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Probabilistic Reliability Based Grid Expansion Planning of Power System Including Wind Turbine Generators

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Abstract – This paper proposes a new methodology for evaluating the probabilistic reliability based grid expansion planning of composite power system including the Wind Turbine Generators. The proposed model includes capacity limitations and uncertainties of the generators and transmission lines. It proposes to handle the uncertainties of system elements (generators, lines, transformers and wind resources of WTG, etc.) by a Composite power system Equivalent Load Duration Curve (CMELDC)-based model considering wind turbine generators (WTG). The model is derived from a nodal equivalent load duration curve based on an effective nodal load model including WTGs. Several scenarios are used to choose the optimal solution among various scenarios featuring new candidate lines. The characteristics and effectiveness of this simulation model are illustrated by case study using Jeju power system in South Korea.

Keywords: Power system reliability, Wind energy generation, Nodal reliability indices, Grid expansion planning, Multi-state model

1. Introduction

As a result of being environment conscious, the utilization of renewable resources such as the wind and the solar energy to generate electricity have received considerable attention in recent years [1-3]. Wind energy in particular has been fast growing and is recognized as the most successful energy source among all the alternative energy sources. The location of wind turbine generators (WTG) depends on the available wind speed conditions. Therefore, grid-constrained reliability evaluation has become very important for grid expansion planning and operation when wind turbine generators are added in a power system. However, it is difficult to simulate operation of WTG and evaluate its reliability contribution point of view due to small ELCC(Effective load carrying capability) which means "how much can a generator cover load?" [4-6].

The reason is large uncertainty of resource supply for WTG.

The uncertainties in power system may be categorized to two kinds as like aleatory uncertainty and epistemic uncertainty [7]. Former includes the forced outage rate of generator, transmission lines and main transformers etc.. The latter includes lack of information occurred in load forecasting, wind speed and solar radiation etc.. Therefore, latter is occurred at renewable power plants while former occurred in conventional power plants.

Fig. 1 shows differences of the uncertainties of the renewable energy resource power and conventional plants.

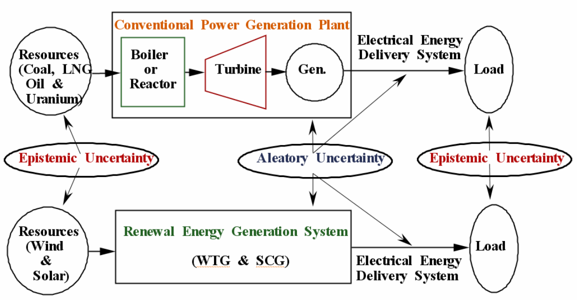

Fig. 1. Uncertainties of the renewable energy resource power and conventional plants

Composite power system reliability evaluation is complex and WTG cannot be adequately represented by simple two-state models [6]. Since the two-state models create large errors in accuracy, multi-state models are required for WTG. Relevant wind speed models are combined with WTG characteristics to create multi-state WTG models. Research has been carried out to evaluate the reliability of generation systems (HLI; Hierarchical Level I) while including WTG by using multi-state WTG models [4-6, 8]. As major WTG penetration levels are expected in the near future, the development of a methodology for evaluating the wind integrated composite power system reliability has become an important and necessary task to accomplish.

This paper proposes a new methodology for grid-constrained probabilistic reliability evaluation of power system expansion including WTG. The reliability

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evaluation methodology based on the composite power system effective load model without WTG has been already developed by the authors [9-11]. This methodology utilizes two-state models for both generators and transmission lines. But, this paper proposes a model extended from the two-state representation to multi-state models for generators in order to consider WTGs. By using the proposed model, this paper illustrates a grid expansion planning considering not only capacity limitations and uncertainties of lines and generators but also the uncertainty of power outputs of WTGs. The simulation methodology requires a nodal probabilistic model in order to implement the reliability evaluation of the composite power system including WTGs. This paper describes effectiveness of the proposed method through a case study with Jeju Island's power system in South Korea.

2. The Multi-State Operation Model of WTG

2.1 The WTG power output model

Fig. 2 shows the relationship between the power output of a WTG and the wind speed [4-8, 12-15], where, V_{ci} is the cut-in speed [m/sec], V_R the rated speed [m/sec], V_{co} the cut-out speed [m/sec], and P_R the rated power [MW].

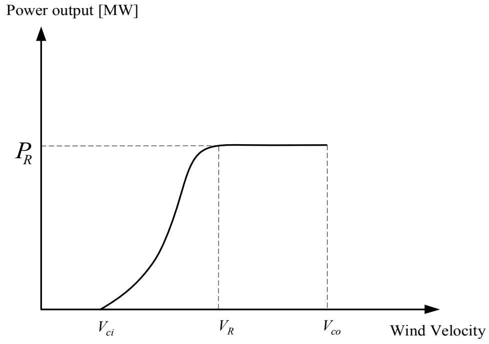


Fig. 2. A typical power output curve for a WTG.

A mathematical model for the power output of a WTG is given by (1) [8, 12-15]. The power P_i generated by wind speed band SW_i is formulated in (1) [9], where, i is the wind speed index. The A, B and C parameters are given by (A.1-A.3) and in [9-12].

$$\begin{aligned} P_i &= 0, 0 \le SW_i < V_{ci} \\ &= P_R(A + B \times SW_i + C \times SW_i^2), V_{ci} \le SW_i < V_R \\ &= P_R, V_R \le SW_i \le V_{co} \\ &= 0, V_{co} < SW_i \end{aligned} \tag{1}$$

2.2 Wind speed model

Wind speeds vary in both time and space. It has been reported that the actual wind speed distribution is described by a Weibull probability distribution near to a normal distribution [9].

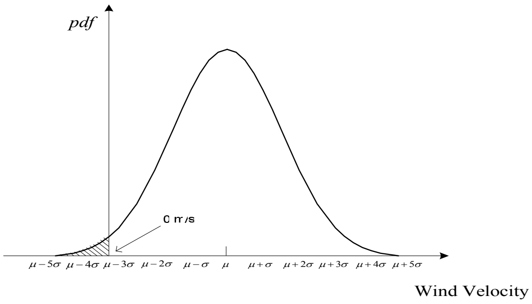


Fig. 3. Wind speed model.

This paper uses the normal probability distribution function (*pdf*) to model the wind speed in terms of the mean wind speed value μ and the standard deviation σ as shown in Fig. 3. The negative wind speeds in Fig. 3 has no physical meaning and can be considered as zero wind speed.

2.3 The multi-state model of a WTG using normal probability distribution function

The power output curve of the WTG is combined with the wind speed model shown in Fig. 4 to create the multi-state WTG model. Each state has a pair of associated parameters; namely, the power(P_i) and probability(PB_i) of #*i* wind band. Where, PB_i is probability of #*i* wind speed band(SW_i) as shown in Fig. 4. Because this paper uses the normal probability distribution function(*pdf*) in terms of the mean wind speed value μ and the standard deviation σ, the probability(PB_i) corresponding to wind speed band(SW_i) can be calculated as (2).

$$PB_i = \int_{CSW_{i-1}}^{CSW_i} \frac{1}{\sigma\sqrt{2\pi}} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right) dx \tag{2}$$

Where,

μ : mean of wind speed.

σ : standard deviation of wind speed.

$CSW_i = SW_1 + SW_2 + \ldots + SW_i$

The operating model of a WTG is a multi-state model, which is described by a capacity outage probability density function. The number of multi-states depends on capacity of WTG. More states permits better accuracy. Even if the number increases over a multi-state number, however, the accuracy is increased no more and is saturated at a state number. While the accuracy is saturated, computation time is exhausted more. Sensitivity analysis according to number variation, typically, from 2 states to 100states of multi- states should be evaluated previously.

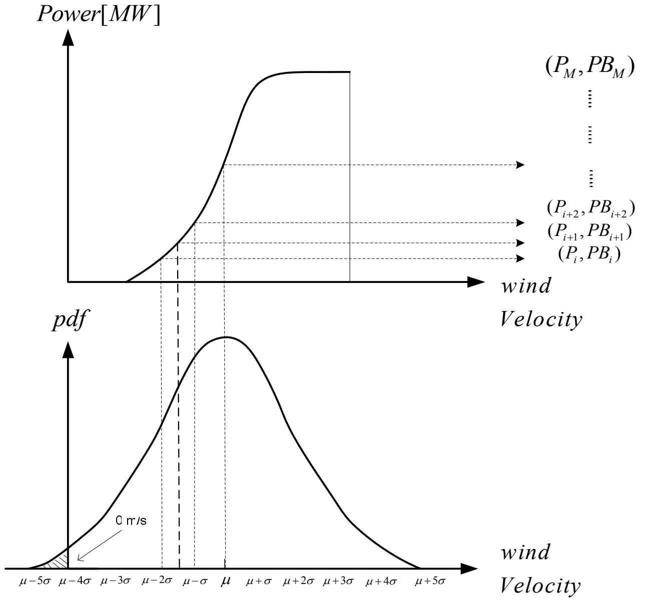
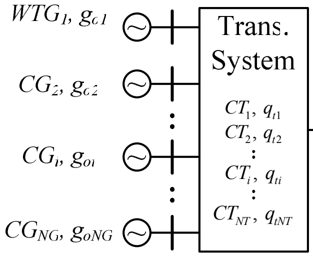


Fig. 4. Components of a model describing the power output states of a WTG and the corresponding probabilities.

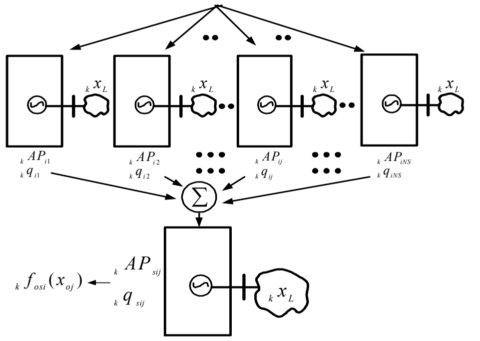
3. Reliability Evaluation of a Composite Power System Including WTG

Composite power system reliability evaluation methodologies based on both enumeration methods and Monte Carlo methods have been developed [16]. A composite power system reliability evaluation methodology based on the composite power system effective load model has also been developed [10]. This methodology uses two-state models to describe the generators and transmission lines. The reliability indices for composite power systems (HLII; Hierarchical Level II) can be classified as load point indices and bulk system indices depending on the objective of the evaluation. They can be evaluated using a Composite power system Equivalent Load Duration Curve (CMELDC) based on the composite power system effective load model in Fig. 5 [10]. Parameters, *CG, CT,* g_o and q_l in Fig. 4 are the capacities and capacity outage density functions of the generators and the unavailability of the transmission lines, respectively. The model uses the capacity outage density functions of the WTG and considers them as multi-state generators [12-15]. The state model for transmission lines remains a two-state one.

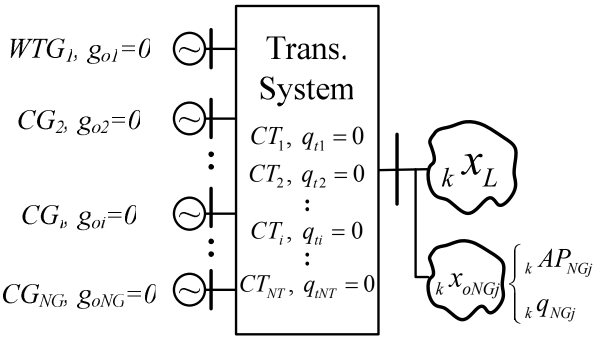
The capacity outage *pdf* of the synthesized fictitious generator created by generators 1-*i*, at load point *k* (${}_kf_{osi}$) is also a multi-state function. The convolution integral involving the original load duration curve at load point *k* (${}_k\Phi_0$) and ${}_kf_{osi}$ is processed at HLII. The general multi-state convolution integral calculation method for probabilistic reliability evaluation has been used extensively for generation expansion and can be calculated using the multi-state recursive equation shown in (3).



(a) Actual system



(b) Synthesized fictitious equivalent generator



(c) Equivalent system

Fig. 5. Composite power system effective load model at HLII

$$
\begin{aligned}
{}_k\Phi_i &= {}_k\Phi_{i\text{-}1} \otimes {}_kf_{osi} \\
&= (1 - \sum_{n=1}^{\mathrm{NS}} {}_k\mathrm{q}_{ni})\, {}_k\Phi_{i\text{-}1}(x) + \sum_{n=1}^{\mathrm{NS}} {}_k\mathrm{q}_{ni}\, {}_k\Phi_{i\text{-}1}(x - {}_k\mathrm{C}_{ni})
\end{aligned}
\tag{3}
$$

Where,

$\otimes$: operator representing the convolution integral

${}_k\Phi_0$: original load duration curve at load point *k*

${}_kf_{osi}$: outage capacity pdf of the synthesized fictitious generator created by generators 1 to *i,* at load point *k*

x : random variable of Φ

NS : the multi-state number of the synthesized fictitious generator

${}_kC_{ni}$: outage capacity of state *n* of the synthesized fictitious generator created by generator at load point *k*

${}_kq_{ni}$: the probability correspond to the outage capacity of state k of the synthesized fictitious generator at load point k

3.1 Reliability indices at load points(Buses)

The load point reliability indices, $LOLE_k$ and $EENS_k$ can be calculated using (4) and (5) using the CMELDC, ${}_k\Phi_{NG}(x)$. EIR(Energy Index of Reliability) is calculated as (6). Where, $DENG_k$ is demand energy at load point #k,

$$LOLE_k = {}_k\Phi_{NG}(x)\,\Big|_{x=AP_k} \quad \text{[hours/yr]} \tag{4}$$

$$EENS_k = \int_{AP_k}^{AP_k+Lp_k} {}_k\Phi_{NG}(x)dx \quad \text{[MWh/yr]} \tag{5}$$

$$EIR_k = 1 - EENS_k / DENG_k \text{ [p.u]} \tag{6}$$

Where,

$DENG_k$: demand energy at bus k

L_{pk} : peak load at load point k [MW]

AP_k : maximum arrival power at load point k [MW]

3.2 System reliability indices

The $EENS_{HLII}$ of a bulk system is equal to the summation of the $EENS_k$ at the load points as given by (7). The $LOLE$ of a bulk system, however, is entirely different from the summation of the $LOLE_k$ at the load points. The ELC_{HLII} (Expected load curtailed) of a bulk system is equal to the summation of ELC_k at the load points as given by (8). An equivalent representative $LOLE_{HLII}$ of a bulk system can be obtained using (9). EIR of system is calculated as (10). Where, $DENG_{HLII}$ is sum of load point demand energy, $DENG_k$

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \quad \text{[MWh/yr]} \tag{7}$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \quad \text{[MW/yr]} \tag{8}$$

$$LOLE_{HLII} = EENS_{HLII} / ELC_{HLII} \quad \text{[hours/yr]} \tag{9}$$

$$EIR_{HLII} = 1 - EENS_{HLII} / DENG_{HLII} \text{ [p.u]} \tag{10}$$

Where,

NL : number of load points

ELC_k : Expected Load Curtailed ($=EENS_k / LOLE_k$)

Fig. 6 shows a flow chart of the proposed method to evaluate the reliability of grid including WTGs.

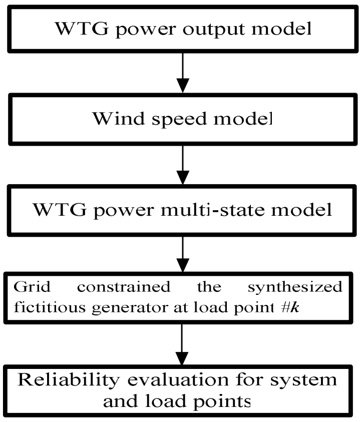


Fig. 6. The flow chart for reliability evaluation of a power system involving WTGs

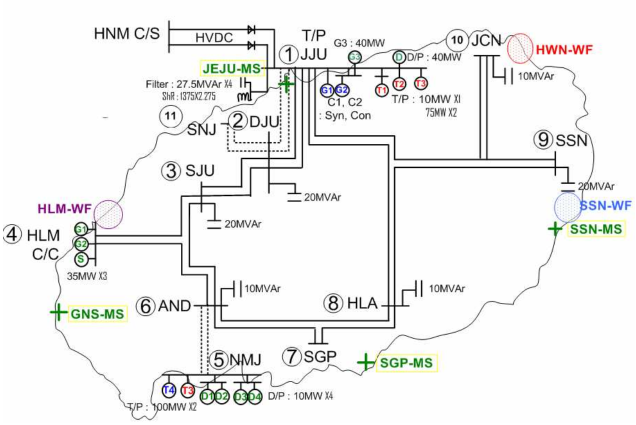


Fig. 7. Power System of Jeju Island

Table 1. Bus Number Matched Bus Name in Fig. 7

Bus name	JJM	DJU	SJU	HLM	NMJ	AND	SGP	HLA	SSN	JCN	SNJ
Bus number	1	2	3	4	5	6	7	8	9	10	11

Table 2. Data of the Jeju's Power System (2012 year)

Bus name	Unit Name	Type	C [MW]	Unit & cct	FOR
10	JCN1	WTG	50	1	-
9	SSN2	WTG	30	1	-
4	HLM3	WTG	20	1	-
1	HVDC	HVDC	150	2	0.028
5	NMJ3	T/P	100	2	0.012
1	JJU1	T/P	55	3	0.015
1	JJU2	T/P	75	2	0.012
4	HNM1	G/T	35	2	0.013
4	HNM1	S/T	35	1	0.013
1	JJU3	D/P	40	2	0.018
5	NMJ1	D/P	10	4	0.018
Total			1140	21	-

4. Case Study

The proposed method was implemented on the power system of 2012 of Jeju. Fig. 7 shows the Jeju power system [12-15]. Table 1 shows bus number matching bus name. Table 2 shows generation system in Jeju power system. The HVDC between main peninsular and Jeju can be modeled as equivalent generator. Fig. 8 shows the system's load variation curve pattern in 2007 [12-15]. It is assumed that the load pattern in 2012 is same as that of 2007. In 2012, the system's generation capacity and peak load will have reached 1140MW and 681MW respectively. Table 3 shows the transmission System of Jeju Power System. In Jeju Island, three wind farms are constructed at three different locations namely; Hangwon(HWN), Sungsan(SSN) and Hanlim(HLM). Data related to the three wind farms are given in Table 4. The parameters A, B, and C of the power function of WTG, calculated using (A.1~3) for the three wind farms are presented in Table 5.

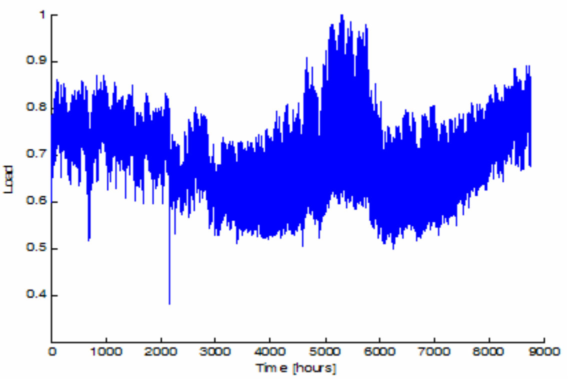


Fig. 8. The load variation curve (pattern) of Jeju Island power system in 2007

Table 3. Transmission System of Jeju Power System

Line #	SB	EB	Capacity [MW]	Type	cct	FOR	Remark
1	1	2	300	T/L	2	0.001713	
2	1	2	200	C/L	2	0.001000	
3	2	3	200	T/L	2	0.005710	
4	3	4	200	T/L	1	0.001142	
5	4	6	200	T/L	1	0.001142	
6	3	6	200	T/L	1	0.001142	
7	6	7	200	T/L	1	0.001142	
8	5	6	226	C/L	2	0.001000	
9	7	8	200	T/L	1	0.005710	
10	6	8	200	T/L	1	0.001142	
11	8	9	200	T/L	1	0.004568	
12	8	1	200	T/L	1	0.001142	
13	1	10	200	T/L	1	0.004568	
14	10	9	200	T/L	1	0.001142	
15	2	11	220	C/L	1	0.001000	

Table 4. Data of HWN, SSN and HLM Wind Farms

Wind Data			
Wind farm	HWN-WF	SSN-WF	HLM-WF
Peak speed	45 m/s	40 m/s	35 m/s
Mean wind speed	8.5 m/s	7.6 m/s	6.4 m/s
Standard deviation	7 m/s	6 m/s	5 m/s
WTG Data			
WTG capacity	50MW	30MW	20MW
Cut-in speed(Vci)	5 m/s	5 m/s	5 m/s
Rated speed(VR)	16 m/s	15 m/s	14 m/s
Cut-out speed(Vco)	25 m/s	25 m/s	25 m/s

Table 5. The A, B and C Parameters of WTGs

	HWN-WF	SSN-WF	HLM-WF
A	0.1203	0.1111	0.0928
B	-0.06 $[\text{m/sec}]^{-1}$	-0.063$[\text{m/sec}]^{-1}$	-0.0649$[\text{m/sec}]^{-1}$
C	0.0072 $[\text{m/sec}]^{-2}$	0.0081$[\text{m/sec}]^{-2}$	0.0093$[\text{m/sec}]^{-2}$

The outage capacity probability distribution function (OCPDF) considering a 5-state, a 7-state and an 11-state models for the three wind farms are obtained as shown in Fig. 9, Fig. 10 and Fig. 11 respectively. The number of multi-states depends on capacity of WTG. More states permits better accuracy. Even if the number increases over a multi-state number, however, the accuracy is increased no more and is saturated at a state number. While the accuracy is saturated, computation time is exhausted more. Sensitivity analysis according to number variation (from 2 states to 100states) of multi- states in Jeju power system at HLI was worked previously [12-15]. The saturation curve of accuracy according to number variation of the multi-states of WTGs in Jeju power system at HLI is shown in Appendix Fig. A1. In order to certify more stable accuracy,

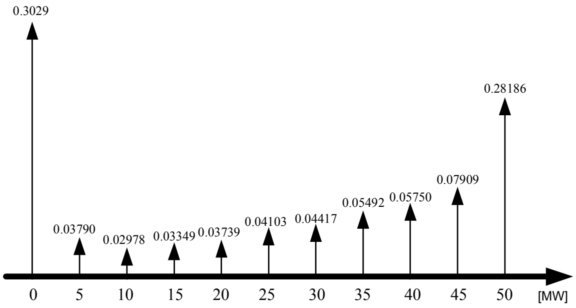


Fig. 9. OCPDF of HWN wind farm (11-state model)

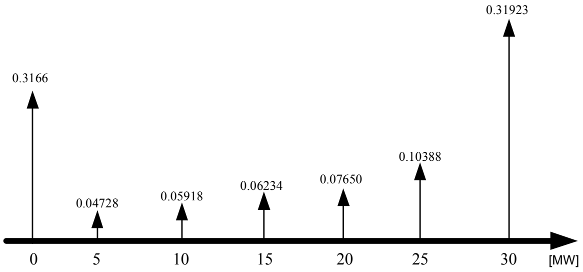


Fig. 10. OCPDF of SSN wind farm (7-state model)

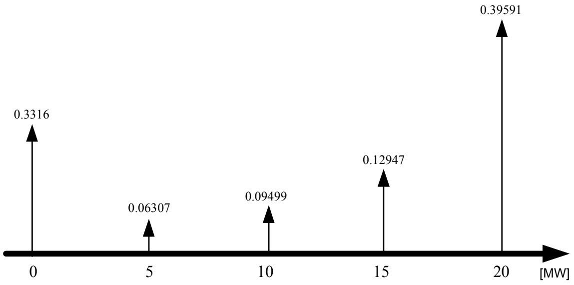


Fig. 11. OCPDF of HLM wind farm (5-state model)

11 states at HWN, 7 states at SSN and 5 states at HLM are selected in this case study.

Table 6 and Table 7 show the calculated LOLE, EENS and EIR reliability indices for buses and system respectively.

Table 6. Reliability Indices at Buses of Jeju System

Load Point #	Load Name	L_p [MW]	LOLE [Hours/year]	EENS [MWh/year]	EIR [pu]
1(bus1)	JEJU	200	7.89042	1371.88	0.999099
2(bus3)	SIJU	230	7.98118	1633.79	0.999092
3(bus7)	SEGP	100	7.98039	680.604	0.999092
4(bus8)	HALA	50	7.98019	340.301	0.999092
5(bus9)	SUSN	30	7.98088	213.103	0.999092
6(bus4)	HALM	20	7.97815	136.121	0.999092
7(bus11)	SAJI	100	7.98039	680.604	0.999092

Table 7. System Reliability Indices of Jeju System

	Grid not constrained	Grid constrained Case
LOLE [hours/day]	1.26	7.95598
EENS [MWh/day]	44.52	5056.40
EIR [pu]	0.99999	0.999094

Table 8 shows comparison results of reliability indices for five assumed scenarios of transmission plans in Jeju System. The result yields that plan 2 is the best plan of the given five scenarios. The five scenarios(plans) are assumed entirely in order to evaluate the proposed method just only.

Table 8. Comparison of Reliability Indices for Five Transmission Expansion Plans of Jeju Power System

Plan # (Scenario)	Addition Item	LOLE [Hours/year]	EENS [MWh/year]	EIR [pu]
Plan 1	HVDC 150x2cct	7.802	4919.73	0.999111
Plan 2	$T_{2\text{-}11}$ (200x1cct)	0.112	62.10	0.999989
Plan 3	$T_{1\text{-}8}$ $T_{8\text{-}7}$	7.898	5020.82	0.999100
Plan 4	$T_{5\text{-}6}$	7.948	5052.95	0.999095
Plan 5	$T_{1\text{-}2}$ $T_{2\text{-}3}$ $T_{3\text{-}4}$	7.947	5052.42	0.999095

5. Conclusions

This paper presents a new method for grid expansion planning considering the probabilistic reliability of a composite power system with wind turbine generators (WTG). The new model results from an extension of the composite power system effective load model including WTG. The proposed model utilizes a multi-state operation model of WTG obtained by combining the wind speed model and the WTG's power output model. Test results on an Jeju power system demonstrate the effectiveness of the proposed method to perform grid expansion planning considering wind turbine generator. The just five scenarios are assumed in order to evaluate the proposed method just only in this paper. From effective practicality of the proposed method in the case study, however, actual grid expansion planning problem involving WTGs can be evaluated for more scenarios.

It is expected that the proposed method can provide useful information in determining grid expansion planning and operation according to location and capacity of WTGs in view of reliability of composite power system reliability.

Acknowledgements

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6. Appendix

The parameters A, B, and C are given by (A.1)-(A.3).

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

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

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

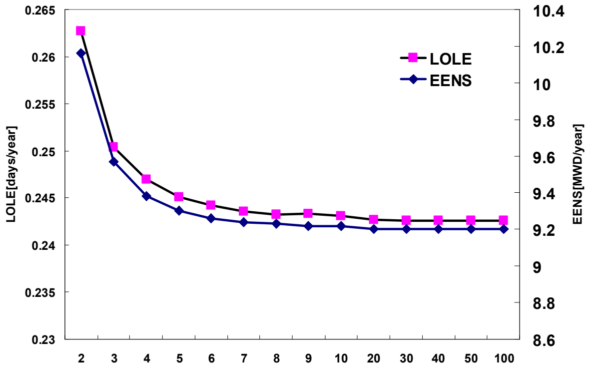

Fig. A1. Saturation of accuracy according to number variation of multi-states of WTGs in Jeju power system at HLI

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