The Best Line Choice for Transmission System Expansion Planning on the Side of the Highest Reliability Level

Sungrok Kang*, Trungtinh Tran*, Jaeseok Choi*, Junmin Cha, Daeseok Rho*** and Roy Billinton******

Abstract - This paper presents a new method for choosing the best line for transmission system expansion planning considering the highest reliability level of the transmission system. Conventional methodologies for transmission system expansion planning have been mainly focused on economics, which is the minimization of construction costs. However, quantitative evaluation of transmission system reliability is important because successful operation and planning of an electric power system under the deregulated electricity market depends on transmission system reliability management. Therefore, it is expected that the development of methodology for choosing the best lines considering the highest transmission system reliability level while taking into account uncertainties of transmission system equipment is useful for the future. The characteristics and effectiveness of the proposed methodology are illustrated by the case study using a MRBTS. *Copyright © 2003 IFAC*

Keywords: Best transmission line choice, Transmission system expansion planning, Transmission system reliability.

1. Introduction

Deregulation with open access to the transmission system has become a hot issue in electricity energy industries [1, 2]. Deregulation with open access has moved the industry from conventional monopolistic electricity markets to competitive markets. In a competitive market, the price of the delivered energy and the quality of electrical energy including voltage quality and reliability of service are the main factors for business success [3]. Transmission system operators and decision makers for planning have long since dealt with system reliability issues and the question of quantifying system reliability. However, a key factor in today's competitive environment is the orientation toward customer needs and willingness to pay for quality [4, 5]. Methodologies for transmission system expansion planning based on appropriate concepts of transmission system reliability evaluation, therefore still have to be developed for independent transmission system planners under the competitive electricity environment [6].

This paper presents a new method for determining the most suitable line/plan for transmission system expansion planning under various given candidate lines/plans to achieve the highest reliability level of the transmission system. A methodology for assessing and evaluating nodal probabilistic reliability indices of a transmission system is proposed in order to choose the best line/plan. The proposed method for evaluating the transmission system reliability is based on the concept that the reliability level of a transmission system is equal to the difference in the reliability levels of the composite power system (HLII) and the generation system (HLI). The risk indices of the composite power system are larger than those of the generation system because the transmission system includes related uncertainties (forced outage rates) [7, 8].

The effective load duration curve of the composite power system (CMELDC) developed earlier by the authors is used in order to obtain the reliability indices of composite power systems at HLII. The reliability indices of the generation system at HLI can be evaluated using the conventional effective load duration curve (ELDC) [7].

The proposed algorithm can reveal information such as the sensitivity of the reliability level of transmission lines to transmission system planning as well as provide useful data for reasonable transmission system expansion planning and operation to the electricity market, to an ISO and to customers at the load points. It is expected that the proposed method can be used beneficially not only for the best lines/plan choice in achieving the highest level of reliability but also in determining an optimal reliability level of the transmission system under a deregulated

* Power System Lab., Department of Electrical Engineering Gyeongsang National University, Chinju, GN, KOREA(jschoi@nongae.gsnu.ac.kr)
** Power System Lab., Department of Electrical Engineering Daejin University, Pocheon, KG, KOREA(chamin@road.daejin.ac.kr)
*** Power System Lab., Department of Electrical Engineering University of Technology and Education, Chonan, CN, KOREA (dsrho@kut.ac.kr)
**** Department of Electrical Engineering University of Saskatchewan, Saskatoon, SK, CANADA(roy_billinton@engr.usask.ca)
Received September 24, 2003 ; Accepted May 18, 2004

electricity market in the future. The characteristics and effectiveness of this proposed methodology are illustrated by a case study of the MRBTS (Modified Roy Billinton Test System) [8-11].

2. Reliability Evaluation of Power Systems Hierarchical Levels

2.1 Hierarchical Level of Power Systems

The basic techniques for adequacy assessment can be categorized in terms of their application to segments of a complete power system. These segments are shown in Fig. 1 and can be defined as the functional zones of generation, transmission and distribution systems. The target of this study is not reliability evaluation of HLII but only of the transmission system. We can take inspiration from the hierarchical level diagram in which the reliability indices of a transmission system are equal to the difference in reliability levels between HLII and HLI only if the reliability indices of HLII and HLI are compatible.

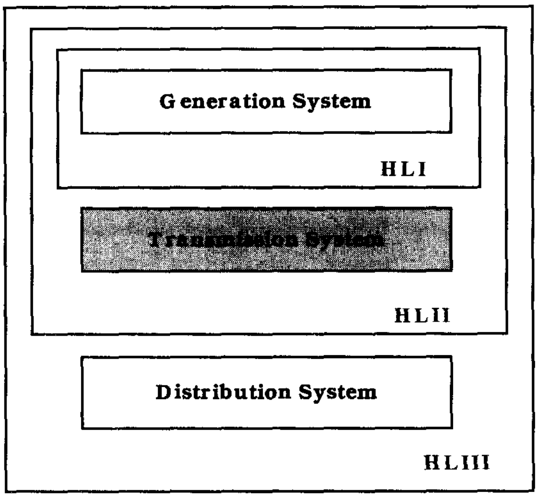


Fig. 1 Power system hierarchical level diagram.

2.2 Reliability Evaluation of HLI

Reliability indices of $LOLE_{HLI}$ (Loss of load expectation) and $EENS_{HLI}$ (Expected energy not served) of only generation systems using ELDC (Effective load duration curve) ${}_{HLI}\Phi(x)$ of HLI are calculated by Eq. (1) and Eq. (2), respectively.

$$LOLE_{HLI} = {}_{HLI}\Phi(x)\big|_{x=IC} \quad \text{[days]} \tag{1}$$

$$EENS_{HLI} = \int_{IC}^{IC+Lp} {}_{HLI}\Phi(x)dx \quad \text{[MWh]} \tag{2}$$

Where, IC : total installed capacity of generators [MW]

$$\begin{aligned} {}_{HLI}\Phi_i(x_e) &= {}_{HLI}\Phi_{i-1}(x_e) \otimes_{HLI} f_{oi}(x_{oi}) \\ &= \int {}_{HLI}\Phi_{i-1}(x_e - x_{oi})_{HLI} f_{oi}(x_{oi})dx \end{aligned} \tag{3}$$

Where, $\otimes$: operator meaning convolution integral

${}_{HLI}\Phi_o(x_e - x_{oi}) = {}_{HLI}\Phi(x_L)$

${}_{HLI}f_{oi}(x_{oi})$: the probability distribution funtion of outage capacity of generator $\#i$

L_P : peak load of system [MW]

2.3 Reliability Evaluation of HLII

Many reliability indices for HLII have been developed to date. The indices of HLII can be classified mainly into two kinds, for load point indices and bulk system indices according to the object of evaluation. Compatible indices for HLII and HLI have to be used in order to evaluate whether the reliability indices of a transmission system are equal to the difference in the reliability level between HLII and HLI. Therefore, *LOLE*, *EENS*, *EDNS* (Expected demand not supplied) and *ELC* (Expected load curtailments) based on *LOLE* and *LOEE* (Loss of energy expectation) index concepts can be used in this study.

2.3.1 Reliability indices at load points

Reliability indices and CMELDC at load point $\#k$ are illustrated in Fig. 2. Where, L_{pk} and AP_k of the horizontal axis express peak load and arrival power at load point $\#k$ respectively. In this figure, the load point reliability indices, $LOLE_k$ and $EENS_k$ can be calculated using Eq. (4) and Eq. (5) with ${}_k\Phi_{NG}(x)$. T and L_{pk} are the study period and peak load at load point #k in Fig. 2.

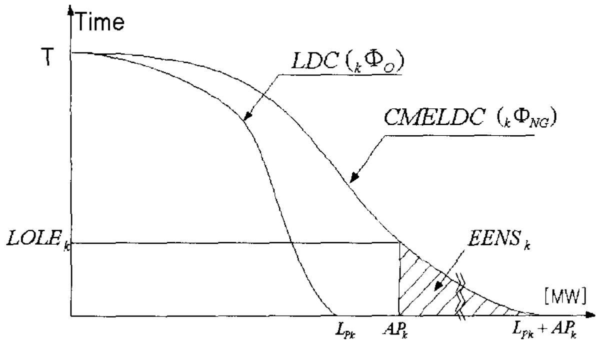


Fig. 2 Reliability indices and ELDC at load point #k.

$$LOLE_k = {}_k\Phi_{NG}(x)\big|_{x=AP_k} \quad \text{[day]} \tag{4}$$

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

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

$$_k\Phi_i(x_e) = {}_k\Phi_o(x_e) \otimes_k f_{osi}(x_{oi}) = \int {}_k\Phi_o(x_e - x_{oi})_k f_{osi}(x_{oi})dx_{oi} \quad (6)$$

where, $\otimes$: the operator meaning convolution integral

$_k\Phi_o$ = LDC at load point #k

$_kf_{osi}$: outage capacity pdf of synthesis fictitious generator operated by generators from #1 to #i at load point #k

State Probability

Total contingency enumeration could require 2^{100} states to be considered for a system composed of 100 generators and transmission lines. This is obviously impractical. Fortunately, the probability of a relatively large number of generators and transmission lines failing at the same time is virtually zero. It is impractical to consider all states for an actual system. Eq. (7) is more useful for a practical system and can be used to calculate the state probability.

$$_kq_j = \begin{cases} \sum_{\forall j \in e_j}[P(B_j)\, P_{lj}] & n(\bar{e}_j) \le 8 \\ 0 & n(\bar{e}_j) > 8 \end{cases} \quad (7)$$

where, $\bar{e}_j$: set of elements on outage of system state #j

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

$P(B_j)$: probability of the outage capacity B_j

$P(B_{lj})$: loss of load time probability at state #j

Arrival Power Evaluation

Reliability indices of HLII can be obtained differently according to the objective function of optimal power flow in order to evaluate the probability distribution function of outage capacity of a fictitious generator at the load point. In this study, the objective function was established to minimize the maximum outage power rate at load points assuming that transmission line losses are ignored and only effective power is considered in the following Eqs.

(1) Objective function

$$Minimize\ \{max(L_{pk} - x_k)/L_{pk}\} \qquad k \in B_L \quad (8)$$

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

B_L : set of loads buses

max : abbreviation of *maximum*

(2) Constraints

(a) constraint of incident circuit

$$\sum_{l=1}^{NB} a_{il}x_l \le CG_i \qquad i \in B_B \quad (9)$$

where, a_{ij} : node - incidence matrix

B_B : set of generator buses

NB : total number of branches

CG_i : generation capacity at bus #i [MW] (= 0 for load buses)

(b) constraint of transmission line capacity

$$-CT_{l\max} \le x_l \le CT_{l\max} \quad (10)$$

where, CT_{lmax} : capacity of transmission line #l [MW]

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

B_T : set of transmission lines

The CMELDC can be calculated by convoluting the original load duration curve with the probability distribution function of the powers not served at the load points using Eq. (11). Lambda in Eq. (11) is a parameter.

$$\begin{aligned} &Minimize \quad \lambda \\ &Subject\ to \\ &\left.\begin{aligned} &\sum_{l=1}^{NB} a_{il}x_l \le CG_i && i \in B_B \\ &-CT_{lmax} \le x_l \le CT_{lmax} && l \in B_T \\ &(L_{pk}-x_k)/L_{pk} \le \lambda && k \in B_L \end{aligned}\right\} \end{aligned} \quad (11)$$

where, B_T : set of transmission lines

We can obtain the AP_{kj}, arrival power at load point #k as like as in Eq. (12) for system state #j with optimal solution x_k^* of Eq. (11).

$$AP_k = x_k^* \qquad k \in B_L \quad (12)$$

Therefore, the probability distribution function of outage capacity of a fictitious generator at the load point can be constructed and the reliability indices of HLII can be obtained as Eq. (4) and Eq. (5) using Eq. (6).

2.3.2 Reliability indices of bulk system

While the $EENS_{HLII}$ of the bulk system is equal to summation of $EENS_k$ at load points as in Eq. (13), *LOLE* of the bulk system is entirely different from summation of $LOLE_k$ at load points. However, as the ELC_{HLII} of the bulk system is equal to the summation of ELC_k at load points, $LOLE_{HLII}$ of the bulk system can be calculated and divided by ELC_{HLII} as in Eq. (15).

$$EENS_{HLII} = \sum_{k=1}^{NL} EENS_k \quad \text{[MWh]} \qquad (13)$$

$$ELC_{HLII} = \sum_{k=1}^{NL} ELC_k \qquad (14)$$

$$LOLE_{HLII} = EENS_{HLII} / ELC_{HLII} \quad \text{[pu]} \qquad (15)$$

Where, NL : number of load points

R : set of states of not suppiled powers

$ELC_k = EENS_k / LOLE_k$ [MW/cur.yr]

3. Reliability Evaluation of Transmission System

LOLE and *EENS* of only a transmission system using the reliability indices of HLI and HLII are calculated as Eq. (16) and Eq. (17), respectively.

$$LOLE_{TS} = LOLE_{HLII} - LOLE_{HLI} \quad \text{[days]} \qquad (16)$$

$$EENS_{TS} = EENS_{HLII} - EENS_{HLI} \quad \text{[MWh]} \qquad (17)$$

Also, EDNS (expected demand not supplied) and ELC (Expected load curtailment) of the transmission system can be calculated using Eq. (18) and Eq. (19), respectively.

$$EDNS_{TS} = EENS_{TS} / T \quad \text{[MW/yr]} \qquad (18)$$

$$ELC_{TS} = EENS_{TS} / LOLE_{TS} \quad \text{[MW/cur.yr]} \qquad (19)$$

Where, T is total period for study [year]

In order to evaluate the effectiveness from the view of an additional transmission line, RGTAI defined as in the following Eq. (20) is used in this study [8]. The RGTAI signifies Ratios of Generation-Transmission Adequacy Indices [8]. The greater this value, the higher the level of effectiveness because the reliability level (index) of the transmission system is higher (lower) relatively than that of generation system.

$$RGTAI = R_G/R_T = R_{HLI}/(R_{HLII}-R_{HLI}) \qquad (20)$$

4. Case Study

The program has been applied to the MRBTS in order to demonstrate the effectiveness of the proposed method. Capacities and forced outage rates of generators and transmission lines are represented in Fig. 3. Straight lines are the existing transmissions and dotted lines in Fig. 3 signify the candidate lines for new construction.

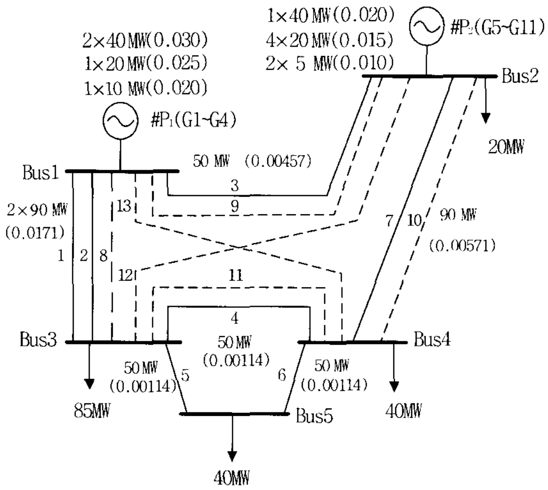


Fig. 3 MRBTS for case study.

The difference and reliability indices evaluated in HLI and HLII are shown in Table 1. The difference relates only to the reliability level of the transmission system. In this study, a one day load has been used for convenience and evaluated for study. In order to illustrate the effect of adding transmission facilities selected additions were analysed.

Table 1 Reliability Indices - Case 1 (base case)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0459	0.0277	0.0181	1.5302
EENS [MWh/day]	1.1599	0.06659	0.4940	1.3480
ELC [MW/cur.day]	25.2828	24.0009	27.2444	0.8809

Table 2 Reliability Indices - Case 2(case of a cct added at T/L8 between buses #1 and #3)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0454	0.0277	0.0176	1.5752
EENS [MWh/day]	1.1305	0.6659	0.4646	1.4331
ELC [MW/cur.day]	24.9248	24.0009	26.3800	0.9097

Table 3 Reliability Indices - Case 3(case of a cct added at T/L9 between buses #1 and #2)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0287	0.0277	0.0010	29.1765
EENS [MWh/day]	0.7120	0.6659	0.0461	14.4376
ELC [MW/cur.day]	24.8128	24.0009	48.5026	0.4948

Table 4 Reliability Indices - Case 4(case of a cct added at T/L10 between buses #2 and #4)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0279	0.0277	0.0001	187.2202
EENS [MWh/day]	0.6724	0.6659	0.0066	101.4113
ELC [MW/cur.day]	24.1088	24.0009	44.3091	0.5417

Table 5 Reliability Indices - Case 5(case of a cct added at T/L11 between buses #3 and #4)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0457	0.0277	0.0180	1.5408
EENS [MWh/day]	1.1538	0.6659	0.4879	1.3647
ELC [MW/cur.day]	25.2200	24.0009	27.0984	0.8857

Table 6 Reliability Indices - Case 6(case of a cct added at T/L12 between buses #2 and #3)

	HLII	HLI	Transmissio n system	RGTAI
LOLE [hrs/day]	0.0280	0.0277	0.0003	101.6803
EENS [MWh/day]	0.6784	0.6659	0.0125	53.2740
ELC [MW/cur.day]	24.2133	24.0009	45.8088	0.5239

Table 7 Reliability Indices - Case 7(case of a cct added at T/L13 between buses #1 and #4)

	HLII	HLI	Transmission system	RGTAI
LOLE [hrs/day]	0.0453	0.0277	0.0175	1.5832
EENS [MWh/day]	1.1255	0.6659	0.4596	1.4488
ELC [MW/cur.day]	24.8630	24.0009	26.2279	0.9151

Table 1 is a standard base case (Case 1). The results presented from Table 2 to Table 7 summarize the effect of adding transmission lines between buses for the reliability indices of a transmission system. From the results, transmission lines between buses #2 and #4 can be chosen for the most reliable line because the RGTAI is the highest value. This likewise means that the reliability level of HLII is the highest. As it is, the order of RGTAI is identical to the order of LOLE for HLII. This results from the fact that adding new transmission lines does not effect the reliability index of HLI, which is based on the model considering a generation system only.

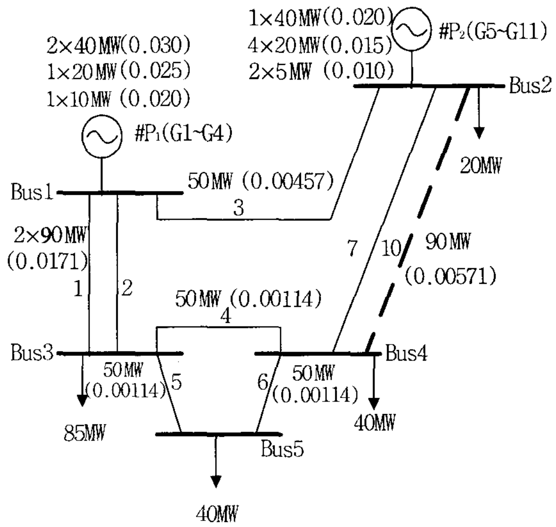


Fig. 4 The best line considering the reliability level of MRBTS.

5. Conclusions

This paper presents a new methodology for choosing the best line for transmission system expansion planning considering the highest level of reliability. A methodology for assessing and evaluating nodal probabilistic reliability indices of a transmission system is proposed in order to choose the optimal line/plan. The proposed method for evaluating the transmission system reliability is based on the concept that the reliability level of a transmission system is equal to the difference in the reliability levels of the composite power system (HLII) and the generation system (HLI). The risk indices of the composite power system are larger than those of the generation system because the transmission system includes related uncertainties (forced outage rates). In order to obtain the reliability indices of a composite power system at HLII, the CMELDC previously developed by the authors is used in this study. Development of methodology considering reliability of the transmission system as well as reasonable nodal reliability criteria and economics under the deregulated electricity market will remain for future works.

Aknowledgements

This work was supported by grant No. 2000-1-30200-006-3 from the Basic Research Program of the Korea Science & Engineering Foundation.

References

[1] CEA (March 2000). Industry Restructuring - News & Info. CEA connections online news.

[2] IMO (November 1998). Participating in Ontario's New Competitive Electricity Market. Overview Report by IMO.

[3] M. Ilic, et al (1998). *Power Systems Restructuring; Engineering and Economics,* Kluwer Academic.

[4] W.S Read, W.K. Newman, I.J. Perez-Arriaga, H.Rudnick, M.R. Gent & A.J. Roman (December 1999). Reliability in the New Market Structure (Part1). *IEEE Power Engineering Review*, p.4-14.

[5] W.S Read, W.K. Newman, I.J. Perez-Arriaga, H.Rudnick, M.R. Gent & A.J. Roman (January 2000). Reliability in the New Market Structure(Part2). *IEEE Power Engineering Review*, p.10 ~ 16.

[6] X. Wang. and J.R. McDonald (1994). *Modern Power System Planning*, McGraw-Hill.

[7] Jaeseok Choi, Daeho Do, Seungpil Moon and Roy Billinton (June 1999). Development of a Method for ELDC Construction in a Composite Power System. *LESCOPE '99 proceedings*, Halifax.

[8] Roy Billinton and Wenyuan Li (1994). *Reliability Assessment of Electric Power Systems Using Monte Carlo Methods,* Plenum Press.

[9] Roy Billinton and A. Sankarakrishnan (1995). A Comparison of Monte Carlo Simulation Techniques for Composite Power System Reliability Assessment. *IEEE WESCANEX '95 proceedings*, pp.145-150.

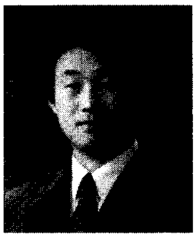
[10] Roy Billinton and Ronald N. Allan (1996). *Reliability Evaluation of Power Systems,* Second Edition, Plenum Press.

[11] Roy Billinton and W. Zhang (1996). Enhanced Adequacy Equivalent for Composite Power System Reliability Evaluation. *IEE, Proc.-GTD 143(5),* pp. 420-426.

[12] L. Chen, H. Suwa and J. Toyoda (Feb. 1991). Power Arrival Evaluation of Bulk System Including Network Constraints Based on Linear Programming Approach. *IEEE Trans.*, Vol. 6, No. 1, pp. 37-42.

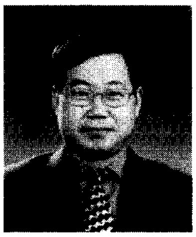
[13] J. Toyoda, L. Chen, T.Minakawa and T. Yamada (1991). New Indices and Computational Techniques for Composite System Reliability Evaluation. *Cigre Symposium,* Montreal, A1-01.

[14] S. Niioka, R. Yokoyama K. Okada & H. Asano (January 2000). Impact Evaluation of Reliability Management and Operation under the Deregulated Electric Power Market. *IEEE PES WM2000,* Singapore.



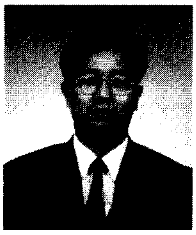
Sungrok Kang
He was born in Jinju, Korea in 1975. He obtained his B.Sc. degree from Gyeongsang National University in 2002. His research interests include Expansion Planning, Probabilistic Production Cost Simulation, Reliability Evaluation, Outage Cost Assessment and Fuzzy Applications of Power Systems. He is now working toward a M.Sc. degree at Gyeongsang National University.

Trungtinh Tran
He was born in LongAn, Vietnam in 1973. He obtained his B.Sc. degree from Cantho University in 1997. His research interests include Expansion Planning and Reliability Evaluation. He is now working toward a M.Sc. degree at Gyeongsang National University.



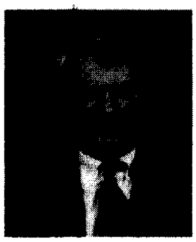
Jaeseok Choi (M88)
He was born in Kyeongju, Korea in 1958. He obtained his B.Sc., M.Sc. and Ph.D. degrees from Korea University in 1981, 1984 and 1990, respectively. His research interests include Fuzzy Applications, Probabilistic Production Cost Simulation, Reliability Evaluation and Outage Cost Assessment of Power Systems. He was a Post-Doctor at the University of Saskatchewan, Canada in 1996. Since 1991, he has been part of the faculty of Gyeongsang National University where he now serves as a Professor.

Tel: +82-55-751-5347, Fax: +82-55-759-2723



Junmin Cha (M96)
He was born in Inchon, Korea in 1964. He obtained his B.Sc., M.Sc. and Ph.D. degrees from Korea University in 1989, 1991 and 1996, respectively. His research interests include Fuzzy Applications, Probabilistic Production Cost Simulation, Reliability Evaluation, Outage Cost Assessment of Power Systems and Operation and Planning of Deregulated Power Markets. Since 1996, he has been part of the faculty of Daejin University where he now serves as an Associate Professor.
Tel: +82-31-539-1915, Fax: +82-31-535-3579

Daeseok Rho
He was born in Korea in 1964. He obtained his B.Sc. and M.Sc. degrees from Korea University in 1985 and 1987, respectively, and his Ph.D. degree from Hokkaido University of Japan in 1997. His research interests include Reliability Evaluation of Distribution Systems as well as Operation and Planning of Deregulated Power Markets. Since 1993, he has been part of the faculty of the University of Technology and Education where he now serves as an Associate Professor.
Tel: +82-41-560-1167, Fax: +82-41-564-3261



Roy Billinton (F78)
He came to Canada from England in 1952. He obtained his B.Sc. and M.Sc. degrees from the University of Manitoba and his Ph.D. and D. Sc. Degrees from the University of Saskatchewan. He then went on to work for Manitoba Hydro in the System Planning and Production Divisions. He joined the University of Saskatchewan in 1964. He was formerly Head of the Electrical Engineering Department. Currently, he is the C.J. Mackenzie Professor of Engineering and Acting Dean for Graduate Studies, Research and Extension of the College of Engineering. He has authored papers on Power System Analysis, Stability, Economic System Operation and Reliability and authored or co-authored eight books on reliability. He is a fellow of the IEEE, the EIC and the Royal Society of Canada as well as a Professional Engineer in the Province of Saskatchewan.