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# Energy Management of CHP-based Microgrid with Thermal Storage for Reducing Wind Curtailment

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**Abstract:** Large amount of wind energy curtailment is observed during winter off-peak period in Northern China area. Since heat demand is high but electric demand is low, combined heat and power (CHP) units have to generate power to supply heat, leaving no load for wind farms to serve. To solve this problem, this paper proposes an energy management method to take advantage of the flexibility in different heating resources in a CHP based microgrid, so as to relief wind power curtailment. A novel two-layer coordinated strategy including schedule layer and real-time layer is proposed to control all the components including distributed generation (DG) units, different heating sources and electrical energy storage (EES). In schedule layer, a centralized optimization model based on forecasting data is implemented. The real-time layer calculates control signals based on metrical data and received reference values from the upper layer. Flexible control of EES and electric heater scheme (FCEE) is developed to further increase grid integration of wind generation. A 14-bus test system is designed to illustrate the performance of the proposed approach. Results show that the presented method is able to significantly reduce wind curtailment and ensure promising operation efficiency of the studied CHP-based microgrid.

**Author keywords:** CHP-based microgrid, electrical energy storage, two-layer coordinated strategy, thermal energy storage

(TES), wind curtailment.

## Introduction

Wind power has been rapidly developed in many countries and regions around the world over the past decade (Kabouris et al. 2014). At the end of 2015, the cumulative installed capacity in China was 145GW with an annual market growth rate of 22%. The cumulative curtailed wind power nationwide in 2015 was 33,900GWh, producing a $3.13 billion economic loss. The curtailment rate reached 15% in the same year.

The use of CHP units with limited operation flexibility is the major factor for wind curtailment especially in Northern provinces of China (CREIA 2014). The power of CHP units are conventionally constrained by their heat load (Lund 2005). At off-peak hours in winter heating period with low electrical loads but high heat loads, CHP units are fully utilized to meet heat demands and supply a large portion of the power demand, which brings heavy wind curtailment.

Hence, it is significant to improve the operation flexibility of CHP units to overcome contradiction between heat supply and wind curtailment. The natural way is turning on the electric heat boilers to use the wasted wind power, which can increase heating supply and allow CHP units to reduce their power output (Lund et al. 2006; Meibom et al. 2007). The flexibility of CHP units was increased by using heat pumps(IHPC 2007; Papaefthymiou et al. 2012). These measures have been proved to enhance operation efficiency and to decrease wind curtailment.

In addition, TES can also improve the flexibility of CHP units( Lund 2005; Chen et al. 2015). Part of the heat demand can be replaced by TES, correspondingly reducing the power generations of CHP units and increasing output of the wind power. Heat storage tanks are utilized to reduce wind curtailment in many European countries such as Denmark (SGC 2017). A paradigmatic example of wind powered islanded microgrid can be found in the Faroe Islands (Denmark), in which the small island of Nólsoy contains a remote village inhabited by 250 people in 100 households. Notice that most community size systems are combined wind-diesel generation. The idea on Nólsoy was to use traditional Danish version induction generator wind turbines, as they are readily available and cheap, because they are dismantled in high numbers from their sites to give place for new and larger turbines (Thomsen et al. 2014).

The aforementioned solutions are utilized intensively to reduce wind curtailment in main grid. Also they can be used in CHP-based microgrid that exists wind curtailment and heat demand. This paper mainly discusses how to use electric heater and TES to reduce wind curtailment for CHP-based microgrid. How to schedule the power of dispatchable DG units and other power equipments to maximize the economic benefits is the main problem to be tackled.

A novel double-layer coordinated control approach for microgrid energy management is proposed in (Jiang et al. 2013). The authors uses Berkeley Lab's Distributed Energy Resources Customer Adoption Model (DER-CAM) to optimize the operation of commercial-building microgrid (Marnay et al. 2008). Plug-in electric vehicles are taken into account in CHP-based microgrid by Derakhshandeh et al. (2013), Roy et al. (2014). An optimal scheduling model is presented for a microgrid considering technical and economic constraints based on temperature dependent thermal load modeling (Tasdighi et al. 2014). An optimization of locations of distributed energy resources to reduce operation costs is presenteed (Basu et al. 2010 ). Different storage devices such as battery, water bank, ice storage unit, heat storage unit are studied for comparing their influence on operation costs of CHP-based microgrid (Xu et al. 2012). Economic emission load dispatch model that considers emission and fuel cost is built (Basu et al. 2012). Jiang et al. (2014) propose an energy ecosystem: a cost-effective smart microgrid based on intelligent hierarchical agents with dynamic demand response and distributed energy resources management. In further, a new expected thermal discomfort metric is defined to quantify user discomfort (Good et al. 2015). A new algorithm in order to optimize the day-ahead thermal and electrical scheduling of a large scale virtual power plant which contains many small-scale producers and consumers (Hong et al. 2012).

CHP-based microgrid with wind curtailments is rarely considered in these above references. However, CHP-based microgrid studied in this paper in northern China exists the scenario with a large scale wind curtailment (CREIA 2014). Based on the special circumstances, an optimal energy management is proposed to balance the power and heat demands at multiple time periods. Two-layer coordinated strategy and FCEE scheme is used to improve flexibility and security of

CHP-based microgrid. In the context of the previous research, the paper provides the following:

1) FCEE scheme is adopted in real-time layer to reduce frequent charging and discharging of EES and enhance power ramp ability of microgrid.

2) With the aim to manage the impacts of uncertainty brought by wind power in the special CHP-based microgrid, an optimal energy management using two coordinated layers is proposed .

## CHP-based Microgrid with Thermal Energy System

### *Problem Statement*

Wind energy in microgrid is often abandoned at off-peak hours in winter heating period in northern China as the exchange power between microgrid and main grid is often limited. In order to reduce wind curtailment, EES is utilized to store wind energy and release it at proper time. However, the capacity of EES is required to be very large if wind curtailment is large. As investment of EES is expensive at present, owner of microgrid prefers to abandon wind energy rather than using EES.

Using wind curtailment to meet heat demand is another choice because investment of electric heater and TES is cheaper than EES. This scheme applies to CHP-based microgrid that exists wind curtailment and heat demand at the same time. Electric heater converts wind curtailment to heat energy and heat supply of microgrid can be met by the converted heat energy. When coupled to TES, it is not necessary to product exact heat energy that satisfies heat supply at a given time t .

In this scenario, it is crucial to propose energy management in order to optimize operation of microgrid with equipping electric heater and TES. A novel two-layer coordinated strategy including schedule layer and real-time layer is proposed to balance long-term economic benefits and short-term security performance in CHP-based microgrid. The power reference is optimized in schedule layer by solving a multi-period dynamic power flow problem. The real-time layer receives power reference and calculates control signals further based on metrical data. The real-time layer asks for new power reference if control signals are not feasible.

### *CHP-based Microgrid Frame*

A comprehensive frame of CHP-based microgrid is proposed which consists of CHP units, wind turbines (WT), other DG units, energy storage and loads, as shown in Fig. 1. The types of demand considered in this paper include electrical demand and heating demand. Two types of energy storage which are TES and EES are included. Microgrid is also connected to the main grid for selling/buying energy if there is energy excess/shortage.

### *Modeling CHP Unit*

The feasible operating area for heat and electrical power production in the combined heat and power plant is shown in Fig. 2. The boundaries of AD, CD, BC, and AB represent the minimum limit of steam injection, the maximum heat rate, the maximum limit of fuel injection, and the maximum limit of power output, respectively. Above features of CHP units can be defined[9],

$$\begin{aligned}&\underline{P_{CHP}} - c_{v2}H_{CHP}^{t} \le P_{CHP}^{t} \le \overline{P_{CHP}} \text{-} c_{v1}H_{CHP}^{t}\\&c_{m}(H_{CHP}^{t} - H_{CHP0}) \le P_{CHP}^{t}\\&0 \le H_{CHP}^{t} \le \overline{H_{CHP}}\end{aligned} \tag{1}$$

The fuel cost of a CHP power plant is generally defined as a quadratic function of the electrical power and heat output, including the product of the power and heat production [9],

$$f_{CHPi} = \sum_{t\in S_T}(b_{0i} + b_{1i}P_{CHPi}^{t} + b_{2i}H_{CHPi}^{t} + b_{3i}{P_{CHPi}^{t}}^{2} + b_{4i}{H_{CHPi}^{t}}^{2} + b_{5i}P_{CHPi}^{t}H_{CHPi}^{t}) \tag{2}$$

## Mathematical Model of Energy Management

The operation objective of CHP-based microgrid is to minimize cost according to market price. Besides, it is also important to reduce wind curtailment and remain stable by coordinated control. The requirements of voltage and power flow are considered especially at the point of common coupling (PCC). Constraints of each power equipment are taken into account at the same time. All above constraints are satisfied by a two-layer coordinated strategy, which includes schedule layer and real-time layer.

### *Schedule Layer*

The control variables include active and reactive power of EES, TES, CHP units, other dispatchable DG units and exchange power with the main grid over the given time horizon. Besides, active power of electrical heater, thermal output of CHP units, wind power are also considered as control variables. Others are state variables, as shown below.

$$\boldsymbol{x}_d = \begin{cases} \text{Control variables:} \\ P_{ESi+}^t, P_{ESi-}^t, P_{TSi+}^t, P_{TSi-}^t, P_{\mathrm{G}i}^t, P_{CHPi}^t, P_{grid+}^t, P_{grid-}^t, P_{EHi}^t, H_{CHPi}^t, P_{Wi}^t, V_i^t, \theta_i^t \\ \text{State variables: } E_{ESi}^t, E_{TSi}^t \end{cases}$$

The proposed model is designed to minimize the operation cost with the penalties of wind curtailment. The penalties of wind curtailment is included in the objective function because the renewable energy law mandates the priority of wind power integration within the technical limit. In the schedule layer, power of wind and load is deterministic, so the uncertainty problem turns into certain problem. The objective function is given as bellow:

$$\min\ f(x_d) = f_G(x_d) + f_{CHP}(x_d) + f_{ES}(x_d) + f_{TS}(x_d) + f_{EH}(x_d) + f_g(x_d) + f_W(x_d) \tag{3}$$

$$f_G(x_d) = \sum_{i \in S_G} \sum_{t \in S_T} (a_{2i} {P_{Gi}^t}^2 + a_{1i} P_{Gi}^t + a_{0i} + C_{OMi} \cdot P_{Gi}^t) \tag{4}$$

$$\begin{aligned} f_{CHP}(x_d) = \sum_{i \in S_{CHP}} \sum_{t \in S_T} (& b_{0i} + b_{1i} P_{CHPi}^t + b_{2i} H_{CHPi}^t + b_{3i} {P_{CHPi}^t}^2 \\ & + b_{4i} {H_{CHPi}^t}^2 + b_{5i} P_{CHPi}^t H_{CHPi}^t) \end{aligned} \tag{5}$$

$$f_{ES}(x_d) = \sum_{i \in S_{ES}} \sum_{t \in S_T} c_{ESi} (P_{ESi+}^t + P_{ESi-}^t) \tag{6}$$

$$f_{TS}(x_d) = \sum_{i \in S_S} \sum_{t \in S_T} c_{TSi} (H_{TSi+}^t + H_{TSi-}^t) \tag{7}$$

$$f_{EH}(x_d) = \sum_{i \in S_{EH}} \sum_{t \in S_T} c_{EHi} P_{EHi}^t \tag{8}$$

$$f_g(x_d) = c_{grid+} P_{grid+} - c_{grid-} P_{grid-} \tag{9}$$

$$f_W(x_d) = \sum_{i \in S_W} \sum_{t \in S_T} u_{Wi} (P_{Wpi}^t - P_{Wi}^t)^2 \tag{10}$$

where $f_G$ and $f_{CHP}$ are the cost of dispatchable DG units and CHP units, including fuel costs, operation and maintenance. $f_{ES}$ is the cost of the EES. $f_{TS}$ is the cost of the TES. $f_{EH}$ is the cost of electric heater. $f_g$ is the revenue obtained from selling/buying energy to the main grid. $f_W$ is the penalty term for wind curtailment.

All constraints are listed as follows:

$$\begin{aligned} P_{INJk}^t - P_{Lk}^t &= V_k^t \sum_{m \in k} V_m^t (G_{ij} \cos\theta_{ij}^t + B_{ij} \sin\theta_{ij}^t) \\ Q_{INJk}^t - Q_{Lk}^t &= V_k^t \sum_{m \in k} V_m^t (G_{ij} \sin\theta_{ij}^t - B_{ij} \cos\theta_{ij}^t) \end{aligned} \tag{11}$$

$$\underline{V} \le V^t \le \overline{V} \tag{12}$$

$$\sum_{i\in S_G}(\overline{P_{Gi}} - P_{Gi}^t) + \sum_{i\in S_G}(\overline{P_{CHPi}} - P_{CHPi}^t) + \overline{P_{grid+}^t} - P_{grid+}^t + P_{grid-}^t \ge R_{percent}(\sum_{i\in S_L} P_{Li}^t + \sum_{i\in S_H} P_{EHi}^t - \sum_{i\in S_W} P_{Wi}^t) \tag{13}$$

$$\underline{P_{Gi}^t} \le P_{Gi}^t \le \overline{P_{Gi}^t} \tag{14}$$

$$\Delta T \cdot \underline{\Delta P_{Gi}} \le P_{Gi}^{t+1} - P_{Gi}^t \le \Delta T \cdot \overline{\Delta P_{Gi}} \tag{15}$$

$$0 \le P_{Wi}^t \le P_{Wpi}^t \tag{16}$$

$$E_{ESi}^t = E_{ESi}^{t-1} + \Delta T(P_{ESi+}^{t-1}\eta_{ch} - P_{ESi-}^{t-1} / \eta_{dch}) \tag{17}$$

$$(\underline{E_{ESi}} + \underline{\Delta E_{ESi}}) \le E_{ESi}^t \le (\overline{E_{ESi}} - \overline{\Delta E_{ESi}}) \tag{18}$$

$$0 \le P_{ESi+}^t \le \overline{P_{ESi+}} - \overline{\Delta P_{ESi+}} \tag{19}$$

$$\underline{P_{ESi-}} - \underline{\Delta P_{ESi-}} \le P_{ESi-}^t \le 0 \tag{20}$$

$$E_{TS}^t = E_{TS}^{t-1} + \Delta T(H_{TSi+}^t - H_{TSi-}^t) \tag{21}$$

$$H_{TS+} - H_{TS-} = H_{CHPi}^{t-1} + \eta_{EH} P_{EH}^{t-1} - H_{TL}^{t-1} \tag{22}$$

$$(\underline{E_{TS}} + \underline{\Delta E_{TS}}) \le E_{TS}^t \le (\overline{E_{TS}} - \overline{\Delta E_{TS}}) \tag{23}$$

$$0 \le P_{EH}^t \le \overline{P_{EH}} \tag{24}$$

$$0 \le P_{grid+}^t \le (\overline{P_{grid+}} - \overline{\Delta P_{grid+}}) \tag{25}$$

$$0 \le P_{grid-}^t \le \overline{P_{grid-}} - \overline{\Delta P_{grid-}} \tag{26}$$

$$\lambda \le \frac{P_{grid}^2}{P_{grid}^2 + Q_{grid}^2} \le 1 \tag{27}$$

Equation (11) represents constrains on power flow, whereas $P_{Lk}^t$, $Q_{Lk}^t$ denote active power and reactive power load at bus $k$; $P_{INJk}^t$ and $Q_{INJk}^t$ denote injection active power and reactive power of power sources at bus $k$. Equation (12) defines min/max voltage limits. Due to the load and wind power random variability, it is required to keep certain amount of power reserve, as shown in (13). The power reserve $R_{percent}$ depends on forecasting accuracy of wind generation and load level, which leaves adequate power margin of controllable to manage the power fluctuation in the real time owing to forecasting error. As keeping too large reserve is not economic, appropriate value should be obtained. Min/max power limits and ramp limits of dispatchable units are defined in (14)-(15). CHP units are required to meet constrains (1) except for (14)-(15). Actual wind power output is less than the predicted wind power, as presented in (16). The relation of the EES energy level between two time steps is defined in (17)-(18) and (19)-(20) represent power limits of EES. Energy level of TES between two time steps is represented in (21)-(23). Power limit of electric heater is defined in (24). (25)-(26) are constraints on the exchange power between microgrid and main grid. Finally, the power factor at PCC is controlled by (27).

As fuel cost of the dispatchable DG units is a quadratic function, the formulated programming problem in the schedule layer is nonlinear and nonconvex. Interior point optimizer (IPOPT) is a software library for large scale nonlinear and nonconvex optimization of continuous systems (Wächter et al. 2006, IPOPT homepage 2017 ). The number of variables and constraints in the formulated programming are just a few thousands , it is suitable to use IPOPT here for finding optimal solutions.

## Real-time Layer

Control complexity arises of the CHP-based microgrid due to a number of factors: a variety of elements and different operating modes. FCEE scheme is adopted in the real-time layer to control every element for different operating modes. When the CHP-based microgrid operates in grid-connected mode, the control commands sent to every element are power references. In stand-alone mode, elements except for EES receive power reference as control commands. EES adopts Vf control in stand-alone mode and its commands are frequency reference and voltage reference. In order to verify the presented FCEE scheme, dynamic model of each element is built in the MATLAB to simulate the microgrid operation.

### Grid-Connected Mode

Set-points of power $\hat{P}$ is obtained by schedule layer. Assuming that power of PCC $P_{gm}$ can be measured and sent to distributed local controller, thus power fluctuation of PCC $\Delta P_g$ can be represented,

$$\Delta P_g = P_{gm} - \hat{P}_{grid} \tag{28}$$

EES and EH coordinate with each other in order to decrease or remove the power fluctuation of PCC. As unit cost of EES is expensive, compared with TES. Electric heater is first regulated to decrease the power fluctuation of PCC , and EES is finally adjusted. As the electric heater used in the CHP-based microgrid will participate in addressing power fluctuation, the specially designed electric heater should be able to adjust its power consumption at fast time scale. The design technologies of the special electric heater is borrowed from variable frequency air conditioner. A silicon controlled rectifier (SCR) is added to the special electric heater. The electric heater can adjust its power consumption quickly by controlling SCR (Titus 2002). Therefore, the real power of EES and EH can be presented,

$$P_{EH} = \begin{cases} \overline{P_{EH}} & (\Delta P_g \le P_{b2}) \\ -\Delta P_g + \hat{P}_{EH} & (P_{b2} \le \Delta P_g \le P_{b3}) \\ 0 & (\Delta P_g \ge P_{b3}) \end{cases} \tag{29}$$

$$P_{ES} = \begin{cases} \overline{P_{ES+}} & (\Delta P_g \le P_{b1}) \\ -\Delta P_g + \hat{P}_S + \hat{P}_{EH} - \overline{P_{EH}} & (P_{b1} \le \Delta P_g \le P_{b2}) \\ \hat{P}_{ES} & (P_{b2} \le \Delta P_g \le P_{b3}) \\ -\Delta P_g + \hat{P}_{ES} + \hat{P}_{EH} & (P_{b3} \le \Delta P_g \le P_{b4}) \\ \underline{P_{ES-}} & (\Delta P_g \ge P_{b4}) \end{cases} \tag{30}$$

Where $P_{b1} = \hat{P}_{EH} + \hat{P}_{ES} - \overline{P_{EH}} - \overline{P_{ES+}}$ , $P_{b2} = \hat{P}_{EH} - \overline{P_{EH}}$ , $P_{b3} = \hat{P}_{EH}$ , $P_{b4} = \hat{P}_{EH} + \hat{P}_{ES} + \underline{P_{ES-}}$ .

When $\Delta P_g \in [P_{b2}, P_{b3}]$, power of EH change the value according to the power fluctuation. Power of EES keeps changeless. If $\Delta P_g$ exceeds the range with $[P_{b2}, P_{b3}]$, only adjusting EH power is not enough and EES need adjust its power as well.

FCEE scheme (as shown in Fig. 3) can reduce frequent charging and discharging of EES and save operation cost. In grid-connected mode, EES and other dispatchable units adopt PQ control. The control signals of dispatchable units can be calculated,

$$P_{Gi} = \hat{P}_{Gi} + r_{pi} \Delta P_g \tag{31}$$

$$Q_{Gi} = \hat{Q}_{Gi} \tag{32}$$

Where $r_p$ is usually determined by experience, $r_p$ is set as 0.1.

***Stand-Alone Mode***

In stand-alone mode, the highest priority is to keep a reliable power supply. Supposing that $f_m$ denotes the measured frequency, and the frequency deviation can be derived,

$$\Delta f = f_m - f_{base} \tag{33}$$

EES is required to use *V-f* control and other dispatchable DG units adopt *PQ* droop control. Control signals of EES is shown,

$$\Delta P_s = -r_{SP}(f_m - f_{base}) \tag{34}$$

$$\Delta Q_s = -r_{SQ}(U_m - U_{base}) \tag{35}$$

And the control signals of other dispatchable DG units are defined,

$$P_{Gi} = \hat{P}_{Gi} + r_{GPi}(f_m - f_{base}) \tag{36}$$

$$Q_{Gi} = \hat{Q}_{Gi} + r_{GQi}(U_m - U_{base}) \tag{37}$$

For electric heater, its control signals can be calculated by ,

$$P_{EH} = \hat{P}_{EH} + r_{EH}(f_m - f_{base}) \tag{38}$$

Feedback coefficient of controllers is based on the frequency response characteristic of the microgrid. As PQ droop control is used in stand-alone mode, each dispatchable unit and controllable load will participate in frequency regulation. Electric heater, considered as controllable load, can also cooperate with EES to smooth frequency fluctuation.

## Two-Layer Coordinated Strategy

The time steps in the schedule layer are of the whole time horizon, looking $M$ time steps into future. The schedule layer is based on forecasting data to determine the planned power of controllable units for each time step. The time granularity of the schedule layer optimization is 10 minutes and period length is 24 hours, as shown in Fig. 4. The first OP ( OP is short for operating point ) at $t_0$ is sent to local controllers and the remaining OPs are used only for the purpose of validating operation feasibility at the given predicted conditions in future time slots. As the schedule layer optimization is calculated every 10 minutes, the real-time layer will receive new optimal data every 10 minutes and then calculate control signals based on both received and measured data by using the above method. In this study, the control signals update frequency is set as 0.1 second.

Detailed procedure of two-layer coordinated control is presented as follows (shown in Fig. 5 ):

Step 1) Initialize time step=0 and then get initial state of all units .

Step 2) Forecast day-ahead data of wind energy and loads for a horizon of $M$ time step and then solve schedule layer's problem to get planned power of all units.

Step 3) Receive optimization results from upper layer and obtained measured data. Calculate local control signals using FCEE scheme and then issue control instruction.

Step 4) if this time step is not over, go to step 3. Otherwise, send the current status of controllable devices to the schedule layer and go to step2.

## Case Studies

A 14-bus test system is used to illustrate the proposed optimal energy management, as shown in Fig. 6. The controllable units include a fuel cell (FC), a diesel engine (DE), a combined heat and power unit (CHP), two wind turbine(WT) units. The energy storage contains a battery storage (BS) and thermal energy storage (TES). In addition to conventional loads, an electric heater (EH) is included also in the test system. There is a static switch (SD) at the PCC which can disconnect the microgrid from the utility grid. Each power equipment of the CHP-based microgrid is modeled based on its own features and constrains (see Table I). The value of $R_{percent}$ of the test system is set as 10%. More parameters are provided in the appendix.

All electrical loads can be divided into two categories, namely household and industrial loads, and the typical demand curves (Tsikalakis et al. 2008) are provided in Fig. 7(a). Taking a single day as an example, dividing it into 144 periods with 10 minutes as an interval. Heat demand is also provided in Fig. 7(a). Assuming that the market price is certain, as shown in Fig. 7(b). Forecasting data for WT units are provided in Figs. 7(c) and 7(d). A normal distribution is used to describe the forecasting errors of wind and load. The maximum forecasting error is 10% and average error is 4.82%.

First, the presented nonlinear and nonconvex optimization problem can be solved well by IPOPT. The average computation time of invoking IPOPT once is 14.03 seconds and the maximum computation time is 18.16 seconds. The average number of iterations is 203 and the maximum number of iterations is 387.

Besides, in order to analyze the performance of the CHP-based microgrid in different situations, two types of cases are studied here: grid-connected mode and stand-alone mode. In grid-connected mode, different cases are used to illustrate the economic benefit of adopting two-layer coordinated strategy. The security and stability of the microgrid is considered in stand-alone mode since power balance and voltage problem is quite serious in this situation. Cases analyze emphatically benefit of adopting FCEE scheme in the real-time layer.

## *Grid-connected mode*

In grid-connected mode, the total electrical load is met by the DG units, the EES and the main grid. Heat demand is assumed to be served by different combinations of heating sources in four different scenarios. In addition to one CHP unit, a 200 kW electric heater and a thermal energy storage with a maximum heat storage capacity of 1 MWh is considered as heating sources. The combination of heating sources for different scenarios is shown in Fig. 8.

Wind curtailment and total wind power for each scenario is presented in Fig. 9. For case 1, lack of different heating sources leads to large wind curtailment which is 8.7 % of total wind energy, especially in the winter evening. One kind of heating sources is used in case 2 and case 3 to improve microgrid flexibility, so wind curtailment is reduced in comparison with case 1. Wind curtailment is largely reduced when combinations of heating sources scheme is adopted in case 4. Electric heater absorbs wind curtailment and transforms it to heat which can be stored in TES. Operation cost of case 1 and case 2 is presented in Table 2. Using TES and EH can earn extra 147.68 ¥.

It is obvious that combinations of heating sources can improve the flexibility of the CHP-based microgrid that exists a large amount of wind curtailment. This scheme is appropriate for most of CHP-based microgrid in northeast China that is confronted with the problem of serious wind curtailment.

Case 4 is used to explain the dispatch model by using the two-layer coordinated strategy with schedule layer and real-time layer. Power reference values is acquired by the schedule layer optimization and then is broadcasted to the real-time layer every 10 minutes. After receiving reference values from the schedule layer, the real-time layer calculates control signals based on received reference values and local measurement data. FCEE scheme is utilized in order to balance power and reduce wind curtailment. The simulation results of DG units are presented in Fig. 10. Power of DG units in the evening is limited because wind power is abundant and the exchange power between microgrid and main grid is limited to 200 kW. The interior status of CHP unit is flexible, as illustrated in Fig. 11.

Except for providing electric energy, CHP unit here produces 1.02 MWh of heat, which composes 70 % of total heat production. 0.46 MWh of wind curtailment is consumed by electric heater to provide the rest of total heat production, as shown in Fig. 12. EES mainly charges its power between 0:00am-5:00m and 8:00pm-12:00pm respectively since wind energy is abundant at the same moment, as shown in Fig. 13. The power exchange at the PCC with and without the proposed two-layer control approach are shown in Fig. 14 and the close-up view of power exchange at the PCC are shown in Fig. 15. As wind power is large in most of the time， the exchange power with main grid is sometimes limited to the maximum power. As shown in Fig.15, the real power exchange at the PCC almost keeps constant in every 10 minutes with the proposed two-layer control approach. But the real power exchange at the PCC changes much in every 10 minutes without the proposed two-layer control approach. Therefore, the proposed two-layer control approach could smooth the fluctuations of the PCC. The TES plays an important part of meeting thermal demand. Fig. 16 presents the temperature of TES. When CHP units turns on, TES begins to store thermal energy and its temperature rises fast.

Above statements illustrate the optimization of schedule layer and real-time layer is presented as bellow. The real-time layer receives power reference values from the schedule layer every 10 minutes. Electric heater, as controllable load, and EES participate in smoothing power fluctuation in a cooperative way, as shown in Fig. 17 and Fig. 18. At this moment, power of electric heater is changed to reduce power fluctuation at the PCC, but power of EES is changeless. With smoothing power fluctuation of PCC, CHP-based microgrid is friendly to main grid.

In grid-connected mode, 4 cases are used to demonstrate advantages of using electric heater and EES to reduce wind curtailment.

### *Stand- alone mode*

In stand-alone mode, also named islanding operation, the security and stability of CHP-based microgrid is more important than its economic benefit. Electric heater is used as a kind of controllable load participating in power balance. EES and electric heater are vital equipments, which can quickly change their own power output. FCEE increases the range of fast dispatchable power which can enhance the security and stability of CHP-based microgrid in an effective way, as shown bellow.

For the test system, case 5 is designed to illustrate the control strategy in stand-alone mode. Case 5 is similar with case 4 except that the microgrid is operating in stand-alone mode. The simulation results are provided in Figs. 19-22. The power of dispatchable units is presented in Fig. 19. DE and FC are shut down when there is wind curtailment in microgrid. CHP unit is always operating as most of heat supply is met by CHP unit. As shown in Fig. 20, electric heater is not only a kind of heating sources bus also a controllable load that cooperates with EES to improve stability of CHP-based microgrid.

Fast dispatchable power here refers to the power which can be adjusted within a few seconds. EES and electric heater can adjust their power quickly, so their ability on adjusting their power are considered as Fast dispatchable power in this paper. Fast dispatchable power by using FCEE scheme is presented in Fig. 21. One curve in Fig. 21 stands for maximum value of fast dispatchable power and the other curve stands for the minimum value of fast dispatchable power. Fast dispatchable power with using EES only is shown in Fig. 22. In comparison with only using EES to balance power, the presented control strategy is more flexible as it extends range of fast dispatchable power.

The security and stability of the microgrid is another one of concerns in energy management, including voltage, frequency and transmission power. The dynamic Simulink model of the 14-bus test system is built in MATLAB. The above security constrains are ensured by the distributed local control. As shown in Fig. 23, the voltages of typical bus nodes change in safe rang (± 10 %). Frequency is controlled in safe rang because EES adopts VF control in stand-alone mode, as shown in Fig. 24.

Case 6 is considered here to further emphasize the advantages of taking control strategy in the real-time layer. Assumed that power of WT1 suddenly increases 100 kW in a short time, as shown in Fig. 25. As power fluctuation exceeds adjustment ability of EES, generation trip and wind curtailment is alternative measures to smooth the fluctuation. The aforementioned two measures are feasible but not economical.

If electric heater is used as a controllable load participating in power balance, generation trip and wind curtailment can be avoided. With flexible control, electric heater will increase its power consumption when system frequency increases. EES adjusts its power output based on the system frequency at the same time. The simulation results with FCEE scheme show that power fluctuation can be smoothed in an effective way, as shown in Fig. 26. Electric heater will increase its power to around 75 kW and the power of EES is around -85 kW at the same time when the power fluctuation takes place. In stand-alone mode, frequency is important and its simulation results is provided in Fig. 27 within the prescribed scope (±0.1 HZ). Thus FCEE scheme can enhance power ramp ability to tackle the impacts of uncertainty brought by wind power.

## Conclusions

In this paper, an optimal energy management of CHP-based microgrid using two-layer coordinated strategy is presented in order to balance power and heat demands at multiple time periods. With two-layer coordinated strategy and FCEE scheme presented in this paper, economic benefit and security of CHP-based microgrid is improved obviously.

Taking advantage of FCEE scheme in the real-time strategy, wind curtailment rate is largely reduced because the operation flexibility is enhanced as shown in case 1 to case 4. In the FCEE scheme, electric heater as a controllable load in stand-alone mode is utilized to increase rapid dispatchable power and enhance power ramp ability of microgrid. When wind energy suddenly changes violently, FCEE scheme can reduce the possibility of DG units tripping to a certain degree and ensure the operation stability of microgrid.

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## Notation list

The following symbols are used in this paper:

### *Variables*

| | |
|---|---|
| $P, Q$ | Active and reactive power |
| $E$ | Energy level |
| $H$ | Thermal power |
| $V, \theta$ | Amplitude and phase angle of the bus voltage |

### *Subscripts*

| | |
|---|---|
| $G$ | Dispatchable DG unit except CHP units and wind turbines |

| | |
|---|---|
| $CHP$ | Combined heat and power units |
| $W$ | Wind turbines |
| $EH$ | Electric heater |
| $ES+, ES-$ | Charging/discharging state of EES |
| $TS+, TS-$ | Charging/discharging state of TES |
| $grid+, grid-$ | Buying from/selling to the main grid |

## *Parameters*

| | |
|---|---|
| $S_T$ | Time set |
| $a_{(\square)}$ | Parameters of DG unit's fuel cost |
| $c_{om}$ | Operation and maintenance costs of dispatchable DG unit |
| $b_{(\square)}$ | Parameters of CHP unit's fuel cost |
| $c_{ES}$ | Charging/discharging cost of EES |
| $c_{TS}$ | Charging/discharging cost of TES |
| $c_{EH}$ | Cost of EH |
| $c_{grid+}, c_{grid-}$ | Price of power buying from/selling to the main grid |
| $u_{Wi}$ | Penalty factor for wind curtailment |
| $P_{Wp}$ | Predicted available wind energy |
| $P_L$ | Electric load |
| $R_{percent}$ | Power reserve coefficient |
| $\Delta T$ | Time step |
| $\underline{P}, \overline{P}$ | Limits of power |
| $\underline{V}, \overline{V}$ | Limit of voltage |
| $\underline{\Delta P}, \overline{\Delta P}$ | Limits of dispatchable DG unit's ramp rate |
| $\underline{E_E}, \overline{E_E}$ | Limits of EES's energy level |

| | |
|---|---|
| $\underline{\Delta E_{ES}},\overline{\Delta E_{ES}}$ | Reserve energy level of EES |
| $\underline{E_{TS}},\overline{E_{TS}}$ | Limits of TES’s energy level |
| $\underline{\Delta E_{TS}},\overline{\Delta E_{TS}}$ | Reserve energy level of TES |
| $\eta_{EH}$ | Efficiency of Electric heater |
| $\eta_{ch},\eta_{dch}$ | Charging/discharging efficiency of EES |
| $H_{TL}$ | Heating load |
| $c_{v1},c_{v2},c_m$ | Slope of CHP units |
| $f_{base}$ | Reference frequency |
| $\lambda$ | Power factor |
| $r_p,r_{SP},r_{SQ},r_{GP},r_{GQ},r_{EH}$ | Feedback coefficient of local controllers |

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**Fig. 26.** The simulation results with FCEE scheme

**Fig. 27.** The simulation results with FCEE scheme

**Table 1.** Device parameters

| Type | | DE | CHP | FC | WT | BS | EH |
|---|---|---|---|---|---|---|---|
| Output Limit(kW) | upper | 60 | 75 | 80 | 250 | 90 | 200 |
| | lower | 11.11 | 12.74 | 14 | 0 | -90 | 0 |
| Climbing Limit(kW/h) | upper | 240 | 280 | 170 | -- | -- | -- |
| | lower | 240 | 280 | 170 | -- | -- | -- |

**Table 2.** Comparison between case1 and case 4

| —— | Type | The presented method (¥) | Without TES and EH (¥) |
|---|---|---|---|
| Cost | DE | -524.87 | -524.87 |
| | FC | -787.39 | -785.34 |
| | CHP | -1269.21 | -1738.52 |
| | EES | -90.00 | -90.00 |
| | TES | -49.99 | 0 |
| | EH | -8.46 | 0 |
| Revenue | Sell power to the main grid | 4402.71 | 4663.83 |
| Total | —— | 1672.76 | 1525.08 |

# APPENDIX

**Table. 1** Parameters of DG unit's fuel cost (without CHP)

| Type | $a_2$(¥/kW$^2$) | $a_1$(¥/kW) | $a_0$(¥/kW) | $C_{OMi}$(¥) |
|---|---|---|---|---|
| DE | 0.0015 | 0.4668 | 8.6609 | 0.085 |
| FC | 0.0047 | 0.6797 | 4.4117 | 0.028 |

**Table. 2** Parameters of CHP unit's fuel cost

| Type | $b_5$ (¥/kW$^2$) | $b_4$ (¥/kW$^2$) | $b_3$ (¥/kW$^2$) | $b_2$ (¥/kW) | $b_1$ (¥/kW) | $b_0$ (¥) |
|---|---|---|---|---|---|---|
| CHP | 0.0001 | -0.0001 | -0.0003 | 0.4 | 1.200 | 15.08 |

**Table. 3** Parameters of DG unit

| Type | Bus | $\overline{P}$(kW) | $\underline{P}$(kW) | $\underline{\Delta P}$(kW) | $\overline{\Delta P}$(kW) |
|---|---|---|---|---|---|
| CHP | 4 | 75 | 12.74 | 280 | -280 |
| DE | 8 | 60 | 11.11 | 240 | -240 |
| FC | 7 | 80 | 14 | 170 | -170 |

**Table. 4** Parameters of branches

| Fbus | Tbus | R | X | b |
|---|---|---|---|---|
| 1 | 2 | 0.01536 | 0.008 | 0 |
| 2 | 3 | 0.0048 | 0.0025 | 0 |
| 3 | 4 | 0.0048 | 0.0025 | 0 |
| 3 | 5 | 0.0096 | 0.005 | 0 |
| 3 | 6 | 0.00384 | 0.002 | 0 |
| 1 | 7 | 0.0096 | 0.005 | 0 |
| 7 | 8 | 0.0048 | 0.0025 | 0 |
| 7 | 9 | 0.0096 | 0.005 | 0 |
| 9 | 10 | 0.0192 | 0.01 | 0 |
| 1 | 11 | 0.0048 | 0.0025 | 0 |
| 11 | 12 | 0.0096 | 0.005 | 0 |
| 12 | 13 | 0.00768 | 0.004 | 0 |
| 12 | 14 | 0.0048 | 0.0025 | 0 |

**Table. 5** Detailed load parameters

| Bus | Type | $P_{Lk}$(kW) | $Q_{Lk}$(kW) | $\overline{V_k}$ | $\underline{V_k}$ |
|---|---|---|---|---|---|
| 1 | 2 | 12 | 1.5 | 1.1 | 0.9 |
| 2 | 1 | 7.56 | 1.512 | 1.1 | 0.9 |
| 3 | 1 | 6.48 | 0.648 | 1.1 | 0.9 |
| 4 | 3 | 12 | 1.5 | 1.1 | 0.9 |

| | | | | | |
|---|---|---|---|---|---|
| 5 | 4 | 3.24 | 0.463 | 1.1 | 0.9 |
| 6 | 2 | 4.32 | 0.48 | 1.1 | 0.9 |
| 7 | 2 | 15 | 3.75 | 1.1 | 0.9 |
| 8 | 2 | 12 | 2 | 1.1 | 0.9 |
| 9 | 1 | 6.48 | 0.926 | 1.1 | 0.9 |
| 10 | 4 | 6.76 | 0.54 | 1.1 | 0.9 |
| 11 | 1 | 4.32 | 0.432 | 1.1 | 0.9 |
| 12 | 1 | 9.72 | 1.08 | 1.1 | 0.9 |
| 13 | 1 | 5.4 | 0.675 | 1.1 | 0.9 |
| 14 | 1 | 7.56 | 0.756 | 1.1 | 0.9 |

**Table. 6** Auxiliary parameters for microgrid operation

| Parameters | values | Parameters | values |
|---|---|---|---|
| $c_{v1}$ | -0.13 | $\eta_{ET}$ | 0.99 |
| $c_{v2}$ | 0.8 | $r_p$ | 0.1 |
| $c_m$ | -0.13 | $R_{percent}$ | 0.10 |
| $H_{CHP0}$ (kW) | 22.5 | $c_{ES}$ ( ￥/ kW ) | 0.3 |
| $\eta_{ch}$ | 0.98 | $c_{TS}$ ( ￥/ kW ) | 0.04 |
| $\eta_{dch}$ | 0.98 | $c_{EH}$ ( ￥/ kW ) | 0.02 |