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# The Dual Control with Consideration of Security Operation and Economic Efficiency for Energy Hub

Qiuye Sun, *Member, IEEE,* Ning Zhang, Shi You, *Member, IEEE,* Jiawei Wang

*Abstract*—This paper proposes a dual control of energy hub (DCEH) considering security operation and economic efficiency which is constituted by the control of energy hub outputs and inner devices. As security operation is a significant requirement of multi-carrier energy system (MCES) with energy hubs, it is necessary for MCES to regulate the outputs of hubs which highly influence the performance. The control approach of energy hub outputs can proportionally allocate the electricity and heat outputs of energy hubs. Meanwhile, the decentralized control of energy hubs can be realized to eliminate the impact of communication on security operation by implementing the proposed method. Furthermore, in view of the characteristics of energy hub, the elements in hubs also need to be regulated to reduce the energy consumption. The control of inner devices based on the improved equal incremental consumption principle can reach to the minimal loss of the energy. Numerical simulations demonstrate the effectiveness of the proposed method.

*Index Terms*—Energy hub; dual control; security operation; economic efficiency.

## Nomenclature

| | |
|---|---|
| $L_h$ | Heat output power of the energy hub |
| $L_e$ | Electricity output power of the energy hub |
| $L_{hN}$ | Nominal heat output power of the energy hub |
| $L_{eN}$ | Nominal electricity output power of the energy hub |
| $L_{h\max}$ | Maximal heat output power of the energy hub |
| $L_{e\max}$ | Maximal electricity output power of the energy hub |
| $D_l$ | Heat obtained by entire pipelines of loads |
| $Q_t$ | Heat loss at the transmission pipeline |
| $m_l$ | Mass flow rate of entire pipelines of loads |
| $m_j$ | Mass flow rate of each pipeline of loads |
| $\Delta T_l$ | Temperature difference between inlet and outlet of thermal loads |
| $\Delta T_t$ | Temperature difference of hot water after flowing through the transmission pipeline |
| $V_l$ | Volume flow rate of entire pipelines of loads |

| | |
|---|---|
| $V_t$ | Volume flow rate of the transmission pipeline |
| $M$ | Number of pipelines of loads |
| $I$ | Number of energy hubs |
| $S_l$ | Resistance of entire pipelines of loads |
| $S_t$ | Resistance of the transmission pipeline |
| $P_u$ | Corresponding input of DSE $u$ |
| $L_u$ | Corresponding output of DSE $u$ |
| $K$ | Numbers of the DSE |
| $\bar{K}$ | Numbers of the DME |
| $k_p$ | Adjustment coefficient for heat output |
| $k_q$ | Adjustment coefficient for electricity output |
| $p$ | Outlet pressure of energy hub |
| $p_{in}$ | Inlet pressure of thermal loads |
| $p_{out}$ | Outlet pressure of thermal loads |
| $f$ | Measured frequency of electricity network |
| $f_N$ | Nominal frequency of electricity network |
| $p'_N$ | Nominal inlet pressure of thermal loads |
| $b$ | Different kinds of energies and $\forall b \in e, g$ |
| $\tilde{b}$ | Different kinds of energies and $\forall \tilde{b} \in e, h$ |
| $\lambda^*$ | Standard incremental ratio of cost when the hub reaches the optimal operation |
| $\lambda_r$ | Incremental ratio of cost of energy hub inner device $r$ |
| $c$ | Specific heat capacity of water |
| $v$ | The index for the DME |
| $\rho$ | Density of water |
| $n, i$ | The index for energy hub |
| $\alpha, \beta, \gamma$ | Cost parameters of the DSE |
| $\bar{a}, \bar{b} \ldots, \bar{e}$ | Cost parameters of the DME |

## I. Introduction

THE energy hub concept has been recently introduced as a new model for the future MCES. An energy hub can be considered as an unit that offers the basic features like conversion, as well as storage of different energy carriers. It includes a variety of components, such as combined heat and power (CHP), transformers, boilers in order to meet energy demands [1]. A new model of energy hub considering system efficiencies, storage losses and operating limits was presented in [2]. Thermal and electrical storages were simultaneously modeled and a detailed evaluation about the benefit of energy storages was given in [3]. All technical potential interconnections between different equipments of energy hub was surveyed in [4], and using storage facility at both sides of converters were also considered in this reference.

In addition to traditional energy hub concept, different

kinds of energy hub concept and MCES structures were studied by some researches. The energy hub concept and models at urban level were introduced in [5]. In these models, energy-autonomy and ecological performance of energy systems were evaluated. A model of energy hub combined with distributed energy supply/combined cooling heating and power (DES/CCHP) was proposed in [6], and the electric vehicle was considered as a significant storage in the model.

Along with the attaching importance to clean energy, more and more researches paid attention to the model of hydrogen. The utilization of hydrogen in energy hub was studied in [7]-[10]. The energy hub model using hydrogen was first introduced in [7]. Reference [8] and [9] presented an energy hub model which considers the hydrogen energy storage. Moreover, nuclear energy was also taken into account in the model that was presented in [9]. Hydrogen was considered as an input of combined cycle power plant in [10], where the energy hub model was composed of combined cycle power plant, hydrogen energy storage and renewable energy sources which provide electricity for electrolysis.

Besides the researches on the energy hub modeling, a considerable amount of studies focused on the optimal operation of energy hub and this issue was studied from multiple aspects. Some researches dealt with the influence of various electricity markets and games on the optimal operation of energy hubs. Efficient operation of energy hubs in time-of-use and dynamic pricing electricity markets were developed in [11]. Reference [12] investigated the smart energy hub model and formulated the interaction between smart energy hubs as a noncooperative game. Compared with [12], the game player in [13]-[14] changed from hubs to energy companies and hubs. The uncertainties in MCES were addressed in several studies. Reference [15] resolved the uncertainties of wind and electricity price by using corresponding methods. Moreover, two decision-making models were given and the risk aversion in management was considered. Compared with [15], reference [16]-[17] also investigated the uncertainty of demand. Reference [18] discussed the impact of the presence of data uncertainty which was calculated by an affine arithmetic-based methodology. A stochastic bi-level model which considered three types of uncertainties in electricity market was proposed in [19], and the optimal operation issue based on the model was solved by using the KKT optimality condition. The multi-objective optimization problem of energy hubs and the optimal power flow problem of MCES were concerned in some researches. A multi-objective optimization issue which used two rival criteria of economics and environmental performance was solved by utilizing a Pareto optimal solution in [20]. Reference [21] proposed a modified teaching-learning based optimization method to resolve the optimal operation problem of energy power flow in MCES. A multi-objective mixed integer linear programming model of MCES with a district heating network was presented in [22]. The optimal option of equipments, distribution of district heating network and operation of hubs were determined in the model. Long-term optimal planning was proposed in [23]-[24] for energy hubs in multi-energy system.

As an important issue, many studies focused on the security

operation of energy system [25]-[31]. Reference [25] and [26] considered the stability of the system with virtual synchronous generator (VSG). The droop control method that could resolve the problem of power distribution and ensure the security operation was deeply studied. Reference [27]-[28] focused on the effect of power sharing and could greatly improve the reliability of the system. But the influence of parameters were overlooked in these studies. The model, stability analysis as well as the influence of parameters for the multi-inverter system were discussed in [29]. In MCES, most researches took into account of reliability of the system in optimal problem. The reliability-based optimal problem was investigated in [30]-[31]. The minimal cut-maximal flow algorithm was used to solve the reliability-based optimal planning problem for multiple energy hubs in [30]. Reference [31] extended the network reliability, power loss, and voltage profile as the constraints for optimal planning problem. But neither of them discussed the security operation of the energy hub.

Most of researches for energy hub focused on the modeling and optimal operation of energy hub. On the other hand, few studies considered about the control and security operation of energy hub. As the most basic and significant requirement of MCES, the security operation can be achieved by regulating the energy hub working at a secure range with the proportional power sharing. The contribution of this paper can be expressed as follow:

1) A DCEH which contains the control of outputs and inner devices for each energy hub is proposed to carry out the security operation of MCES and ensure the economic efficiency of energy hubs.

2) The control of outputs is presented based on the characteristics of corresponding energy system. The control approach can proportionally allocate the electricity and heat outputs of energy hub. All energy hubs can undertake the demands jointly and the system parameters will not change greatly in heavy loads.

3) The control of inner devices based on the improved equal increment consumption principle is proposed. So that constituent elements of energy hub can be appropriately adjusted to reduce the energy consumption.

4) The proposed DCEH is a kind of decentralized control that each energy hub only need to detect the change of parameters without exchanging information with other hubs. So the impact of communication on security operation can be avoided by using the DCEH.

The rest of this paper is organized as: Section II introduces the typical architecture and mathematical model of energy hub and presents the DCEH which contains the control of energy hub outputs and inner devices. Section III introduces illustrative examples to show the proposed method applied to a simulated MCES. The conclusion drawn from this paper is provided in Section IV.

## II. ENERGY HUB MODEL AND THE DUAL CONTROL OF ENERGY HUB

For each energy hub in MCES, it is an important issue to know how much energy will be received from networks
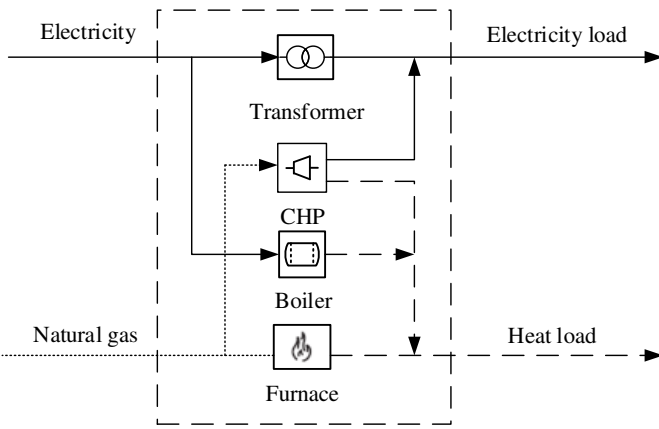
Fig. 1. Energy hub with electricity, natural gas, and heat systems.

when loads changed. Proportional power sharing is requisite if there is no communication between hubs. And the inputs also need to be figured out when outputs are determined due to the characteristics of energy hub. To resolve the issues and guarantee the security operation of MCES, the DCEH which can determine the inputs and the outputs of energy hub is proposed.

### A. Energy Hub Model

Energy hub is defined by a series of energy carriers and each energy hub includes multiple energy carriers as inputs and outputs. There are many elements such as connectors, converters and storage facilities that can process multi-energy in energy hub. Owing to these elements, the input energy of hub can be converted to diversified forms or be stored in order to fulfill the energy demand at the output ports. Considering a common energy hub with multiple energy carriers, the energies transfer from input energies to output energies can be expressed as:

$$
\underbrace{\begin{pmatrix} L_\omega \\ \vdots \\ L_\upsilon \end{pmatrix}}_{L} = \underbrace{\begin{pmatrix} C_{\omega\omega} & \cdots & C_{\omega\upsilon} \\ \vdots & \ddots & \vdots \\ C_{\omega\upsilon} & \cdots & C_{\upsilon\upsilon} \end{pmatrix}}_{C} \underbrace{\begin{pmatrix} E_\omega \\ \vdots \\ E_\upsilon \end{pmatrix}}_{E}, \tag{1}
$$

in which the various kinds of input energies and output energies are figured by $E = [E_\omega, \ldots, E_\upsilon]^T$ and $L = [L_\omega, \ldots, L_\upsilon]^T$, respectively. The matrix $C$ is the forward coupling matrix which describes the conversion of energy from the input to the output. The elements of coupling matrix are coupling factors which are determined by the converters efficiencies and dispatch factors. The energy transfers from the $\omega$th energy carrier to the $\upsilon$th energy carrier by a converter device with a coupling factor of $C_{\omega\upsilon}$ can be expressed as:

$$ L_\upsilon = C_{\omega\upsilon} E_\omega, \tag{2} $$

where $E_\omega$ and $L_\upsilon$ are energy input and output, respectively. For the energy hub with single converter, the coupling factor only corresponds to the efficiency of the element. While the coupling factors are determined by the converters efficiencies and dispatch factors for the energy hub with various converters.

Fig. 1 depicts an energy hub model consisting of the transformer, the CHP, the boiler and the furnace [2], [20], [32]-[34]. The inputs energies of the hub are electricity and natural gas, Energy hub can transform electricity and natural gas to two different energy formats i.e. heat and electricity by utilizing the four inner transformation devices like CHP.

### B. The Control of Energy Hub Outputs

Since the proportional power sharing cannot be achieved spontaneously, the control of energy hub outputs is necessary. While the outputs of energy hub contain heat and electricity, the control of heat output and electricity output are proposed, respectively.

In this paper, both the heating system model and power system model are the classical models used for derivation and all corresponding parameters like pressure, resistance, frequency and so on are important and common parameters in literatures [35]-[39] and practical applications. The heating system is consisted of energy hub, outlet pipeline (OP), inlet pipeline (IP) and the pipeline of loads (LP). The IP and OP form the transmission pipeline (TP). The relationship among the OP, IP and LP is presented in the module of energy hub to the loads to show the structure of heating system as shown in Fig. 5. The way that an energy hub transmits heat to loads can be described as follow: hot water which is outputted from the outlet of the energy hub flows through OP into LPs, and then water passes the IP back to the inlet of energy hub. The power balance equation of the district heating sub-network is expressed as:

$$ D_l = \sum_{n=1}^{I} L_h - Q_t \tag{3} $$

$$ Q_t = cm_l \Delta T_t, \quad m_l = \sum_{j=1}^{M} m_j. \tag{4} $$

Equation (3) denotes that the heat output of energy hub can be divided into the getting power of thermal loads and the energy loss of the TP. Commonly, a thermal-protective coating wraps the outside of the TP to reduce the heat loss. So $\Delta T_t$ is much lower than $\Delta T_l$ and it can be ignored. Hence, the heat power obtained by demand side is equal to the heat output of energy hubs and can be expressed as:

$$ D_l = \sum_{n=1}^{I} L_h = cm_l \Delta T_l, \tag{5} $$

There are two energy regulation ways for the heating network according to (5): flow control and temperature control. Since the temperature variation is a slowly changing process, flow control is chosen as the control method of energy hubs to improve the response speed of system in this paper. It is supposed the change of $\Delta T_l$ is ignored when the flow control method is implemented [40]. In this context, all the temperature of hot water which is outputted from each energy hub follows a standard value. The only difference among each hub heat output is mass flow rate. Mass flow rate can be transformed to volume flow rate $V_l$ by following equation:
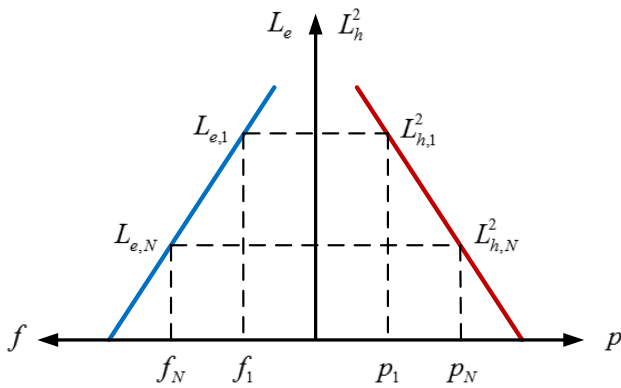
$$ m_l = \rho V_l, \tag{6} $$

Fig. 2. The curve of energy hub outputs control.

Conventionally, hot water pipelines at demand side are connected in parallel. Each pipeline has the resistance of water flow, the pipeline resistance is determined by the characteristics of pipeline and does not change with water flow rate [41]. The inlet flow rate and outlet flow rate for thermal loads are identical, and the flow rate is equal in one pipeline. The whole resistance of LPs $S_l$ can be expressed as:

$$\frac{1}{\sqrt{S_l}} = \frac{1}{\sqrt{S_1}} + \frac{1}{\sqrt{S_2}} + \cdots \frac{1}{\sqrt{S_M}} , \tag{7}$$

The change of resistance for loads is inversely proportional to the variation of loads as shown in (7).

The correlation between pressure droop and volume flow rate is expressed as [41]:

$$p_{in} - p_{out} = S_l V_l^2 , \tag{8}$$

The pressure drop is proportional to the total volume flow rate squared when the thermal load is determined as indicated in (8) .

Similarly, the relationship between volume flow rate and pressure drop of corresponding TP can also be expressed as:

$$p - p_{in} = S_t V_t^2 , \tag{9}$$

Since the flow rate is equivalent in one pipeline and LPs share the same inlet and outlet flow rate, the flow rates in IP and OP are also equal. The resistance of IP is integrated into the resistance of OP to facilitate the analysis. In this regard, the outlet pressure of thermal loads $p_{out}$ is equal to the inlet pressure of energy hub which is set as the basic value. According to (5), (6) and (8), the following expression can be deduced for :

$$\left( \frac{\sum\limits_{n=1}^{I} L_h}{c\rho\Delta t} \right)^2 S_l = p_{in} - p_{out}, \tag{10}$$

where the correlation between the pressure drop of the LP and the total heat output of energy hub is indicated in (9).

The thermal power flow which is outputted from the energy hubs to loads should be properly controlled for meeting the demands and ensuring the security operation of MCES. Therefore, it is necessary to make each energy hub respond

to the load change automatically and allocate output power proportionally based on its capacity. In this way, the overload of energy hubs without communication can be avoided. As shown in (10), the change of pressure droop follows the variation of loads resistance and heat output power of hubs. Generally, the heat output power will not change without control command, so the variation of pressure droop can reflect the change of loads based on the relationship between loads and loads resistance. Since the outlet pressure of thermal loads is set as the basic value, the value changes of $p$ represent the changes of the pressure droop for corresponding pipelines. However, each energy hub outlet pressure $p$ is various since $S_t$ for each energy hub is different. In this regard, $p$ needs to be amended to eliminate the influence factor. Based on (9), (10), the control of heat output can be expressed as:

$$L_h^2 - L_{hN}^2 = k_p \left( p_N' - p + V_t^2 S_t \right), \tag{11}$$

As shown in (11), $L_h$ is controlled to vary inversely with the $p$ which is after the amendment. In this context, the relationship between the maximal heat output $L_{h\,\max}$ and the adjustment coefficient $k_p$ needs to be set as follow to implement the proportional heat power sharing:

$$\frac{L_{hn\,\max}^2}{L_{hi\,\max}^2} = \frac{k_{ip}}{k_{np}}, \tag{12}$$

In view of the specifics of energy hub and the droop characteristics in modern power systems, the control method which is used to determine the electricity output of the energy hub can be expressed as:

$$L_e - L_{eN} = k_q \left( f_N - f \right), \tag{13}$$

According to equation (11) and (13), the curve of energy hub outputs control can be plotted like Fig. 2. $p$ denotes the pressure after correction and $p_N$ stands for the nominal value of $p$ in this figure. Because of the increasing of $f$, $P_e$ is changed with a downtrend as shown in Fig. 3. Similarly, $P_g$ is altered with a downside due to the increasing $p$. Since $p$ is corrected in the control method and $f$ is equal everywhere in the power system, the detection parameters of all energy hubs are equivalent. In this context, energy hubs can achieve proportional power sharing by utilizing the proposed control approaches.

### C. The Control of Energy Hub Inner Devices

The utilization of the proposed control method can determine the outputs of energy hub. But the outputs cannot determine the operating state of energy hub due to its characteristics. In fact, some operational objectives are realized by controlling the operation of constituent elements and the inputs of hub. In view of the important function of energy hub which is decreasing the energy consumption, it is more important to propose a control strategy for the inner elements of hub to ensure the security operation and reduce the energy cost simultaneously.

Conventionally, in electric power system, the equal incremental consumption principle is used to resolve the economic dispatch issue. The core concept of the principle can be
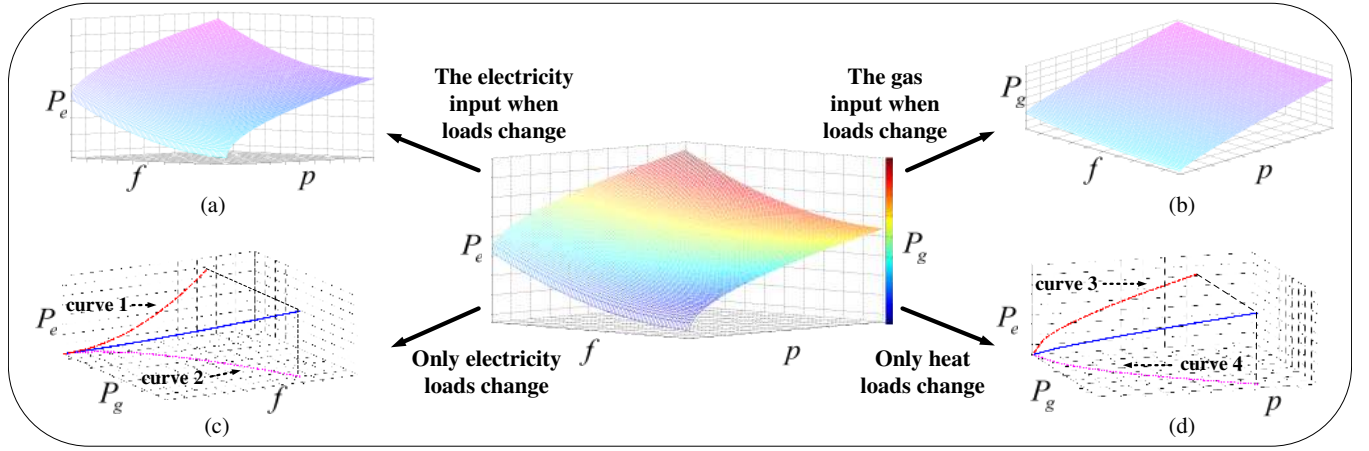
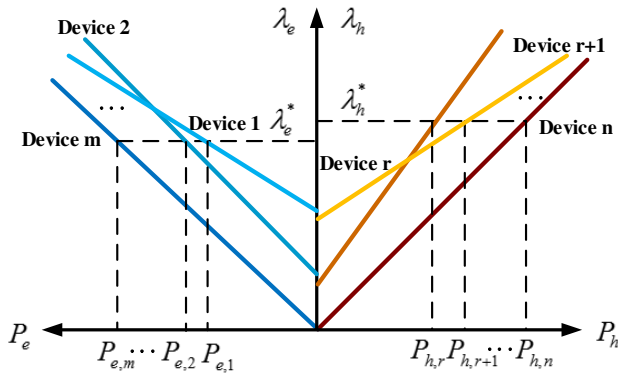Fig. 3. The diagram of energy hub dual control.



Fig. 4. The curve of energy hub devices control.

expressed as the power consumption is minimum when the cost incremental ratio of each device in power system is identical. In MCES, this principle can be improved to figure out the optimal operation issue of energy hub when the output is determined by the proposed scheme. Since there are various kinds of energies in MCES and some devices in hub are different from the devices in electric power system, the optimal operation problem of heat and electricity output should be solved respectively. The incremental ratio function of each device in the energy hub need to be built. The improved equal incremental consumption principle can be expressed as:

$$
\begin{cases}
\lambda_{b,r} = \lambda_b^*, & P_{b,r}^{\min} < P_{b,r} < P_{b,r}^{\max} \\
\lambda_{b,r} \le \lambda_b^*, & P_{b,r} = P_{b,r}^{\max} \\
\lambda_{b,r} \ge \lambda_b^*, & P_{b,r} = P_{b,r}^{\min}
\end{cases}, \quad (14)
$$

Commonly, energy hub model contains various kinds of converter devices and all these devices can be classified into two classes, namely, the device produced single energy (DSE) and the device produced multiple energy (DME). These costs will surely be different in different types of DSEs, but their patterns of variation might remain the same [42]. The fuel cost can usually be represented by second-order quadratic functions. The cost function and the incremental ratio of the DSE can be expressed as:

$$
P_u(L_u) = \alpha_u L_u^2 + \beta_u L_u + \gamma \quad (15)
$$

$$
\lambda_u = \frac{dP_u(L_u)}{dL_u}, \quad (16)
$$

The fuel consumption function of DMEs for electricity and heat generation is considered as:

$$
P_v(L_{e,v}, L_{h,v}) = \bar{a}_v L_{e,v}^2 + \bar{b}_v L_{e,v} + \bar{c}_v L_{h,v}^2 + \bar{d}_v L_{h,v} + \bar{e}, \quad (17)
$$

The incremental ratio of cost function of the DME can be expressed as:

$$
\lambda_{b,v} = \frac{\partial P_v(L_{e,v}, L_{h,v})}{\partial L_{b,v}}. \quad (18)
$$

The correlation between the outputs of the energy hub and the outputs of inner devices can be expressed as:

$$
L_b = \sum_{u=1}^{K} L_{b,u} + \sum_{v=1}^{\bar{K}} L_{b,v}, \quad (19)
$$

In addition, the corresponding output energy that inner devices can not produce is zero.

All incremental ratios of energy hub inner devices can be figured out by (16) and (18). Therefore, the outputs of inner devices are controlled based on the improved equal incremental consumption principle. Moreover, the input of each inner device is obtained based on (15) and (17). The input of energy hub can be calculated :

$$
P_{\tilde{b}} = \sum_{u=1}^{K} P_{\tilde{b},u} + \sum_{v=1}^{\bar{K}} P_{\tilde{b},v}, \quad (20)
$$

Similarly, the corresponding input energy that inner devices can not produce is zero.

The energy hub inner devices can be controlled by the method based on the equal increment principle of MCES as shown in (14)-(20). The curve of energy hub inner devices control is drawn like Fig. 4. Combining the control of outputs and the inner device control approach, the DCEH is obtained. Based on the DCEH, the energy network and the demand side are connected by energy hubs, and certain energy will be obtained from networks to satisfy loads by controlling energy hubs.

The DCEH is described by Fig. 3. The relationships between variables frequency, pressure, electricity input and gas input
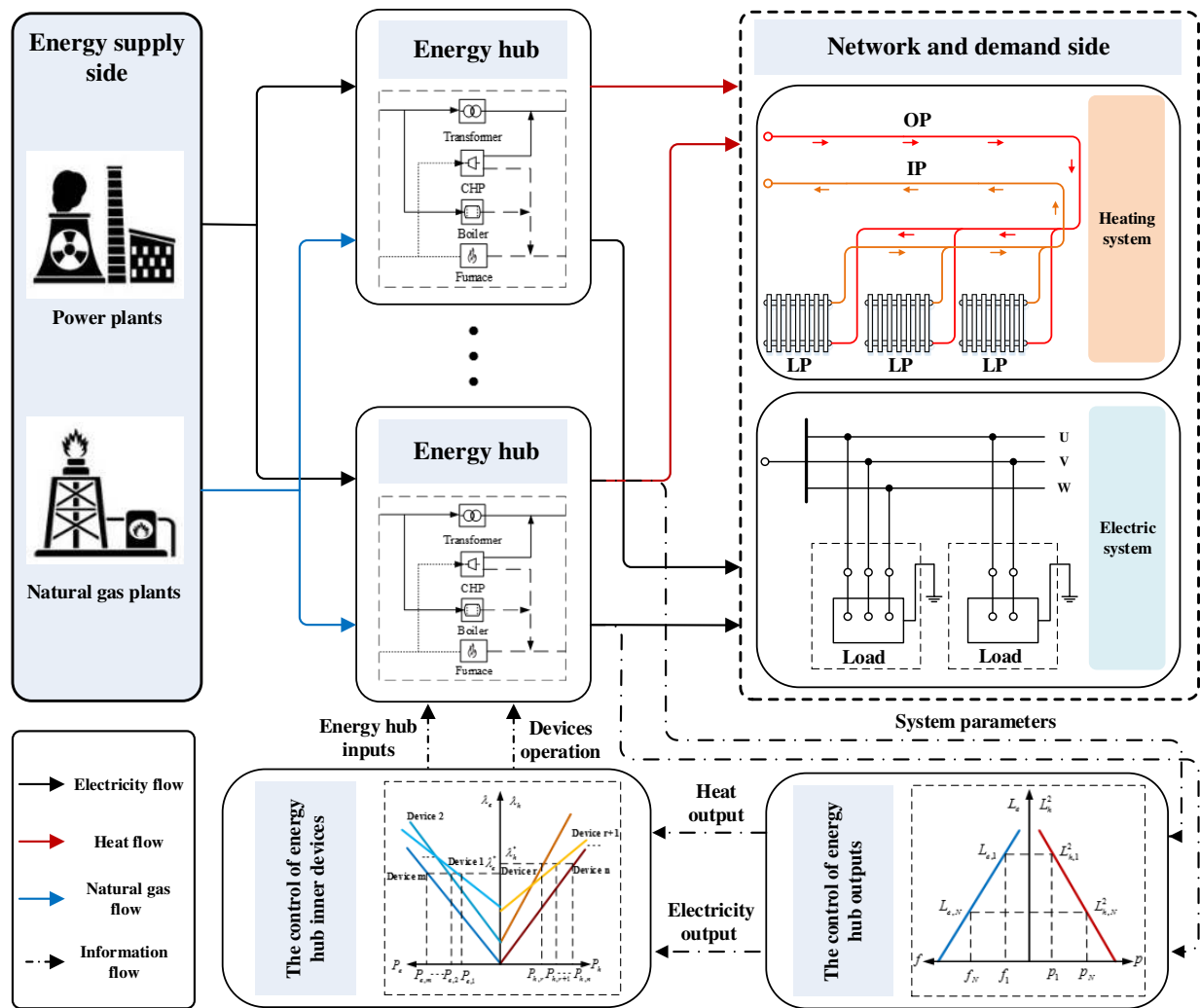
Fig. 5.  The operation process of energy hub which is controlled by the DCEH.

are presented in the middle chart of Fig. 3, and different colors stand for different values of the gas input in the chart. Each point of the middle chart represents a kind of working position for energy hub. Based on the chart, the inputs of hub can be known for certain system parameters. Figure (a), (b), (c) and (d) in Fig. 3 present the relationship between other variables when one variable does not change. As shown in this figure, the variations of the electricity input and the gas input are denoted by figure (a) and (b) respectively when system parameters change. Figure (c) and (d) represent the changing of inputs in the situation that only electricity loads and heat loads vary similarly. Due to the increase of $f$ and $p$, $P_e$ and $P_g$ are changed with a downtrend. From (a) and (b), it is easy to figure out that the variations of $P_e$ and $P_g$ share the identical trend since both inputs can be converted to all kinds of outputs. But changes of different inputs have different amplitudes since the efficiency of each inner device is diverse. The solid curve in (c) represents the relationship between $f$ and both inputs when only electricity loads change. Curve 1 and 2 are projections of the solid curve. The correlation between $f$ and $P_e$ is denoted by curve 1 and the correlation between $f$ and $P_g$ is stated by curve 2. Moreover, the plane where curve 1

is located actually represents the corresponding section of (a) that is perpendicular to $p$-axis and the one section of (b) which is perpendicular to $p$-axis is described by the plane where curve 2 is located. Similarly, the relationship between $p$ and both inputs when only thermal loads change is denoted by the solid curve in (d). Curve 3 and 4 stand for the correlation between $f$ and the corresponding input, respectively. And the planes where curve 3 and 4 are respectively located describe the sections of (a) and (b) that are perpendicular to $f$-axis.

Fig. 5 shows the whole operation process of energy hub which is controlled by the DCEH. The energy hub is controlled by the DCEH and the energies from energy supply side are given to the loads after the conversion of the energy hub. The DCEH proposed in this paper contains two parts: the control of energy hub outputs and the control of energy hub inner devices. The corresponding parameters of MCES like frequency and pressure will be varied based on the characteristic of the system when loads changed. By detecting the variations of the parameters, each energy hub can determine their outputs via utilizing the control of energy hub outputs. Then the operation of inner devices and the energies gotten from energy supply side can be decided by the control of energy hub inner devices.
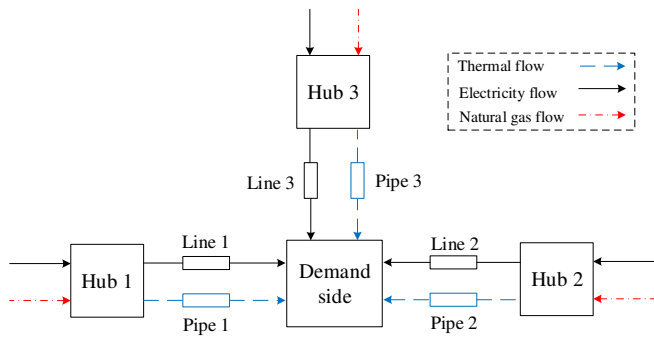
Fig. 6. Energy hubs supply energy to demand.

### TABLE I
### CHP FUEL FUNCTION COEFFICIENTS AND CAPACITIES

| Hub | $\bar{a}$ | $\bar{b}$ | $\bar{c}$ | $\bar{d}$ | $\bar{e}$ | capacity(e/h)(kW) |
|---|---|---|---|---|---|---|
| 1 | 0.00216 | 0.90625 | 0.00188 | 0.86250 | 16.56 | 320/520 |
| 2 | 0.00203 | 0.89513 | 0.00194 | 0.78138 | 20.24 | 160/260 |
| 3 | 0.00224 | 0.93452 | 0.00174 | 0.75463 | 18.72 | 80/130 |

## III. CASE STUDIES

The proposed model is designed in view of a real regional energy system in an industrial park in Changsha, China, and the model with three energy hubs is illustrated in Fig. 6. The structure of energy hubs is the same as Fig. 1. Each energy hub is connected to electricity and natural gas networks to satisfy the requirement of inner facilities. The energy forms of demand side are electricity and heat. Both heat and electric transmission lines exist resistance.

The capacities and fuel function coefficients of CHPs are shown in Table I. The fuel function coefficients and capacities of DSEs in energy hub such as transformers, furnaces are described in Table II. The units of the capacities show in all tables are kW. Similarly, the units of all parameters in Table III and TableIV are kW.

The specific heat capacity of water $c$ is equal to 4.2kJ/(kg · K) and the density of water $\rho$ is equal to $10^3$kg/m$^3$. The temperature difference between thermal loads inlet and outlet

### TABLE II
### EFFICIENCIES AND CAPACITY OF DEVICES

| Devices | $\alpha$ | $\beta$ | $\gamma$ | capacity(kW) |
|---|---|---|---|---|
| The transformer in hub1 | 0.00012 | 0.95123 | 30.12 | 2800 |
| The gas furnace in hub1 | 0.00031 | 0.87623 | 22.63 | 640 |
| The electric boiler in hub1 | 0.00029 | 0.89176 | 25.47 | 640 |
| The transformer in hub2 | 0.00014 | 0.93433 | 27.73 | 1400 |
| The gas furnace in hub2 | 0.00032 | 0.88385 | 23.57 | 320 |
| The electric boiler in hub2 | 0.00027 | 0.90046 | 27.24 | 320 |
| The transformer in hub3 | 0.00011 | 0.93858 | 24.78 | 700 |
| The gas furnace in hub3 | 0.00029 | 0.92945 | 31.44 | 160 |
| The electric boiler in hub3 | 0.00027 | 0.94577 | 20.64 | 160 |

### TABLE III
### OUTPUTS AND LOSSES OF HUBS BEFORE THE 360TH SECOND

| Hub | output(e) (kW) | output(h) (kW) | input(e) (kW) | input(g) (kW) | loss(e) (kW) | loss(g) (kW) |
|---|---|---|---|---|---|---|
| 1 | 1972 | 986 | 2704.74 | 708.12 | 390.32 | 64.54 |
| 2 | 981 | 495 | 1231.83 | 376.76 | 102.08 | 30.50 |
| 3 | 491 | 249 | 584.82 | 230.37 | 38.13 | 37.06 |

### TABLE IV
### OUTPUTS AND LOSSES OF HUBS AFTER THE 360TH SECOND

| Case/ Hub | output(e) (kW) | output(h) (kW) | input(e) (kW) | input(g) (kW) | loss(e) (kW) | loss(g) (kW) |
|---|---|---|---|---|---|---|
| 1/1 | 1579 | 782 | 2091.12 | 560.16 | 246.67 | 43.64 |
| 1/2 | 788 | 396 | 971.52 | 312.88 | 72.25 | 28.15 |
| 1/3 | 387 | 195 | 457.26 | 197.75 | 35.58 | 37.42 |
| 2/1 | 2533 | 1321 | 3674.11 | 961.34 | 667.95 | 113.62 |
| 2/2 | 1258 | 661 | 1636.51 | 484.43 | 163.95 | 38.02 |
| 2/3 | 633 | 329 | 766.09 | 279.01 | 45.70 | 37.39 |
| 3/1 | 2361 | 881 | 3178.65 | 675.12 | 545.98 | 65.83 |
| 3/2 | 1183 | 414 | 1420.35 | 352.09 | 142.39 | 32.95 |
| 3/3 | 589 | 210 | 664.67 | 215.22 | 43.26 | 37.63 |
| 4/1 | 1417 | 1267 | 2164.15 | 844.22 | 240.94 | 83.42 |
| 4/2 | 709 | 634 | 1011.21 | 428.1 | 65.83 | 30.49 |
| 4/3 | 359 | 318 | 488.53 | 259.86 | 34.58 | 36.81 |

$\Delta t$ is set as 10K. The distance between loads and energy hub 1, 2 and 3 are about 5.7km, 7.4km and 8.3km, respectively. The resistance magnitudes of pipe 1, 2 and 3 are 8.62Pa/$(m^3/h^2)^2$, 12.15Pa/$(m^3/h^2)^2$ and 13.62Pa/$(m^3/h^2)^2$ Impedance of line 1, 2 and 3 are equal to 0.175$\Omega$ + 0.2mH, 0.265$\Omega$ + 0.3mH and 0.315$\Omega$ + 0.3mH, respectively. The nominal inlet pressure of thermal loads is 1.132MPa and the nominal heat output powers are 1000kW, 500kW and 250kW, respectively. The nominal frequency is 50Hz and the nominal active powers of energy hub 1, 2 and 3 are 3000kW, 1500kW and 750kW, respectively.

Four cases are presented to illustrate the performance of the DCEH. The consequences of case studies are compared and analyzed based on outputs of energy hubs and elements in the same demand condition. Case1 and case 2 study the energy hubs performance when the thermal load and the electricity load both suddenly decrease or increase into new values. The situations that the loads of heat and electricity change in different tendencies are considered in case 3 and case 4.

These cases are discussed as follows and loads are the same for all cases before the 360th second. There are no electricity loads and thermal loads in the system at beginning, then 1700kW thermal loads and 3400 kW electricity loads are joined into the system. Each energy hub shares the same initial pressure and initial frequency. Table III represents the simulation result data of case 1 before the 360th second. Table IV shows the simulation result data of all cases after the 360th second.

### A. Case 1 and Case 2

In case 1 and case 2, the proposed DCEH is used when all kinds of loads decrease or increase simultaneously. Thermal loads decrease 350kW and electricity loads decrease 700kW in case 1 while thermal loads increase 600kW and electricity loads increase 1000kW in case 2.

Detailed Sankey diagram of case 1 when the MCES stops changing before the 360th second is shown in Fig. 7, in which the values display the energy flows from energy networks to demand side and each line stands for different energy flow. Moreover, the width of line represents the amount of energy. Fig. 7 provides a clear description for the proportion of energies which flow through each hub and each inner device. In Fig. 7, the energy flows with same color mean the flows
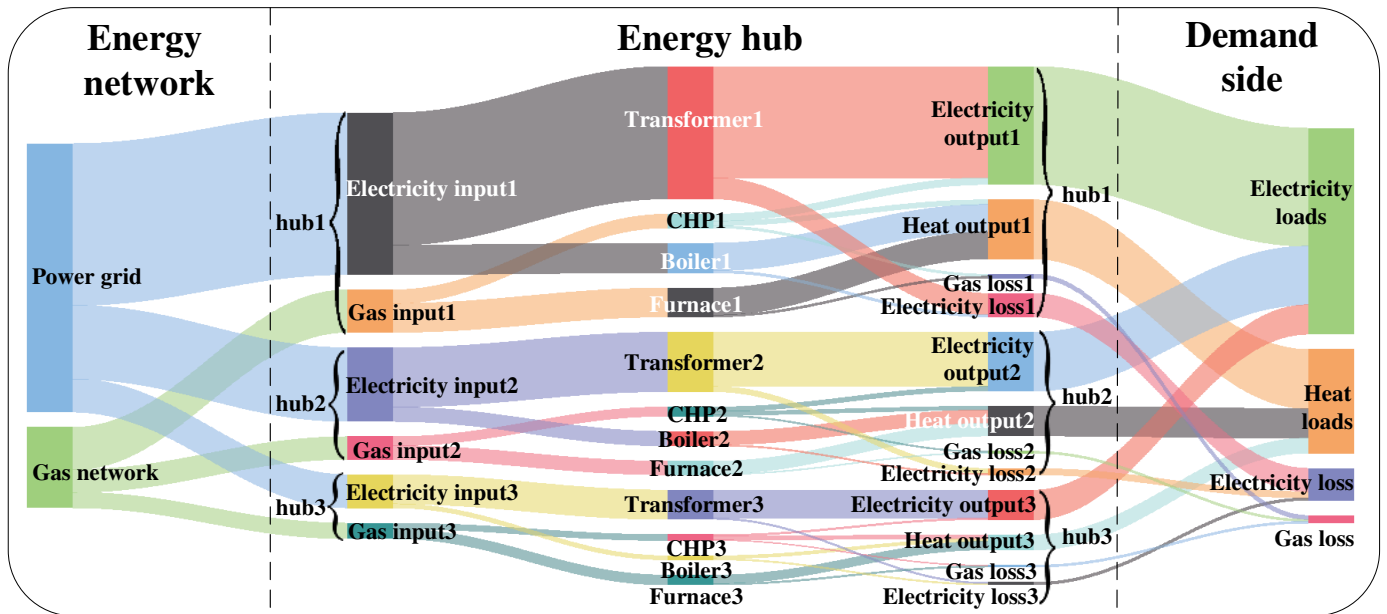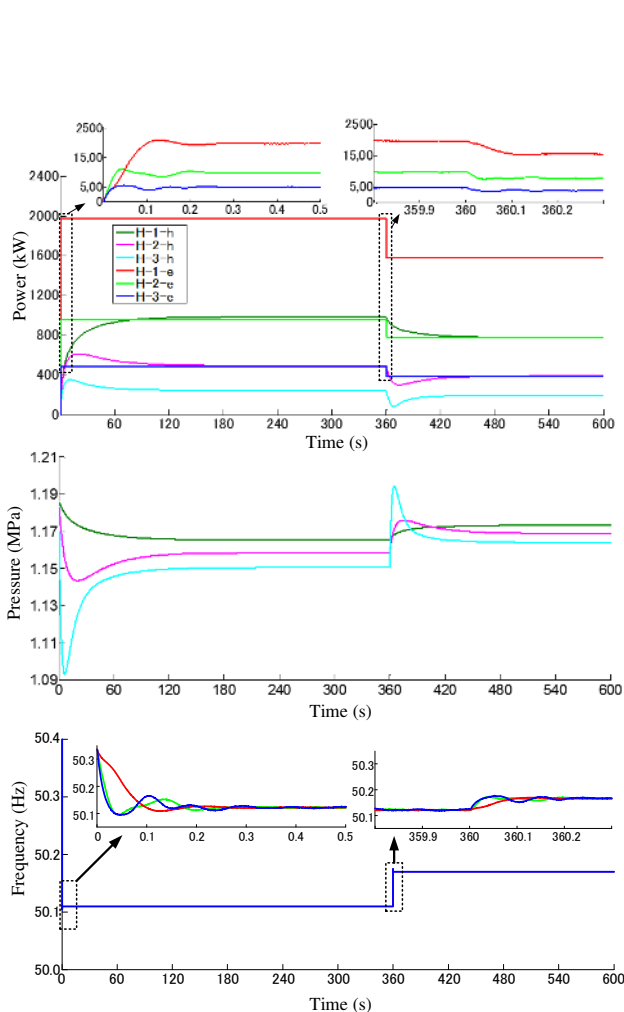
Fig. 7. Sankey diagram of case 1.



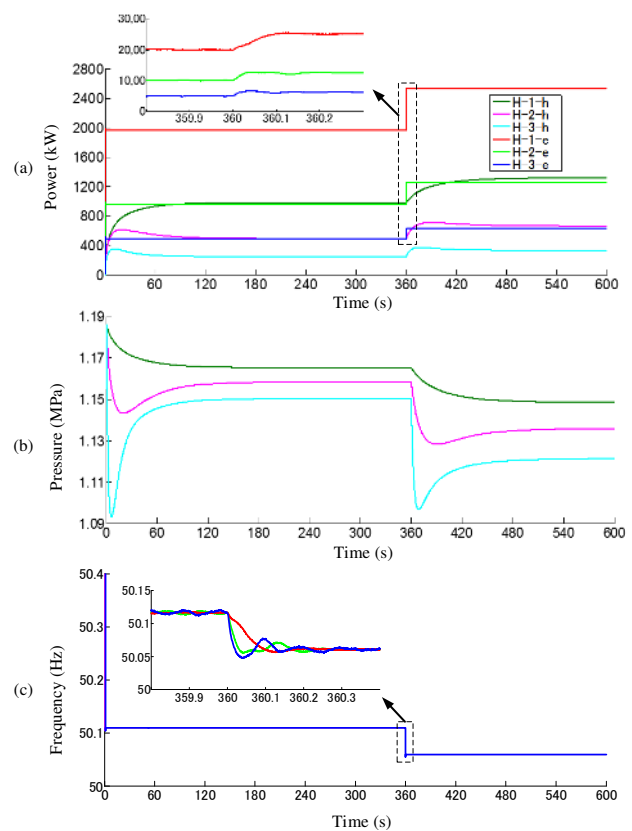Fig. 8. The simulation diagram of case 1.



Fig. 9. The simulation diagram of case 2.

come from the same device. From the Sankey diagram, the operation state of each hub and corresponding inner devices in case 1 can be noticed conveniently.

As shown in Fig. 8 (a) and Fig. 9 (a), the corresponding outputs of energy hubs are proportional allocated in every given case. The time that makes heat outputs stable is more than 100 seconds and electricity outputs only need about 0.1
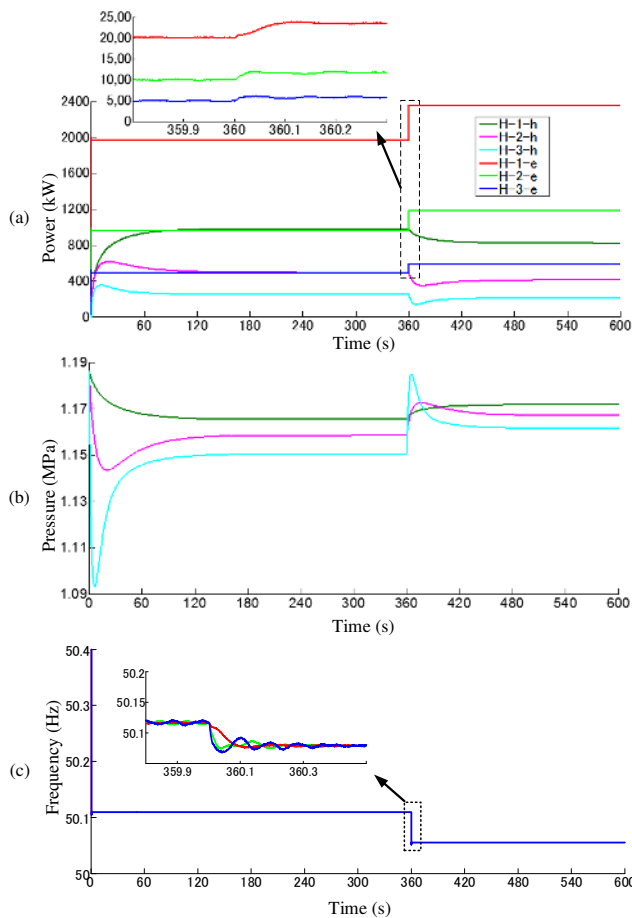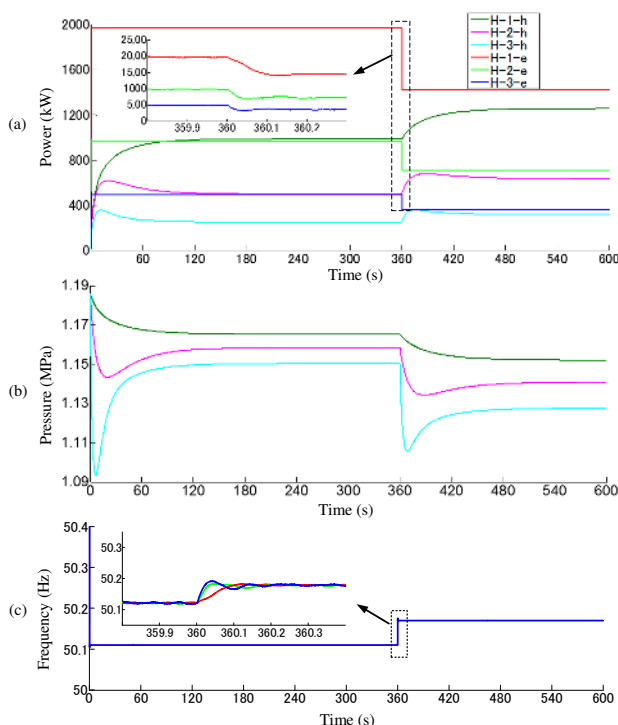
Fig. 10. The simulation diagram of case 3.



Fig. 11. The simulation diagram of case 4.

second to be stabilized. It shows that more time is required for heat supply network to reach steady state than power grid. Also, the time for case 1 to make outputs stable is less than the second one as the variations of loads in case 2 is higher. This consequence indicates that the extent of the loads change has clear influence on stabilizing the outputs.

The changes of thermal loads and electricity loads cause the changes of outlet pressure and frequency. The outlet pressures of hubs vary inversely with thermal loads as shown in Fig. 8 (b) and Fig. 9 (b). Similar results about frequency are developed from Fig. 8 (c) and Fig. 9 (c). These figures show the frequency is same when MCES steady state but the outlet pressure of each hub is not due to the different pipe resistance. It proves that the control of heat output eliminate the impact of the resistance successfully.

### B. Case 3 and Case 4

The effect of DCEH is considered under the situation in which the changing trends of electric and thermal loads are different. In case 3, thermal loads decrease 300kW and electricity loads increase 700kW while thermal loads increase 500kW and electricity loads decrease 1000kW in case 4.

The energy hub outputs are also distributed on the basis of corresponding capacity as shown in Fig. 10 (a) and Fig. 11 (a). Other diagrams in Fig. 10 and 11 show that variations of pressure and frequency are negatively correlated with the changing of hub outputs. Table IV shows that both gas loss and electricity loss increase with loads. Since the fuel cost of inner devices are denoted by second-order quadratic functions, more fuel is required to meet per unit load with the loads increasing. Correspondingly, the loss caused by per unit energy will increase as well.

As shown in the result of case studies, the DCEH can proportionally allocate each energy hub outputs no matter how loads change and it determines the inputs of each hub without communication.

### C. Case 5

Generally, most of energy hub researches only consider the economic efficiency of energy hub like reference [4] and [5]. The classical control method (CCM) in these reference does not proportionally allocate the outputs of energy hubs and can't realize the decentralized control. Because this paper proposes the DCEH considering security operation and economic efficiency. A comparative simulation of the DCEH with the CCM that used in [4] and [5] is represented in this case.

Since the parameters of the corresponding device in different hubs in case 1-4 are similar, devices in this state will not reflect the difference in comparison methods. Therefore, another state of hub1 has been chosen in case 5. The devices efficiencies in hub 1 are adjusted and the operational efficiency of hub 1 is different with other hubs. The pressure and frequency are also regulated to nominal value by additional methods for a clearer presentation of pressure and frequency changing. The devices efficiencies of hubs in this case are presented in TABLE V and VI. Other parameters in case 5 are same as the parameters in other case studies of paper.
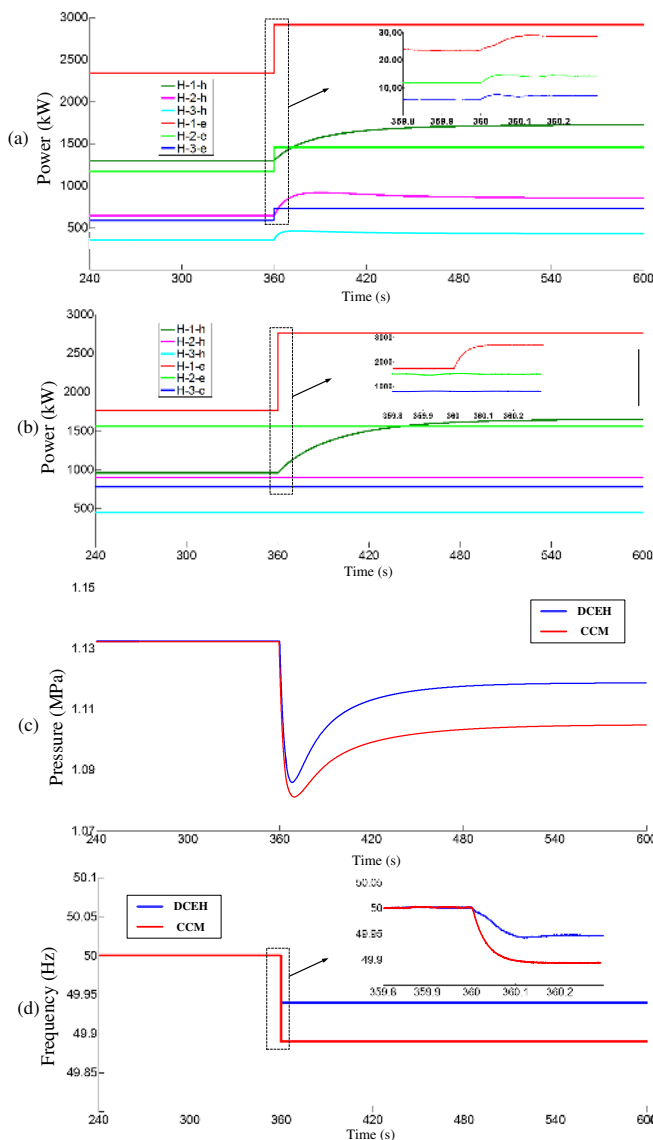
Fig. 12. The simulation diagram of case 5.

TABLE V
CHP FUEL FUNCTION COEFFICIENTS AND CAPACITIES

| Hub | $\bar{a}$ | $\bar{b}$ | $\bar{c}$ | $\bar{d}$ | $\bar{e}$ | capacity(e/h)(kW) |
|---|---|---|---|---|---|---|
| 1 | 0.00325 | 0.97734 | 0.00304 | 0.93254 | 20.57 | 320/520 |
| 2 | 0.00203 | 0.89513 | 0.00194 | 0.78138 | 20.24 | 160/260 |
| 3 | 0.00224 | 0.93452 | 0.00174 | 0.75463 | 18.72 | 80/130 |

TABLE VI
EFFICIENCIES AND CAPACITY OF DEVICES

| Devices | $\alpha$ | $\beta$ | $\gamma$ | capacity(kW) |
|---|---|---|---|---|
| The transformer in hub1 | 0.00064 | 0.99331 | 31.12 | 2800 |
| The gas furnace in hub1 | 0.00098 | 0.98731 | 24.63 | 640 |
| The electric boiler in hub1 | 0.00097 | 0.99625 | 28.57 | 640 |
| The transformer in hub2 | 0.00014 | 0.93433 | 27.73 | 1400 |
| The gas furnace in hub2 | 0.00032 | 0.88385 | 23.57 | 320 |
| The electric boiler in hub2 | 0.00027 | 0.90046 | 27.24 | 320 |
| The transformer in hub3 | 0.00011 | 0.93858 | 24.78 | 700 |
| The gas furnace in hub3 | 0.00029 | 0.92945 | 31.44 | 160 |
| The electric boiler in hub3 | 0.00027 | 0.94577 | 20.64 | 160 |

proposed DCEH realizes the proportional allocation of energy hub outputs without communication and has more benefits in security operation than the CCM. But some economic benefits are also sacrificed to ensure the security operation.

## IV. CONCLUSION

This paper proposed an DCEH which contains the control of outputs and inner devices. A general energy hub model has been formulated along with the MCES and multiple energy hubs meet loads together in the system. The deducing process of the control method of outputs has been proposed to demonstrate the relationship between system parameters and outputs of energy hub. The control of outputs makes energy hubs proportionally allocate their outputs alone and achieve the decentralized control of the MCES. Namely, the proposed method reduces the impact of communication and ensures the security operation of system. The control of inner devices that is based on the improved equal increment consumption principle has been presented to minimize the loss of the energy. The proposed method has been tested on a MCES with three energy hubs. Case studies have revealed that proposed method can proportionally allocate the thermal and electric outputs by the corresponding capacity of energy hubs and the results of case studies also showed the effect of control method for constituent elements.

The thermal loads change from 2300kW into 3000kW and the electricity loads change from 4100kW into 5100kW in this case.

As shown in Fig. 12 (a), the corresponding outputs of energy hubs are proportionally allocated by utilizing the DCEH no matter how loads and the parameters of devices changed. Since the efficiencies of devices in hub 1 are lower than corresponding devices in other hubs of this case, hub 2 and hub 3 are leaded in full load conditions respectively when the load demands are large by using the CCM as shown in Fig. 12 (b). Therefore, the changing loads can only be satisfied by hub 1. In Fig. 12 (c) and Fig. 12 (d), the fluctuations of frequency and pressure that used the DCEH are much lower than the fluctuations of frequency and pressure that utilized the CCM. Moreover, the system that control by the DCEH need less time to be stabilized. In this case, the electric and heat power cost of the system controlled by the DCEH are totally about 14559.54kW and the total cost of system controlled by the CCM is 13858.36kW. In this context, the

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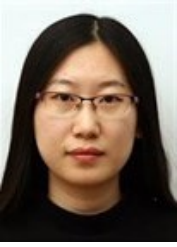
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