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Distributed Consensus Hierarchical Optimization and Control Method for Integrated Energy System Based on Event-Triggered Mechanism

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Abstract: For integrated energy systems (IES) composed of a set of energy hubs (EHs), a consensus control method is usually adopted to achieve accurate sharing of electrical and thermal composite energies. To solve the communication redundancy problem of the consensus control method, a hierarchical optimization and distributed control scheme based on a dynamic event-triggered mechanism of EHs is proposed to realize stable operation of IES. An economic optimization strategy based on equal increment principle is improved to minimize the operation costs of IES in the second layer. Due to consensus control being integrated into the supply-demand power deviation calculations of EHs, the desired electrical and thermal power trajectories are accurately determined. To improve dynamic response performances in the presence of uncertain disturbances, an event-triggered communication mechanism is designed in the primary layer. The triggering threshold can be adjusted dynamically according to changes of electrical and thermal power outputs, and the redundant communication requirement in the electrical branches is reduced. Considering the coupling characteristics of IES energy networks, a consensus control method is promoted to synchronously track the desired electric and thermal power trajectories of EHs, and the goal of accurate power sharing is achieved. The frequency and pipeline pressure fluctuations are also limited within the allowable range. The economic optimization and coordinated operation of electrical and thermal composite energies in IES are guaranteed by the proposed hierarchical control structure. Additionally, only information from neighboring EHs at the event-triggered time is involved, so the computation simplicity and control performance can be obtained simultaneously. The hardware-in-loop experimental results are conducted to demonstrate the effectiveness of the proposed control strategy.

Keywords: integrated energy system; event-triggered mechanism; economic optimization strategy; consensus control; equal increment principle



Citation: Ye, J.; Liu, B.; Yuan, Z.; Chen, Y.; Wang, Y.; Xue, H.; Ling, C.; Zhang, K. Distributed Consensus Hierarchical Optimization and Control Method for Integrated Energy System Based on Event-Triggered Mechanism. *Energies* **2023**, *16*, 5146. <https://doi.org/10.3390/en16135146>

Academic Editor: Surender Reddy Salkuti

Received: 7 June 2023

Revised: 30 June 2023

Accepted: 1 July 2023

Published: 4 July 2023



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1. Introduction

Energy shortages and environmental pollution are major obstacles to develop sustainable economic and social development. Comprehensive energy supply systems, such as integrated energy systems (IES), have become an important way for implementing energy conservation and for establishing a clean, low-carbon, safe and efficient energy systems [1,2]. As an important supplement of centralized energy supply, the distributed energy systems may transform the rigid “source–network–load” chain into a flexible “source–load” connection. An active direction is shown for achieving energy transformation and technological innovation [3]. Located at or near load centers, the distributed energy systems can avoid energy losses and infrastructure investment caused by large-scale energy transmission and encourage local energy production and consumption [4]. The redundant energy flow paths in multi-energy systems provide improvement space for consensus optimization and

control. With optimization operation strategies, energy efficiency is raised, peak–valley energy differences are regulated, and IES safety and reliability are enhanced [5,6]. However, the characteristics of multi-energy coupling, multi-time scale modeling, multiple uncertainties and multi-objective optimization make IES control increasingly complex. The traditional optimization and scheduling methods of energy systems are no longer applicable to IES [7–9]. Therefore, novel distributed consensus optimization and control methods are required for IES that consider the dynamic interactions of multi-flow energy conversion equipment.

The energy hub (EH) is a key technology for optimizing the integrated operation of electricity and heat. Active power outputs of different energy sources according to energy supply and demand are properly shared in EHs. Multi-energy system scheduling and optimization operation for EHs have been reviewed in the literature [10], including various application scenarios such as residential buildings, commercial buildings, industrial parks and agricultural applications. For EH optimization operation, the interaction between energy stations and external networks is considered in the literature [11]. An energy efficiency matrix of IES based on graph theory is constructed and an optimization energy management framework is established for combining electrical and thermal power outputs under the background of energy marketization. However, the dynamic characteristics of electrical and thermal equipment are not considered with IES optimization operation based on EH models. The work in [12] addresses the impact of equipment operating conditions on the optimization operation strategy, but there is currently no research on the operation optimization for more precision resolution when equipment dynamic characteristics are taken into account. By analyzing IES energy network with EHs, an optimal multi-energy flow model is proposed in the literature [13]. Similar to the electric power system, the model can be carried out for coordinated optimization of EHs and network operation. The literature [14] considers the detailed parameters of EHs and energy networks in multi-energy systems, and a general EH expansion model is constructed to control active power outputs in IES. The flexibility and generality of the model are validated for coupled electrical and thermal networks with various topologies. However, there is a lack of consideration for the synergistic outputs of different energy sources from an economic perspective.

Distributed consensus control methods are usually adopted for coordinated operation of EHs, but lead to frequent communication issues. The event-triggered mechanism is an effective strategy to reduce redundant communication requirements in consensus control [15,16]. A consensus control algorithm that combines an event-triggered mechanism and model predictive control has been proposed in the literature [17,18]. Model predictive control is performed only when EH states meet the trigger conditions, and the switch statuses are maintained until the next even trigger. So, computational burden and switch losses are decreased. However, uncertain disturbance or state change would affect the control performance, for the original static event trigger condition may not be suitable for updated EH states [19,20]. The event-triggered mechanism proposed above ensures optimized operation under predetermined conditions but cannot guarantee the stable operation in presence of uncertain disturbances.

A consensus hierarchical optimization and control method based on dynamical event-triggered mechanism is proposed in this paper. A distributed real-time economic optimization method based on the consensus theory of multiple intelligent agents is promoted in the second layer. Each EH is treated as an intelligent agent and a collaborative control is adopted to allocate active power outputs of EHs. By keeping the incremental cost of each EH equal, the minimum IES generation costs are achieved and the desired electrical and thermal power outputs are operating in an economical state. In the primary layer, a dynamical event-triggered consensus control scheme is designed to further reduce communication redundancy and computational burden. By embedding the event-triggered mechanism into the EH model, the triggering threshold is dynamically adjusted, which adapts to the multi-time scale characteristics of IES electric and thermal composite energy. When the event-triggering threshold is met, the consensus control method is

activated and the electrical and thermal power outputs of EHs are quickly adjusted to synchronous tracking of the desired trajectories. The adverse effects of uncertainty disturbances are suppressed and the pressure and frequency deviations are limited within the allowable range.

This paper is organized as follows: Section 2 provides the scheme of hierarchical economic optimization and control considering all entities in IES, and introduces the distributed consensus control method based on event-triggered mechanism. Section 3 presents the experimental results of the proposed method. Finally, Section 4 concludes this work.

2. Distributed Consensus Hierarchical Optimization and Control Method for IES Based on Event-Triggered Mechanism

In order to achieve accurate power sharing of IES, a collaborative control method based on the equal increment principle is proposed in the second layer. A dynamic event-triggered distributed control method based on the consensus algorithm for EHs is designed in the primary layer. The economic optimization and coordinated operation of electrical and thermal composite energies in IES can be achieved simultaneously.

2.1. Economic Optimization Strategy Based on Equal Increment Principle for IES in the Second Layer

First, the IES is modeled, and the incremental cost economic optimization strategy is proposed to realize the stable operations of EHs at minimum economic cost.

2.1.1. System Model

The structure of IES is shown in Figure 1. EH includes devices such as a furnace, a cogeneration unit, a boiler and a transformer. The conversion and storage of electrical and thermal energies with interactive coupling characteristics are executed and the balance of electrical and thermal powers between sources and loads of IES are achieved.

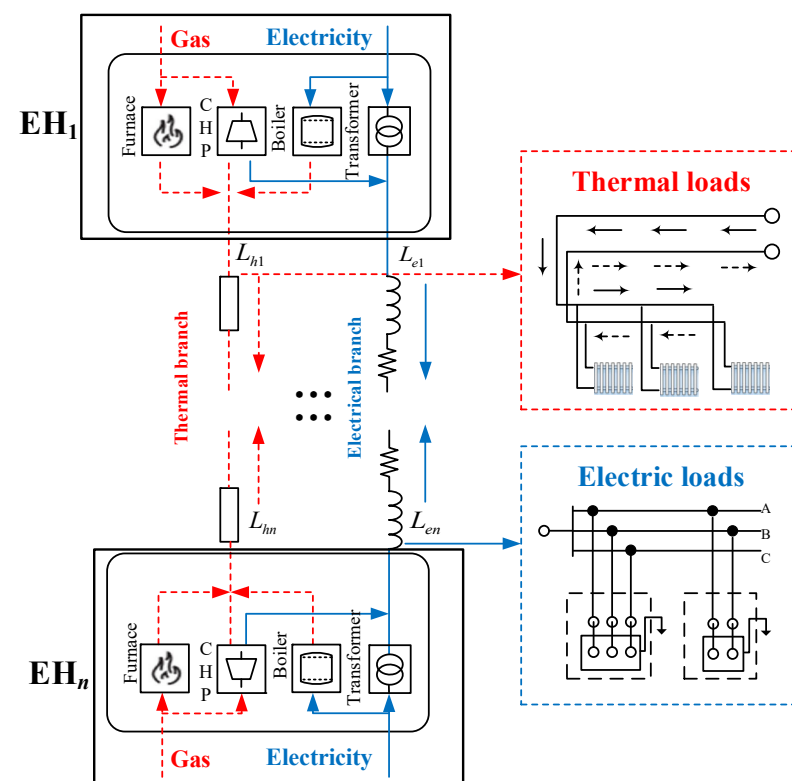


Figure 1. IES structure.

A hierarchical control framework of electrical and thermal hybrid energy systems is proposed to minimize the generation cost of IES and ensure EHs stable operation. The hierarchical control includes two objectives: the desired trajectories of electric and thermal power outputs are calculated in the second layer, and the tracking of desired trajectories is obtained in the primary layer. Once the optimal solutions of the cost functions are achieved in the second-layer, they are adopted as desired trajectories of EH power outputs and fed into the event-triggered consensus controller to realize the global stable operation objective.

To account for the economic benefits of IES, a mathematical model with the total operation cost of IES as optimization objective is developed in the second layer, which is demonstrated below:

$$\min F = C_{ON} \quad (1)$$

$$C_{ON} = \sum_{i=1}^H (a_{h,i} P_{h,ON,i}^2 + b_{h,i} P_{h,ON,i} + a_{e,i} P_{e,ON,i}^2 + b_{e,i} P_{e,ON,i} + c_i) \quad (2)$$

where F is the total operating cost of IES, C_{ON} is the output cost of IES, i is the i -th EH in IES, H is the total number of EHs, $a_{x,i}$, $b_{x,i}$, ($x \in \{h, e\}$) and c_i are the thermal or electric output cost coefficients of the i -th EH, respectively, and $P_{x,ON,i}$ is the thermal or electric power outputs of the i -th EH in IES. When $x = h$, x represents the thermal branch. When $x = e$, x represents the electric branch.

2.1.2. Incremental Cost Economic Optimization Strategy

To optimize electric and thermal power outputs for EHs, all EHs' incremental costs must be equal. To achieve this, the incremental cost of each EH is treated as a consensus control variable integrated in the incremental cost economic optimization strategy. The supply-demand mismatch as a consensus control error is fed back to the incremental cost function and the supply-demand balance is obtained. By communication links among intelligent agents of EHs, the consensus control algorithm guarantees the incremental cost of each EH to converge to the desired equilibrium point. Then, the optimal power outputs as desired trajectories are calculated and conveyed to the electrical and thermal power controllers in the primary level. Accurate power sharing of EHs is enabled under the economic optimum constraint.

Taking an IES with two EHs as an example, the cost functions of two EHs are $C_1(P_{EH1})$ and $C_2(P_{EH2})$, respectively, and the load power is P_L . To achieve economic dispatch, a Lagrange function is constructed to obtain the optimal solution of objective function, that is $\min F = C_1(P_{EH1}) + C_2(P_{EH2})$ with the constraint $P_L = P_{EH1} + P_{EH2}$. The Lagrange function is expressed as:

$$L(P_i, \lambda) = F - \lambda(P_{EH1} + P_{EH2} - P_L) = C_1(P_{EH1}) + C_2(P_{EH2}) - \lambda(P_{EH1} + P_{EH2} - P_L) \quad (3)$$

where λ is the Lagrange multiplier.

Setting the partial derivatives of the variables P_{EH1} , P_{EH2} and λ to zero, respectively, and we have:

$$\begin{cases} \frac{\partial L}{\partial P_{EH1}} = \frac{\partial C_1(P_{EH1})}{\partial P_{EH1}} - \lambda = 0 \\ \frac{\partial L}{\partial P_{EH2}} = \frac{\partial C_2(P_{EH2})}{\partial P_{EH2}} - \lambda = 0 \\ \frac{\partial L}{\partial \lambda} = P_{EH1} + P_{EH2} - P_L = 0 \end{cases} \quad (4)$$

Solving the equations yields:

$$\frac{\partial C_1(P_{EH1})}{\partial P_{EH1}} = \frac{\partial C_2(P_{EH2})}{\partial P_{EH2}} = \lambda^* \quad (5)$$

where λ^* is the optimal solution of the Lagrange function.

By setting λ as the incremental cost, it is inferred that the equal marginal cost criteria are satisfied, and active power can be shared accurately among EHs. To minimize the total power cost, principle of equal increment is executed. If the electrical and thermal power output limitations are not considered, the incremental costs of EHs can be defined as the derivative of the cost function with respect to its output power:

$$\lambda_{x,i} = \frac{\partial C_i}{\partial P_{x,ON,i}} = 2a_{x,i}P_{x,ON,i} + b_{x,i} \quad (6)$$

According to equal increment principle, when the incremental costs of EHs are equal, the operation cost of IES is minimized and the system operates more economically. According to Equation (6), the desired trajectories of the electrical and thermal power outputs for EHs can be represented as:

$$P_{x,ON,i}^{des} = \frac{\lambda_{x,i} - b_{x,i}}{2a_{x,i}} \quad (7)$$

IES economic optimization strategy based on equal increment principle is specifically designed as follows:

(1) Establish the cost functions for EHs in IES, and set the initial states as follows:

$$\begin{cases} \lambda_{x,i} = 2a_{x,i}P_{x,ON,i}(0) + b_{x,i} \\ P_{x,ON,i}(0), \sum_{i=1}^N P_{x,ON,i}(0) = P_{x,LN} \\ P_{x,DN,i} = 0 \end{cases} \quad (8)$$

where $P_{x,DN,i}$ is the local supply-demand power deviation, which is determined by the weight matrix M and the deviation of EH power outputs from the previous sample time to the current sample time. $P_{x,LN}$ is the active power of loads in IES.

(2) Determine the communication topology of the electrical and thermal IES, write the adjacency matrix A and Laplacian matrix L of communication network, and calculate the weight matrix M .

(3) To determine the desired power output trajectories of each EH, calculate the EH's power outputs and its neighboring EHs' power outputs at the current sample time ($t = k$), which are used to calculate the local supply-demand power deviation and subsequently the incremental cost at the next sample time ($t = k + 1$). By substituting the local supply-demand power deviation into Equation (9), the desired power output trajectories of the EHs at the next sample time are calculated. The iteration process can be described as

$$\begin{cases} \lambda_{x,i}(k+1) = \sum_{j=1}^N m_{ij}\lambda_{x,j}(k) + \sigma P_{x,DN,i}(k) \\ P_{x,ON,i}(k+1) = \frac{\lambda_{x,i}(k+1) - b_{x,i}}{2a_{x,i}} \\ P_{x,DN,i}(k+1) = \sum_{j=1}^N m_{ij}P_{x,DN,j}(k) - [P_{x,ON,i}(k+1) - P_{x,ON,i}(k)] \end{cases} \quad (9)$$

where m_{ij} is the communication weight coefficient, which is an element of the weight matrix M . σ is the convergence coefficient, which affects the convergence speed.

(4) When the iteration process ends, the incremental costs of EHs reach consensus and IES achieves the most economical operation.

The above represents the incremental cost algorithm based on consensus control when power output limitations for electrical and thermal energy systems are not considered. Considering the limitations, the process for IES economic optimization strategy is similar,

and only the expression for determining the power outputs of EHs in the iterative process changes. Equation (9) can be replaced by:

$$\begin{cases} \lambda_{x,i}(k+1) = \sum_{j=1}^N m_{ij} \lambda_{x,j}(k) + \sigma P_{x,DN,i}(k) \\ P_{x,ON,i}(k+1) = \begin{cases} P_{x,ON,i\min}, P_{x,ON,i}(k) < P_{x,ON,i\min} \\ \frac{\lambda_{x,i}(k+1) - b_{x,i}}{2a_{x,i}}, P_{x,ON,i\min} \leq P_{x,ON,i}(k) \leq P_{x,ON,i\max} \\ P_{x,ON,i\max}, P_{x,HG,i}(k) > P_{x,ON,i\max} \end{cases} \\ P_{x,DN,i}(k+1) = \sum_{j=1}^N m_{ij} P_{x,DN,j}(k) - [P_{x,ON,i}(k+1) - P_{x,ON,i}(k)] \end{cases} \quad (10)$$

When the goal of the incremental cost economic optimization strategy is accomplished, that is to minimize the power output costs of IES, the desired trajectories of the electrical and thermal power outputs for EHs, $P_{x,ON,i}^{des}$, and the optimal incremental cost, λ^* , are simultaneously determined. It is in preparation for the power sharing control method in the primary level.

2.2. Event-Triggered Consensus Control Method for EHs in the Primary Level

Secondly, a dynamic event-triggering mechanism is designed to reduce the communication requirement and computation burden among EHs. Combined with the dynamic event-triggering conditions, a distributed control method based on the consensus algorithm is proposed to synchronously track the desired trajectories of electrical and thermal power outputs. The frequency and pipeline pressure fluctuations are also limited within the allowable range.

2.2.1. Dynamic Event-Triggered Communication Mechanism

To accurately share power outputs of EHs, a consensus control method is proposed. The traditional consensus control requires frequent communications between EH and its neighboring EHs to generate control inputs, which results in redundant communications in the thermal network due to the response time difference between electrical and thermal networks. Frequent communications also lead to a heavy computation burden. To overcome the effect, a dynamic event-triggered communication mechanism is designed to achieve consensus control goals, while bandwidth and computational resources are saved.

Based on the power deviations of EHs between the previous event time and the current time, the event-triggered conditions for thermal and electrical power control are described respectively as

$$\begin{cases} \|\hat{e}_{hi}(t)\|_2^2 \leq \sigma_i \|\hat{v}_{hi}(t)\|_2^2, t \in [t_{kh}^i, t_{kh+1}^i) \\ \|\hat{e}_{ei}(t)\|_2^2 \leq \rho_i \|\hat{v}_{ei}(t)\|_2^2, t \in [t_{ke}^i, t_{ke+1}^i) \end{cases} \quad (11)$$

where $\hat{e}_{hi}(t)$ and $\hat{e}_{ei}(t)$ are the thermal and electrical power deviations of the i -th EH between the previous event time and the current time, respectively. σ_i and ρ_i are the event triggering coefficients for electrical and thermal power control, respectively. $\hat{v}_{hi}(t)$ is the sum of the deviations of the current thermal power outputs and the desired trajectory between the i -th EH and its neighboring EHs. $\hat{v}_{ei}(t)$ is the sum of the deviations of the current electric power and the desired trajectory between the i -th EH and its neighboring EHs. t_{kh}^i and t_{kh+1}^i are the latest event time and the next event time of thermal power control, respectively. t_{ke}^i and t_{ke+1}^i are the latest event time and the next event time of electric power control, respectively.

Unlike the thermal and electrical power control, the objectives of frequency control for the electrical branch and pressure control for thermal branch are to regulate the current values at the rated values. The event trigger condition of frequency control is designed as follows:

$$t_{kf+1}^i = \inf \left\{ t > t_{kf}^i : \|\hat{e}_{fi}(t)\|_2^2 > d_i \|\hat{g}_{fi}(t)\|_2^2 \right\} \quad (12)$$

where t_{kf}^i and t_{kf+1}^i are the latest event time and the next event time of frequency control, respectively. $\hat{e}_{fi}(t)$ is the frequency deviation of the previous event time and the current time. d_i and $\hat{g}_{fi}(t)$ are the event trigger coefficient and event trigger threshold of frequency control, respectively.

The event trigger condition of pressure control is designed as follows:

$$t_{kF+1}^i = \inf \left\{ t > t_{kF}^i : \|\hat{e}_{Fi}(t)\|_2^2 > \varphi_i \|\hat{s}_{Fi}(t)\|_2^2 \right\} \quad (13)$$

where t_{kF}^i and t_{kF+1}^i are the latest event time and the next event time of frequency control, respectively. $\hat{e}_{Fi}(t)$ is the pressure deviation of the previous event time and the current time. φ_i and $\hat{s}_{Fi}(t)$ are the event trigger coefficient and event trigger threshold of pressure control, respectively.

2.2.2. Distributed Consensus Control Based on Event-Triggered Mechanism for EHs

In order to achieve accurately power sharing and coordinated operation of EHs in IES, a distributed consensus control method for tracking desired trajectories of electric and thermal power outputs based on dynamic event-triggered mechanism is proposed.

Each EH can broadcast its own state information to neighboring EHs at the event-triggered time by communication network. For thermal power control, setting $\tilde{P}_{h,ON,i}(t)$ as the deviation of thermal power outputs between the latest event time and the current time, that is

$$\tilde{P}_{h,ON,i}(t) = P_{h,ON,i}(t_{kh}^i) - P_{h,ON,i}(t) \quad (14)$$

For i -th EH, a thermal power consensus control law based on event-triggered mechanism is described as

$$\hat{v}_{hi}(t) = R_{h,i} \tilde{P}_{h,ON,i}(t) + \sum_{j=1}^N m_{ij} \tilde{P}_{h,ON,j}(t) + d_{h,i} [P_{h,ON,i}(t_{kh}^i) - P_{h,ON,i}^{des}(t)] \quad (15)$$

where $R_{h,i}$ is the thermal power control gain. $d_{h,i}$ is the pinning control gain of thermal power outputs. Equation (15) indicates that only the states of i -th EH and its neighboring EHs are required to be sampled and the global information of IES is not needed. In this sense, the proposed thermal power consensus control law based on the event-triggered mechanism is completely distributed. A proportional integral (PI) controller is designed to eliminate thermal power tracking error $u_{hi} = -R_H \hat{v}_{hi}(t)$. The PI controller reduces rapidly the diversionary terms generated according to the desired trajectories of thermal power outputs. When $u_{hi}(t)$ approaches to 0, the desired trajectories of thermal power outputs and the goal of minimizing the economic costs are achieved.

Similarly, for electrical power control, it is defined $\tilde{P}_{e,ON,i}(t)$ as the deviation of electrical power outputs between the latest event time and the current time, that is

$$\tilde{P}_{e,ON,i}(t) = P_{e,ON,i}(t_{ke}^i) - P_{e,ON,i}(t) \quad (16)$$

In order to realize accurate sharing of electrical power outputs with uncertain disturbance, an electrical power consensus control law based on the event-triggered mechanism is designed as:

$$\hat{v}_{ei}(t) = R_{e,i} \tilde{P}_{e,ON,i}(t) + \sum_{j=1}^N m_{ij} \tilde{P}_{e,ON,j}(t) + d_{e,i} [P_{e,ON,i}(t_{ke}^i) - P_{e,ON,i}^{des}(t)] \quad (17)$$

where $R_{e,i}$ is the electrical power control gain. $d_{e,i}$ is the pinning control gain of electrical power outputs. A PI controller is adopted to decrease electrical power error $u_{ei} = -R_E \hat{v}_{ei}(t)$. When u_{ei} approaches to 0, the desired trajectories of electrical power outputs and the goal of optimal economic operation are obtained.

In order to realize frequency regulation of the electrical branch, a frequency consensus control law based on the event-triggered mechanism is proposed as follows:

$$u_{fi}(t) = -R_{f,i} \left[\sum_{i,j=1}^N m_{ij} (f_i(t_{kf}^i) - f_j(t_{kf}^j)) + d_{f,i} (f_i(t_{kf}^i) - f_l) \right] \quad (18)$$

where $u_{fi}(t)$ is the frequency compensation of i -th EH. $R_{f,i}$ is the frequency control gain. $f_i(t_{kf}^i)$ and $f_i(t)$ are the frequencies of the latest event time and the current time of i -th EH, respectively. $f_j(t_{kf}^j)$ is the frequency of the latest event time of j -th EH. $d_{f,i}$ is the frequency pinning control gain. f_l is the rated frequency. A PI controller is designed to track the rated frequency, when $u_{fi}(t)$ approaches 0.

Due to the different resistances of the thermal branches, the pressures of EHs cannot be controlled at a constant value like electrical frequency. Based on the event-triggered mechanism, a distributed consensus controller for pressures is proposed. When the pressure deviation between the previous event time and the current time meets the trigger condition of Equation (13), the controller will be updated. EHs only exchange information with their neighbors at the trigger time, and diversionary terms are generated according to the upper pressure limit. In order to control the pressure of the thermal branch within the allowable range, a pressure consensus control law is presented as

$$u_{Fi}(t) = -R_{F,i} \left[\sum_{i,j=1}^N m_{ij} (F_i(t_{kp}^i) - F_j(t_{kp}^j)) + d_{F,i} (F_i(t_{kp}^i) - F_l(t_{kp}^i)) \right] \quad (19)$$

where $u_{Fi}(t)$ is the pressure compensation of i -th EH. $R_{F,i}$ is the pressure control gain. $F_i(t_{kp}^i)$ and $F_i(t)$ are the pressures of the latest event time and the current time of i -th EH, respectively. $F_j(t_{kp}^j)$ is the pressure of the latest event time of j -th EH. $d_{F,i}$ is the pressure pinning control gain. $F_l(t_{kp}^i)$ is the upper boundary of the pressure allowable range at the latest event time of thermal power control. A PI controller is designed to adjust the pressure error $u_{Fi}(t)$. When $u_{pi}(t)$ approaches 0, the desired pressure is tracked.

The whole control flowchart of the proposed distributed consensus hierarchical optimization and control method based on event-triggered mechanism is shown in the Figure 2.

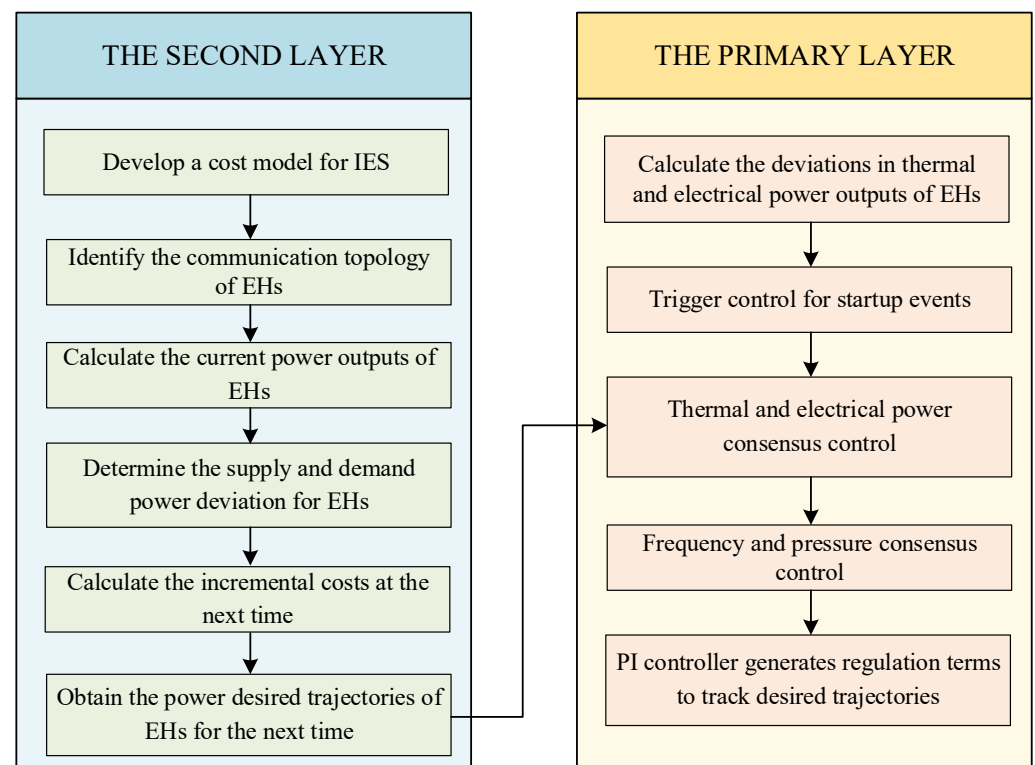


Figure 2. Control flowchart of the proposed method.

3. Experimental Results Analysis

To verify the effectiveness of the distributed consensus hierarchical optimization and control method based on an event-triggered mechanism, a hardware-in-the-loop (HIL) experiment based on dSPACE was conducted. The performance of the proposed method was tested in a IES that includes three EHs. An electrical network and a thermal network were connected to all EHs, as shown in Figure 1. The structure of the HIL experimental platform is shown in Figure 3. The IES model was realized in MATLAB/Simulink. The hardware codes of the IES model could be automatically downloaded from MATLAB/Simulink to Control Desk of dSPACE by real-time workshop (RTW) and real-time interface (RTI). The DSP TMS320F28335 high-speed processor was adopted as the controller of the proposed method. The IES operation information was sampled from Control Desk to DSP by the DS4002 component of dSPACE. The control signals of electrical and thermal energy systems generated by DSP were transferred to the Control Desk by the DS2201 component of dSPACE. The closed control loop was formed with the Control Desk of dSPACE and DSP. The experimental parameters for IES with combined electrical and thermal energy are presented in Table 1 [20].

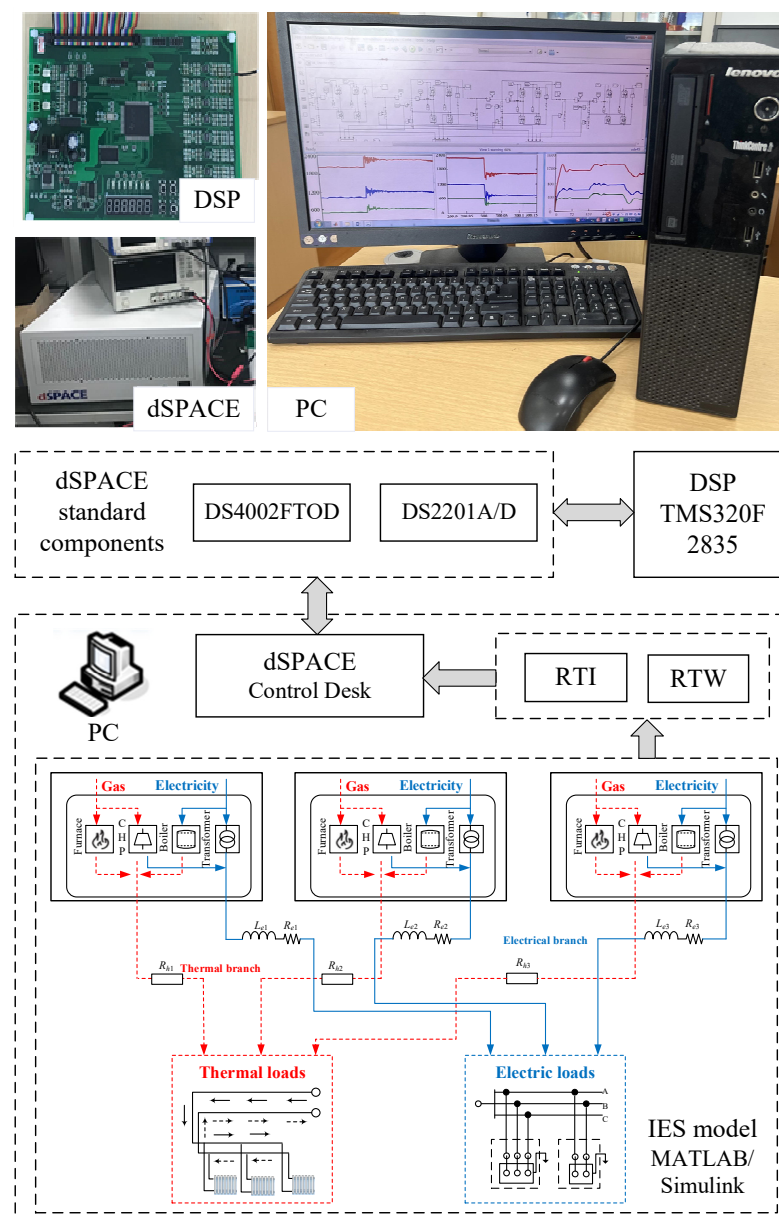


Figure 3. The structure of the HIL experimental platform.

Table 1. Parameters of experiment.

Parameter		Value
EH1	Electric power output	2049.3 kW
	Thermal power output	982.3 kW
	Economic cost	2882.1 RMB
EH2	Electric power output	981.8 kW
	Thermal power output	471.5 kW
	Economic cost	787.8 RMB
EH3	Electric power output	489.3 kW
	Thermal power output	237.3 kW
	Economic cost	405.9 RMB
Rated frequency of electrical branch		50 Hz
Allowable range of pressure for thermal branch		1.08–1.12 MPa

Based on the dSPACE plant, experimental results are analyzed in three cases:

- (1) In Case 1, the dynamic response performances of EHs are tested when both the electrical and thermal loads increase or decrease simultaneously.
- (2) In Case 2, the dynamic response performances of EHs are tested when the electrical load decreases while the thermal load increases or when the electrical load increases while the thermal load decreases.
- (3) In Case 3, the dynamic response performances of EH2 are compared with the proposed method in this paper and the control method proposed in the literature [20].

3.1. Experimental Results Analysis for Case 1

At $t = 150$ s, the IES experiment is configured to simulate the decreases of 700 kW in electrical load and 350 kW in thermal load. At $t = 300$ s, the increases of 1000 kW in electrical load and 600 kW in thermal load follow. The dynamic response results of electrical and thermal networks are shown in Figure 4.

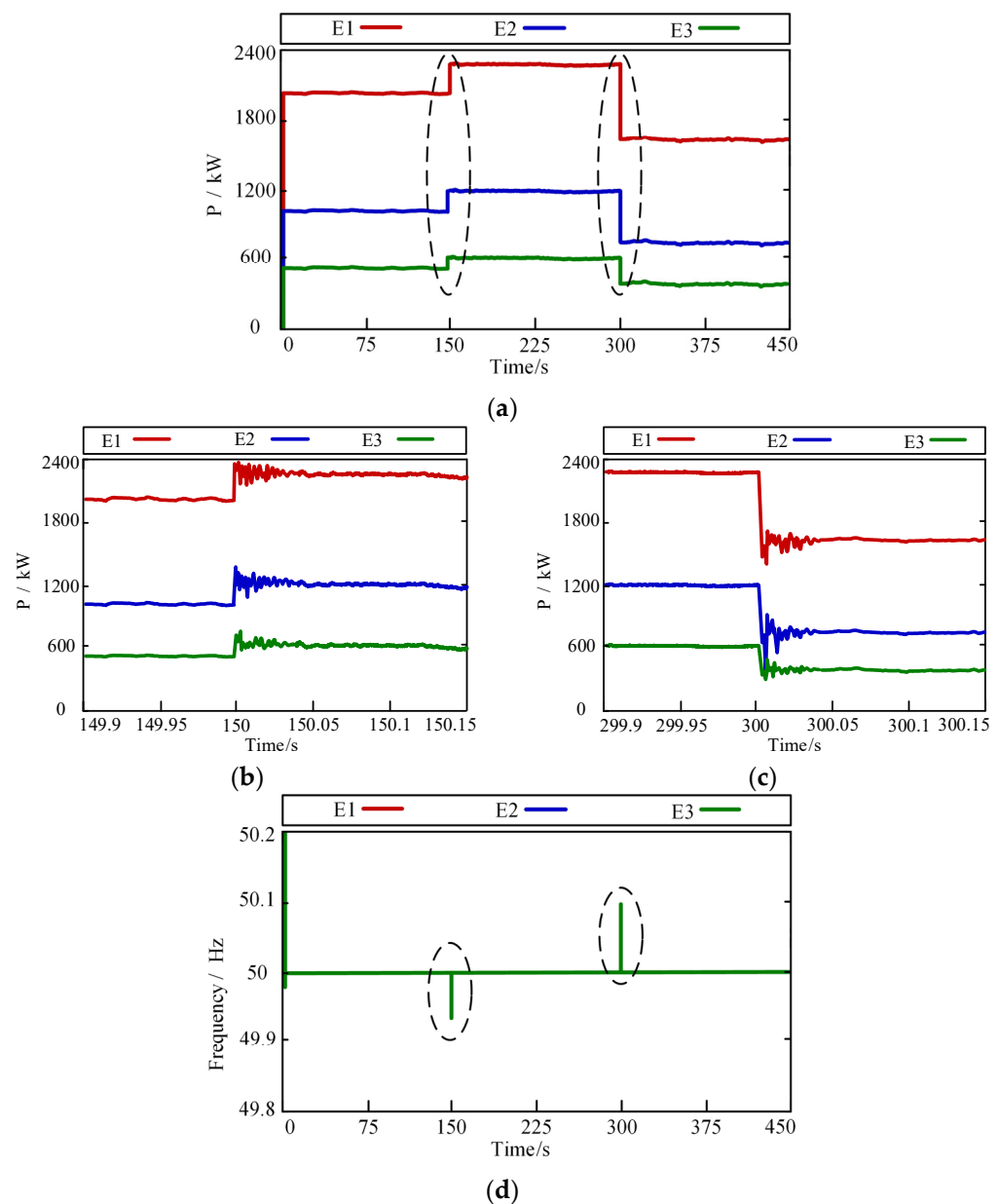


Figure 4. Cont.

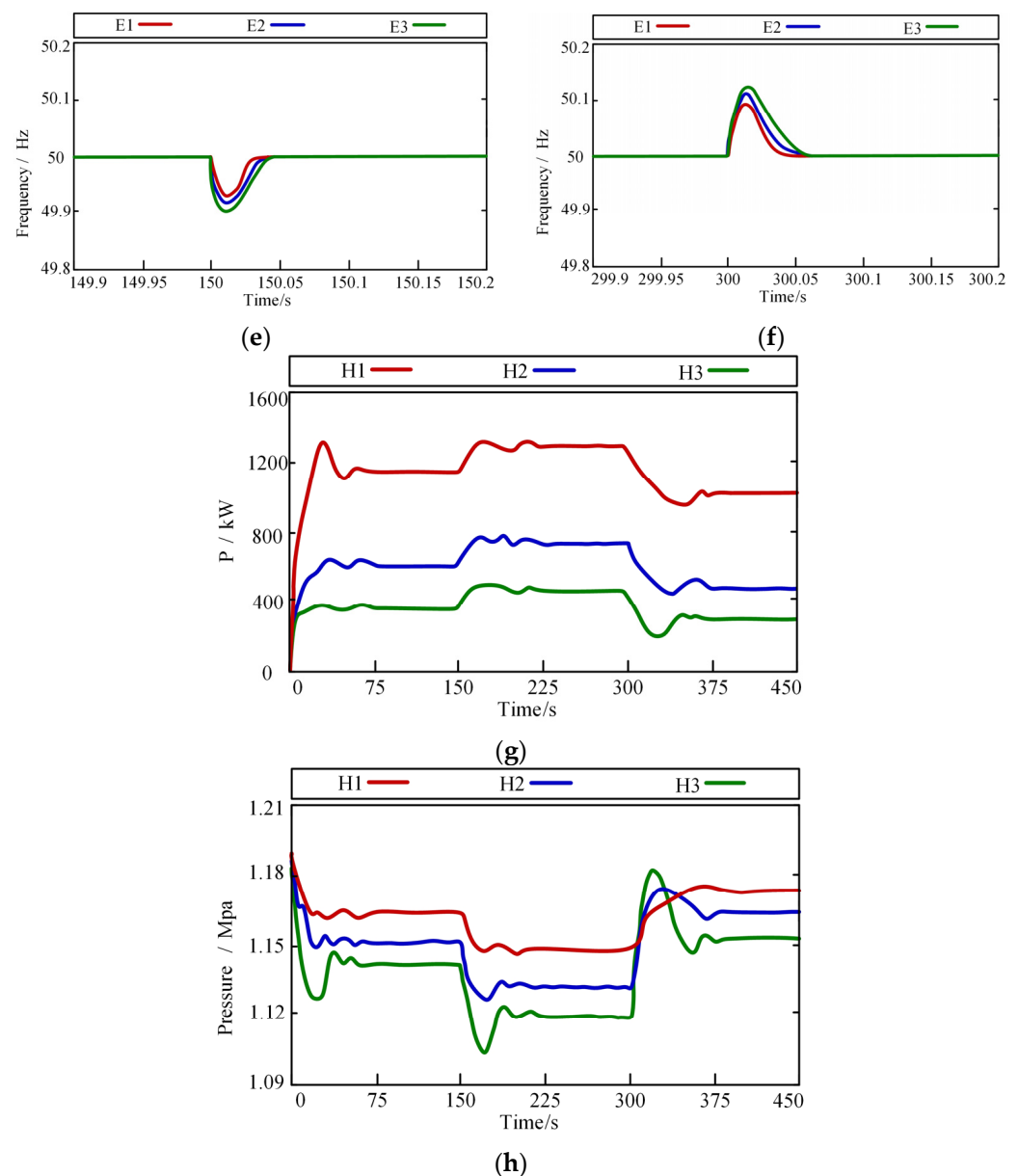


Figure 4. EH response waveforms of electrical and thermal networks in Case 1. (a) Active powers of electrical network. (b) Responses of electrical powers at 150 s. (c) Responses of electrical powers at 300 s. (d) Frequency of electrical network. (e) Frequency responses at 150 s. (f) Frequency responses at 300 s. (g) Powers of thermal network. (h) Pressure of thermal network.

Figure 4 shows the electrical power outputs, frequency, thermal power outputs and pressure of the EHs with the proposed method in Case 1. In Figure 4, E1, E2 and E3 indicate the electrical variables of the EHs, and H1, H2 and H3 indicate the thermal variables of the EHs. Analyzing Figure 4a–c,g, it can be seen that the dynamic event-triggered communication mechanism responds quickly when simultaneous decreases and increases occur in electrical and thermal loads, and there is no need for the global IES information. The proposed consensus control method can share electrical and thermal power outputs of the EHs accurately and remain small tracking errors of the desired trajectories.

Due to changes in electrical load demand, frequency adjusts with electrical power output mutation. From Figure 4d–f, it is shown that after a short adjustment, the frequency deviations caused by electrical power output fluctuations of the EHs are quickly suppressed and regulated to the rated value of 50 Hz. Due to changes in thermal load demand, pressure also adjusts with thermal power output mutation. From Figure 4h, it is shown

that pressures in the thermal branches are controlled within the allowed range and the proposed distributed consensus control method ensures a safe and stable operation of IES.

The electrical power outputs and frequency response waveforms are analyzed. It can be concluded that the proposed distributed consensus control method only requires 0.05 s to achieve the stable recovery of electrical branches, while the thermal power outputs and pressure response waveforms show that it takes 75 s to recover smoothly in the thermal branches, which verifies the necessity of setting a dynamic event-triggered communication mechanism. From the response waveforms of electrical and thermal branches, it is shown that the proper event-triggered conditions are suggested and redundant communications in the electrical branches are saved when the dynamic response performances of both electrical and thermal branches are guaranteed.

To verify the effectiveness of the proposed economic optimization strategy based on equal increment principle, the power outputs and economic cost changes of EHs in Case 1 are shown in Table 2. By comparing Tables 1 and 2, it can be seen that the increases or decreases of IES economic costs are in the demands of electrical and thermal loads. When the optimal incremental cost is determined by consensus control of the EHs, the goal of minimizing the power output costs is accomplished, which enhances the overall economic operation performance of IES.

Table 2. EHs' experimental results in Case 1.

Time	EH	Electric Output	Thermal Output	Economic Cost
150 s	EH1	1668.4 kW	794.5 kW	2276.9 RMB
	EH2	798.9 kW	381.4 kW	622.4 RMB
	EH3	353.2 kW	165.2 kW	320.7 RMB
300 s	EH1	2685.7 kW	1368.7 kW	3660.3 RMB
	EH2	1261.4 kW	687.4 kW	1003.7 RMB
	EH3	574.6 kW	235.2 kW	515.5 RMB

3.2. Experimental Results Analysis for Case 2

At $t = 150$ s, the IES experiment is set to simulate a decrease of 1000 kW in the electrical load and an increase of 500 kW in the thermal load. At $t = 300$ s, an increase of 500 kW in the electrical load and a decrease of 300 kW in the thermal load follow. The dynamic response results of electrical and thermal networks are shown in Figure 5.

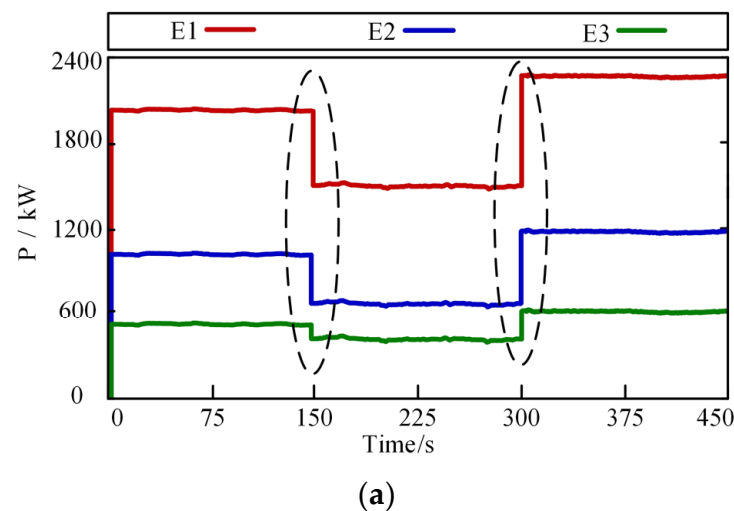


Figure 5. Cont.

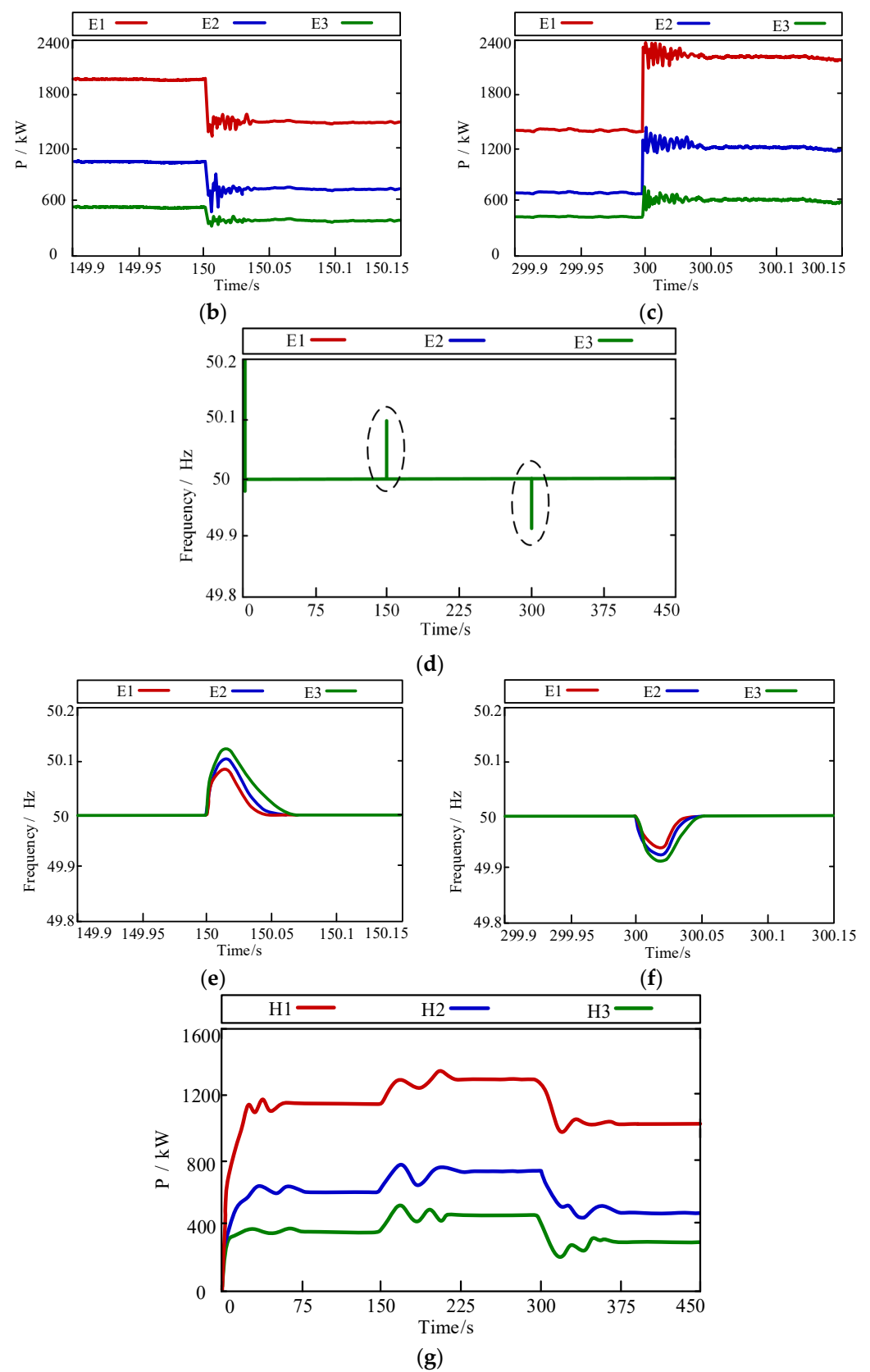


Figure 5. Cont.

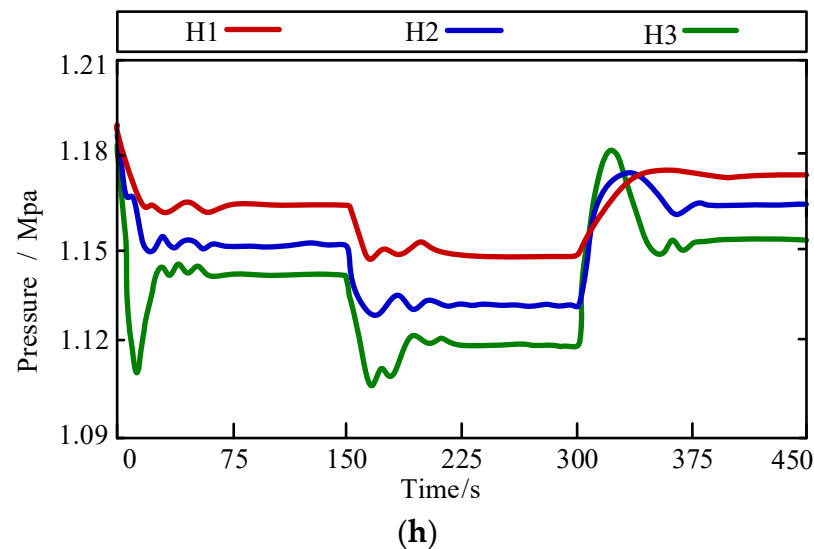


Figure 5. EH response waveforms of electrical and thermal networks in Case 2. (a) Active powers of electrical network; (b) Responses of electrical powers at 150 s. (c) Responses of electrical powers at 300 s. (d) Frequency of electrical network. (e) Frequency responses at 150 s. (f) Frequency responses at 300 s. (g) Powers of thermal network. (h) Pressure of thermal network.

Figure 5 shows the electrical power outputs, frequency, thermal power outputs and pressure of the EHs with the proposed method in Case 2. It can be seen from Figure 5a–c,g that when the demands of electrical and thermal loads increase or decrease in opposite trends, the good dynamic response performance of the electrical and thermal networks are still maintained. With the consensus coordinated control based on dynamic event-triggering mechanism, the electrical and thermal power outputs of the EHs can quickly track the desired trajectories, and the accurate power sharing between sources and loads is realized. EHs enter steady states synchronously, and the stable operation of IES is guaranteed.

Due to changes in the electrical demand, frequencies in the electrical branches respond quickly. From Figure 5d–f, it is indicated that the EHs adopted the proposed distributed consensus control method and experienced a short downward fluctuation during an increase in the electrical load and a quick upward fluctuation during a decrease in the electrical load. After a quick adjustment, the frequencies of the EHs regulate at the rated value of 50 Hz. Due to changes in the thermal demand, pressure also responds accordingly. From Figure 5h, it is shown that the EHs experience a decrease in the dynamic pressure response during an increase in the thermal load and an increase during a decrease in the thermal load. Pressures in the thermal branches are always kept within an allowable range.

Compared with Case 1, when the electrical and thermal demands increase or decrease in opposite trends, the smooth recovery of the electrical branch is achieved in 0.05 s, while the thermal branch takes slightly longer, about 80 s. The proposed dynamic event-triggered communication mechanism effectively obtains the control objectives in a fast manner.

The power outputs and economic costs of EHs in Case 2 are shown in Table 3. From the dynamic adjustments in economic costs with the changes in electrical and thermal demands, it is demonstrated that the proposed economic optimization strategy based on the equal increment principle is carried out with effect, and the desired trajectories of the electrical and thermal power outputs for the EHs are accurate, which improves the performance of distributed consensus control in the primary layer.

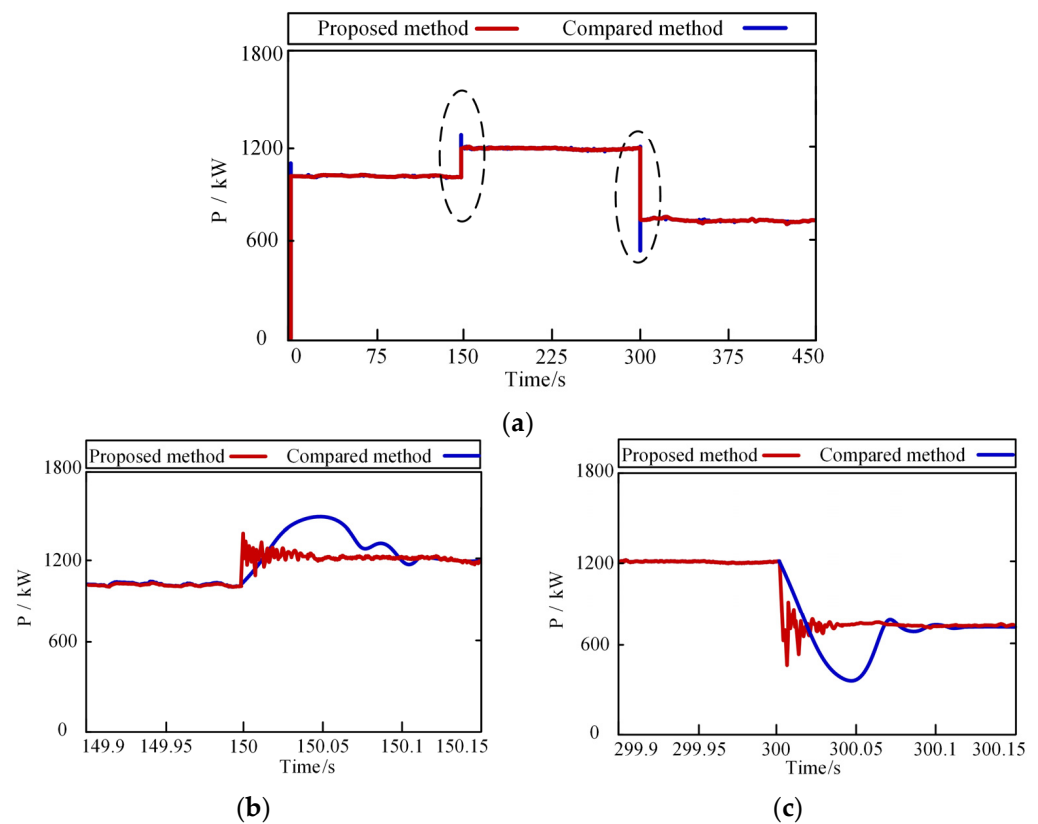
Table 3. EHs' experimental results in Case 2.

Time	EH	Electric Output	Thermal Output	Economic Cost
150 s	EH1	1442.8 kW	1326.7 kW	2507.5 RMB
	EH2	784.6 kW	598.2 kW	685.4 RMB
	EH3	293.4 kW	266.2 kW	353.1 RMB
300 s	EH1	2346.3 kW	783.4 kW	3112.7 RMB
	EH2	1017.8 kW	456.5 kW	811.4 RMB
	EH3	656.3 kW	151.2 kW	418.1 RMB

3.3. Performance Comparison of Different Control Methods

To compare the dynamic response performances of the proposed method in this paper with the method promoted in the literature [20], the experimental conditions of electrical and thermal load changes are set as the same as Case 1. The dynamic response results of EH2 electric and thermal networks with different control methods are shown in Figure 6.

Figure 5 shows the electrical power output, frequency, thermal power output and pressure of EH2 with the proposed method and the compared method. From Figure 6a–c,g, it can be seen that both consensus control methods can achieve the adjustment of EH electrical and thermal power outputs to meet the accurate power sharing goal when there is an increase or decrease in electrical and thermal demands. The proposed method based on the dynamic event-triggering mechanism can quickly adjust the desired trajectories of electrical and thermal power outputs, so smaller overshoot and shorter adjustment time are required than in the compared method.

**Figure 6.** Cont.

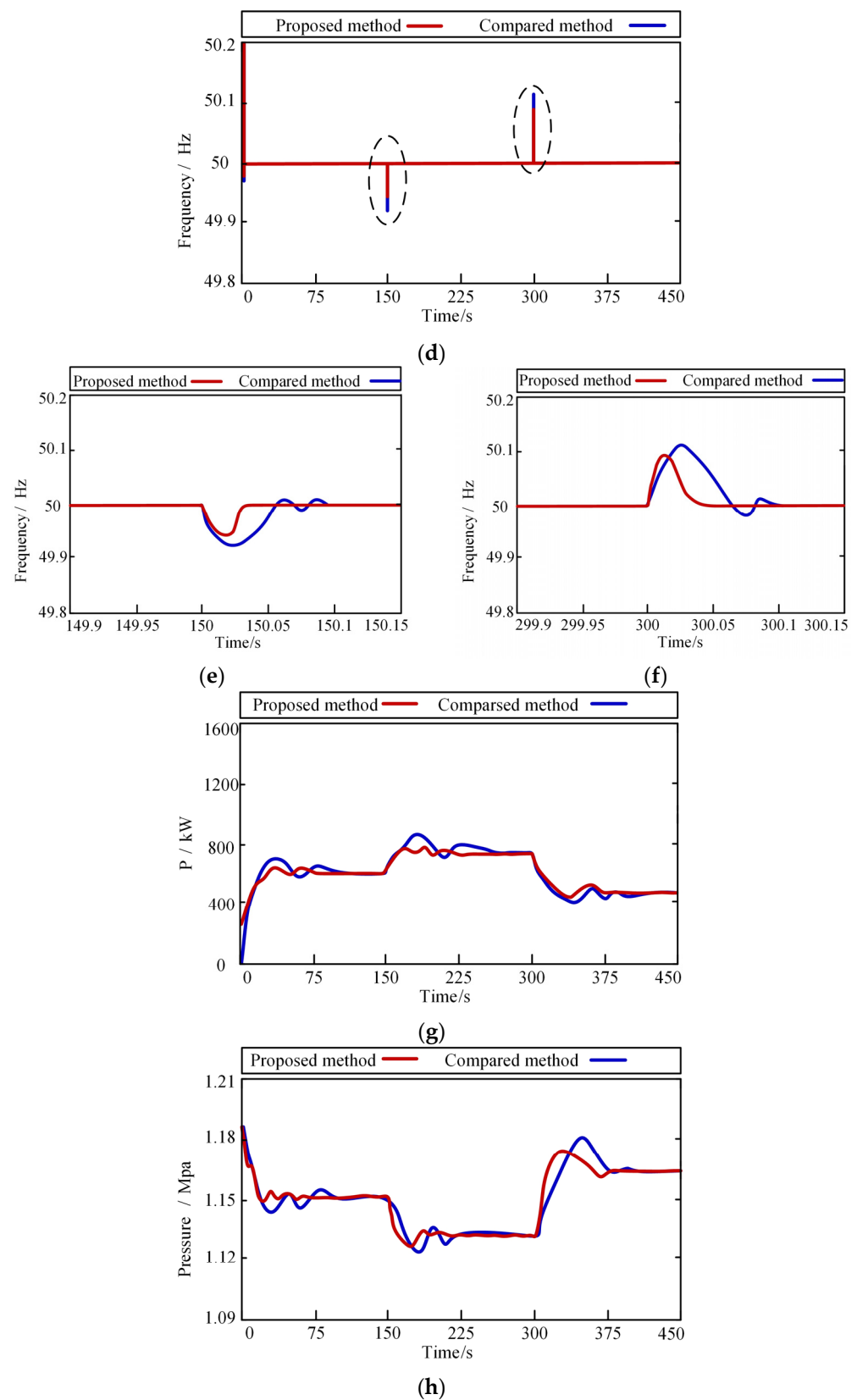


Figure 6. EH2 response waveforms of electrical and thermal networks in Case 3. (a) Active powers of electrical network. (b) Responses of electrical powers at 150 s. (c) Responses of electrical powers at 300 s. (d) Frequency of electrical network. (e) Frequency responses at 150 s. (f) Frequency responses at 300 s. (g) Powers of thermal network. (h) Pressure of thermal network.

From Figure 6d–f, it is shown that both methods can ensure frequency of EH2 at the rated value of 50 Hz, but the proposed method has a faster response. Because the tracking speed of the frequency of the desired trajectory is closely related to the electrical power output, the proposed dynamic event-triggering mechanism enables the effective suppression of the frequency deviation caused by electrical load changes. From Figure 6h, it is shown that the proposed method can also quickly control pressure in the thermal branch within the allowable range and ensure stable operation of IES.

From the analysis of electrical power output and frequency response, as well as thermal power output and pressure response, it is inferred that the proposed method has better dynamic response performance. The time required to recover in the electrical and thermal branches is reduced by half compared to the compared method. From Table 2, it is shown that the proposed method achieves an economic cost saving of CNY 58.3 (1.78% reduction) compared with the compared method when there is an increase in electrical and thermal demands and saves CNY 100.1 (1.89% reduction) when there is a decrease in electrical and thermal demands. It is indicated that the proposed economic optimization strategy based on the equal increment principle has better performance in minimizing the power output costs of IES.

4. Conclusions

A two-layer hierarchical structure to achieve economic optimization and consensus control of IES is proposed in this paper. An economic optimization strategy based on the incremental cost consensus algorithm is promoted, which ensures that IES economically operates and the power outputs of the EHs converge to the optimal working points while the supply-demand balance target is satisfied. To accurately share electric and thermal power outputs of the EHs, a consensus control method based on the dynamic event-triggering mechanism is designed. The redundant communication in the electrical branches is effectively reduced and the desired trajectories of electrical and thermal power outputs are tracked precisely in the presence of uncertain disturbances. The frequency deviation is rapidly suppressed and the pipeline pressure is kept within the allowable range. The effectiveness of the proposed method is validated on a hardware-in-the-loop dSPACE platform consisting of three EHs. With the changes of electrical and thermal demands, the goal of minimizing IES economic costs is achieved, and the coordinated control of electric and thermal energy systems is accomplished. The proposed method has the advantages of small overshoot, short adjustment time and optimal economic cost.

Author Contributions: Conceptualization, J.Y.; methodology, B.L.; software, Z.Y.; investigation, Y.C.; data curation, Y.W.; writing, H.X. and C.L.; visualization, K.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by National Natural Science Foundation of China, grant number 52207025; Local University Capacity Enhancement Project of Shanghai Science and Technology Commission, grant number 22010501400; Science And Technology Project of Power Construction Corporation of China, Ltd., grant number DJ-ZDZX-2021-01.

Data Availability Statement: Not applicable.

Acknowledgments: The authors are grateful to the editors and reviewers for their comments regarding manuscript improvement. We also thank Jiawen Zheng for her help in the data process.

Conflicts of Interest: The authors declare no conflict of interest.

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