Allowed capacity calculation of wind farm based on probabilistic constraint

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Received 1 October2014, www.cmnt.lv

Abstract

This paper presents a method for penetration capacity calculation of wind farm based on probabilistic constraint. According to the stochastic programming theory, under a confidence interval, a mathematical model that considers the randomness of wind speed is established based on the static safety and power quality constrains. The solving method is proposed according to particle swarm optimization algorithm and stochastic simulation technique too. According to a real power system in Yunnan, the penetration capacity of wind power is calculated under different confidence interval, and the feasibility and effectiveness of this method are verified too. The related factors of affecting the penetration capacity of wind power are analysed, which provide the reference for the planning and design of wind farm.

Keywords: penetration capacity of wind power, chance constraint, stochastic simulation, confidence interval, particle swarm optimization

1 Introduction

Energy crisis and environmental pollution have become the two problems that must be faced in the development of modern society. As a renewable energy, because of low cost and less pollution, wind energy has received great attention around world. In recent years, with the rapid development of power electronic technology, the technology of wind power has made great progress. The national policy of strong support for renewable energy has made a period of rapid development of wind power construction in China. Wind power has becomes one of the most mature, large-scale development and commercialization of new energy technologies [1-14].

The random, intermittence and fluctuation of wind energy result in the wind power dispatching and have a severe impact on grid security, stability and power quality, which is the main factor restricting the installed capacity of wind power and capacity of grid connected. Therefore, to evaluate the maximum wind power capacity of system, that is, allowed capacity of wind power, is the key problem during the planning stage of wind farm.

There are no unified algorithm and formula, because of penetration capacity calculation involving many factors. The system was proposed, based on power structure, load and peak load capacity, which could evaluate the penetration capacity of wind power through power grid [4]. The wind power in Beijing Tianjin Tangshan power grid were assessed comprehensively through comprehensive analysis of the power structure, load characteristics, peak load capacity of thermal power, self capacity, pumped storage power station and tie lines planning, without considering the effect of increasing capacity of wind farm on the system static security. A mathematical model is established for wind power penetration limit in power system based on the static security constrains of power system and a new method for solving the problem is given based on interior point method [5], while there in no considering dynamic constrains related to wind power grid connected operation, which may be the key factor determining the penetration limit of wind power. According to the analysis of environmental uncertainty of wind power grid connected and dependent chance programming theory, the model was established that considered the static operation safety, the traditional power grid output limit constrains, the wind farm power down measures and wind power capacity. The wind power allowed capacity was calculated too [7].

In this paper, we propose a method to calculate the allowed capacity of wind power, based on probability constrains. At the same time, the random of wind power and equation constrains of trend are considered. According to the probability distribution of wind speed, the model is established and solved, based on the Particle Swarm Optimization (PSO) algorithm of stochastic simulation technique.

2 The wind farm and system load model

2.1 WIND FARM

The captured wind power of a fan is a function of wind speed at hub height, and the function can be expressed as

$$p = \frac{1}{2} K \rho S v^3 , \tag{1}$$

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p is the captured wind power; K is the power coefficient and the nonlinear function of the tip speed ratio and pitch angle; S is swept area of wind wheel; v is wind speed at hub height. The relationship between active power generated by the generator and wind speed can be expressed as follow

$$p=\begin{cases}0, v<v_{in}, \text{or } v>v_{out}\\ \dfrac{v^3-v_{in}{}^3}{v_n{}^3-v_{in}{}^3}p_n, v_{in}<=v<=v_n\\ p_n, v_n<v<v_{out}\end{cases}, \quad (2)$$

v_{in}, v_{out}, v_n denote cutting in speed, cutting out speed and the rated wind speed respectively; p_n is the rated power. Because of random of wind speed, the power generated by wind power has the character of random. The probability of wind speed between 0~25m/s is very high and the annual averaged distribution of wind speed in YunNan can be expressed by Weibull distribution function [10]

$$f(v)=\frac{k}{c}\left(\frac{v}{c}\right)^{k-1}\exp\left(-\left(\frac{v}{c}\right)^k\right). \quad (3)$$

The probability distribution of wind speed is shown in Figure 1.

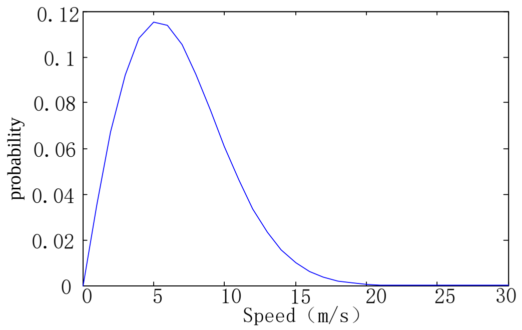

FIGURE 1 The probability distribution curve of wind speed

2.2 SYSTEM LOAD MODEL

Load changes directly affect the wind farm access capacity, experimental results show that, the system load distribution of most area can describe according to the normal distribution function in the long run.

$$\psi(p_{Li})=\frac{1}{\sigma\sqrt{2\pi}}\exp[-\frac{(p_{Li}-\mu_i)^2}{2\sigma^2}], \quad (4)$$

where p_{Li} is the system load of the i-th node; μ_i is the average load of the node; σ is variance.

3 Probabilistic constrain model of power system of wind farm

Under the condition of constrains containing random variables, if the decision making under disadvantage may not satisfy the constraints, then the decision making should make the probability of establishment for constraint condition established not less than a certain confidence level [8].

The constraint condition mainly means that power flow do not overload, the node voltage and the output of active power and wattles power of conventional generator are limited. If the loss of net is not considered, the summation of power increment of all nodes in the power grid connected wind farm is zero, in order to meet the power balance. Due to the randomness of active power output from wind power and the volatility of system load, the state variable calculated through system flow is random. The inequality constraints with random variable are expressed as the form of probability, which is established at a specified confidence level. The confidence level has a general value between 0.9 and 1. The value is smaller, the risk is bigger. The value is closer to 1.0, the result becomes more conservative. Taking the accepted largest installed capacity of wind power as goal function, the goal function can be expressed as follow:

$$f=\max(\sum_{i=1}^{n}p_{fi}). \quad (5)$$

The inequality constraints can be expressed as follow

$$\begin{aligned}&\Pr ob\{p_{x\min}\le p_{xj}\le p_{x\max}\}\ge\partial\\&\Pr ob\{U_{\min}\le U_i\le U_{\max}\}\ge\partial\\&\Pr ob\{Q_{g\min}\le Q_{gi}\le Q_{g\max}\}\ge\partial\\&p_{g\min}\le p_{gi}\le p_{g\max}\end{aligned}. \quad (6)$$

The equality constraints can be expressed as follow

$$\begin{aligned}&P_{Gi}+P_{fi}-P_{Li}=U_i\sum_{j\in i}U_j(G_{ij}\cos\delta_{ij}+B_{ij}\sin\delta_{ij})\\&Q_{Gi}+Q_{fi}-Q_{Li}=U_i\sum_{j\in i}U_j(G_{ij}\sin\delta_{ij}-B_{ij}\cos\delta_{ij})\end{aligned}. \quad (7)$$

P*rob* is the probability, p_{xj} is the flow of x line, p_{fi} is the wind power of grid connected at i node; p_{Li} is the system load at i node; p_{xj} is power flow at j line; ∂ is confident probability of inequality constraints.

4 Particle Swarm Optimization algorithm base on stochastic simulation

4.1 THE TECHNIQUE OF STOCHASTIC SIMULATION

The stochastic simulation, i.e., Monte Carlo simulation, provides an effective way to verify the probability constraints. The stochastic variables are sampled from known probability, which provides the basis for decision-making or tests the decision making for system. For chance constraints with stochastic variable

$$\begin{cases}\Pr ob\{p_{x\min}\le p_{xj}\le p_{x\max}\}\ge\partial\\ \Pr ob\{U_{\min}\le U_i\le U_{\max}\}\ge\partial\\ \Pr ob\{Q_{g\min}\le Q_{gi}\le Q_{g\max}\}\ge\partial\end{cases}. \quad (8)$$

The method of random simulation can be expressed as follow: n independent random individual, for example, $v_1, v_2, ...v_n$ are sampled from probability distribution $f(v)$. The n' is the number of satisfying constraints in n trials. According to the law of large numbers n'/n can be used to estimate the value of Equation (8). If $n'/n >= \partial$, the particle satisfies the probability constraints; if $n'/n < \partial$, the particle violates the probability constraints, and the value of fitness is penalized.

4.2 PARTICLE SWARM OPTIMIZATION ALGORITHM

Particle Swarm Optimization algorithm (PSO) stems from the research on group prey behavior of birds was proposed by Kennedy and Eberhart in 1995. Starting from stochastic solution, the optimal solution is searched by means of the iteration and the global optimum can be founded by following the searched optimal value. The vector $X_i = (x_{i1}, x_{i2}, ...x_{in})^T$ denotes the position of particle in space; the vector $p_i = (p_{i1}, p_{i2}, ...p_{in})^T$ denotes the optimal solution of vector of i particle in iteration; the vector $v_i = (v_{i1}, v_{i2}, ...v_{in})^T$ denotes the speed of i particle in N dimensional solution space.

In order to avoid falling into local optimum, the evolution route of particle depends not only on current position also on the previous evolution route. At the same time, the method of linear weight is employed, which ensures fast convergence speed and gets higher convergence precision. The flow- chart of program is shown in Figure 2. The evolution equation of particle is expressed as follow

$$\begin{aligned} v_i(t+1) = w * v_i(t) + c_1 * r_1[Z_{best}(t) - x_i(t)] + \\ c_2 * r_2[G_{best}(t) - x_i(t)] + \\ c_1 * r[Z_{best}(t-1) - x_i(t-1)] + \\ c_2 * r_2[G_{best}(t-1) - x_i(t-1)] \end{aligned}, \quad (9)$$

t is the number of iteration; c_1 and c_2 are learning factor and represent the weight of two optimal solutions respectively; r_1 and r_2 are independent random number between zero and one.

The inertia weight is

$$w = (N-n)\frac{w_{\max}(w_{\max} - w_{\min})}{N}, \quad (10)$$

n is current cycle number; N is total cycle number.

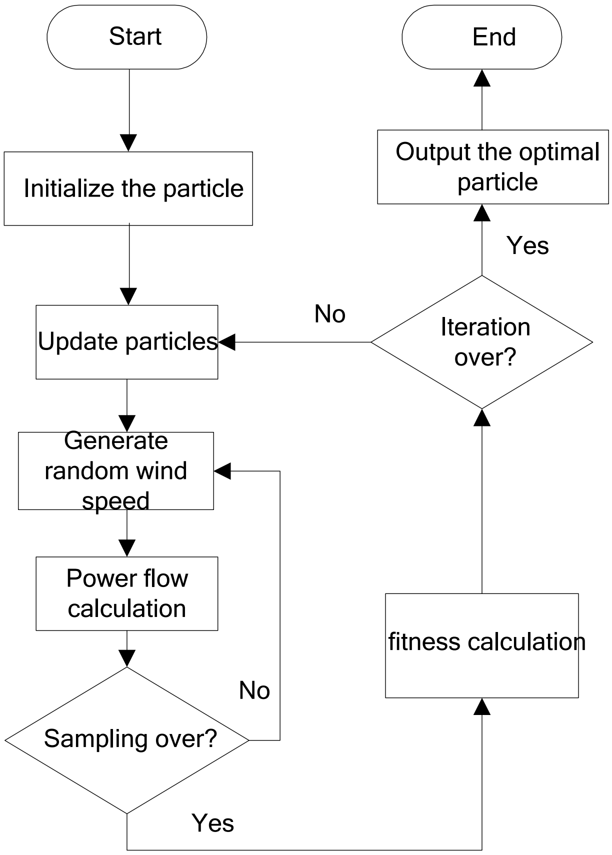

FIGURE 2 The flowchart of PSO based on stochastic simulation

5 Analysis of examples

In this paper a certain practical power grid of Yunnan is used to be analysed and calculated. The system simple topology is shown in Figure 3.

No. 1 generator is defined as the balanced unit. No. 25 and 29 base load generators do not participate in the active power regulation. The rate of wind power is 1.5 MW. The system benchmark capacity is 1000 MVA. No.13, 16, 18, 27 etc. are selected as wind farms and connected grid. The limit and upper limit of active power of conventional unit parameters for optimization are shown in Table 1.

TABLE 1 Conventional unit parameters

Unit node	Lower limit of active power (pu)	Upper limit of active power (pu)
1(Man wan)	0.56	0.94
2(Da chaoshan)	0.243	0.85
3(Zong yanghai)	0.42	0.56

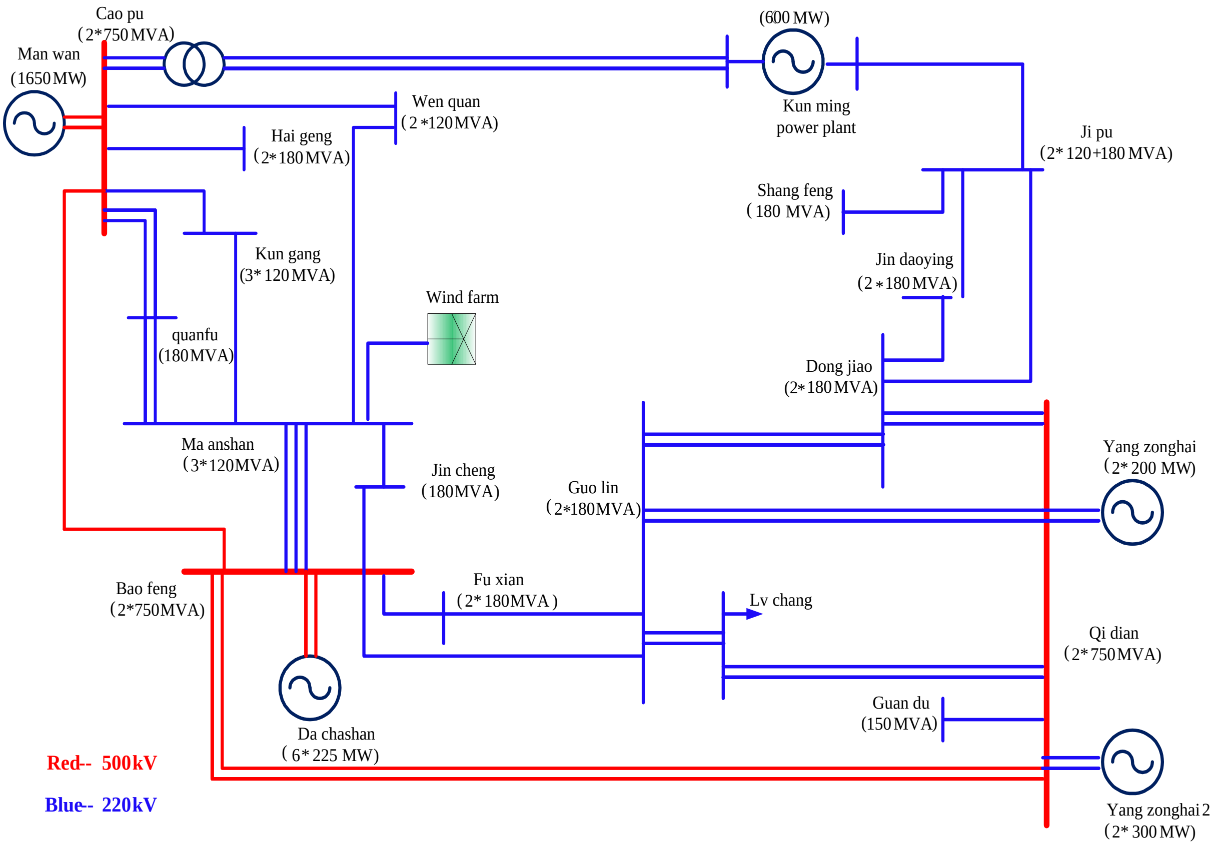

FIGURE 3 The system simple topology of a certain practical power grid of Yunnan

This paper analyses the three factors that affect the wind-power allowed capacity:

(*1*) *Different confidence level and connected grid.* Average wind speed μ =7.5m/s, the shape factor k=2, load variance=1. Wind-power allowed capacities are calculated as shown in Table 2.

TABLE 2 Penetration powers with different confidence levels and connected grids

Connected grid	Penetration powers (p_u)		
	α=0.99	*α=0.99*	*α=1.0*
13(Hai geng)	0.5145	0.4095	0.3795
16(Ma anshan)	0.5790	0.4620	0.4260
18(Fu xian)	0.8100	0.6540	0.6065
27(Pu ji)	0.8355	0.6585	0.6075

As seen from Table 3, wind-power allowed capacities are different when wind farms are connected into the system. Different wind-power allowed capacities can be used to determine the best access point for maximizing the acceptance of wind power. Meanwhile, wind-power allowed capacities increase relatively with the confidence probability reducing. The essence of the phenomenon is to allow some low probabilities, which violate constraint conditions, thus conservative calculation results are avoided.

(*2*) *Load levels.* To study, the total load of the system is increased by 10% compared with Table 2. Penetration powers are calculated as shown in Table 3. Due to the demand for electrical energy increasing, wind-power allowed capacities of most nodes increase with load increasing after the system load increases. Figure 4 shows the evolution curve of the optimal solution in the 16th node when α=1.0.

TABLE 3 The effect of load on wind power access capacity

Connected grid	Wind-power allowed capacity (p_u)		
	α=0.95	*α=0.99*	*α=1.0*
13(Hai geng)	0.6015	0.4890	0.4500
16(Ma anshan)	0.7875	0.6270	0.5790
18(Guo lin)	0.9150	0.7695	0.7065
27(Pu ji)	1.035	0.8310	0.7675

Compared with Table 2 and Table 3, wind-power allowed capacities of most nodes increase with load increasing after the system load increases. Wind-power allowed capacities of some nodes is not significantly increased because of other restrictions constraints

(*3*) *Wind speed*: The confidence probability is 0.99 in order to investigate effects of different average wind speeds. Other parameters are same as Table 2. Penetration powers are calculated as shown in Table 4 under different average wind speeds.

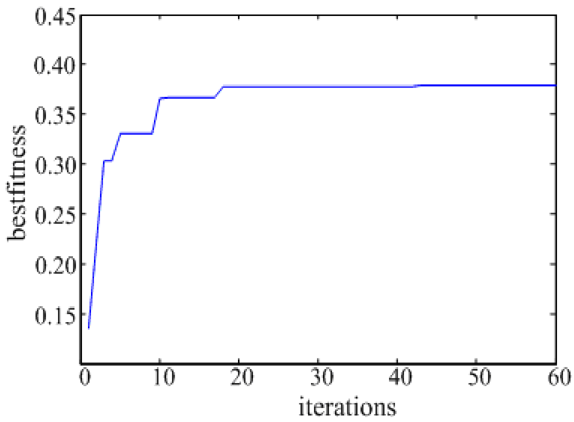

FIGURE 4 Particle-swarm optimal evolutions

TABLE 4 Effect of average wind speed of wind power access capacity

Connected grid	Wind-power allowed capacity (p_u)		
	μ=6.5m/s	μ=7.5m/s	μ=8.5m/s
13(Hai geng)	0.4680	0.4095	0.3915
16(Ma anshan)	0.5130	0.4620	0.4410
18(Guo lin)	0.7425	0.6540	0.6255
27(Pu ji)	0.7440	0.6585	0.6300

Compared with Table 2 and Table 4, the fan output increases with the increase of the average wind speed. The level of system disturbance also increases and the wind-power capacity decreases.

7 Conclusions

In this paper, an analysis method is proposed based on probability constraints. The optimization analysis model of evaluating allowed capacity is established considered wind-power randomness under uncertain environment. The program of MATLAB is developed based on stochastic simulation techniques and particle-swarm optimization algorithms. The analysis of examples demonstrates the feasibility and effecttiveness of the algorithm and model. The analytical method of allowed wind-power capacity is also suitable for other renewable energy. The limitation of this method is time consuming because of the use of Monte Cano simulation techniques and only the consideration of the static system constraint. The wind power system dynamic constraint is also a key factor in the decision of the wind power access capability. How to consider these dynamic constraints into the optimization model is the focus of future research.

Acknowledgments

This work was financially supported by the NSFC (61307041) and Natural Science Foundation project of Shandong province of China (ZR2012FL11, ZR2013AL014).

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