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PLANNING OF COMMUNITY INTEGRATED ENERGY STATION FOR PARTICIPATING IN THE AUXILIARY SERVICE OF DISTRIBUTION NETWORKS

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ABSTRACT

With the extensive integration of high penetration renewable energy sources and electric vehicles, frequency regulation service is required to eliminate the impact of uncertainty of load and distributed generation on system frequency. The community integrated energy station (CIES) is an effective way to participate in the service. To realize the optimal configuration of CIES, a method for the planning of CIES for participating in the auxiliary service of the distribution networks is presented. First, the model of frequency regulation and energy station planning is established. Then, the model is solved by the mixed integer linear programing (MILP). Case studies are conducted under different scenarios and results show that participating in the frequency regulation service can effectively reduce the annual total cost of CIES.

Keywords: renewable energy resources, community integrated energy station (CIES), frequency regulation service, mix-integer linear programming (MILP)

NONMENCLATURE

Abbreviations

CHP	Combined heating and power
EB	Electric boiler
EC	Electric cooling
HP	Ground source heat pump
CON	Converter
ES	Electrical storage
HS	Heat storage
PV	Photovoltaic
WT	Wind turbine

Symbols

S_t^{REG}	Bid capacity in period t
$H_t^{\mathrm{CHP}}/P_t^{\mathrm{CHP}}$	Heat/electric power of CHP in period t
$H_{\mathrm{CH},t}^{\mathrm{HS}}/H_{\mathrm{DIS},t}^{\mathrm{HS}}$	Charging/discharging power of HS in period t
$P_t^{\mathrm{EB}}/H_t^{\mathrm{EB}}$	Electric/heat power of EB in period t
$P_t^{\mathrm{EC}}/C_t^{\mathrm{EC}}$	Electric/cooling power of EC in period t
$H_t^{\mathrm{HP}}/C_t^{\mathrm{HP}}$	Heat/cooling power of HP in period t
P_t^{PV}	Electric power of PV in period t
P_t^{WT}	Electric power of WT in period t
P_t^{GRID}	Electric power of tie-line in period t
P_τ^{GRID}	Electric power of tie-line at time τ
$P_{\mathrm{CH},t}^{\mathrm{ES}}/P_{\mathrm{DIS},t}^{\mathrm{ES}}$	Charging/discharging power of ES in period t
G_t^{CHP}	Input gas volume of CHP in period t
E_t^{HS}	Heat power stored in HS in period t
E_t^{ES}	Heat power stored in ES in period t
$z_{\mathrm{CH}}^{\mathrm{HS}}/z_{\mathrm{DIS}}^{\mathrm{HS}}$	Modes of charging/discharging of HS
$z_{\mathrm{CH}}^{\mathrm{ES}}/z_{\mathrm{DIS}}^{\mathrm{ES}}$	Modes of charging/discharging of ES
$\eta_{\mathrm{H}}^{\mathrm{CHP}}/\eta_{\mathrm{P}}^{\mathrm{CHP}}$	Efficiencies of heat/electricity of CHP
η^{EB}	Efficiency of EB
E^{EC}	COP of EC
$E_{\mathrm{H}}^{\mathrm{HP}}/E_{\mathrm{C}}^{\mathrm{HP}}$	COPs of heat/cooling of HP
η^{HS}	Heat loss coefficient of HS
η^{ES}	Power loss coefficient of ES
$\underline{\eta_{\mathrm{CH}}^{\mathrm{ES}}/\eta_{\mathrm{DIS}}^{\mathrm{ES}}}$	Charging/discharging efficiency of ES
$\overline{P_{\mathrm{CH}}^{\mathrm{ES}}}/\overline{P_{\mathrm{DIS}}^{\mathrm{ES}}}$	Limits of charging/discharging of ES
I_t	Solar irradiance in period t
v	Wind speed in period t
q	Calorific value of natural gas
y	Service life of the equipment
r	Discount rate
c_i^{I}	Investment cost of per unit capacity of facility i

p_i	Minimum planning unit of facility i
x_i	Number of p_i
Ω	Set of candidate devices
c_i^{M}	Maintenance cost of per unit capacity of facility i
$P_{i,t}^{\mathrm{OUT}}$	Output power of facility i in period t
c_t^{E}	Electricity price in period t
c^{F}	Gas price
c_t^{RMCCP}	Capability clearing price in period t
c_t^{RMPCP}	Performance clearing price in period t
η_t	Performance score in period t
β_t^{M}	Mileage ratio of frequency regulation signal in period t
P_t^{LD}	Electric load in period t
H_t^{LD}	Heat load in in period t
C_t^{LD}	Cooling load in period t

1. INTRODUCTION

With the rapid growth of distributed generation, the intermittent and random output power of distributed generator will cause network congestion and stability problems in power system. Therefore, additional frequency regulation capacity is required to provide frequency regulation service.

Compared with other ancillary services, frequency regulation requires short duration and rapid response of active power, while energy storage can provide fast frequency regulation support, so the community integrated energy station (CIES) is an effective way to participate in the auxiliary service of distribution networks.

In previous studies, the effect of the electrical energy in CIES was investigated. The main sources of profit and the performance of energy storage equipment are analyzed in Ref. [1]-[2]. Ref. [3] proposed an optimal control method and an optimal bidding strategy for battery energy storage participating in performance-based regulation market. Therefore, it is necessary to optimize the configuration of CIES participating in frequency regulation market to improve the benefits of CIES operation.

In this paper, taking the minimum annual total cost as the objective function, a planning model is established to realize the optimal configuration of CIES for participating in the auxiliary service of the distribution networks. Then, the model is solved by the mixed integer linear programing (MILP) to optimize the type and capacity of the equipment. Finally, case studies are conducted under different scenarios.

2. OPTIMAL CONFIGURATION OF THE CIES

In our study, the candidate devices consist of electric boiler, electric cooling, combined heating and power, ground source heat pump, heat storage, electrical storage, converter, photovoltaic and wind turbine, which covers most used equipment of CIES. Usually, the input energy forms are electricity and natural gas. The energy supply structure of the CIES is shown in Fig 1.

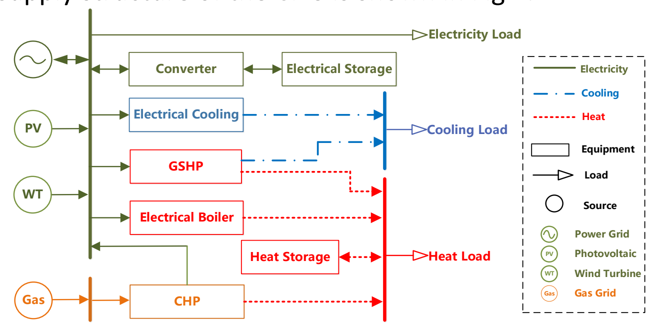

Fig 1 Structure of the CIES

2.1 *Modeling of frequency regulation*

In order to participate in the frequency regulation market, the CIES needs to determine the frequency regulation bid capacity in period t. In this paper, it is assumed that the assigned quantity is equal to the bid quantity. And in case of the violent fluctuation of the tie line power, the upper limit of bid capacity is specified. In regulation markets, the power of frequency regulation is often less than the bid capacity and is determined by the frequency regulation signal. A representative PJM RegD regulation command signal is shown in Fig 2[1].

$$P_\tau^{\mathrm{REG}} = \gamma_\tau^{\mathrm{REG}} S_t^{\mathrm{REG}} \tag{1}$$

$$S_t^{\mathrm{REG}} \leq S^{\mathrm{REG,MAX}} \tag{2}$$

$$\int_t^{t+1} P_\tau^{\mathrm{REG}} d\tau = (\gamma_t^{\mathrm{RD}} - \gamma_t^{\mathrm{RU}}) S_t^{\mathrm{REG}} \tag{3}$$

where $\gamma_\tau^{\mathrm{REG}}$ is the value of the regulation signal at time τ, $\gamma_t^{\mathrm{RD}}/\gamma_t^{\mathrm{RU}}$ is the fraction of the RegDown/RegUp bid capacity actually deployed in t.

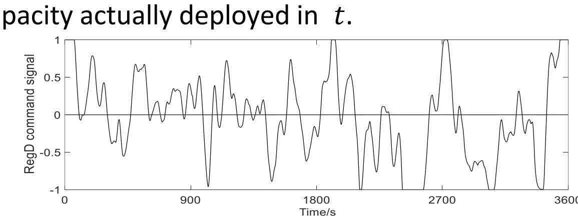

Fig 2 Typical PJM RegD regulation command signal[1]

2.2 *Objective function*

The minimum annual total cost is taken as the objective function, which consists of investment cost C^{I}, maintenance cost C^{M}, operation cost C^{O} and frequency regulation revenue R^{REG}.

$$\min C^{\mathrm{COST}} = C^{\mathrm{I}} + C^{\mathrm{M}} + C^{\mathrm{O}} - R^{\mathrm{REG}} \tag{4}$$

1) Investment cost

$$C^{\mathrm{I}}=\frac{r(1+r)^{y}}{(1+r)^{y}-1}=\sum_{i\in\Omega}c_i^{\mathrm{I}}p_i x_i \tag{5}$$

2) Maintenance cost

$$C^{\mathrm{M}}=\sum_{i\in\Omega}\sum_{t=1}^{8760}c_i^{\mathrm{M}}P_{i,t}^{\mathrm{OUT}} \tag{6}$$

3) Operation cost

The operation cost C^{O} consists of electricity purchase cost C^{E} and gas purchase cost C^{F}, which is formulated as follows.

$$C^{\mathrm{O}}=C^{\mathrm{E}}+C^{\mathrm{F}} \tag{7}$$

$$C^{\mathrm{E}}=\sum_{t=1}^{8760}c_t^{\mathrm{E}}\left[P_t^{\mathrm{GRID}}+\left(\gamma_t^{\mathrm{RD}}-\gamma_t^{\mathrm{RU}}\right)S_t^{\mathrm{REG}}\right] \tag{8}$$

$$C^{\mathrm{F}}=c^{\mathrm{F}}\sum_{t=1}^{8760}G_t^{\mathrm{CHP}}q \tag{9}$$

4) Frequency regulation revenue

The frequency regulation revenue R^{REG} consists of capability revenue R^{CAP} and performance revenue R^{PERF}.

$$R^{\mathrm{REG}}=R^{\mathrm{CAP}}+R^{\mathrm{PERF}} \tag{10}$$

$$R^{\mathrm{CAP}}=\sum_{t=1}^{8760}S_t^{\mathrm{REG}}\eta_t c_t^{\mathrm{RMCCP}} \tag{11}$$

$$R^{\mathrm{PERF}}=\sum_{t=1}^{8760}S_t^{\mathrm{REG}}\eta_t\beta_t^{\mathrm{M}}c_t^{\mathrm{RMPCP}} \tag{12}$$

2.3 Operation constraints of the equipment

1) Operation constraints of electric boiler (EB)

$$H_t^{\mathrm{EB}}=P_t^{\mathrm{EB}}\eta^{\mathrm{EB}} \tag{13}$$

$$0\le P_t^{\mathrm{EB}}\le p^{\mathrm{EB}}x^{\mathrm{EB}} \tag{14}$$

2) Operation constraints of electric cooling (EC)

$$C_t^{\mathrm{EC}}=P_t^{\mathrm{EC}}E^{\mathrm{EC}} \tag{15}$$

$$0\le P_t^{\mathrm{EC}}\le p^{\mathrm{EC}}x^{\mathrm{EC}} \tag{16}$$

3) Operation constraints of combined heating and power (CHP)

$$H_t^{\mathrm{CHP}}=G_t^{\mathrm{CHP}}q\eta_{\mathrm{H}}^{\mathrm{CHP}} \tag{17}$$

$$P_t^{\mathrm{CHP}}=G_t^{\mathrm{CHP}}q\eta_{\mathrm{P}}^{\mathrm{CHP}} \tag{18}$$

$$0\le P_t^{\mathrm{G,CHP}}\le p^{\mathrm{CHP}}x^{\mathrm{CHP}} \tag{19}$$

4) Operation constraints of ground source heat pump (HP)

HP supplies cold during the summer and heat during the winter.

$$H_t^{\mathrm{HP}}=P_t^{\mathrm{HP}}E_{\mathrm{H}}^{\mathrm{HP}} \tag{20}$$

$$C_t^{\mathrm{HP}}=P_t^{\mathrm{HP}}E_{\mathrm{C}}^{\mathrm{HP}} \tag{21}$$

$$0\le P_t^{\mathrm{HP}}\le p^{\mathrm{HP}}x^{\mathrm{HP}} \tag{22}$$

5) Operation constraints of heat storage (HS)

$$E_t^{\mathrm{HS}}=E_{t-1}^{\mathrm{HS}}\left(1-\eta^{\mathrm{HS}}\right)+\left(H_{\mathrm{CH},t}^{\mathrm{HS}}\eta_{\mathrm{CH}}^{\mathrm{HS}}-\frac{H_{\mathrm{DIS},t}^{\mathrm{HS}}}{\eta_{\mathrm{DIS}}^{\mathrm{HS}}}\right)\Delta t \tag{23}$$

$$E_0^{\mathrm{HS}}=E_{8760}^{\mathrm{HS}} \tag{24}$$

$$0\le \mathrm{E}_t^{\mathrm{HS}}\le p^{\mathrm{HS}}x^{\mathrm{HS}} \tag{25}$$

6) Operation constraints of electrical storage (ES)

$$E_{t+1}^{\mathrm{ES}}=E_t^{\mathrm{ES}}\left(1-\eta^{\mathrm{ES}}\right)+\left(P_{\mathrm{CH},t}^{\mathrm{ES}}\eta_{\mathrm{CH}}^{\mathrm{ES}}-\frac{P_{\mathrm{DIS},t}^{\mathrm{ES}}}{\eta_{\mathrm{DIS}}^{\mathrm{ES}}}\right)\Delta t+\left(\gamma_t^{\mathrm{RD}}\eta_{\mathrm{CH}}^{\mathrm{ES}}-\frac{\gamma_t^{\mathrm{RU}}}{\eta_{\mathrm{DIS}}^{\mathrm{ES}}}\right)S_t^{\mathrm{REG}} \tag{26}$$

$$E_0^{\mathrm{ES}}=E_{8760}^{\mathrm{ES}} \tag{27}$$

$$0\le \mathrm{E}_t^{\mathrm{ES}}\le p^{\mathrm{ES}}x^{\mathrm{ES}} \tag{28}$$

$$\mathrm{SOC}_{\min}\le\mathrm{SOC}_t\le\mathrm{SOC}_{\max} \tag{29}$$

$$0\le P_{\mathrm{CH},t}^{\mathrm{ES}}\le z_{\mathrm{CH}}^{\mathrm{ES}}\overline{P_{\mathrm{CH}}^{\mathrm{ES}}} \tag{30}$$

$$0\le P_{\mathrm{DIS},t}^{\mathrm{ES}}\le z_{\mathrm{DIS}}^{\mathrm{ES}}\overline{P_{\mathrm{DIS}}^{\mathrm{ES}}} \tag{31}$$

$$0\le z_{\mathrm{CH}}^{\mathrm{ES}}+z_{\mathrm{DIS}}^{\mathrm{ES}}\le 1 \tag{32}$$

7) Operation constraints of converter (CON)

$$0\le P_t^{\mathrm{DIS}}+S_t^{\mathrm{REG}}\le p^{\mathrm{CON}}x^{\mathrm{CON}} \tag{33}$$

$$0\le P_t^{\mathrm{CH}}+S_t^{\mathrm{REG}}\le p^{\mathrm{CON}}x^{\mathrm{CON}} \tag{34}$$

8) Operation constraints of photovoltaic (PV)

$$P_t^{\mathrm{PV}}=\begin{cases}\frac{I_t}{I^{\mathrm{R}}}p^{\mathrm{PV}}x^{\mathrm{PV}}, & 0\le I_t\le I^{\mathrm{R}}\\ p^{\mathrm{PV}}x^{\mathrm{PV}}, & I^{\mathrm{R}}\le I_t\end{cases} \tag{35}$$

9) Operation constraints of wind turbine (WT)

$$P_t^{\mathrm{WT}}=\begin{cases}0, & v\le v^{\mathrm{in}}\ or\ v\ge v^{\mathrm{out}}\\ p^{\mathrm{WT}}x^{\mathrm{WT}}\frac{v-v^{\mathrm{in}}}{v^{\mathrm{r}}-v^{\mathrm{in}}}, & v^{\mathrm{in}}\le v\le v^{\mathrm{r}}\\ p^{\mathrm{WT}}x^{\mathrm{WT}}, & v^{\mathrm{r}}\le v\le v^{\mathrm{out}}\end{cases} \tag{36}$$

10) Operation constraints of tie-line

When the CIES participates in the power grid frequency market in period t, since the frequency of the frequency regulation signal changes rapidly (adjusted every 2s), the tie line power does not remain unchanged in $(t,t+1)$, which is formulated as follows:

$$P_\tau^{\mathrm{GRID}}=P_t^{\mathrm{GRID}}+P_\tau^{\mathrm{REG}} \tag{37}$$

where P_t^{GRID} is the constant economic operation power of the tie line in period t.

2.4 Power balance constraints

1) Electric power balance

$$P_t^{\mathrm{LD}}=P_t^{\mathrm{GRID}}+P_t^{\mathrm{CHP}}+P_{\mathrm{DIS},t}^{\mathrm{ES}}+P_t^{\mathrm{PV}}+P_t^{\mathrm{WT}}-P_t^{\mathrm{EB}}-P_t^{\mathrm{EC}}-P_t^{\mathrm{HP}}-P_{\mathrm{CH},t}^{\mathrm{ES}} \tag{38}$$

2) Heat power balance

$$H_t^{\mathrm{LD}}=H_t^{\mathrm{EB}}+H_t^{\mathrm{CHP}}+H_{\mathrm{DIS},t}^{\mathrm{HS}}+H_t^{\mathrm{HP}}-H_{\mathrm{CH},t}^{\mathrm{HS}} \tag{39}$$

3) Cooling power balance

$$C_t^{\mathrm{LD}}=C_t^{\mathrm{AC}}+C_t^{\mathrm{HP}} \tag{40}$$

The economic scheduling model of the CIES can be described as follows:

$$\begin{cases}\min C^{\mathrm{COST}}\\ s.t.(1)-(3),(13)-(40)\end{cases}$$

where the constraints include the frequency regulation constrains (1)-(3), the operational constraints (13)-(37), and the power balance constraints of electric, heat and cooling, namely (38)-(40).

3. CASE STUDY

In this paper, the proposed method is conducted in the OPTI optimization toolbox using MATLAB R2016a and solved by IBM ILOG CPLEX 12.6. The parameters of the equipment and the price of electricity and natural gas refers to [4]. Three scenarios are considered to verify the effectiveness of the proposed method.

Scenario 1: ES only participates in the economic operation but does not participate in the frequency regulation market.

Scenario 2: ES only participates in frequency regulation market but does not participate in the economic operation.

Scenario 3: ES participates in economic operation as well as the frequency regulation market.

Table 1 Planning results of the three scenarios

Candidate devices	Scenario 1	Scenario 2	Scenario 3
EB/kW	3800	4100	3700
EC/kW	2300	2600	2300
CHP/kW	100	4900	100
HP/kW	700	500	700
CON/kW	3900	0	5800
ES/kW	10600	0	11000
HS/kW	5100	5500	4900
PV/kW	2200	4500	2100
WT/kW	4600	0	4700

The optimal configuration is shown in Table 1. Comparing Scenarios 1 and 3, since the ES in Scenario 3 participates in the economic operation and provides the frequency regulation service, the exchange power between the ES and the electric bus increases, so the capacity of the CON increases from 3900kW to 5800kW. But the charging and discharging electric quantity of the frequency regulation service is almost balanced in each time period, so the planned capacity of the electric energy storage increased only 400kW. Comparing Scenarios 1 and 2, since the ES in Scenario 2 only provides the frequency regulation service, the planning result indicates that the ES is not selected. Meanwhile, due to the fluctuation of the output, WT needs to operate with the cooperation of ES. The capacity of WT reduced from 4600kW to 0 in Scenario 2 since ES is not selected.

The annual total cost and electricity/gas consumption are shown in Table 2. Comparing Scenarios 1 and 3, the annual total cost of Scenario 3 is reduced by 6.03million RMB, and the frequency regulation revenue is 5.35 million RMB, indicating that CIES participating in frequency regulation market can effectively reduce the annual total cost. Comparing Scenarios 1 and 2, since the configuration of Scenario 2 plan does not include ES, the operation cost, electricity consumption and gas consumption in Scenario 2 increase by 5.79 million RMB, 3.71 million kWh, and 1.56 million m^3, respectively.

Table 2 Annual cost of the three scenarios

Cost and energy consumption	Scenario 1	Scenario 2	Scenario 3
Annual total cost/10^4 RMB	1352.34	1931.72	748.84
Investment cost/10^4 RMB	647.41	504.15	685.67
Maintenance cost/10^4 RMB	107.86	97.12	109.78
Operation cost/10^4 RMB	597.08	1330.45	518.63
Frequency regulation revenue/10^4 RMB	--	0	535.80
Electricity consumption/10^4 kWh	863.10	1233.86	841.67
Gas consumption/10^4 kWh	2.19	158.32	2.11

4. CONCLUSION

This paper proposes an optimal configuration method for the energy station in CIES for participating in the auxiliary service of the distribution networks. This paper establishes the model of energy station planning and frequency regulation, with the objective function of the minimum annual total cost. Then the planning model is solved by MILP to optimize the type and capacity of the equipment. Finally, case studies are conducted under different scenarios. But the congestion problem in distribution networks is not considered in this paper. The tie line congestion may affect the performance of the frequency regulation service. Therefore, the congestion problem will be considered in the further research.

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