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Wind Integrated Bulk Electric System Planning

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1. Introduction

The utilization of the wind to generate electrical energy is increasing rapidly throughout the world. By the end of 2009, the worldwide installed wind capacity reached 159,213 MW (World Wind Energy Report 2009). Wind turbine generators can be added and are being added in large grid connected electric power systems. Wind power, however, behaves quite differently than conventional electric power generating facilities due to its intermittent and diffuse nature. The incorporation of wind energy conversion system (WECS) in bulk electric system (BES) planning, therefore, requires distinctive and applicable modeling, data and method considerations to ensure BES reliability levels as wind power penetration levels increase.

The objective of power system planning is to select the most economical and reliable plan in order to meet the expected future load growth at minimum cost and optimum reliability subject to economic and technical constraints. Reliability assessment, which consists of adequacy and security, is an important aspect of power system planning. A BES security assessment normally utilizes the traditional deterministic criterion known as the N-1 security criterion (North American Electric Reliability Council Planning Standards, 2007) in which the loss of any BES component (a contingency) will not result in system failure. The deterministic N-1 (D) planning criterion for BES has been used for many years and will continue to be a benchmark criterion (Li, 2005). The D planning criterion has attractive characteristics such as, simple implementation, straightforward understanding, assessment and judgment. The N-1 criterion has generally resulted in acceptable security levels, but in its basic simplest form does not provide an assessment of the actual system reliability as it does not incorporate the probabilistic nature of system behaviour and component failures.

Probabilistic (P) approaches to BES reliability evaluation can respond to the significant factors that affect the reliability of a system. There is, however, considerable reluctance to use probabilistic techniques in many areas due to the difficulty in interpreting the resulting numerical indices. A survey conducted as part of an EPRI project indicated that many utilities had difficulty in interpreting the expected load curtailment indices as the existing models were based on adequacy analysis and in many cases did not consider realistic operating conditions. These concerns were expressed in response to the survey and are summarized in the project report (EPRI report, 1987).

This difficulty can be alleviated by combining deterministic considerations with probabilistic assessment in order to evaluate the quantitative system risk and conduct

system development planning. A relatively new approach that incorporates deterministic and probabilistic considerations in a single risk assessment framework has been designated as the joint deterministic-probabilistic (D-P) approach (Billinton et al., 2008). This chapter extends this approach and the concepts presented in (Billinton et al., 2010; Billinton & Gao, 2008) to include some of the recent work on wind integrated BES planning.

2. Study methods and system

2.1 Study methods

The D planning criterion for transmission systems has been used for many years and will continue to be a benchmark criterion. In a basic D approach, using the N-1 criterion, the system should be able to withstand the loss of any single element at the peak load condition. An N-2 criterion is used in some systems. The likelihood of the designated single element failing is not included in an analysis using the D approach.

The P method is used in transmission planning (Fang R. & Hill, 2003; Chowdhury & Koval, 2001) as it provides quantitative indices which can be used to decide if the system performance is acceptable or if changes need to be made, and can be used for performing economic analyses. In the P approach, the system risk should not exceed a designated criterion value (R_c).

The D-P approach includes both deterministic and probabilistic criteria and is defined as follows: The system is required to satisfy a deterministic criterion (N-1) and also meet an acceptable risk criterion (P_c) under the designated (N-1) outage condition (Billinton et al., 2008). The D-P technique provides a bridge between the accepted deterministic and probabilistic methods. The basic deterministic N-1 technique results in a variable risk level under each critical outage condition. This is particularly true when the critical outage switches from a transmission element to a generating unit or vice versa. In the D-P approach the system must first satisfy the D criterion. The system risk given that the critical element has failed must then be equal to or less than a specified probabilistic risk criterion (P_c). If this risk is less than or equal to the criterion value, the D and D-P approaches provide the same result. If the risk exceeds this value then the load must be reduced to meet the acceptable risk level (P_c). The D-P technique provides valuable information on what the system risk level might be under the critical element outage condition using a quantitative assessment.

The MECORE (Li, 1998) software package which utilizes the state sampling Monte Carlo simulation method (Billinton & Allan, 1996) is used to conduct the reliability studies described in this chapter.

2.2 Study system

The well known reliability test system IEEE-RTS (IEEE Task Force, 1979) has a very strong transmission network and a relatively weak generation system. The total installed capacity in the RTS is 3405 MW in 32 generating units and the peak load is 2850 MW. It was modified in this chapter to create a system with a relatively strong generation system and a weak transmission network. The modified RTS is designated as the MRTS.

Three steps were used to modify the IEEE-RTS to create the MRTS:

Step 1. Generating unit modifications: The FOR of the four 20 MW units were changed from 0.1 to 0.015 and the mean time to repair (MTTR) modified from 50 to 55 hrs.

The FOR of the two 400 MW units were changed from 0.12 to 0.08 and the MTTR modified from 150 to 100 hrs.

Step 2. Transmission line modifications: The lengths of all the 138 kV lines were doubled except for Line 10 which is a 25.6 km cable. The 230 kV lines were extended as follows: the lengths of lines L21, L22, L31, L38 were increased by a factor of three; the lengths of lines L18 to L20, L23, L25 to L27 were increased by a factor of four; the lengths of lines L24, L28 to L30, and L32 to L37 were increased by a factor of six. The transmission line unavailabilities were modified based on Canadian Electricity Association data (CEA, 2004).

Step 3. The numbers of generating units were doubled at Buses 16, 18 and 21, and 2×50 MW and 1×155 MW generating units were added at Bus 22 and Bus 23 respectively. The rating of Line 10 was increased to 1.1 p.u. of the original rating.

The total number of generating units in the MRTS is now 38 units. The total system capacity is 4615 MW. The load value at each load points was increased by a factor of 1.28. The reference peak load of the MRTS is 3650 MW.

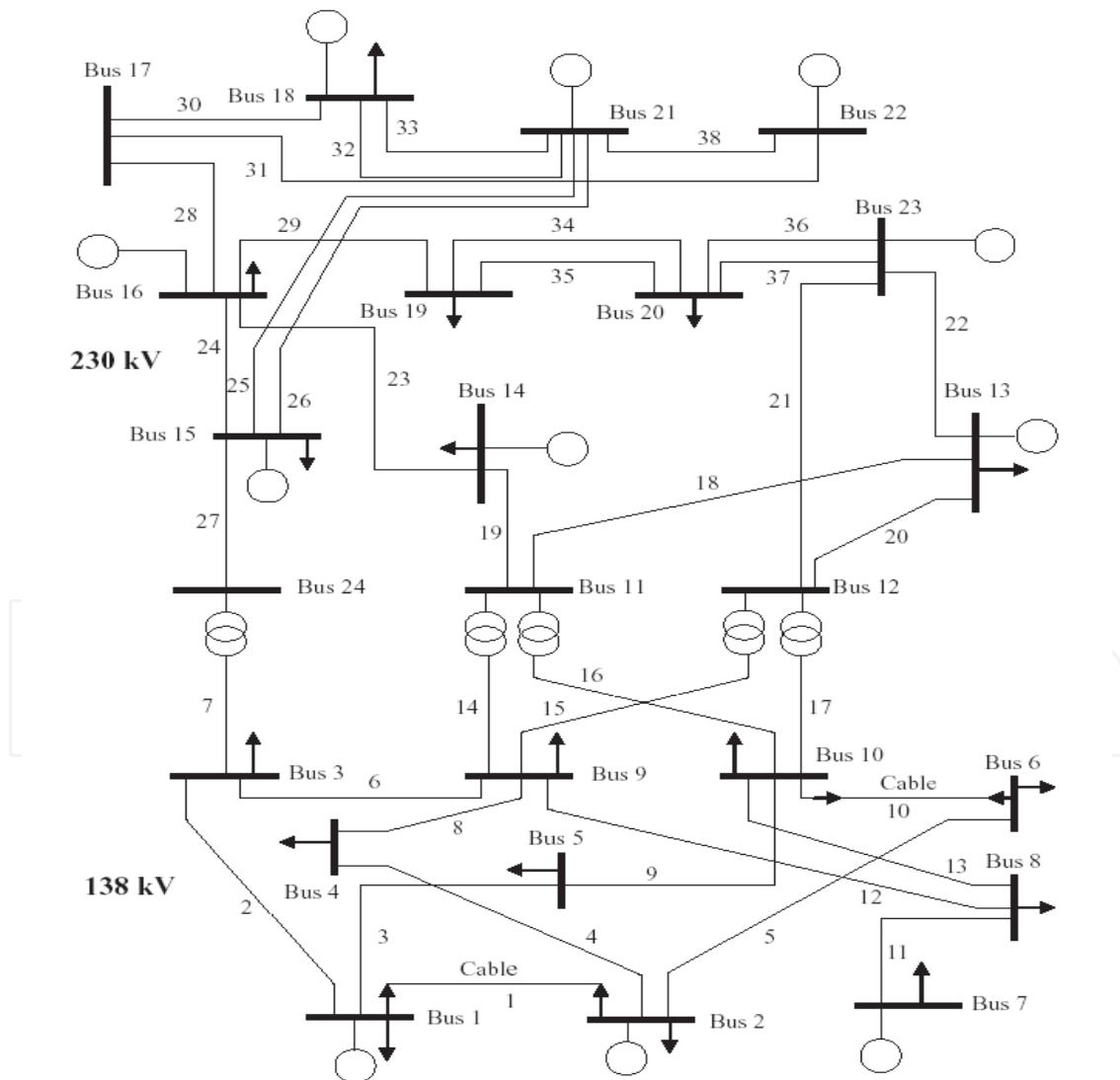


Fig. 1. Single line diagram of the MRTS

3. Wind energy conversion system model

3.1 Modeling and simulating wind speeds

One of the first steps for a utility company to consider when developing wind as an energy source is to survey the available wind resource. Unfortunately, reliable wind speed data suitable for wind resource assessment are difficult to obtain, and many records that have been collected are not available to the general public. Many utilities and private organizations, however, are now engaged in collecting comprehensive wind speed data. These data can be used to create site specific wind speed models.

A time series model has been developed (Billinton et al., 1996) to incorporate the chronological nature of the actual wind speed. Historical wind speeds are obtained for a specific site, based on which, future hourly data are predicted using the time series model. This time series model is used in the research described in this chapter to generate synthetic wind speeds based on measured wind data at a specific location.

The wind speed model and data for the Swift Current and Regina sites located in the province of Saskatchewan, Canada have been used in the studies described in this chapter. Table 1 shows the hourly mean wind speed and standard deviation at the Regina and Swift Current sites.

Sites	Regina	Swift Current
Mean wind speed (km/h), μ	19.52	19.46
Standard deviation (km/h), σ	10.99	9.70

Table 1. Wind speed data for the two sites

The Swift Current and Regina wind models were developed and published in (Billinton et al., 1996) and (Wangdee & Billinton, 2006) respectively. The ARMA models for the two sites are given in (1) and (2) respectively.

Regina: ARMA (4, 3):

$$y_t = 0.9336y_{t-1} + 0.4506y_{t-2} - 0.5545y_{t-3} + 0.1110y_{t-4} + \alpha_t - 0.2033\alpha_{t-1} - 0.4684\alpha_{t-2} + 0.2301\alpha_{t-3} \quad (1)$$

where $\alpha_t \in \text{NID}(0, 0.4094232)$ is a normal white noise process with zero mean and the variance 0.4094232.

Swift Current: ARMA (4, 3):

$$y_t = 1.1772y_{t-1} + 0.1001y_{t-2} - 0.3572y_{t-3} + 0.0379y_{t-4} + \alpha_t - 0.5030\alpha_{t-1} - 0.2924\alpha_{t-2} + 0.1317\alpha_{t-3} \quad (2)$$

where $\alpha_t \in \text{NID}(0, 0.5247602)$ is a normal white noise process with zero mean and the variance 0.5247602.

The wind speed time series model can be used to calculate the simulated time dependent wind speed SW_t using (3):

$$SW_t = \mu_t + \sigma_t \times y_t \quad (3)$$

where μ_t is the mean observed wind speed at hour t ; σ_t is the standard deviation of the observed wind speed at hour t .

Figure 2 shows a comparison of the observed wind speed probability distributions for the original 20 years of Swift Current wind speed data and the simulated wind speed probability distribution obtained using the ARMA (4, 3) model shown in Equation 2 and a large number (8,000) of simulated years. The observed average wind speed is 19.46 km/h, and the simulated value is 19.52 km/h. The observed wind speed probability distribution is not as continuous as the simulated distribution, as it is based on only 20 years of data.

Figure 2 shows that the ARMA (4, 3) model provides a reasonable representation of the actual wind regime. The observation is often made that wind speed can be represented by a Weibull distribution. Simulation results are used to generate the wind speed probability distributions in the studies described later in this chapter.

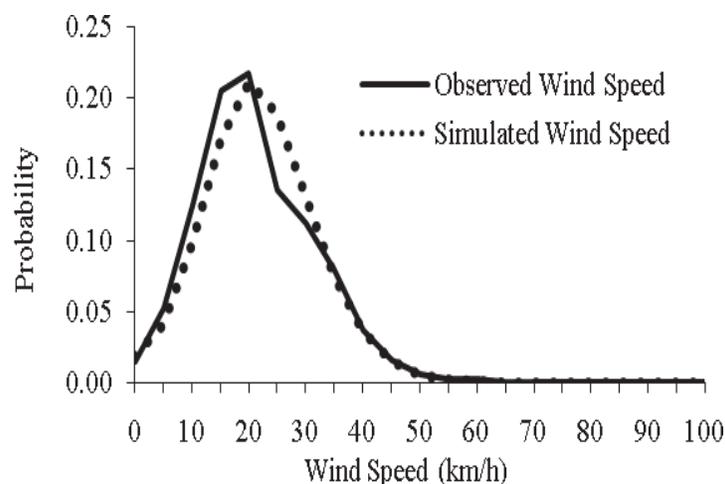


Fig. 2. Observed and simulated wind speed distributions for the Swift Current site

In practice, wind farms are neither completely dependent nor independent but are correlated to some degree if the distances between sites are not very large. The wind speed correlation between two wind farms can be calculated using cross correlation. The cross-correlation coefficient equation is shown in (4).

$$R_{xy} = \frac{\frac{1}{n} \sum_{i=1}^n (x_i - \mu_x)(y_i - \mu_y)}{\sigma_x \sigma_y} \quad (4)$$

where x_i and y_i are elements of the first and second time series respectively, μ_x and μ_y are the mean values of the first and second time series, σ_x and σ_y are the standard deviations of the first and second time series, and n is the number of points in each time series.

The ARMA time series model has two parts, one part is the autoregressive (AR) model involving lagged terms in the time series itself, the other one is the moving average (MA) model involving lagged terms in the noise or residuals. It is possible to adjust the wind speed correlation level between two or more different wind locations by selecting the

random number seeds (initial numbers) for a random number generator process used in the MA model. Reference (Wangdee & Billinton, 2006) uses a trial and error process to generate appropriate random number seeds by selecting a factor K between the dependent wind locations. This is a relatively straightforward method, but can require considerable time and effort and is not very flexible. Reference (Gao & Billinton, 2009) extends this application by describing a Generic Algorithm used to select the optimum random number seeds in the ARMA model to adjust the degree of wind speed correlation for two wind sites. A genetic algorithm can quickly scan a vast solution set. It is a very useful method coupled with ARMA models to adjust the simulated wind speed correlation levels for different wind sites (Gao & Billinton, 2009).

The simulated wind speed time series during a selected period for the Regina and Swift Current sites with high correlation level ($R_{xy}=0.8$), middle correlation level ($R_{xy}=0.5$) and low correlation level ($R_{xy}=0.2$) are shown in Figure 3. The simulated average wind speeds for the Regina and Swift Current sites are 19.58 km/h and 19.52 km/h respectively.

3.2 Modeling wind turbine generators

The power output characteristics of a Wind Turbine Generator (WTG) are quite different from those of a conventional generating unit. The output of a WTG depends strongly on the wind regime as well as on the performance characteristics (power curve) of the generator. Figure 4 shows a typical power curve for a WTG.

The hourly wind speed data are used to determine the time dependent power output of the WTG using the operational parameters of the WTG. The parameters commonly used are the cut-in wind speed V_{ci} (at which the WTG starts to generate power), the rated wind speed V_r (at which the WTG generates its rated power) and the cut-out wind speed V_{co} (at which the WTG is shut down for safety reasons). Equation 5 can be used to obtain the hourly power output of a WTG from the simulated hourly wind speed.

$$P(SW_t) = \begin{cases} 0 & 0 \leq SW_t < V_{ci} \\ (A + B \times SW_t + C \times SW_t^2) \times P_r & V_{ci} \leq SW_t < V_r \\ P_r & V_r \leq SW_t < V_{co} \\ 0 & SW_t \geq V_{co} \end{cases} \quad (5)$$

where P_r , V_{ci} , V_r and V_{co} are the rated power output, the cut-in wind speed, the rated wind speed and the cut-out wind speed of the WTG respectively. The constants A , B , and C depend on V_{ci} , V_r and V_{co} are presented in (Giorsetto P, 1983). The WTG units used in the studies in this chapter are considered to have a rated capacity of 2 MW, and cut-in, rated, and cut-out speeds of 14.4, 36 and 80 km/h, respectively.

3.3 The capacity outage probability table of the WTG

The hourly mean wind speeds and output power for a WTG unit without considering its unavailability or forced outage rate (FOR) are generated using the ARMA time series model and the power curve respectively. The capacity outage probability table (COPT) of a WTG unit can be created by applying the hourly wind speed to the power curve. The procedure is briefly described by the following steps (Billinton & Gao, 2008):

1. Define the output states for a WTG unit as segments of the rated power.

2. Determine the total number of times that the wind speed results in a power output falling within one of the output states.
3. Divide the total number of occurrences for each output state by the total number of data points to estimate the probability of each state.
4. The WTG COPT can be formed using this approach.

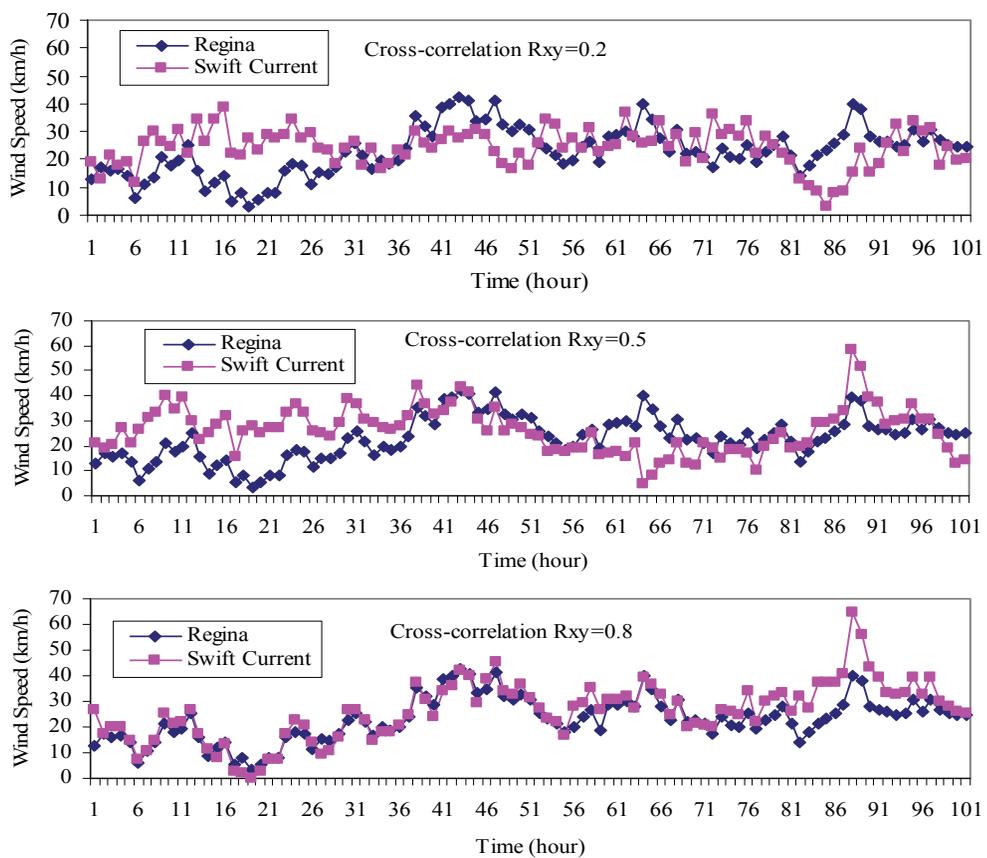


Fig. 3. Different simulated wind speed correlation levels between the Regina and Swift Current sites

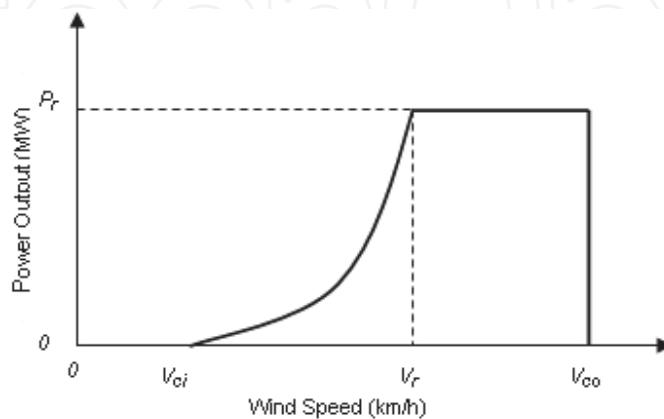


Fig. 4. Wind turbine generating unit power curve

Two cases are illustrated in this example. The first case utilizes the actual observed 20 years of Swift Current data. The second case uses the 8,000 simulated years of data. Figure 5 shows the two capacity outage probability distributions. The class interval width is 5% in this figure and the indicated capacity outage level is the midpoint of the class.

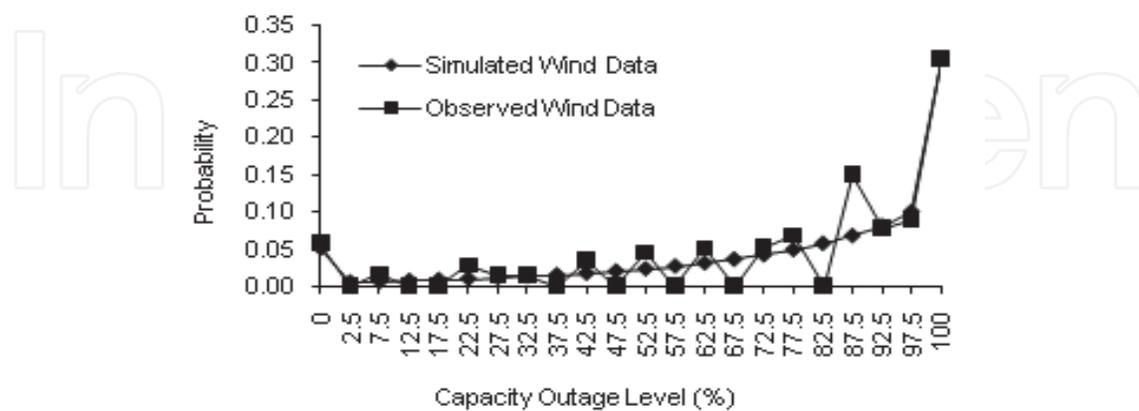


Fig. 5. Capacity outage probability profile for the WTG unit

Figure 5 shows that the observed data probability profile is discontinuous due to the limited wind data collection and that the simulated wind data provides a reasonable representation for adequacy assessment. The power output characteristics of a WTG are very different from those of conventional generating units. The WTG can be considered as a generating unit with many derated states (Billinton & Allan, 1996). Figure 5 shows that the probability of having full WTG output (0% capacity outage) is relatively low for this wind regime. There are many derated states in which the output of a WTG can reside in over the course of its operating history. A basic requirement in practical adequacy assessment is to represent the WTG by an acceptable reduced number of derated states.

3.4 Multi-state WECS model

There are many derated states in which the output of WECS can reside in the course of its operating history. The apportioning method (Billinton & Allan, 1996) can be used to create selected multi-state models for a WTG and the WECS. In this approach, the residence times of the actual derated states are apportioned between the completely up, selected derated and completely down states. A detailed analytical procedure that incorporates the WTG FOR is presented and used to build a series of multi-state WECS models in (Billinton & Gao, 2008). The probability of being in the full outage state is known as the Equivalent Forced Outage Rate (EFOR) in the NERC Generation Availability Data System and the Derated Adjusted Forced Outage Rate (DAFOR) (Billinton & Allan, 1996) in the CEA Equipment Reliability Information System. A wind energy conversion system can contain one or more WTG. A WECS has two basic parts: one is the wind resource and the other is the actual WTG units. If the WECS consists of identical WTG units with zero FOR, the WECS multi-state model is basically the same as that of the single WTG unit. If the FOR of the WTG units is not zero, the WECS derated state capacity outage probability table is not the same as that of a single WTG unit (Billinton & Gao, 2008).

Studies have shown that a five state capacity outage probability table can be used to reasonably represent a WTG in a capacity adequacy assessment (Billinton & Gao, 2008)

using the state sampling method. This model can also be used to represent a wind farm containing a number of WTG. Table 2 shows the capacity and probability values in a five state model for a 20 MW wind energy conversion system (WECS) containing identical 2 MW WTG.

	Regina Site	Swift Current Site
Capacity Outage (%)	Probability	Probability
0	0.07585	0.07021
25	0.06287	0.05944
50	0.11967	0.11688
75	0.23822	0.24450
100	0.50340	0.50897
DAFORW	0.75761	0.76564

Table 2. The independent WECS five-state models

Reference (Gao & Billinton, 2009) shows that the multi-state WECS models created for independent wind sites can be used in the state sampling simulation method to represent WECS considering wind speed correlation between the wind farms. The WECS models shown in Table 2 will be used in the following studies.

4. MRTS analysis with WECS

Two 400 MW WECS with Regina and Swift Current site data are added in the MRTS through transmission lines. The wind penetration level is about 15%. The length of each transmission line is 88 km. The admittance, unavailability and repair time of the facility connection line is 4.73485 (p.u.), 0.00058, 10 hrs respectively. The assumed carrying capacity of the circuit is the installed capacity of the WECS. The series of 400 MW WECS multi-state models for the Regina and Swift Current wind sites are very similar to the 20 MW WECS multi-state models shown in Table 2. The WECS model shown in Table 2, therefore, are used in the MECORE program applications described in this chapter. The annual wind speeds between the Regina and Swift Current wind sites are moderately correlated based on hourly wind speed time data from 1996-2003 found from the National Climate Data and Information Archive on the Environment Canada web site (Gao et al., 2009).

In the state-sampling technique, the states of all components are sampled and a non-chronological system state is obtained. The basic state sampling procedure is conducted assuming that the behaviour of each component can be categorized by a uniform distribution under $\{0, 1\}$ and component outages are independent events. Detailed descriptions of a state sampling simulation procedure are provided in (Gao & Billinton, 2009). Conventional unit and independent WECS outages are assumed to be independent events in the basic state sampling simulation procedure. This assumption, however, is not applicable to partially dependent WECS. It is therefore necessary to generate correlated random numbers, which have a uniform distribution and specified correlations, in the simulation process.

Random numbers distributed uniformly under $\{0, 1\}$ are divided into two clusters in this approach. Random numbers in the first cluster represent conventional units or independent WECS. Random numbers X_1, X_2 between 0 and 1 in the second cluster represent correlated WECS. If the second variable vectors X_2 are generated from the first independent random number set with probability P and generated from the second independent random number set with probability $(1-P)$, the cross-correlation coefficient R_{xy} between X_1 and X_2 in the second cluster is equal to the probability P . This approach was used in the state sampling simulation method to generate correlated random numbers to represent the correlated WECS. A detailed development of this approach is given in (Gao & Billinton, 2009).

4.1 Wind capacity credit analysis using the ELCC method

The Effective Load Carrying Capacity (ELCC) reliability measure was developed in order to measure the adequacy impacts of generating unit additions (Garver, 1966). The ELCC method is also a popular reliability-based approach to assess wind capacity credit (Milligan, 2007; Billinton et al., 2010). The basic concept in this approach is to gradually increase the system peak load until the level of system reliability in the wind assisted system is the same as that of the original system without WECS and therefore determine the increase in load carrying capability. The most commonly used reliability index in the ELCC approach is the Loss of Load Expectation (LOLE) (Billinton & Allan, 1996).

The wind capacity credit of the 400 MW WECS with the two site data shown in Table 2 was calculated using this method. The system LOLE for the MRTS is 0.75 hrs/yr utilizing a chronological load profile. The MRTS can carry a peak load of 3770 MW at a LOLE of 0.75 hrs/yr after the two 400 MW WECS are added. The increase in peak load carrying capability is 120 MW. Reference (Billinton et al., 2010) shows that it is reasonable to evenly divide the total wind capacity credit between the two farms when the two WECS have identical installed capacities. The wind capacity credit for each 400 MW WECS is therefore 60 MW and is used in the following studies described in this chapter.

4.2 Effects of the WECS location

In this section, the effects of the WECS location on the system adequacy are analyzed using the D, P and D-P methods. The WECS locations in the MRTS are considered in two cases:

Case 1: the WECS are added at Buses 1 and 3.

Case 2: the WECS are added at Buses 1 and 6.

4.2.1 Application of the D method

A contingency list for the two cases were obtained by applying the D criterion, involving single generating unit or single transmission elements. The purpose of a contingency selection process is to reduce and limit the set of outage components to be considered. In the case of generation facilities, the largest generating units at different locations in the system are considered. In the case of transmission facilities, the transmission line selections can be done through power flow analyses. The most severe single contingency can be determined from the contingency analysis list. The rank contingency order and the corresponding system peak load carrying capacity (PLCC) for the two cases are shown in Table 3. In Table 3, the designation G18-400/ G21-400 indicates the removal of a 400 MW unit at Bus 1 or Bus 21 and L10 means Line 10 is removed from service.

Rank Order	Case 1		Case 2	
	Outage	PLCC (MW)	Outage	PLCC (MW)
1	L10	3670	L23	3910
2	L23	3940	L7/L27	3958
3	L7/L27	3958	L19	4275
4	L5	4046	L21	4286
5	L21	4286	G18_400/G21_400	4334
6	L19	4305	G23_350	4378
7	G18_400/G21_400	4334	L10	4487

Table 3. The rank orders for the two cases using the D method

Table 3 shows that the line outages tend to have a higher rank than generating unit outages in the two cases. L10 and L23 outages are the most severe contingency for Cases 1 and 2 respectively. The MRTS associated with the WECS have obvious transmission deficiencies, especially in the southeast part of the system. Table 3 shows that the system PLCC values using the D approach for Cases 1 and 2 are 3670 MW and 3910 MW respectively. The system PLCC improves to 3910 MW in Case 2 due to the fact that the transmission stress on Line 10 is reduced by adding a WECS at Bus 6.

4.2.2 The P method

Probabilistic analyses for the two cases were conducted using the state sampling technique. The variations in the system severity index (SI) (SM/yr) (Billinton & Allan, 1996) as a function of the peak load are shown in Table 4 obtained using the P method. Table 4 shows that there is relatively little difference in the system SI between Case 1 and Case 2 using the P method.

Peak load (MW)	Case 1	Case 2
3650	1.740	1.506
3750	2.765	2.617
3850	4.715	4.52
3950	8.472	8.153
4050	14.678	14.364
4150	25.774	25.29
4250	43.613	42.793
4350	72.314	71.074
4450	119.155	117.135
4550	187.834	184.529

Table 4. The system SI (SM/yr) obtained using the P method

4.2.3 The D-P method

The procedure for D-P analysis of Case 1 is briefly illustrated as follows:

- Step 1.** Apply the deterministic N-1 criterion to the system. The largest generating unit in the MRTS with the WECS installed at Buses 1 and 3 has a capacity of 400 MW. The outage of a WECS with 60MW capacity credit does not therefore constitute the most severe contingency under the D criterion.
- Step 2.** Probabilistic analysis is then conducted using the MECORE program. The analysis is conducted on the MRTS with the WECS installed at Buses 1 and 3 with L10 removed from the system. The analysis results for Case 1 are shown in Table 5.

Case 1 (L10)	Peak load (MW)	3650	3670
	SI (SM/yr)	33.68	33.89
Case 2 (L23)	Peak load (MW)	3650	3910
	SI (SM/yr)	86.48	157.78

Table 5. The system SI obtained using the D-P method

It can be seen from Table 5 that the system PLCC for Case 1 is 3670 MW and the corresponding system SI is 33.89 SM/yr under the condition of L10 outage. The procedure for D-P analysis of Case 2 is same as that of Case 1. When Line 23 (L23) is removed from service, the system PLCC is 3910 MW and the corresponding system SI is 157.78 SM/yr. The PLCC for Case 2 is larger than that of Case 1.

The studies in this section show the effect of connecting two correlated WECS at different locations in the MRTS. The WECS locations have obviously impact on the system PLCC using the D and D-P methods. The effects of WECS location on the system SI differ when using the P and D-P methods. The MRTS associated with WECS located at Bus 1 and Bus 6 (Case 2) is considered as the base system in the following planning studies described in this chapter.

5. Wind integrated MRTS reinforcement planning using the D, P and D-P methods

As noted earlier, the MRTS with the two 400 MW WECS located in Bus 1 and Bus 6 is designated as the base system in these studies. The total installed generation capacity includes 4615 MW of conventional capacity and 900 MW of wind power. The system peak load is 3650 MW.

The analysis results for the base system obtained using the three methods are given in Tables 3 to 5. Table 3 shows that the most critical element contingency for the base system is a L23 outage. The variation in the system SI as a function of the peak load is shown in Table 4 obtained using the P method. Table 5 indicates that under the most critical contingency, the base system PLCC is 3910 MW using the D-P method and a Pc of 157.78 SM/yr. Table 6 shows the yearly peak loads in a next ten year planning time frame assuming that the peak load in Year 0 is 3900 MW and each year has a 2% peak load growth.

Year	0	1	2	3	4	5
Peak Load	3900	3980	4060	4140	4220	4300
Year	5	6	7	8	9	10
Peak Load	4300	4390	4480	4570	4660	4760

Table 6. Annual peak load (MW)

The base system PLCC of 3910 MW obtained using the D-P method and shown in Table 5 cannot meet the system peak load growth over the next ten years. The selection of the P_c and R_c values impact the system acceptable risk level using the D-P and P approaches. The particular P_c value used in the D-P method and R_c value used in the P approach are very dependent on the utility management philosophy and what constitute an acceptable risk level. A P_c of 50 SM/yr and a R_c of 10 SM/yr are applied as the base system risk criteria respectively in the following studies.

The planning time frame is an eleven year period and is considered to include two stages: Stage 1 is from the 0th to 4th year to meet the system peak load of 4220 MW. Stage 2 is from the 5th to 10th year to meet the system peak load of 4760 MW.

5.1 The system planning using the D approach

The intent of this study is not to cover all the aspects of the planning process. The focus is on transmission reinforcement planning. It is assumed that generation expansion has determined that 6x50 MW conventional generating units will be installed at Bus 22, 1x350 MW and 3x155 MW units will be added at Bus 23. The total installed conventional generating capacity therefore increases to 5730 MW in the eleven year planning time frame. The selection of planning alternatives to meet the N-1 criterion over a planning time frame is examined. Six expansion planning alternatives are proposed based on practical planning considerations. In the case of a large-scale transmission system, it is reasonable to limit the study to an area or subsystem. Doing so can provide more realistic results than evaluating the whole system (Li, 2005). These alternatives are listed in Table 7.

5.2 System planning using the P approach

The probabilistic evaluation for the six alternatives over the planning time frame was conducted using MECORE. The system SI values for the peak loads of 4220 MW and 4760 MW are shown in Table 8.

It can be seen from Table 8 that although the six alternatives meet the system load requirement in the second planning time period based on the R_c of 10 SM/yr, the system SI values for Alternatives 1 and 3 exceed the designated R_c in Stage 1. Alternatives 1 and 3 are unacceptable schemes using the P method.

5.3 The system planning using the D-P approach

In applying the D-P method, the D analysis described above is followed by probabilistic analysis to determine the system risk under each critical outage condition. A probabilistic evaluation for each alternative is conducted with the most severe contingency to determine the system risk for the alternative in the planning time period. The system load requirement at the end of Stage 1 and Stage 2 are 4220 MW and 4760 MW respectively. The system SI values for the peak load of 4220 MW and 4760 MW under the D criterion are shown in Table 9.

Alternative 1		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Double Lines 23 and 19	L7	4080
	Step 2: Double Line 6	G23_350	4250
Stage 2	Step 3: Add 6×50 MW units at Bus 22, a 350 MW and 3×155 MW units at Bus 23	L12/L13	4575
	Step 4: Double Line 12	L21	4835
Alternative 2		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Add a line between Buses 11 and 15	L7	4060
	Step 2: Double Line 6	G18_400	4330
Stage 2	Step 3: Add 6×50 MW units at Bus 22, a 350 MW and 3×155 MW units at Bus 23	L12/L13	4575
	Step 4: Double Line 12	L21	4800
Alternative 3		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Double Line 23	L7	4080
	Step 2: Double Lines 7 and 27	G23_350	4250
Stage 2	Step 3: Add 6×50 MW units at Bus 22, a 350 MW and 3×155 MW units at Bus 23	L12/L13	4575
	Step 4: Double Line 12	L12	4880
Alternative 4		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Double Lines 23 and 19, add 6×50 MW units at Bus 22 and a 350 MW at Bus 23	L7	4080
	Step 2: Double Line 6	L12/L13	4575
Stage 2	Step 3: Double Line 12	G23_350	4680
	Step 4: Add 3×155 MW units at Bus 23	L21	4835
Alternative 5		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Add a line between Buses 11 and 15, add 6×50 MW units at Bus 22 and a 350 MW at Bus 23	L7	4080
	Step 2: Double Line 6	L12/L13	4575
Stage 2	Step 3: Double Line 12	L7	4760
	Step 4: Add 3×155 MW units at Bus 23	L21	4800
Alternative 6		Most severe outage condition	PLCC (MW)
Stage 1	Step 1: Double Line 23, add 6×50 MW units at Bus 22 and a 350 MW at Bus 23	L7	4080
	Step 2: Double Lines 7 and 27	L12/L13	4575
Stage 2	Step 3: Add a line between Buses 6 and 8	G23_350	4720
	Step 4: Add 3×155 MW units at Bus 23	L21	4880

Table 7. The system PLCC value for the six alternatives using the D method

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6
Stage 1	39.8	2.72	31.5	2.95	2.04	1.64
Stage 2	8	9.8	5.5	7.2	9.8	5.4

Table 8. The system SI (SM/yr) for the alternatives obtained using the P method

	Alt. 1	Alt. 2	Alt. 3	Alt. 4	Alt. 5	Alt. 6
Stage 1	175	184	168	38.4	39	37.5
Stage 2	36	41	40	36	41	40

Table 9. The system SI values (SM/yr) for the alternatives at the end of two stages obtained using the D- P method

As noted earlier, a P_c of 50 SM/yr and a R_c of 10 SM/yr were selected as system criteria in this study. Table 9 shows that the system SI for Alternatives 1, 2 and 3 exceed 50 SM/yr in Stage 1. Alternatives 1, 2 and 3 were, therefore, eliminated from the candidate planning list due to their inability to meet the designated P_c value in the first planning time period and Alternatives 4, 5 and 6 are therefore acceptable planning alternatives using the D-P method. The selected planning schemes for the D, D-P and P techniques are shown in Table 10. It can be seen from this table that the planning alternatives selected are different for the different criteria. All six alternatives are satisfied under the D criterion. Alternatives 4, 5 and 6 are acceptable using the D-P method. Alternatives 2, 4, 5 and 6 are candidate planning schemes using the P method.

Method	D	P	D-P
Selected Alternatives	1, 2, 3, 4, 5, 6	2, 4, 5, 6	4, 5, 6

Table 10. The selected planning schemes for the different techniques

Analysis results shown in Table 10 indicate that the application of the D-P method provides more stringent results for a system with wind energy than the D method. The D-P approach introduces an element of consistency in the assessment by introducing the concept of an acceptable risk level under the critical element outage condition. The D-P technique is driven by the deterministic N-1 criterion with an added probabilistic perspective which recognizes the power output characteristics of a WECS.

6. Conclusions

The research described in this chapter is focused on the utilization of state sampling Monte Carlo simulation in wind integrated bulk electric system reliability analysis and the application of these concepts in system planning and decision making. The techniques and multi-state models developed to permit dependent wind energy facilities to be incorporated in bulk electric system adequacy evaluation using the state sampling Monte Carlo

simulation technique are presented. The wind capacity credit of a WECS is examined using the Effective Load Carrying Capacity (ELCC) method.

The increasing use of wind power as an important electrical energy source clearly indicates the importance of considering the impacts of wind power in power system planning and design, and developing appropriate evaluation techniques. Most electric power utilities use deterministic techniques such as the traditional N-1 security criterion to assess system reliability in transmission system planning. These deterministic (D) approaches are not consistent and do not provide an accurate basis for comparing alternate equipment configurations and performing economic analyses as they do not incorporate the probabilistic or stochastic nature of system behavior and component failures. There is therefore growing interest in combining deterministic considerations with probabilistic (P) assessment in order to evaluate the quantitative system risk and conduct bulk power system planning. A relatively new approach that incorporates deterministic and probabilistic considerations in a single risk assessment framework has been designated as the joint deterministic-probabilistic (D-P) approach.

The MRTS was created in order to conduct planning analysis in a transmission weak system using the D, P and D-P techniques. The studies in this chapter show the effects of connecting two correlated WECS at different locations in the MRTS have obviously impact on the system peaking load carrying capacity using the D and D-P methods. The effects of WECS location on the system SI differ when using the P and D-P methods. The MRTS with WECS located at Bus 1 and Bus 6 was used as the base system in the planning studies described in this chapter.

Six planning alternatives are proposed as candidate development options in this chapter. Although the six planning schemes meet the deterministic N-1 planning criterion, three of the six alternatives are selected as the candidate planning alternatives based on the D-P method. The reason is that the SI values for Alternatives 1, 2, 3 do not meet the specified P_c requirement at the end of Stage 1. The six designated alternatives in the planning time period are also examined using the P method. Alternatives 1 and 3 are eliminated from the candidate list due to their inability to meet the specified R_c value. The research work illustrates that the joint deterministic-probabilistic approach can be effectively used as a planning tool in bulk power systems containing wind energy.

It is believed that the models, methodologies, and results presented in this chapter should assist system planners to conduct wind integrated bulk electric system planning.

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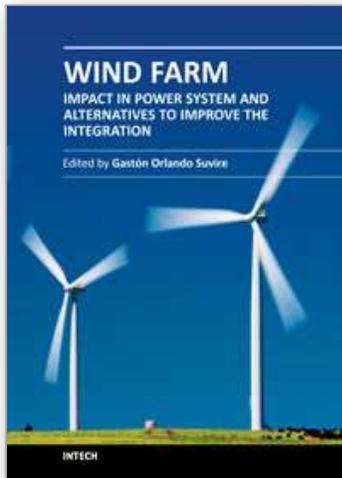
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Wind Farm - Impact in Power System and Alternatives to Improve the Integration

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During the last two decades, increase in electricity demand and environmental concern resulted in fast growth of power production from renewable sources. Wind power is one of the most efficient alternatives. Due to rapid development of wind turbine technology and increasing size of wind farms, wind power plays a significant part in the power production in some countries. However, fundamental differences exist between conventional thermal, hydro, and nuclear generation and wind power, such as different generation systems and the difficulty in controlling the primary movement of a wind turbine, due to the wind and its random fluctuations. These differences are reflected in the specific interaction of wind turbines with the power system. This book addresses a wide variety of issues regarding the integration of wind farms in power systems. The book contains 14 chapters divided into three parts. The first part outlines aspects related to the impact of the wind power generation on the electric system. In the second part, alternatives to mitigate problems of the wind farm integration are presented. Finally, the third part covers issues of modeling and simulation of wind power system.

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