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Study of assessment on capability of wind power accommodation in regional power grids

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ABSTRACT

With the development of large-scale wind power integration, wind curtailment appears around the world, especially in China. It is essential to perform the assessment on capability of wind power accommodation (ACWPA) by calculating the maximum admissible wind power which plays an important role in system planning and operation. This paper proposes a long-term assessment on the maximum level of wind power installed capacity in future years based on peak power regulation, with consideration of potential wind curtailment. Meanwhile, a short-term assessment based on wind power forecasting is developed through day-ahead unit commitment to get admissible zone of wind power in grid operation. In particular, the extreme wind variation scenario (EWVS) calculated by quadratic programming (QP) is applied to optimize upper limit of admissible zone. Case studies are carried out to analyze wind power characteristics in a province in Southern China. Results show that the proposed approaches can effectively and accurately evaluate the capability of wind power accommodation in regional power grids.

1. Introduction

Wind power has the intermittence nature and fluctuating characteristics, leading to the output of wind farms with stochastic property compared with the conventional generation units [1,2]. Integration of large scale of wind farms may cause impacts on system operation and stability of power grids [3–5]. China has abundant wind energy resources both on shore and offshore, which plays an irreplaceable role in shaping energy structure. Wind energy that could be transformed into electricity (with the wind power density over 150 W/m^2) is estimated to be 1400 GW on shore (at 50 m height) and 600 GW offshore respectively by the United Nations Environment Programme (UNEP) [6]. As shown in Fig. 1, China almost doubled its wind power capacity from 2011 to 2014, and became the global leader in cumulative installed capacity with a total capacity of 115 GW [7].

According to the National Energy Agency (NEA), the national average wind curtailment was about 20% in 2017. The overall curtailment rates do not tell the whole story, as curtailment rates in several provinces were well above this average. The 11 provinces with three-quarters of the country's installed wind power capacity, totally curtailed wind power enough to power Beijing city for six months. Gansu and Xinjiang experienced the highest curtailment rates, respectively curtailing 40 and 37% of variable renewable energy (VRE). These provinces, together with Inner Mongolia, have the greatest installed VRE capacity and a large share of production, which reflects severe wind curtailment in China. This phenomenon has resulted in sharp decline of utilization hours of wind farms, seriously affecting economic benefits of the wind farms and causing fearful wind energy waste [8,9]. Therefore, a precise assessment on capability of wind power accommodation (ACWPA) is well needed to make the most of wind energy, especially in high wind curtailment countries, such as China.

Based on practical operation experience, one of the main reasons of wind curtailment lies in contradiction between the dramatic growth of wind power installed capacity and insufficient system admissible capacity. System planners give priority to local energy resources without comprehensively considering generation structure, transmission line capacity and wind power accommodation and so forth, during period of wind farms construction [10]. During operation, high wind curtailment normally occurs in valley load due to deficient peak power regulation flexibility and

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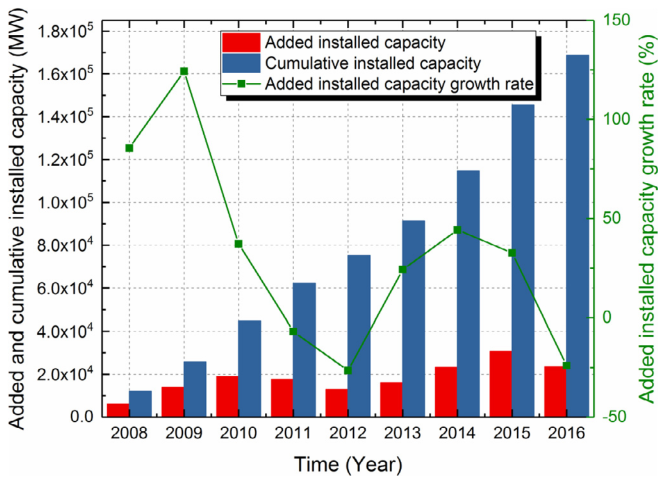


Fig. 1. Schematic of wind power installed capacity in China.

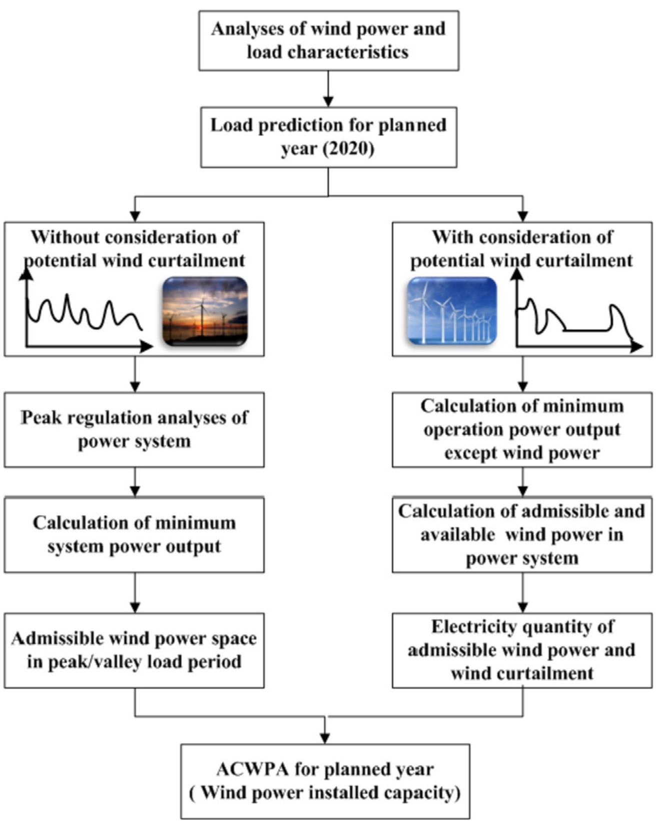


Fig. 2. Computation diagram of long-term assessment.

operation security constraints. Moreover, there is not a precise and reliable reference for wind power accommodation calculation during operation. Therefore, it is of great significance to propose a novel ACWPA for regional power grid in both long-term and short-term time scales.

The purpose of ACWPA is to calculate the maximum admissible wind power by various methods in multiple timescales. There are many factors that have an effect on capability of wind power accommodation, such as wind power characteristics, power system flexibility, transmission line capacity, control strategies, active power dispatch and policy criterion [11–13]. ACWPA is divided into long-term and short-term in timescales. The year-based or month-based long-term assessment provides reference for wind farms planning and scheduled maintenance. Short-term assessment works in day-ahead to make active power dispatch and tie-line schedules.

Many worldwide academic investigations have been devoted to the study of wind integration and ACWPA. A number of studies of long-term ACWPA carried on recent years [14–21]. Kaldellis et al. have done a lot of work on estimating wind energy penetration in autonomous electrical networks [14–16]. Optimum size and maximum wind energy penetration limit of Greek were evaluated and an integrated study is carried out based on long-term wind-potential experimental measurement [14]. Another integrated methodology is developed to estimate the maximum wind penetration in the Aegean Archipelago area with investigating many types of wind potential [15]. Reference [17] proposes a probabilistic optimization model utilizing a combination of recourse and chance-constrained approaches to assign optimal wind power capacity for long-term assessment. Regarding to the transmission constraint on wind power penetration [18,19], reference [19] study the potential of the transmission expansion planning which can lead to private investment absorption for development of the wind power. An estimation of potential wind curtailment is developed under a regional wind power expansion model to assess capacity factors and curtailments with deep penetration of wind power into the New York State electricity grid [20]. Moreover, a comprehensive assessment of the capacity credit of potential wind power developments in Mexico has been conducted for the first time [21].

Short-term ACWPA is also developed to discuss the integration problem to improve wind power accommodation [22,23]. Reference [22] presents an assessment model of wind power accommodation solved with day-head unit commitment, obtaining an envelope of accepted wind power. Dispatch Strategy, electric power transmission and additional energy storages including pumped hydroelectric energy storage and hydroelectric production are investigated to increase wind power accommodation [24–27]. Furthermore, wind power integration in power grids is maximized from many other aspects addressing voltage stability [28], wind-thermal coordinated scheduling [29,30] and frequency stability [31]. ACWPA also can be performed through several computational approaches, like static optimization [32,33], frequency constraint method [34]. Reference [32] takes minimum total cost of system including wind power cost, transmission cost and operation cost etc. as an objective function. The optimum wind penetration capacity is calculated through repetitive iteration. Another aspect is that wind penetration can be limited by frequency response criteria. An estimation tool of maximum wind penetration level is developed from the frequency response, of which input is inertia and headroom while the output is the highest margin of wind power [34].

In above mentioned investigations, many different approaches and constraints are applied to ACWPA. Nevertheless, none of them propose both long-term and short-term evaluation in terms of the data and wind power characteristics from practical regional power grids. Most of long-term assessments do not consider potential wind curtailment for wind power penetration planning, and most short-term assessment results consider operation constraints deficiently, which cannot provide enough precise information for system operators. The main work of ACWPA in this paper can be summarized as follows:

a) In order to make a practical and reliable long-term wind power planning, the paper presents a long-term assessment approach considering potential wind curtailment. It is calculated through peak power regulation, and the proposed long-term method can obtain precise and reasonable wind power installed capacity for wind farms planning. Therefore, redundant installed capacity and reserve capacity could be reduced for saving construction cost.

b) A short-term ACWPA is proposed to obtain admissible zone of wind power in advance for active power dispatch in this paper. The approach combines short-term wind power forecasting and unit-commitment to optimize the limit of admissible wind power, and results show an admissible zone that reflects variation tendency and accepted space of wind power.

The remainder of this paper is organized as follows. In Section 2, detailed descriptions of the proposed ACWPA methods are presented, including long-term assessment and short-term assessment. Section 3 analyzes wind power development based data set in a province in Southern China. Section 4 is devoted to the simulations and discussions of results. Conclusions and future works are given in section 5. Research is under auspicious of the National Natural Science Foundation of China (51477174) and NSFC-UK Royal Society International Cooperation & Exchange Program (51711530227).

2. Methodology

There are two ACWPA methods developed in this paper. The first one is a long-term assessment based on peak power regulation that serves wind farm planning, and the other is a short-term assessment based on wind power forecasting, which is mainly for power system operation.

2.1. Long-term assessment based on peak power regulation

This assessment contains two scenarios distinguished by whether concerning potential wind curtailment. In general, the power system should consider preserving adequate reserve capacity and peak power regulation capability so as to cope with the wind power uncertainties. Peak power regulation is a phenomenon that power output of generators increase or decrease so as to satisfy load demand during peak or valley load period. The capability of wind power accommodation can be calculated during peak or valley load period, which obtains results without considering potential wind curtailment. Particularly, According to the relationship between the wind power and load curve, the valley load period and peak wind power period are often arising simultaneously, which has an influence on accepting more wind power. Hence, the analysis of load characteristics and peak power regulation characteristics are significant before long-term ACWPA.

Assuming that the monthly peak load is P_{Lpeak}, and β denotes the average peak-valley difference rate that represents the difference between peak and valley load. In the following expressions, the time resolution of each parameter is 1 h. So the monthly valley load can be defined as:

$$P_{Llow} = (1-\beta)P_{Lpeak} \tag{1}$$

If we consider transmission line losses, the system self-supported power output that represents local supply power except tie-line transmission power from other grids during peak and valley period can be shown as:

$$P_{Sup}^{peak} = P_{Lpeak} + P_{Loss} - P_{Tie} \tag{2}$$

$$P_{Sup}^{low} = P_{Llow} + P_{Loss} + P_{Pump} - \lambda_1 P_{Tie} \tag{3}$$

where P_{Sup}^{peak} and P_{Sup}^{low} respectively refers to the system self-supported power output among the period of peak and valley load, P_{Tie} is the tie-line transmission power that is the power flow in transmission lines connecting two interconnected power grids, P_{Loss} denotes grid loss, P_{Pump} is the capacity of pumped hydroelectric energy storage, λ_1 denotes the peak adjustment coefficient of tie-line. If P_{Tie} is greater than 0 and λ_1 equals to 90%, it means that the tie-line transmission power can be declined 10% to support peak power regulation of power system.

During the heat period in winter, the calculation should consider units that do not participate in peak power regulation, such as heating units that provide heat in winter. So the potential self-regulated power output of regulated units that participates in peak power regulation can be expressed as:

$$P_{Reg}^{peak} = P_{Sup}^{peak} - \lambda_2 P_{Heat} \tag{4}$$

$$P_{Reg}^{low} = P_{Sup}^{low} - \lambda_2 P_{Heat} \tag{5}$$

where P_{Reg}^{peak} and P_{Reg}^{low} are the potential self-regulated power output during peak and valley load period respectively. P_{Heat} is the installed capacity of heating units, λ_2 is the output adjustment rate of heating units. The heating units cannot be able to export maximum power due to heat supply tasks. According to operation experience, heating units often gets 70–80% of rated power to support heat addition and drop out of peak power regulation.

The above potential self-regulated power output neglects system reserve capacity, so with the consideration of reserve capacity, the maximum and minimum self-regulated power output during peak and valley load period can be calculated respectively by following equations.

$$\begin{cases} P_{Maxr}^{peak} = P_{Reg}^{peak} + P_{Res} \\ P_{Maxr}^{load} = P_{Reg}^{load} + P_{Res} \end{cases} \tag{6}$$

$$\begin{cases} P_{Minr}^{peak} = \lambda_3 P_{Maxr}^{peak} \\ P_{Minr}^{low} = \lambda_3 P_{Maxr}^{low} \end{cases} \tag{7}$$

where P_{Res} denotes reserve capacity of power system, and λ_3 is minimum output rate of regulated generators, which is obtained by operation experience considering the adjustable capability of different types of units. The minimum self-regulated power output represents the possible minimum power output when regulated generators decrease to the minimum output to participate in peak power regulation.

Therefore, at the valley load period, minimum system power output consists of minimum self-regulated power output, unregulated power output, tie-line transmission power and power output of pumped hydropower energy storage, except wind power. It can be computed via Eq. (8).

$$P_{Sys}^{low} = P_{Minr}^{low} + \lambda_1 P_{Tie} + \lambda_2 P_{Heat} - P_{Pump} \tag{8}$$

Consequently, capability of wind power accommodation can be obtained from the difference value between valley load and the minimum system power output, as shown in Eq. (9). It should be noted that the result P_{Wind}^{spa} denotes admissible space of wind power rather than wind power installed capacity. The admissible installed capacity of wind power should be computed through Eq. (10).

$$P_{Wind}^{spa} = P_{Llow} + P_{Loss} - P_{Sys}^{low} = P_{Reg}^{low} - P_{Minr}^{low} \tag{9}$$

$$P_{Wind}^{ins} = P_{Wind}^{spa} \Big/ \delta \tag{10}$$

where P_{Wind}^{ins} is admissible installed capacity of wind power, δ is the wind power output coefficient which could be different by locations of wind farms and obtained through wind power data analysis, reflecting wind power output level. It can be found that P_{Wind}^{spa} is the difference of potential self-regulated power output and minimum self-regulated power output at valley load period.

Meanwhile, if the system is at non-heating period or does not need to support heat, the output adjustment rate λ_2 of heating units is equal to 0. So the above mentioned equations can be modified without heating units.

$$P_{Reg}^{peak} = P_{Sup}^{peak} \tag{11}$$

$$P_{Reg}^{low} = P_{Sup}^{low} \tag{12}$$

Hence, minimum system power output is defined as Eq. (13), and calculation of capability of wind power accommodation is same as Eq. (9).

$$P_{Sys}^{low} = P_{Minr}^{low} + \lambda_1 P_{Tie} - P_{Pump} \tag{13}$$

Most evaluation methods have ignored practical conditions of wind power production, just considering extreme peak power regulation situation. It will lead to a relatively smaller result due to coarse boundary conditions, which is against for wind power development. According to analyses of system operation experience, wind curtailment is inevitable under contemporary techniques, and restricting wind power during hard period of peak power regulation is a comparatively economical way to increase power quality in peacetime.

Firstly, the minimum local operation power output except wind power is computed based on actual operation condition and load profile.

$$P_{mins,i}^{sys} = \lambda_3 \left(P_{Lmax} + P_{Loss,i} + P_{Res} - P_{Tie,i} \right) \tag{14}$$

where $P_{mins,i}^{sys}$is the minimum local operation power output except wind power that represents the minimum local power output without tie-line transmission power during peak power regulation, $P_{Loss,i}$ is grid loss, $P_{Tie,i}$ denotes tie-line transmission power, the i in above mentioned variables means i period, P_{Lmax} is maximum load forecasting value. The formula in parentheses of Eq. (14) represents the maximum supply power which should supply the maximum load value P_{Lmax} during each i period.

The admissible space of wind power that represents at i period can be determined as:

$$P_{Wind,i}^{adm} = P_{Load,i} - P_{mins,i}^{sys} \tag{15}$$

where $P_{Load,i}$ is load prediction value during each i period.

And the available wind power from wind farms at i period, that represents the potential output generated from wind farms, could be computed through wind power output coefficient and installed capacity.

$$P_{Wind,i}^{ava} = P_{Wind}^{ins} \cdot \delta_i \tag{16}$$

where δ_i is the wind power output coefficient which is consistent with the meaning in Eq. (10).

The admissible wind power and potential wind curtailment is determined by the comparison between $P_{Wind,i}^{adm}$ and $P_{Wind,i}^{ava}$. Hence, the admissible wind power that could be completely accommodated by power system can be expressed in followings.

$$P_{Wind,i}^{acc} = \begin{cases} P_{Wind,i}^{adm}, & P_{Wind,i}^{ava} \geq P_{Wind,i}^{adm} \\ P_{Wind,i}^{ava}, & P_{Wind,i}^{ava} \leq P_{Wind,i}^{adm} \end{cases} \tag{17}$$

So the potential wind curtailment is shown as:

$$P_{Wind,i}^{cur} = P_{Wind,i}^{ava} - P_{Wind,i}^{acc} \tag{18}$$

Finally, due to the data resolution that is hour, the annual electricity quantity from wind farms integrated from 1 to 8760, can be calculated by expressions in followings.

$$E_{Wind}^{acc} = \int_{1}^{8760} P_{Wind,i}^{acc} di \tag{19}$$

$$E_{Wind}^{cur} = \int_{1}^{8760} P_{Wind,i}^{cur} di \tag{20}$$

$$K_{Cur} = E_{Wind}^{cur} / E_{Wind}^{acc} \tag{21}$$

$$E_{Gen}^{con} = \int_{1}^{8760} P_{Load,i} di - E_{Wind}^{acc} \tag{22}$$

where $E_{Wind}^{acc}$is admissible wind electricity quantity from wind farms in the whole year, E_{Wind}^{cur}denotes wind curtailment electricity quantity, K_{Cur} is the annual wind curtailment rate, $E_{Gen}^{con}$is the yearly generation electricity quantity except wind power.

In summary, the diagram of computational procedure for long-term assessment is shown as:

2.2. Short-term assessment based on wind power forecasting

The proposed long-term method is mainly applicable to wind farms planning. However, as for short-term operation, wind power uncertainties like wind power ramping events can have a negative impact on system security and economy [35–38]. In order to cope with these uncertainties, system operators wish to estimate the maximum wind power in advance during operation, which is helpful for dispatch schedule.

The deep sense of short-term assessment in this paper can be concluded as followings:

a) Most available long-term assessment researches discuss the ACWPA during extreme periods, such as peak or valley load period. However, the matching result of load and wind power curve always has diversity. So there is also a possible deficiency on capability of wind power accommodation at peace time, which indicates a comprehensive full time estimation is imperative.
And as for short-term evaluation, it is needful to develop an assessment method considering variety of operation factors.
b) Although the accuracy of wind power forecasting is not as high enough as the precision of load prediction, it provides much precious information for system dispatch and operation. Therefore, how to effectively integrate prediction information into researches on assessment is a priority for development of power system dispatch containing wind power.
c) The available study on ACWPA is mainly presented by one-dimensional results that provide a determine value. However,

it cannot reflect precise variation and admissible space of practical wind power, which has no support for operators to judge if wind power can be accommodated. It is desiderative to propose a new method to solve this problem.

Firstly, day-ahead unit commitment is optimized with the consideration of short-term wind power and load prediction. The admissible zone of wind power is constructed based on results of first step. Moreover, in order to extend positive direction of admissible zone, the extreme wind variation scenario (EWVS) that represents the most serious fluctuant scenario as a criterion for the assessment, is calculated through quadratic programming. Ultimately, the final admissible zone of wind power can be decided through optimization with EWVS. The range consists of two curves, the upper limit curve and the lower limit curve. If actual wind power production exceeds the former one, there will be wind curtailment or actions of energy storage because of scarcity of peak power regulation ability. If actual wind power less than the latter one, redundant conventional reserve units or AGC units should prepare to compensate for power vacancy in power system. Consequently, the admissible zone can be a reference for wind power dispatch. Moreover, in order to improve assessment accuracy, receding optimization and feedback correction are adopted during overall process, and the receding and optimization horizon is 1 h and 24 h respectively.

The unit commitment regards tracking wind power prediction and minimum wind curtailment and fluctuation as a principle, so the objective function is presented in followings. It should be noted that the assessment regards the wind power in power system as an entirety, which means the optimization variable is not set as each wind farm.

$$\min F(P_{Wind,t}) = \sum_{t=1}^{T}\left\{\left[\sum_{i=1}^{N}\left(k_i C_{i,t}^{o} + C_{i,t}^{s} + C_{i,t}^{c}\right)\right] + \left[(P_{Fore,t} - P_{Wind,t})\right]\right\} \tag{23}$$

where $P_{Fore,t}$ is short-term wind power prediction during period t, the optimization variable $P_{Wind,t}$ represents the basic wind power output which is utilized to subsequent upper limit optimization, T is optimization horizon that is the same as prediction horizon, $C_{i,t}^{o}$, $C_{i,t}^{s}$, $C_{i,t}^{c}$ are operation coal consumption, starting coal consumption and closing coal consumption respectively. These three parameters can be calculated according to reference [39]. The constraints can be shown as:

$$\begin{cases} P_{Load,t} - \sum_{i=1}^{N} k_i P_{C,i,t} - P_{Wind,t} = 0 \\ P_{C,i,t}^{\min} \le P_{C,i,t} \le P_{C,i,t}^{\max} \\ P_{C,i,t} - P_{C,i,t-1} \le \Delta R_{Cup,i}^{\max} \\ P_{C,i,t-1} - P_{C,i,t} \le \Delta R_{Cdown,i}^{\max} \\ \sum_{i=1}^{N} k_i P_{C,i,t}^{\max} - \sum_{i=1}^{N} k_i P_{C,i,t} - P_{Wind,t} \ge S_{up,t}^{\min} \\ \sum_{i=1}^{N} k_i P_{C,i,t} + P_{Wind,t} - \sum_{i=1}^{N} k_i P_{C,i,t}^{\min} \ge S_{down,t}^{\min} \\ 0 \le P_{Wind,t} \le P_{Fore,t} \\ k_i = \begin{cases} 1, & \text{the unit cannot be shut down} \\ 1 \text{ or } 0 & \text{the unit can be shut down} \end{cases} \end{cases} \tag{24}$$

where $K = \{k_i | i \in 1 \cdots N\}$ is the on-off state of conventional units, k_i equals 1 means the unit is on and 0 represents off. $P_{C,i,t}$ is the power output of conventional units during t period, $P_{Wind,t}$ is the planning wind power of system. $P_{Load,t}$ is the load prediction during period t, $P_{C,i,t}^{\min}$ and $P_{C,i,t}^{max}$ are the minimum and maximum generation power limit respectively. As for the tie-line power, $P_{C,i,t}^{\min}$ and $P_{C,i,t}^{max}$ are the minimum and maximum transmission power capacity. $R_{Cdown,i}^{\max}$ and $R_{Cup,i}^{\max}$ are the ramping rate limit of conventional units. If they represent tie-line transmission power, they mean the allowable fluctuation value of transmission lines under checking standards. $S_{up,t}^{\min}$ and $S_{down,t}^{\min}$ are the minimum positive and negative reserve capacity, which guarantee the safety of power system operation.

The optimal result for on-off state K and basic wind power output $P_{Wind,t}$ are shown as K^* and $P_{Wind,t}^*$ respectively during the next optimization, and they are both regarded as known values. Actually, $P_{Wind,t}^*$ is not the minimum or maximum wind power that could be admitted by power system. Extending the admissible wind power to positive and negative direction from the start point $P_{Wind,t}^*$ can get a range for system operations. So as for obtaining the lower limit $\{P_{Wind,t}^{low}\}$, the objective function and constraints are defined as:

$$\min F\left(P_{Wind,t}^{low}\right) = \sum_{t=1}^{T} P_{Wind,t}^{low} \tag{25}$$

$$\begin{cases} P_{Load,t} - \sum_{i=1}^{N} k_i^* P_{C,i,t} - P_{Wind,t}^{low} = 0 \\ P_{C,i,t}^{\min} \le P_{C,i,t} \le P_{C,i,t}^{\max} \\ P_{C,i,t} - P_{C,i,t-1} \le \Delta R_{Cup,i}^{\max} \\ P_{C,i,t-1} - P_{C,i,t} \le \Delta R_{Cdown,i}^{\max} \\ \sum_{i=1}^{N} k_i^* P_{C,i,t}^{\max} - \sum_{i=1}^{N} k_i^* P_{C,i,t} - P_{Wind,t}^{low} \ge S_{up,t}^{\min} \\ \sum_{i=1}^{N} k_i^* P_{C,i,t} + P_{Wind,t}^{low} - \sum_{i=1}^{N} k_i^* P_{C,i,t}^{\min} \ge S_{up,t}^{\min} \\ P_{Wind,t}^{low} \ge 0 \end{cases} \tag{26}$$

Although the lower limit can be computed by a single optimization, the upper limit is too complex to be calculated by this type of optimization. This is because that the single optimization cannot ensure completeness and reliability on accommodating wind power, and some wind ramp events are probably overlooked. Therefore, we should consider the most serious scenario and iteratively compute through EWVS to improve the dependability of admissible zone. The objective function of the upper limit is presented as:

$$\min F\left(P_{Wind,t}^{up,n}\right) = \sum_{t=1}^{T}\left(\varphi_n \cdot P_{Wind,t}^{*} - P_{Wind,t}^{up,n}\right) \tag{27}$$

Most constraints are consistent with Eq. (26), but the wind power constraint should be changed.

$$0 \le P_{Wind,t}^{up,n} \le \varphi_n \cdot P_{Wind,t}^{*} \tag{28}$$

where φ_n is the expansion factor of upper limit. At the nth time, the initial upper limit will be extended by the product of φ_n and $P_{Wind,t}^*$.

There is a priority to produce the EWVS that can be indirectly computed by system equivalent load. According to definition, system equivalent load represents the residual load that is undertaken by conventional units, which equals load value except wind power. So fluctuation characteristics of wind power are also included in that of system equivalent load, and the wind power problem could be converted to analyses of system equivalent load. Because the lower limit of admissible zone has become determinate through Eqs. (25) and (26), the upper limit and lower limit of equivalent load are certainly defined as:

$$P_{Sys,t}^{up} = P_{Load,t} - P_{Wind,t}^{low} \tag{29}$$

$$P_{Sys,t}^{low,n} = P_{Load,t} - P_{Wind,t}^{up,n} \tag{30}$$

The admissible zone of equivalent load should be ensured that it can accept load curves as far as possible under constraints of power system. However, the zone at present is unreliable since it may not encompass the maximum peak-valley load curve and the fastest upward/downward wind power ramp events. Therefore, the EWVS which could also reflect to the extreme equivalent load scenarios is needed to solve this issue. The extreme equivalent load scenarios enables the system to face the most difficult peak power regulation and load tracking so as to test the reliability of the admissible zone. So two conditions should be satisfied: a) It should be within the scope of definite equivalent load limit. b) It should have the most extreme variation.

According to above conditions, with the definition of $P_{Sys,t}^{ex,n}$ regarding as the extreme equivalent load scenario for the nth expansion, constraints are shown as:

$$P_{Sys,t}^{ex,n} \in \left[P_{Sys,t}^{low,n}, P_{Sys,t}^{up}\right] \tag{31}$$

$$\Delta P_{Sys,t}^{ex,n} = P_{Sys,t}^{ex,n} - P_{Sys,t-1}^{ex,n} \tag{32}$$

$$\min F\left(P_{Sys,t}^{ex,n}\right) = -\left[\frac{1}{T-1}\sum_{t=2}^{T}\left(P_{Sys,t}^{ex,n} - P_{Sys,t-1}^{ex,n}\right)^2\right] \tag{33}$$

where Eqs. (32) and (33) respond to the condition b), which obtains the extreme fluctuation characteristics for EWVS.

The matric manifestation of Eq. (33) is:

$$\begin{cases} B_{t-1,t-1}^{(t)} = B_{t,t}^{(t)} = 1 \\ B_{t-1,t}^{(t)} = B_{t,t-1}^{(t)} = -1 \end{cases} \tag{34}$$

$$B^{(t)} = \begin{bmatrix} 0 & & & & & \\ 0 & \ddots & & & & \\ & \ddots & 1 & -1 & & \\ & & -1 & 1 & \ddots & \\ & & & & \ddots & 0 \\ & & & & & 0 \end{bmatrix} \tag{35}$$

$$\left(P_{Sys,t}^{ex,n} - P_{Sys,t-1}^{ex,n}\right)^2 = \left[P_{SYS}^{ex,n}\right]^T B^{(t)} P_{SYS}^{ex,n} \tag{36}$$

$$\min F\left(P_{Sys,t}^{ex,n}\right) = -\left[\frac{1}{T-1}\sum_{t=2}^{T}\left[P_{SYS}^{ex,n}\right]^T B^{(t)} P_{SYS}^{ex,n}\right] \tag{37}$$

where $P_{SYS}^{ex,n}$ is the $t \times 1$ vector of $P_{Sys,t}^{ex,n}$, $B^{(t)}$ is a $t \times t$ matrix.

The objective function Eq. (37) and the constraint (31) can constitute a convex quadratic programming model. Hence, the EWVS is shown as:

$$P_{Wind,t}^{ex,n} = P_{Load,t} - P_{Sys,t}^{ex,n} \tag{38}$$

Then the upper limit of admissible wind power as mentioned before can be iteratively computed by the reference of$P_{Wind,t}^{ex,n}$. The objective function is defined as:

$$\min F\left(P_{Wind,t}^{test}\right) = \sum_{t=1}^{T}\left(P_{Wind,t}^{ex,n} - P_{Wind,t}^{test}\right) = \Delta P_{Wind}^{ex,n} \tag{39}$$

The constraints are the same as Eq. (26), but the wind power constraint should be altered to:

$$0 \le P_{Wind,t}^{test} \le P_{Wind,t}^{ex,n} \tag{40}$$

Meanwhile, the optimal result should be validated by a kind of index. This paper proposed a wind curtailment coefficient ε that can testify if EWVS could be accommodated completely. It is defined as following:

$$\frac{\Delta P_{Wind}^{ex,n}}{\sum_{t=1}^{T} P_{Wind,t}^{ex,n}} \le \varepsilon \tag{41}$$

There are two situations about the final optimization result. The first is that Eq. (41) is satisfied after the optimization, which means that power system can completely accept the wind power within the range from $[P_{WIND}^{\min}]$to$[P_{WIND}^{\max,n}]$. It also indicates that the upper limit still has potential to be extended, so the expansion factor φ_n can be increased by the following expression.

$$\varphi_{n+1} = \varphi_1 + (n-1)\Delta d \tag{42}$$

where φ_1 is the initial expansion factor, n denotes the times of expansion, Δd is the step length of expansion. Then calculate the upper limit in cycles from Eq. (27)–(42) until Eq. (41) is not satisfied.

However, when Eq. (41) is dissatisfied, which represents that the admissible zone cannot accommodate the EWVS. So the result from the last circulation is the final upper limit of admissible zone of wind power. The combination of the upper limit and the lower limit comprise the final assessment result that represents the short-term capability of wind power accommodation. After a complete optimization during one period, feedback correction is utilized to improve the forecasting precision. The latest real value from data acquisition system would be brought into the input of wind power forecasting as a new historical data, so the forecasting method could utilize the latest information.

The computation diagram of proposed short-term assessment is shown as following:

3. Analysis of wind power development in a regional power grid

In order to validate two proposed assessment approaches, practical data is adopted from a province which is located in Southern China. Wind power characteristics in this province have been analyzed before assessment, which is one of this paper's works and is showed in this section. It is vicariously called PSC (Province in Southern China) due to the confidentiality of the data.

3.1. Wind energy resource

In recent years, PSC has already accomplished the second wind energy resource assessment. It indicates that wind energy resources at 70 m high of the entire province is about 90000 MW, including 8000 MW exploited resources. According to results of wind energy evaluation, wind resources contained in PSC mainly concentrate upon the northern freshwater lake region and the southern high altitude terrain, especially the lake region that is one of the five largest freshwater lakes in China. Fig. 4 shows

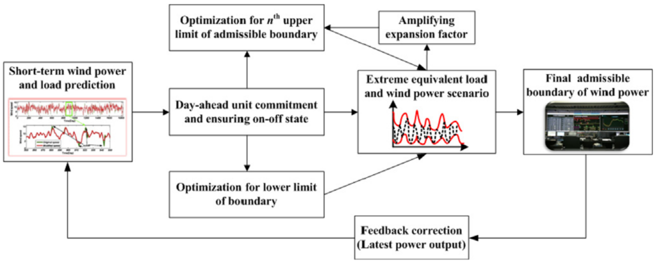


Fig. 3. Computation diagram of the short-term assessment.

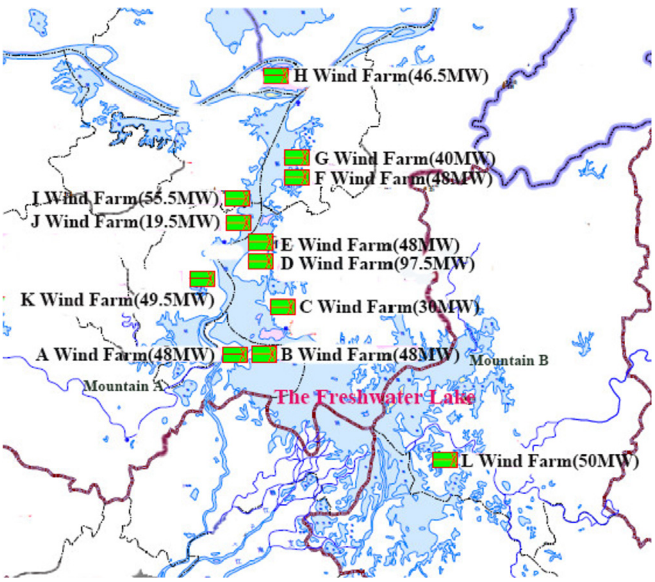


Fig. 4. Distribution of wind farms around the freshwater lake.

distribution of wind farms around the freshwater lake. This region can be divided into five partitions according to the wind energy resource, including wasteland zone ($\leq$50 W/m^2), slight wasteland zone (50 ~ 100 W/m^2), available zone (100 ~ 150 W/m^2), slight abundant zone (100 ~ 150 W/m^2) and abundant zone ($\geq$200 W/m^2), as shown in Table .1. Moreover, the abundant zone in this region is from the lake to the mountain A and mountain B, which amounts to 60 km and has been shown in Fig. 2. The evaluation indicates the quality of wind energy resource in this area is affluent so that it should apply to wind power development. Moreover, the exploration data shows that the technology developing potentiality of wind energy resource in PSC makes up 8000 MW, which means these wind energy could be transformed into wind power potentially.

3.2. Structure of wind power and load demand

By the end of December 31, 2015, the total generation plants in PSC amount to 39, including 13 thermal power plants, 11 hydraulic power plants, 12 wind farms and 3 photovoltaic power stations. The total installed capacity of the whole grid amounts to 18637.9 MW. Furthermore, thermal power installed capacity is 15940 MW that makes up 85.52%. Compared with hydroelectric power installed capacity accounting for 9.5% and summing to 1769.7 MW, the 4.98% of total capacity are wind power and photovoltaic power, among which is 808.2 MW and 120 MW respectively. According to the statistics, wind power installed capacity in PSC consists of 12 wind farms, including A Wind Farm (48 MW), B Wind Farm (48 MW), C Wind Farm (30 MW), D Wind Farm (97.5 MW), E Wind Farm (48 MW), F Wind Farm (48 MW), I Wind Farm (55.5 MW), M Wind Farm (46.2 MW) and, N Wind Farm (48 MW), O Wind Farm (47.5 MW), P Wind Farm (48 MW), Q Wind Farm (180 MW), R Wind Farm (49.5 MW) and S Wind Farm (44 MW). Locations of some wind farms have been shown in Fig. 2. Meanwhile, it should be noted that B Wind Farm has been merged into A Wind Farm, and M to S Wind Farm are in the mountain region so that they are not shown in Fig. 2. There are also some wind farms in the freshwater lake region like C, G, H, J, K, L Wind Farms are still offline for the power grid. According to the data from Nation Energy Administration [40], annual wind power utilization hour of PSC in 2015 ranked the eighth among 32 provinces in China, which is 17.5% higher than the national average level. Therefore, the development of wind power in PSC has taken forefront among most provinces.

However, as one of the developing provinces in China, PSC has a low load level. As shown in Table .2 [41], the average per capita electricity consumption of PSC was less than one-half the national average for a long time, which hovered between 46% and 49%. It eventually broke through the 50% of national average in 2010. And in 2012 and 2014, it reached the 52% and 54% respectively. Hence,

Table 2
Average per capita electricity consumption (unit: kWh).

Year	PSC	Jiangsu	Zhejiang	Guangdong	Nation
2000	504	1326	1606	1780	1067
2001	533	1466	1839	1874	1158
2002	586	1687	2175	2148	1286
2003	707	2032	2634	2554	1477
2004	796	2446	2931	2875	1695
2005	912	2935	3353	2908	1913
2006	1032	3359	3764	3171	2180
2007	1174	3833	4252	3512	2482
2008	1247	4017	4457	3545	2607
2009	1380	4213	4688	3554	2781
2010	1575	4900	5187	3889	3134
2011	1866	5426	5706	4188	3497
2012	1930	5789	5868	4384	3684
2013	2092	6243	6280	4537	3993
2014	2242	6297	6365	4881	4133

Table 1
Wind energy resource of PSC.

Location	Wind power density(W/m^2)	Area(m^2)	Wing energy resources(MW)	Technology developing potentiality(MW)
The freshwater lake region	$\geq$200	600	6350	3100
	150 ~ 200	790	6350	
	100 ~ 150	2190	7750	
	50 ~ 100	5060	8800	
	< 50	13690	8450	
The mountain region	$\geq$150	800	6300	4900
	<150	59260	24900	
Other region	<50	84510	21100	/
Total	/	166900	90000	8000

from the point of view of per capita electricity consumption, it is conspicuous that PSC legs behind the nation about 6 or 7 years and has a certain gap compared with developed provinces, such as Guangdong province. In addition, according to data from the State Grid Corporation of China (SGCC), maximum load level of PSC was still far from high level, which is 15400.8 MW in 2014 and ranked 23 in the whole nation. Although PSC has developed rapidly and load level growing each year, its electricity consumption is limited to accommodate more wind power. Considering this situation, if the proportion of wind power has reached the degree which can cause influences in system operation, issues of accommodation will come out in PSC because of its low load level. Therefore, there is no doubt that the study of ACWPA in PSC is essential.

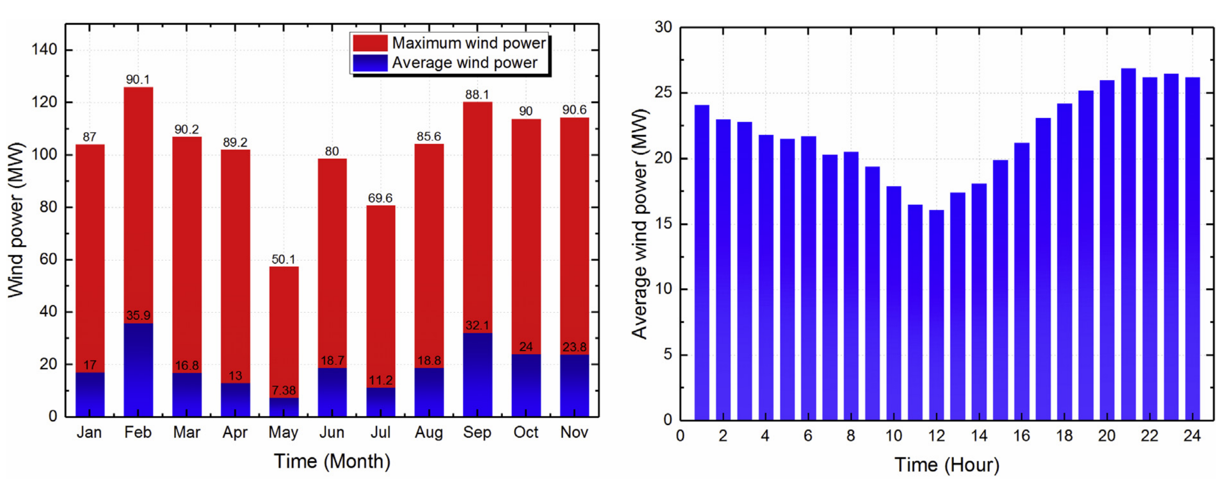
3.3. Analyses of wind power characteristics

On the basis of real data, an example of A Wind Farm, which is located in the freshwater lake region and composed of 48 wind turbines (2 MW) amounting to 96 MW, is cited to illustrate the characteristics of wind power in PSC. This wind farm is one of the most typical and earliest established wind farms in PSC. The time scale of data is from August 2014 to August 2015, with 15 min resolution. Fig. 5 depicts wind power statistic of A Wind Farm, including monthly wind power statistic and hourly wind power statistic. As can be seen from the monthly wind power statistic, the maximum wind power exceeds 90 MW in February, March, October and November. It is obvious that power output in winter is mostly higher than that in summer. Although average power output in other months are vastly different, wind power in summer is generally less than that in winter. According to the hourly wind power statistic, it can be seen that the maximum average wind power is at 21:00. Moreover, the output at 19:00–1:00 is higher relatively. Compared with that, the minimum average wind power appears at 12:00 and 10:00–14:00 is lower during the whole day. Consequently, it is conceivable that the average output at night is greater than the output during the day. In other words, variation trend of wind power is in contrast with load curve, which is one of characteristics that reverse peak power regulation. It may cause some problems when system is dispatching and controlling. Therefore, ACWPA is necessary to alleviate impacts caused by the undesired characteristic.

Characteristics of the whole province are discussed in this paragraph. Table .3 depicts the monthly electricity quantity of total wind farms and wind electricity quantity utilization ratio from 2013 to 2015. The wind electricity quantity utilization ratio is the specific value of monthly electricity quantity and rated electricity quantity that is the product of installed capacity and time of month. It can be seen that wind electricity quantity has an upward tendency, and the seasonal feature indicates that most months in winter have more generating electricity than that in summer. However, the wind electricity utilization ratio of each year is relatively low with irregular variation, such as maximum value which is 43.4% in February 2014 but minimum ratio is just 8.79%. It is unquestionable that the overall utilization ratio of PSC is immediately needed to be improved. Otherwise, based on practical data in 2015, wind power output level of PSC is shown in Fig. 6. The ordinate represents daily wind power utilization ratio which is the specific value of the average wind power and rated power. Three periods are selected in the figure to analyze wind power characteristics of PSC, including high wind period in winter (January 15th to February 14th), summer (August 1st to August 31th) and high flood period (May 1st to May 31th). Meanwhile, according to statistics of historical data, the low load period is about at 4 a.m. and high load period is almost at 11 a.m. The analysis indicates that daily wind power utilization ratio is respectively 27%, 27.5% and 20.3% at low load period. Simultaneously, at high load period, the result provides respectively 27.9%, 13.2% and 8.7%. Consequently, it means that the wind power output of PSC at low load level is generally greater than that during high load period, which is another phenomenon that is against to peak power regulation and corresponding to analyses of Fig. 3. What also can be found is that winter has the higher power output than that of summer since the seasonal peculiarity of wind speed.

Fig. 7 depicts comparison between monthly electricity quantity of wind power and hydroelectric power in 2014. According to the report of weather condition in PSC, the high flood period is from May to August. So it is obvious that the hydroelectric power has a high generation during high flood period. During other periods, in order to guarantee the safety of daily consumption of water, the region reduces hydroelectric power generation because of the decrease of precipitation intensity. However, wind power has a contrary feature because of the high wind speed in autumn and winter. As a result, wind power and hydroelectric power are complementary to each in PSC, which is really conducive to develop wind power.

In conclusion, PSC is different from some areas which possess

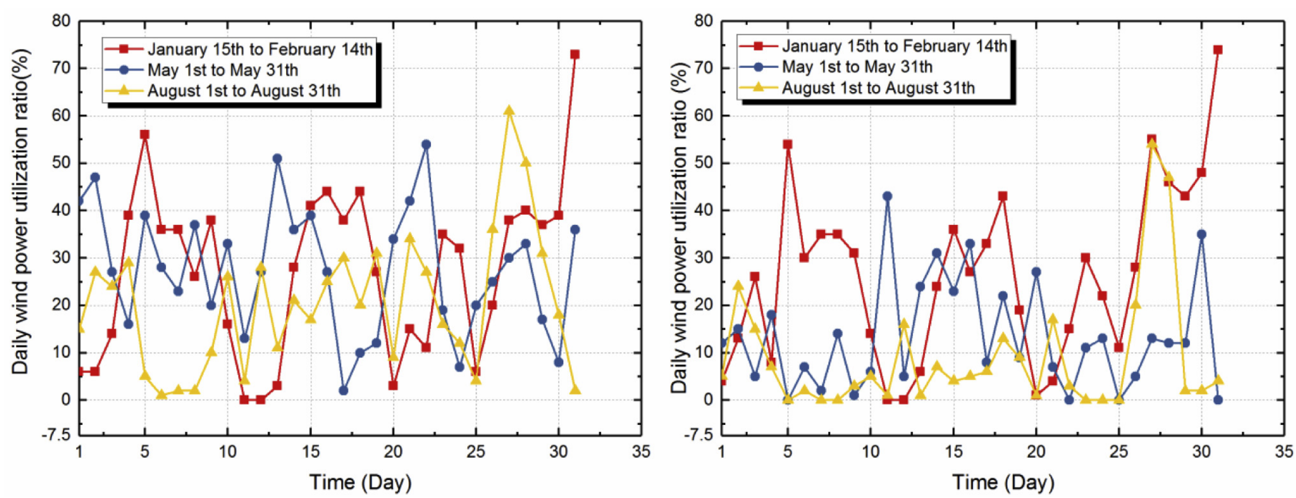


(a) Monthly wind power statistic (b) Hourly wind power statistic

Fig. 5. Wind power statistic of the A Wind Farm.

Table 3
Wind electricity quantity utilization ratio from 2013 to 2015 (unit: $\times$ 10^4kWh).

Month	Electricity quantity (2013)	Electricity quantity (2014)	Electricity quantity (2015)	Wind electricity quantity utilization ratio (2013)	Wind electricity quantity utilization ratio (2014)	Wind electricity quantity utilization ratio (2015)
1	2371	3867	8485	30.35%	20.87%	29.15%
2	2846	7262	7647	36.83%	43.40%	29.09%
3	2890	4084	7868	30.11%	22.05%	26.03%
4	2479	3374	7362	26.69%	18.82%	25.17%
5	1468	2668	6455	12.90%	14.40%	21.15%
6	1557	2077	8156	14.13%	11.59%	24.94%
7	2693	1628	10130	23.66%	8.79%	26.71%
8	3234	3378	6862	28.41%	18.23%	18.01%
9	5238	5253	8675	29.22%	29.30%	22.28%
10	6727	4904	10388	36.31%	22.98%	24.55%
11	4762	5709	9846	26.56%	26.86%	24.05%
12	5460	5022	12374	29.47%	22.87%	29.25%
Average	3477	4102	8687	27.05%	21.68%	25.03%



(a) Low load(4 a.m.) *(b) High load(11 a.m.)*

Fig. 6. Daily wind power utilization ratio in different load level.

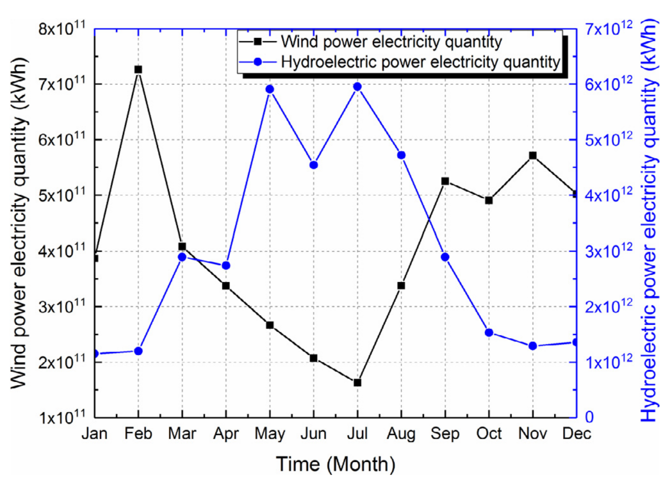


Fig. 7. Monthly electricity quantity of wind and hydroelectric power.

high proportion of wind power, such as Inner Mongolia and Gansu in China. Due to high requirements and resources for developing wind power, PSC is currently going through a dramatic progress for wind power development, with high demand of wind farms planning. Therefore, implementing precise ACWPA is of great significance for PSC to promote wind power utilization efficiency and accommodation capability.

4. Results and discussions

4.1. Case study of the long-term assessment and discussions

The proposed long-term method is validated through the data of PSC, and the wind power characteristics in PSC have been described in section 3. By the end of the December 31, 2015, the total installed capacity is 18637.9 MW, which has 31 thermal generators, 49 hydropower generators, 12 wind farms, 3 photovoltaic stations, 1 pumped hydroelectric power station, 31 500 kV transformers, 247 220 kV transformers, 50 500 kV transmission lines and 452 220 kV transmission lines. This paper regards the 2020 year that is the end of the 13th Five Year Plan of China as the evaluation level year for long-term assessment. Without detailed forecasting process, this paper directly presents the prediction results computed by support vector machine model, because load forecasting is not the main topic and task of this paper.

Table .4 shows that maximum load of 2020 is 36200 MW in August when air conditioners are frequently utilized. On the contrary, minimum load would appear in February. It is because that

Table 4
Monthly load data of PSC in 2020.

Month	Average Load (MW)	Maximum Load (MW)	Average Load Rate (%)	Average Peak-valley Difference (MW)	Maximum Peak-valley Difference (MW)	*Average Peak-valley Difference Rate (%)*
1	24024.54	33498.05	0.72	12229.48	15532.10	0.37
2	18316.36	26282.58	0.70	10172.82	14167.98	0.39
3	21009.36	27892.53	0.75	9651.97	10497.98	0.35
4	20381.83	26553.50	0.77	9311.14	10243.83	0.35
5	19918.70	27226.66	0.73	9368.12	10854.39	0.34
6	21596.59	32091.80	0.67	9357.53	11001.12	0.29
7	26725.53	34623.08	0.77	9506.99	11028.63	0.27
8	28523.95	36200.00	0.79	9414.86	11211.20	0.26
9	23856.49	32242.75	0.74	9911.57	11804.52	0.31
10	22651.96	28904.23	0.78	9842.10	10652.99	0.34
11	23695.71	30661.80	0.77	10439.23	11121.38	0.34
12	26287.84	34826.43	0.75	12272.37	13905.67	0.35

the Spring Festival is coming during that period in China. Many factories and corporations would take a holiday, so the load level is lower than other months. Furthermore, the load rate is the specific value of the average load and the maximum load. It can be seen that the load rate equaling to 67% in June is smaller than others, which implies that the load fluctuation is relatively large in that month, but overall, the load rate is relatively stable. Fig. 8 and Fig. 9 give variation tendency of monthly load level and monthly load peak-valley difference rate. It should be noted that the load peak-valley difference is the difference of peak and valley load in that month, and the denominator of peak-valley difference rate is maximum load of each month. It also can be seen that February has not only minimum load but also maximum peak- valley difference rate in both maximum and average category. Therefore, the peak power regulation in February of 2020 is visibly burdensome with large-scale wind power integration.

Before the calculation, there are some assumed requirements for peak power regulation. Since PSC has many hydroelectric power generators, it is requested that these stations should guarantee reservoirs to be at normal levels so that they can provide regulation ability for peak power regulation. Meanwhile, hydropower generators should keep the largest output as much as possible during the flood period, so the main regulated units are thermal generators during this period.

Simultaneously, the tie-line transmission power in PSC is also pivotal for the calculation. According to historical operation experience, PSC needs transmission power from other power grids since the load cannot be supported by local electricity supply. The following prediction result is referred from the overall planning of State Grid Corporation of China and power flow study of the Central China grid. The main supply region is composed by the hydroelectric power from the Three Gorge and Sichuan province, the thermal power transmitted by ultra-high voltage AC transmission lines from northern China, which has been particularly shown in Table .5.

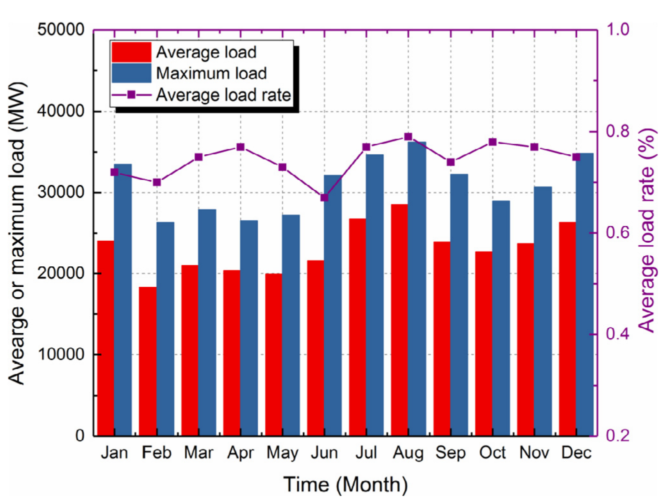


Fig. 8. Monthly load level of PSC in 2020.

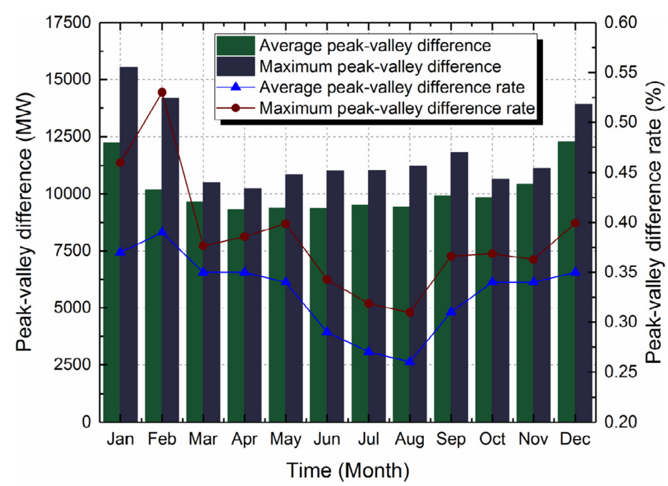


Fig. 9. Monthly load peak-valley difference of PSC in 2020.

It is obvious that the maximum tie-line transmission power is approximately 18440 MW. Consequently, with the load prediction and the above restrains, the long-term assessment without limiting wind power can be calculated by the method in section 2.1. Primarily, there are some border conditions initially set for the calculation. The average rate β of valley-to-peak can be set values from Table .4. The wind power output coefficient δ is set 25% at valley period and 15% at peak period, according to analysis of Fig. 6. The output adjustment rate λ_2 of heating units is 0 due to no need of

Table 5
Tie-line transmission power planning of PSC (2016–2020) (unit: MW).

Project	2016	2017	2018	2019	2020
Total	2440	2440	8440	13440	18440
1.500 kV AC Transmission	2440	2440	1440	1440	1440
Three Gorge	1440	1440	1440	1440	1440
Sichuan	1000	1000	–	–	–
2. Ultra-high Voltage AC Transmission	–	–	2000	2000	3000
3. DC Transmission	–	–	5000	10000	14000
Yazhong-PSC		–	5000	10000	10000
Jinshang-PSC	–	–	–	–	4000

heating units in PSC. The minimum output rate λ_3 of regulated units is set to 40% at valley period and 50% at peak period. The line loss rate is 4% and the percentage reserve is 8% in this paper. Eventually, the following Table .6 depicts results with modulation for the peak adjustment coefficient $\lambda_1$of tie-line.

The result illustrates the capability of wind power accommodation with variation of tie-line regulation capacity. A positive correlation can be found between these two variables. When peak adjustment coefficient equals to 10% and 20%, the result demonstrates that there is no space for wind power, which suggests the conventional generation structure and weakness of peak power regulation of PSC. The capability of wind power accommodation will become active and get 708 MW when λ_1 is 28%, and the admissible installed capacity will increase to more than 4000 MW after 32.5%. When maximum regulation capacity is 9220 MW, the capability can reach 16936 MW. As a consequence, it is apparent that the peak adjustment coefficient of tie-line has a great effect on the capability of wind power accommodation, under a positive correlation.

Moreover, 13th Power Development Five Year Plan for PSC has indicated that the goal of wind power installed capacity by 2020 is 4000 MW. Therefore, what long-term ACWPA could provide for PSC is not only the maximum wind power installed capacity, but also how to accommodate 4000 MW wind power in 2020. Detail results calculated by the proposed method are displayed in Table .8 while the λ_1 is 32.5%, which refers to results in Table .6.

Computational results in Table .6 prove that the peak adjustment coefficient λ_1 of tie-line should be more than 32.5% if 4000 MW wind installed capacity is planned to be accommodated in PSC. Table .7 shows consequences under not only valley load but also peak load. The result depicts that the monthly admissible wind power during peak load is extremely larger than that during valley load. At valley period, it is obvious that the maximum admissible installed capacity is 31841 MW in August when admissible wind power equals to 7960 MW, but the minimum admissible installed capacity is in February that is computed to 4028 MW. The main reason of the phenomenon is that the different load level in every month. August has the maximum load level while February has the minimum load level during valley period, which can be found according to Table .4. In contrast with the former result, the admissible wind power at peak period is less in some months, such as June to September. It is because that the minimum self-regulated power output and tie-line transmission power are higher than these during valley load, which reduces the admissible space for wind power. However, the admissible installed capacity is still greater since the less wind power output coefficient during peak load via Eq. (10). In general, the load level and tie-line transmission power play an important role in the minimum output of regulated units regardless of valley or peak load. According to Table .7, the final result should be the least value in view of the presented method without limiting wind power output, because the wind power should be fully accommodated all year around. Hence, it is obvious that 4028 MW in February during valley load is the minimum result. Meanwhile, the wind power installed capacity is 808.2 MW in 2015 which has been mentioned before in section 3. Compared with 4028 MW, it is obvious that there is a dramatic increase on the capability of wind power accommodation.

Subsequently, another estimation of PSC is performed by the method considering potential wind curtailment as mentioned in section 3.1. The admissible installed capacity of wind power is variable with 3000 MW initial value. The minimum output rate λ_3 of regulated units is 40%, and the wind power output coefficient δ is 20% and other terminal conditions are same as former. According to the former case study, the peak adjustment coefficient λ_1 of tie-line is set to 32.5%. The evaluation result is shown in Table .8.

The result shows that the annual wind curtailment rate is 6.22% while the system accepts 4000 MW installed capacity. In order to find the maximum capability of wind power accommodation, this paper regards 10% as the threshold value. The selected value is smaller than it in Jilin (32%) and Gansu (39%) in 2015, which has 10 GW-scale wind power base. Therefore, the final result described in Table .8 is 6500 MW with 9.45% annual wind curtailment rate. Compared with 4000 MW, the admissible installed capacity efficiently improves 62.5%. It is because that this method is computed on hour time scale which is more precise than the long-term assessment on day or month time scale. Furthermore, the system allows appropriate degree of wind curtailment so that the accommodation ability of wind power is increasing at peace period. A proportion of wind curtailment will benefit the peak power regulation via decreasing the regulation times of regulated units, which matches practical scenarios better. All in all, it is verified that the assessment method with potential wind curtailment obtains a greater result than that of assessment approach without limiting wind power.

4.2. Case study of the short-term assessment and discussions

As we mentioned before, the long-term assessment mainly applies to the planning construction of wind farms. With higher requirement of system operation, evaluating maximum wind power at day-head time scale is also necessary after large-scale wind power penetration. The presented short-term approach in this paper is simulated by practical data from a regional power grid nearby the freshwater lake of PSC. This grid contains 32 generators, and its load level is more than 2000 MW. The simulation exerts practical data on a typical day of August 2016, and wind power installed capacity of this grid has exceeded 500 MW, which has been shown in Fig. 10. As for short-term wind power forecasting model, some works have been done by our research group based on spatial model, which can be referred to [42] for more details. The time resolution of data is set to 30min (48 points on a day) considering the compatibility of control requirements and

Table 6
Variation relationship between wind power accommodation and peak adjustment coefficient of tie-line (unit: MW).

Peak Adjustment Coefficient of Tie-line (λ_1)	The Minimum Tie-line Transmission Power	The Maximum Regulation Capacity	Capability of Wind Power Accommodation
0%	18440	0	–
10%	16596	1844	–
20%	14752	3688	–
28%	13277	5163	708
30%	12908	5532	2184
32.5%	12447	5993	4028
35%	11986	6454	5872
40%	11064	7376	9560
45%	10142	8298	13248
50%	9220	9220	16936

Table 7
Detailed estimation results when λ_1 is 32.5% (unit: MW).

Month	Minimum system power output except wind power (Valley load)	Minimum system power output except wind power (Peak load)	Admissible wind power space (Valley load)	Admissible wind power space (Peak load)	Admissible installed capacity (Valley load)	Admissible installed capacity (Peak load)
1	7566	9458	3417	5362	13666	35743
2	4588	5736	1007	1640	4028	10931
3	5276	6594	2558	2498	10233	16656
4	4730	5912	2081	1816	8323	12109
5	4992	6240	2417	2144	9666	14291
6	6965	8706	5386	4610	21546	30732
7	8059	10074	6879	5978	27516	39854
8	8719	10898	7960	6802	31841	45350
9	7061	8827	4977	4731	19909	31537
10	5707	7133	3015	3037	12059	20248
11	6426	8033	3497	3937	13989	26245
12	8134	10167	4225	6071	16900	40473

Table 8
Estimation results with consideration of potential wind curtailment.

Admissible installed capacity (MW)	Admissible wind electricity quantity ($\times 10^8$kWh)	Wind curtailment electricity quantity ($\times 10^8$kWh)	Annual wind curtailment rate K_{Cur} (%)	Wind Annual utilization hours(h)
3000	74.94	3.90	5.21	2498
3500	87.03	4.95	5.69	2487
4000	98.97	6.15	6.22	2474
4500	110.74	7.52	6.79	2461
5000	122.33	9.07	7.42	2447
5500	133.74	10.80	8.08	2432
6000	144.98	12.70	8.76	2416
6500	156.07	14.75	9.45	2401
7000	166.99	16.97	10.16	2386
8000	188.18	22.06	11.72	2352
9000	208.43	28.09	13.48	2316
10000	227.78	35.02	15.37	2278
12000	264.02	51.34	19.45	2200
14000	296.93	70.99	23.91	2121
16000	326.32	94.16	28.86	2039

computation speed.

It is shown from Fig. 10 that the wind power forecasting curve demonstrates the pernicious characteristic on peak power regulation, which means that wind power has the minimum output during the peak load period. On the contrary, the maximum wind power appears at the valley load period, which would cause wind curtailment because of the pressure of peak power regulation.

There is day-ahead unit commitment in presented short-term ACWPA that is a mixed integer nonlinear programming problem. Directly using MATLAB to optimal the model is complex and tardive, so this paper combines MATLAB with MOSEK mathematic optimal software. As for the peak power regulation, Table .9 gives a standard for different types of generators.

The optimization result of unit commitment indicates that every unit is on-state. Fig. 11 depicts the dispatching output of three typical units in system, including the 120 MW hydroelectric power unit, 220 MW thermal unit and 400 MW thermal unit. It is obvious that the 400 MW thermal unit has a little dispatch variation, since its main task is to undertake basic load of system. Meanwhile, regulation times of the 220 MW thermal unit are as frequent as the hydroelectric power unit, especially the latter. During 4:30 to 6:00 period, the hydroelectric power unit is even out of operation with

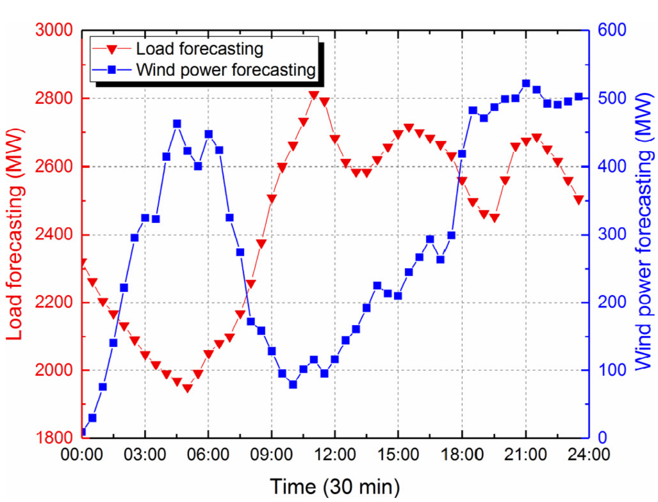


Fig. 10. Wind power and load prediction of the typical day.

Table 9
Adjustable capability of different types of units.

Type of Units	Adjustable Capability (%)
Thermal Power Unit (More than 600 MW)	100–50
Thermal Power Unit (300–600 MW)	100–50
Thermal Power Unit (200–300 MW)	100–60
Thermal Power Unit (100–200 MW)	100–70
Thermal Power Unit (Less than 100 MW)	100–80 or 0
Heating Unit (Heating Period)	100
Compressor-turbine Unit	100–0
Nuclear Power Unit	100
Hydroelectric power Unit	100–0
Pumped hydroelectric energy storage	100∼-100

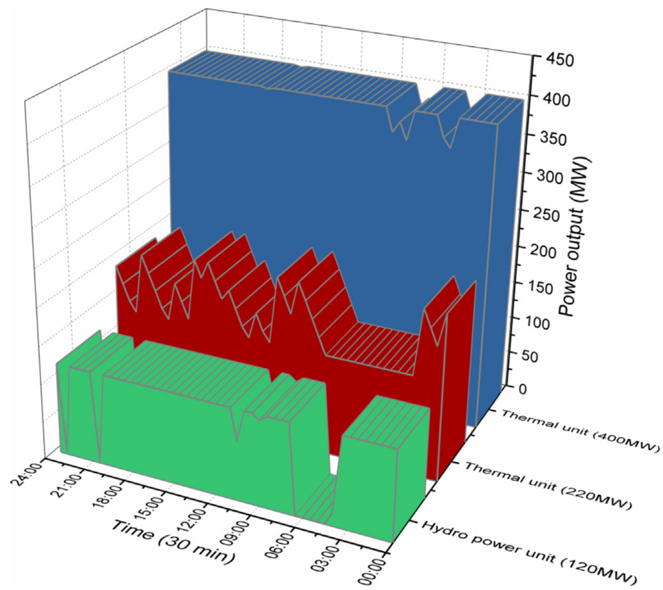


Fig. 11. Power output of typical units.

no output, thereby accommodating more wind power during valley load period. The power curve of 220 MW thermal unit appears to serration after 9:00, which suggests the pressure on peak power regulation of regulated units. And the operation state of the performed system after unit commitment optimization is shown in Fig. 12. It is can be seen that conventional units should reduce output to accept wind power during the period from 4:30 to 6:00.

Regarding results of unit commitment as the basic value for the next optimization, this paper primarily extends the lower limit of the admissible zone. Calculation results illustrate that the lower limit of admissible wind power is 0, which means that the conventional units except wind farms in the system are capable of supplying load demand under operation constrains. It denotes that there is still a high ratio of conventional units as reserve capacity in this grid. Although this is a common phenomenon in China nowadays, large-scale wind power integration will play a major role in power supply, which is inevitable in the future. The

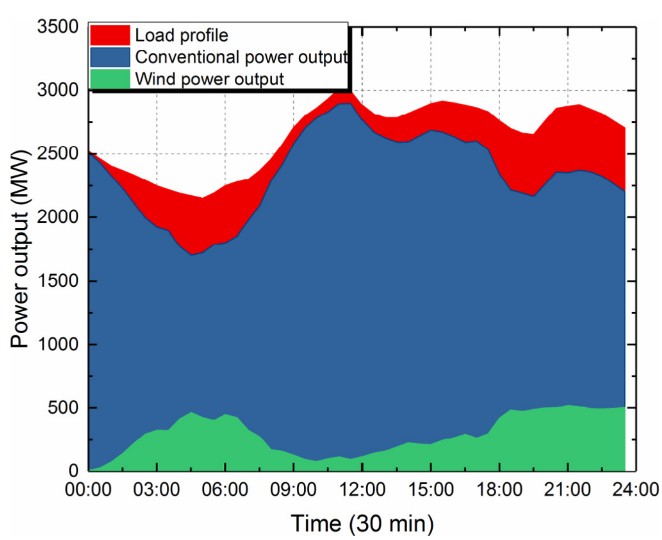


Fig. 12. Operation state after unit commitment.

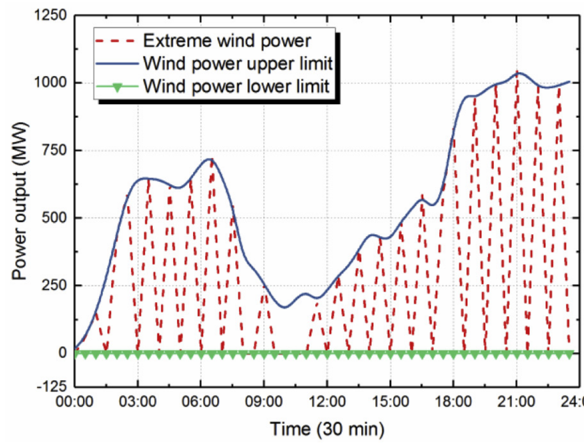
admissible wind power lower limit may no longer 0 by the time.

Subsequently, the upper limit is computed through the model defined in section 2.2. The initial expansion factor φ_1 of upper limit is set to 2 and the step length Δd is set to 1. As a result, the optimization consequence of each expansion process is presented as Fig. 13.

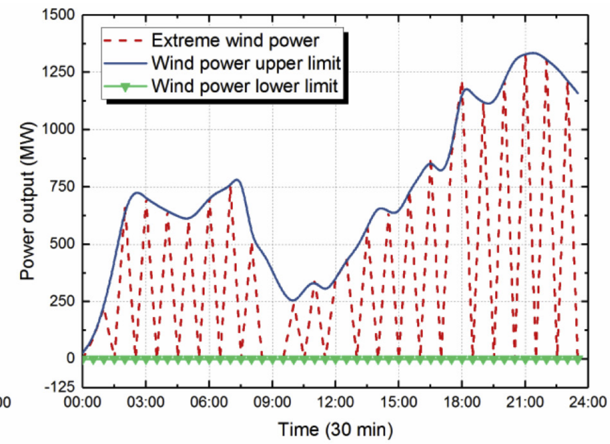
The Fig. 14 depicts the expansion process of upper limit. Furthermore, the circulation of the procedure is ended taking into consideration of threshold value ε named wind curtailment coefficient which is mentioned in section 2.2 and set to 5% in this paper. The wind curtailment coefficient is less than the wind power curtailment rate K_{Cur} of the long-term assessment, which is because that the short-term assessment needs higher accuracy and strict requirement than the long-term assessment. In addition, the purpose of wind curtailment coefficient ε is to testify the accommodation of EWVS so as to determine the upper limit.

It can be seen from the Figs. 13 and 14 that the extreme wind power which represents EWVS has a severe variation. Meanwhile, the shape of the upper limit is similar in every expansion since its optimization in view of the prediction information. In terms of the process, three typical periods are analyzed in this paper. The first period is from 3:00 to 7:30 when optimal values are nearly invariant. The reason is that this period is the most difficult moment of peak power regulation, which can be seen from the Fig. 14. Due to high wind power output but low load level, with the restriction of the system adjustment like ramping rate, the admissible wind power is limited during that period. Furthermore, although the load level is high enough at the second period from 10:00 to 12:30, the upper limit is relatively small. The first reason is that the wind power production is low at that time. Another reason is that the system adjustment and wind curtailment index limit its next expansion. No matter how high the load level is at the second period, the wind power is limited at the first period leading to the growth of the wind curtailment coefficient. Therefore, ε has exceeded threshold value before the higher expansion. It suggests that the estimation is efficient with the consideration of many operation constraints in system and it has intense interaction within it. The third period is from 15:00 to17:30. This period has a sustainable upward trend on upper limit. It is mainly because of the high load level and sufficient capability of peak power regulation, and wind power output is also higher than that at second period.

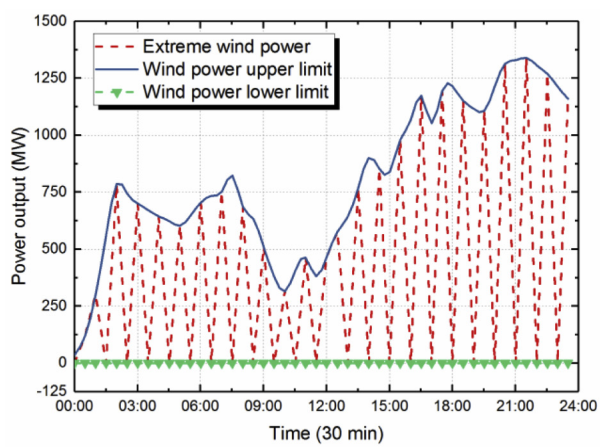
Fig. 15 depicts the admissible zone of the equivalent load and the quantitative result is shown in the Table .10. It illustrates that the maximum value of extreme equivalent load is equal to the maximum value of equivalent load upper limit. Simultaneously, the minimum value of extreme equivalent load is equal to the minimum value of equivalent load lower limit. Therefore, the extreme equivalent load has the largest peak-valley difference within the range, which would make the system face the most severe load tracking. It also can be found from the Table .10 that the load rate of extreme equivalent load is visibly lower than that of the range. The reason of it is that extreme equivalent has the most drastic fluctuation among three curves, which is also the characteristic of EWVS. Consequently, the ultimate admissible zone of wind power is shown in Fig. 16. It is apparent that the admissible zone integrates information from wind power and load prediction. Therefore, the reliability and accuracy of the short-term assessment can be increased with the improvement of forecasting accuracy. Otherwise, in order to validate the reliability of the range, this paper adopts practical wind power data amount to 90 daily curves from the same system and period to verify its effectiveness. The consequence shows that 78 curves are absorbed completely within the range, accounting for 86.7%, which illustrates the range is reliable enough.



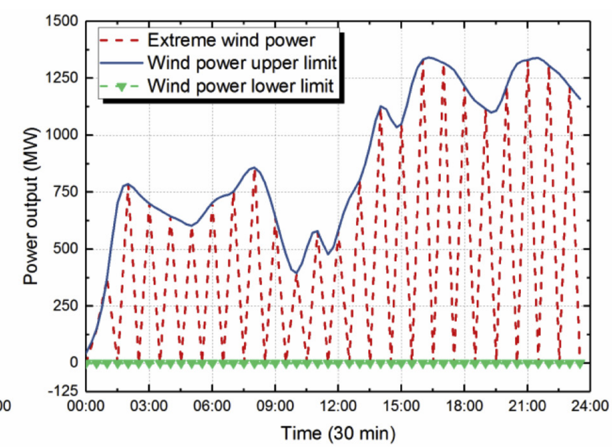
(a) First expansion



(b) Second expansion



(c) Third expansion



(d) Forth expansion

Fig. 13. Optimization result for upper limit.

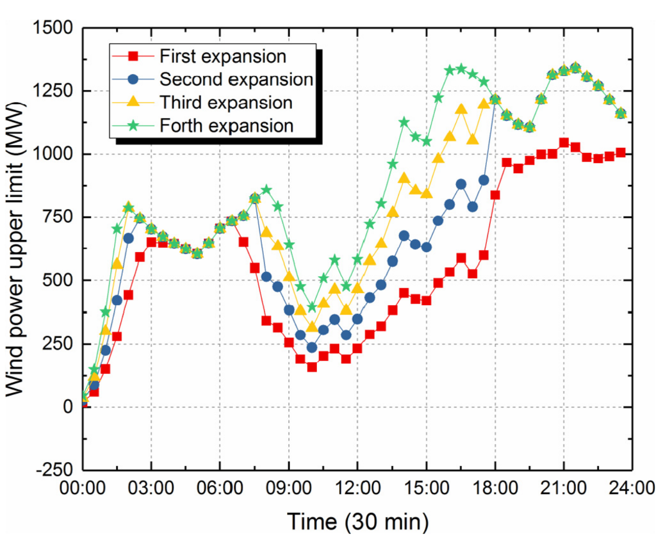


Fig. 14. Expansion process for upper limit.

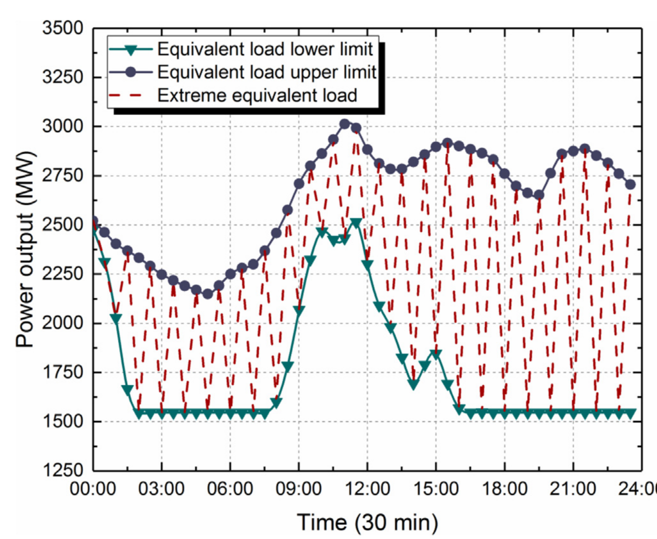


Fig. 15. Admissible zone of equivalent load.

5. Conclusions and future works

This paper performs an analysis of ACWPA in regional power system of China. Two assessment methods on both long-term and short-term are proposed in this paper. The long-term assessment considering potential wind curtailment is developed based on the peak power regulation of system. Meanwhile, a short-term method is presented for obtaining admissible zone of wind power with the

Table 10
Details of extreme equivalent load and admissible zone.

Project	The maximum load level	The minimum load level	Peak-valley difference	Load rate
Equivalent Load Upper Limit	3012.53	2149.63	862.90	0.88
Equivalent Load Lower Limit	2515.88	1546.36	969.52	0.70
Extreme Equivalent Load	3012.53	1546.36	1466.17	0.68

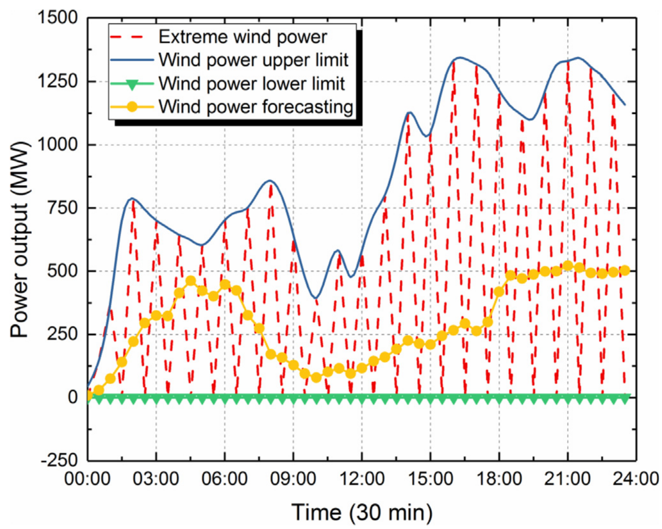


Fig. 16. Final admissible zone of the short-term assessment.

consideration of wind power prediction. Particularly, both evaluation approaches are validated through the data of power grid that is in Southern China called PSC in this paper. As for consequences, on the one hand, the long-term assessment without potential wind curtailment obtains the result that the peak adjustment coefficient of tie-line should be more than 32.5% to accept 4000 MW wind power installed capacity, corresponding to the 13th Power Development Five Year Plan of PSC. The other result illustrates that the method considering potential wind curtailment takes the accommodation at peace periods into account and the accommodation ability would reach 6500 MW, which is better fit the practical development than the former method based on extreme regulation period. On the other hand, the consequence of the short-term assessment gives an admissible zone of wind power for the next day which is subsidiary to the power system operation. The admissible zone can make full use of forecasting information and provide the anticipatory accommodation information for system operators during the dispatch procedure. Moreover, its reliability has been testified thorough practical wind curve making up 86.7%.

The wind power installed capacity is not high but its development is in the midst of the acceleration period in PSC, and the structure of power source in this province is currently limiting wind power admissible space. Therefore, the ACWPA is undoubtedly imperative for this kind of region. However, the long-term assessment still has some shortcoming like rough constrains, which may lead to deviations during evaluation. So the research on short-term or real-time ACWPA would become hotpot, and the combination between ACWPA and power system dispatch is extremely significant for improving operation stability under large-scale wind power penetration. Moreover, intellectual optimization methods for admissible zone should be carried on for further study, and there are still many details to be addressed for accuracy and speed of algorithms.

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