2010 3rd International Conference on Computer and Electrical Engineering (ICCEE 2010)
IPCSIT vol. 53 (2012) © (2012) IACSIT Press, Singapore
DOI: 10.7763/IPCSIT.2012.V53.No.1.46

Bulk Power Systems Reliability Assessment with Wind Farms in Electricity Market Environment

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Abstract. With the energy crisis and the strengthening of the human consciousness on environmental protection, the usage of new energy sources for power generation has attracted wide attention, in which wind power with low-cost and mature technology become relatively faster growth among new energy power generation technology. Because wind energy has the characteristics of random and intermittent, which may affect power systems reliability, it is necessary to assess power systems reliability containing wind farm. Unlike sensitivity method and weighting factor method calculating load loss, the optimal scheduling model is proposed in this paper, which could embody the difference of load and fault duration. The case study results show that the different types of grid-connected wind farms could influence bulk power systems reliability, which should be paid more attentions under actual situation.

Keywords: Grid-connected wind farms; bulk power systems; reliability assessment; electricity market

1. Introduction

Energy shortages and environmental degradation have become two global problems, the traditional structure of energy development can not meet the economic, social and environmentally sustainable development. In recent years, with the energy crisis and the strengthening of the human consciousness of environmental protection, the usage of new energy sources for power generation has attracted wide attention, in which wind power with low-cost and mature technology become relatively faster growth among new energy power generation technology [1-5]. Because wind energy has the characteristics of random and intermittent, and the presence of wind farm may affect power systems reliability, it is necessary to assess power systems reliability containing wind farm.

At present, the study of power systems reliability assessment containing wind farm has seriously attracted wide attention and certain results have been achieved,such as the wind farm's contribution to power systems reliability[6-7], adequacy evaluation of generating capacity[2,8-10], adequacy evaluation of generating capacity with storage systems[11-12], reliability assessment of composite generation and transmission systems[13-15], reliability assessment of power generation transmission and distribution systems[5]. Among above studies, the amount of load loss may be decided by either sensitivity method[16-17] which could not reasonably reflect the different loads' loss cost, or weighting factor method of load[14] which could not reflect the difference between the load loss cost under different fault duration. Therefore, it is necessary to determine the load loss cost according to difference in various types of load and fault duration.

In addition, wind farms should be compared with conventional generator in evaluating the value of power systems reliability. Although the traditional reliability indices including Loss Of Load Probability (LOLP) and Expected Energy Not Supplied (EENS) can reflect the systems reliability, they can not directly show the wind

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farm's contribution to power systems reliability. Relevant researches[6-7,14] have proposed some reliability evaluation indices closely related to wind farms, which can reflect the wind farm's contribution to power systems reliability, and provide important reference information.

Due to the characteristic of wind resource is random and intermittent, the wind generations connected to grid have some effect on the reliability of power systems. For composite generation and transmission with wind farms, this paper not only reasonably simulates the wind speed and wind power, but simulates the sequential operation condition of generating units and transmission lines through sequential Monte-Carlo simulation. Because of the difference of unit load loss in different fault duration, the optimal operation model presented aiming at minimizing generating cost and load loss cost in power systems, would fully consider the difference of load and duration, and conform to the actual electricity market situation. The case study results show that the load loss cost by the proposed model is smaller than other models, and the wind turbine can influence reliability of composite generation and transmission systems in different types of wind speed zones, different capacities or different incorporation nodes, which should be analyzed under actual situation.

2. Reliability Assessment and Model of Composite Generation and Transmission Systems with Wind Farms

2.1 The model of wind speed

Although the wind speed changes randomly, the wind speed is time series and self-relevance, that is, the wind speed in certain moments is relevance to the previous occasion, therefore the wind speed can be forecast by time series [18-19]. In this paper, the wind speed in future is predicted by the model of Auto-Regressive and Moving Average (ARMA)[8].

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

where $y_t = (V_{Owt} - \mu_t) / \sigma_t$, V_{OWt} is the wind speed data observed, μ_t and σ_t are the average wind speed data observed and estimation of variance, ϕ_i (i=1, 2, ···, n) is the auto-regressive coefficient, θ_i (i=1, 2, ···, n) is the moving average coefficient, $\{\alpha_t\}$ is a normal white noise sequences whose mean value is zero and variance is σ_α^2, that is, $\alpha_t \in N(0, \sigma_\alpha^2)$.

Therefore the wind speed data predicted is $V_{SWt} = \mu_t + \sigma_t y_t$.

2.2 The output power model of wind turbine

The relationship between the output power of wind turbine and the wind speed of hub-height can be described as[20],

$$P = \begin{cases} 0 & v \le v_{ci} 或 v \ge v_{co} \\ P_r \dfrac{v^3 - v_{ci}^3}{v_r^3 - v_{ci}^3} & v_{ci} \le v \le v_r \\ P_r & v_r \le v \le v_{co} \end{cases} \tag{2}$$

where v is the wind speed of hub-height, v_{ci} is cut-in speed, v_{co} is cut-out speed, v_r is reted speed, P_r is rated output power of wind turbine.

2.3 Outage model of generators and transmission equipments

Wind turbines, conventional generators and transmission equipments all have two states, that is, normal working condition and outage condition. Sequential Monte Carlo simulation method can sample the duration of each component on the current state in a time span, and different states such as the operation or maintenance procedure are assumed that there are different state duration probability distributions. Under normal circumstances, the working time and repair time are exponentially distributed, that is, component failure rate λ and repair rate μ are constant[21], then its value of state duration sampling is,

$$\tau_1 = -\frac{1}{\lambda} \ln R \tag{3}$$

$$\tau_2 = -\frac{1}{\mu}\ln R \tag{4}$$

where τ_1 and τ_2 are running duration and maintenance time, R is a uniformly distributed random number between 0 and 1.

2.4 Sequential state simulation of systems

Reliability Assessment approaches of Composite Generation and Transmission Systems with Wind Farms contain analytical approach and simulation approach[5,9-10,12,22-23], and the simulation approach is simpler than the analytical approach in modeling and algorithms, which can simulate wind speed's time-varying uncertainty and evaluate the wind farms' impact on power systems reliability. Then this paper simulates the states of all generators and transmission equipments by Sequential Monte Carlo simulation method, which can sample systems components' state and duration, makes optimal scheduling under the premise of full usage of wind power, and calculates reliability indices of power systems.

3. Optimal Scheduling Model Containing Load Loss Cost

3.1 The model of load loss cost

Load loss cost is associated with many relevant factors, such as the timing of load loss, the loss of electricity, advance notice of the time, duration, frequency and types of load [24]. The amount of load loss may be decided by either sensitivity method [16-17] which could not reasonably reflect the different loads' loss cost, or weighting factor method of load[14] which could not reflect the difference between the load loss cost under different fault duration. Therefore, it is necessary to determine the load loss cost according to difference in various types of load and fault duration.

In order to reflect the impact of load loss, Sector Customer Damage Function (SCDF) should be established though investigating all types of customers, which can reflect the relationship between the load loss of various types of customer and duration. Then according to the SCDF and annual peak load power consumption of all kinds of customers, Composite Customer Damage Function (CCDF) should be found in units of node, which can illustrate the relationship between overall customers' load loss and the outage time. At last, Interrupted Energy Assessment Rate (IEAR) should be made, which can reflect the customers' economic loss caused by the power supply interruption, and load loss cost is calculated with Expected Energy Not Supplied (EENS)[24-26]. As IEAR is determined through the statistical systems reliability indices, which can not reflect the impact of different types of load and fault duration on reliability indices, this paper calculates the load loss cost with CCDF.

$$OLC_j(t) = CCDF_j(t)\bullet P_{Rj,t} \tag{5}$$

$$CCDF_j(t) = \sum_{k=1}^{N} SCDF_k(t)\bullet\frac{P_k}{\sum_{k=1}^{N} P_k} \tag{6}$$

where $OLC_j(t)$ is Outage Loss Cost (OLC) on node j with t duration of customers, $CCDF_j(t)$ is CCDF on node j with t duration of customers, $P_{Rj,t}$ is the mount of load loss on node j with t duration of customers, N is the type number of customer, $SCDF_k(t)$ is the loss cost of kth customer type with t duration of customers, P_k is the annual peak load.

3.2 Optimal scheduling model of systems

According to the principle of making full use of wind power, the optimal operation model presented aimming at minimizing generating cost and load loss cost in power systems is,

$$obj.\quad \min C = \boldsymbol{\rho}_G\bullet\boldsymbol{P}_{G,t} + \boldsymbol{CCDF}(t)\bullet\boldsymbol{P}_{R,t} \tag{7}$$

$$s.t.\quad \boldsymbol{P}_t = \boldsymbol{B}_t\boldsymbol{\theta}_t \tag{8}$$

$$\sum_{i\in S_G} P_{Gi,t} = \sum_{j\in S_L} P_{Lj,t} - \sum_{j\in S_L} P_{Rj,t} \tag{9}$$

$$\left|\boldsymbol{P}_{l,t}\right| \le \overline{\boldsymbol{P}_l} \tag{10}$$

$$\boldsymbol{P}_{G\min} \le \boldsymbol{P}_{G,t} \le \boldsymbol{P}_{G\max} \tag{11}$$

$$\boldsymbol{P}'_{L,t} = \boldsymbol{P}_{L,t} - \boldsymbol{P}_{R,t} \tag{12}$$

$$\boldsymbol{P}_{L\min} \le \boldsymbol{P}'_{L,t} \le \boldsymbol{P}_{L\max} \tag{13}$$

$$P_{Rj,t} \ge 0 \quad (j \in S_L) \tag{14}$$

where the object is to minimize generating cost and load loss cost of power systems with the duration of t hours, $\boldsymbol{\rho}_G$ is the coefficient vector in cost function of generator, $\boldsymbol{P}_{G,t}$ is the output power vector of generator in this state, $\boldsymbol{CCDF}(t)$ is CCDF in this state, $\boldsymbol{P}_{R,t}$ is the load loss vector in this state, $\boldsymbol{P}_t$ is the nodal injection power vector in this state, $\boldsymbol{B}_t$ is the nodal susceptance matrix in this state, $\boldsymbol{\theta}_t$ is the nodal voltage phase angle vector in this state, $P_{Gi,t}$ is the output power of generator i in this state, $P_{Lj,t}$ is the load active power of node j in this state, $P_{Rj,t}$ is the loss of load active power of node j in this state, $\boldsymbol{P}_{l,t}$ is the power flow vector on transmission line in this state, $\bar{\boldsymbol{P}}_l$ is the limit vector on transmission line in this state, $\boldsymbol{P}_{Gmin}$ and $\boldsymbol{P}_{Gmax}$ are upper and lower limits of generator's output power, $\boldsymbol{P}_{Lmin}$ and $\boldsymbol{P}_{Lmax}$ are upper and lower limits of nodal load, $\boldsymbol{P}'_{L,t}$ is the load vector after load loss in this state.

4. Reliability Evaluation Indices of Power Systems Related to Wind Farms

Wind farms should be compared with conventional generator in evaluating the value of power systems reliability. Although the traditional reliability indices including Loss Of Load Probability (LOLP) and Expected Energy Not Supplied (EENS) can reflect the systems reliability, they can not directly show the wind farm's contribution to power systems reliability. Relevant researches have proposed some reliability evaluation indices closely related to wind farms, which can reflect the wind farm's contribution to power systems reliability, and provide important reference information. The main reliability evaluation indices include Equivalent Conventional Generating Capacity (ECGC) which can reflect the capacity of conventional generators replaced by wind turbines, Wind Generation Interrupted Energy Benefit (WGIEB), Wind Generation Interrupted Cost Benefit (WGICB) .

$$ECGC = \frac{RCCG_{EENS}}{RCWTG_{EENS}} \tag{15}$$

$$WGIEB = \frac{\Delta EENS}{C_{WTG}} \tag{16}$$

$$WGICB = \frac{\Delta OLC}{C_{WTG}} \tag{17}$$

where $RCCG_{EENS}$ and $RCWTG_{EENS}$ are the capacity of conventional generators or wind turbines under certain level of reliability, $\Delta EENS$ is the difference of EENS between no wind farms and adding wind turbines in power systems, ΔOLC is the difference of OLC between no wind farms and adding wind turbines in power systems, C_{WTG} is the rated capacity of wind farms.

5. The Case Study

Adding wind farms to IEEE-RTS79 test systems [27], whose capacity is 150×1.5MW. The cut-in speed, rated speed and cut-out speed of each wind turbine are 3m/s, 12m/s and 30m/s, and the Forced Outage Rate (FOR) of each wind turbine is 0.05, then the results of reliability assessment of bulk power systems with wind farms are as follows.

5.1 The load loss and cost under different ways

The comparative analysis of load loss and cost in system or each node have been made by weighting factor method of load and minimizing cost method of load loss, in which some load loss cost is calculated by CCDF[28], and others are calculated by linear interpolation.

The comparative results of TABLE I show that the load loss and cost are different according to the difference of objective function under above two load loss styles. Although the load loss by minimizing cost method of load loss is larger than weighting factor method of load, the load loss cost by the former method is smaller than the latter method, and the former method can conform to the actual electricity market situation.

Table 1. The results of load loss under different ways

The number of node	Weighting factor method of load		Minimizing cost method of load loss	
	Load loss(MW/a)	*Load loss cost(Million Dollars/a)*	*Load loss(MW/a)*	*Load loss cost(Million Dollars/a)*
1	553.44	25.73	0	0
2	541.15	12.59	7.26	0.28
3	686.65	3.18	2631.23	36.37
4	510.12	23.77	0	0
5	506.32	11.80	6.97	0.29
6	670.74	31.02	0	0
7	93.31	0.38	338.97	4.12
8	689.18	31.92	0	0
9	687.87	15.92	9.53	0.35
10	721.98	3.34	2639.84	35.90
13	618.66	28.65	0	0
14	718.66	3.33	2715.31	37.08
15	631.53	29.43	0	0
16	515.72	2.41	1674.11	24.31
18	682.33	31.82	0	0
19	637.48	14.82	9.70	0.35
20	534.13	24.86	0	0
Systems	9999.27	294.97	10032.92	139.05

5.2 Analysis of reliability with different wind generation capacity

Table 2 Reliability indices of systems with different wind generation capacity

Reliabiliy indices of systems	*No wind farms*	*Adding 50 wind turbines*	*Adding 100 wind turbines*	*Adding 150 wind turbines*
LOLP	0.081873	0.078632	0.075397	0.074525
EENS（MWh/a）	119913.33	93297.17	84669.42	80605.59
OLC（Million Dollars/a）	139.05	133.95	130.57	128.43

The comparative results of TABLE II show that the reliability assessment of composite generation and transmission systems with wind farms can be impacted by different capacity of wind farms (mean wind speed is 6m/s), and the more capacity of wind farms, the more contribution to reliability of systems. As the increase of capacity of wind farms, the increment of contribution to reliability of systems is gradually reducing, we could not blindly increase capacity of wind farms, and should determine a reasonable wind farm capacity considering the reliability and economy of systems.

Meanwhile, reliability of systems is increasing by adding wind farms whose capacity is 150×1.5MW, among which the reduction of LOLP, EENS and OLC are 0.007348, 39307.74MWh/a and 10.62 Million Dollars/a. In order to compare the reliability of wind turbines with conventional generators, all wind turbines are replaced by conventional generators whose capacity is 46.44MW and EENS of systems is unchanged. Therefore, ECGC of wind farms is 0.2064, that is, 0.2064MW conventional generator capacity can be saved by 1MW wind farms capacity, and the reliability of wind farms is lower than conventional generators. Furthermore, WGIEB and WGICB are 174.70 MWh/MW·a and 0.47 Million Dollars/MW·a, which show that wind farms can raise reliability of systems and reduce the load loss cost.

5.3 The analysis of impact on systems' reliability with different wind speed

Table 3 Reliability indices of systems with different wind speed

Reliabiliy indices of systems	*The mean wind speed on node 1 (m/s)*		
	6	**7**	**8**
LOLP	0.074525	0.066864	0.062373
EENS（MWh/a）	80605.59	72953.21	68349.37
OLC（Million Dollars/a）	128.43	118.27	115.36

Analyzing impact of mean wind speed on systems' reliability by changing the mean wind speed on node 1. The comparative results of TABLE III show that the faster of the wind speed, the more output power of wind farms, and the more contribution to reliability of systems.

5.4 The analysis of impact on systems' reliability with different incorporation bus

Table 4 Reliability indices of systems under different incorporation bus (mean wind speed is 6 m/s)

Reliabiliy indices of systems	*No wind farms*	*Adding 150 wind turbines to node 1*	*Adding 70 and 80 wind turbines to node 1 and 2*	*Adding 50 wind turbines to node 1,2 and 3*
LOLP	0.081873	0.074525	0.070953	0.069876
EENS（MWh/a）	119913.33	80605.59	74294.72	72765.34
OLC（Million Dollars/a）	139.05	128.43	123.67	121.83

Analyzing impact with different incorporation bus on systems' reliability by changing incorporation bus. The comparative results of TABLE IV show that because of the constraint of the limit on transmission line and other factors, the reliability of systems is restricted by incorporating all wind turbines into the same node. According to the independent character of wind speed, adding wind turbines to different nodes would contribute much more to reliability of systems, and the level of reliability is decided by the wind speed of wind farms.

6. Conclusion

In electricity market environment, minimizing cost method of load loss would obtain much more reasonable results than traditional methods, which can reflect the differences of unit load loss under different outage duration dynamically. The IEEE-RTS79 test system study results show that the wind farms would raise reliability of system, which lower than traditional generators, and the wind turbine can influence reliability of composite generation and transmission systems in different types of wind speed zones, different capacities or different access nodes. We could not blindly increase capacity of wind farms, and should determine a reasonable wind farm capacity considering the reliability and economy of systems.

7. Acknowledgements

The National Key Technology R&D Program (No. 2008BAA13B11).

8. References

[1] Andrea P.Leite, Carmen L.t.Borges, Djalma M.Falcao. Probabilistic Wind Farms Generation Model for Reliability Studies Applied to Brazilian Sites[J]. IEEE Transactions on Power Systems, 2006, 21(4):1493-1501.

[2] Roy Billinton, Yi Gao. Multistate Wind Energy Conversion System Models for Adequacy Assessment of Generating Systems Incorporating Wind Energy[J]. IEEE Transactions on Energy Conversion, 2008, 23(1):163-170.

[3] Francois Vallee, Jacques Lobry, Olivier Deblecker. System Reliability Assessment Method for Wind Power Integration[J]. IEEE Transactions on Power Systems, 2008, 23(3):1288-1297.

[4] Roy Billinton, Bipul Karki, Rajesh Karki, G.Ramakrishna. Unit Commitment Risk Analysis of Wind Integrated Power Systems[J]. IEEE Transactions on Power Systems, 2009, 24(2):930-939.

[5] LIU Wei, ZHAO Yuan, ZHOU Jia-qi, et al. Reliability assessment of power generation transmission and distribution systems containing wind farms [J]. Power System Technology, 2008, 32(13):69-74.

[6] Wang P, Billinton R. Reliability Benefit Analysis of Adding WTG to A Distribution System [J]. IEEE Transactions on Energy Conversion, 2001, 16(2):134-139.

[7] WANG Hai-chao, LU Zong-xiang, ZHOU Shuang-xi. Research on the capacity credit of wind energy resources [J]. Proceedings of the CSEE, 2005, 25(10):103-106.

[8] R.Billinton, Hua Chen, R.Ghajar. A Sequential Simulation Technique for Adequacy Evaluation of Generating Systems Including Wind Energy[J]. IEEE Transactions on Energy Conversion, 1996, 11(4):728-734.

[9] CHEN Shu-yong, DAI Hui-zhu, BAI Xiao-min, et al. Reliability model of wind power plants and its application [J]. Proceedings of the CSEE, 2000, 20(3):26-29.

[10] LI Wen-yi, ZHANG Bao-hui, Bagen. Reliability impacts of large scale utilization of wind energy on electric power systems [J]. Proceedings of the CSEE, 2008, 28(1):100-105.

[11] R.Billinton, Bagen, Y.Cui. Reliability Evaluation of Small Stand-Alone Wind Energy Conversion Systems Using A Time Series Simulation Model [J]. IEE Proceedings-Generation, Transmission and Distribution, 2003, 150(1):96-100.

[12] LI Wen-yi, ZHANG Bao-hui, Bagen. Capacity adequacy evaluation of wind-diesel-storage system[J]. Proceedings of the CSEE, 2006, 26(16):62-67.

[13] Ubeda J R, Rodriguez Garcia M A R. Reliability and Production Assessment of Wind Energy Production Connected to the Electric Network Supply [J]. IEE Proceedings – Generation, Transmission and Distribution, 1999, 146(2):169-175.

[14] WU Yi-chun, DING Ming, LI Sheng-hu. Reliability assessment of wind farms in generation and transmission systems [J]. Transactions of China Electrotechnical Society, 2004, 19(11):72-76.

[15] Dange Huang, Roy Billinton. Effects of Wind Power on Bulk System Adequacy Evaluation Using the Well-Being Analysis Framework [J]. IEEE Transactions on Power Systems, 2009, 24(3):1232-1240

[16] CHENG Lin, GUO Yong-ji. Multiple fault assessment algorithm for reliability evaluation[J]. Journal of Tsinghua University (Science and Technology), 2001, 41(3):69-72.

[17] GUO Yong-ji. Power system reliability analysis[M]. Beijing: Tsinghua University Press, 2003.

[18] H Nfaouia, J Bureta, A A.M Sayigh. Stochastic Simulation of Hourly Avergae Wind Speed Sequences inTangiers (Morocco)[J]. Solar Energy, 1996, 56(3):301-314.

[19] Lalarukh Kamal, Yasmin Zahra Jafri. Time Series Models to Simulate and Forecast Hourly Averaged Wind Speed in Quetta, Pakistan[J]. Solar Energy, 1997, 61(l):23-32.

[20] SUN Yuan-zhang, WU Jun, LI Guo-jie, et al. Dynamic economic dispatch considering wind power penetration based on wind speed forecasting and stochastic programming [J]. Proceedings of the CSEE, 2009, 29(4):41-47.

[21] LI Wen-yuan. Risk assessment of power systems–models, methods, and applications [M]. Beijing: Science Press, 2006.

[22] Castro Sayas F, Allan R N. Generation Availability Assessment of Wind Farms [J]. IEE Proceedings-Generation, Transmission and Distribution, 1996, 143(5):507-518.

[23] Desrochers G, Balanchard M. A Monte Carlo Simulation Method for the Economic Assessment of the Contribution of Wind Energy to Power Systems [J]. IEEE Transactions on Energy Conversion, 1986, 1(4):50-56

[24] CHENG Hao-zhong, ZANG Yan. Method and application of electric power network planning [M]. Shanghai: Shanghai Science and Technology Press, 2002.

[25] DING Ming, ZHANG Jing, LI Sheng-hu. A sequential Monte-Carlo simulation based reliability evaluation model for distribution network [J]. Power System Technology, 2004, 28(3):38-42.

[26] WEI Gang, WU Wei-li, ZHANG Zi-yang, et al. Power network planning considering reliability cost and unerved energy cost [J]. Relay, 2006, 34(17):38-41, 46.

[27] IEEE Committee. IEEE reliability test system [J]. IEEE Transactions on Power Apparatus and Systems, 1979, 98(1):2047-2054.

[28] R. Billinton, S. Kumar, N. Chowdhury, et al. A Reliability Test System For Educational Purposes[J]. IEEE Transactions on Power Systems, 1989, 4(3):1238-1244.