}_p$, respectively. The thermal conductive coefficient and the cross-sectional area of pipe $\tilde{i}$ can be denoted by $\bar{R}_{\tilde{i}}$ and $\bar{A}_{\tilde{i}}$, respectively. The model of the electric power system can be expressed as

$$\begin{aligned} V_{\tilde{i},t} &= |V_{\tilde{i},t}| (\cos \theta_{\tilde{i},t} + j \sin \theta_{\tilde{i},t}) \\ S_{\tilde{i},t} &= P_{\tilde{i},t} + jQ_{\tilde{i},t} = V_{\tilde{i},t} \sum_{\tilde{j}}^{N_e} (Y_{\tilde{i}\tilde{j}} V_{\tilde{j},t})^* \end{aligned} \quad (2)$$

where the phase angle and the voltage magnitude of bus $\tilde{i}$ at time t are described by $|V_{\tilde{i},t}|$ and $\theta_{\tilde{i},t}$, respectively. $S_{\tilde{i},t}$ is the complex power of corresponding bus. The active power and the reactive power are denoted by $P_{\tilde{i},t}$ and $Q_{\tilde{i},t}$, respectively. The

admittance from node $\tilde{i}$ to $\tilde{j}$ is indicated by $Y_{\tilde{i}\tilde{j}}$. N_e is the bus number in the IES.

It is analyzed that the conduction of heat is related to the pipe temperature and the mass flow. The regulation of the heat system can be achieved by adjusting either the temperature or the mass flow. Based on the well-known alternating current power flow equations, the electric power system model can be applied in the arbitrary electric network. Different energy networks share different time scales in the IES. The response speed of the electric power system is much faster than that of the heat system; the regulation process of the electric power system can usually be ignored when the regulation of the heat system is considered. Therefore, in the general dynamic model of the IES, the power system uses the steady-state model instead of the transient model. Based on the characteristics of the IES, a control approach that can proportionally allocate the outputs of EHs was presented in [25] to achieve the power sharing of the IES. However, the control method has problems as shown in the introduction. Therefore, a novel control approach for the EH needs to be proposed.

B. Distributed EH Output Control

To achieve accurate power sharing and the parameter restoration in the IES, a distributed control method for the outputs of the EH based on the containment and consensus algorithm is designed. On the basis of the features of the corresponding network, a heat output control approach of the EH is described as [25]

$$L_h^2 = L_{hN}^2 + k_p (p_N - p) \quad (3)$$

where p_N and p are nominal and actual outlet pressures, respectively. The nominal and actual heat output powers are denoted by L_{hN} and L_h , respectively. k_p is the adjustment coefficient of the control approach. The relationship between the output power of EHs and adjustment coefficients needs to be controlled as

$$\frac{L_{h1}^2}{k_{p1}} = \frac{L_{h2}^2}{k_{p2}} = \dots = \frac{L_{hN}^2}{k_{pN}} \quad (4)$$

where n is the number of EHs. However, the approach cannot realize accurate power sharing because the resistances of heat branches are different. By implementing the approach, the pressure will also be deviated from the nominal value without boundary.

To realize accurate power sharing, a control method based on the consensus algorithm is designed. Make $L_h^2 = H$ and the multiagent system dynamic can be expressed as

$$\frac{\dot{H}_i}{k_{pi}} = u_{Hi} \quad (5)$$

where i is the index of the corresponding EH. According to the consensus control, u_{Hi} is the auxiliary control input and can be expressed as

$$u_{Hi} = -R_H q_{Hi} \quad (6)$$

where q_{Hi} is the heat power sharing error. R_H is the coupling gain of heat output power. Let $\frac{H_i}{k_{pi}} = DH_i$. In order to accurately share the heat power, the consensus protocol needs to be designed that each DH_i should be equal. Namely, q_{Hi} can be expressed as

$$q_{Hi} = \sum_{j=1, j \neq i}^n a_{ij} (DH_i - DH_j). \quad (7)$$

In (5), a_{ij} is the element in the adjacency matrix, which can reflect the connected situation of EHs.

A proportional–integral (PI) controller $D_i(s)$ is utilized to dispose the input u_{Hi} and generate a correction term δH_i . The correction term is formulated as

$$\delta H_i = D_i(s) u_{Hi}. \quad (8)$$

The outlet pressures of EHs cannot be controlled at a set value since the resistances of heat branches are different, as shown in Fig. 1. If the outlet pressures of EHs are restored to the reference, the proportion of power sharing will be determined by the resistance of each branch and be controlled hardly. Therefore, making outlet pressures within an acceptable range should be the control objective. In this situation, it is hard to bound the pressures within a set range by utilizing the consensus algorithm. To adjust the outlet pressures, the containment-based controller for pressure is proposed, and the controller expression is

$$\dot{c}_{pi} = u_{pi} = -R_p \left(\sum_{j \in N_i} a_{ij} (p_i - p_j) + \sum_{l \in M_i} b_{il} (p_i - p_l) \right) \quad (9)$$

where $\dot{c}_{pi}$ is the pressure error calculated by the containment-based controller for each EH. There are two leaders, which can be either the upper or lower pressure boundary, in the containment-based control to form the range. The set of leaders is represented by M_i , and the set of followers is represented by N_i . Thus, b_{il} is the element in another adjacency matrix. If node i can receive information from one of the two leaders, $b_{il} = 1$. Otherwise, $b_{il} = 0$. R_p is the gain parameter for the controller. The pressure magnitudes of the i th EH and the j th EH are denoted by p_i and p_j , respectively. The pressure leader is described by p_l , and p_l can be either lower boundary p_{Lbou} or upper boundary p_{Ubou} .

Then, the pressure error u_{pi} is fed to a PI controller G_i , and the pressure correction term δp_i is generated. δp_i can be expressed as

$$\delta p_i = G_i(s) u_{pi}. \quad (10)$$

Like the method shown in (3), a control approach is investigated for the electricity output of the EH and can be expressed as

$$L_e = L_{eN} + k_q (f_N - f) \quad (11)$$

where L_e is the electricity output power and L_{eN} is the nominal electricity output power. k_q is the adjustment coefficient of the corresponding method. f_N is the nominal frequency and f is the measured frequency of electricity network. Just similar to (4), the relationship between k_q and L_e for each EH needs to be controlled as

$$\frac{L_{e1}}{k_{q1}} = \frac{L_{e2}}{k_{q2}} = \dots = \frac{L_{en}}{k_{qn}}. \quad (12)$$

Though the electricity power sharing can be realized by using the control approach shown in (11), the frequency will be deviated from the reference value during the control process. Because the electricity network has a high sensitivity to the frequency change, the deviation of frequency may induce great impact on the electricity network.

To restore the frequency and achieve accurate power sharing, the dynamic consensus-based controllers for electricity output are defined as

$$\dot{c}_{ei} = u_{ei} = -R_e \sum_{j=1, j \neq i}^n a_{ij} \left(\frac{L_{ei}}{L_{eiN}} - \frac{L_{ej}}{L_{ejN}} \right) \quad (13)$$

$$\dot{c}_{fi} = u_{fi} = -R_f \sum_{j=1, j \neq i}^n a_{ij} (f_i - f_j) - \tilde{R}_f (f_i - f_{ref}) \quad (14)$$

where u_{ei} and u_{fi} are the inputs for the electricity output controllers. R_f and $\tilde{R}_f$ are the gains for neighborhood and virtual leader frequency. Then, all the errors $\dot{c}_{ei}$ and $\dot{c}_{fi}$ are fed to corresponding PI controllers.

As shown in (13) and (14), two controllers are presented to realize the electricity output control. One controller is proposed to follow the virtual leader, meanwhile, to reduce the frequency errors between adjacent nodes and oneself. The frequency value of the virtual leader is always equal to f_{ref} , and each EH follows the leader by the controller to let the frequency revert to f_{ref} . Though the controller can restore the frequency, accurate power sharing of electricity cannot be achieved. Thus, another controller is presented to proportionally allocate the electricity output of the EH in (13). The electricity loads are accurately shared when the controller makes $L_{ei}/L_{eiN} = L_{ej}/L_{ejN}$. For each EH, the loads are accurately shared, and the frequency is adjusted to the value f_{ref} when u_{ei} and u_{fi} trend to 0.

C. Event-Triggered Distributed Control Approach

As the distributed control method shown in Section II-B, each EH needs the information of own and its neighbors to generate the control input. However, communication may cause

heavy burden, and it is undesirable to update the control actions periodically. Actually, to realize the control objectives of the EH, lots of communication may be redundant in the periodic method. The event-triggered control approach, which can realize satisfactory performance while saving the usage of bandwidth and signal processing resources, has been utilized in the control system recently. By designing a proper approach, the communication and computation can be reduced to a lower level without affecting the realization of control objectives. In this way, the event-triggered method is introduced to further design the proposed distributed EH output control, and the event-triggered method is suitable for the control of the IES to reduce the communication and computation since some kinds of energy have long adjusting times in the system. The consensus protocols with the event-triggered mechanism for EH power are proposed

$$\begin{cases} u_{Hi}(t) = -R_H \sum_{j=1, j \neq i}^n a_{ij} \left(DH_i(t_{kh}^i(t)) - DH_j(t_{kh}^j(t)) \right) \\ u_{ei}(t) = -R_e \sum_{j=1, j \neq i}^n a_{ij} \left(\frac{L_{ei}(t_{ke}^i(t))}{L_{eiN}} - \frac{L_{ej}(t_{ke}^j(t))}{L_{ejN}} \right) \end{cases} \quad (15)$$

where $kh(t) = \arg \max_{kh} \{t_{kh}^i | t_{kh}^i \leq t\}$ represents the subscript of the latest event time instant to the current time t for heat output power control, and $ke(t) = \arg \max_{ke} \{t_{ke}^i | t_{ke}^i \leq t\}$ denotes the subscript of the latest event time instant to the current time t for electricity output power control. In order to utilize the protocols with the event-triggered mechanism, event detectors need to be designed for each EH to decide when the control actions should be updated by utilizing the sampled information. The event conditions of EH power control can be expressed as

$$\begin{cases} \|\hat{e}_{Hi}(t)\|_2^2 \leq \sigma_i \|\hat{v}_{hi}(t)\|_2^2, & t \in [t_{kh}^i, t_{kh+1}^i) \\ \|\hat{e}_{ei}(t)\|_2^2 \leq \rho_i \|\hat{v}_{ei}(t)\|_2^2, & t \in [t_{ke}^i, t_{ke+1}^i) \end{cases} \quad (16)$$

where σ_i and $\tilde{\sigma}_i$ are positive scalars. The measurement errors of heat and electricity power sharing deviations between the current time and the latest event instant are denoted by $\hat{e}_{Hi}(t)$ and $\hat{e}_{ei}(t)$, respectively. The sum of the heat and electricity power sharing deviations between the i th EH and neighboring EHs is represented by $\hat{v}_{hi}$ and $\hat{v}_{ei}$. $\hat{e}_{Hi}(t)$ and $\hat{v}_{hi}$ can, respectively, be expressed as

$$\hat{e}_{Hi}(t) = DH_i(t_{kh}^i(t)) - DH_i(t) \quad (17)$$

$$\hat{v}_{hi}(t) = \sum_{j=1, j \neq i}^n a_{ij} \left(DH_i(t_{kh}^i(t)) - DH_j(t_{kh}^j(t)) \right). \quad (18)$$

Similarly, $me_{ei}(t)$ and $\hat{v}_{ei}(t)$ are described as

$$\hat{e}_{ei}(t) = \frac{L_{ei}(t_{ke}^i(t)) - L_{ei}(t)}{L_{eiN}} \quad (19)$$

$$\hat{v}_{ei}(t) = \sum_{j=1, j \neq i}^n a_{ij} \left(\frac{L_{ei}(t_{ke}^i(t))}{L_{eiN}} - \frac{L_{ej}(t_{ke}^j(t))}{L_{ejN}} \right). \quad (20)$$

In this way, the event-triggered protocols are presented, and the event conditions are designed to realize the heat and electricity power sharing of the IES in (15)–(19).

Different from the power control of the EH, the control of frequency should restore the parameter to the reference value. Following the distributed control method proposed in (14), the protocol for frequency with the event-triggered mechanism can be expressed as

$$\begin{aligned} u_{fi}(t) = & -R_f \sum_{j=1, j \neq i}^n a_{ij} \left(f_i(t_{kf}^i(t)) - f_j(t_{kf}^j(t)) \right) \\ & - \tilde{R}_f \left(f_i(t_{kf}^i(t)) - f_{ref} \right) \end{aligned} \quad (21)$$

where $kf(t) = \arg \max_{kf} \{t_{kf}^i | t_{kf}^i \leq t\}$ denotes the subscript of the latest event time instant to the current time t for frequency control. An event detector is also designed to apply the event-triggered protocol. A corresponding event condition for (21) can be expressed as

$$t_{kf+1}^i = \inf \left\{ t > t_{kf}^i : \|\hat{e}_{fi}(t)\|_2^2 > \hat{g}_{fi}(t) \right\}. \quad (22)$$

$\hat{e}_{fi}(t)$ and $\hat{g}_{fi}(t)$ can, respectively, be expressed as

$$\hat{e}_{fi}(t) = f_i(t_{kf}^i(t)) - f_i(t) \quad (23)$$

$$\hat{g}_{fi}(t) = \varphi_i \left\| \frac{\tilde{R}_f}{R_f} \left(f_i(t_{kf}^i(t)) - f_{ref} \right) + \sum_{j=1, j \neq i}^n a_{ij} \left(f_i(t_{kf}^i(t)) - f_j(t_{kf}^j(t)) \right) \right\|_2^2 \quad (24)$$

where φ_i is a positive number. Combined with the protocol and event condition from (21)–(24), the frequency restoration for the IES can be achieved with the event-triggered mechanism.

Due to the different resistance of each heat branch, the outlet pressures of EHs cannot be controlled at a set value like frequency, and the consensus algorithm cannot be utilized in the pressure control. Based on the distributed containment algorithm shown in (9), an event-triggered containment controller for pressure is proposed and can be expressed as

$$u_{pi}(t) = -R_p \left(\sum_{j \in N_i} a_{ij} \left(p_i(t_{kp}^i(t)) - p_j(t_{kp}^j(t)) \right) + \sum_{l \in M_i} b_{il} \left(p_i(t_{kp}^i(t)) - p_l(t_{kp}^l(t)) \right) \right) \quad (25)$$

where the subscript of the latest event time instant to the current time t for pressure control is represented by $kf(t) = \arg \max_{kf} \{t_{kf}^i | t_{kf}^i \leq t\}$. And the event condition for (25) is defined as

$$t_{kp+1}^i = \inf \left\{ t > t_{kp}^i : \|\hat{e}_{pi}(t)\|_2^2 > \hat{d}_i \|\hat{s}_{pi}(t)\|_2^2 \right\}. \quad (26)$$

$\hat{e}_{pi}(t)$ and $\hat{s}_{pi}(t)$ are defined as

$$\hat{e}_{pi}(t) = p_i(t_{kp}^i(t)) - p_i(t) \quad (27)$$

$$\hat{s}_{pi}(t) = \sum_{j \in N_i} a_{ij} \left(p_i(t_{kp}^i(t)) - p_j(t_{kp}^j(t)) \right)$$

$$+ \sum_{l \in M_i} b_{il} \left(p_i \left(t_{kp(t)}^i \right) - p_l \left(t_{kp(t)}^l \right) \right) \quad (28)$$

where $i \in N_i$. Let $E_{ei}(t) = L_{ei}(t)/L_{eiN}$; the dynamics of the closed-loop system for agent i can be expressed as

$$\dot{E}_e(t) = -R_e \mathcal{L} \hat{E}_e(t) = -R_e \mathcal{L} (E_e(t) + \hat{e}_e(t)) \quad (29)$$

where $E_e(t) = [E_{e1}(t), \dots, E_{en}(t)]^T$, $\hat{e}_e(t) = [\hat{e}_{e1}(t), \dots, \hat{e}_{en}(t)]^T$, $\hat{E}_e(t) = [\hat{E}_{e1}(t), \dots, \hat{E}_{en}(t)]^T$, and $\hat{E}_{ei}(t) = E_{ei}(t_{ke}^i)$ for $t_{ke}^i \leq t < t_{ke+1}^i$. The number of EHs is expressed by n . The Laplacian matrix for the communication topology is denoted by $\mathcal{L}$. We presume that the graph $\mathcal{G}$ is connected and undirected. The Lyapunov functional candidate can be considered as

$$V(t) = \frac{1}{2} E_e^T(t) E_e(t). \quad (30)$$

The time evolution of the above equation along the trajectory obtained by (29) can be expressed by

$$\begin{aligned} \dot{V}(t) &= -R_e E_e^T(t) \mathcal{L} \hat{E}_e(t) \\ &= -R_e \left(\hat{E}_e^T(t) - \hat{e}_e^T(t) \right) \mathcal{L} \hat{E}_e(t) \\ &= -R_e \hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t) + R_e \hat{e}_e^T(t) \mathcal{L} \hat{E}_e(t). \end{aligned} \quad (31)$$

By utilizing the inequality

$$\hat{e}_e^T(t) \mathcal{L} \hat{E}_e(t) \leq \frac{1}{2} \hat{e}_e^T(t) \mathcal{L} \hat{e}_e(t) + \frac{1}{2} \hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t). \quad (32)$$

$\dot{V}(t)$ can be bounded as

$$\begin{aligned} \dot{V}(t) &\leq -R_e \hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t) \\ &\quad + \frac{R_e}{2} \left(\hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t) + \hat{e}_e^T(t) \mathcal{L} \hat{e}_e(t) \right) \\ &= -\frac{R_e}{2} \hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t) + \frac{R_e}{2} \hat{e}_e^T(t) \mathcal{L} \hat{e}_e(t). \end{aligned} \quad (33)$$

Based on the event condition (16) and (33), we can obtain

$$\dot{V}(t) \leq -\frac{R_e}{2} (1 - \lambda_n^2 \rho_{\max}) \hat{E}_e^T(t) \mathcal{L} \hat{E}_e(t) \quad (34)$$

where $\rho_{\max} = [\rho_i, i = 1, \dots, n]$ and the maximum eigenvalue of $\mathcal{L}$ is denoted by λ_n . Since $R_e > 0$ and $0 < \rho_{\max} < 1/\lambda_n^2$, $\dot{V}(t) \leq 0$ for any $t \in [t_{ke}^i, t_{ke+1}^i)$. According to the LaSalle's invariance principle, $\dot{V}(t) \leq 0 \forall t \geq 0$ implies consensus for all agents. Hence, based on the principle of the droop control, the electricity output of the EH can be properly allocated by utilizing the proposed method.

The exclusion of the Zeno behavior is proofed now. The upper right-hand Dini derivative of $\hat{e}_e(t)$ can be expressed as

$$D^+ \hat{e}_{ei}(t) = R_e \sum_{j=1, j \neq i}^n a_{ij} \left(\hat{E}_{ei}(t) - \hat{E}_{ej}(t) \right). \quad (35)$$

With $\hat{e}_{ei}(t_{ke}^i) = 0$ and $t \in [t_{ke}^i, t_{ke+1}^i)$, it is obtained that

$$\|\hat{e}_{ei}(t)\| = R_e \left\| \int_{t_{ke}^i}^t \sum_{j=1, j \neq i}^n a_{ij} \left(\hat{E}_{ei}(t) - \hat{E}_{ej}(t) \right) d\sigma \right\|$$

$$= R_e (t - t_{ke}^i) \|\hat{v}_{ei}(t)\|. \quad (36)$$

According to the event condition, the following equation can be given:

$$R_e (t_{ke+1}^i - t_{ke}^i) \|\hat{v}_{ei}(t)\| > \left(\rho_i \|\hat{v}_{ei}(t)\|_2^2 \right)^{\frac{1}{2}}. \quad (37)$$

Since $R_e > 0$ and $0 < \rho_{\max} < 1/\lambda_n^2$, $t_{ke+1}^i - t_{ke}^i$ must be positive. The results imply that the intervals between trigger instants are strictly positive. Therefore, the exclusion of the Zeno behavior is proofed.

The allocation results of electricity outputs of EHs under the proposed event-triggered distributed controller can be denoted in Theorem 1.

Theorem 1: Under the assumption that the graph is connected and undirected, the accurate allocation issue for the electricity outputs of EHs is resolved asymptotically by the proposed event-triggered consensus control (15), and the time instants are decided by event condition (16). Furthermore, the Zeno behavior can also be excluded.

It is worthy to remark here that the heat outputs of EHs can be accurately shared, and frequency can be restored to the reference value by the corresponding event-triggered consensus controls. Furthermore, the time instants are decided by corresponding event conditions. The control of frequency and heat output based on the similar consensus algorithm can be proofed similarly as Theorem 1 and thus is omitted here.

The proposed event-triggered containment controller for pressure is expressed in (25). For the network topology, two assumptions are given.

Assumption 1: For each follower, at least one leader has a directed path to that follower.

Assumption 2: The subgraph $\mathcal{G}_s$ associated with the N_{fol} followers is undirected. The Laplacian matrix $\mathcal{L}_c$ can be expressed as

$$\mathcal{L}_c = \begin{pmatrix} 0_{N_{\text{led}} \times N_{\text{led}}} & 0_{N_{\text{led}} \times N_{\text{fol}}} \\ \mathcal{L}_d & \mathcal{L}_u \end{pmatrix} \quad (38)$$

where N_{fol} and N_{led} denote the number of followers and leaders, respectively.

Lemma 1 (see[28]): Under Assumptions 1 and 2, $\mathcal{L}_u$ is positive definite. Furthermore, each entry for $-\mathcal{L}_u^{-1} \mathcal{L}_d$ is non-negative, and the sum of each row for $-\mathcal{L}_u^{-1} \mathcal{L}_d$ is equal to 1.

Define $\bar{d}_i = \sum_{j \in N_i} a_{ij}$. In the follower group, $\bar{d}_i$ presents the number of neighbors for agent i . Let $N = N_{\text{fol}} + N_{\text{led}}$ and

$$\eta(t) = \left([\mathcal{L}_u^{-1} \mathcal{L}_d I_{N_{\text{fol}}}] \right) p(t) \quad (39)$$

where $p(t) = [p_1(t), \dots, p_N(t)]^T$ and can be further expressed by $p_l(t) = [p_1(t), \dots, p_{N_{\text{led}}}(t)]^T$ and $p_f(t) = [p_{N_{\text{led}}+1}(t), \dots, p_N(t)]^T$. Consider the Lyapunov functional candidate as follows:

$$V_1(t) = \eta^T(t) \mathcal{L}_u \eta(t). \quad (40)$$

According to [29], with the definitions that $0 < \hat{d}_i < 1/2(\bar{d}_i^2 + \bar{d}_i(N_{\text{fol}} - 1))$ and $R_p \lambda_{\min}(\mathcal{L}_u) > 1$, the following equation can be obtained:

$$\dot{V}_1(t) \leq -\lambda_{\min}(\mathcal{L}_u) \eta^T(t) \eta(t). \quad (41)$$

From (41), it can be given that

$$V_1(\infty) - V_1(0) \leq -\lambda_{\min}(\mathcal{L}_u) \int_0^\infty \eta^T(\sigma) \eta(\sigma) d\sigma \quad (42)$$

which further implies that

$$\int_0^\infty \eta^T(\sigma) \eta(\sigma) d\sigma \leq \frac{V_1(\infty) - V_1(0)}{\lambda_{\min}(\mathcal{L}_u)}. \quad (43)$$

By utilizing the Barbalat's lemma [30], it can be seen that $\eta \rightarrow 0$, as $t \rightarrow \infty$, which implies that the issue of the proposed containment control is resolved. The rest of the proof for the Zeno behavior is similar to the proof denoted in Theorem 1 and is omitted here. The control results of pressure under the proposed event-triggered containment controller can be denoted in Theorem 2.

Theorem 2: Under Assumptions 1 and 2, the issue for bounding the pressure within the set range is resolved asymptotically by the proposed event-triggered containment control (25), and the time instants are decided by event condition (26). Furthermore, the Zeno behavior can also be excluded.

In conclusion, the event-triggered control scheme can realize accurate power sharing without the network parameters. Meanwhile, the pressure can be bounded within an acceptable range, and the frequency can be restored to eliminate the influence of parameter deviation. The adoption of the event-triggered mechanism also dramatically reduces the communication among EHs.

D. Devices Control Based on EIP

The proposed event-triggered distributed control can decide the outputs of the EH and adjust the frequency and the pressure. However, since the energy is coupled in each EH, the determined outputs can achieve numbers of operation outcomes. In this way, the regulation of devices is necessary for achieving the objectives of the EH. Because of the flexibility of the EH, reducing the cost is an important purpose for EH operation. And the investigation of the control approach for devices to decrease the economic cost is necessary.

As a conventional approach, the EIP is widely utilized in engineering practice [31] to decide the minimum energy cost. On the basis of the corresponding device characteristics and the EIP, the control of devices is designed to solve the operation issue of the EH with considering the energy prices. The cost of an EH can be expressed as $C_{\text{total}} = \sum_{r \in D_i} C_r$, in which C is the economic cost of the device input, r is the index of devices, and $r \in D_i$. The principle is shown as

$$\begin{cases} \vartheta_{z,r} = \vartheta_z^*, & C_{z,r}^{\min} < C_{z,r} < C_{z,r}^{\max} \\ \vartheta_{z,r} \leq \vartheta_z^*, & C_{z,r} = C_{z,r}^{\max} \\ \vartheta_{z,r} \geq \vartheta_z^*, & C_{z,r} = C_{z,r}^{\min} \end{cases} \quad (44)$$

where z denotes kinds of energy, and $z \in e, h$. ϑ_r and ϑ^* are the incremental ratio of device r and the standard incremental ratio, respectively.

As shown in Fig. 1, each EH contains multiple devices, which are classified into two categories: the device only outputs one kind of energy (DOE) like boiler, and the device outputs two kinds of energy (DTE) like CHP. Different DOEs have different performance characteristics. However, the cost of fuel

is generally represented by a quadratic [32]. Thus, the economic cost and the incremental ratio of the DOE can be defined as

$$\vartheta_w = \frac{dC_w(\hat{L}_w)}{d\hat{L}_w} \quad (45)$$

$$C_w(\hat{L}_w) = \text{Pr}_z \left(\bar{\mu} \bar{\varepsilon}_w \hat{L}_w^2 + \bar{\varepsilon}_w \hat{L}_w + \bar{\gamma} \right) \quad (46)$$

where the fuel cost parameters of the DOE are denoted by $\bar{\mu}$, $\bar{\varepsilon}$, and $\bar{\gamma}$. Pr_z is the price for the corresponding energy, w is the index of the DOEs, and $\hat{L}_w$ is the output of the corresponding DOE.

Similarly, the incremental ratio and the economic cost function of DTEs for heat and electricity generation like CHP are expressed as

$$\vartheta_{z,v} = \frac{\partial C_v(\hat{L}_{e,v}, \hat{L}_{h,v})}{\partial \hat{L}_{z,v}} \quad (47)$$

$$C_v(\hat{L}_{e,v}, \hat{L}_{h,v}) = \text{Pr}_z \left(\tilde{\alpha}_v \hat{L}_{e,v}^2 + \tilde{\beta} \hat{L}_{e,v} + \tilde{\tau} \hat{L}_{h,v}^2 + \tilde{\varepsilon} \hat{L}_{h,v} + \tilde{\lambda} \hat{L}_{e,v} \hat{L}_{h,v} + \tilde{\gamma} \right) \quad (48)$$

where v is the index of DTE and $[\tilde{\alpha}, \tilde{\beta}, \dots, \tilde{\gamma}]$ denotes the fuel cost parameters of corresponding devices.

The economic cost functions and incremental ratios of devices are defined in (45)–(48). It can be clearly noticed that one kind of energy load change can cause all inputs change, so the operation of devices can be controlled with the energy coupling feature. Moreover, each EH can reduce the economic cost since the method is designed based on the EIP.

The event-triggered DHC scheme is realized by combining the output control and the device control. Hence, the complete configuration of the DHC scheme is shown in Fig. 2. The information format of the follower can be expressed as $\Upsilon_j = [f_j, L_{ej}, DH_j, p_j]$. Similarly, the information format of the leader can be expressed as $\Upsilon_l = [0, 0, 0, p_l]$. The output power of each EH is determined, and the parameters are regulated according to the event-triggered output control. Furthermore, the operation of devices is decided, and the economic cost of the EH is reduced by implementing the device control. Since the energy, which is supplied by the EH to meet the loads, is necessary to pass through the corresponding branch, as shown in Fig. 1, the different parameters of branches will greatly influence the operation of the IES. Considering the problem, the EH implementing the DHC scheme only requires the information of neighbors and the variations of parameters. Because of the utilization of the event-triggered mechanism, the communication cost can be dramatically reduced.

By utilizing the proposed event-triggered DHC scheme, a global model of the IES and dynamics of neighbors are not required for each EH. Only the information from local and neighboring EHs is necessary to determine the updating and communicating instants. Since the updating of control actions and the communication between EHs are only occurred at some instants, the execution of the event-based control offers the advantage of communication reduction among EHs. According to the discussion, the event-triggered mechanism can reduce

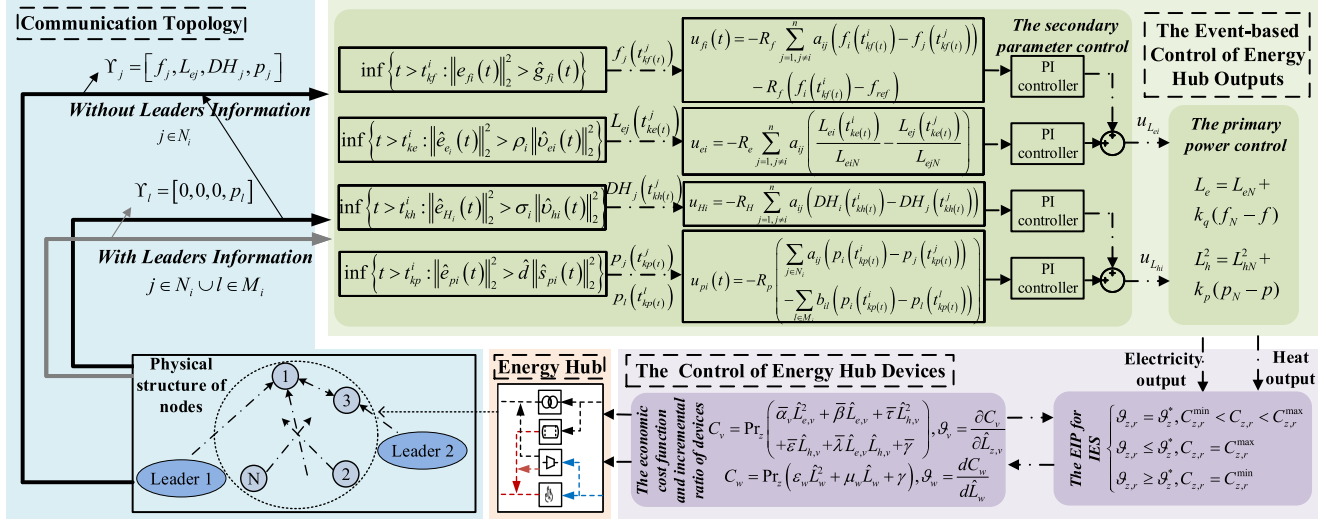


Fig. 2. Complete configuration of the DHC scheme.

TABLE II
CORRESPONDING PARAMETERS OF DOES

EH	Device	$\bar{\mu}$	$\bar{\varepsilon}$	$\bar{\gamma}$	Capacity(kW)
1	Gas furnace	0.00089	0.99425	21.06	640
1	Electric boiler	0.00096	0.98742	24.54	640
1	Transformer	0.00062	0.98560	30.22	2800
2	Gas furnace	0.00028	0.87638	23.17	320
2	Electric boiler	0.00021	0.89056	24.85	320
2	Transformer	0.00012	0.91354	25.33	1400
3	Gas furnace	0.00031	0.97002	29.51	160
3	Electric boiler	0.00025	0.95348	23.13	160
3	Transformer	0.00011	0.91632	21.19	700

TABLE III
CORRESPONDING PARAMETERS OF CHPs

EH	$\bar{\alpha}$	$\bar{\beta}$	$\bar{\tau}$	$\bar{\varepsilon}$	$\bar{\lambda}$	$\bar{\gamma}$	Capacity (h/e)(kW)
1	0.00343	0.97966	0.00320	0.94314	0.00199	19.55	520/320
2	0.00208	0.89687	0.00194	0.77629	0.00178	20.89	260/160
3	0.00223	0.90264	0.00179	0.75996	0.00184	19.37	130/80

TABLE IV
OPERATION OF EHS BEFORE LOADS CHANGE

EH	output(h) (kW)	output(e) (kW)	input(g) (kW)	input(e) (kW)	economic cost (CNY)
1	893	1863	1495.5	3519.8	2506.2
2	449	935	455.6	1019.7	736.3
3	226	466	285.9	479.9	379.3

TABLE V
OPERATION OF EHS AFTER LOADS CHANGE

Case/ EH	output(h) (kW)	output(e) (kW)	input(g) (kW)	input(e) (kW)	economic cost (CNY)
1/1	761	1542	1196.9	2695.1	1942.8
1/2	385	769	412.5	815.8	611.0
1/3	193	383	247.8	399.5	320.3
2/1	1084	2171	1881.3	4452.4	3165.4
2/2	546	1091	515.1	1235.9	875.4
2/3	276	544	334.3	564.3	455.2

the communication significantly [23], [24]. Furthermore, global clock synchronization and all areas to exchange information at the same time are required for the synchronous communication strategies such as the traditional periodic sampling strategy. The above requirements are hard to achieve for an actual operating IES. The asynchronous communication such as event-triggered communication can avoid the requirement of global clock synchronization, which is more flexible and easier to be executed [33].

III. CASE STUDIES

The model for simulation is framed on the basis of a regional system in Changsha, China. Like the structure of the IES shown in Fig. 1, the simulation model includes three EHs. Moreover, the interior structure of each EH is the same as in Fig. 1. Gas and electricity networks are connected with all EHs to satisfy their requirements.

Table II describes the parameters of devices such as boilers and furnaces. Table III shows the parameters of CHPs. The reference frequency is 50 Hz. The upper and lower boundaries are 1.12 and 1.08 MPa, respectively. The electricity price is 0.517 CNY/kW · h and the gas price is 4.26 CNY/m³. Since the system adjustment time is not long in the cases, the economic cost for each EH is calculated based on the output power when

the operation reaches stability. The performance of the DHC scheme is studied in the first case for the condition that electricity and heat loads decrease. Case 2 shows the effectiveness of the proposed method when electricity and heat loads increase. To further express the effectiveness of the DHC scheme, the proposed method is compared with another method in case 3.

The same loads are shared in cases 1 and 2 before the 300 s. The heat loads is 1600 kW and the electricity loads is 3300 kW. Table IV denotes the operation results of each EH before the 300 s. Table V represents the operation consequence of each EH after the 300 s.

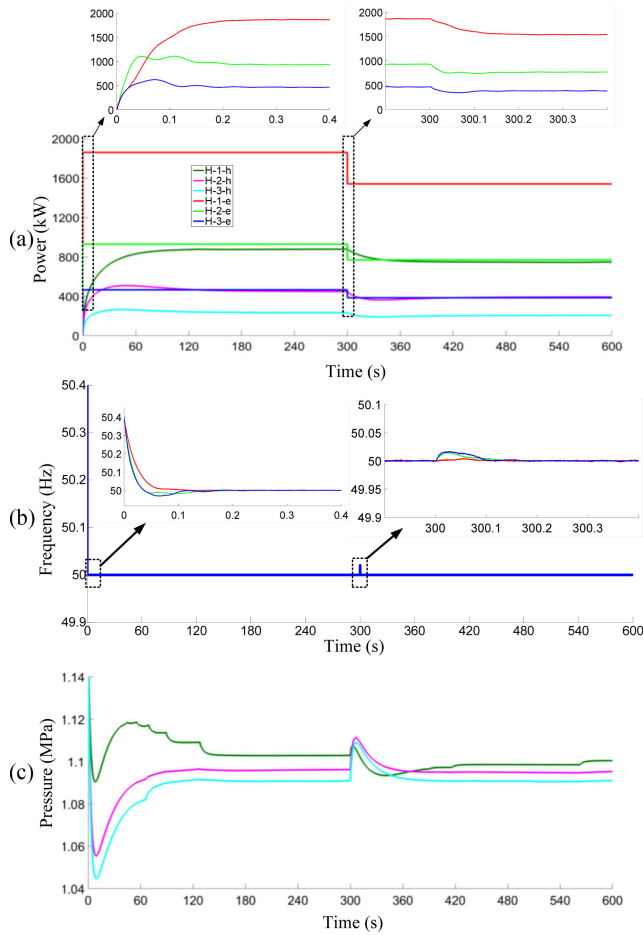


Fig. 3. Changes of power and parameters in case 1.

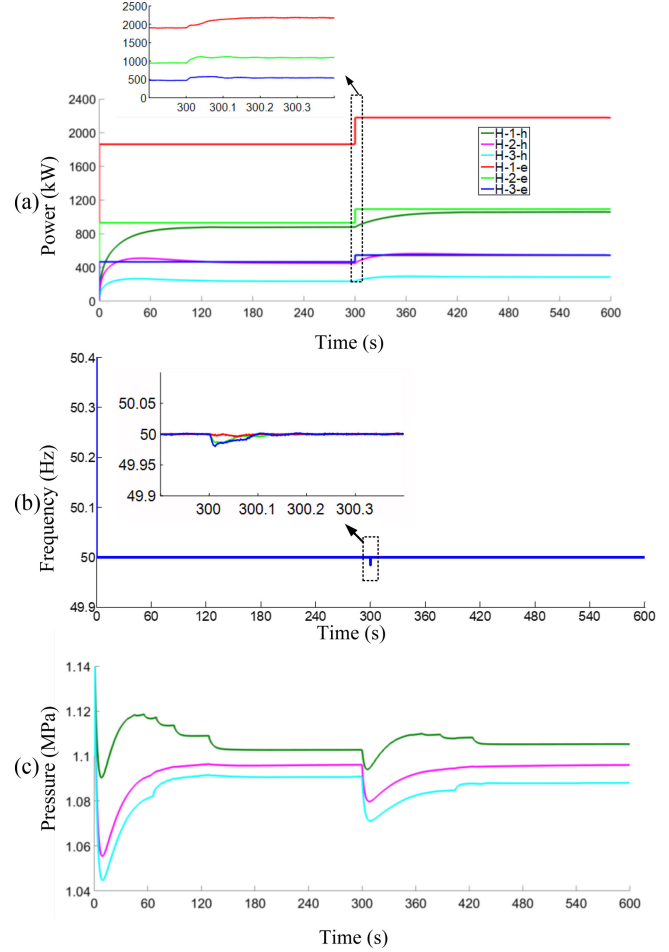


Fig. 4. Changes of power and parameters in case 2.

A. Cases 1 and 2

The validity of the DHC scheme is shown in the two cases when the loads decrease or increase. In case 1, the heat loads and electricity loads decrease to 1320 and 2670 kW, respectively. In case 2, the heat loads and electricity loads in the IES are increased by 350 and 560 kW, respectively. The operation data such as input, output, and economic cost of each EH are shown in Tables IV and V. Since the efficiencies of devices in EH 1 are lower than those of other devices, more energy is needed in EH 1 to satisfy the demands, as shown in Tables II and III.

Figs. 3 and 4 show the changes of power and parameters in cases 1 and 2, respectively. As shown in Figs. 3(a) and 4(a), both electricity loads and heat loads of the IES are accurately shared by utilizing the proposed DHC scheme no matter how loads changes. The frequency and the pressure are also changed, and the changing is caused by the variations of loads. As shown in Figs. 3(b) and 4(b), the deviation of frequency, which is induced by electricity load change, can be eliminated, and the frequency is adjusted to the reference value of 50 Hz. Since different heat branches share different parameters, the pressure cannot be restored to a certain value like frequency especially with large resistance magnitudes of heat branches. By utilizing the DHC scheme, the pressure can be bounded in the set boundary, as

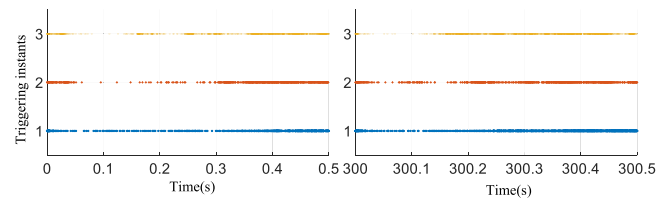


Fig. 5. Event time instants of EHs.

shown in Figs. 3(c) and 4(c). The IES takes only about 0.2 s to make the electricity network stable. However, the stabilization time for the heat network needs more than 150 s. The difference shows that more time is needed for the heat network to achieve the stabilized state than the electricity network. Combined with the results shown in the two figures, it can be shown that the IES is stable by utilizing the DHC scheme, and the performance of the proposed scheme is not affected by the change of loads.

In order to prove that the DHC scheme with the event-triggered mechanism is able to reduce the amount of communication between EHs, the time instants of event are represented. Fig. 5 shows the event instants of EHs. Compared with the mechanism that communication between EHs is required at each

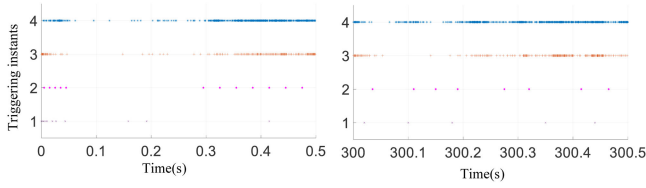


Fig. 6. Event time instants of controllers.

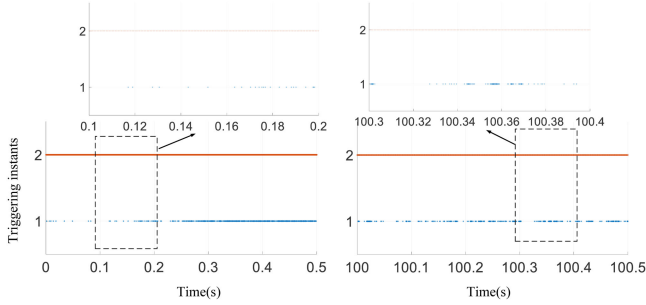


Fig. 7. Trigger instants between different controls.

step, the event-triggered control can greatly reduce the number of control updates for achieving consensus, as shown in Fig. 5.

The event time instants of different controllers for EH 2 are shown in Fig. 6, where numbers 1–4 denote the controllers of pressure, heat output, electricity output, and frequency, respectively. It is clear that the number times the communication was triggered is significantly different due to the different time scales of different systems. From this point of view, the proposed event-triggered DHC scheme fits well with multi-time-scale characteristic.

The trigger instants of frequency controllers for EH 1 between two different methods are shown in Fig. 7. The effect of the proposed method is denoted by number 1, and number 2 shows the performances of the traditional periodic sampling strategy. The proposed method adaptively and intermittently adjusts the triggering instants according to the set events. The periodic sampling strategy samples periodically according to time. As shown in the figure, the proposed event-triggered control can reduce the communication regardless of the operating status of the IES. The proposed control adjusts the trigger instants according to the set event, and the interval between two adjacent trigger instants changes during the operation of the system. The number of trigger instants for the traditional sampling strategy does not change. The traditional periodic sampling strategy only samples periodically and cannot be adjusted according to the change of system operation status. As the loads in the IES change frequently, the EH needs to constantly adjust the output to meet the load. Therefore, the proposed control method can reduce the communication and is suitable for the IES with complex operating conditions. It is concluded that the proposed event-triggered control is more suitable for the IES than traditional sampling control since the proposed event-triggered control can reduce the communication and avoid the requirement of global clock synchronization.

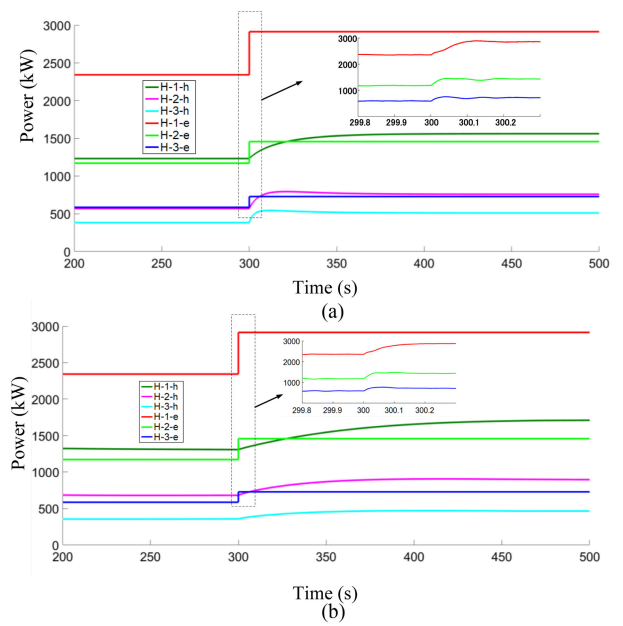


Fig. 8. Power performances of DHC and CEH.

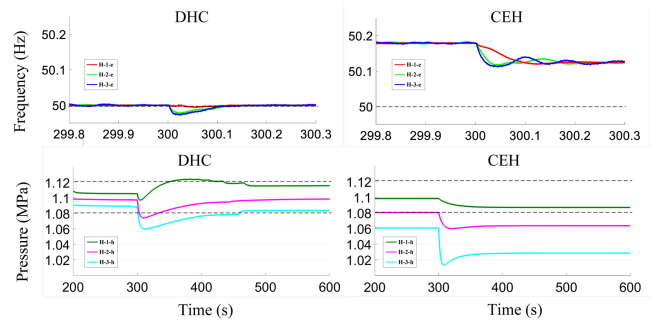


Fig. 9. Parameters performances of DHC and CEH.

B. Cases 3 and 4

In cases 3 and 4, the heat loads and electricity loads are changed from 2300 to 3000 kW and 4100 to 5100 kW, respectively. Case 3 represents the effectiveness of the DHC scheme by comparing the proposed method with a control method of EH (CEH) represented in [25], which is proposed to achieve the accurate power sharing of loads. The results of case 3 are shown in Figs. 8 and 9.

The outputs of EHs with the CEH and the DHC scheme are denoted in Fig. 8(a) and (b), respectively. As shown in Fig. 8(a), due to the characteristic of the frequency, the load power of electricity is shared proportionally among EHs by utilizing the CEH. However, the load power of heat cannot be accurately shared with unknowable network parameters. In contrast, the load power of the IES, no matter electricity loads or heat loads, can be proportionally shared according to the proposed DHC scheme without knowing network parameters such as branch resistances, as shown in Fig. 8(b). Fig. 9 represents the comparison of frequency and pressure changes between the two

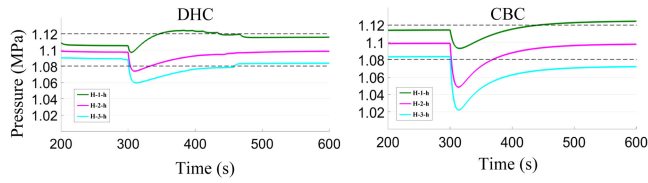


Fig. 10. Parameters performances of DHC and CBC.

methods. The variation of frequency is restored by using the DHC scheme, but the CEH cannot realize the restoration, as denoted in Fig. 9. The fluctuation of pressure with the CEH is high, and the pressures of EHs during operation are not bounded. By comparison, the proposed DHC scheme can also constrain the pressure of EHs in the set boundary. The economic performance of the DHC scheme is better than that of the CEH. In this case, the economic costs of the IES controlled by the CEH and the DHC scheme are about 7284.1 and 7047.6 CNY, respectively.

Case 4 is also presented to further explain the significance of using the containment algorithm. A consensus-based control (CBC) method proposed in [16] is utilized to adjust the outlet pressure, and the performance of DHC and CBC is shown in Fig. 10. Fig. 10 shows that the pressures of EHs during operation are not bounded by utilizing the CBC. The CBC can adjust the pressure to a certain extent. However, the performance of the CBC is influenced by the resistances of heat branches, and the performance of the control also cannot be predicted. By contrast, the proposed DHC scheme can constrain the pressure of EHs in the set range.

Remark 1: By utilizing the proposed DHC scheme, the stability of the system is achieved. The power sharing of the system is also realized accurately without the impact of the network parameters. Since the frequency can be adjusted to the reference value and the pressure can be bounded in the set boundary no matter how the load changes, the proposed method improves the robustness of the system with the comparison of the method in [25].

In this context, power sharing among EHs can be realized proportionally according to the proposed DHC scheme without knowing the network parameters, and the pressure and the frequency can also be regulated effectively. Furthermore, the economic benefits are improved compared with other methods.

IV. CONCLUSION

An event-triggered DHC scheme was proposed in this article. The deducing process of EH outputs control via containment and consensus algorithm was provided. The EH outputs control can achieve the accurate power sharing of loads without knowing the network parameters. According to the DHC scheme, the pressure was bounded, and the frequency was restored to avoid the deviation of parameters. By utilizing the proposed event-triggered control, the communications between EHs can also be reduced effectively. Furthermore, the control of device was presented to reduce the economic cost. The event-triggered DHC scheme was verified on the simulation model containing three EHs, and the

results of cases were provided to prove the effectiveness of the proposed method.

At present, the research on the secondary control of the IES is still in the primary stage. This article proposed the event-triggered DHC scheme to achieve security and economic operation of the IES. However, the DHC scheme was proposed based on the premise of the ideal communication environment. Different situations such as network attack and noise may impact the effectiveness of the DHC scheme. Moreover, the multi-time-scale characteristic of the IES has brought a lot of difficulties for the related research. Considering the characteristic, this article proposed an event-triggered DHC scheme to fit the IES. However, how to solve the problems caused by the multiple time scales more deeply in the IES is still an open problem for now. All the issues can be put in focus as the object of subsequent research.

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