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Coordinated Control Strategy for Multi Micro Energy Systems Within Distribution Grid Considering Dynamic Characteristics and Contradictory Interests

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ABSTRACT As a typical form of integrated energy system, micro energy system (MES) is promoted and popularized at the terminal of distribution grid. To achieve the efficient and reliable energy utilization of MES, two main problems need to be solved: how to consider the dynamic characteristics of heterogeneous energy resources and diverse MES operating states under multiple time scales and how to coordinate the interests of both MES operator and distribution grid operator. This paper aims to establish the models of specific energy devices in MES and propose a coordinated control strategy for multi MESs within distribution grid considering dynamic characteristics and contradictory interests. The proposed strategy is presented from the MES side and distribution grid side with consideration of different control objectives under day-ahead dispatch, intra-day dispatch and emergency control circumstances. A case study based on IEEE 33-bus system with MESs connected is conducted to verify the effectiveness of the proposed strategy.

INDEX TERMS Micro energy system, optimal scheduling, emergency control, dynamic characteristics.

I. INTRODUCTION

To improve the energy utilization efficiency and fulfill the diverse consumer energy demands [1], the traditional power system is gradually developed into an integrated energy system (IES) [2], where electricity, gas and heat dispatch and control in a highly coupled and coordinated manner [3]. As a typical form of IES, micro energy system (MES) is a regional network where distributed energy resources are complemented and coordinated to make energy supply and demand balance [4]. The two main functions of MES include: 1) multi energies can be comprehensively utilized and allocated through effective scheduling and control method [5]; 2) the flexible power potential of MESs makes it possible to solve the power balance problem in the traditional distribution grid [6].

Many attempts have been made to cope with the MES modeling and optimal control. In regard of the modeling, diverse models of MES have been constructed to reflect the static or dynamic characteristics of energy devices and systems in terms of formulated problems including: 1) single coupling component modeling [7] and single energy system modeling [8]. These modeling methods apply to the discrete device or system, so it can’t reflect the multi-device linkage characteristics in multi-energy system. 2) multiple energy flow modeling [9] and simulation-based dynamic characteristics modeling. The former focuses on the analysis of energy flow distribution in multi-energy coupled networks. The latter utilizes the simulation tool to establish the coupled energy system and analyze the dynamic characteristics. They both place the emphasis on system characteristics analysis rather than system optimal operation. 3) energy hub modeling [10] and standardized matrix modeling [11]. These unified modeling methods are proposed to reflect the relationships between

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the energy inputs and outputs of multi-energy system using coefficient, however, the inner connection and dynamic characteristics are not within the scope of their research. Hence, how to construct a MES optimization model considering the inner linkage and dynamic characteristics of multi energy devices is of vital importance.

As for multi-energy complementary operation and coordinated control, many researches have been carried out on the operation evaluation index construction [12], multi-objective collaborative optimization [13] and safety control [14]. The present researches of MES tend to develop corresponding models and strategies according to control objectives and time scales, however, the overall dynamic process of MES operation and management didn't take enough thought of coordination under different circumstances. To characterize the dynamic regulation process of MES, two crucial points still need more attention: 1) coordinating the different regulation time constants of multi energies; 2) determining the main task of MES under normal circumstance and emergency circumstance. Therefore, how to establish a comprehensive multi-time-scale model adapting to different circumstances and objectives still stays paramount to be further studied.

MESs are connected to the power system at the terminal of distribution grid, so the coordination of MESs and distribution utility is also of vital significance. However, MES operator and distribution utility have contradictory interests, which means that the interests of MES operator and distribution utility conflict with each other in some circumstances [15]. For MES operators, they have the responsibility to manage all the energy devices inside and operate the micro energy system (MES) in an economic, efficient, reliable and eco-friendly manner. When MES operators stand on their own place, the power exchange between the MES and distribution gird is guided by the purchase/sell time-of-use (TOU) price. The objective of the MES operation is to minimize the overall operation cost. For distribution grid operators, they expect MES can operate economically and balance autonomously in normal but utilize flexible power potential to provide power grid ancillary services at emergency [16]. At emergency circumstance, the objective of MES operation transfers from the economic operation of MES to supporting the safe and stable operation of distribution grid. The power exchange is guided by the control signals delivered from the distribution grid rather than the electricity price. Thus, how to coordinate the interests of two contradictory subjects is one of the crucial problems to be solved.

On account of the aforementioned background, this paper proposes a coordinated control strategy for multi micro energy systems within distribution grid considering dynamic characteristics and contradictory interests. The main contributions are summarized as follows:

- To reflect the dynamic characteristics of MES operation under multiple time scales, a day-ahead scheduling optimization model with multi-objective constraints is first proposed, followed by a two-layer intra-day scheduling optimization to suppress the cooling and heat power fluctuation and electricity fluctuation sequentially on a double-axis time scale.

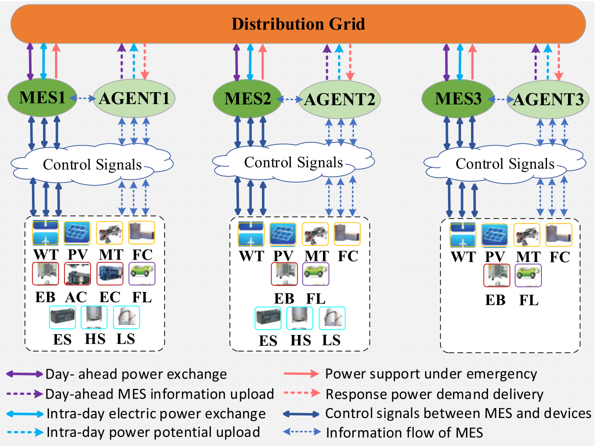


FIGURE 1. **Structure of MESs within distribution grid.**

- To coordinate interests of MES and distribution system, the MES scheduling optimization strategy is exerted in normal. When the distribution grid faces power shortage, the emergency control scheme is proposed to demonstrate the system-wide value of MES's flexible power potential.

The rest of the paper is organized as follows: Section II illustrates the framework of the paper; Section III constructs the specific model of energy production, conversion and storage devices; Section IV, Section V and Section VI explain coordinated control strategy of multi-MESs within distribution grid. The case studies and their corresponding results are illustrated in Section VII. Finally, the conclusions are drawn in Section VIII.

II. FRAMEWORK OF PROPOSED COORDINATED CONTROL STRATEGY

Three typical regulation modes of MESs participating in the power grid auxiliary service are elaborated as follows: 1) centralized control mode uploads all information to the distribution grid, which requires high computing and communicating performance [17]; 2) distributed control mode operates independently and autonomously through neighbor communication, but the authority of grid utility is undermined [18]; 3) The multi-agent control mode [19] employs MES agents to evaluate the overall flexible power potential and transfer the value to distribution grid for decision-making, which combines the merits of above two control modes and is suitable for MES control in this paper.

The multi-agent structure of multi MESs within distribution grid is illustrated in Fig.1, which is a deep coupled electricity, gas and heat system with power exchange and information interaction with the distribution system. There are some basic components constructing MES, including energy production devices (e.g. wind turbine (WT), photovoltaic (PV), micro turbine (MT) and fuel cell (FC)), energy conversion devices (e.g. electric boiler (EB), electric chiller (EC) and absorption chiller (AC)) and energy storage devices (e.g. electric storage (ES), heat storage (HS) and cooling storage (LS)).

Fig. 2 demonstrates the multi-time scale framework of the coordinated control strategy, which includes four different time scale processes: day-ahead schedule, intra-day cooling and heat schedule, intra-day electricity schedule and emergency control under power shortage. They are distinguished in terms of input data, control objectives and time scales and have been marked with different color blocks in Fig. 2.

There are mainly two MES operation circumstances according to different distribution grid operating states: 1) If the failure information of distribution grid isn't detected (normal condition), the MESs are assumed to be self-produced and autonomous. The scheduling optimization method of MES will be introduced to ensure the system operated in a multi-objective optimal state, which goes through day-ahead schedule and intra-day schedule stages. 2) If the failure information of distribution grid is detected (emergency condition), the emergency control is paramount to be conducted to guarantee the safe and stable operation of the system.

The more details of the four operation conditions under different time scales are explained as follows.

- **Day-ahead schedule (with purple blocks)**: At the day-ahead scheduling stage, if some basic data (predicted PV power, predicted WT power, predicted load and TOU price) are obtained, day-ahead optimization model can be established to determine the operating states of energy devices with the objective of minimizing the operation cost. Other multiple objectives can be achieved at the same time by constructing the constraints considering environmental benefits, energy consumption and energy supply reliability. The day-ahead optimization model is conducted at each hourly-level period ahead of day.
- **Intra-day schedule**: At the intra-day scheduling stage, the rolling correction will be processed to follow the wind, photovoltaic and load prediction errors through a two-layer dispatch for the regulation time differs between cooling and heat energy and electricity energy.

➢ **Intra-day cooling and heat schedule (with yellow blocks)**: The upper layer is applied to suppress the cold and heat dispatch error. The cooling and heat load data will be corrected and updated intra the day, so the output of controllable devices concerning the cooling and heat generation need to change with it. For the long regulation time constant of cooling and heat energy, the rolling correction will be controlled at span of 2h (marked with red rectangle on the upper axis) and interval of 1h (marked with black dots on the upper axis).

➢ **Intra-day electricity schedule (with blue blocks)**: The lower layer is employed to stabilize the electricity dispatch error. The error comes from two sources: 1) the intra-day correction of PV power, WT power and electric load; 2) the changed MT power in the upper layer. The electricity regulation time constant is short, so the rolling correction will be conducted at span of 1h (marked with red rectangle on the lower axis) and interval of 5min (marked with black dots on the lower axis).

- **Emergency control under power shortage (with pink blocks)**: When distribution grid faces power shortage failure, the adjustable power potential of controllable units in MESs is evaluated and interacted with the distribution system periodically before the power shortage failure falls down. When the power shortage failure occurs, the distribution grid allocates the response power of MESs proportionally to their flexible power potential according to the failure time and power shortage severity. Once the response power demand is delivered from the distribution to the MES, the MES performs the emergency control process according to the priority and adjustable capacity of the devices to compensate for power shortage.

III. MODELING OF BASIC DEVICES IN MES

A. MODELS OF ENERGY PRODUCTION DEVICES

The power output of renewable resources like PV and WT are obtained from the predicted data. The models of distributed gas generating units like MT and FC are constructed as followed.

The mathematical model of MT is described as follows:

$$Q_{MT}(t) = \frac{P_{MT}(t)(1 - \eta_{MT}(t) - \eta_L)}{\eta_{MT}(t)} \tag{1}$$

$$Q_{MTh}(t) = Q_{MT}(t).\eta_h.C_{OPh} \tag{2}$$

$$L_{MTh}(t) = Q_{MT}(t).\eta_l.C_{OPh} \tag{3}$$

$$V_{MT} = \sum_{t=1}^{N_T} \frac{P_{MT}(t)\Delta t}{\eta_{MT}(t).L} \tag{4}$$

where $Q_{MT}(t)$, $P_{MT}(t)$ and $\eta_{MT}(t)$ are exhaust heat amount, electric power, power efficiency of MT. $Q_{MTh}(t)$ and $L_{MTh}(t)$ are heat power and cooling power generated from exhaust heat respectively. η_L, η_h, η_l and C_{OPh} are the heat dissipation loss coefficient, heat generation and cooling coefficient of bromine cooler and recovery rate of flue gas respectively. N_T is the total scheduling time. L is 9.7 kW.h/m3, which means the low calorific value of natural gas. V_{MT} is the total amount of natural gas.

The fuel cost of MT is calculated as:

$$C_{MT} = C_{CH4}V_{MT} \tag{5}$$

where C_{MT} is the fuel cost of MT; C_{CH4} is the unit cost of natural gas, 2.5 yuan/m3 in this paper.

FC is a device that converts the chemical energy of fuel into electricity efficiently, the fuel cost of which is:

$$C_{FC} = C_{CH4} \sum_{t=1}^{NT} \frac{P_{FC}(t)\Delta t}{\eta_{FC}(t).L} \tag{6}$$

where C_{FC} is the fuel cost of FC; $P_{FC}(t)$ and $\eta_{FC}(t)$ represent power and power generation efficiency of FC at time period t respectively.

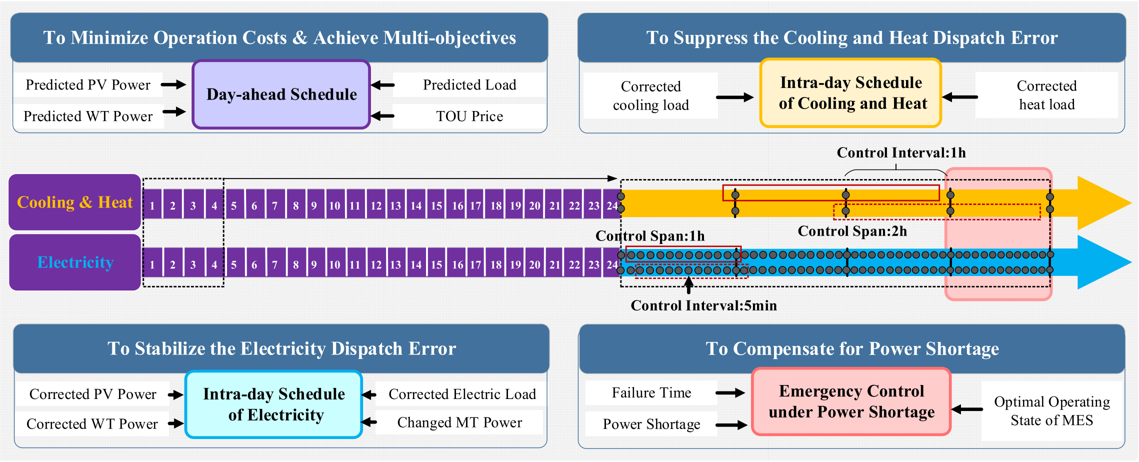


FIGURE 2. Multi-time scale framework of the coordinated control strategy for multi MESs within distribution grid.

B. MODELS OF ENERGY CONVERSION DEVICES

EB is a kind of typical electro-thermal conversion device, the mathematical model of which is expressed as follows:

$$Q_{EB}(t) = P_{EB}(t).\eta_{ah} \tag{7}$$

where $Q_{EB}(t)$ and $P_{EB}(t)$ represent the heat production and the electricity consumption of EB at time period t; η_{ah} is the electric-to-heat conversion efficiency of EB.

Two typical refrigeration devices in the combined cooling, heat and power system are AC and EC.

AC can make full use of the residual heat generated by FC and MT, the mathematical model of which is:

$$L_{AC}(t) = Q_{AC}(t).COP_{AC} \tag{8}$$

where $L_{AC}(t)$ represents output cold power of AC and $Q_{AC}(t)$ represents input heat power of AC. COP_{AC} is the refrigeration coefficient of AC.

The mathematical model of EC is described as follows:

$$L_{EC}(t) = P_{EC}(t).COP_{EC} \tag{9}$$

where $L_{EC}(t)$ is the cold output of EC; $P_{EC}(t)$ is input power of EC; COP_{EC} is the refrigeration coefficient of EC.

C. MODELS OF ENERGY STORAGE DEVICES

Storage system achieves the decoupling of energy production and consumption over the time horizon, which contributes to alleviate the mismatch between peak and valley periods. In this paper, three storage models (ES, HS and LS) are established to make the joint dispatch and unified management of multi energies in MES.

The remaining electricity of the battery at period t is related to the remaining electricity at period $t-1$, the charging and discharging power and efficiency of the battery during unit dispatching time Δt. Therefore, it is necessary to establish a dynamic model of the battery, as shown in (10):

$$E_{ES}(t)=(1-\zeta)E_{ES}(t-1)+[P_{ESch}(t)\eta_{ESch}-\frac{P_{ESdis}(t)}{\eta_{ESdis}}]\Delta t \tag{10}$$

where $E_{ES}(t)$ is the capacity of ES at time t; ζ denotes self-discharge rate of ES; $P_{ESch}(t)$ and $P_{ESdis}(t)$ are charging and discharging power of ES at time t; η_{ESch} and η_{ESdis} are charging and discharging efficiency of ES respectively.

The dynamic performance of heat tank is related to the device capacity, the efficiency of heat absorption and release, and the rate of heat loss. Its mathematical model is:

$$H_{HS}(t)=(1-\psi)H_{HS}(t-1)+[Q_{HSch}(t)\eta_{HSch}-\frac{Q_{HSdis}(t)}{\eta_{HSdis}}]\Delta t \tag{11}$$

where $H_{HS}(t)$ is the capacity of HS at time t; ψ is the heat loss rate of HS; $Q_{HSch}(t)$ and $Q_{HSdis}(t)$ are the heat absorption and release power at time t; η_{HSch} and η_{HSdis} are the heat absorption and release efficiency of HS respectively.

The mathematical model of cooling tank is expressed as:

$$L_{LS}(t) = (1-\sigma)L_{LS}(t-1) + [L_{ECc}(t)\eta_{lch} - \frac{L_{ECd}(t)}{\eta_{ldis}}]\Delta t \tag{12}$$

where $L_{LS}(t)$ is the capacity of LS; σ is the cold loss rate of LS; $L_{ECc}(t)$ and $L_{ECd}(t)$ are the ice storage and ice melting power at time t; η_{lch} and η_{ldis} are the ice storage coefficient and ice melting coefficient of LS.

IV. MULTI-OBJECTIVE DAY-AHEAD SCHEDULING OPTIMIZATION MODEL

This section expresses the day-ahead scheduling optimization model which aims to minimize the operation costs and achieve multiple objectives.

A. EVALUATION INDEX

Energy consumption evaluation index is calculated as:

$$F_{fuel}(t) = \frac{P_{MT}(t)\Delta t}{\eta_{MT}(t).L} + \frac{P_{FC}(t)\Delta t}{\eta_{FC}(t).L} \tag{13}$$

where $F_{fuel}(t)$ denotes the total consumption of fuel.

Environment protection evaluation index is calculated as:

$$E_{CO_2}(t) = \lambda_{CO_2}F_{fuel}(t) \tag{14}$$

where λ_{CO_2} represents the CO_2 emission factor of natural gas. $E_{CO_2}(t)$ is the emission amount of CO_2 at time t.

Loss of power supply probability is calculated as follows:

$$\begin{aligned} P_e^{loss}(t) = {} & P_l(t) - (P_{MT}(t) + P_{FC}(t) + P_{WT}(t) + P_{PV}(t) \\ & + P_{ex}(t) - P_{ESch}(t) + P_{ESdis}(t) - P_{EB}(t)) \end{aligned} \tag{15}$$

$$LPSP = \frac{\sum_{t=1}^{N_T} \max(0, P_e^{loss}(t))}{\sum_{t=1}^{N_T} P_l(t)} \tag{16}$$

where $P_{WT}(t)$ and $P_{PV}(t)$ are wind power and photovoltaic power at time t. $P_{ex}(t)$ is grid exchange power at time t. $P_l(t)$ represents the power of electric load at time t. $P_e^{loss}(t)$ denotes the total amount of electric power loss. *LPSP* means the loss of power supply probability.

Loss of heat supply probability is calculated as follows:

$$\begin{aligned} Q_h^{loss}(t) = {} & Q_l(t) - (Q_{MTh}(t) + Q_{EB}(t) \\ & - Q_{HSch}(t) + Q_{HSdis}(t) - Q_{AC}(t)) \end{aligned} \tag{17}$$

$$LHSP = \frac{\sum_{t=1}^{N_T} \max(0, Q_h^{loss}(t))}{\sum_{t=1}^{N_T} Q_l(t)} \tag{18}$$

where $Q_l(t)$ is the heat load power at time t; $Q_h^{loss}(t)$ is the total amount of heat load loss; *LHSP* is the loss of heat supply probability.

Loss of cooling supply probability is calculated as follows:

$$L_c^{loss}(t) = L_l(t) - (L_{MTh}(t) + L_{AC}(t) + L_{ECa}(t) + L_{ECd}(t)) \tag{19}$$

$$LCSP = \frac{\sum_{t=1}^{N_T} \max(0, L_c^{loss}(t))}{\sum_{t=1}^{N_T} L_l(t)} \tag{20}$$

where $L_{ECa}(t)$ is the cooling power output of electric chiller at time t. $L_l(t)$ is the power of cooling load at time t. *LCSP* is the loss of cooling supply probability.

B. OBJECTIVE FUNCTION

The objective function of MES's day-ahead scheduling is:

$$\begin{aligned} \min F_{IES} = {} & \sum_{t=1}^{N_T} [C_{fuel} F_{fuel}(t) + C_{CO_2} E_{CO_2}(t) + C_{grid} P_{ex}(t) \\ & + C_{heat} Q_l(t) + C_{cold} L_l(t) + \sum_{i=1}^{n} C_{device,i} . P_i(t) \\ & + \sum_{j=1}^{ng} C_{ST,j} . \max\{0, S_j(t) - S_j(t-1)\}] \Delta t \end{aligned} \tag{21}$$

where C_{fuel}, C_{CO_2}, C_{grid}, C_{heat}, C_{cold}, $C_{device,i}$ and $C_{ST,j}$ are the unit fuel cost, unit carbon treatment cost, unit grid exchange power cost, unit heat selling cost, unit cooling selling cost, device i's maintenance cost and controllable unit j's restart-up cost respectively; $P_i(t)$ is the output power of device i at time t. $S_j(t)$ denotes the start-up/shut-down state of controllable unit j at time t. ng is the number of controllable units.

C. CONSTRAINTS

The capacity constraint of controllable unit is expressed as:

$$S_j^{CG}(t).P_{j,\min}^{CG} \le P_j^{CG}(t) \le S_j^{CG}(t).P_{j,\max}^{CG} \tag{22}$$

where $S_j^{CG}(t)$ and $P_j^{CG}(t)$ are the operational state and the power of controllable unit j at time t; $P_{j,\min}^{CG}$ and $P_{j,\max}^{CG}$ are the lower and upper limits of controllable unit j.

The ramping constraint of controllable unit is expressed as:

$$-R_j^{down} \Delta t \le P_j^{CG}(t) - P_j^{CG}(t-1) \le R_j^{up} \Delta t \tag{23}$$

where R_j^{down} and R_j^{up} are ramp-down/ramp-up limits of controllable unit j.

The related constraints of battery are shown as follows:

$$\begin{cases} -\gamma_{ESdis}.C_{apES} \le -P_{ESch}(t) + P_{ESdis}(t) \le \gamma_{ESch}.C_{apES} \\ 0 \le P_{ESch}(t) \le \gamma_{ESch}.C_{apES} \\ 0 \le P_{ESdis}(t) \le 2 \times \gamma_{ESch} \times C_{apES} \\ k_{\min}^{SOC}.C_{apES} \le E_{ES}(t) \le k_{\max}^{SOC}.C_{apES} \\ E_{ES}(1) = E_{ES}(NT \times \Delta T) \end{cases} \tag{24}$$

where γ_{ESch} and γ_{ESdis} are maximum charge and discharge ratio of battery; C_{apES} is the total capacity of battery; $k_{\max}^{SOC}$ and $k_{\min}^{SOC}$ are the maximum and minimum state of charge coefficient of the battery.

The related constraints of heat tank are shown as follows:

$$\begin{cases} -\gamma_{HSdis}.C_{apHS} \le -Q_{HSch}(t) + Q_{HSdis}(t) \le \gamma_{HSch}.C_{apHS} \\ 0 \le Q_{HSch}(t) \le \gamma_{HSch}.C_{apHS} \\ 0 \le Q_{HSdis}(t) \le 2 \times \gamma_{HSch} \times C_{apHS} \\ k_{\min}^{SOHC}.C_{apHS} \le H_{HS}(t) \le k_{\max}^{SOHC}.C_{apHS} \\ H_{HS}(1) = H_{HS}(NT \times \Delta T) \end{cases} \tag{25}$$

where γ_{HSch} and γ_{HSdis} are maximum heat absorption and release ratio of heat tank; C_{apHS} is the total capacity of heat tank; $k_{\max}^{SOHC}$ and $k_{\min}^{SOHC}$ are the maximum and minimum state of heat coefficient of the heat tank.

The related constraints of cooling tank are shown as follows:

$$\begin{cases} -S_{ECa}(t).L_{ECa}^{\min} \le L_{ECa}(t) \le S_{ECa}(t).L_{ECa}^{\max} \\ 0 \le L_{ECc}(t) \le S_{ECc}(t).L_{ECc}^{\max} \\ L_{ECa}^{\min} \le L_{ECa}(t) + L_{ECc}(t) \le L_{ECa}^{\max} \\ 0 \le L_{ECd}(t) \le S_{ECd}(t).L_{ECd}^{\max} \end{cases} \tag{26}$$

where $S_{ECa}(t)$, $S_{ECc}(t)$ and $S_{ECd}(t)$ are the on/off state of electric chiller in terms of cooling production, ice storage and ice melting; $L_{ECa}^{\min}$, $L_{ECa}^{\max}$, $L_{ECc}^{\max}$ and $L_{ECd}^{\max}$ are minimum capacity of cooling, maximum capacity of cooling, maximum capacity of ice storage and maximum capacity of ice melting respectively.

The grid exchange power constraint of tie line is expressed as:

$$P_{ex,\min} \le P_{ex}(t) \le P_{ex,\max} \tag{27}$$

where $P_{ex,\min}$ and $P_{ex,\max}$ are lower and upper limits of grid exchange power of tie line.

The constraint of carbon emission is expressed as follows:

$$\sum_{t=1}^{N_T} E_{CO_2}(t) \le \psi_{CO_2} \tag{28}$$

where ψ_{CO_2} is the upper limit of carbon dioxide emission.

The constraint of energy supply reliability is expressed as:

$$LESP \le \varphi_q \tag{29}$$

where φ_q is equal to φ_e, φ_h and φ_c when $LESP$ represents $LPSP$, $LHSP$ and $LCSP$ respectively.

V. TWO-LAYER INTRA-DAY SCHEDULING OPTIMIZATION MODEL

The intra-day scheduling optimization model is adopted in this section to suppress the cooling and heat dispatch error and electricity dispatch error sequentially according to the different regulation time constants.

A. INTRA-DAY SCHEDULING OF COOLING AND HEAT

The upper layer of the established MES intra-day scheduling optimization model aims to suppress the cooling and heat power fluctuations by regulating the controllable units concerning the cooling and heat supply, such as MT, EB, EC and AC. The intra-day scheduling domain of cooling and heat is 2h while the control time window is 1h.

1) OBJECTIVE FUNCTION

The upper objective function of MES's intra-day scheduling in terms of cooling and heat can be expressed as follows:

$$\begin{aligned}\min F_{IES1} = {} & C_{CH_4}\sum_{t=1}^{NT}\frac{(P_{MT}(t)+\Delta P_{MT}(t))\Delta t}{\eta_{MT}(t).L}\\ & +[\omega_{MT}(\Delta P_{MT}(t))^2+\omega_{EB}(\Delta P_{EB}(t))^2\\ & +\omega_{EC}(\Delta P_{EC}(t))^2+\omega_{AC}(\Delta Q_{AC}(t))^2]\Delta t\end{aligned} \tag{30}$$

where $\Delta P_{MT}(t)$, $\Delta P_{EB}(t)$, $\Delta P_{EC}(t)$ and $\Delta Q_{AC}(t)$ represent the power regulation amount of MT, EB, EC and AC respectively. ω_{MT}, ω_{EB}, ω_{EC} and ω_{AC} are unit punishment cost of MT, EB, EC and AC respectively.

2) CONSTRAINTS

The constraint of modified heat power balance is:

$$\bar{Q}_{MTh}(t)+\bar{Q}_{EB}(t)-Q_{HSch}(t)+Q_{HSdis}(t)=Q_l(t)+\bar{Q}_{AC}(t) \tag{31}$$

where $\bar{Q}_{MTh}(t)$ denotes the modified heat power generated from exhaust heat at time t; $\bar{Q}_{EB}(t)$ is the modified heat power of electrical boiler at time t; $\bar{Q}_{AC}(t)$ is the modified heat input of absorption chiller at time t.

The constraint of modified cooling power balance is:

$$\bar{L}_{MTh}(t)+\bar{L}_{AC}(t)+\bar{L}_{ECa}(t)+L_{ECd}(t)=Ll(t) \tag{32}$$

where $\bar{L}_{MTh}(t)$ denotes the modified cooling power generated from exhaust heat at time t; $\bar{L}_{AC}(t)$ is the modified cooling power of absorption chiller at time t; $\bar{L}_{ECa}(t)$ is the modified cooling power output of electric chiller at time t.

The constraint of MT's power regulation amount is:

$$-0.05\times P_{MT,\max} \le \Delta P_{MT}(t) \le 0.05\times P_{MT,\max} \tag{33}$$

where $P_{MT,\max}$ represents the maximum MT power output.

B. INTRA-DAY SCHEDULING OF ELECTRICITY

The lower layer of the established MES intra-day scheduling optimization model aims to adjust the electricity-relevant units like FC, EX and ES to maintain the balance between generation and load according to the wind, photovoltaic and load prediction errors together with the output power change of MT in the upper layer. The intra-day scheduling domain of electricity is 1h while the control time window is 5min.

1) OBJECTIVE FUNCTION

The lower objective function of MES's intra-day scheduling in terms of electricity can be expressed as follows:

$$\begin{aligned}\min F_{IES2} = {} & C_{CH_4}\sum_{t=1}^{NT}\frac{(P_{FC}(t)+\Delta P_{FC}(t))\Delta t}{\eta_{FC}(t).L}\\ & +\frac{SD(t)+GD(t)}{2}(P_{ex}(t)+\Delta P_{ex}(t))\\ & +\frac{GD(t)-SD(t)}{2}\left|P_{ex}(t)+\Delta P_{ex}(t)\right|\\ & +[\omega_{FC}(\Delta P_{FC}(t))^2+\omega_{ex}(\Delta P_{ex}(t))^2\\ & +\omega_{ESch}(\Delta P_{ESch}(t))^2+\omega_{ESdis}(\Delta P_{ESdis}(t))^2]\Delta t\end{aligned} \tag{34}$$

where $\Delta P_{FC}(t)$, $\Delta P_{ex}(t)$, $\Delta P_{ESch}(t)$ and $\Delta P_{ESdis}(t)$ represent the power regulation amount of fuel cell, grid exchange power regulation amount, battery charge and discharge power regulation amount with the unit punishment cost of ω_{FC}, ω_{ex}, ω_{ESch} and ω_{ESdis} respectively.

2) CONSTRAINTS

The constraint of modified electricity power balance is:

$$\begin{aligned}\bar{P}_{MT}(t)+\dot{P}_{FC}(t)+\hat{P}_{WT}(t)+\hat{P}_{PV}(t)\\ -\dot{P}_{ESch}(t)+\dot{P}_{ESdis}(t)+\dot{P}_{ex}(t)\\ =P_l(t)+\bar{P}_{EB}(t)+\bar{P}_{EC}(t)\end{aligned} \tag{35}$$

where $\hat{P}_{WT}(t)$ and $\hat{P}_{PV}(t)$ are modified power of wind turbine and photovoltaic at time t intra daytime; $\dot{P}_{FC}(t)$, $\dot{P}_{ex}(t)$, $\dot{P}_{ESch}(t)$ and $\dot{P}_{ESdis}(t)$ represent the modified power of fuel cell, the modified grid exchange power and the modified battery charge and discharge power at time t.

The constraint of FC's power regulation amount is:

$$S_{FC}(t) \times P_{FC,\min} \leq P_{FC}(t) + \Delta P_{FC}(t) \leq S_{FC}(t) \times P_{FC,\max} \tag{36}$$

where $P_{FC,\min}$ and $P_{FC,\max}$ are the minimum and maximum power output of FC.

The constraint of grid exchange power regulation amount is:

$$-0.05 \times P_{ex,\max} \leq \Delta P_{ex}(t) \leq 0.05 \times P_{ex,\max} \tag{37}$$

where $P_{ex,\max}$ is the maximum grid exchange power.

The constraints of battery's power regulation amount are:

$$\begin{aligned} -0.05 \times C_{apES} &<= \eta_{ESch} \times \Delta P_{ESch} - \Delta P_{ESdis}/\eta_{ESdis} \\ \eta_{ESch} \times \Delta P_{ESch} &- \Delta P_{ESdis}/\eta_{ESdis} \\ &<= 0.05^{*} C_{apES} \\ 0 &<= P_{ESch} + \Delta P_{ESch} <= y_{ES,C}{}^{*} C_{apES} \\ 0 &<= P_{ESdis} + \Delta P_{ESdis} <= 2^{*} y_{ES,C} * C_{apES} \end{aligned} \tag{38}$$

VI. EMERGENCY CONTROL STRATEGY

This section elaborates the proposed emergency control strategy for power shortage compensation from evaluating the adjustable power potential, distributing the response power demand to determining the priority and capacity of controllable devices.

A. UPLOADING ADJUSTABLE POWER POTENTIAL

Once the optimal operating state of the MES is determined, the adjustable power potential of each MES can be evaluated considering the regulation capacity and rate of storage system, controllable units and flexible load. And then the adjustable power potential information of MESs is uploaded to the distribution grid to prepare for the emergency conditions. The adjustable power potential considering the regulation capacity and rate can be evaluated as follows:

$$P_{CD_j,i}^{potential}(t_f) = \left| P_{CD_j,i}^{\lim} - P_{CD_j,i}(t_f) \right| \tag{39}$$

$$P_{MES,i}^{potential}(t_f) = \sum_{j=1}^{4} P_{CD_j,i}^{potential}(t_f) + P_{FL,i}^{potential}(t_f) \tag{40}$$

$$t_k = t_f + (k-1) \cdot dt \quad dt = 1/12, \quad k = 1, 2, \cdots, 12 \tag{41}$$

$$\bar{P}_{CD_j,i}^{potential}(t_k) = \min([P_{CD_j,i}^{potential}(t_f), (k-1) \cdot dt \cdot R_{CD_j,i}^{f,\lim}]) \tag{42}$$

$$\bar{P}_{MES,i}^{potential}(t_k) = \sum_{j=1}^{4} \bar{P}_{CD_j,i}^{potential}(t_k) + \bar{P}_{FL,i}^{potential}(t_k) \tag{43}$$

where t_f is the time scale of the daily scheduling with interval of 1h and span of 24h; $P_{CD_j,i}^{potential}(t_f)$ and $P_{FL,i}^{potential}(t_f)$ are the adjustable power potential of the jth controllable device (MT, FC, EB, ES) and flexible load (FL) in the ith MES at time t_f; $P_{CD_j,i}^{\lim}$ is the upper/lower capacity limits of the jth controllable device in the ith MES; $P_{MES,i}^{potential}(t_f)$ is the total adjustable power potential of the ith MES at t_f considering the regulation capacity; t_k is the time scale of the emergency control with control interval of 5min and span of 1h; $\bar{P}_{CD_j,i}^{potential}(t_k)$ and $\bar{P}_{FL,i}^{potential}(t_k)$ are the adjustable power potential of the jth controllable device and flexible load in the ith MES at time t_k; $R_{CD_j,i}^{f,\lim}$ is emergency ramp-down/ramp-up limits of the jth controllable device in the ith MES; $\bar{P}_{MES,i}^{potential}(t_k)$ is the total adjustable power potential of the ith MES at time t_k considering the regulation rate.

B. DELIVERING RESPONSE POWER DEMAND

When power shortage occurs to the distribution grid, the distribution grid operator will make full use of the adjustable capacity uploaded in advance to calculate the actual response power required from each MES considering its flexibility and adjustable capacity according to the failure time and power shortage. The response power demand delivered from distribution grid to MES can be calculated as:

$$\Delta P_{MES,i}^{response}(t_k) = \frac{P_{MES,i}^{potential}(t_k)}{\sum\limits_{i=1}^{m} P_{MES,i}^{potential}(t_k)} . \Delta P(t_k) \tag{44}$$

where $\Delta P(t_k)$ is the power shortage at time t_k; m is the number of MES; $\Delta P_{MES,i}^{response}(t_k)$ is the response power demand delivered to the ith MES at time t_k.

C. PRIORITY AND CAPACITY OF RESPONSE DEVICE

When the system is at emergency circumstance when facing power shortage problem, the potential of controllable units in MESs can be utilized to make a compensation. The emergency control scheme considering the priority and capacity of response device is illustrated in Fig. 3, which mainly contains the following steps.

STEP 1: Sort the responsive controllable units (MT, FC and EB) participating in the emergency control in descend order according to regulation ability index, the calculation method of which is presented in (45):

$$\chi_i^{CG_j} = \frac{\alpha \cdot P_{CG_j,i}^{potential}(t_k)}{\max(P_{CG_j,i}^{potential}(t_k))} + \frac{\beta \cdot R_{CG_j,i}^{up/down}(t_k)}{\max(R_{CG_j,i}^{up/down}(t_k))} \tag{45}$$

where $\chi_i^{CG_j}$ is the regulation ability index of the jth controllable unit in ith MES; $P_{CG_j,i}^{potential}(t_k)$ is the regulation capacity of the jth controllable unit in ith MES at time t_k; $R_{CG_j,i}^{up/down}(t_k)$ is the ramping rate of the jth controllable unit in ith MES; α and β are the regulation capacity and regulation rate evaluation index respectively.

STEP 2: take no measure at initial moment when $\Delta P_{MES,i}^{response}(t_k) = 0$, $t_k = t_f + (k-1) \cdot dt$, $dt = 1/12$, $k = 1$.

STEP 3: if $k < 12$, $k = k + 1$, $t_k = t_f + (k-1) \cdot dt$, the response power delivered from the distribution system to the ith MES is $\Delta P_{MES,i}^{response}(t_k)$ and turn to STEP 4. Otherwise, turn to STEP 7.

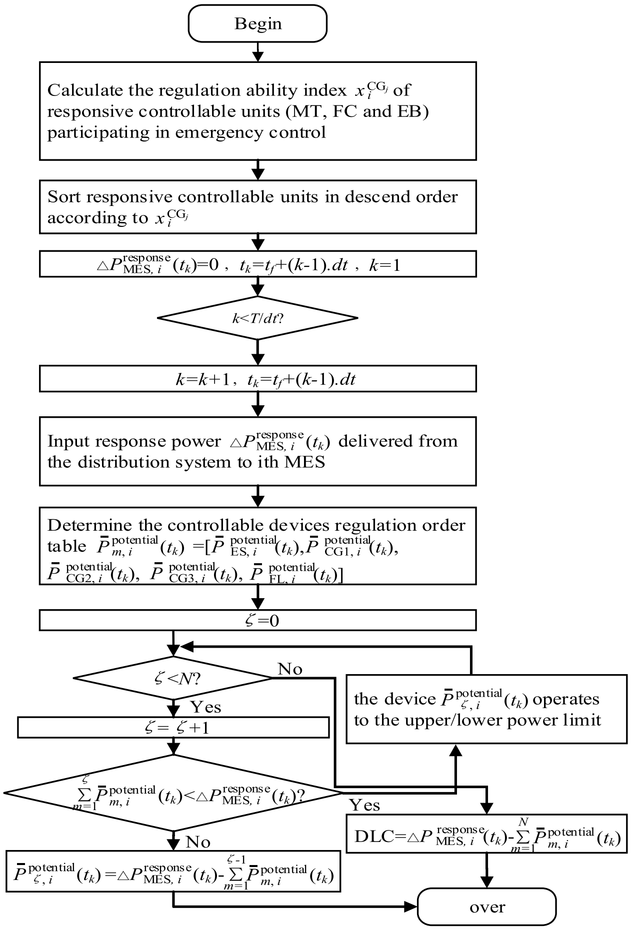


FIGURE 3. Flow chart of emergency control strategy procedures.

STEP 4: determine the regulation order table of all the controllable devices and take it as the devices' response priority.

STEP 5: if the total response power is above the power shortage when the present device operates at full power or the flexible load is of full response, the chosen device is controlled to just compensate for the power shortage. Otherwise, the chosen device is given priority to operate to the upper/lower power limit and continue to judge the next device as the same.

STEP 6: if all the devices in the table are chosen to participate in order but the power shortage is still not compensated, calculate the remaining power shortage and make up with the direct load control (DLC) and turn to step 3.

STEP 7: end the all algorithm.

VII. CASE STUDY

A. DATA ANALYSIS

In order to verify the effectiveness of the proposed method, IEEE 33-bus system is modified to design case studies regarding optimal scheduling and emergency control, the network of which is shown in Fig.4. Three micro energy systems namely MES1, MES2 and MES3 are connected to the node 4, 7, 10 respectively. The structure of MES1 is demonstrated in Fig.4, the devices of which contain PV, WT, MT, FC, EB, AC, EC, ES, HS and LS. The MES has the authority to interact and exchange power with distribution grid. The basic data of system like the day-ahead prediction data and intra-day correction data of PV, WT and load together with the time-of-use (TOU) price are shown in Fig.6. The operating parameters of controllable units like minimum and maximum power output, ramp-down/ramp-up value and units' maintenance costs are shown in Table 1.

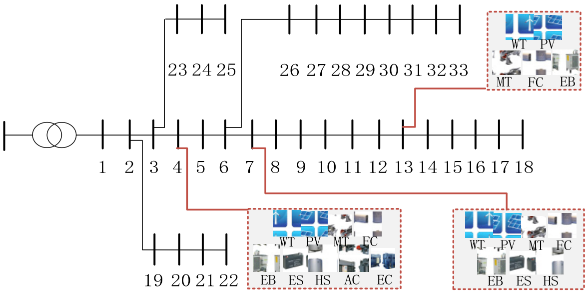


FIGURE 4. IEEE 33-bus system with multi MESs.

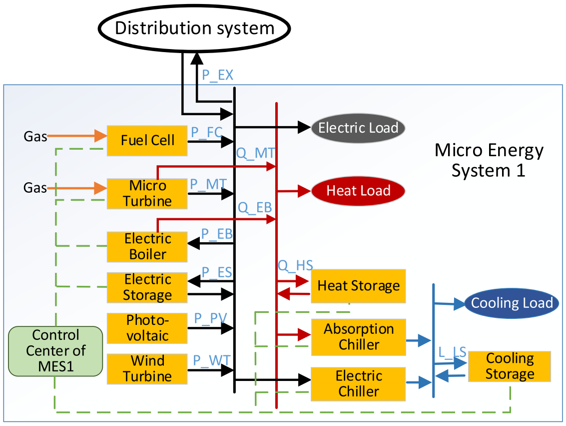


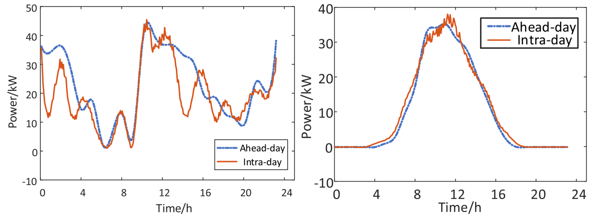
FIGURE 5. The structure of MES.

TABLE 1. Operating parameters of controllable units.

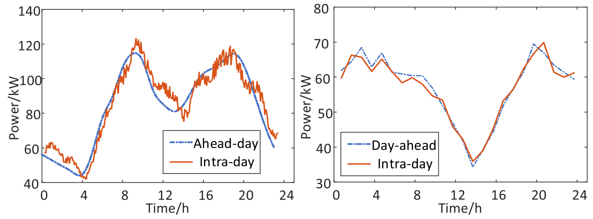
ID	Name	$P_{\min}$ (kW)	$P_{\max}$ (kW)	R_{down} (kW/h)	R_{up} (kW/h)	$C_{\mathrm{device},i}$ (Yuan/kW)
1	MT	15	65	5	10	0.250
2	FC	5	40	4	5	0.260
3	EB	0.1	50	3	5	0.160
4	EX	-60	60	0	0	0
5	AC	0.1	40	0	0	0.120
6	EC	0.1	50	2	2	0.130

B. RESULT ANALYSIS

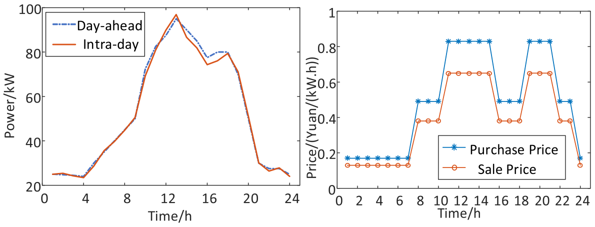
Based on the proposed coordinated control strategy together with the example data and the evaluation scenarios, the results are obtained from the following aspects: 1) the optimal operation of cooling, heat and electric schedule at day-ahead stage; 2) the long-interval cooling and heat power regulation and short-interval electric power regulation at intra-day stage; 3) the evaluation of MESs' adjustable power potential and the analysis of response priority and capacity of controllable devices in MESs.



(a) wind power (b) photovoltaic



(c) electric load (d) heat load



(e) cooling load (f) TOU price

FIGURE 6. **Basic data of PV, WT, Load and TOU price.**

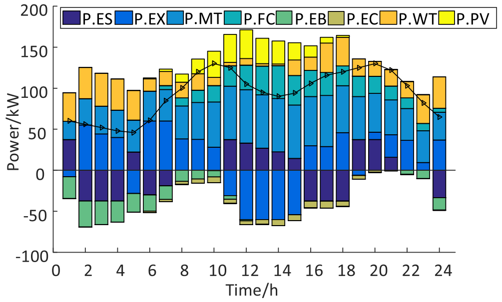
1) RESULTS OF DAY-AHEAD SCHEDULE IN MES

From the optimal day-ahead dispatch results of cooling, heat and electric power between different devices shown in Fig. 7, it can be found that:

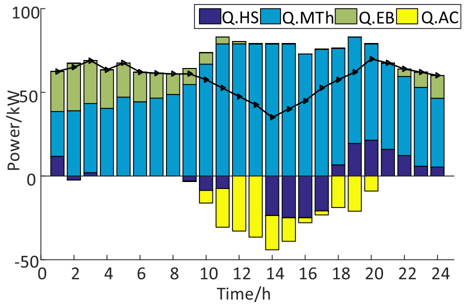
a) TOU price is a crucial factor guiding the power exchange between MES and distribution grid, the charging and discharging behavior of ES and running period of FC and EB. When the TOU price stays at valley, the MES purchases electricity from the grid with battery charging while EB is put into producing heat; when the TOU price stays at peak, the MES sells electricity to the grid with battery discharging while FC is employed to generate power;

b) MT is the core device of the MES, which can realize the cogeneration of cooling, heat and electricity. When the TOU price is high, MT contributes as much as possible to meet the power supply demand and obtains profit by selling electricity to the grid. Meanwhile, the cogeneration of MT makes cooling and heat demand primarily satisfied. The insufficient heat demand is compensated by EB and HS and the insufficient cooling demand is made up by EC, AC and LS.

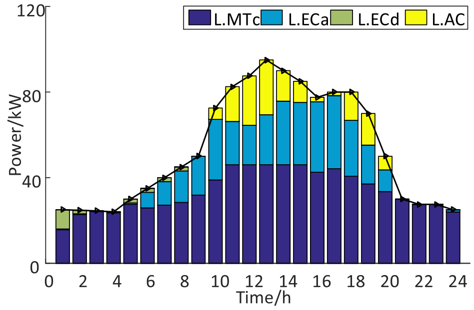
c) The existence of energy conversion device and energy storage device enables electricity dispatch and cooling/heat scheduling to participate and penetrate with each other. Among them, EB gives priority to transfer the electricity to heat when the electricity price is low, thereby the electricity dispatching is guided by the TOU price to involve in the heat dispatching. When the TOU price is high, the MT raises its power output to decline the generation from the electricity like the grid exchange power and the EB output power. The mismatch electricity is made up by the HS and LS which can release the multi-energy coupling state according to its storage transfer characteristics.



(a) Optimal operation results of electricity schedule



(b) Optimal operation results of heat schedule



(c) Optimal operation results of cooling schedule

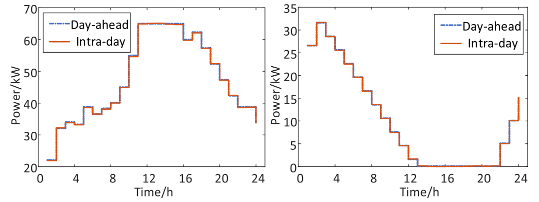
FIGURE 7. **Results of day-ahead schedule in MES.**

2) RESULTS OF INTRA-DAY SCHEDULE IN MES

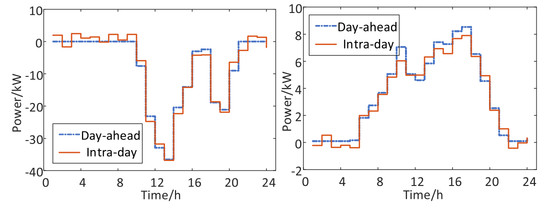
The power regulation of controllable devices during long-interval cooling and heat dispatch process and short-interval electricity dispatch process are demonstrated in Fig. 8 and Fig. 9 respectively, where following findings can be obtained:

a) During the intra-day dispatch process, a two-layer dispatch is conducted to correct the output of controllable devices so as to narrow the cold and heat dispatch error with long control interval and reduce the electricity dispatch error with short control interval, which effectively suppresses fluctuations between supply and demand.

b) Both day-ahead and intra-day scheduling of heat and cooling are executed at hourly scale, but the intra-day forecast is more accurate than the previous forecast, so the related devices' output has to be corrected. MT plays a significant role in the combined cooling, heat and power supply, the output of which should not be drastically adjusted, so its regulation capacity is constrained. Thus, the prediction error

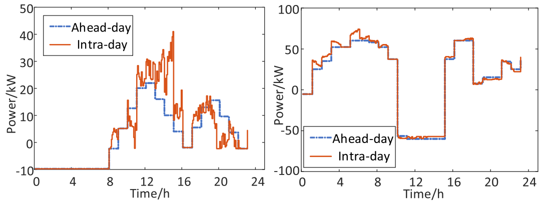


(a) MT (b) EB

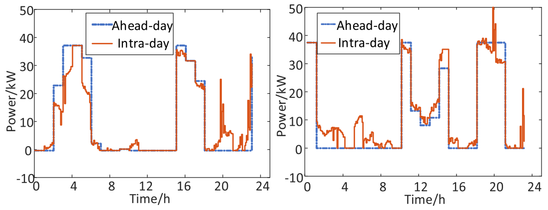


(c) AC (d) EC

FIGURE 8. **Power regulation of controllable devices during upper heat and cooling dispatch process.**



(a) FC (b) EX



(c) ESch (d) ESdis

FIGURE 9. **Power regulation of controllable devices during lower electricity dispatch process.**

of cooling and heat load is mostly made up from AC and EC during the upper intra-day dispatch process.

c) The day-ahead dispatch and intra-day dispatch of electricity are conducted at quite different time scales. Besides, wind power, photovoltaic and load have prediction errors at the same time, so the total power fluctuation of lower intra-day dispatch is large. The regulation amount of the exchange power and ES are constrained in order to maintain stable operation of the grid and protect the life of ES, so the power fluctuation mainly suppressed by FC.

3) COMPARISON WITH OTHER STRATEGIES

A group of different control strategies for micro energy system are supplemented and compared to demonstrate the strength of the proposed optimization model for MES scheduling. They are descripted as follows.

Strategy A: All the electricity, heat and cooling demand are met by purchasing electricity from the distribution grid. Heat demand is fulfilled by EB and cooling demand is fulfilled by EC. The distributed gas units like MT aren't taken into the generation process.

TABLE 2. **The operation cost employing the different strategies.**

Cost/Profit (Yuan)	Strategy A	Strategy B	Strategy C
MT fuel cost	0	0	797.4
FC fuel cost	0	257.7	137.6
GB fuel cost	0	992.2	0
Electricity purchase cost	1386.9	323.4	-53.3
Heat and cooling selling profit	266.7	266.7	266.7
Device maintenance and pollution treatment cost	40.9	110.2	59
Restart-up cost	0	1.2	1.2
Total cost	**1694.4**	**1951.4**	**1209.6**

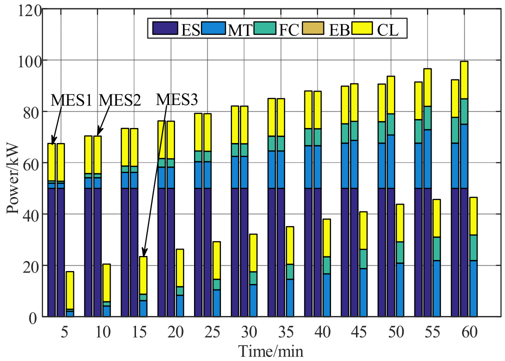


FIGURE 10. **Evaluation results of adjustable power potential of MESs.**

Strategy B: Multi energy systems operate in a discrete mode. The heat and cooling energy is supplied by gas boiler and absorption chiller. The coefficient of gas boiler (GB) is set as 83.5%. The fuel cost is calculated as same as MT's formula. Other devices' deployment remains unchanged except for the coupling component (MT, EB and EC) and heat and cooling storage.

Strategy C: The coordinated control strategy proposed in this paper.

The operation cost employing the different strategies is compared in Table 2. It can be summarized from Table 2 that different control strategies influence the system operation economy. The combined cooling, heat and power dispatch is beneficial to reduce the operating cost, that' why the total cost of strategy C is much smaller than strategy A and strategy B. The coordinated strategy proposed in this paper is the most economical and can fully reflect the advantages of multi-energy complementary and promote the maximum proportion of renewable energy consumption.

4) ANALYSIS OF EMERGENCY CONTROL STRATEGY

In order to verify the effectiveness of the emergency control strategy proposed in this paper, the case study is designed as follows: it is assumed that the load power (PL) and generation power (PG) are balanced at initial time, as the blue curve shown in Fig.11. At 17:00, there appears a power shortage caused by disturbance from the generation side in the distribution grid. Through the emergency control strategy proposed in this paper, the adjustable potential evaluation result of each MES is shown in Fig. 10. The response power demand delivered to each MES is shown in Fig. 11, where the blue

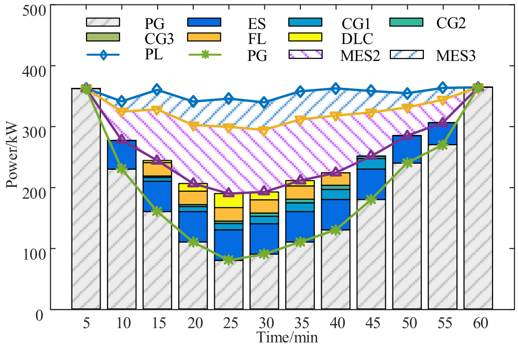


FIGURE 11. Priority and response capacity of controllable units in MESs.

oblique block denotes that is sent to MES3 and the pink diagonal block denotes that is sent to MES2. Taking MES1 as an example, the priority and capacity of the controllable devices are further displayed.

It can be concluded from the comprehensive analysis of Fig. 10 and Fig. 11 that:

a) The regulation capacity and regulation rate of controllable devices like WT, FC and EB are simultaneously considered by subdividing the control interval during the occurrence period of power shortage. Comparing the adjustment amount of WT and FC at each time interval and the climbing amount between the neighbor time intervals of MES1 and MES2 in Fig. 10, it can be found that MT in MES1 reaches its maximum adjustable capacity at 45 min with maximum climbing rate while the maximum adjustable capacity of MT in MES2 is larger than that of MT in MES1, so it continues to climb until the power shortage disappears. In addition, the TOU price is highest at 17:00, thus, EB doesn't make heat and it have no potential to adjust.

b) ES is not only an important guarantee for economical and efficient operation of the MES, but also an effective support for compensating the power shortage of distribution grid. The adjustable potential of ESs in MES1 and MES2 are large at 17:00 and the adjustment rate of ES is considerably fast, so the power regulation can be a step value without exceeding the maximum regulation capacity. That's why ES is preferentially applied to compensate for the power shortage and accounts for the largest share of the total response power in Fig. 11.

c) In the light of the regulation capacity, regulation ability and regulation influence, the participating order of devices in MES is electric storage, controllable units (MT, FC and EB) and flexible load. The remaining is compensated by the direct load control as the yellow block shown in Fig. 11. The regulation ability index of MT, FC and EB is 1, 0.3829 and 0.1500 respectively according to the calculation method in the emergency control step 1. Therefore, the regulation order is MT, FC and EB. Since EB is off during this period, MT is preferentially arranged, and then FC.

VIII. CONCLUSION

This paper proposes a coordinated control strategy for multi MESs within distribution grid. At normal circumstance, the MES executes the day-ahead and intra-day dispatch to optimally arrange the output of controllable devices with the objective of minimizing the total operation cost. At the emergency control stage, an emergency control strategy considering the regulation capacity and regulation rate of controllable devices under power shortage is proposed. The main conclusions of this paper are as follows:

a) TOU price is the key factor affecting the economic dispatch of MES and has a guiding effect on the behaviors of devices in MES like ES, EB and EC. The existence of coupling components makes the electricity dispatch and heat/cooling dispatch participate and penetrate with each other to obtain comprehensive utilization.

b) The proposed intra-day hierarchical dispatch strategy can suppress the cooling and heat power prediction error and electricity prediction error sequentially according to the different regulation time constants, which can effectively stabilize fluctuations on supply side and demand side.

c) In an emergency, the controllable devices in MES can compensate for the power shortage according to the regulation capacity, regulation ability and regulation influence, the adjustment sequence of which is electric storage, controllable units and flexible load.

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