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A Study on the Fuzzy ELDC of Composite Power System Based on Probabilistic and Fuzzy Set Theories

Jaeseok Choi, Hongsik Kim, Seungpil Moon, Junmin Cha, Daeseok Rho and Roy Billinton

Abstract - This paper illustrates a new fuzzy effective load model for probabilistic and fuzzy production cost simulation of the load point of the composite power system. A model for reliability evaluation of a transmission system using the fuzzy set theory is proposed for considering the flexibility or ambiguity of capacity limitation and overload of transmission lines, which are subjective matter characteristics. A conventional probabilistic approach was also used to model the uncertainties related to the objective matters for forced outage rates of generators and transmission lines in the new model. The methodology is formulated in order to consider the flexibility or ambiguity of load forecasting as well as capacity limitation and overload of transmission lines. It is expected that the Fuzzy CMELDC (CoMposite power system Effective Load Duration Curve) proposed in this study will provide some solutions to many problems based on nodal and decentralized operation and control of an electric power systems in a competitive environment in the future. The characteristics of this new model are illustrated by some case studies of a very simple test system.

Keywords - fuzzy effective load, fuzzy effective load duration curve, flexibility and ambiguity, over load of transmission lines, composite power system, integral convolution

1. Introduction

The effective load duration curve(ELDC) plays an important part in probabilistic production simulation and reliability evaluation for power system planning as it supplies some very useful information [1,2]. This curve has been used widely since Baleriaux and Jamoulle in 1967[3] developed recursive equations which could consider the forced outage rate of generators within the LDC in order to obtain probabilistic production costs and reliability indices. This method was extended by Booth, Jenkins, Joy, Sager, Ringlee and Wood and is used in WASP. In 1980, J.P. Stremel, R.T. Jenkins, R.A. Babb and W.D. Bayless developed the cumulant method in which the function values of every point on the curve can be obtained by using the expansion formula of the Gram-Charlier series when all orders of cumulants of the effective load duration curve are known[4]. The MONA(Mixture of Normals Approximation) method was developed by Gross, Garapic and McNutt in 1986 to overcome some of the difficulties[5]. All these methods, however, consider only the forced outage rates of the generation system without considering the uncertainty associated with forced outages in the transmission system.

The effective load duration curve, tentatively CMELDC (CoMposite power system Effective Load Duration Curve), based on the effective load model of a composite power system has already been proposed by authors[6,7,8]. The uncertainty of some parameters, e.g. mean time to failure/repair and forecasted load etc., is difficult to deal with by a conventional probabilistic approach under an incomplete and insufficient historical D/B with related parameters. Specially, it is necessary to consider the constraint of the overload of transmission lines for the practical reliability evaluation of a transmission system. It has not crisp but fuzzy subjective matter characteristics because of the ambiguity of the permissible limitation of the line capacity in operation. Fuzzy set theory is useful to represent information having a vague nature, to model related to subjective matter or due to incomplete/insufficient data.

In this study, a new fuzzy ELDC model for reliability evaluation of a transmission system using the fuzzy set theory is proposed for considering the flexibility and ambiguity of the capacity limitation and overload of transmission lines which are subjective matter characteristics. A conventional probabilistic approach was also used to model uncertainties related to objective matters for forced outage rates of generators and transmission lines. The proposed new approach is tested in a case study of a very simple system. The obtained results are compared with conventional ones obtained without considering the flexibility or ambiguity of capacity limitation and overload of transmission lines.

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2. Modeling of Nodal Fuzzy Effective Load for Composite Power Systems

2.1 Hierarchical Levels

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 Figure 1 and can be defined as the functional zones of generation, transmission and distribution systems. The purpose of this research is to develop a nodal fuzzy effective load model and Fuzzy CMELDC considering not only the probabilistic uncertainty of some parameters, e.g. mean time to failure/repair and forecasted load but also the flexibility and ambiguity of capacity limitation and overload of transmission lines and peak load which are subjective matter characteristics for fuzzy probabilistic production cost simulation and reliability evaluation in composite power systems(HLII).

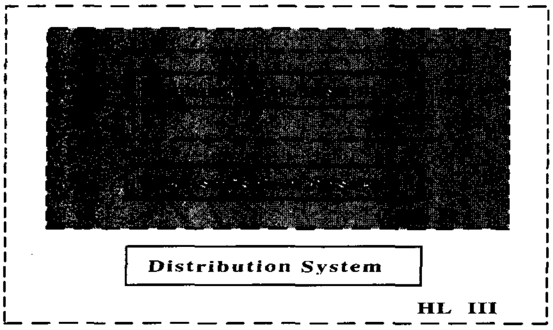
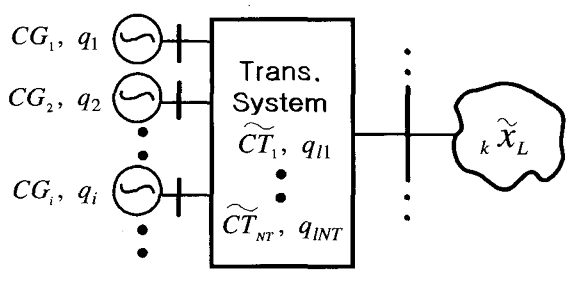


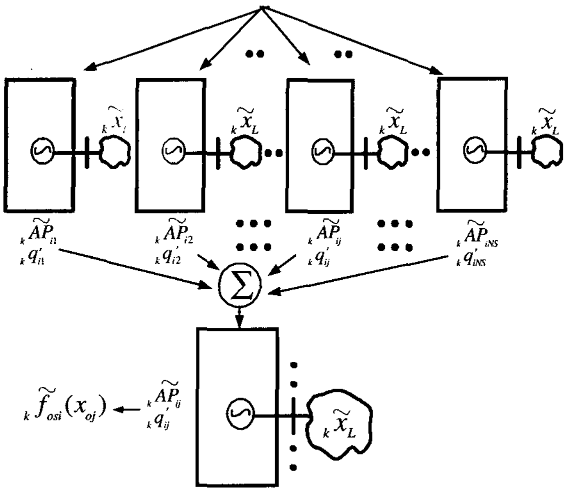
Fig. 1 System hierarchical level diagram.

2.2 Fuzzy Effective Load at HLII

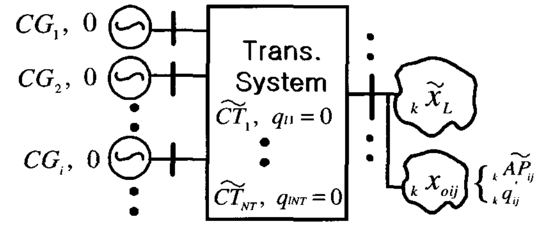
A new model for nodal fuzzy effective load at a load point of a composite power system considering the forced outage rates of the generation as well as transmission system facilities is proposed. Figure 2 presents the main concept of the equivalent system and the fuzzy effective load at HLII developed in this study. *CG*, *CT*, q and q_l in Figure 2 mean capacities and forced outage rates, respectively, of generators and transmission lines. It is a checkpoint that the capacity limitation of transmission lines is not crisp but ambiguous and fuzzy. Figure 2(a) is the original composite power system. Instead of the original generators, it is possible to consider the fuzzy arrival power($\tilde{AP}_{kj}$) supplied at a load point under fuzzy capacity limitation of transmission lines and the probability of the state(q_{kj}) for a system state *#j* as shown in Figure 2(b). This can be designated as a fictitious generator of fuzzy capacity $\tilde{AP}_{kj}$ and forced outage rate q'_{kj} at the load point. The fictitious generator system is equivalent to the equivalent system as in HLI. ${}_k\tilde{f}_{osi}$ in Figure 2(b) is the fuzzy outage capacity pdf of the synthesized fictitious generator operated by generators *#1* to *#i*. Fuzzy effective load at HLII is also defined by the summation of the fuzzy original load and the probabilistic load caused by the forced outage of generators and transmission lines. This can be formulated as shown in Eq. (1).



(a) Actual system



(b) Synthesized fictitious generator



(c)Equivalent system

Fig. 2 Actual and equivalent systems and nodal fuzzy effective load at HLII proposed in this study.

$$ {}_k\tilde{x}_e = {}_k\tilde{x}_L + \sum_{j=1}^{NS} {}_kx_{oj} \qquad (1) $$

where ${}_k\tilde{x}_e$: fuzzy random variable of the effective load on the composite power system at *# k* load point

${}_k\tilde{x}_L$: fuzzy random variable of the original load at *# k* load point

${}_kx_{oj}$: crisp random variable of the probabilistic load caused by the forced outage of generators and transmission lines at load point *# k*

j : number of system states occured at the load point

NS : total number of system states

After loading the generators from *#1* to *#i*, the fuzzy probability distribution function of CMELDC at load point *#k* can be calculated as shown in Eq. (2).

$$\begin{aligned} {}_k\tilde{\Phi}_i(x_e) &= {}_k\tilde{\Phi}_o(x_e) \otimes_k \tilde{f}_{osi}(x_{oi}) \\ &= \int {}_k\tilde{\Phi}_o(x_e - x_{oi})_k \tilde{f}_{osi}(x_{oi}) dx_{oi} \end{aligned} \qquad (2)$$

where $\otimes$: the operator meaning convolution integral

${}_k\tilde{\Phi}_o$ = fuzzy LDC at load point *#k*

${}_k\tilde{f}_{osi}$: fuzzy outage capacity pdf of synthesized fictitious generator created by generators from *#*1 to *#i* at load point *#k*

3. Nodal Fuzzy Probabilistic Reliability Evaluation and Production Cost Simulation

After loading generators from *#1* to *#i* according to the merit order or bidding order of the electricity market, the fuzzy reliability indices and the fuzzy CMELDC(${}_k\tilde{\Phi}_i(x)$) at the load point *#k* of the composite power system are obtained as shown in Figure 3.

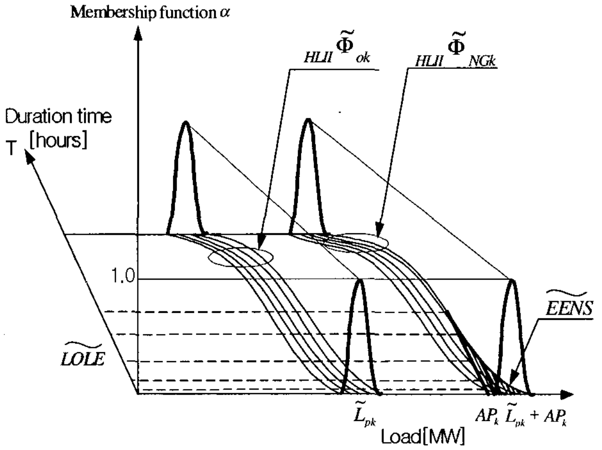


Fig. 3 Fuzzy reliability indices and fuzzy ELDC at load point *#k*.

In this Figure, $\tilde{L}_{pk}$ and $A\tilde{P}_{ik}$ on the horizontal axis express respectively, the fuzzy peak load and the fuzzy maximum arrival power at load point #k with generators from #1 to #i loaded according to the merit order or bidding order of electricity market.

The fuzzy maximum arrival power obtained from considering fuzzy capacity limitation of transmission lines is different from conventional maximum arrival power not considering overload of transmission lines. In this figure, the fuzzy reliability indices, Fuzzy Loss of Load Expectation ($FLOLE_{ik}$) and Fuzzy Expected Energy Not Supplied ($FEENS_{ik}$) can be calculated using Eq. (3) and Eq. (4) with ${}_k\tilde{\Phi}_i(x)$. It is important to note that $A\tilde{P}_{ik}$ has noncoherent characteristics and that the CMELDC can not be recursively obtained unlike that at HLI because of capacity limitations of the transmission system[8].

$$FLOLE_{ik} = {}_k\tilde{\Phi}_i(x)\Big|_{x=AP_{ik}} \quad \text{(hours)} \qquad (3)$$

$$FEENS_{ik} = \int_{A\tilde{P}_{ik}}^{A\tilde{P}_{ik}+\tilde{L}_{pk}} {}_k\tilde{\Phi}_i(x)dx \quad \text{(MWh)} \qquad (4)$$

The nodal fuzzy probabilistic production energy $\Delta\tilde{E}_i$ of a generator *#i* at the load point *#k* can be calculated as the difference between $FEENS_{i\text{-}1k}$ after loading the generator system without the generator and the $FEENS_{ik}$ after loading the generator system with the generator as in Eq.(5). The probabilistic production cost $\Delta P\tilde{C}_{ik}$ of generator *#i* at the load point *#k* can also be obtained as Eq.(6).

$$\Delta\tilde{E}_{ik} = FEENS_{i-1k} - FEENS_{ik} \qquad \text{(MWh)} \qquad (5)$$

$$\Delta P\tilde{C}_{ik} = F_i\ (\Delta\tilde{E}_{ik}, FLOLE_{i-1k}) \qquad (\$) \qquad (6)$$

where F_i : operating cost function of generator *#i* (\$/h)

4. Fuzzy and Probability Distribution Functions($\tilde{f}_{os}$) of the Synthesized Fictitious Generators

4.1 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 not practical 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.

$${}_kq_j = \begin{cases} \sum\limits_{\forall j \in e_j} [P(B_j)\, P_{lj}] & n(\bar{e}_j) \le 5 \\ 0 & n(\bar{e}_j) > 5 \end{cases} \qquad (7)$$

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*

4.2 Fuzzy Arrival Power Evaluation

Reliability indices of HLII can be obtained differently according to the objective function of the optimal power flow in order to evaluate the probability distribution function of the outage capacity of a fictitious generator at the load point[7,9,10]. 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 effective power only is considered as in the following Eqs.

4.2.1 Objective function

$$Minimize\ \{\max(\tilde{L}_{pk} - x_k)/\tilde{L}_{pk}\} \qquad k \in B_L \tag{8}$$

where $\tilde{L}_{pk}$: fuzzy peak load power at load point #*k*

B_L : set of loads buses

max : abbreviation of *maximum*

4.2.2 Constraints

(a) constraint of incident circuit

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

where B_B : set of generator buses

NB : total number of branches

CG_i : capacity of generator #*i* [MW]

a_{il} : bus - branch incidence matrix

(b) fuzzy constraint of transmission line capacity

$$-CT_{lmax} \lesssim x_l \lesssim CT_{lmax} \qquad l \in B_T \tag{10}$$

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

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

where B_T : set of transmission lines

The optimal solution of the problem can be obtained by an optimization algorithm. The linear shape of the membership functions is available for fuzzy linear programming because the fuzzy linear programming is originally linear programming. If the membership function $\mu_i(\mathbf{B(x)})$ has linear characteristics as in eq.(12), eq.(11) can be formulated as eq.(13) where $d^{(i)}$ means the permissible width of a i-th fuzzy constraint equation.

$$\mu_i(\mathbf{Bx}) = \left\{ \begin{array}{ll} 1 & (\mathbf{B(x)})_i \le b_i' \\ 1 - \{(\mathbf{B(x)})_i \le b_i'\}/d^{(i)} & b_i' < (\mathbf{B(x)})_i \le b_i' + d^{(i)} \\ 0 & b_i' + d^{(i)} < (\mathbf{B(x)})_i \end{array} \right\} \tag{12}$$

4.2.3 Equivalent Linear Programming

Eq.(11) can be formulated equivalently to conventional linear programming by introducing parameter λ as in Eq.(13) where γ^* are represents the aspiration level of the outage power rate at the load point(bus) which the maximum outage power rate shall be supposed.

$$\begin{aligned} & Maximize \quad \lambda \\ & Subject\ \ to \\ & \sum_{j=1} a_{ij} x_j \le CG_i \qquad i \in B_B \\ & x_l + d_l \lambda \le CT_l + d_l \qquad l \in B_T \\ & -x_l + d_l \lambda \le CT_l + d_l \qquad l \in B_T \\ & x_k + \tilde{L}_{pk} \gamma \ge \tilde{L}_{pk} \qquad k \in B_L \\ & \gamma + d_r \lambda \le \gamma^* + d_r \end{aligned} \tag{13}$$

Therefore, the $\tilde{AP}_{kj}$, fuzzy arrival power at load point #*k* as in Eq.(11) for a system state #*j* with the optimal solution x_k^* of Eq.(14) can be obtained.

$$\tilde{AP}_k = x_k^* \qquad k \in B_L \tag{14}$$

Therefore, the fuzzy probability distribution function($\tilde{f}_{os}$) of the outage capacity of a fictitious generator at the load point can be constructed and reliability indices of HLII can be obtained as in Eq.(3) and Eq.(4) using Eq.(2).

5. Membership Functions

5.1 Membership function of fuzzy load

The arbitrary shape of the membership functions is available for the fuzzy load because the operation of convolution permits nonlinear characteristics. In this study, piecewise nonlinear membership function as in Figure 4 has been applied.

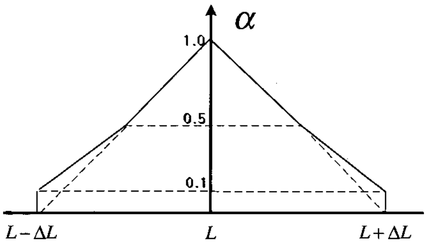


Fig. 4 Membership function of fuzzy load.

5.2 Membership function of fuzzy capacity of transmission line

The linear shape of the membership function is only available for the fuzzy capacity of transmission lines because AP_k can be calculated from equivalent linear programming Eq.(16). Therefore, the linear membership function as in Figure 5 can be accepted in this study.

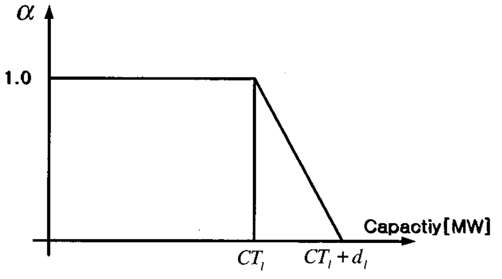


Fig. 5 Membership function of capacity of transmission line.

6. Example

This proposed new methodology for fuzzy reliability evaluation has been applied to a very simple system as shown in Fig. 6.

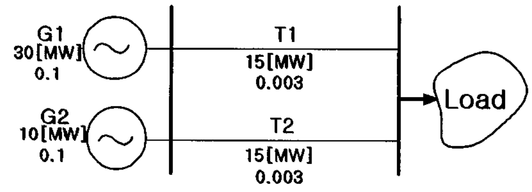


Fig. 6 Simple system for case study.

6.1 Case 1(Fuzzy Load)

A load duration curve has been assumed fuzzily as shown in Fig. 7 for case 1. Permission width of the membership function of the fuzzy load , ΔL is assumed as 5(MW) and 10(MW) for two cases in case study 1.

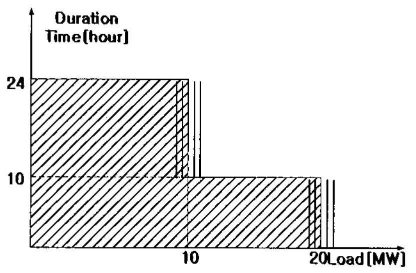


Fig. 7 Fuzzy load ($\tilde{\Phi}_{ok}$).

And so, the membership functions of the fuzzy load duration curve are shown in Fig. 8.

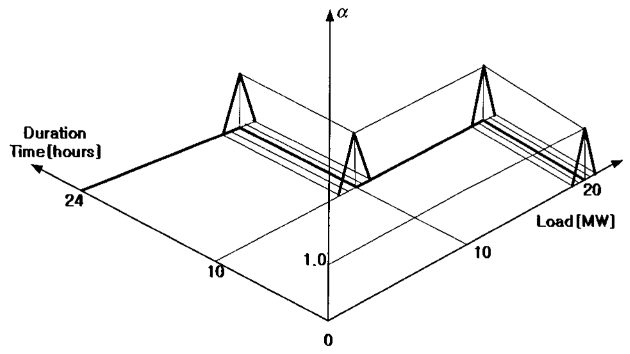


Fig. 8 Membership function of fuzzy load for case study.

Fuzzy CMELDC considering the fuzzy load has obtained a three-dimensional curve with a membership grade. Results of crisp and fuzzy load are shown in Table 2.

Table 2 Comparison of Results of Crisp and Fuzzy Loads of the Simple System (HLII)

	LOLE[hours/day]	EENS[MWh/day]
Crisp	1.19	12.67
Fuzzy L1 (ΔL=5(MW))	0.1/12.49 1.0/0.05	0.1/34.70 0.5/34.83 1.0/32.35
Fuzzy L2 (ΔL=10(MW))	0.1/0.13 0.5/12.49 1.0/0.05	0.1/62.65 0.5/71.10 1.0/6.47

6.2 Case 2(Fuzzy capacity of transmission lines)

For case 2, the membership function of the fuzzy capacity of transmission lines for this case study has been assumed as shown in Fig.9.

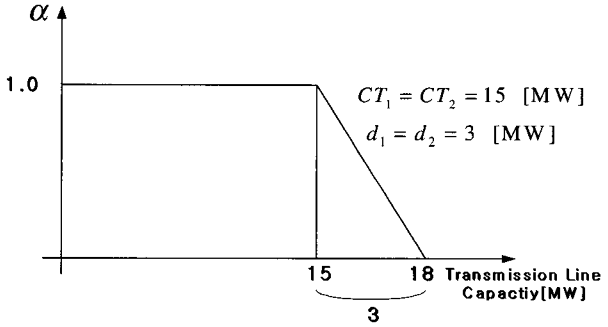


Fig. 9 Membership function of fuzzy capacity of transmission lines, T_1 and T_2.

The CMELDCs within the outage power area and the bulk reliability indices of crisp and three fuzzy capacity cases are shown in Fig. 10 and Table 3, respectively. As the permissible width of the membership function of the fuzzy capacity of the transmission lines increases, the bulk reliability indices decrease because of the flexibility of flows in lines.

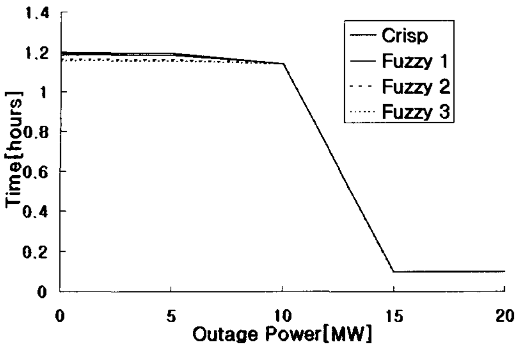


Fig. 10 CMELDCs of case studies.

Table 3 Comparison of Results of Crisp and Fuzzy Capacity of Transmission Lines (HLII)

	LOLE[hours/day]	**EENS[MWh/day]**
Crisp	1.19	12.67
Fuzzy T1 **(d_l=1(MW))**	1.1833	12.6183
Fuzzy T2 **(d_l =3(MW))**	1.1617	12.5106
Fuzzy T3 **(d_l =5(MW))**	1.1556	12.4799

(γ^*=0.0, d_r=0.1)

7. Conclusions

This paper illustrates the basic theory of a new nodal fuzzy effective load model for constructing a fuzzy effective load duration curve for probabilistic production cost simulation and reliability evaluation at the load point in a composite power system. The new fuzzy effective load model includes uncertainties of generators as well as transmission lines. This paper also proposes a fuzzy CMELDC based on the fuzzy effective load model at HLII. This technique will provide practical essential solutions for many problems based on the nodal and decentralized operation and control philosophy of electrical power systems under competitive electricity markets. The fuzzy CMELDC concept based on the new fuzzy effective load model at HLII will extend the various application research areas of nodal fuzzy probabilistic production cost simulation, outage cost assessment and reliability evaluation, etc. at load points. This basic concept of fuzzy CMELDC is only the first step and inquiry for more studies for real system application in the future.

Acknowledgement

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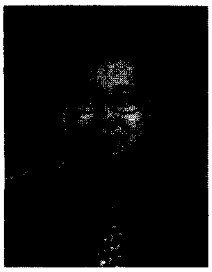

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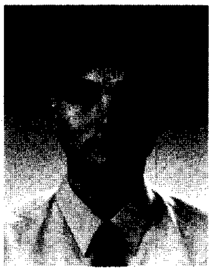

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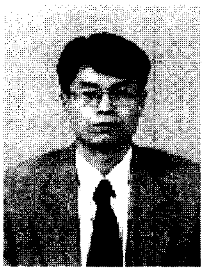

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