KIEE International Transactions on PE, Vol. 4-A No. 2, pp. 91~99, 2004 **91**

Tie Line Constrained Equivalent Assisting Generator Model (TEAG) Considering Forced Outage Rates of Transmission Systems

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Abstract - This paper illustrates a tie line constrained equivalent assisting generator (TEAG) model considering forced outage rates of transmission systems for reliability evaluation of interconnected power systems. Interconnections between power systems can provide improved levels of reliability. It is expected that the TEAG model developed in this paper will prove useful in the solution to problems related to the effect of transmission system uncertainties in the reliability evaluation of interconnected power systems. The characteristics and concept of this TEAG considering transmission systems are described in detail by sample studies on a simple test system.

Keywords: Reliability evaluation of interconnected power systems, Synthesized fictitious equivalent generator (SFEG), Tie line constrained equivalent assisting generator model (TEAG) at Hierarchical level II).

1. Introduction

The primary function of an electric power system is to provide electrical energy to its customers as economically as possible and with an acceptable degree of continuity and quality [1]. The adequacy of the generating capacity in a power system is normally improved by interconnecting the system to other power systems [1]. However, the quantitative evaluation of the effects of the interconnections is difficult because the interconnection assistance between power systems is a function of many variables such as the system installed capacity, generation dispatch, forced and scheduled outages of equipments, 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 in the past. There are several probabilistic methods designated basically as the probability array method and equivalent assistance unit model method [1] and more recently, large deviation method [3], equivalent energy function approach [4], decomposition-simulation method [5-7], Monte-Carlo simulation methods [8, 9], and the frequency and duration method [10], are available at the present time to provide a quantitative probabilistic reliability assessment of interconnected power systems. Most of the conventional methodologies are derived from a basic model that considers the probabilistic available transfer capability (ATC) incorporating the uncertainties and capacity limitations of the generators and tie lines without considering the capacities and uncertainties of the transmission systems.

This paper proposes an alternative method for the tie line constrained equivalent assisting generator model (TEAG) considering the forced outage rates of the transmission systems in the interconnected power systems. It is expected that the proposed TEAG model will prove useful in dealing with the problems related to quantitative evaluation of transmission system uncertainties in interconnected power systems. The proposed model (TEAG) comes from the synthesized fictitious equivalent generator (SFEG) model considering the uncertainties of generators as well as transmission lines already developed by the authors [11-16]. The characteristics and concept of this TEAG considering transmission systems are described in detail by sample studies on a simple test system.

2. New Model for Reliability Evaluation of Two Interconnected Power Systems

2.1 Basic Model at HLI

The hierarchical level I (HLI) model shown in Fig.1 is

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Received September 29 2003 ; Accepted April 28, 2004

the configuration for two interconnected systems without considering their transmission systems with the assumption that the delivery capability of the transmission systems is unlimited and is entirely reliable. Quantitative reliability analysis incorporating transmission system uncertainties cannot be evaluated using this model. The two most essential methods for reliability evaluation of this HLI model are provided below [1].

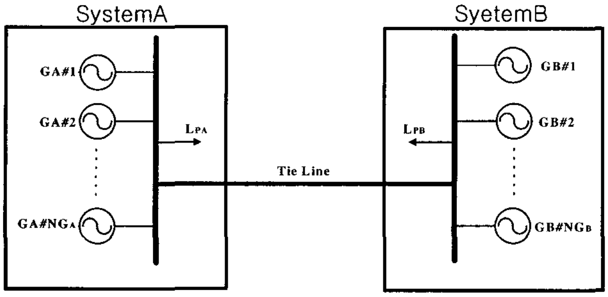
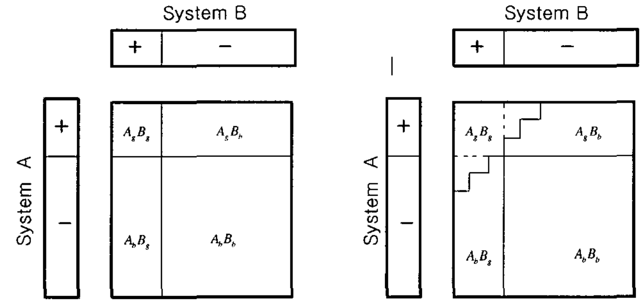


Fig. 1 Two power systems interconnected with a tie line

2.1.1 Probability Array Method

The generating facilities in each system can be represented by a two-dimensional probability array covering all possible combinations of capacity outages in the two systems. This amalgamated array represents the overall interconnected system capacity model with ideal interconnections. This representation can then be modified by including the load levels in each system and the tie line constraints. The concept is shown diagrammatically in Fig. 2, which illustrates the boundaries between good and bad states.



(a) without tie line (b) with tie line

Fig. 2 Concept of the probability array method(g: good states, b: bad states)

2.1.2 Equivalent Assisting Unit Method

The equivalent unit approach represents the benefits of interconnection between the two systems in terms of an equivalent multi-state unit that describes the potential ability of one system to accommodate capacity deficiencies in the other. This is described considering System A as the assisted system and System B as the assisting system. The capacity assistance level for a particular outage state in System B is given by the minimum of the tie capacity and available system reserve at that outage state. The process for modeling the equivalent assisting unit is shown in Fig. 3 [1].

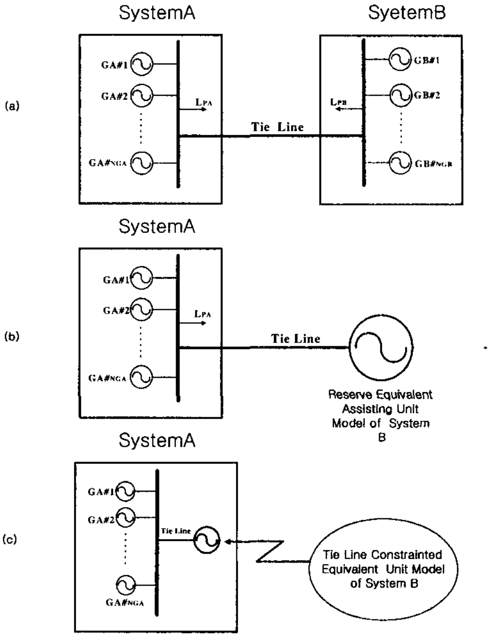


Fig. 3 Process for modeling the equivalent assisting unit

2.2 The New Tie Line Constrained Equivalent Assisting Generator Model (TEAG) at HLII

In order to conduct quantitative reliability analysis including transmission system uncertainties, this paper proposes a tie line constrained equivalent assisting generator model (TEAG) incorporating the forced outage rates of the transmission lines within the power systems interconnected with tie lines. The two composite generation and transmission systems interconnected by one tie line are shown in Fig. 4. Composite generator and transmission system evaluation is known as hierarchical level II (HL II) assessment.

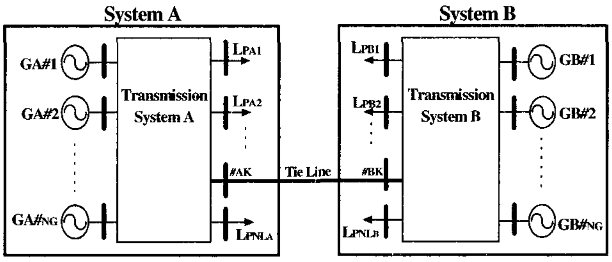


Fig. 4 The two composite generation and transmission systems interconnected by one tie line (systems A and B are the assisted and assisting systems, respectively)

The objective of the analysis is not only the development of the tie line constrained equivalent assisting generator model (TEAG) considering the forced outage rates of transmission lines of the assisting system B, but also the reliability evaluation of system A based on TEAG considering the forced outage rates of the transmission lines in the assisted system A.

2.2.1 Synthesized Fictitious Equivalent Generator (SFEG) at HLII

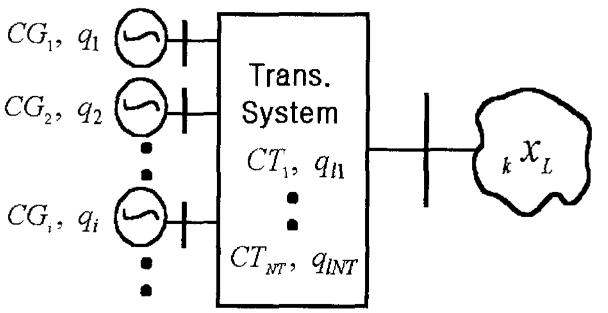
Fig. 5 presents the main concept of the synthesized fictitious equivalent generator (SFEG) model. *CG*, *CT*, *q* and q_l in Fig. 5 are the capacities and forced outage rates of generators and transmission lines, respectively. Fig. 5(a) is the original composite power system. Using optimal load flow with a certain objective function in the case of operating generators from *#1* to *#i*, it is possible to calculate the maximum arrival power (${}_kAP_{sij}$) at the load point and the state probabilities (${}_kq_{sij}$) for system state *#j* as shown in Fig. 5(b). This can be designated as a synthesized fictitious equivalent generator with multi-operating states of forced outage rate ${}_kq_{sij}$ with operating power ${}_kAP_{sij}$ at the load point. The capacity of the synthesized fictitious equivalent generator comes from the largest maximum arrival power (${}_kAP_{sij}$). The synthesized fictitious equivalent generator system is similar to the actual system at HLI without the transmission system. The synthesized generator here means the generators operating together from *#1* to *#i*. Therefore, the ${}_kf_{osi}$ in Fig. 5(b) is the outage capacity probability distribution function of the synthesized fictitious equivalent generator created by generator units *#1* to *#i*. This generator is abbreviated as SFEG in this paper [11-16].

2.2.2 Probability Distribution Function of the Synthesized Fictitious Equivalent Generator

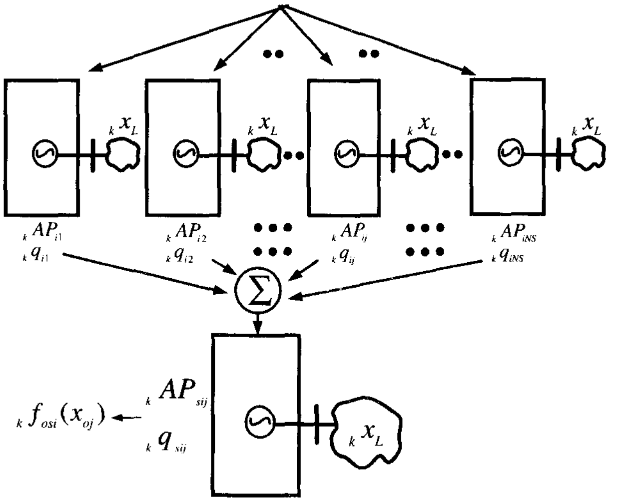
Both analytical enumeration methods and Monte Carlo simulation can be used to create the probabilistic distribution function (PDF) of the SFEG. The former can be employed to obtain accurate solutions in small sized test systems while the latter is more practical for large sized actual power systems [8, 9, 17, 18, 20]. In this study, the analytical enumeration method was used because the eventual purpose of this study is to develop and focus on a new effective load model and to clearly review the identities of the new proposed model prior to application in actual large 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 [13, 14, 16].

A. State Probability Calculation

Total contingency enumeration would require $NS=2^{100}$ states to be considered for a system composed of 100 generators and transmission lines. This is obviously impractical in an actual system. Fortunately, the probability of a relatively large number of generators and transmission lines failing simultaneously is virtually zero. And so, it is not necessary to consider all contingency states in an actual system. Eq. (1) can be used practically in these cases for the state probabilities (${}_kq_{sij}$) for system state *#j*. The state probabilities become the values of the outage capacity PDF, ${}_kf_{osi}$ of the synthesized fictitious equivalent generator created by generator units *#1* to *#i*.



(a) Actual system



(b) Synthesized fictitious equivalent generator

Fig. 5 Synthesized Fictitious Equivalent Generator Model at HLII

$$q_{sij} = P(e_j)Q(\bar{e}_j) \qquad \exists\forall\ n(\bar{e}_j) \le \text{Ncont} \qquad (1)$$

where, e_j and $\bar{e}_j$: sets of elements on operation and outage respectively of system state $\# j$

$n(\bar{e}_j)$: number of elements on outage of set, $\bar{e}_j$

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

$Q(\bar{\ })$: unavailable probability of set, $\bar{e}_j$

Ncont : the number of contingencies of generators and transmission lines (Ncont=7used in this study)

B. Maximum Arrival Power Evaluation

Since there are several possible solutions when calculating the power on outage at the load points for each state, the objective function for minimum outage power must be set up and an optimal solution obtained by optimal power flow at HLII. The objective function was established to minimize the outage power at a load point. The maximum rate of outage power is as shown in Eq. (2). AC or DC load flows can be used in this situation in order to obtain more accurate maximum arrival power [13]. In this study, however, transmission line losses are ignored and only effective power is considered for computational convenience in the following equation [19].

1) Objective function

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

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

B_L : set of buses that have loads

max : abbreviation of maximum

2) Constraints

a) constraint of incident circuit

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

where, a_{ij} : node – branch incidence matrix

B_B : set of all buses

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

CG_i : generation at bus # i (MW)

limitation constraints of transmission line capacity

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

where, CT_{lmax} : capacity of transmission line # l (MW)

x_l : control variable signifying effective power flow of branch # l

B_T : set of transmission lines

Eqs. (2) ~ (4) can be summarized similar to Eq. (5).

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

Using Linear Programming, the maximum arrival power (${}_kAP_{sij}$) of the state #j at the load points can be easly obtained from solutions of Eq. (5) at the contingency state #j.

The outage capacity PDF (${}_kf_{osi}$) of the SFEG in Eq. (5) can be obtained from the state probabilities (${}_kq_{sij}$) of Eq. (6) and the maximum arrival power (${}_kAP_{sij}$) of Eq. (5).

The SFEG$_{\#BK}$ at load point #BK of the assisting system B is modeled equivalently in Fig. 6.

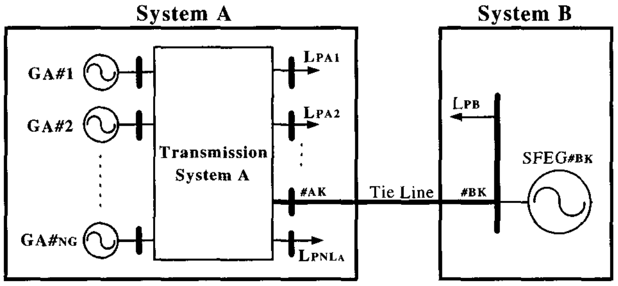


Fig. 6 The SFEG$_{\#BK}$ at load point #BK of assisting system B

2.2.3 Equivalent Assistance Generator (EAG$_{\#BK}$) Model

The actual available capacity assistance from SFEG$_{\#BK}$ at load point #BK of system B to system A must be limited to the peak load at the bus. The limited assisting capacity of the SFEG$_{\#BK}$ can be calculated using Eq. (6). It is called the Equivalent Assistance Generator (EAG$_{\#BK}$) Model and is shown in Fig. 7.

$$AP_j^{new1} = \text{maximum}\{(AP_j - L_{p\#BK}), 0.0\} \qquad (6)$$

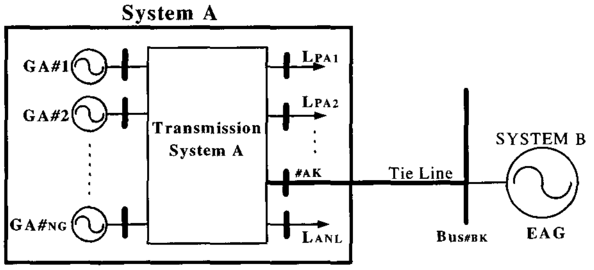


Fig. 7 Equivalent Assistance Generator (EAG$_{\#BK}$) Model

2.2.4 Tie line constrained equivalent assisting generator model (TEAG)

More actual available capacity assistance from the Equivalent Assistance Generator (EAG$_{\#BK}$) of system B to system A may be constrained by tie line capacity limitations. Therefore, the tie line constrained assisting capacity of the EAG$_{\#BK}$ can be calculated using Eq. (7). It is called the Tie line constrained equivalent assisting generator model (TEAG) and is illustrated in Fig. 8.

$$AP_j^{new2} = \text{minimum}\{AP_j^{new1}, TICP\} \qquad (7)$$

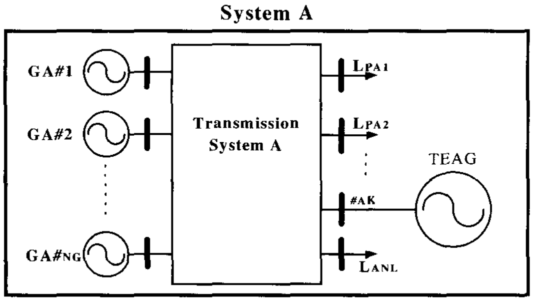


Fig. 8 Tie line constrained equivalent assisting generator (TEAG) model

In conclusion, therefore, a tie line constrained equivalent assisting generator (TEAG) is installed within system A. The unit comes from assisting system B and considers tie line capacity and the uncertainties associated with the generators and transmission lines in the two systems. The reliability of system A can be evaluated using the TEAG model.

Algorithm

The basic algorithm can be briefly described as follows.

STEP I: Modeling the SFEG$_{\#BK}$ at the connection point of assisting System B.

STEP II: Modeling the EAG$_{\#BK}$ considering the peak load at the connection point of assisting System B.

STEP III: Modeling the TEAG$_{\#AK}$ considering the tie line capacity limitations.

STEP IV: Calculate SFEG$_{\#AI}$ at a load point (#AI) for reliability evaluation incorporating the forced outage rates of the transmission lines in System A.

3. Sample study

The characteristics and validity of this TEAG considering transmission systems are illustrated in detail by sample studies of the simple test system shown in Fig. 9.

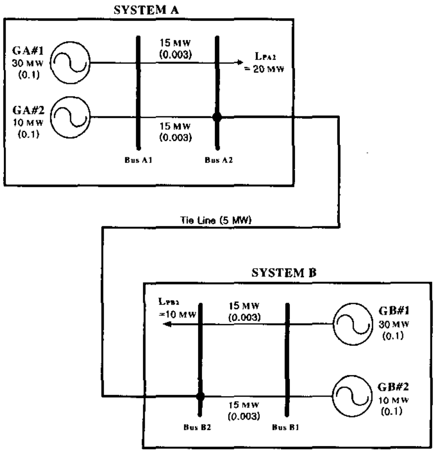


Fig. 9 Simple test system for sample study

STEP I: Modeling the SFEG$_{\#B2}$ at the connection point of assisting System B.

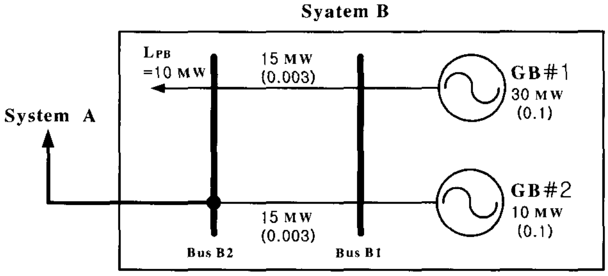


Fig. 10 The Power System B

The probabilities of the maximum arrival power state at Bus B2 of System B are shown in Table 1.

Table 1 States Probability and Maximum Arrival Powers at Bus B2 of System B

State #	GB#1	GB#2	T	Probability		AP_j
1	30	10	0	0.9^2x0.997^2	= 0.80514729	30
2	30	10	1	0.9x0.9x0.003x0.997x2	= 0.00484542	15
3	30	10	2	0.9x0.9x0.003^2	= 0.00000729	0
4	0	10	0	0.1x0.9x0.997^2	= 0.08946081	10
5	0	10	1	0.1x0.9x0.003x0.997x2	= 0.00053838	10
6	0	10	2	0.1x0.9x0.003^2	= 0.00000081	0
7	30	0	0	0.9x0.1x0.997^2	= 0.08946081	30
8	30	0	1	0.9x0.1x0.003x0.997x2	= 0.00053838	15
9	30	0	2	0.9x0.1x0.003^2	= 0.00000081	0
10	0	0	0	0.1x0.1x0.997^2	= 0.00994009	0
11	0	0	1	0.1x0.1x0.003x0.997x2	= 0.00005982	0
12	0	0	2	0.1x0.1x0.003^2	= 0.00000009	0
Total					1.00000000	

(Where, AP_j: maximum arrival power (available capacity) [MW])

The capacity CFEG of the SFEG can be calculated as follows.

$$
\begin{aligned}
CFEG &= \text{maximum}\,(AP_j) \ - \text{minimum}\,(AP_j) \\
&= 30 - 0 = 30[\text{MW}]
\end{aligned}
$$

The outage capacity PDF of the SFEG can be obtained as shown in Table 2.

Table 2 Probabilistic Distribution Table ($_{B2}f_{os2j}$) of the Synthesized Fictitious Equivalent Generator (SFEG$_{B2}$) at Bus B2 of System B

AP_j	OP_j	PDF ($_{B2}f_{os2}$) of SFEG$_{B2}$
30	0	0.89460810
25	5	0.0
20	10	0.0
15	15	0.00538380
10	20	0.08999919
5	25	0.0
0	30	0.01000891
Total		1.00000000

(Capacity Outage, $OP_j = CFEG - AP_j$)

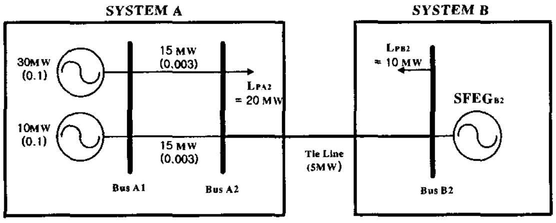


Fig. 12 Synthesized Fictitious Equivalent Generator ($SFEG_{B2}$) at Bus B2 of System B

Table 3 PDF of $SFEG_{B2}$ at Bus B2 of System B

State #	AP_j	OP_j	PDF of $SFEG_{B2}$	Cumulative Prob.
1	30	0	0.89460810	1.00000000
2	15	15	0.00538380	0.10539190
3	10	20	0.08999919	0.10000810
4	0	30	0.01000891	0.01000891
Total			1.00000000	0.00000000

Therefore, $LOLP_{B2}$ is 0.01000891 assuming a constant load in System B.

STEP II: Equivalent Assisting Generator (EAG_{B2}) of System B considering Peak Load at Bus B2.

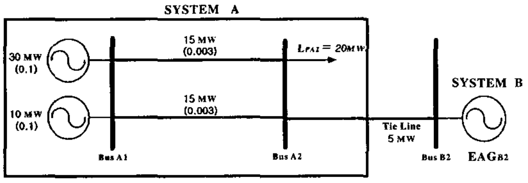


Fig. 13 System A interconnected with the Equivalent Assisting Generator (EAG_{B2}) of System B

$$AP_j^{new1} = \text{maximum}\ \{\ (AP_j - Lp_{B2})\ ,\ 0.0\ \}$$

Table 4 PDF of Equivalent Assisting Generator (EAG_{B2}) of System B at Bus B2

State #	$AP_j - Lp_{B2}$	AP_j^{new1}	OP_j	PDF of EAG_{B2}
1	20	20	0	0.8946081
2	5	5	15	0.0053838
3	0, -10	0	20	0.1000081
Total				1.0000000

STEP III: Tie Line Constrained Equivalent Assisting Generator ($TEAG_{A2}$) at Bus A2 of System B considering Tie Line Capacity (TICP).

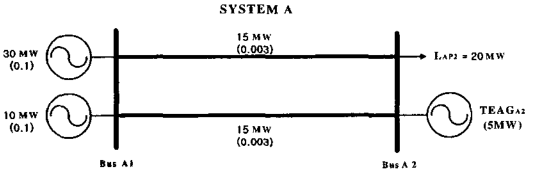


Fig. 14 Tie Line Constrained Equivalent Assisting Generator ($TEAG_{A2}$) of System B at Bus A2 of Case 1

$$AP_j^{new2} = \text{minimum}\ \{\ AP_j^{new1},\ 5\ \}$$

Table 5

(a) PDF of the Tie Line Constrained Equivalent Assisting Generator ($TEAG_{A2}$) of System B at Bus A2

State #	$\{AP_j^{new1}, 5\}$	AP_j^{new2}	OP_j	PDF of $TEAG_{A2}$	Cumulative Prob.
1	{20,5}	5	0	0.8946081	1.0000000
2	{5,5}	5	0	0.0053838	0.1053919
3	{0,5}	0	5	0.1000081	0.1000081
Total				1.0000000	0.0000000

(b) Modified PDF of the Tie Line Constrained Equivalent Assisting Generator ($TEAG_{A2}$) of System B at Bus A2

State #	AP_j^{new2}	OP_j	PDF
1 & 2	5	0	$0.8999919 \approx 0.9$
3	0	5	$0.1000081 \approx 0.1$
Total			1.00000000

STEP IV: Composite SFEG at Bus A2: Case 1 of Sample Study I

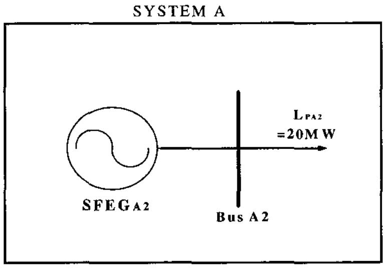


Fig. 15 Composite $SFEG_{A2}$ considering $TEAG_{A2}$ of the Power System B

The reliability index (LOLE) of load point A2 in system A assuming constant load is shown in Table 6.

Table 6 PDF of Composite $SFEG_{A2}$ at Bus A2

AP_j	OP_j	PDF of Com. $SFEG_{A2}$	Cumulative Probability
35	0	0.805147290	1.000000000
30	5	0.089460810	0.194852710
20	15	0.004845420	0.105391900
15	20	0.081537651	0.100546480
10	25	0.008999919	0.019008829
5	30	0.009008019	0.010008910
0	35	0.001000891	0.001000891
Total		1.000000000	0.000000000

Therefore, $LOLP_{A2} = 0.10054648$!

The results of four cases with different interconnection points in the two systems are compared in Table 7.

Table 7 Comparison of Results of Cases of Sample Study II

	System A [MW]	System B [MW]	TICP [MW]	Inter. Points	LOLP$_{A2}$ L$_{PA2}$=20[MW]	LOLP$_{B2}$ L$_{PB2}$=10[MW]
Case 1	30 & 10	30 & 10	5	A2-B2	0.10054648	0.01000891
Case 2	30 & 10	30 & 10	5	A1-B2	0.10539190	0.01000891
Case 3	30 & 10	30 & 10	5	A2-B1	0.10054648	0.01000891
Case 4	30 & 10	30 & 10	5	A1-B1	0.10539190	0.01000891

(Refer: When not interconnected, LOLP$_{A2}$ of System A = 0.10539190)

4. Conclusion

This paper illustrates a new tie line constrained equivalent assisting generator model (TEAG) considering the forced outage rates of the transmission systems of the interconnected power systems. It is expected that the proposed TEAG model will prove useful in the solution of problems related with the quantitative evaluation of transmission system uncertainties in the interconnected power systems. The proposed model (TEAG) is derived from the synthesized fictitious equivalent generator (SFEG) considering the uncertainties of generators as well as the transmission lines in a power system developed by the authors [11-16]. The characteristics and concept of this TEAG considering transmission systems are described by sample studies on a simple test system.

This paper described the first step in the application of the new TEAG model. Research on the development of the methodology using optimal AC or DC load flow for evaluating more accurate maximum arrival powers and the application of Monte Carlo simulation in large size real power systems will be carried out in the future.

Acknowledgement

This work was supported by the NEAREST project of the Korea Electro-technology Research Institute funded by the Ministry of Commerce, Industry & Energy.

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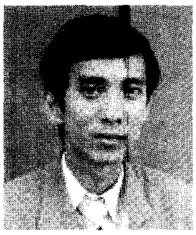

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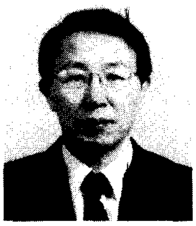

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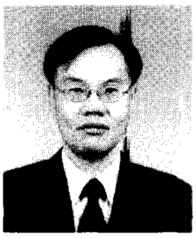

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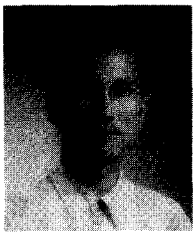

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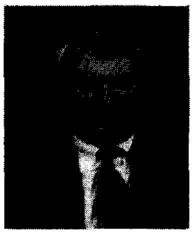

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