Development of Tie Line Constrained Equivalent Assisting Generator Model (TEAG) For Reliability Evaluation of NEAREST-III

TrungTinh Tran*, Jae-Seok Choi†, Hyung-Chul Kim*, Seung-Il Moon and Roy Billinton*****

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. It is important that interconnection between power systems can provide the improved levels of reliability. Therefore, It is expected that the TEAG model developed in this study will provide some solution among many problems for interconnected power systems as an optimal tie line capacity and a connected point between assisting systems and assisted system. The characteristics and validity of this developed TEAG considering transmission systems are introduced by case study of three IEEE MRTS interconnected.

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

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 three power systems which are agreement assumed Russia, North Korea and South Korea. It is also shown effectives of tie line capacity and connected point to reliability level of interconnection system. 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 three 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 characteri-

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stics and concept of this TEAG considering transmission systems are described in detail by case study of three IEEE MRTS interconnected.

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

2.1 Basic Model at HLI

The hierarchical level I (HLI) model shown in Fig.1 is the configuration for three 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].

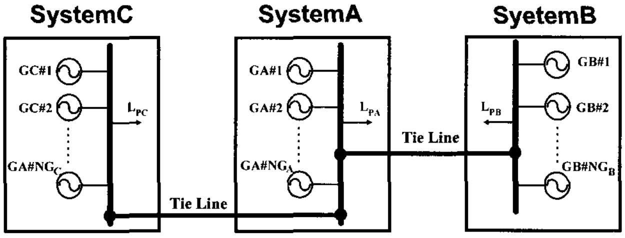
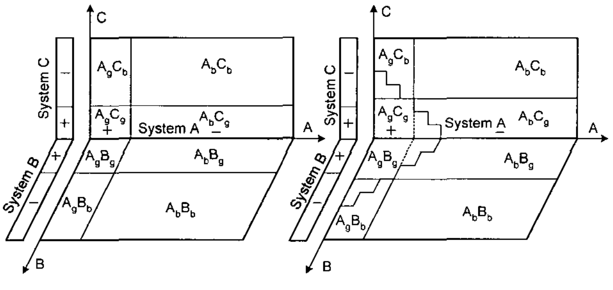


Fig. 1 Three power systems interconnected with a tie line

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. Including the load levels in each system and the tie line constraints can modify this representation. 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 three systems in terms of an equivalent multi-state unit, which describes the potential ability of one system to accommodate capacity deficiencies in the other. This is described considering System A as assisted system, and System B and System C as the assisting systems. The capacity assistance level for a particular outage state in System B and System C are given by the minimum of the tie capacity and available system reserve at that outage state respectively. The process for modeling the equivalent assisting unit is shown in Fig. 3.

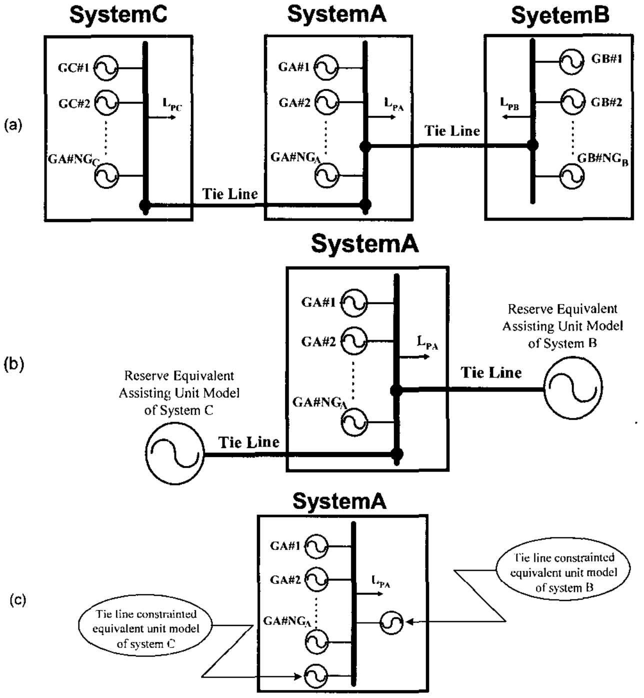


Fig. 3 Process for modeling the equivalent assisting unit

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 three composite generation and transmission systems interconnected by two tie lines are shown in Fig. 4. Composite generator and transmission system evaluation are known as hierarchical level II (HL II) assessment.

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, C 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.

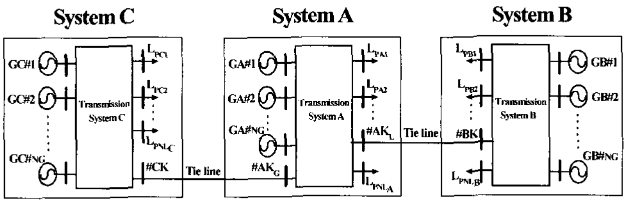


Fig. 4 The three composite power systems (HLII) interconnected by two tie lines (systems C – System A – System B)

2.2.1 Synthesized Fictitious Equivalent Generator (SFEG) at HLII

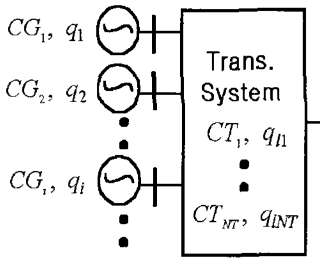
Fig. 5 presents the main concept of the synthesized fictitious equivalent generator (SFEG) model. *CG, CT, q* and q_l in Fig. 5 are the capacities and forced outage rates of generators and transmission lines, respectively. Fig. 5(a) is the original composite power system. Using optimal load flow with 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

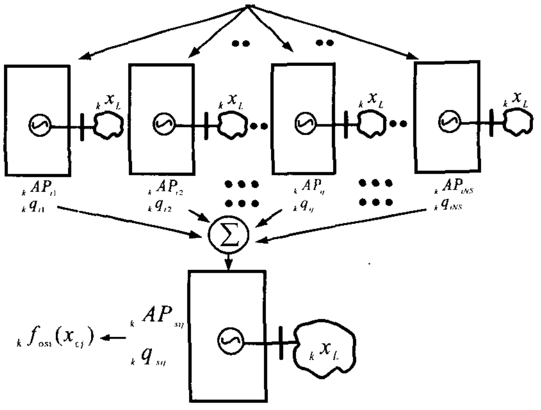
Both analytical enumeration methods and Monte Carlo simulation can be used to create the probabilistic distribution function (PDF) of the SFEG. The former can be employed to obtain accurate solutions in small sized test systems while the latter is more practical for large sized actual power systems [8, 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

$Q(\bar{e}_j)$: 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).

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

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.

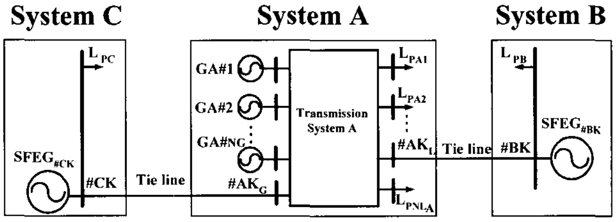


Fig. 6 The SFEG$_{\#BK}$ and SFEG$_{\#CK}$ at load point #BK and #BK respectively of assisting system B, C

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

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

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

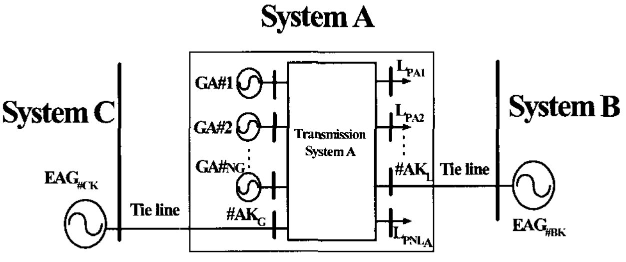


Fig. 7 Equivalent Assistance Generator (EAG$_{\#BK}$ and EAG$_{\#CK}$) Model

2.2.4 Tie line constrained equivalent assisting generator model (TEAG)

More actual available capacity assistance from the Equivalent Assistance Generator (EAG$_{\#BK}$, EAG$_{\#CK}$) of system B, C to system A may be constrained by tie line capacity limitations. Therefore, the tie line constrained assisting capacities of the EAG$_{\#BK}$ and EAG$_{\#CK}$ can be calculated using Eq. (7) and there are called the tie line constrained equivalent assisting generator models (TEAG$_B$ and TEAG$_C$) and shown in Fig. 8.

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

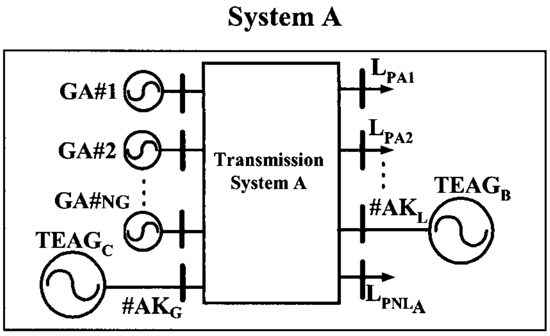


Fig. 8 Tie line constrained equivalent assisting generators (TEAG$_B$ and TEAG$_C$) model

In conclusion, therefore, two tie lines constrained equivalent assisting generators (TEAG$_B$ and TEAG$_C$) are installed within system A. The units come from assisting systems B and C and consider tie lines capacity and the uncertainties associated with the generators and transmission lines in the three 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$_{\#BK}$ and SFEG$_{\#CK}$ at the connection point of assisting System B and C.

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

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. Case Study

The characteristics and validity of this TEAG considering forced outage rates of the transmission systems are illustrated in detail by IEEE-MRTS system as shown in Fig. 9. A case 0 is without tie line for interconnecting system, With agreement assumption that interconnected points can be at bus 1, 2, 3 or 6, the same tie line capacity as shown Table 1.

Table 1 Four proposed interconnected points

Cases	Interconnected Points	Tie Line Capacity [MW]
Case 0	-	-
Case 1	**1**	**500**
Case 2	**2**	**500**
Case 3	**3**	**500**
Case 4	**6**	**500**

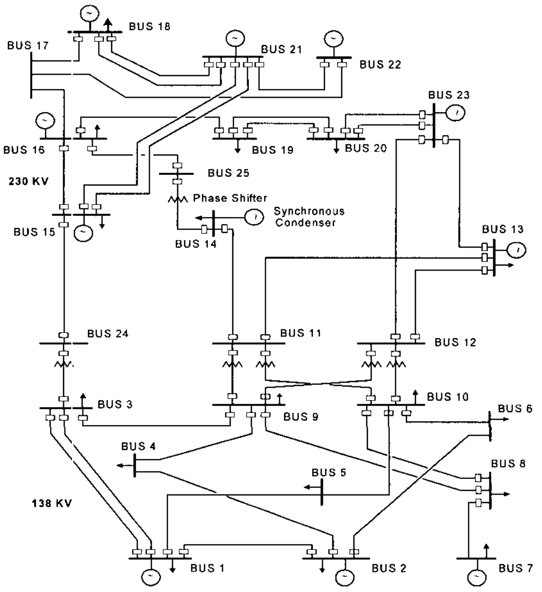


Fig. 9 IEEE – MRTS system

3.1 The reasonable interconnected point of assisting system for interconnecting systems

The probability distribution function of SFEG$_{\#BK}$ and SFEG$_{\#CK}$, EAG$_{\#BK}$ and EAG$_{\#CK}$, TEAG$_{\#AK}$ and TEAG with two states at case 1 are shown from Fig.10 to Fig. 13 respectively and the results of other cases are sequent calculated as like as case 1. The reliability indices at case 3 is smallest compared with each other. Therefore, it can be selected as like as an optimal case for decision making the best point for interconnecting system at bus #3, where is as like as a start bus of tie line in the assisting system.

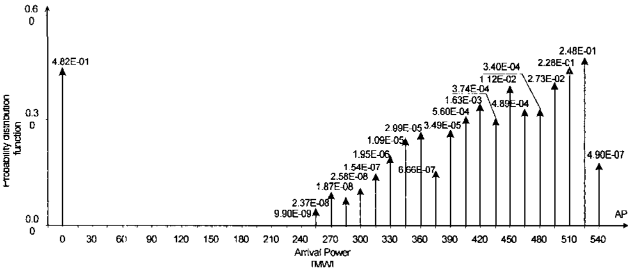


Fig. 10 *pdf* of SFEG (SFEG$_{\#BK}$, SFEG$_{\#CK}$) at bus #1 when a tie line with 500MW is interconnected at bus #1.

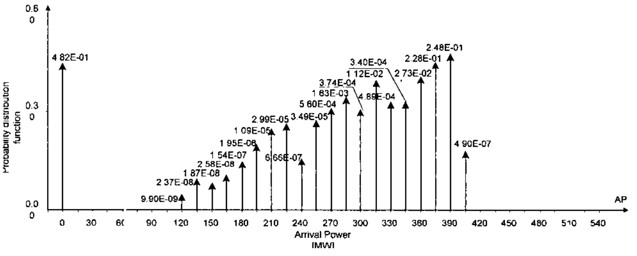


Fig. 11 pdf of EAG (EAG$_{\#BK}$ and EAG$_{\#CK}$) at bus #1 when a tie line with 500MW is interconnected at bus #1.

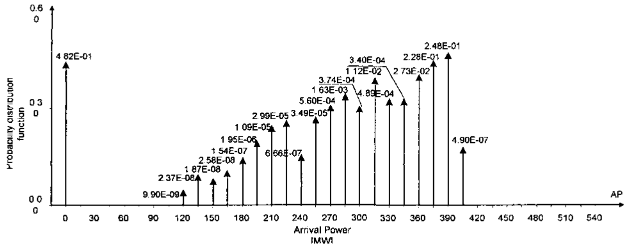


Fig. 12 *pdf* of TEAG (TEAG$_{\#AK}$) at bus #1 when a tie line with 500MW is interconnected at bus #1.

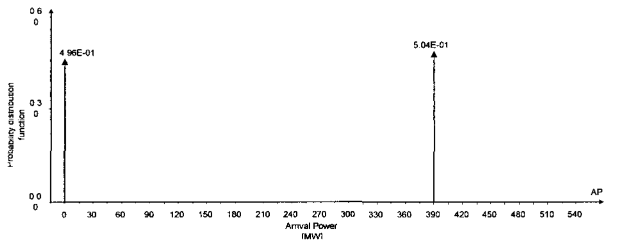


Fig. 13 *pdf* of TEAG (TEAG$_{\#AK}$) with two state at bus #1 when a tie line with 500MW is interconnected at bus #1.

Table 2 Reliability indices at interconnected points as well as assisting system

Cases	Reliability indices at interconnected point		Bulk system reliability indices	
	LOLE [Hrs/Year]	EENS [MWh/Year]	LOLE [Hrs/Year]	EENS [MWh/Year]
Case 0	-	-	6.634	3,127.61
Case 1	0.00468	0.2398	2,010.394	780,979.55
Case 2	0.00468	0.4329	0.4142	2,623,382.75
Case 3	0.0	0.0	0.0	524,705.75
Case 4	6.72845	168.6085	8,202.244	10,119,538.5

3.2 The reasonable tie line capacity for interconnecting systems

It is the characteristics of reliability indices LOLP and EENS according to change tie line capacity as shown Fig. 14 and Fig. 15. The reasonable tie line capacity can be 400 MW, because tie line capacity is increasing but TEAG capacity is saturation at 390 MW as shown Table 3. If the tie line capacity 400 MW is used and so the tie line constrained equivalent assisting generators (TEAG$_B$ and TEAG$_C$) are installed within system A is 390 MW.

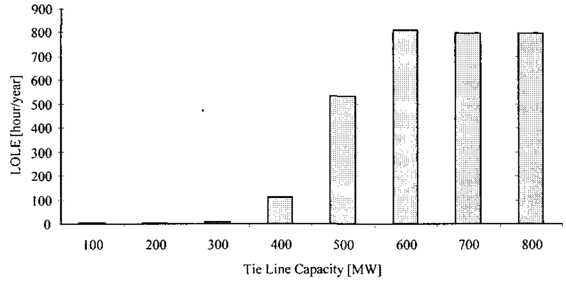


Fig. 14 Reliability indices, LOLE according to change capacity of tie line of case 3

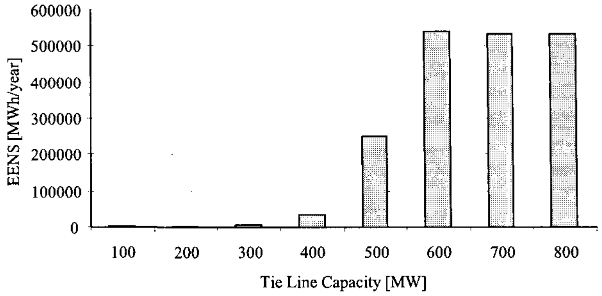


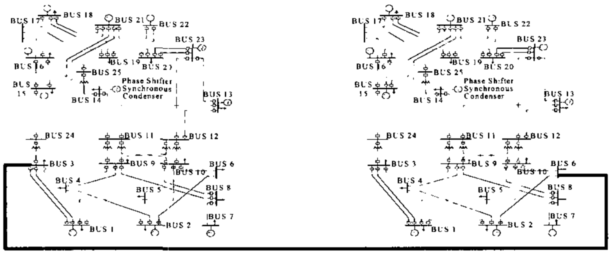
Fig. 15 Reliability indices, EENS according to change capacity of tie line of case 3

Table 3 The effective capacity of TEAG according to change of tie line capacity

Tie line capacity	TEAG capacity [MW]	Forced outage rate (FOR)
0	0	0.0
100	90	0.4831
200	195	0.4830
300	300	0.4830
400	390	0.4897
500	390	0.4896
600	390	0.4894
700	390	0.4894
800	390	0.4894

3.3 The reasonable interconnected point of the assisted system A from assisting system C.

The configuration and reliability indices of two interconnected IEEE-MRTS systems from assisting system C to assisted system A at TEAG capacity 390 MW as shown at Fig. 16. The tie line can be connected at reasonable places, where are assumed agreement by designers and planners, in system A. The best interconnected point of the assisted system A is at bus #6 as like as a end bus of tie line from assisting system C, because the reliability indices of bulk system A is smallest compared with each other agreement consumption reasonable interconnected points in system A as shown at Table 4 and Table 5. Therefore, start bus (assisting system C) and end bus (assisted system A) of tie line is bus #3 and bus #6 respectively, with capacity 400MW.



System C System A

Fig. 16 The configuration of the tow interconnection systems (C$_{\text{BUS 3}}$ – $_{\text{BUS 6}}$A)

Table 4 Reliability indices of assisted system A from assisting system C ($C_{BUS\,3}-{}_{BUS\,6}A$)

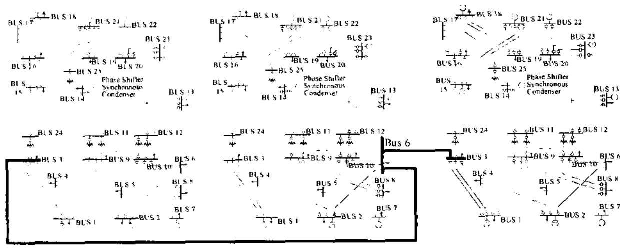
System	TEAG Capacity	LOLE [hours/day]	EENS [MWh/day]	Interconnected point
A	0	0.01829	8.568	-
C + A	390	0.002189	1.420	$A_{BUS\,6}$

Table 5 Reliability indices of assisted system A from assisting system C

Connected point	System A	
	LOLE [hours/day]	EENS [MWh/day]
$C_{BUS\,3}-{}_{BUS\,3}A$	0.006338	4.833
$C_{BUS\,3}-{}_{BUS\,4}A$	0.006880	5.028
$C_{BUS\,3}-{}_{BUS\,6}A$	**0.002189**	**1.420**
$C_{BUS\,3}-{}_{BUS\,8}A$	0.006781	4.962
$C_{BUS\,3}-{}_{BUS\,9}A$	0.006721	4.911
$C_{BUS\,3}-{}_{BUS\,10}A$	0.006841	5.017
$C_{BUS\,3}-{}_{BUS\,11}A$	0.006524	4.781
$C_{BUS\,3}-{}_{BUS\,12}A$	0.006659	4.867
$C_{BUS\,3}-{}_{BUS\,17}A$	0.006671	4.870
$C_{BUS\,3}-{}_{BUS\,20}A$	0.006745	4.962

3.4 The reasonable interconnected point of the assisted system A from assisting system C & B.

The configuration and reliability indices of three interconnected IEEE-MRTS systems from assisting system C and B to assisted system A at two TEAG capacity 390 MW as shown at Fig. 17. The best interconnected point of the assisted system A is also at bus #6 as like as end bus of tie line which is start bus at bus #3 within assisting system B, because the reliability indices of bulk system A is smallest compared with each other agreement consumption reasonable interconnected points as shown at Table 6 and Table 7. It is also shown the reliability indices at bulk system A is decreased very much compared without interconnection system. It can be demonstrated that interconnections between three power systems can provide improved levels of reliability.



System C System A System B

Fig. 17 The configuration of the three interconnection systems ($C_{BUS\,3}-{}_{BUS\,6}A_{BUS6}-B_{BUS\,3}$)

Table 6 Reliability indices of assisted system A from assisting system C and B

System	TEAG Capacity	LOLE [hours/day]	EENS [MWh/day]	Interconnected point
A	0	0.01829	8.568	0
C + A	390	0.002189	1.420	$A_{BUS\,6}$
C+A+ B	390 x 2	0.000374	0.134	A_{BUS6}

Table 7 Reliability indices of assisted system A from assisting system B with agreement assumed reasonable interconnected point

Connected point	System A	
	LOLE [hours/day]	EENS [MWh/day]
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,3}-B_{BUS\,3}$	0.000931	0.690
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,4}-B_{BUS\,3}$	0.001235	0.778
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,6}-B_{BUS\,3}$	**0.000374**	**0.134**
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,8}-B_{BUS\,3}$	0.001214	0.767
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,9}-B_{BUS\,3}$	0.001210	0.757
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,10}-B_{BUS\,3}$	0.001226	0.781
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,11}-B_{BUS\,3}$	0.001166	0.752
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,12}-B_{BUS\,3}$	0.001198	0.753
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,17}-B_{BUS\,3}$	0.001198	0.753
$C_{BUS\,3}-{}_{BUS\,6}A_{BUS\,20}-B_{BUS\,3}$	0.001192	0.765

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 three 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 interconnected power systems. It is not only shown an optimal interconnected point of assisting system and assisted system but also shown an optimal tie line capacity of interconnection 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.

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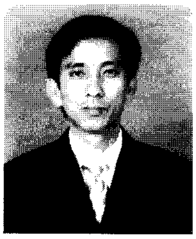

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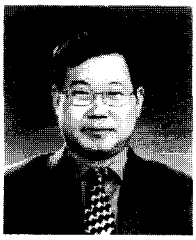

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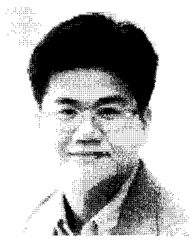

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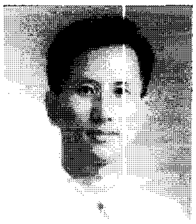

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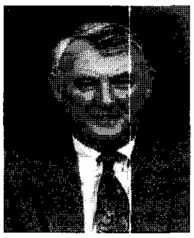

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