Energy 78 (2014) 235–246

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Integrated electricity and heating demand-side management for wind power integration in China

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A R T I C L E I N F O

Article history:
Received 17 December 2013
Received in revised form
16 September 2014
Accepted 2 October 2014
Available online 31 October 2014

Keywords:
Wind power
Combined heat and power (CHP)
Thermal inertia
Thermal comfort
Electric heat pump

A B S T R A C T

The wind power generation system will play a crucial role for developing the energy conservative, environmentally friendly, and sustainable electric power system in China. However, the intermittency and unpredictability of wind power has been an obstacle to the deployment of wind power generation, especially in the winter of northern China. In northern China, a combined heat and power (CHP) unit has been widely utilized as a heat and electricity source.

Considering the flexible operation of CHP with introduction of electric heat pumps (EHPs), this paper proposes a new method of electricity and heating demand side management to facilitate the wind power integration with the purpose of energy conservation in a unit-commitment problem. The thermal characteristics of demand side such as the thermal inertia of buildings and thermal comfort of end users are taken into consideration. Moreover the distributed electric heat pumps (EHPs) widely used by city dwellers are introduced into the wind-thermal power system as the heating source and spinning reserve so as to increase the flexibility of heating and electricity supply. The simulation results show that the new method can integrate more wind power into power grid for electricity and heating demand to reduce the coal consumption.

1. Introduction

Facing to the growth of energy demand and the persistent dependent on the fossil fuel, the wind power as a clean renewable energy resource is very helpful for developing the energy conservative, environmentally friendly, and sustainable electric power system. In China, especially in the northern part, the wind power resource is abundant [1–3]. Therefore, in the last decade, China has a remarkable development in the utilization of wind power generation [4,5]. However, the intermittency and unpredictability of wind power generation would cause some negative impacts on the stable operation of electric power system. Approximately 20% of the wind power could not be integrated into the power network and must be abandoned in China [6]. There are several reasons for this restriction of wind power generation in China, i.e. insufficient transmission line capacity and insufficient capability to balance the power supply and demand, etc [7]. In China, the large capacity of combined heat and power (CHP) units has been widely utilized as a heat and electricity source. The gross installed capacity of CHP units is 100.91 GW in China until the end of 2007, which accounted for 14.05% of the total installed generating capacity [8]. However, the CHP units always operate at fixed load and have no peak regulation capacity due to the constraint of a huge demand for space heating. This inflexible operation mode increases the difficulty in integration of wind power [9].

In general, energy storage devices are utilized to reduce the impact of intermittency of wind power generation [10–15], but the heavy additional investment is necessary for the high penetration of wind power. According to Refs. [16–20], the flexible operation of CHP with introduction of electric heat pumps (EHPs) can compensate the wind power fluctuation more easily. In northern China, the district heating system is widely used for heating in winter from early on, but the distributed EHPs such as air-conditioner has also been installed in recent years and is nearly only used for cooling in summer. With respect to the space heating

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http://dx.doi.org/10.1016/j.energy.2014.10.008
0360-5442/

demand, the thermal characteristics of demand-side such as the thermal inertia of buildings and the thermal comfort of end users described in Refs. [21–25] have seldom been realized by researchers in the field of electric power system. Thus, this paper proposed a method for integrated electricity and heating demand side management which introduces the distributed electric heat pumps (EHPs) of the end users, and incorporates the improved spinning reserve strategy into the traditional unit commitment problem of thermal-wind power system with taking account of the thermal characteristics of demand-side. In the new method, the space heating demand can be assumed by not only CHP's hot water but also distributed EHPs, thus the flexibility of CHP's heating and electricity supply is increased and surplus wind power can be consumed; On the other hand, the thermal inertia of buildings and thermal comfort of end users can be taken advantage of to further integrate fluctuant wind power and increase the flexibility of CHP by heat storage of buildings. Moreover, the distributed EHPs can serve as the spinning reserve by means of the thermal comfort of end users to compensate the wind power prediction errors based on Refs. [26,28] and increase the flexibility of electricity supply of thermal power units.

The remainder of the paper is organized as follows: The methodology and mathematical model are presented in Sections 2 and 3. Section 4 describes the MINLP (mixed integer non-linear programming) formulation and its solution method briefly. Then the study cases are given in Section 5, the simulation results are presented in Section 6, and finally a conclusion is given in Section 7.

2. Methodology

The integrated electricity and heating demand side management is a novel method which can improve the integration of fluctuant and unpredictable wind power in a wind-thermal power system, by introducing the distributed EHPs.

2.1. The effect of distributed EHPs

The distributed EHPs such as air-condition are commonly used in Chinese cities and can be used to provide parts of heating load in the new method. This makes it possible to utilize surplus wind power for space heating. Therefore, this method can increase the flexibility of CHP's heating and electricity supply, and thus increase the capability to balance the power supply and demand [18,27]. In addition, the EHPs can also serve as the spinning reserve, as described in Section 2.3.

2.2. The utilization of thermal inertia of buildings and thermal comfort of end users

The buildings have a considerable heat storage capacity. Heat is stored in buildings and the indoor temperature rises when the heating supply is greater than the space heating load; On the contrary, heat is released from buildings, and the indoor temperature drops. Considering the thermal comfort of end users, the indoor temperature is allowed vary in a certain range. Thus, the heat output of CHP and EHPs can be adjusted to change the heat balance of buildings and make the power consumption of EHPs and power output of CHP follow the wind power. For example the surplus wind power can be converted into heat to be stored in buildings temporarily and make indoor temperature increase in a certain range, and then the heat stored in buildings can reduce dependence on the heat from CHP in the next period, so as to benefit in energy conservation.

2.3. The improved spinning reserve strategy

The traditional spinning reserve strategy for wind power only involves the thermal power units. This may restrict the flexible operation of thermal power units [29]. Thus, by taking the building thermal inertia and human thermal comfort into account, the improved spinning reserve strategy with the introduction of distributed EHPs can enhance the flexibility of electricity supply and compensate the wind power prediction errors better.

3. Mathematical model

Existing work on the modeling of wind power or CHP consists of the introduction of heating pipeline length [19], unit commitment problem [18,28,30] and spinning reserve in real time schedule [26,28]. On the basis of aforementioned work, the proposed model introduces the modeling of thermal characteristic of end users such as the thermal inertia of buildings and thermal comfort of humans. Additionally, a new model of spinning reserve with the introduction of EHPs is built.

3.1. Time step and distance step

In this model, t represents the discrete time index, and the actual continuous time can be expressed as $t\Delta T$, where ΔT is discrete time step length. l represents discrete distance index of heating pipeline from CHP to end users, therefore $l\Delta S$ is the actual continuous heating pipeline length, where ΔS is the discrete distance step from CHP to end users. Furthermore, Eq. (1) enables the conversion of the distance step ΔS to the time step ΔT.

$$\Delta S = v \cdot \Delta T \tag{1}$$

where v is the hot water flow rate.

According to the discrete distance, all of the end users whose heating supplied by the CHP units can be approximately divided into a number of groups, i.e. 0, 1, …, $l_{\max}$.

3.2. Electricity load control

3.2.1. Electricity balance

The electricity balance should be hold in Eq. (2):

$$P_{\text{load}}(t) + p_{\text{EHP}}^{\text{sum}}(t) = \sum_i p_{\text{CHP}}(t,i) + \sum_i p_{\text{CON}}(t,i) + p_{\text{wind}}(t) \tag{2}$$

where $P_{\text{load}}(t)$ is the electricity load without containing the part for heating. $p_{\text{CHP}}(t,i)$ and $p_{\text{CON}}(t,i)$ are the power output of CHP units and condensing power units respectively, and i is the unit index, $p_{\text{wind}}(t)$ is the wind power integrated into power grid, and $p_{\text{EHP}}^{\text{sum}}(t)$ is the sum of electrical power of EHPs $p_{\text{EHP}}(t,l)$ at different distance of end user group and expressed as Eq. (3):

$$p_{\text{EHP}}^{\text{sum}}(t) = \sum_{l=0}^{l_{\max}} p_{\text{EHP}}(t,l) \tag{3}$$

3.2.2. The unit commitment of thermal power units

The fluctuation of wind power aggravates the start-up and stop of thermal power units for following the wind power curve. However the start-stop of thermal power units not only indicates the operation status but also must meet the minimum start-up or stop time limit. Therefore operation status X, start-up status Y and shut-down status Z are brought into the model and bound in (4),