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Probabilistic Reliability Evaluation of Power Systems Including Wind Turbine Generators Considering Wind Speed Correlation

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Abstract – The importance of renewable energy sources has been growing at a high rate as a result of being environment friendly. In particular, wind power is one of the most successfully utilized of such sources to produce electrical energy. Because of the randomness of wind speed, the reliability impact on this highly variable energy power is important aspect that needs to be assessed. In this paper, the impact on the reliability indices of wind speed correlation between two farms is considered.

Keywords: Renewable energy, Wind, Reliability impact, Wind speed correlation

1. Introduction

The utilization of renewable resources such as wind and solar to generate electric power has been receiving considerable attention in recent years [1],[2]. Wind energy in particular has been fast growing and is recognized as the most successful energy source of all available sources. As a result of available high capacities of wind turbine generators, the generation costs are becoming competitive. The reliability impact on this highly variable energy power is important aspect that needs to be assessed. The reliability impact on the wind speed correlation is also considered along with the development on reliability evaluation of WFs. Because wind speed does not maintain a specified stable level, a multi-state model is used to estimate systems reliability. The power output model of the WTG coupled with the wind speed model is used to develop a multi-state model [2]. The convolution integral in effective load duration curve (ELDC) is utilized to calculate the indices of reliability evaluation.

In this paper, the power system includes Hanlim (HLM), Hangwon (HWN) and Songsan (SSN) wind farms (WF) where are located in northwest, northeast and east of Jeju Island. The reliability indices considering wind speed correlation are compared between HLM-HWN and SSN-HWN in three years (2005, 2006 and 2007).

2. Wind Speed Correlation

The wind speed correlation between two WF does not only depend on the distance between the site locations but also on the geographical dispersion and the uniqueness of the individual wind regimes. The most obvious factor is the distance between the wind sites [9]. The wind speed correlation can be calculated using cross correlation. Cross correlation coefficient $r_{xy}(k)$ is a measure of how well two time series follow each other. The value of $r_{xy}(k)$ is near the maximum value of 1, if the up and down movements of the two time series occur in the same direction (positively correlated). The value is close to zero, if the two time series are basically uncorrelated. The equation is shown in (1) and (2) [8].

$$r_{xy}(k) = \frac{C_{xy}(k)}{\sqrt{C_{xx}(0)C_{yy}(0)}} \tag{1}$$

$$C_{xy}(k)\frac{1}{n}\sum_{t=1}^{n-k}(X_t - X_M)(Y_{(t+k)} - Y_M) \tag{2}$$

Where,

n: the time lag length

X_t and Y_t : a pair of wind speed time series in a given period

X_M and Y_M: the average of X_t and Y_t

$C_{xx}(0)$ and $C_{yy}(0)$: $C_{xy}(k)$ values for y=x and x=y when k=0

The diagram of the cross correlation in wind speed time series indicated the time lag in which the correlation is strongest. The diagram is constructed by the results of (1) for a number of time lags that describe the tendency of the cross correlation coefficient.

3. Wind Turbine Generators

3.1 Wind Power Plants

A modern type, Doubly-Fed Induction Generator (DFIG) structure of wind turbine generators (WTG) is given in Fig. 1. The unit operates by extracting kinetic energy from the wind passing through its unit's rotor [1].

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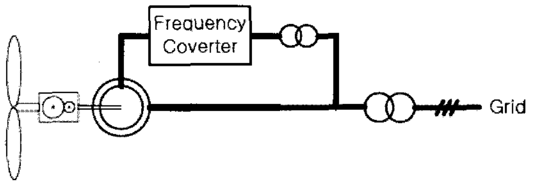

Fig. 1. An example of a wind turbine generator (WTG-DFIG)

The theoretical power generated by the WTG is expressed as (3).

$$P = \frac{1}{2} C_p \rho V^3 A \tag{3}$$

Where,
P: power [W]
C_p: power coefficient
ρ: air density (1.225 kg/m3)
V: wind velocity (m/sec)
A: swept area of rotor disc (m2)

3.2 WTG Power Output Model

Fig. 2 presents the relationship between the power output of a WTG and wind speed [1]-[4].

Where,
V_{ci}: the cut-in speed [m/sec].
V_R: the rated speed [m/sec].
V_{co}: the cut-out speed [m/sec].
P_R: the rated power [MW].

A mathematical model for the power output of WTG is given as (4) [2]. The power, P_i generated by wind speed band SW_i can be formulated as (4) [2]. Where, 'i' is the number of wind speed band. The parameters A, B, and C are given by (5)-(7) [3].

$$\begin{aligned} P_i &= 0, 0 \le SW_i < V_{ci} \\ &= P_R(A + B \times SW_i + C \times SW_i^2), V_{ci} \le SW_i < V_R \\ &= P_R, V_R \le SW_i \le V_{co} \\ &= 0, V_{co} < SW_i \end{aligned} \tag{4}$$

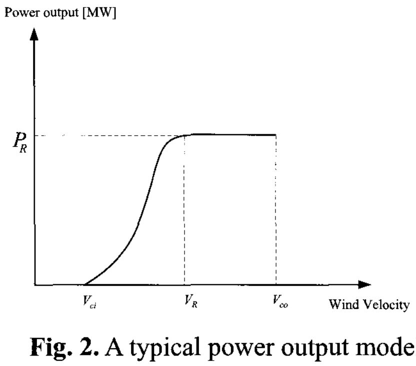

Fig. 2. A typical power output model of WTG

$$A = \frac{1}{(V_{ci} - V_R)^2}\left[V_{ci}(V_{ci}+V_R) - 4(V_{ci}V_R)\left(\frac{V_{ci}+V_R}{2V_R}\right)^3\right] \tag{5}$$

$$B = \frac{1}{(V_{ci} - V_R)^2}\left[4(V_{ci}+V_R)\left(\frac{V_{ci}+V_R}{2V_R}\right)^3 - (3V_{ci}+V_R)\right] \tag{6}$$

$$C = \frac{1}{(V_{ci} - V_R)^2}\left[2 - 4\left(\frac{V_{ci}+V_R}{2V_R}\right)^3\right] \tag{7}$$

4. Wind Speed Model

Wind speeds vary both in time and space. It is has been reported that the actual wind speed distribution may be described as Weibull probability distribution near to normal [2]. This paper uses the wind speed model of normal probability distribution function in terms of the mean wind speed value μ and the standard deviation σ as shown Fig. 3.

Negative wind speed value in Fig. 3 means anti-direction of WTG. They are ignored because they are not useful in reliability assessment of WTGs. To calculate the power (P_i) and the probability (PB_i) corresponding to wind speed (SW_i) of wind speed band i using (4), the probability distributions of wind speeds are divided into Nb equal bands. The band size becomes $10\sigma/Nb$. The distribution considers wind speeds up to 10σ to include extreme values despite their low probability of occurrences. The wind speed SW_i is expressed by (8) in order to make μ set up at midpoint in cases of even Nb as well as odd Nb. The probability PB_i is expressed as (9).

$$\begin{aligned} SW_i &= \mu + (10\sigma / Nb)(i - 0.5Nb) \text{ for even Nb,} \\ &= \mu + (10\sigma / Nb)(i - 0.5(Nb+1)) \text{ for odd Nb} \end{aligned} \tag{8}$$

$$PB_i = N_{swbi} / Ny \tag{9}$$

Where,
μ: mean of wind speed.
σ: standard deviation of wind speed.
N_{SWi}: the number of wind speed band $SW_i(i=1,\ldots,Nb)$
N_y: the total number of wind speed data of the sample years.

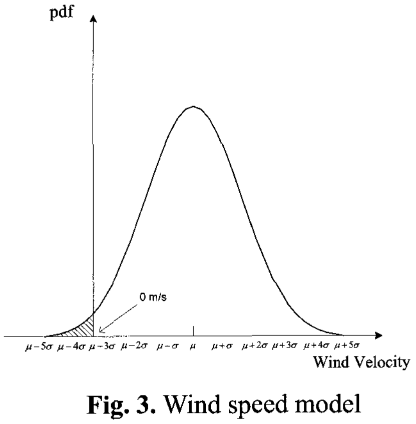

Fig. 3. Wind speed model

Table 1. The caption must be followed by the table

	A (ampere)	B (voltage)
a	0.65 A	0.83 V
b	1.32 A	1.09 V

5. Reliability Evaluation of Power Systems Including WTG

5.1 A Multi-state Model of WTG

A two-state model has been found suitable to represent conventional generating units in reliability evaluation. However, this model is not suitable to represent the WTGs as an operation model because the wind speed cannot be maintained at a specified stable level and a multi-state model is needed. Fig. 4 describes the multi-state model for WTG's operation model [2]-[4]. Due to the continuously changing wind speed, the transition from state 1 to state 3 without through state 2 cannot be occurred. Therefore, the multi-state model of operation of WTG forms a chain style.

The power output model of WTG is combined with the wind speed model as shown in Fig. 5 to yields the multi-state model. Each state has a pair of associated parameters; namely the power (P_i) and probability (PB_i). Eventually, the reliability indices of WTG are evaluated by Effective Load Duration Curve (ELDC) using convolution integral method based on the multi-state model.

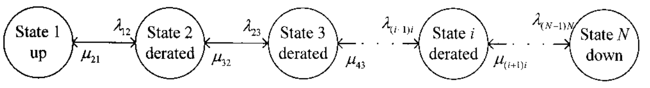

Fig. 4 A multi-state operational model of WTG

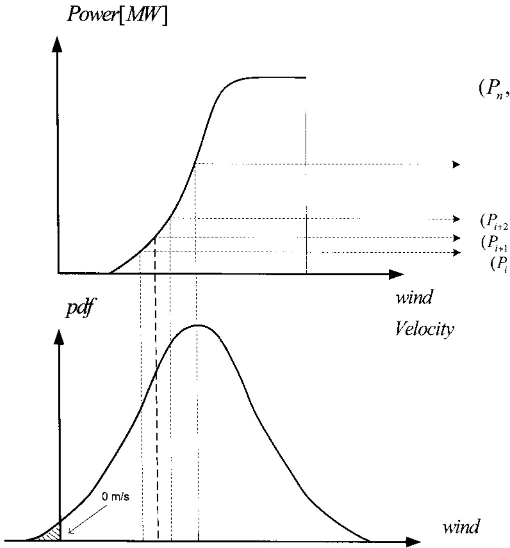

Fig. 5. Development of a model describing the power outputs of WTG and the corresponding probabilities

5.2 A Simplified Multi-state Model

The band sizes of the multi-state model must be equal to use the convolution integral. As a result, the number of bands may become impractically large. In order to reduce the number of bands, the multi-state model may be simplified using the rounding method. And, it is reasonable to use pre-specified multi-states in the case of actual systems.

In this paper, a simplified multi-state model using a linear rounding method is proposed. The linear rounding method is presented graphically in Fig. 6 and mathematically described as by (10) and (11), which share the ratio of probability linearly.

$$PB_k=\left(\frac{P_{k+1}-P_i}{\Delta P}\right)\times PB_i \tag{10}$$

$$PB_{k+1}=\left(\frac{P_i-P_k}{\Delta P}\right)\times PB_i \tag{11}$$

Where,
$\Delta P=P_k+1-P_k$ [MW]
k: the state number of the simplified multi-state model

The P_k and PB_k are the power and probability of the modified (simplified) multi-state k which is separated using the rounding method as expressed by (10) and (11). Although these data have been revised by the rounding method, the total probabilities are still equal to 1 because the probabilities of the modified/simplified multi-state model (posterior) are accumulated from sharing the probabilities of original state model by the rounding method. The purpose of the method is to effectively decrease the state number of the original multi-state model and calculate reliability indices easily by using convolution integral method.

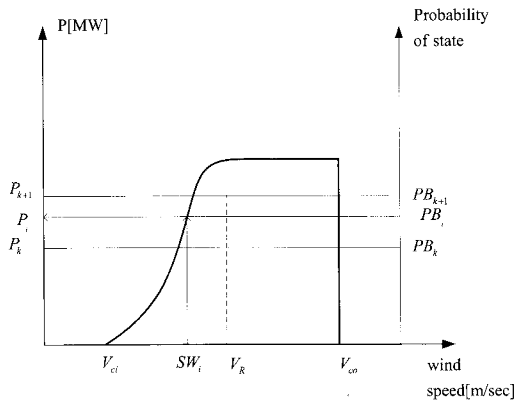

Fig. 6. Illustration of the proposed rounding method

5.3 Reliability Evaluation

Probabilistic reliability indices have been used extensively for generation expansion. They can be calculated by using the Effective Load Duration Curve (ELDC, Φ) as described in (12) [6].

$$\Phi_j = \Phi_{j-1} \otimes f_{oj}$$
$$= (1-\sum_{k=1}^{NS} q_{kj})\Phi_{j-1}(x) + \sum_{k=1}^{NS} q_{kj}\Phi_{j-1}(x-C_{kj}) \qquad (12)$$

Where,
Φ_0: the original Inverted Load Duration Curve (*ILDC*)
x: random variable of Φ
NS: the total state number of the simplified multi-state model
C_{kj}: outage capacity of state k of generator j
q_{kj}: the probability correspond the outage capacity of state k of generator j
f_{oj}: the outage capacity probability distribution function (OCPDF) of generator j

The Loss of Load Expectation (*LOLE*), the Expected Energy Not Supplied (*EENS*) and the Energy Index of Reliability (*EIR*) which are the main reliability indices of power systems are described using ELDC (Φ) as (13)~(15).

$$LOLE = \Phi_{NG}(x)\big|_{x=IC} \qquad \text{[Days/year]} \qquad (13)$$

$$EENS = \int_{IC}^{IC+Lp} \Phi_{NG}(x)\,dx \qquad \text{[MWD/year]} \qquad (14)$$

$$EIR = 1-\frac{EENS}{ED} \qquad \text{[pu]} \qquad (15)$$

Where,
IC: the system installed capacity ($=\sum C_j$)
C_j: the capacity of generator j
L_p: the peak load of demand
NG: the total number of generators
ED: total demand energy [MWD]
Φ_{NG}: final ELDC convoluted with the f_{oj} of all generators

For power systems that include both conventional generators and WTGs, Φ_j is obtained by using convolution integral for each WTG. Fig. 7 shows the proposed flow chart to evaluate the reliability of a power system including WTGs.

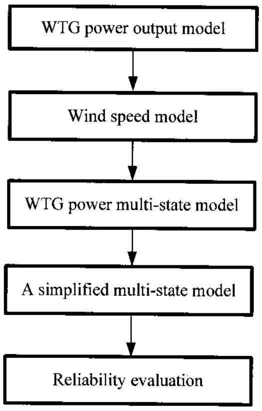

Fig. 7. A step-by-step process for evaluating the reliability of a power system involving WTGs

6. Case Study

The approach described earlier was implemented on the power system of Jeju, which is the largest tourist island in Korea. Jeju is located approximately 100km south of the mainland. It is an Island known for its strong and frequent wind. This is because in the winter season, it poses a higher atmospheric pressure difference between the sea and the land than it does in the summer season. Strong wind forces are mostly seen on the northwest coastal area where winter monsoon has great influence, while the southeast coastal area has a relatively weak wind. Wind around Jeju Island blows hard in spring.

In this paper, HLM, HWN and SSN WFs are located in northwest, northeast and east of Jeju Island. The distances of HLM-HWN, HLM-SSN and HWN-SSN are 55km, 57km and 15km respectively. The HLM WF is covered from GSN weather measuring station (WMS). The HWN and SSN WFs are covered from the SSN WMS. Wind speed data in 2005, 2006 and 2007 are used to obtain the correlation coefficients between two WFs by using (1). HWN and SSN WFs are covered in the same WMS, because of the short distance between HWN and SSN WFs. The maximum correlation coefficient of HWN-SSN is '1'. Fig. 8 shows annual wind speed variances of HLM-SSN and HLM-HWN WFs in three years.

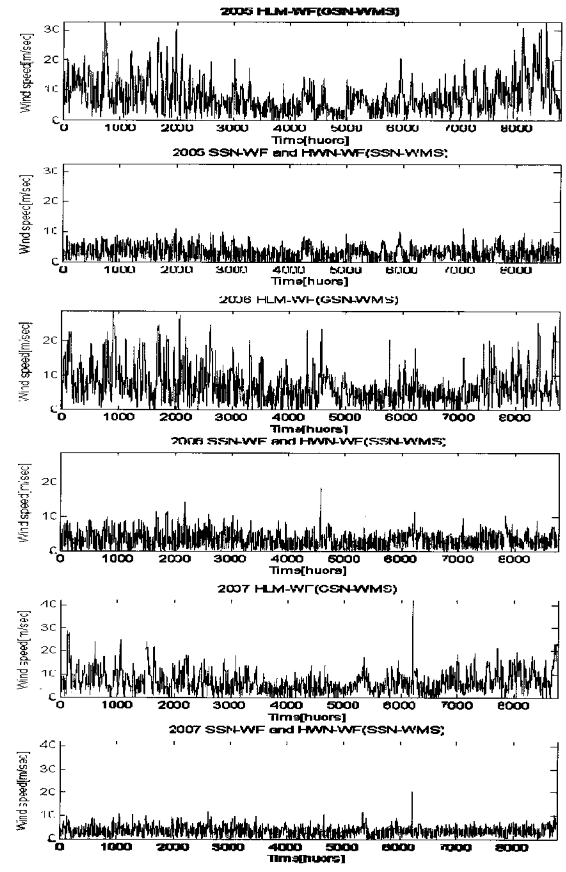

Fig. 8. wind speed variance at HLM, HWN and SSN in 2005, 2006 and 2007

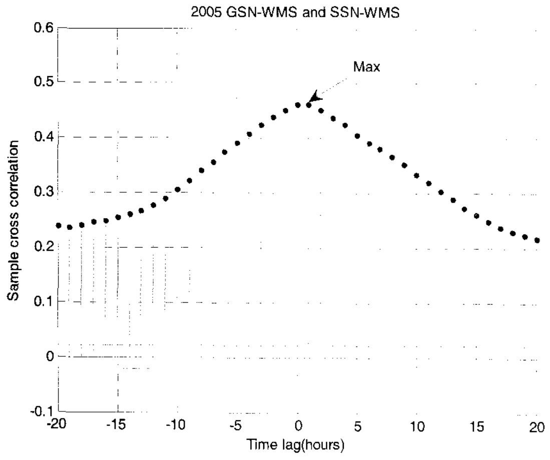

Fig. 9. The correlation diagram in 2005

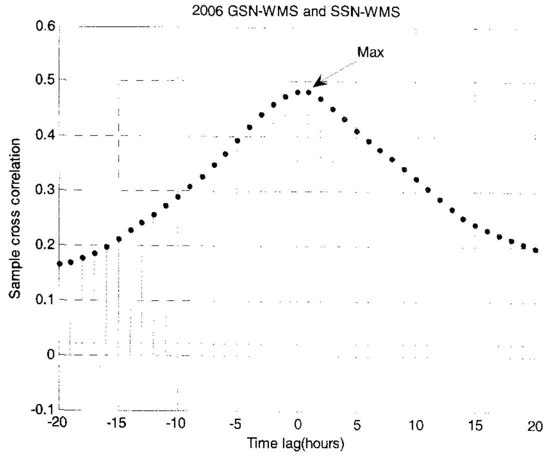

Fig. 10. The correlation diagram in 2006

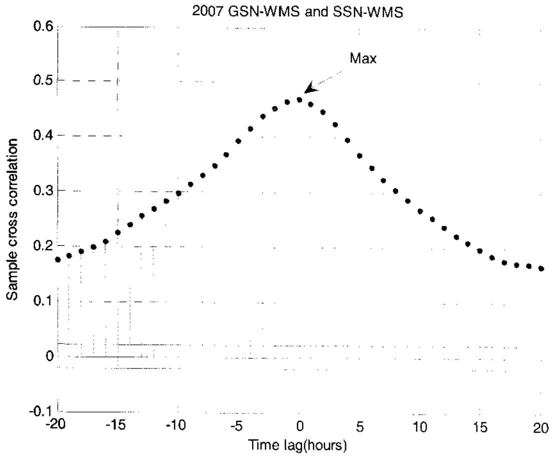

Fig. 11. The wind speed variance and the correlation diagram in 2007

The maximum correlation coefficients are at instantaneous and positive time lags in 2005, 2006 and 2007. It describes the wind almost blows from GSN to SSN WMS. The maximum correlation coefficients from HLM to HWN and SSN in three years are presented in table 1.

Table 1. The maximum correlation coefficients

Year	2005	2006	2007
Maximum R_{xy}	0.46127	0.482	0.46984

Data of HLM, HWN and SSN WFs in 2005, 2006 and 2007 are showed in table 2 and 3.

Table 2. Wind Speed Data of HWN and SSN WFs

	HWN-WF and SSN-WF (SSN-WMS) [m/sec]		
Years	2005	2006	2007
V_M	3.1405	3.2797	3.373
STD	1.8795	1.9442	1.7721
V_{max}	11.4	18.3	20.8

Table 3. Wind Speed Data of HLM WF

	HLM-WF(GSN-WMS) [m/sec]		
Years	2005	2006	2007
V_M	7.9898	6.9451	6.6792
STD	5.3289	4.5908	4.3781
V_{max}	32.7	29	42.3

Input data of HWN, SSN and HLM WFs are showed in table 4.

Table 4. Capacity and Specifications of WTGs of HWM, SSN and HLM WFs

	HWN-WF	SSN-WF	HLM-WF
Capacity	30MW	30MW	30MW
V_{ci}[m/sec]	3	3	5
V_R[m/sec]	5	5	10
V_{co}[m/sec]	25	25	25

Table 5 and fig. 12 show data and the load duration curve of daily peak load of Jeju Island power system in an annual time. The peak load is 681MW.

Table 5. Data of The Jeju's Power System

	Unit Name	Type	C [MW]	No.	FOR
1	HLM	WTG	30	1	-
2	SSN	WTG	30	1	-
3	HWN	WTG	30	1	-
4	NMJ3	T/P	100	2	0.012
5	JJU1	T/P	10	1	0.015
6	JJU2	T/P	75	2	0.012
7	HNM1	G/T	35	2	0.013
8	HNM1	S/T	35	1	0.013
9	JJU3	D/P	40	1	0.018
10	NMJ1	D/P	10	4	0.018
11	HVDC*	HVDC	75/ 150	2	0.010/ 0.028
Total			935	18	-

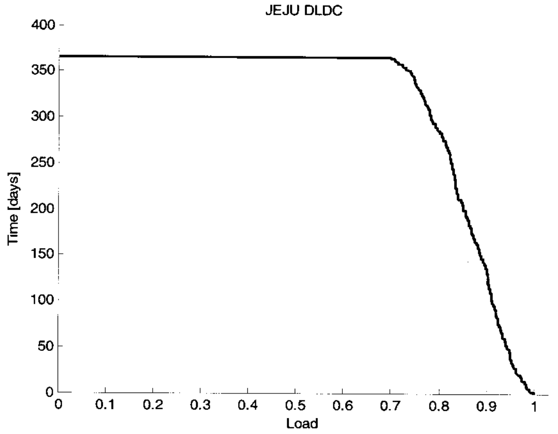

Fig. 12. Load duration curve in an annual time

Using the power output model for WTGs and the wind speed model results the out power and the corresponding probability. The original multi-state model is simplified using the proposed rounding method. The outage capacity probability distribution function (OCPDF) considers a 5-state, a 7-state and an 11-state models for HLM, SSN and HWN WFs. The calculated *LOLE* and *EENS* reliability indices for the Jeju Island's power system are calculated by (12).

For comparing the impact on reliability evaluation of wind speed correlation between two farms, three kinds of systems are presented to calculate the reliability indices. The first power system is a system included SSN and HWN WFs (Case A). The second power system is a system included HLM and HWN WFs (Case B). The third power system is a system included all of the three WFs (Case C).The results are presented in table 6 and table 7.

Table 6. Results of case A and case B

	Case A	Case B
2005		
Maximum R_{xy}	1	0.46127
LOLE[days/year]	0.53	0.48
EENS[MWD/year]	21.04	18.44
2006		
Maximum R_{xy}	1	0.482
LOLE[days/year]	0.51	0.49
EENS[MWD/year]	20.19	19.20
2007		
Maximum R_{xy}	1	0.46984
LOLE [days/year]	0.51	0.50
EENS[MWD/year]	19.94	19.43

Table 7. Result of case C

Year Case C	2005	2006	2007
V_M[m/sec]	4.76	4.50	4.47
LOLE[days/year]	0.39	0.40	0.40
EENS[MWD/year]	14.72	15.02	15.10

The above results are compared. In table 6, although the *LOLE* and *EENS* of case B is smaller than case A's with lower correlation coefficient, it is should be noticed that the wind speed data of HLM are presented in table 2 are much better than HWN's and SSN's are presented in table 3.

By table 2 and 3, the average wind speed that blows the three WFs in 2005, 2006 and 2007 are obtained as 4.76m/sec, 4.50m/sec and 4.47m/sec. The reliability indices of case C in each year is almost corresponding to the variance of average wind speed that blows the three WFs especially to *EENS*. The result of case C is showed in table 7. By the above reason, wind speed has an obvious impact on reliability indices of WFs.

7. Conclusion

This paper presents a reliability evaluation of WFs and an impact on reliability indices of wind speed correlation between two wind farms. The reliability evaluation of an existing power system including WFs was performed using the proposed model. Combining the wind speed model and the WTG's power output model yields the multi-state model. The wind speed correlation does not only depend on the distance between the site locations, but also the geographical dispersion and the uniqueness of the individual wind regimes. The most obvious factor is the distance between the wind sites. Basing on the results of reliability indices are calculated in case study, wind speed correlation between two WFs has not an obvious impact on reliability indices of WFs in Jeju Island power system. The impact of the wind speed correlation on reliability indices is glossed over by the strong wind and an irregular distribution of wind in Jeju Island.

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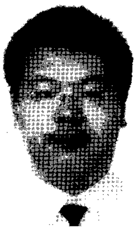

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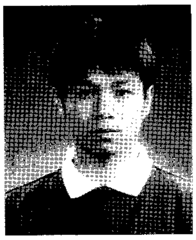

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