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Article

Incorporating the Variability of Wind Power with Electric Heat Pumps

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Abstract: With the mass introduction of wind power in Northern China, wind power variability has appeared. In this article, both existing electric heat pumps (EHPs) and coal-fired combined heat and power (CHP) facilities, which are generally equipped with extraction-condensing steam turbines coupled with district heating for space heating purposes, are proposed to incorporate the variability of wind power equivalently. The authors' proposal arises from the facts that: (1) EHPs can provide space heating in the domestic sector with little thermal comfort change (e.g., energy carriers for space heating purposes can be switched from heating water to electricity); (2) coal-fired CHP units in Northern China can usually generate more electrical power corresponding to a shaved thermal power production. Thus, it is suggested that heating water from CHP units be shaved when the wind generation is low due to the variability of wind power, so as to enable more electrical power production and compensate for the corresponding insufficient wind generation. Following this, in the future and for some space heating loads at appropriate distances, electricity used as energy carrier should be converted by electric heat pumps for space heating. Thus, more electricity consumption will be achieved so as to avoid wasting wind power when the wind generation it is high. A numerical simulation is performed in order to illustrate the authors' proposal. It is shown that the impact of variability of wind generation can be equivalently reduced to a great extent, which enable more wind power integration instead of curtailment and potential energy conservation.

Moreover, in contrast to before, both the thermal and electrical power of coal-fired CHP units are no longer constants. In addition, the ratio of electrical to thermal power of CHP units is no longer constant either, and results in less energy consumption compared with fixed ratio. Finally, electricity consumed by end users' EHPs, which are devoted to space heating for various spatial distances and time points, is figured out.

Keywords: space heating; extraction-condensing steam turbines; coal-fired CHP; energy carriers; variability of wind power

1. Introduction

A considerable number of wind turbines have been installed in Northern China [1–3], where the intermittency of wind power, reflected in its variability and relative unpredictability restrains the full potential benefits of wind power [4]. On the one hand, the fluctuating wind speed profiles illustrate the variability over time, which is the focus of this article; on the other hand, discrepancies between forecast and actual output defines the wind's unpredictability [4]. The wind power intermittency impacts on power systems has been summarized in [5]. Generally speaking, energy storage infrastructures must be introduced to reduce the impact of intermittent wind power. Besides, peak load regulation power plants are usually considered too. According to [6], it seems that the impact of wind power prediction errors on power system can be mitigated by continuously re-calculating the unit commitment and economic dispatch from CHP. Thus with respect to Northern China where there exists high penetration CHP available for space heating purposes, the authors propose that the impact of variability of wind power may be equivalently reduced by controlling the energy carriers used for space heating service during winter, which has seldom been realized by researchers. Thus the authors' proposal appears innovative, in contrast to the past work in which heating water is treated and controlled as the sole energy carrier in Northern China [7,8].

While there exist both centralized coal-fired CHP units [9,10], equipped with extraction-condensing steam turbines and coupled with district heating so as to serve space heating demand, and wind generation units in Northern China [11], some negative impacts of these sources on each other are observed [2,3,11], especially some of wind power has to be curtailed and wasted during high wind and low load periods. These negative impacts can be attributed to the fact that feasible operation regions for the extraction-condensing CHP units exist in the current PQ-charts (electrical power *versus* thermal power chart) [6,12]. In practice, coal-fired CHP units in Northern China usually generate a maximum electrical power corresponding to a certain thermal power production, because this mode of operation seems to conserve energy from the viewpoint of power source efficiency according to [13,14]. In terms of the authors' proposal, if energy carriers for a certain space heating load can be switched from heating water to electricity, a key relationship can be deduced between spatial distance of heating water transmission and delay time of the EHPs' electricity load. With this finding, the authors suggest a possible way to equivalently reduce the impact of variability and curtailment of wind power so as to achieve energy conservation. To illustrate authors' proposal clearly, two wind power profiles are assumed. Profile A is set as objective one, and profile B is set as adjusting one. Here, profile A can be

treated as day-ahead prediction, and profile B can be regarded as hour-ahead prediction. If operation of power units in electric power grid is scheduled according to profile A, profile B may need to follow profile A so as to smooth the operation. With respect to variability of wind power between profile A and B, firstly the authors propose that a set of existing infrastructures [15–21] should be gathered together based on [7,8,22–24] without additional investment, which are to control end users' space heating and centralized CHP units. Secondly, when the wind generation of profile B is less than that profile A, it is suggested that heating water from CHP units be shaved so as to enable more electrical power production and thus reduce the impact of variability of profile B. Following this, at some future time when the wind generation of profile B is more than that of profile A, for some space heating load at appropriate spatial distances, electricity as energy carrier should be converted for space heating by electric heat pumps.

To illustrate the authors' proposal, this article is configured in five sections. Besides this section that serves as Introduction, the methodologies and mathematical model are proposed in Section 2. Section 3 is devoted to a numerical simulation with rational preconditions. Results and Discussion are given in Section 4. Finally, conclusions are drawn in Section 5.

2. Methodologies and Mathematical Model

In practice, the authors have achieved the patents and developed the infrastructures [15–21] which help realize the authors' proposal. Firstly, remote control of heating water radiators has been proven to be feasible [6,7]. Moreover, direct load control on EHPs seems also feasible according to [22,23]. Finally, remote monitoring and dispatch infrastructures for CHP units have been established in the electric power grid [24]. From viewpoint of investment, with authors' proposal no additional infrastructures is needed, because the authors just developed new utilization of the existing infrastructures.

2.1. Methodologies

With respect to variability of wind power between profile A and B, if $B < A$, the corresponding points are named as master points. The remaining points, where $B \geq A$, are named slave points. The authors propose that at the master points, heating water generation from CHP should be shaved so as to enable more electrical power production which compensate the insufficient wind power and reduce the impact of variability of wind power equivalently. On the other hand, the shaved heating water for space heating purpose should be also compensated by electricity through electric heat pump conversion at a certain future time when slave points may predominate. Thus, the more electricity consumption will enable to avoid the curtailment of wind generation of profile B and result in potential energy conservation. The resulting two problems are: (1) when will the slave points occur and (2) how much the electricity consumption is required as energy carrier for space heating purposes at slave points. Two key factors are emphasized: (1) COP, which it is related to the conversion of electricity to thermal power for space heating; (2) the spatial distance between centralized CHP and dispersed end users, which is related to locating the slave points.

2.2. Mathematical Model

In this article, the unit for power is set as MW, the time interval is given in minutes, and for spatial distance it is meters (m). According to the authors' proposal the maximum time T is formulated in (1), and the longest distance L between end users and CHP is formulated in (2). Through (1) and (2), time and distance are connected with each other:

$$T = \frac{D}{\sigma} - 1 \tag{1}$$

$$L = \frac{N}{60 \cdot v \cdot \sigma} + 1 \tag{2}$$

where D is the duration of the numerical simulation (its unit is minutes). σ is the dispatch time interval (unit is minutes). N is the longest spatial distance between end users and CHP (unit is meters, m). v is the heating water flow rate (unit is m/s). According to the authors' proposal, the CHP shaved thermal power $\Delta q_{\mathrm{CHP}}(t)$ (MW) is developed in (3), so as to achieve the adjusted thermal power from CHP $q_{\mathrm{CHP}}(t)$ (MW):

$$q_{\mathrm{CHP}}(t) = H_{\mathrm{CHP}}(t) - \Delta q_{\mathrm{CHP}}(t) \qquad (t = 0,1,2,...,T) \tag{3}$$

where $H_{\mathrm{CHP}}(t)$ (MW) is the original thermal power generated from the CHP, which is constant. In addition, t is a variable integer. The $\Delta q_{\mathrm{CHP}}(t)$ is compensated by EHPs on end users' site through (4):

$$\Delta q_{\mathrm{CHP}}(t) \cdot \eta_h = \sum_{l=0}^{L} q_{\mathrm{EHP}}(t+l,l) \qquad (l = 0,1,2,...,L) \tag{4}$$

where η_h is the heat transmission efficiency, $q_{\mathrm{EHP}}(t+l,l)$ (MW) is the thermal power of EHPs for space heating purposes, which is at the $(t + l)$th time point and lth distance point. l is integer variable. Through (5), the thermal power and electrical power $p_{\mathrm{EHP}}(t,l)$ (MW) of EHPs are connected:

$$q_{\mathrm{EHP}}(t,l) = COP \cdot p_{\mathrm{EHP}}(t,l) \tag{5}$$

where COP is the coefficient of performance (COP) of EHPs at the end users' sites. Adjusted wind power of profile B $p_{\mathrm{wind}}(t)$ (MW) is formulated in (6):

$$p_{\mathrm{wind}}(t) = E_{\mathrm{wind}}(t) + p_{CHP}(t) - E_{CHP}(t) - \frac{\sum_{l=0}^{L} p_{EHP}(t,l)}{\eta_e} \tag{6}$$

where $E_{\mathrm{wind}}(t)$ (MW) is the original wind power of profile B, $p_{CHP}(t)$ (MW) is the adjusted electrical power generation from CHP, $E_{CHP}(t)$ (MW) is the original electrical power generation of CHP and η_e is the electricity transmission efficiency. In (7), the time variables of numerical simulation are constrained:

$$0 \le t + l \le T \tag{7}$$

Through adjustment, the new allowed maximum and minimum electrical power generated from the CHP are $p_{\mathrm{CHP}}^{\max}(t)$ (MW) and $p_{\mathrm{CHP}}^{\min}(t)$ (MW), respectively, which are formulated as (8) and (9):

$$p_{\mathrm{CHP}}^{\max}(t) = l_{\mathrm{CHP}}^{\max} \cdot q_{\mathrm{CHP}}(t) + n_{\mathrm{CHP}}^{\max} \tag{8}$$

$$p_{\mathrm{CHP}}^{\min}(t) = l_{\mathrm{CHP}}^{\min} \cdot q_{\mathrm{CHP}}(t) + n_{\mathrm{CHP}}^{\min} \tag{9}$$

where $l_{\mathrm{CHP}}^{\max}$, $n_{\mathrm{CHP}}^{\max}$, $l_{\mathrm{CHP}}^{\min}$ and $n_{\mathrm{CHP}}^{\min}$ are various constants. The feasible electrical power generation of CHP $p_{\mathrm{CHP}}(t)$ (MW) is constrained in (10). In accordance with (11), allowed thermal power for EHPs is no more than the end users' space heating load $Q_{\mathrm{Load}}(t,l)$ (MW). The adjusted thermal power production of CHP is constrained below original thermal power from CHP, when heating water is treated as sole energy carrier for space heating originally in (12):

$$p_{\mathrm{CHP}}^{\min}(t) \le p_{\mathrm{CHP}}(t) \le p_{\mathrm{CHP}}^{\max}(t) \tag{10}$$

$$0 \le q_{\mathrm{EHP}}(t,l) \le Q_{\mathrm{Load}}(t,l) \tag{11}$$

$$0 \le q_{\mathrm{CHP}}(t) \le H_{\mathrm{CHP}}(t) \tag{12}$$

The objective function is formulated as (13), so as to equivalently reduce the impact of variability of wind power between profile A and B. Finally, this reduction of variability of wind power may result in new energy consumption in contrast to original in (14):

$$\text{Minimum: } \varepsilon = \frac{\sqrt{\dfrac{\sum_{t=0}^{T}\left(E_{\mathrm{wind}}^{\mathrm{A}}(t) - p_{\mathrm{wind}}(t)\right)^2}{T+1}}}{\sqrt{\dfrac{\sum_{t=0}^{T}\left(E_{\mathrm{wind}}^{\mathrm{A}}(t) - E_{\mathrm{wind}}(t)\right)^2}{T+1}}} \times 100\% \tag{13}$$

$$\eta = \frac{\sum_{t=0}^{T} F(q_{CHP}(t), p_{CHP}(t)) \cdot \sigma}{\sum_{t=0}^{T} F(H_{CHP}(t), E_{CHP}(t)) \cdot \sigma} \times 100\% \tag{14}$$

where ε is the ratio of adjusted variability of wind power between profile A and B; $E_{\mathrm{wind}}^{\mathrm{A}}(t)$ (MW) is the wind power of profile A, η is the ratio of adjusted energy consumption of CHP to original, $F(q_{CHP}(t), p_{CHP}(t))$ (MW) is the adjusted energy consumption of CHP and $F(H_{CHP}(t), E_{CHP}(t))$ (MW) is the original energy consumption of CHPBoth $F(q_{CHP}(t), p_{CHP}(t))$ and $F(H_{CHP}(t), E_{CHP}(t))$ can be deduced from (15).

3. Numerical Simulation

As the wind fluctuates every second, if this value is considered, more details may be obtained, but for the numerical simulation described in this article, the dispatch time interval σ is set as 5 min so as to illustrate the feasibility of authors' proposal, because five minutes is adopted as the dispatch time interval of the actual electric power grid in Northern China. Duration of the numerical simulation *D* is set as 240 min. In addition, the longest spatial distance between end users and the CHP is considered to be 9000 m, as limited by present policy [25], heating water flow rate is 2.5 m/s in accordance with [20]. Considering the thermal mass in the domestic sector and individual thermal comfort, $\sigma = 5$ is rational. η_h is set as 0.90, and η_e is set as 0.94 according to [25].

With regard to the C135/N150-13.24 condensing-extraction CHP unit, fuel consumption can be formulated in (15) [15,21]. In addition, a practical PQ-chart (electrical power *versus* thermal power chart) for a condensing-extraction CHP C135/N150-13.24 unit is achieved through built infrastructures [15,21]. This PQ-chart is shown in Figure 1 and can be formulated as in Equations (16) and (17). Thus, constants l_{CHP}^{max} and n_{CHP}^{max} are referred to (16); constants l_{CHP}^{min} and n_{CHP}^{min} are referred to (17). The original thermal power production of C135/N150-13.24 is 140 MW, and the original electrical power is 113 MW. Moreover, COP of existing EHPs on end users' site is considered as 2.0~5.0 in this article to fulfill the authors' proposal, which includes air source, geothermal and water source EHPs *etc.* [26–28]. Finally, Nonlinear Programming (NLP) is performed with GAMS©:

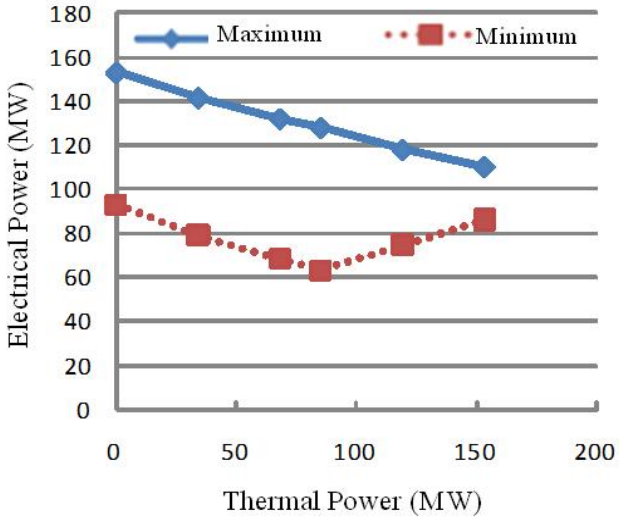
$$F(Q,E)=\begin{Bmatrix} 0.73\cdot Q+2.48E+3.59 & 34<Q\le 68 \\ 0.66\cdot Q+2.43E+12.73 & 68<Q\le 85 \\ 0.73\cdot Q+2.42E+8.11 & 85<Q\le 119 \\ 0.59\cdot Q+2.45E+22.47 & 119<Q\le 153 \end{Bmatrix} \tag{15}$$

where $F(Q,E)$ (MW) is fuel consumed by CHP, Q (MW) is thermal power generated from CHP and E (MW) is electrical power generated from CHP:

$$p_{CHP}^{max}(t)=-0.28\cdot q_{CHP}(t)+151.9 \quad 0<q_{CHP}(t)\le 153 \tag{16}$$

$$p_{CHP}^{min}(t)=\begin{Bmatrix} -0.35\cdot q_{CHP}(t)+92.0 & 0<q_{CHP}(t)\le 85 \\ 0.33\cdot q_{CHP}(t)+35.3 & 85<q_{CHP}(t)\le 153 \end{Bmatrix} \tag{17}$$

Figure 1. PQ-chart of C135/N150-13.24.



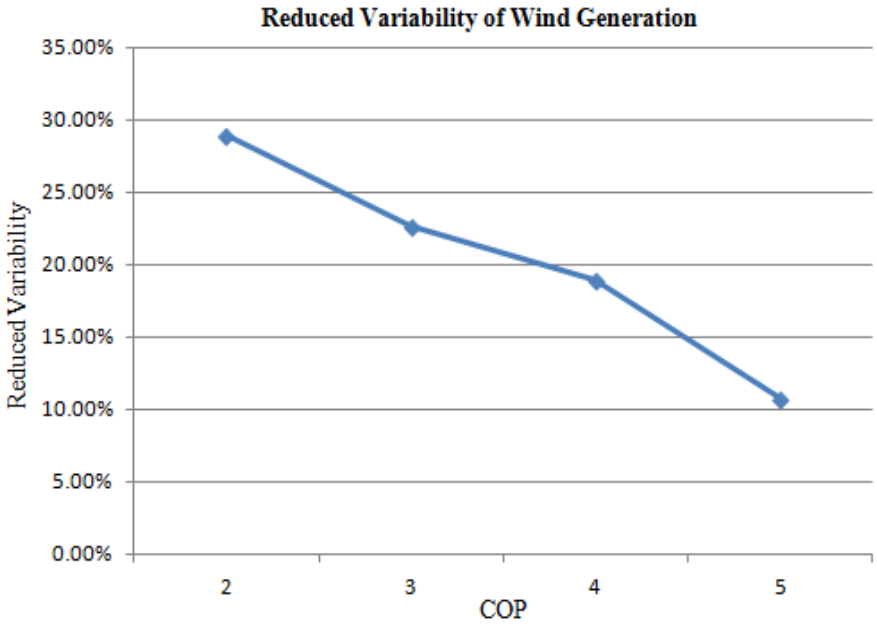
In accordance with the PQ-chart of Figure 1, practical coal-fired CHP units in Northern China usually generate maximum electrical power $p_{CHP}^{max}(t)$ so as to conserve energy, which disables their peak load regulation.

4. Results and Discussion

4.1. Reduced Variability of Wind Power

Figure 2 shows a reduced variability of wind power between profile A and B with COP from 2 to 5. It is seen that with increasing COP, variability of wind power are equivalently reduced.

Figure 2. Reduced Variability of Wind Power.



In Figures 3~5 various equivalent adjusted wind generation values of profile B are revealed with COP = 2~4 in contrast to COP = 5, both of which are compared with the wind power of original profile A and B at the same time. It appears that the higher COP is, less variability of wind power between profile A and B is.

Figure 3. Adjustment of Wind Power (COP = 2&5).

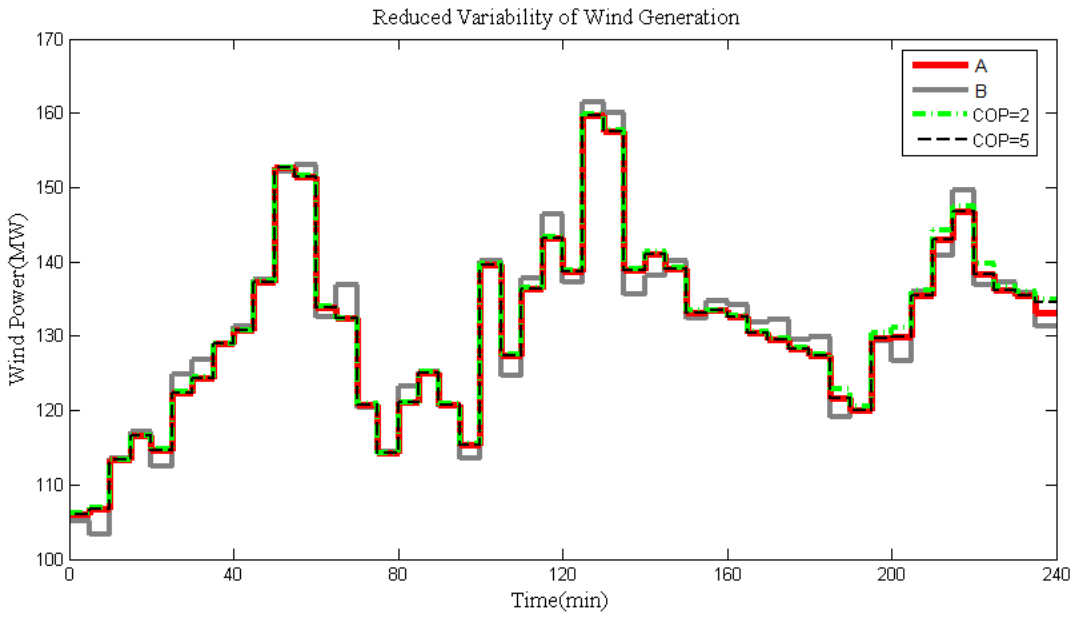


Figure 4. Adjustment of Wind Power (COP = 3&5).

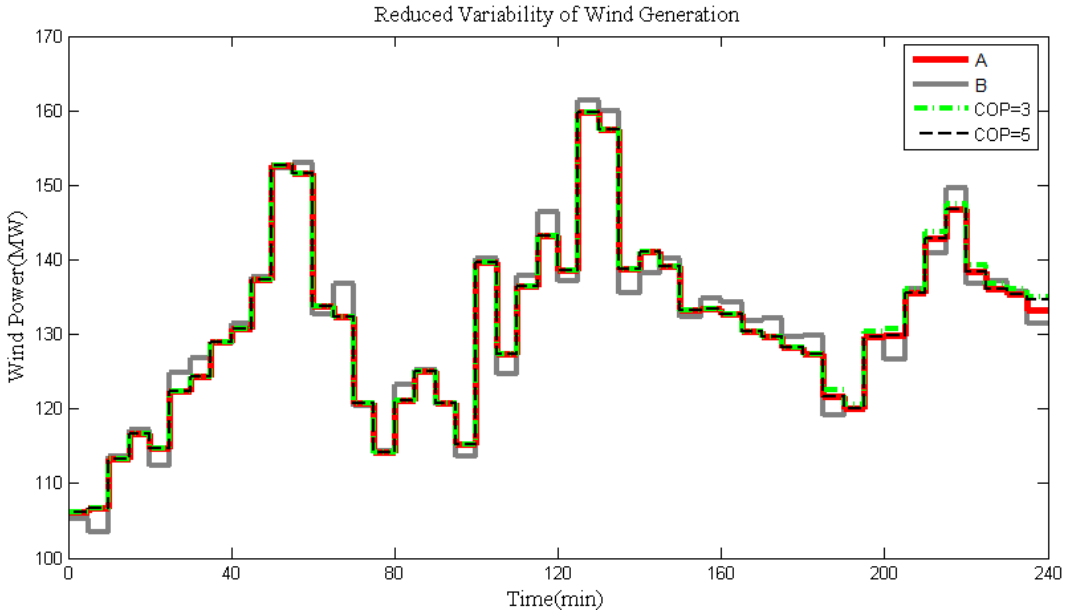
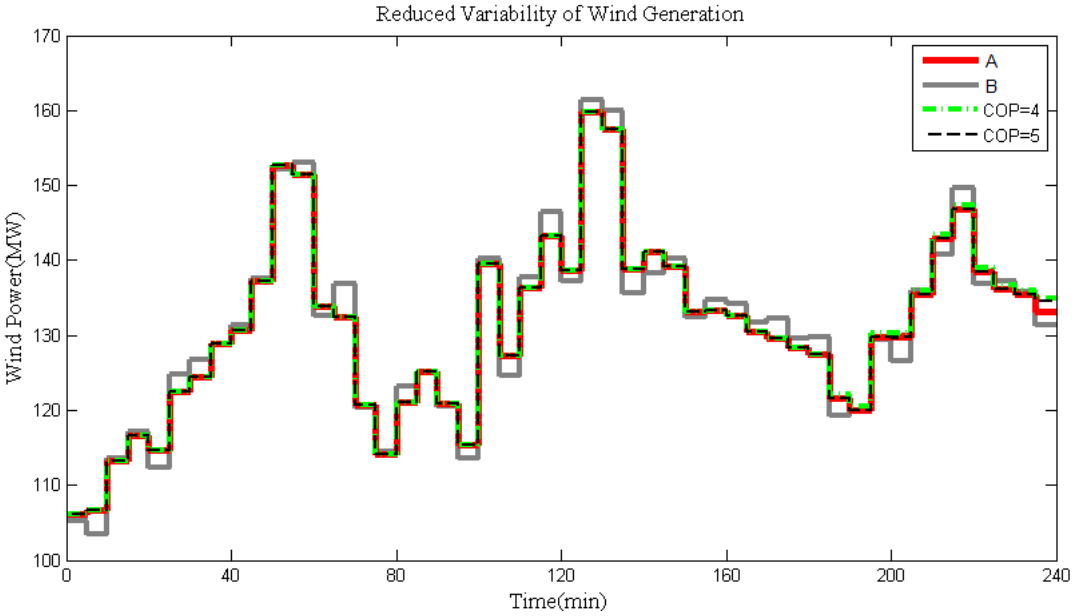
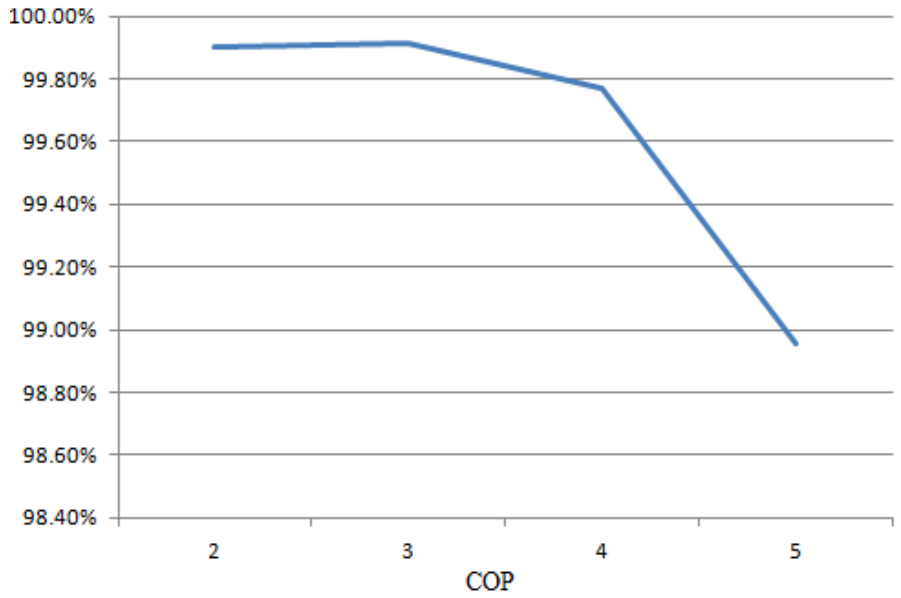


Figure 5. Adjustment of Wind Power (COP = 4&5).



In Figure 6, energy conservation is shown according to (14): (1) With authors' proposal, energy conservation can be observed, which arises from less curtailment and more integration of wind power; (2) With increasing COP, more energy conservation seems to be achieved.

Figure 6. Energy Conservation from More Wind Power Integration.



4.2. Adjusted Power Production from CHP

Adjustment of both electrical and thermal power production from CHP are observed with various COP in Figures 7 and 8.

Figure 7. Adjustment of Electrical Power of CHP.

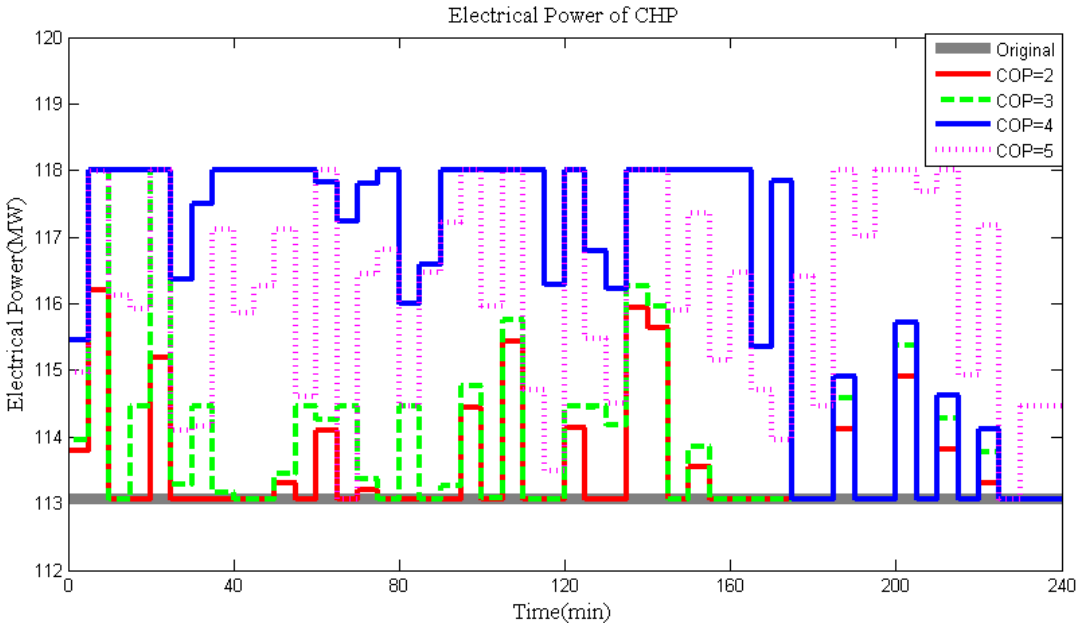
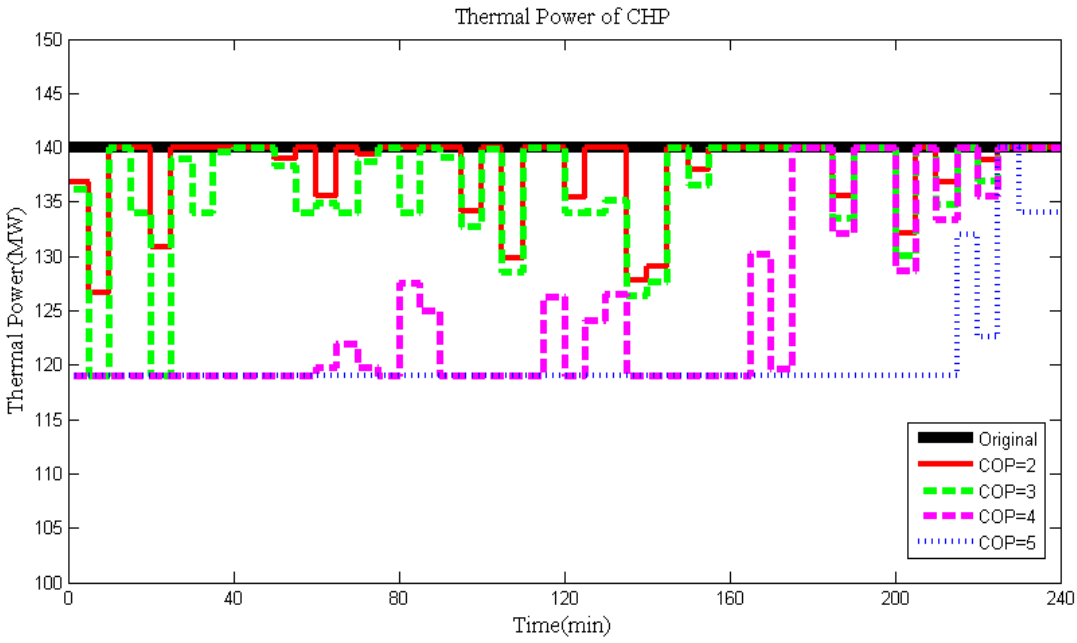
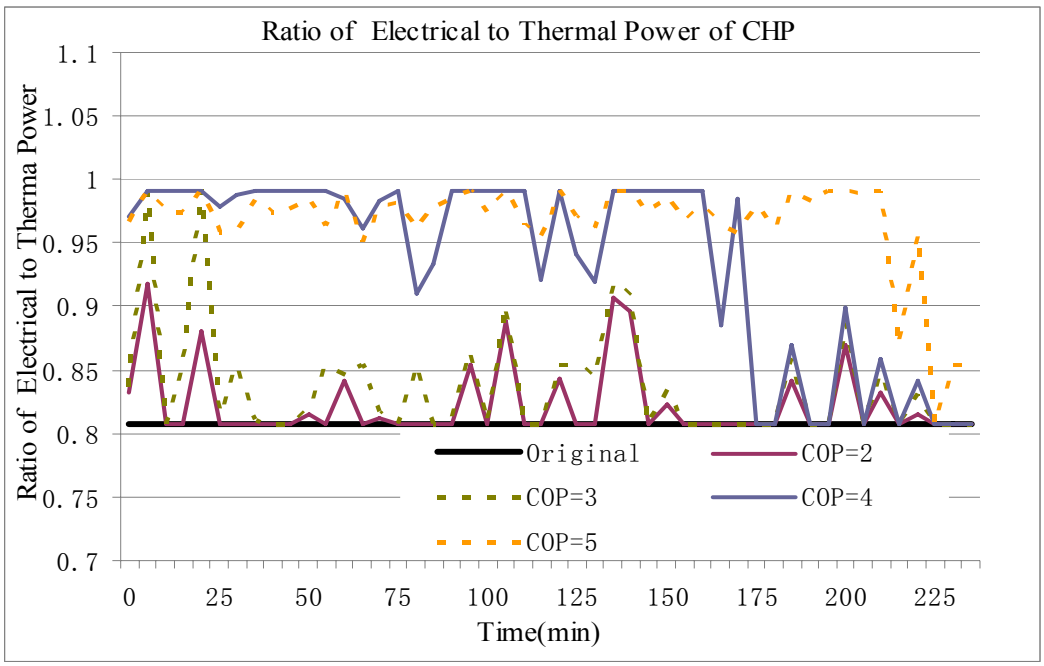


Figure 8. Adjustment of Thermal Power of CHP.



It is revealed that apparently adjusted electrical and thermal power from CHP fluctuates in contrast to the original values which were constants. In addition, in Figure 9 the adjusted ratios of electrical and thermal power production from CHPs with various COP values are depicted, which are different from the original value. From Figures 7~9, CHP is revealed to work for equivalently reducing the impact of variability of wind power between profile A and B.

Figure 9. Adjustment of Ratio of Electrical Power to Thermal Power of CHP.



4.3. Configuration of Space Heating Loads

Figures 10~13 show the configuration of the space heating load, in which some of the gross load is served by EHP through electricity, and the remainder is served by heating water radiators through heating water. It is shown that end users' energy consumption for space heating purpose fluctuates which is caused by the energy compensation used for wind generation. This end users' energy consumption fluctuation seems to impose little impact on the existing electric power grid in Northern China because it is small and can be treated as disturbing quantity. It is shown that higher the COP is, more EHP is used. Besides, with development of urbanization in Northern China, there seems increasing sufficient heat demand, which enables the authors' proposal.

Figure 10. Configuration of Space Heating Load (COP = 2).

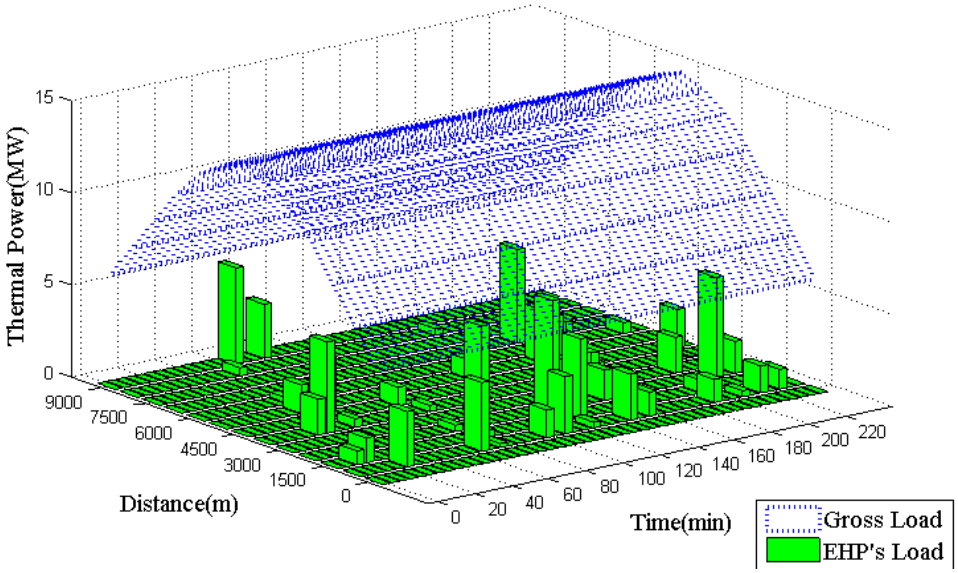


Figure 11. Configuration of Space Heating Load (COP = 3).

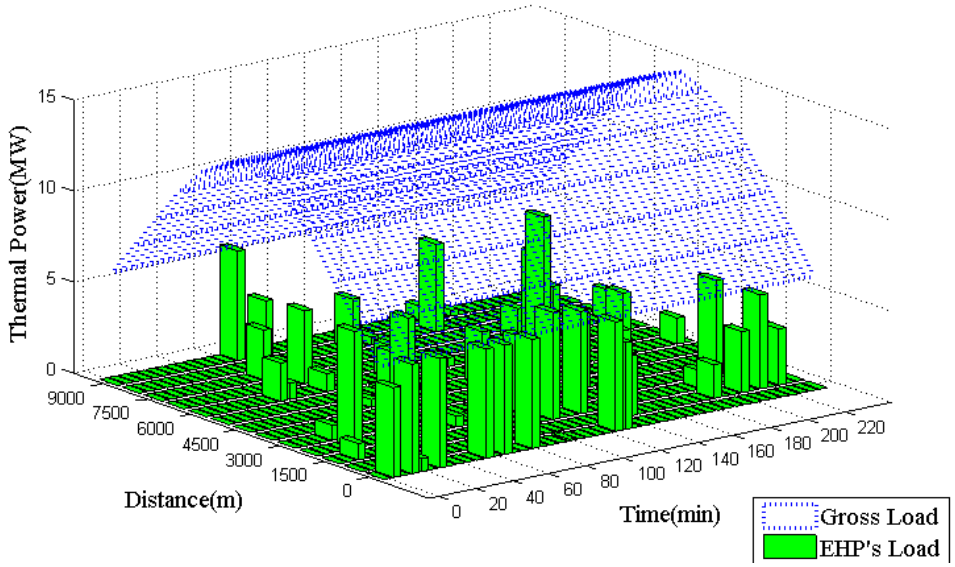


Figure 12. Configuration of Space Heating Load (COP = 4).

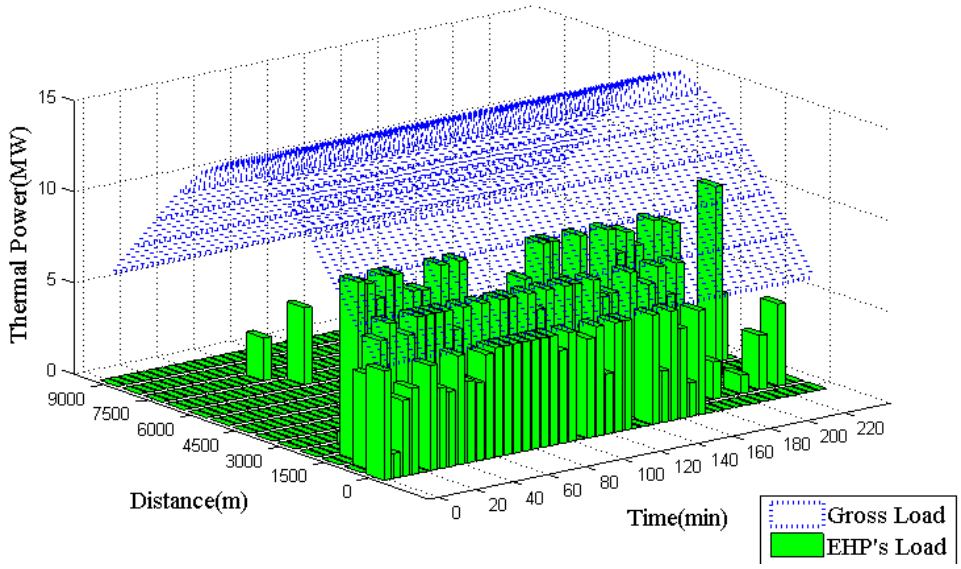
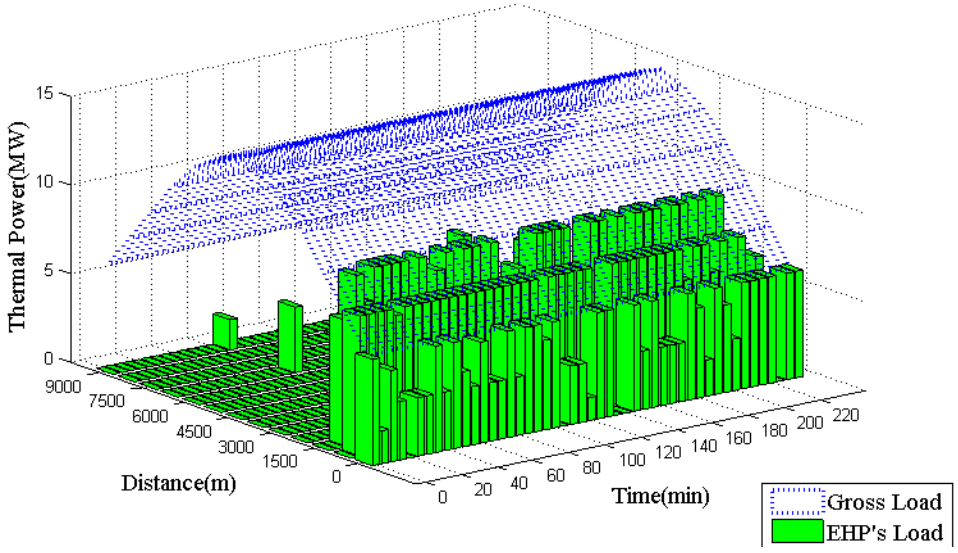


Figure 13. Configuration of Space Heating Load (COP = 5).



This article is solely devoted to feasibility of authors' proposal that a simplified model be introduced. However, the time constants of the space heating and extraction condensing steam turbine are different from the wind generation and the electric heat pumps, which needs to be discussed in future work.

5. Conclusions

In Northern China, a large amount of coal-fired CHP units equipped with extraction-condensing steam turbines are operating during the heating season. From these CHP units, heating water is generated as energy carrier for end users' space heating through district heating networks. The authors propose that at the master points, heating water generation should be shaved so as to enable more electrical power production, which compensate the variability of wind power between profile A and B and the impact are equivalently reduced. On the other hand, the shaved heating water for space heating

purpose should also be compensated by electricity through electric heat pumps' conversion at a future time where slave points are located, which also reduces the impact of variability and avoids the curtailment of wind power. A numerical study of the proposal is carried out, and the following results are obtained:

(1) Impact of variability of wind power can be equivalently reduced, because of the adjusted electrical power production of coal-fired CHP units, which arises from shaved thermal power production, and electricity consumption for space heating purpose. This is attributed to more wind power integration through avoiding the curtailment of wind generation.
(2) Both thermal and electrical power production of coal-fired CHP units are no longer constants in contrast to before, which results in the ratio of electrical to thermal power of CHP fluctuating instead of being constant. Compared with fixed ratio, potential energy conservation is observed.
(3) EHPs are utilized in order to compensate the shaved thermal power production from CHP for space heating purposes. With the COP of EHPs increasing from 2.0 to 5.0, more EHPs are utilized, and less equivalent variability of wind power between profile A and B occur.

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