Peak-shaving Requirement Analysis method based on Sequential Monte-Carlo Simulation for Large Scale Wind Power Integrated System

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***Abstract*— In this paper, a peak-shaving requirement analysis method based on sequential Monte-Carlo simulation for large scale wind power integrated system is presented after analyzing the influence of large-scale wind power on the peak-shaving feature of power system. This method establishes the time sequence model of wind power and load, as well as the conventional generators of which the planned outage is also being considered as a random variable, and a three-state transfer model is established. Then the peak-shaving shortage indices of large scale wind power integrated system are defined, which can be used to probabilistically evaluate the peak-shaving requirement of the system. The convergence of the method is verified by IEEE-RTS79 system. At last, the method is applied in the real large power system of Jibei power grid in North China.**

***Index Terms* — Peak-shaving requirement, wind power, Markov process, sequential Monte-Carlo simulation.**

I. INTRODUCTION

DUEto the characteristics of nature, wind power output is often negatively correlated with load demand [1]. So, in North China with rich wind resources, the wind power curtailment problem has already emerged and become more and more serious due to lack of deep peak-shaving and start-stop peak-shaving units. The peak-shaving requirement has become one of the focused factors to evaluate the wind power accommodation capacity of power system [2]. In the planning stage, the worst case always tends to be considered [3], which assumes that it has no wind power output during peak load period in the daytime and rating output during valley load period in the night. This practice actually amplifies the negative effects of wind power and limits the development of wind resource. Therefore, the uncertain nature of wind power generation as well as conventional generators and loads should be considered and the probabilistic analysis methods should be used to analyze the peak-shaving requirement of large scale wind power integrated system. Paper [3]-[8] discussed the wind power accommodating capacity of system with consideration of peak-shaving constraints, but did not consider the randomness of wind power, load and generators.

Peak-shaving problem of large-scale wind power integrated system, with more obvious timing sequence characteristics [9]-[10], is suitable to be analyzed through sequential Monte-Carlo method which can effectively consider the factors related to timing sequence. In paper [11], a peak-shaving margin evaluation method was discussed for wind power integrated system by using sequential Monte-Carlo simulation, but the conventional generators were simulated by two state models in the Monte-Carlo simulation, which can only consider the up state and forced outage state of generators, without regarding to the planned outage state. Therefore, after each state sampling of the generators, it is necessary to carry out the unit combination calculation, and causes the Monte-Carlo simulation being more time consuming and less practical.

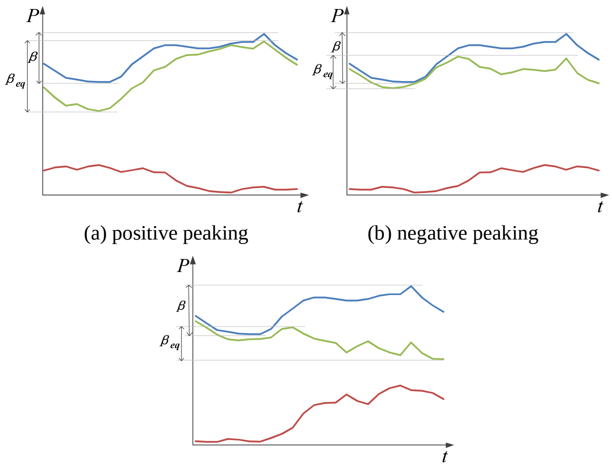
In this paper, a peak-shaving requirement analysis method based on sequential Monte-Carlo simulation for large scale wind power integrated system is presented. By treating the planned outage state also as a random variable, a 3-state model for conventional generator is established in this paper. Through the proposed sampling method, the up states, forced outage states and planned outage states can be determined by Monte-Carlo simulation. This method can be used to analysis the peak-shaving requirement for large scale wind power integrated system or evaluate the wind power accommodation capacity of power system.

II. PEAK-SHAVING INSUFFICIENT INDICES OF WIND POWER INTEGRATED SYSTEM

A. Peak-shaving feature of wind power integrated system

The peak-shaving requirement of the system is mainly affected by the load difference between peak and valley. Considering the wind power output as negative load, and adding to the original load, the equivalent load of the large scale wind power integrated system can be obtained. According to the influence of wind power output on the peak and valley difference of the equivalent load curve, it can be divided into three cases: positive-peak-regulation effect, negative-peak regulation effect and over-peak-regulation effect.

Fig. 1 shows a schematic diagram of the impact of wind power output on the peak-shaving requirement feature of power system, where β represents the peak/valley difference of the original load curve, β_{eq} represents the peak/valley difference of the equivalent load curve, *and* P_{Gmin} is the minimum power generation of the system. As for the negative peak regulation case, the peak/valley difference of equivalent load curve is higher than the original one, and the peak shaving requirement is increased accordingly. When the equivalent valley load is lower than the minimum power generation of the system, the peak shaving capacity insufficient problem appears. In contrast to the negative peak regulation case, the positive peaking regulation of the wind power can reduce the peak-shaving requirement of system. When the penetration of wind power is higher enough, it may even change the feature of load curve, and in some cases, causing over peak regulation, as shown in Fig. 1 (c).



(a) positive peaking (b) negative peaking

(c) over peaking

Fig.1 Schematic of influence of wind power on peaking feature of system

B. Peak-shaving capacity insufficient indices

According to the above the analysis, we can quantitatively analyze the peak-shaving requirement of large scale wind power integrated system, by using the time series of annual wind power output, load, and output of all the generator set of the system.

Firstly, according to the minimum output limits of various generating units in different periods (such as CHP generators in winter seasons, hydro power generators in dry seasons, etc.), the time series of minimum generation of the system can be calculated as (1), where $P_{s,\min}(t)$ represents the minimum power output of the system at t moment, $P_{i,\min}(t)$ represents the technically minimum output of unit i at time t, $S_{g,i}(t)$ is a binary variable sequence indicating whether unit i is in operation at time t, and N is the amount of conventional generators of the system.

$$P_{s,\min}(t) = \sum_{i=1}^{N} S_{g,i}(t) P_{i,\min}(t) \tag{1}$$

Then, by comparing $P_{s,\min}(t)$with the time series of the equivalent load $P_{Load,eq}(t)$, the time series of the system peak-shaving requirement $P_{ps}(t)$ can be obtained by using (2) and (3), where $P_{wind}(t)$ represents the time series of wind power output, and $P_{load}(t)$ represents the time series of original load.

$$P_{ps}(t) = P_{s,\min}(t) - P_{Load,eq}(t) \tag{2}$$

$$P_{load,eq}(t) = P_{load}(t) - P_{wind}(t) \tag{3}$$

According to equation (2), $P_{ps}>0$ means that the equivalent load lower than the minimum power output of the system, and the system will have insufficient peak regulating capacity.

Fig. 2 shows an example curve of peak-shaving requirement of the system for several days. Based on the schematic curve, the definition of three peak-shaving requirement indices can be described below:

- N_{PSCI}——by expanding the time span to one year, the annual times of peak-shaving capacity insufficient incident can be counted through $P_{ps}>0$;
- $P_{PSCI,i}$——the maximum power of the i-th peak-shaving capacity insufficient incident, which is the value of the summit of the shadowed peak;
- $W_{PSCI,i}$——the energy of the i-th peak-shaving capacity insufficient incident, which is the area of the shadowed peak. And the annual peak-shaving energy insufficient can by calculated by (4)

$$W_{PSCI} = \sum_{i=1}^{N_{PSCI}} W_{PSCI,i} \tag{4}$$

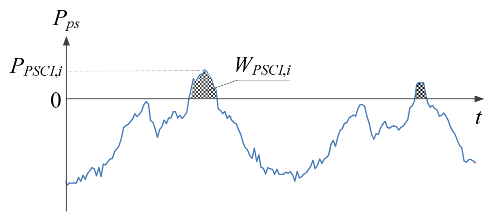
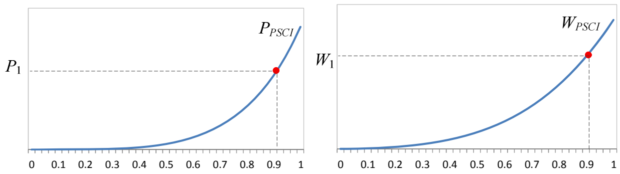


Fig. 2 Schematic curve of peak-shaving capacity insufficient

When peak-shaving capacity insufficient incident happens, because the generation is at minimal output and cannot be shut down for technical or cost reasons, and there is no energy storage to absorb excess power at this time, then wind power output has to be curtailed to maintain balance between generation and load. Therefore, the peak-shaving requirement indices defined above can be used to analyze the need for additional flexible regulating equipment such as peaking units or energy storage for reducing wind power curtailment.

Since it is not economically justifiable to planning the new peak-shaving equipments according to the most serious situation, which might be very low in probability. It is more desirable to determine it considering different probability levels.

By sorting the $P_{PSCI,i}$ and $W_{PSCI,i}$ in an increasing sequence, and normalized by N_{PSCI}, the cumulative probability curves of $P_{PSCI,i}$ and $W_{PSCI,i}$ can be obtained, as shown in Fig. 3. As an example, Fig. 3 shows for 90% of the peak-shaving capacity insufficient cases, the power/energy capacity of peak-shaving requirement will not exceed P_1 and W_1.



(a) $P_{PSCI,i}$ (b) $W_{PSCI,i}$

Fig. 3 Schematic curve of the cumulative probability of peak-shaving requirement

III. SEQUENTIAL MONTE-CARLO SIMULATION MODELS OF WIND POWER INTEGRATED SYSTEM

A. Time sequence model for wind power

Use autoregressive moving average (ARMA) model to generate the wind speed series. The general expression of this model is shown in (5), where y_t is the value of the series at time t, Φ_1, Φ_2, $\cdots$, Φ_n is the autoregressive parameter, θ_1, θ_2,$\cdots$,θ_m is the average sliding parameter, α_t is a normal white noise process with mean of 0 and a variance of σ^2_α, which can be described as $\alpha_t \in N(0, \sigma^2_\alpha)$.

$$\begin{aligned} y_t &= \phi_1 y_{t-1} + \phi_2 y_{t-2} + \cdots + \phi_n y_{t-n} \\ &\quad + \alpha_t - \theta_1 \alpha_{t-1} - \theta_2 \alpha_{t-2} - \cdots - \theta_m \alpha_{t-m} \end{aligned} \tag{5}$$

The wind speed series can be calculated use (6), where μ is the average wind speed, and σ is the standard deviation.

$$v_t = \mu + \sigma y_t \tag{6}$$

Then the time sequence of wind power output can be generated according to the relationship between wind speed and wind power output with being modified by the wake effect coefficient [12].

B. Time sequence model of load

For time series model of loads, it is difficult to model all the uncertain factors, such as weather and holidays. Therefore, two simplified methods are adopted.

- Historical load curve can be obtained.

If the historical load curve is known, the time series model of the load of a target year $P_{load}(t)$ can be obtained by modifying the historical load series$P^0_{load}(t)$ according to the load growth rate n, as shown in (7), where $N(0,\sigma_t^2)$ represents the normal distribution with mean 0 and variance σ_t^2

$$P_{load}(t) = P^o_{load}(t) \times n + N(0,\sigma_t^2) \tag{7}$$

- Historical load curve cannot be obtained.

If the historical load curve is unknown, a practical model [13] can be used to simulate the time series of load, as given in (8) and (9), where $P_{load}(t)$ is the load at time t, $\overline{P}_{load}(t)$ is the expected value of the load at time t, a normal distribution is used to model the influences of uncertain factors; $P^{\max}_{L,f}$ is the maximum load of the target year, $P^*_{L,week}(t)/P^*_{L,day}(t)/P^*_{L,hour}(t)$ is the ratio of the maximum load in the week/day/hour that covers time t to the maximum load in the year/week/day.

$$P_{load}(t) = \overline{P}_{load}(t) + N(0,\sigma_t^2) \tag{8}$$

$$\overline{P}_{load}(t) = P^*_{L,week}(t) \times P^*_{L,day}(t) \times P^*_{L,hour}(t) \times P^{\max}_{L,f} \tag{9}$$

C. Time sequence model for conventional generator

a) Three-state space model of conventional generator

Besides up state and planned outage state, the planned outage stage is also treated as a random variable. And then, a 3-state model of conventional generators is established. Fig. 4 shows the 3-state space of conventional generators, where λ_p/λ is the transition rate of planned/forced outages, μ_p/μ is the recovery rate of planned/forced outages.

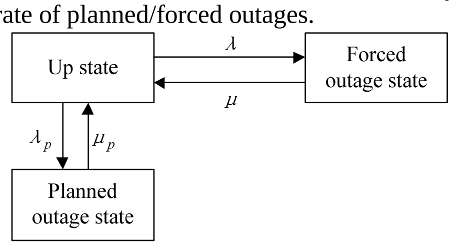


Fig. 3 3-state space of conventional generators

μ_p and can be calculated by (10), where MTTR represents mean time to repair from forced outage, and MTTR$_P$ represents mean time to repair from planned outage.

$$\mu = \frac{8760}{MTTR}, \quad \mu_p = \frac{8760}{MTTR_p} \tag{10}$$

By applying Markov method [14] to the state space diagram, the state transfer matrix can be obtained as (10):

$$T = \begin{pmatrix} 1-\lambda_p-\lambda & \lambda_p & \lambda \\ \mu_p & 1-\mu_p & 0 \\ \mu & 0 & 1-\mu \end{pmatrix} \tag{11}$$

According to the Markov process approximation principle, the probability of each state can be obtained as follows:

$$\begin{cases} P_{up} = \dfrac{\mu_p \mu}{\lambda_p \mu + \lambda \mu_p + \mu_p \mu} \\ P_{fo} = \dfrac{\lambda \mu_p}{\lambda_p \mu + \lambda \mu_p + \mu_p \mu} \\ P_{po} = \dfrac{\lambda_p \mu}{\lambda_p \mu + \lambda \mu_p + \mu_p \mu} \end{cases} \tag{12}$$

The frequency of entering the planned and forced outage state can be calculate as (12), where P_{up}, P_{fo}, P_{po} are the probabilities of up state, forced outage state and planned outage respectively. f_p and f are the frequency (times/year) of planned outage and forced outage respectively.

$$\begin{cases} f_p = \dfrac{\lambda_p \mu_p \mu}{\lambda_p \mu + \lambda \mu_p + \mu_p \mu} \\ f = \dfrac{\lambda \mu_p \mu}{\lambda_p \mu + \lambda \mu_p + \mu_p \mu} \end{cases} \tag{13}$$

Generally, the statistical parameters that can be easily obtained are f, f_p, MTTR and MTTR$_P$. So in order to obtain the result of P_{up}, P_{fo} and P_{po} from (11), λ_p and λ should be calculated firstly by (14), which is derived from (13).

$$\begin{cases} \lambda = \dfrac{f \mu_p \mu}{\mu_p \mu - f \mu_p - f_p \mu} \\ \lambda_p = \dfrac{f_p \mu_p \mu}{\mu_p \mu - f \mu_p - f_p \mu} \end{cases} \tag{14}$$

b) Sampling method of state transfer sequence of conventional generators

Besides the time to failure of forced outage (TTF) and time to repair from forced outage (TTR),the time to failure of planned outage (TTF$_P$) and time to repair from planned outage (TTR$_P$)are also assumed subjecting to the exponential distribution. So the sampling method of the state transfer sequence of conventional generators can be described as (15),where MTTF and MTTF$_P$ represent the mean time to failure of forced outage and planned outage respectively, which can be obtained through statistics.

$$\begin{cases} TTF = -MTTF \ln \gamma_1 \\ TTR = -MTTR \ln \gamma_2 \end{cases} \begin{cases} TTF_P = -MTTF_p \ln \gamma_3 \\ TTR_P = -MTTR_P \ln \gamma_4 \end{cases} \tag{15}$$

γ_1, γ_2, γ_3 and γ_4 are random numbers which subject to the uniform distribution between (0.1).

After a statistical sampling process of many times, the state transition series of conventional generators $S_{g,i}(t)$ can be obtained. Fig. 2 shows the sampling process of conventional generator state transition series.

i. Input the original data, and calculate P_{up}, P_{fo} and P_{po} for each generator in each state by equations (14) and (12).
ii. Determine the initial operating state of each generating set.

   Firstly, compare the uniform random number between (0,1) and P_{po} of the generator, to determine whether the unit is in planned outage state.

   Then, the uniform random number between (0,1) and P_{fo} of the generator are compared if the unit has been judged not in planned outage state to determine whether it is in forced outage state.
iii. If the unit is in planned outage state, calculate TTR$_P$ of the unit using equation (15).
iv. If the unit is in forced outage state, calculate TTR.
v. If the unit is in up state, the calculate TTF$_P$ and TTF.

   If TTF < TTF$_P$, the unit transfers to forced outage state at the next moment, and return to step (iv).

   On the contrary, if TTF$_P$< TTF, the unit will be transferred to the planned outage state at the next moment, and return to step (iii) until the completion of the year-round simulation.
vi. After years of simulation, the statistical value of probabilities of up state for each generator (described by P_{up}^*)can be calculated, until convergence conditions are satisfied, which is described as (16).

$$\frac{\sigma(P_{up}^*)}{\sqrt{N} \times E(P_{up}^*)} < 0.01 \tag{16}$$

N is number of simulated years, $E(P_{up}^*)$ is the mean value of P_{up}^*, and $\sigma(P_{up}^*)$ is the standard deviation of P_{up}^*.

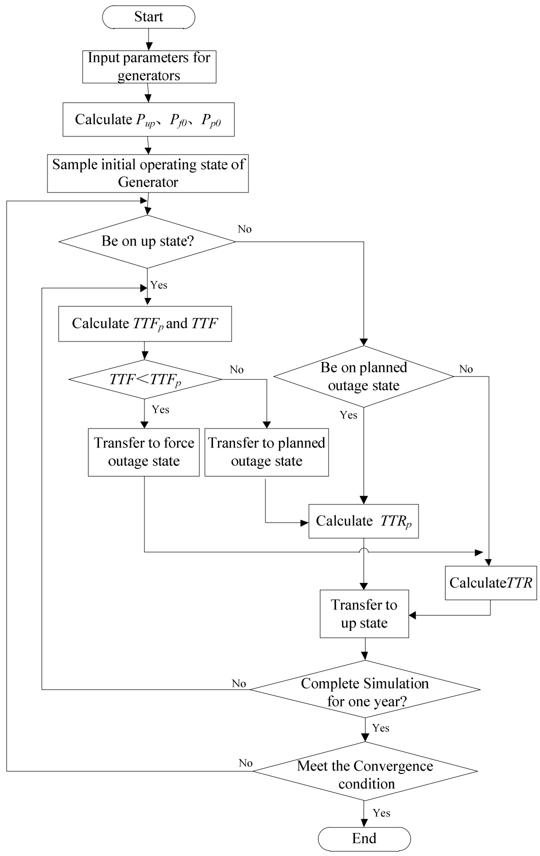


Fig. 4 Flow chart of the sampling process of conventional generator state transition series

c) Verification analysis in IEEE-RTS79 system

The convergence of the proposed Monte-Carlo simulation model is verified in IEEE-RTS79 test system [15].And for the calculation result of operation probability of generators, the deviation between simulated value and actual value is very small. So the effectiveness of the proposed generator simulation method can also be verified.

Tab. 1 shows the convergence process of probabilities of up state of the generators P_{up} and annual peak-shaving energy insufficient W_{PSCI}. According to the result of Tab.1, after 100 years simulation of the test system, the index of P_{up} and W_{PSCI} have both met the convergence criterion, but the convergence speed of W_{PSCI} is less than P_{up}. Therefore, it is reasonable to choose the index of W_{PSCI} as a sign index of convergence in the whole analysis process.

Tab.1 Convergence of P_{up} and W_{PSCI}

Simulation years	Convergence of P_{up}	Convergence of W_{PSCI}
10	0.0477	0.0808
50	0.0154	0.0420
80	0.0126	0.0330
100	0.0092	0.0291

Tab. 2 Comparison of generator operation probability of IEEE-RTS79 system

No.	P_{up}	P_{up}^*	Deviation	No.	P_{up}	P_{up}^*	Deviation
1	0.829	0.833	0.38%	17	0.952	0.958	0.67%
2	0.867	0.870	0.34%	18	0.952	0.960	0.86%
3	0.905	0.905	0.01%	19	0.952	0.951	-0.12%
4	0.905	0.903	-0.19%	20	0.942	0.943	0.04%
5	0.905	0.909	0.45%	21	0.942	0.944	0.19%
6	0.905	0.906	0.12%	22	0.942	0.940	-0.21%
7	0.895	0.892	-0.41%	23	0.942	0.939	-0.36%
8	0.895	0.901	0.60%	24	0.942	0.943	0.08%
9	0.895	0.892	-0.40%	25	0.865	0.868	0.24%
10	0.942	0.935	-0.74%	26	0.865	0.869	0.42%
11	0.942	0.938	-0.50%	27	0.865	0.862	-0.46%
12	0.942	0.945	0.29%	28	0.865	0.862	-0.39%
13	0.942	0.946	0.35%	29	0.905	0.900	-0.53%
14	0.952	0.951	-0.11%	30	0.905	0.902	-0.35%
15	0.952	0.954	0.19%	31	0.905	0.906	0.16%
16	0.952	0.957	0.53%				

Tab. 2 shows the comparison between the simulated P_{up}^* and the actual P_{up} after 100 years of simulation. It can be seen, that the deviation between simulated value and actual value is very small, which the maximum deviation is 0.86%, the minimum deviation is 0.01%.

IV. CASE STUDIES

In order to test the method proposed above, case studies with a 2020 planning scenario of a real large power system in north China were carried out.

According to "Historical load curve can be obtained" method, the load series of is obtained based on the historical load in 2016. Fig. 5 shows the simulated load and wind power output curve of one winter week with the highest peak pressure. It shows that due to large proportion of wind power, the equivalent load curve is much more fluctuating as compared to the original load curve.

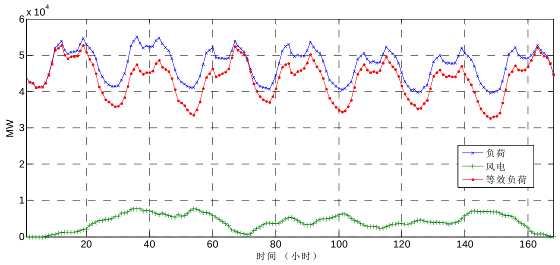


Fig. 5 Part of the simulated curve of load and wind power output

The planned installed capacity of generation and the forecasted peak load of the studied power system are given in Tab. 3.

Tab. 3 Generation capacity and peak load of the system in 2020

Installed capacity of generation	***Coal-fired Thermal Power***	17130MW
	Pumped storage Power	2070MW
	Hydro Power	150MW
	Wind Power	22000MW
Import power	***Through DC Lines***	7000
	Through AC Lines	14120
Peak Load		32100MW

Tab. 4 gives the different output limits of conventional generators in different seasons. The DC imported power is adjusted to 50% of the normal value during the period of deep night and early morning, as shown in Fig. 6.For the power imported through AC lines, it is adjust to 75% of normal value during valley periods.

Tab. 4 Output Limits of Conventional Generators

Types of Generators	Seasons	Maximum Output	Minimum Output
300MW and above normal coal-fired thermal generators	other seasons	100%	50%
200~300MW normal coal-fired thermal generators	other seasons	100%	60%
CHP generators	winter seasons	90%	75%
Pumped storage generators	All seasons	100%	-100%
Hydro power generators	wet seasons	100%	0
	dry seasons	70%	0

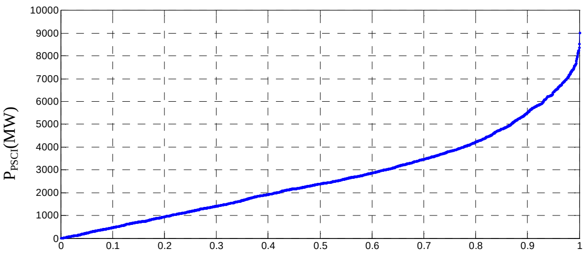
The reliability parameters related to the forced outage which will be used to instate transition model of conventional generators are refer to the historical reliability statistics [16] issued by the Electric Power Reliability Management Center, National Energy Administration of China.

As for planned outages of conventional generators, it is supposed that once a year maintenance is carried out for each generator, the time to repair parameters are given in Tab. 5.

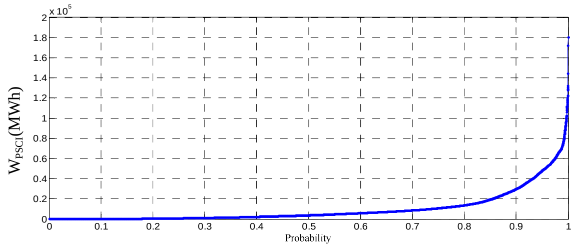
Tab. 5 Time to repair parameters of planned outages

Generator Capacity (MW)	Time to Repair (weeks)
600 and above	5
300~600	4
100~300	3
100 and below	2

N_{PSCI}	68
Maximumof $P_{PSCI,i}$	9038MW
Maximum of $W_{PSCI,i}$	111210MWh



(a)$P_{PSCI,i}$



(a)$W_{PSCI,i}$

Fig.6 Cumulative probability ofpeak-shaving requirement

The analysis result shows that due to peak-shaving insufficient, the annual wind energy curtailment rate is 3.19%.

V. Conclusion

A peak-shaving requirement analysis method based on sequential Monte-Carlo simulation for large scale wind power integrated system is proposed and three peak-shaving insufficient indices are defined and calculated. By treating the planned outage state also as a random variable, a 3-state model for conventional generator is established. Through the proposed sampling method, the up states, forced outage states and planned outage states can be determined by Monte-Carlo simulation, which can save the calculation time and make the Monte-Carlo simulation more practical. The method is verified by IEEE-RTS79 system, and then applied in the real large power system of Jibei power grid in North China. This method can be used to analysis the peak-shaving requirement for large scale wind power integrated system or evaluate the wind power accommodation capacity of power system.

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