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RELIABILITY EVALUATION OF INTERCONNECTED POWER SYSTEMS INCLUDING WIND TURBINE GENERATORS

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Abstract. *Wind energy has become the most successful renewable energy source. This is also evident in the Northeast Asia area including Northeast China, South Korea and Japan, etc. This paper proposes a tie-line constrained equivalent assisting generator model (WTEAG) considering wind turbine generator (WTG) newly. An interconnection power system reliability evaluation program "NEAREL-II" using the proposed model is developed. Additionally, this paper presents results of case studies of reliability evaluation for the actual power systems of six countries in the Northeast Asia area including WTG.*
Keywords: Power system reliability, Interconnecting power systems, NEAREL, Wind turbine generator, Renewable energy resources, Multi-state operation

1. **Introduction.** As a result of being environmental friendly, the utilization of renewable resources to generate electric power has been receiving considerable attention in recent years [1]. Wind energy in particular has been fast growing and is recognized as the most successful energy source of the available renewable sources. The interconnected power system of Asia's Northeastern area has been receiving growing attention irrespective of the different political systems of the countries involved that renders the implementation of such a system difficult. In the meantime, advantages of the system include,

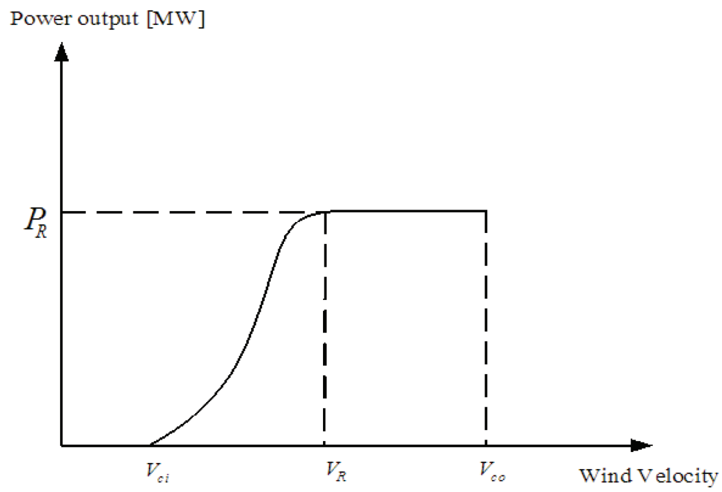
- improved adequacy of the generating capacity of a power system by interconnecting the system to other power systems [2,3] and
- the power systems becoming more attractive from the economics and reliability viewpoints because the system peak in South Korea usually occurs in the summer while that of countries in the North Asian area including the Far East Russia occurs in the winter [2,3].

The location of WTG depends on the available wind speed condition. Therefore, grid constrained reliability evaluation is very important for grid expansion planning and operation when WTG is added to a power system. The similar problem is occurred in interconnection power system. The power generated by a WTG depends mainly on large and frequent fluctuations in wind intensity and directions, while a two-state model is well suited for modeling conventional generators. It is not for WTGs and a multi-state model should be used for the purpose [4-7].

This paper proposes a new equivalent model (WTEAG) for reliability evaluation of interconnected power systems considering WTGs of multi-states operation. Conventional TEAG (tie-line constrained-equivalent assisting generators) model [2] and the SFEG (Synthesized fictitious equivalent generator) model [2] are extended new models; WTEAG (Wind turbine generator considered TEAG) and WSFEG (WTG considered SFEG) model respectively [2,3,8]. A program (NEAREL-II) based on the new proposed models is tested for reliability evaluation of interconnected power systems on the Northeast Asia power system considering multi-states operation of WTGs in this paper.

2. **Equivalent Generator Model of WTG.**

2.1. **WTG power output model.** Figure 1 shows the relationship between the power output of a WTG and the wind speed (velocity) [1,4-7].



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].

FIGURE 1. A typical power output model of a WTG

A mathematical model for the power output P_i of a WTG corresponding to wind speed band (SW_i) is given by (1) [4-7].

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

where i is the wind speed band number and the A, B and C parameters given in [4-7].

2.2. **Wind speed model.** Wind speeds vary both in time and space. It has been reported that the actual wind speed distribution can be described by a Weibull probability distribution and approximated by a normal distribution [4-7]. This paper uses the normal probability distribution function to model the speed in terms of the mean wind speed μ and the standard deviation σ as shown Figure 2. The negative wind speed value in Figure 2 has no physical meaning and can be ignored.

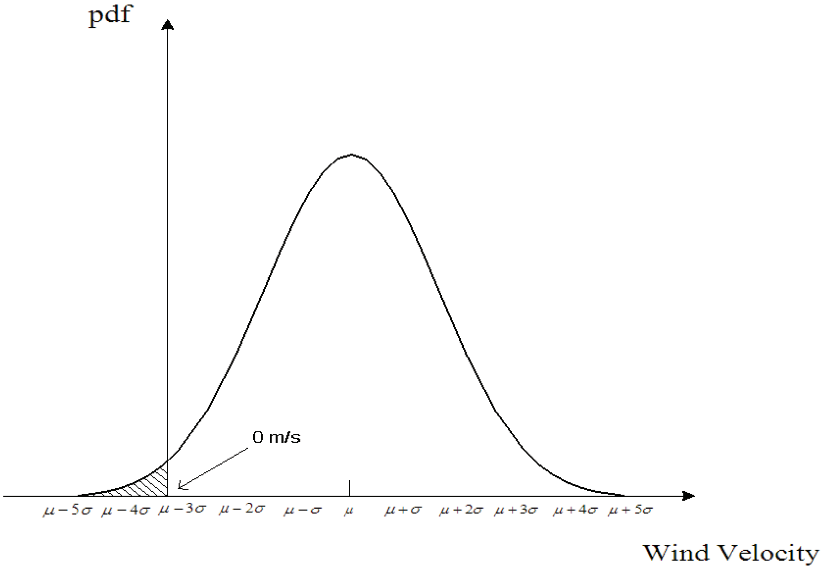


Figure 2. Wind speed model

2.3. **The multi-state model of WTG [4].** The power output model of a WTG shown Figure 1 combined with the wind speed model shown in Figure 3 yields the multi-state model. Each state has a pair of associated parameters; namely the power (P_i) and probability (PB_i). The operation model of a WTG is in the form of a multi-state model described by an outage capacity probability distribution function.

2.4. **The effective forced outage rate of WTG [4].** In order to build the equivalent generator model of WTG shown in Figure 1, the multi-state model has to be made into an equivalent two-state model. In this paper, a simplified model using a linear rounding method is used. The linear rounding method is described mathematically by (2) and (3) and graphically in Figure 4. It is based on sharing the ratio of probability linearly [7].

$$PB_K = \left(\frac{P_{k+1} - P_i}{\Delta P} \right) \times PB_i \tag{2}$$

$$PB_{K+1} = \left(\frac{P_i - P_k}{\Delta P} \right) \times PB_i \tag{3}$$

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 state k of the simplified multi-state model, as calculated using the rounding method as expressed by (2) and (3). The total probabilities remain 1. This is because the probabilities of the modified/simplified multi-state model (posterior) are accumulated from sharing the probabilities of original state model (priori) by the rounding method. The purpose of the method is to effectively decrease the number of states of the original multi-state model and calculate reliability indices easily by using convolution integral method. The probability that the power

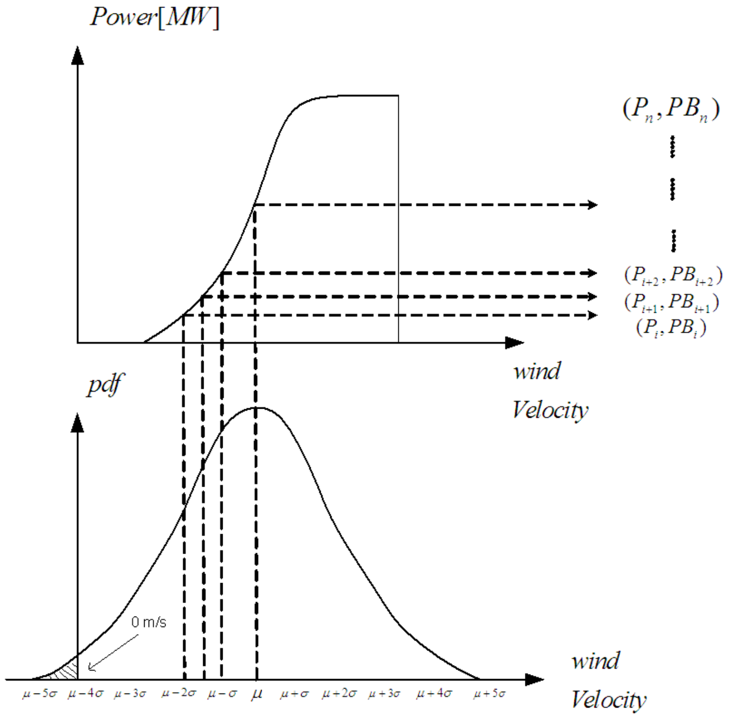


Figure 3. Development of a model describing the power outputs of WTG and the corresponding probabilities

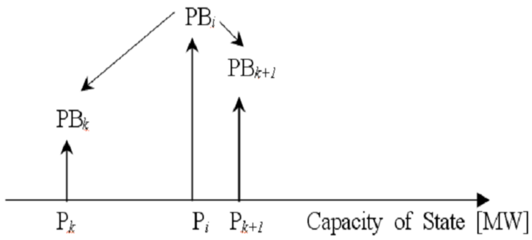


Figure 4. Illustration of the proposed rounding method

output of a WTG simplified by an equivalent two-state model is zero, is called EFOR (Effective Forced Outage Rate).

3. The Tie-Line Constrained Equivalent Assisting Generator Model Considering WTGs.

This paper develops a tie-line constrained equivalent assisting generator model that takes into account WTGs. This is described as WTEG in the paper. This model extends the tie-line constrained equivalent assisting generator model (TEAG), which incorporates the forced outage rates of transmission lines within the interconnected power systems developed by authors [2,3]. The proposed model considers WTGs in three composite systems interconnected by two tie lines as shown in Figure 5.

3.1. The synthesized fictitious equivalent generator (WSFEG) considering WT Gs.

Figure 6 presents the basic concept of the synthesized fictitious equivalent generator (WSFEG) model considering WTGs. Figure 6(a) is the original composite power system considering WTGs in systems. Considering the operation of generators #1 through #i, it is possible to calculate the maximum arrival power ($_kAP_{ij}$) at the load point and the

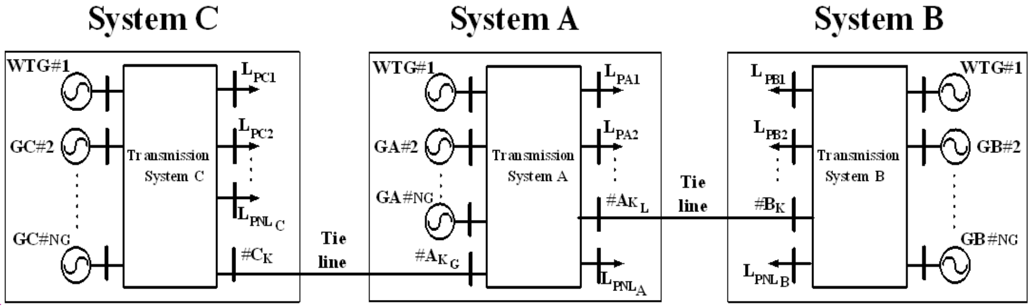


FIGURE 5. Three WTG considered power systems (HLII) interconnected by two tie lines (System C – System A – System B)

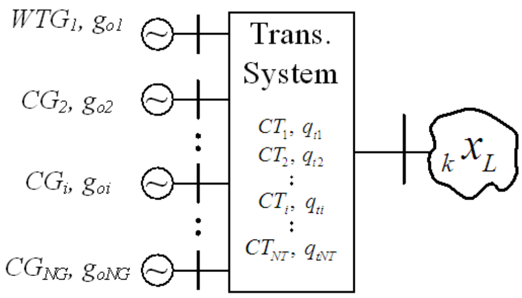
state probabilities ($_kq_{ij}$) for system state $\#j$ using optimal power flow analysis with the maximum arrival power being the objective function.

Equal maximum arrival power conditions with different state probabilities can occur and the probabilities of the states for the same maximum arrival power ($_kAP_{ij}$) can be cumulated. The PDF composed of maximum arrival powers and state probabilities is equivalent to the PDF of a supply source unit with forced outage rate $_kq_{sij}$ and operating power $_kAP_{sij}$ with multi-operating states at the load point. This can be designated as a WTG considered and synthesized fictitious equivalent generator (WSFEG). The capacity of the synthesized fictitious equivalent generator is the largest maximum arrival power. According to the definition of the synthesized generator used here, $_kf_{osi}$ in Figure 6(b) describes the outage capacity PDF of the synthesized fictitious equivalent generator created by the generators #1 through $\#i$. This generator is referred to as SFEG in this paper. The PDF of the WSFEG is usually a multi-state model although the PDF of the original individual generators and lines are two state models [8,9].

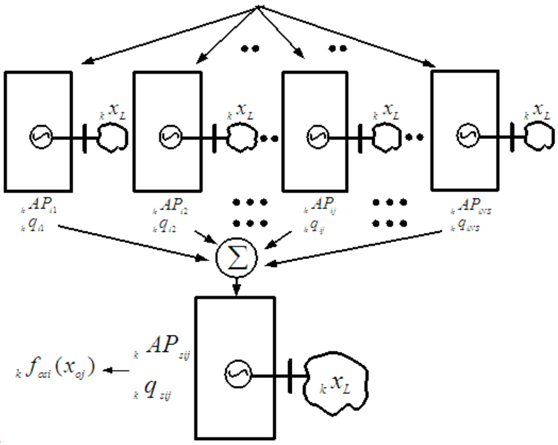
A key question in creating the PDF of the WSFEG is "How is the multi-state probability and nodal arrival power calculated?". In the paper, the enumeration method and maximum arrival power method are used. Also, Monte Carlo simulation and either a DC or an AC optimal load flow can be used [10-12].

3.2. **The probability distribution function of the WTG considered and synthesized fictitious equivalent generator.** The analytical enumeration methods and Monte Carlo simulation can be used to create the PDF of the WSFEG. The former can be used to obtain accurate solutions on small size test systems while the latter is more practical for large size actual power systems. In this paper, the analytical enumeration method was used because the objective of this work is to develop a new effective load model and review clearly the identities of the proposed model prior to applying it to large size real power systems. Some research based on the new effective load model using the Monte Carlo simulation method and DC load flow has been recently conducted by the authors [9,10]. The WSFEG$_{Bk}$ and WSFEG$_{Ck}$ at the load points B_k and C_k of the assisting Systems B and C respectively are represented in Figure 7.

3.3. **The equivalent assistance generator model (WEAG$_{Bk}$ and WEAG$_{Ck}$).** The WTG considered and synthesized fictitious equivalent generator (WSFEG$_{Bk}$) at interconnection point B_k of System B assisting System A should be modified if there is a load at point B_k. The actual available capacity for assistance should be changed to the capacity remained after supplying the self-bus demand. The generator with the self-bus load limited assisting capacity of the WSFEG$_{Bk}$ is called the WTG-considered and Equivalent



(a) The actual system including WTG



(b) The WTG-considered and synthesized fictitious equivalent generator (WSFEG)

FIGURE 6. The proposed WTG-considered and synthesized fictitious equivalent generator model (WSFEG)

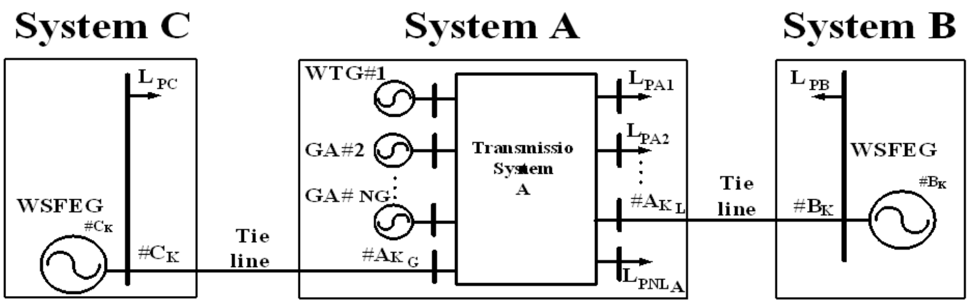


FIGURE 7. The WSFEG_{Bk} and WSFEG_{Ck} at load point B_k and C_k assisting systems B and C respectively

Assistance Generator (WEAG_{Bk}). This is shown in Figure 8. The other assisting System C is dealt with in the same manner.

3.4. **The tie-line constrained equivalent assisting generator model (WTEAG) considering WTG.** The actual available capacity assistance of the WEAG_{Bk} of the assisting System B may be constrained by tie-line capacity limitations. In this paper, the tie-line constrained assisting capacity of the WEAG_{Bk} is referred to as the WTG-considered

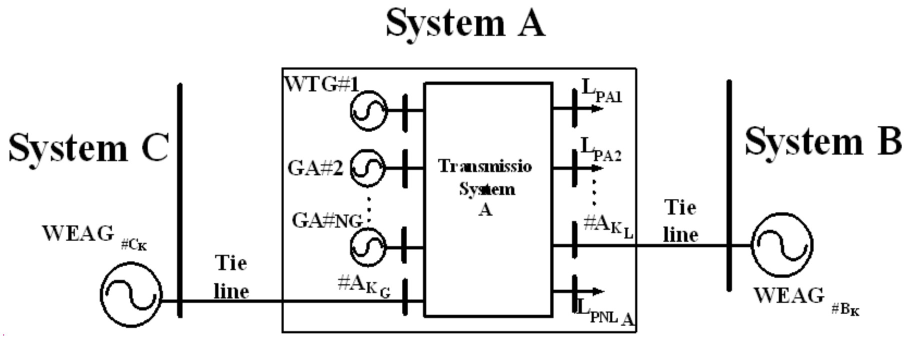


FIGURE 8. The WTG-considered equivalent assistance generator (WEA G_{Bk} and WEAG_{Ck}) model

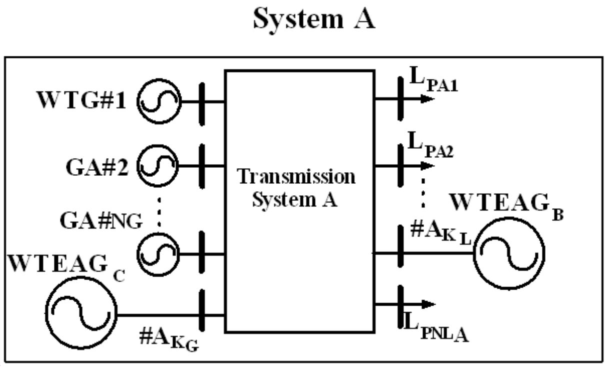


FIGURE 9. The WTG-considered tie-line constrained equivalent assisting generators ($\text{WTEAG}_{B\text{-}A}$ and $\text{WTEAG}_{C\text{-}A}$) model

tie-line constrained equivalent assisting generator model ($\text{WTEAG}_{Bk\text{-}Al}$) as shown in Figure 9. The other assisting System C is dealt with in the same manner. As a result, two WTG-considered tie-line constrained equivalent assisting generators ($\text{WTEAG}_{Bk\text{-}Al}$ and $\text{WTEAG}_{Ck\text{-}Al}$) are added to System A. The $\text{WTEAG}_{B\text{-}A}$ is a tie-line constrained equivalent assisting generator with the assisting System B at bus k and the assisted System A at bus l. The two equivalent units result from the assisting Systems B and C considering the tie-line capacities and the uncertainties associated with the generators and transmission lines in the two systems.

4. **The Solution Algorithm.** Interconnection contracts are important elements in the determination of power exchange between interconnected systems. A system may be considered as an assisted system for some period of the year or for all of the year. After considering any interconnection contract obligations, the identification of a system as an assisting or assisted system is conducted on the basis of reliability evaluation. Based on the proposed model, a NEAREST-WTG simulation program was developed. This program automatically determines whether a system is an assisting or assisted system based on whole system reliability maximization if there were no specified interconnection contracts in the study time period. A summarized description of the proposed algorithm is as follows:

Step 1: Determine whether a system is an assisting or assisted system based on reliability considerations after recognizing any interconnection contract obligations during the time period.

TABLE 1. Data of wind speed and WTG

Wind		WTG	
Wind speed range	0∼35 m/s	WTG capacity	10 MW
Mean wind speed($\boldsymbol{\mu}$)	10 m/s	Cut-in speed(V_{ci})	5 m/s
Standard	8 m/s	Rated speed(V_R)	15 m/s
deviation($\boldsymbol{\sigma}$)		Cut-out speed(V_{co})	25 m/s

TABLE 2. The parameters of A, B and C

A	0.1111
B	–0.063 $[\text{m/sec}]^{-1}$
C	0.0081 $[\text{m/sec}]^{-2}$

Step 2: Construct the WTG-considered and synthesized fictitious equivalent generators at the connection points of the assisting systems using the WSFEG algorithm.

Step 3: Model the WTG-considered equivalent assisting generators (WEAGs) considering the peak loads at the connection points of the assisting systems.

Step 4: Model the WTEAG considering the tie line capacity limitations of the interconnected systems.

Step 5: Evaluate the reliability for the given time period (a month or a season).

Step 6: If all the time period (month or a season) have been considered, sum the period values to obtain the annual indices. If not, go to Step 1 and evaluate the reliability for the next time period.

5. Case Studies.

5.1. The equivalent model of WTGs.

The process of calculating the EFOR of a WTG calculated is shown below as an example. First, the probability distribution function and the power output curve of a WTG are needed to build its equivalent generator model. The wind speed data for the probability distribution function and the WTG's data for the power output curve are shown in Table 1.

The A, B and C parameters needed for Equation (1) can be calculated as in [7].

The power output curve of the WTG and the parameters using (1) and the normal distribution function of wind speed is obtained using its mean and standard deviation given in Table 2.

The multi-state model of a WTG is developed by combining the power output curve with the normal distribution function as shown in Table 3. This result in an EFOR of 0.590982 is shown in Table 4.

5.2. Reliability evaluation of an interconnected system including WTGs.

The interconnected power systems considered in this paper include:

1. Republic of Korea – South Korea (ROK)
2. Korean People's Democratic Republic – North Korea (KPDR)
3. Far East Russia (FER)
4. Japan (JPN)
5. North East China (NEC)
6. Mongolia (MGA).

Table 3. WTG powers and corresponding probability

WTG power [MW]	**Probability**
0	0.3131
0.2667	0.0440
0.6963	0.0465
1.2889	0.0483
2.0444	0.0495
2.9630	0.0499
4.0444	0.0495
5.2889	0.0483
6.6963	0.0465
8.2667	0.0440
10	0.2604
Total	**1**

Table 4. Effective forced outage rate of WTG

WTG power [MW]	**Probability**	$\boldsymbol{PB_k}$ **(0MW)**	$\boldsymbol{PB_{k+1}}$ **(10MW)**
0	0.3131	0.3131	0
0.2667	0.044	0.042827	0.001173
0.6963	0.0465	0.043262	0.003238
1.2889	0.0483	0.042075	0.006225
2.0444	0.0495	0.03938	0.01012
2.963	0.0499	0.035115	0.014785
4.0444	0.0495	0.02948	0.02002
5.2889	0.0483	0.022755	0.025545
6.6963	0.0465	0.015362	0.031138
8.2667	0.044	0.007627	0.036373
10	0.2604	0	0.2604
Total	**1**	**0.590982**	**0.409018**

The loop interconnection, which connects South Korea, North Korea, Far East Russia, North East China, Mongolia, and Japan is considered to be as shown in Figure 10 [2].

Table 5 shows the generator input data, capacity (Cap.), forced outage rate (FOR) of the conventional generators (CG), and equivalent capacity (Ecap) and equivalent forced outage rate (EFOR) of WTGs.

Table 6 shows the probabilistic reliability indices of six countries with and without consideration of WTG, where EIR and ED are Energy Index of Reliability and Energy of Demand respectively. Although the EFOR of the WTG is high (0.3335), the WTG contributes greatly to the reliability of the test interconnected power system as shown in Figure 11.

6. **Conclusion.** This paper proposes a new model (WTEAG) for reliability evaluation of interconnected power systems including wind turbine generators (WTGs) of multi-states operation. The new model was upgraded from conventional TEAG (tie-line constrained-equivalent assisting generators) model and the SFEG (Synthesized fictitious equivalent generator) model. The proposed models were described newly as WTEAG (Wind turbine generator considered TEAG) and WSFEG (WTG considered SFEG) model respectively

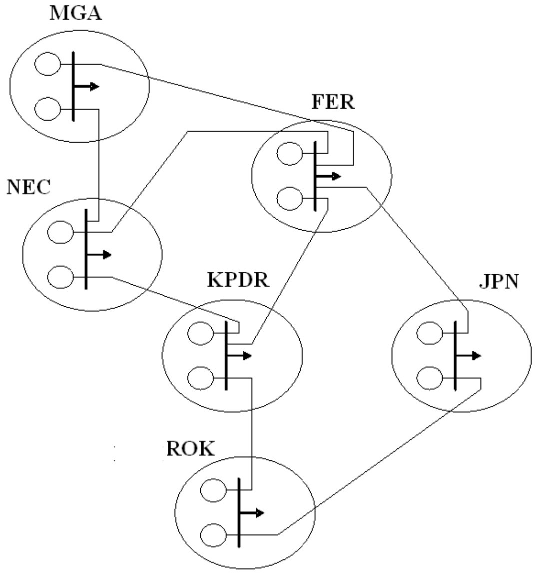


Figure 10. The North-east Asia interconnection topology

Table 5. Generation input data of each country

	CG		Added WTG	
	Cap.	**FOR**	**Ecap**	**EFOR**
ROK	82.4	0.01∼0.015	5	0.3335
DPRK	15.0	0.015∼0.025	0	–
FER	12.5	0.01∼0.02	0	–
NEC	103.2	0.01∼0.02	5	0.3335
MGA	1.8	0.01∼0.02	0	–
JPN*	256.8	0.01∼0.015	43	0.3335
Total	471.7		53	

Table 6. Reliability indices of six countries by adding WTG

	With WTG			Without WTG		
	LOLE [Hrs/Yr]	**EENS [GWh/Yr]**	**EIR [PU]**	**LOLE [Hrs/Yr]**	**EENS [GWh/Yr]**	**EIR [PU]**
ROK	3.35	8.6147	0.99998	10.72	32.2	0.99994
DPRK	1.75	0.9754	0.99999	5.78	3.65	0.99996
FER	1.52	0.5435	0.99999	5.13	2.05	0.99996
NEC	2.01	6.0685	0.99999	6.65	2.31	0.99996
MNG	0.46	0.0928	0.99999	1.80	0.36	0.99996
JPN	1.93	13.756	0.99999	6.40	51.92	0.99996
System	2.17	30.04	0.99999	7.16	113.34	0.99996

(where EIR = 1-EENS/ED)

in this paper. This model is derived from combining two steps. First step is the model development for grid constrained probabilistic reliability evaluation of power systems including WTGs using the composite power system effective load model. The second step is the WTEAG model development for reliability evaluation of interconnected power systems. A simulation program (NEAREL-II) using the proposed method was developed.

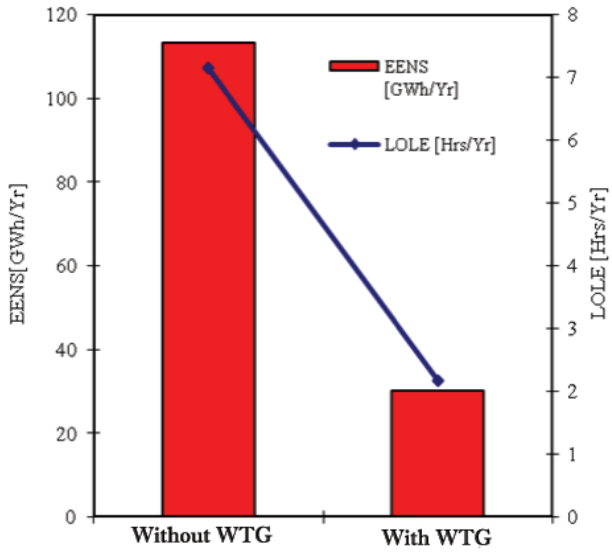


Figure 11. North-east Asian interconnection topology

Testing of this reliability evaluation program was successfully performed on an interconnection that is being proposed for six countries in the Northeastern Asia region including multi-state operation WTGs. Test results indicate effectiveness of the proposed method, which makes it a useful tool for consideration of renewable generators on interconnected power systems. Eventually, it is expected that proposed method and program will be used for quantity evaluation of reliability of interconnection power systems.

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