동북아 전력계통 연계를 위한 신뢰도 산정에 관한 연구

論 文
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A Study on the Reliability Evaluation for Interconnecting Power Systems in Northeast Asia

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Abstract -This paper proposes a reliability evaluation for interconnection planning using a tie line equivalent assisting generator model (TEAG) that considers the uncertainties of the interconnected transmission systems and the tie lines. Development of this model was triggered by the need to perform probabilistic reliability evaluations on the NEAREST (North East Asia Region Electric Systems Tied) interconnection. The TEAG is the basis for the newly developed interconnection systems reliability evaluation computer program, NEAREL. The model is capable of considering uncertainties associated with generators, tie lines, and the tied grids. Reliability evaluations for six interconnection scenarios involving the power systems of six countries in the Asian north eastern region were performed using NEAREL. Sensitivity analysis was used to determine reasonable tie line capacities for three interconnected country scenarios of the six countries. Test results and summarized comments of the scenarios are included in the paper.

Key Words : Interconnection, System reliability evaluation, Northeast Asia, TEAG

I. Introduction

The peak load in South Korea generally occurs in the summer while that of countries in the north Asia area including far east Russia occurs in the winter. As a result, interconnecting these power systems becomes attractive from the view points of economics and reliability.[1] The adequacy of the generating capacity in a power system is normally improved by interconnecting the system to other power systems.[2] The quantitative evaluation of the effects of the interconnections is not easy technically because the interconnection assistance between power systems is a function of many variables such as system installed capacity, generation dispatch, forced and scheduled outages of equipment, load duration characteristics, accuracy of load forecasts, load diversity, capacity of the interconnections as well as the operating limits imposed on the transmission network due to thermal, voltage and stability considerations.[2] Extensive research on reliability evaluation of interconnected power systems has been conducted and systematic methodologies and algorithms have been developed.

This paper presents a tie line-constrained equivalent assisting generator model (TEAG) that considers transmission systems uncertainties[3-4]. Development of this model was triggered by the need to perform probabilistic reliability evaluation on the NEAREST (North East Asia Region Electric Systems Tied) interconnection. The proposed TEAG model is the basis for the newly developed interconnection systems reliability evaluation computer program, NEAREL. The model is capable of considering uncertainties associated with generators, tie lines, and the tied grids. Reliability evaluations for six interconnection scenarios of the power systems of (1) three countries tied case (Study I) and (2) four, five and six countries tied case (Study II) in the Asian north eastern region were performed using the NEAREL program. Sensitivity analysis was used to determine reasonable tie line capacities for the three countries interconnected scenarios among the six countries. Test results as well as summarized comments on the scenarios are included in the paper.

II. New Tie Line Constrained Assisting Generator Model (TEAG) at HLII

The need to conduct quantitative reliability analysis considering transmission system uncertainties triggered the development of the proposed tie line constrained equivalent assisting generator model (TEAG) that incorporates the forced outage rates of transmission lines within the interconnected power systems. In developing

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the model, three composite systems interconnected by two tie lines were considered as shown in Figure 1.

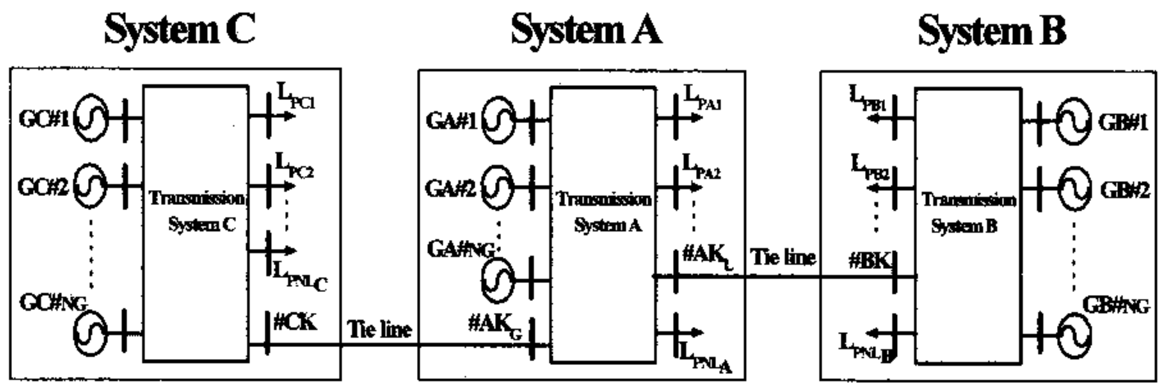


Fig. 1 Three composite power systems (HLII) interconnected by two tie lines (systems C-System A - System B)

The objective of the method is twofold:

(a) Development of tie line constrained equivalent assisting generator model (TEAG) of the systems B and C considering the forced outage rates of the transmission lines and

(b) Reliability evaluation of an assisted system A considering the forced outage rates of its own transmission lines.

To mathematically formulate the proposed TEAG model, the following defined nomenclature is introduced.

Nomenclature:

PDF : abbreviation of probability distribution function

NG : number of generators

NT : number of transmission lines

CG_i : capacity of generator # i (i = 1,⋯, NG)

q_i : forced outage rate of generator # i

CT_n or CT_{nmax} : capacity of trans. line #n (n = 1,⋯, NT)

q_{ln} : forced outage rate of transmission line # n

${}_kAP_{ij}$: maximum arrival powers for system state j at load point #k of gen. from #1st to # ith

${}_kq_{ij}$: state probability for system state j at load point #k considering operation of gen. from #1st to # ith

${}_kAP_{sij}$: operating powers of SFEG at load point #k considering operation of gen. from #1st to # ith

${}_kq_{sij}$: operating state probability of SFEG at load point #k considering operation of gen. from #1st to # ith

${}_kf_{osi}$: PDF of SFEG at load point #k considering operation of gen. from #1st to # ith

e_j and $\overline{e_j}$: set of elements on operation and outage respectively of system state j

$n(\overline{e_j})$: number of elements on outage of set, $\overline{e_j}$

$P(e_j)$: available probability of set, e_j

$Q(\overline{e_j})$: unavailable probability of set, $\overline{e_j}$

Ncont : number of generator and transmission line contingencies. (Ncont=7 used in this study)

L_{pk} : peak load power at load point #k

B_B : set of all buses

B_L : set of buses which have loads

B_T : set of transmission lines

NB : total number of branches (generators, transmission lines and load points)

a_{ij} : elements of the bus-branch incidence matrix

max : abbreviation of maximum

x_l : flow(variable) at branch #l

L_{pBk} : peak load at load point #k of intercon. system B

${}_kAP_j^{EAG}$: arrival powers of equivalent assisting generator (EAG) at load point #k

${}_kq_j^{EAG}$: state probability of EAG at load point #k

${}_kAP_j^{TEAG}$: arrival powers of tie line constraint equivalent assisting generator (TEAG) at load point #k

${}_kq_j^{TEAG}$: state probability of TEAG at load point #k

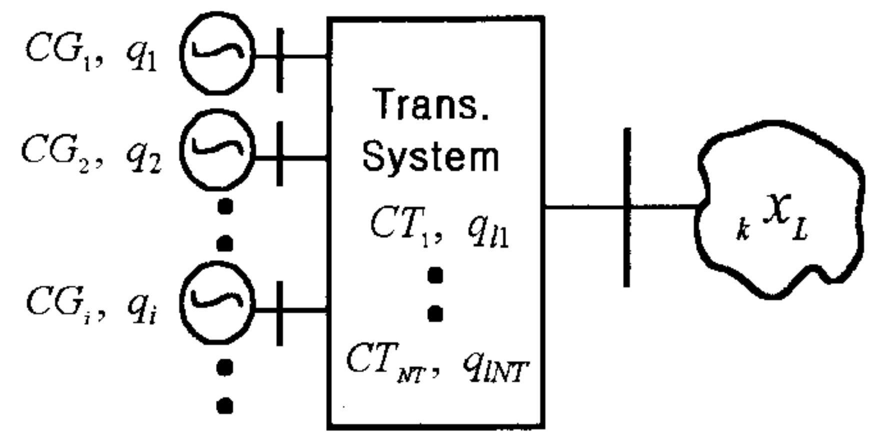
TICP : tie line capacity

Ω_1 : set of system states that ${}_kAP_j$ is smaller than L_{pk}

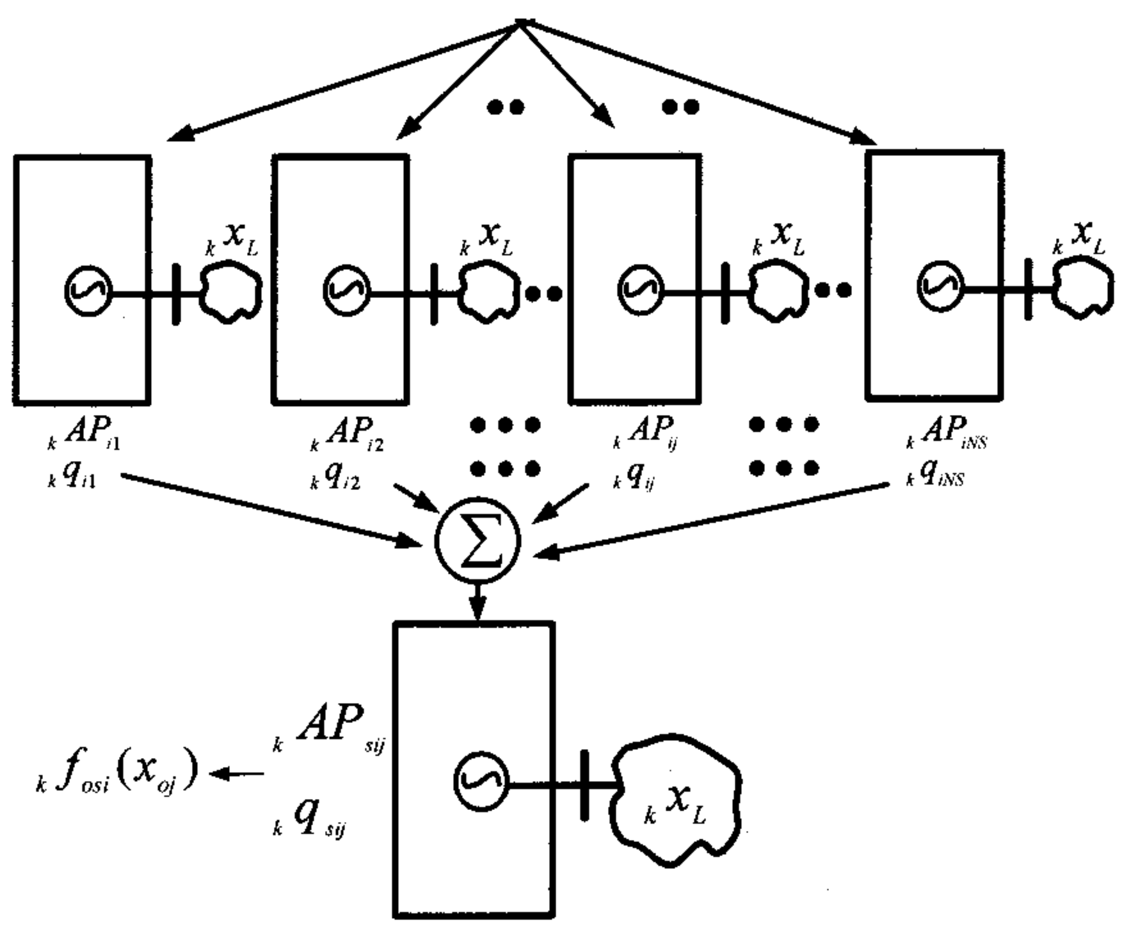
Ω_2 : set of system states that ${}_kAP_j$ is larger than $TICP_k$

2.1 Synthesized Fictitious Equivalent Generator (SFEG) at HLII

Figure 2 presents the basic concept of a synthesized fictitious equivalent generator (SFEG) model.[3-9] The key point in creating the PDF of the SFEG is "How is the state probability and nodal arrival power calculated?". The enumeration method and maximum arrival power method are used in this paper.[8] Monte Carlo simulation methods and DC or AC optimal load flow can also used.[8,10]



(a) Actual system



(b) Synthesized fictitious equivalent generator (SFEG)

Fig. 2 Synthesized Fictitious Equivalent Gen. Model at HLII

2.2 Probability Distribution Function of the Synthesized Fictitious Equivalent Generator

In the study reported in this paper, the analytical enumeration method was used because the eventual purpose of this study is to develop a new effective load model and review clearly the identities of the new proposed model prior to applying it to large real power systems.

I. State Probability Calculation

The probability of a relatively large number of generators and transmission lines failing at the same time is extremely small and it is not necessary to consider all the states in an actual system and high order events. Equation (1) can be used in these cases.

$$q_{ij} = P(e_j)Q(\bar{e}_j) \qquad \exists\forall\ n(\bar{e}_j) \le 4 \text{ or } 5 \quad (1)$$

ii. Maximum Arrival Power Evaluation using the Network Flow Method

In this paper, the objective function for minimizing the maximum power outage rate is set up under the constraints of the generator and line capacity limitations and network connection. In this study, transmission line losses are ignored and only effective power flow is considered. This problem can be formulated as (2), (3) and (4).

1) The Objective function

$$Minimize\ \{max(L_{pk} - x_k)/L_{pk}\} \qquad k \in B_L \quad (2)$$

2) The Constraints

a) The constraint of an incident circuit

$$\sum_{j=1}^{NB} a_{ij}x_j \le CG_i \qquad i \in B_B \quad (3)$$

b) The constraint of transmission line capacity

$$-CT_{lmax} \le x_l \le CT_{lmax} \qquad l \in B_T \quad (4)$$

Optimal network problem can be formulated as in the (5) by introducing the parameter, λ which represents the maximum outage rate. It can be solved using Linear Programming. In the obtained optimal solution, x_k is the maximum arrival power ($_kAP_{ij}$) at the load point k for contingency state j after loading generators from #1 to #i.

$$\begin{aligned} &Minimize \quad \lambda \\ &Subject\ to \\ &\quad \left.\sum_{j=1}^{NB} a_{ij}x_j \le CG_i \qquad i \in B_B \quad \right\} \\ &\quad -CT_{lmax} \le x_l \le CT_{lmax} \quad l \in B_T \\ &\quad (L_{pk}-x_k)/L_{pk} \le \lambda \qquad k \in B_L \end{aligned} \quad (5)$$

Using LP, the maximum arrival power($_kAP_{sij}$) at the load points can be obtained using (5) at system state j. The outage capacity PDF($_kf_{osi}$) of the SFEG can be obtained from the state probabilities($_kq_{sij}$) in (1) and the maximum arrival power($_kAP_{sij}$) from (5). The detailed study using this approach is presented in [9]. The proposed algorithm for creating SFEG is as followings.

STEP①: Set up initial contingency, state number j=1.
STEP②: Calculate the state probability ($_kq_{sij}$) for the j contingency state using (1). Check the state probability($_kq_{sij}$) satisfies the given state probability limitation value or not. If not, go to step 1 after j=j+1.
STEP③: Evaluate the maximum arrival power ($_kAP_{sij}$) of state j at the load points
STEP④: If all states are considered, go to step 5. If not, go to step 2 after j=j+1
STEP⑤: Calculate the outage capacity PDF (kfosi) of the SFEG from the state probabilities (kqsij)

The $SFEG_{Bk}$ and $SFEG_{Ck}$ at load point Bk and Ck of the assisting systems B and C respectively are represented in Fig. 3.

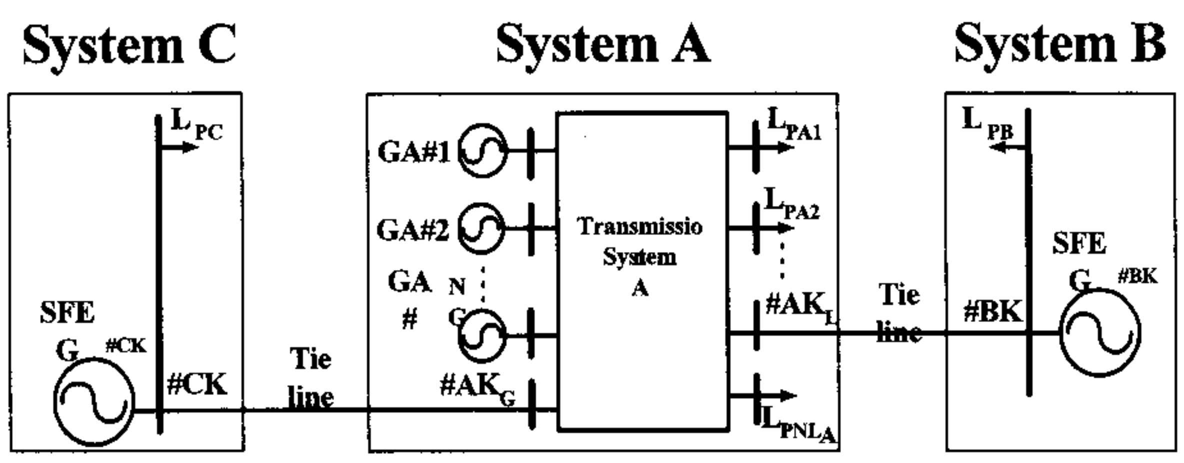


Fig. 3 The $SFEG_{Bk}$ and $SFEG_{Ck}$ at load point Bk and Ck respectively of assisting systems B and C respectively

2.3 Equivalent Assistance Gen. Model

The synthesized fictitious equivalent generator ($SFEG_{Bk}$) at interconnection point #Bk of the system B assisting system A should be modified if there is a load at the point #Bk. The actual available capacity for assistance should be changed to the capacity remained after supplying the self-bus demand. The actual capacity of the assistance generator is reduced by the peak load at the bus as formulated in (6). The generator with the self-bus load limited assisting capacity of the $SFEG_{Bk}$ is called the Equivalent Assistance Generator (EAG_{Bk}). This is shown in Fig. 4. The PDF of the EAG at the point #k can be formulated as (7). The other assisting System C is considered in the same manner.

$$_kAP_{sj}^{\ EAG} = \text{maximum}\ \{(\ _kAP_{sj}^{\ SFEG} - L_{pBk}),\ 0.0\} \quad (6)$$

$$kqj^{EAG} = \begin{cases} \sum_{j=\Omega 1} kqj^{SFEG} & j \in 1 \\ kqj^{SFEG} & j \notin \Omega 1 \end{cases} \quad (7)$$

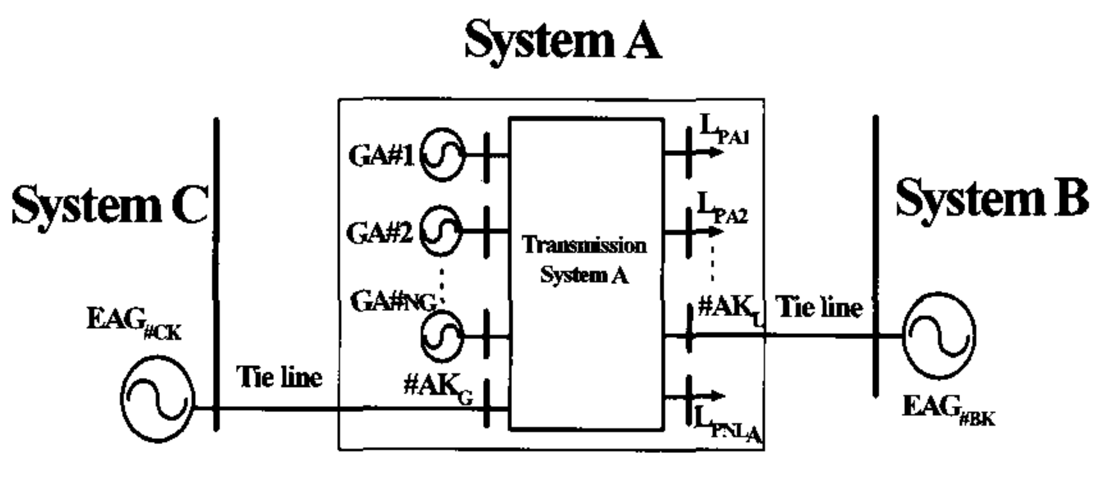


Fig. 4 Equivalent Assistance Generator Model

2.4 Tie line constrained equivalent assisting gen.model

The actual available capacity assistance of the Equivalent Assistance Generator (EAG_{Bk}) of the assisting system B may be constrained by tie line capacity limitations between the interconnected systems. In this case, the actual capacity (${}_{l}AP_{sj}{}^{TEAG}$) of the equivalent assistance generator (EAG) must be limited to tie line capacity ($TICP_{B-A}$) between the interconnected systems as shown in (8). The tie line constrained assisting capacity of the EAG_{Bk} is referred to as the tie line constrained equivalent assisting generator model ($TEAG_{Bk-Al}$) as shown in Fig. 5. The PDF of the $TEAG_{Bk-Al}$ at the point #l of assisted system A can be formulated as (9). The other assisting system C is considered in the same manner.

$${}_{l}AP_{sj}{}^{TEAG} = \text{mimimum}\{{}_{k}AP_{sj}{}^{EAG}, TICP_{B-A}\} \quad (8)$$

$$lqj^{TEAG} = \begin{cases} \sum_{j \in \Omega 2} kqj^{EAG} & j \in \Omega 2 \\ kqj^{EAG} & j \notin \Omega 2 \end{cases} \quad (9)$$

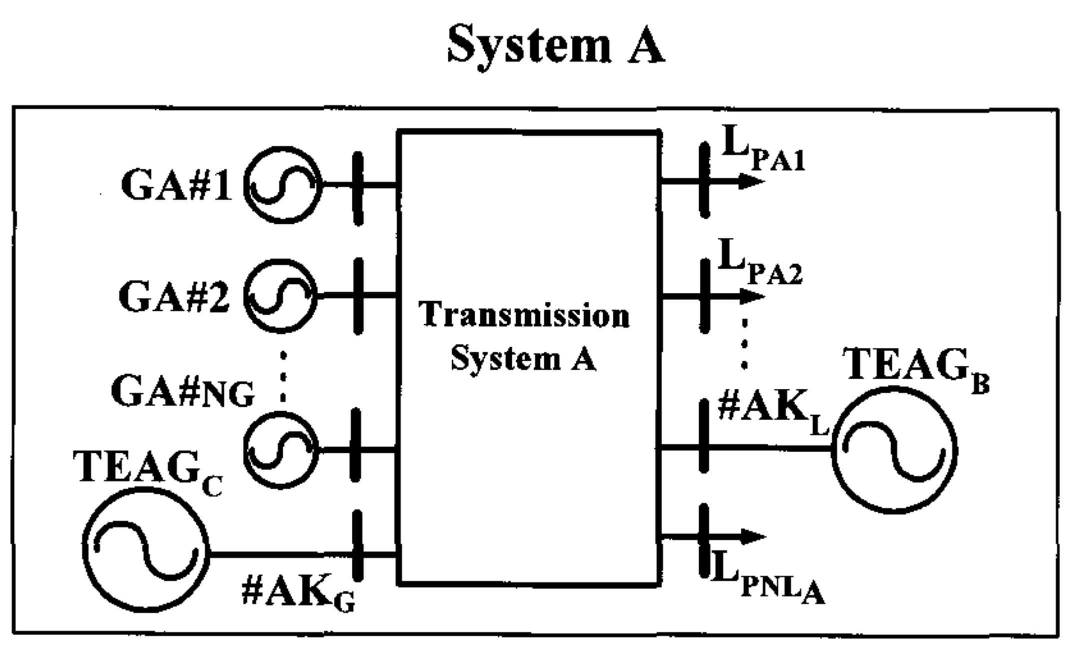


Fig. 5 Tie line constrained equivalent assisting generators (TEAGB-A and TEAGC-A) model

The Solution Algorithm

A summarization of the proposed algorithm is follows.

STEP 1: Determine whether the system is as assisting system or assisted system using level of the reliability of the interconnection systems in viewpoint of reliability if the specified contract not given during the time period.

STEP 2: Construct the synthesized fictitious equivalent generator at the connection points of the assisting systems using the previous SFEG

STEP 3: Model the equivalent assisting generator considering the peak load at the connection point of the assisting System.

STEP 4: Model the TEAG considering the tie line capacity limitations of the interconnection systems

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

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

3. Case Studies

A. Scenarios

The following six scenarios were studied and the results are reported in this paper. In the overall, study was divided into two separate studies. Study I consists of three cases designated as Scenarios I, II and III. Each scenario involves three interconnected countries. Study II consists of three cases designated as Scenarios IV, V and VI containing four, five and six interconnected countries respectively.

Scenario I : A series interconnection that connects South Korea, North Korea and Far East Russia. (Base scenario)

Scenario II: A series interconnection that connects South Korea and Far East Russia directly without NK. (passing through).

Scenario III: A series interconnection that connects South Korea, North Korea, and Far East Russia by using the grid of NK.

The reliability evaluation of Scenario I, which is considered to be the most realizable scenario, was conducted first. Fig. 6 shows the configuration of Scenario I. The generating capacity, peak load and reserve margin for each country in the year 2010 are shown in Table 1.[10-11]

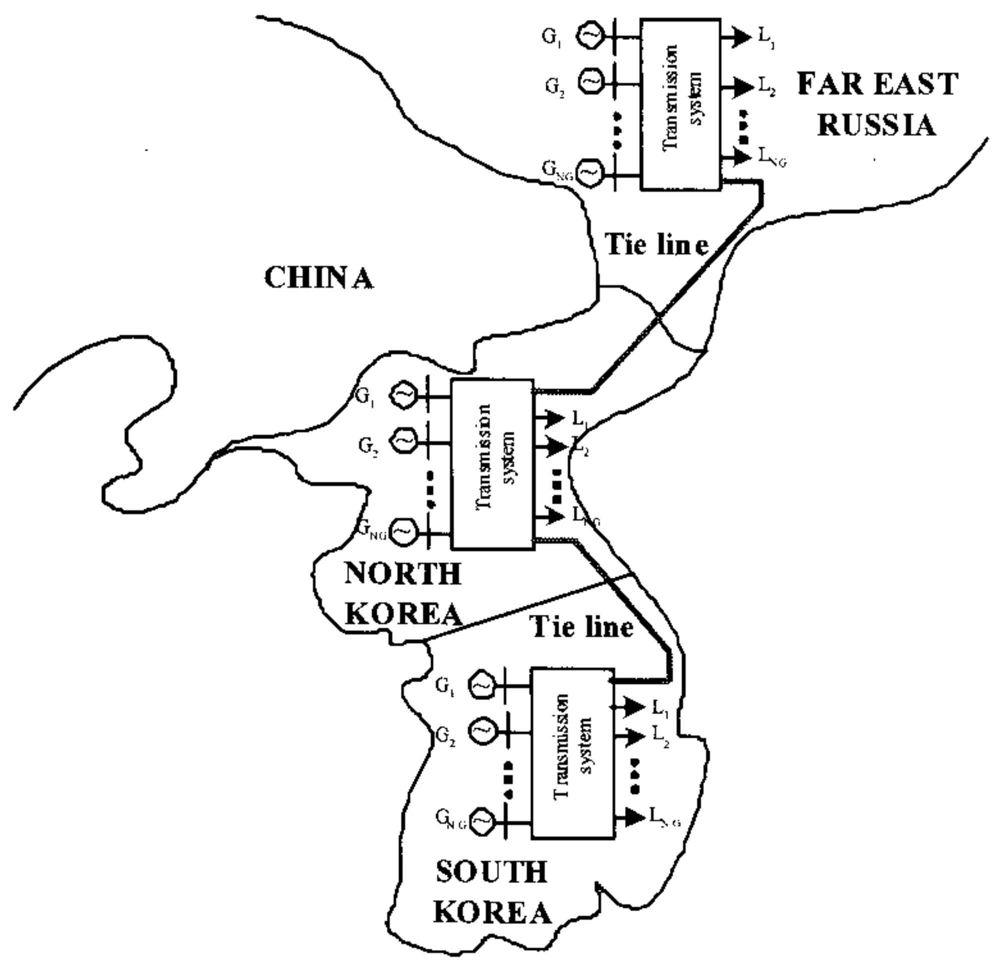


Fig. 6 Three interconnected countries in Scenarios I.

Table 1 System parameters in 2010

Systems	Total generation capacity [GW]	Peak load [GW]	Supply reserve rate [%]
ROK	78.7	60.6(summer)	29.9
NK	11.7	9.9(spring)	18.2
FER	10.2	7.1(winter)	32.4
Total	100.6	77.6	Ave.=26.8

* ROK : Republic of Korea-South Korea
NK : North Korea
FER : Far East Russia

■ Study for the year 2010

Table 2 shows the reliability indices for the ROK, NK and FER systems considering them as isolated systems (no interconnection). The values were obtained using reasonable assumptions of the forced outage rate (FOR) values due to the insufficient FOR data base in these countries.

Table 2 Single system reliability indices for 2010

Systems	LOLE [hrs/yr]	EENS [GWh/yr]	EIR of EENS
ROK	0.682933	1.673132	0.99999
NK	338.45784	658.97156	0.99221
FER	4.907834	4.324243	0.99917
Average	114.68287	221.6563	0.99712

Fig. 7 shows the results of a sensitivity analysis conducted to examine how the reliability indices for South Korea (ROK) change due to changes of the tie line capacity. This figure indicates that the reliability indices saturate at a tie capacity of 3[GW]. As a result, 3[GW] can be considered a reasonable tie line capacity. Very similar sensitivity analysis results were obtained for North Korea and Far East Russia.

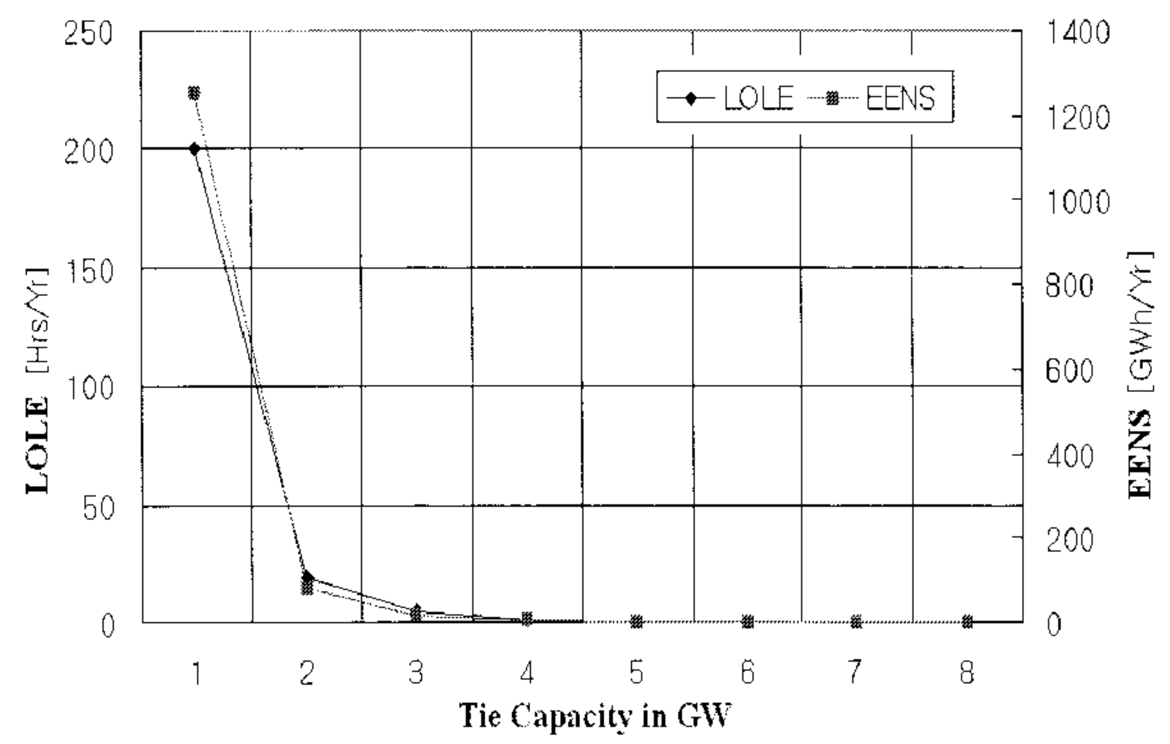


Fig. 7 Reliability indices for South Korea as function of the tie line capacity, 2010 year.

The reliability indices of South Korea are shown in Table 3 assuming 3[GW] of tie line capacity. Table 3 shows that the reliability levels in the spring, fall and winter seasons decrease after interconnection because the electrical energy of the country is used to assist the interconnected countries. It is, however, important to note that the reliability level in summer when the peak load in South Korea occurs is higher.

Table 3 Seasonal and annual reliability indices for South Korea considered as single and interconnected systems: (2010 year, 3[GW])

ROK 2010						
SEASON		SPR	SUM	FALL	WIN	Total
LOLE [hrs/yr]	S	0.0360	0.1165	0.4845	0.04605	0.6829
	I	0.4821	0.0180	1.6468	2.33056	4.4774
EENS [GWh/yr]	S	0.0353	0.2060	1.3894	0.0424	1.6731
	I.	1.4322	0.0365	7.0729	9.6232	18.165
EIR [PU]	S	1.0000	0.9999	0.9999	1.0000	1.0000
	I	0.9999	1.0000	0.9999	0.9999	0.9999

(Where, SPR: Spring, SUM: Summer, WIN: Winter,
S : Single, I : Interconnection)

4. Conclusions

This paper illustrates a series of case studies involving reliability evaluation of the interconnected power systems in north-east Asia using the tie line constrained equivalent assisting generator model (TEAG) considering the forced outage rates of the transmission systems of the interconnected three power systems. The main conclusions in this paper are as follows.

1. From the view point of reliability evaluation excluding economics, 3GW is reasonable tie line capacity for Scenario I which is a series interconnection connecting South Korea, North Korea and Far East Russia. This result is

obtainedunder the assumption that the systems will be interconnected in 2010.

2. It is expected that the proposed TEAG model will prove useful in the solution of problems related to the quantitative evaluation of transmission system uncertainties in the three interconnected power systems.
3. The proposed model (TEAG) comes from the synthesized fictitious equivalent generator (SFEG) considering the uncertainties of generators as well as the transmission lines.[11]
4. A program called NEAREL in order to evaluate hese scenarios was successfully developed.

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