

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

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**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 transmission system using fuzzy set theory is proposed for considering the flexibility or ambiguity of capacity limitation and over load of transmission lines which is subjective matter characteristics. Conventional probabilistic approach was also used to model the uncertainties related with 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 over load 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 under competition environment in future. The characteristics of this new model are illustrated by some case studies of very simple test system.

**Index Terms--** Fuzzy effective load, fuzzy effective load duration curve, flexibility and ambiguity, over load of transmission lines, composite power system, integral convolution.

## I. INTRODUCTION

The effective load duration curve(ELDC) plays an important part in probabilistic production simulation and reliability evaluation for power power system planning as it supplies some very useful information [1,2]. This curve has been used widely since Baleriaux and Jamouille 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 effective load model of composite power system has been already 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 incomplete and insufficient historical D/B with related parameters. Specially, it is necessary to consider the constraint of over load of transmission lines for practical reliability evaluation of transmission system. It has subjective matter characteristics of not crisp but fuzzy because of the ambiguity of permissible limitation of the line capacity on operation. Fuzzy set theory is useful to represent information having a vague nature, to model related with the subjective matter or due to incomplete/insufficient data.

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

## II. MODELING OF NODAL FUZZY EFFECTIVE LOAD FOR COMPOSITE POWER SYSTEMS

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### A. 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 in this research is to develop a nodal fuzzy effective load model and Fuzzy CMELDC considering not only 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 over load 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).

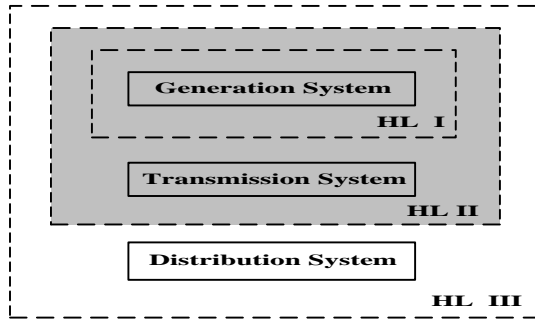


Fig. 1. System hierarchical level diagram.

### B. 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 the Figure 2 mean capacities and forced outage rates respectively of generators and transmission lines. It is checkpoint that the capacity limitation of transmission lines is not crisp but ambiguity 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( $\tilde{A}P_{kj}$ ) supplied at a load point under fuzzy capacity limitation of transmission lines and the probability of the state( $q_{kj}$ ) for system state  $\#j$  as shown as Figure 2(b). This can be designated as a fictitious generator of fuzzy capacity  $\tilde{A}P_{kj}$  and forced outage rate  $q'_{kj}$  at the load point. The fictitious generator system is equivalent to the equivalent system as in HLI.  $\tilde{f}_{osi}$  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).

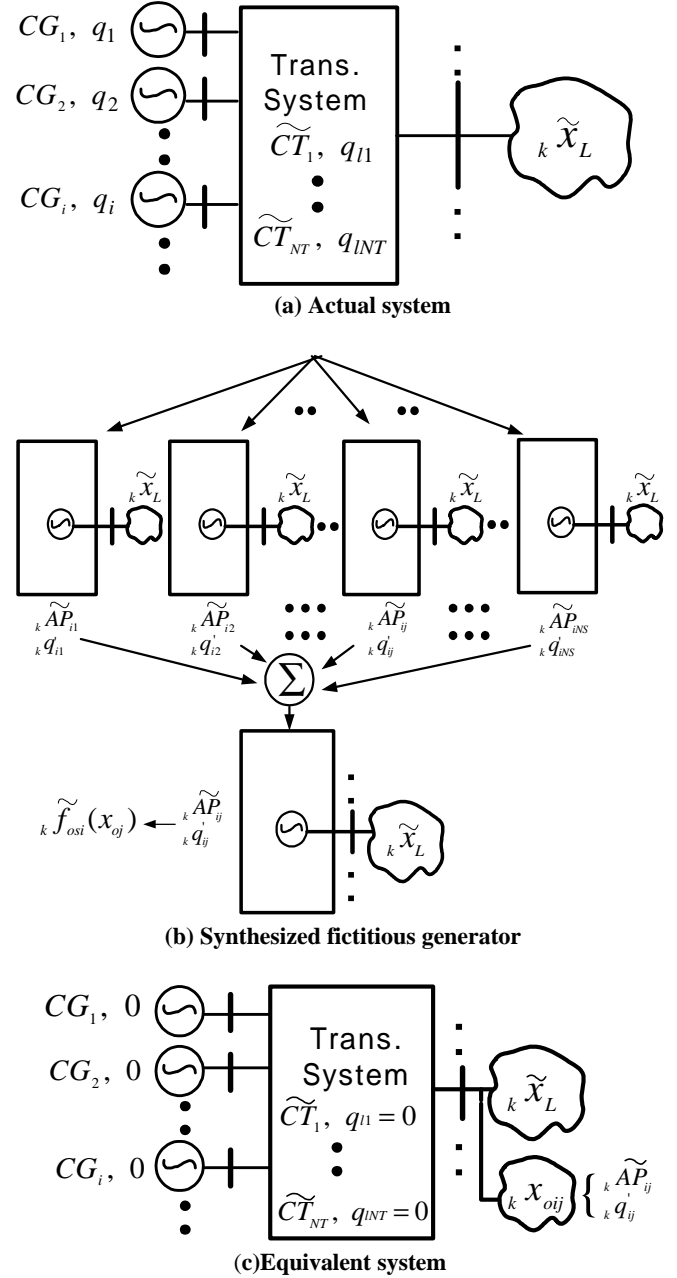


Fig. 2. Actual and equivalent systems and nodal fuzzy effective load at HLII proposed in this study.

$${}_k \tilde{X}_e = {}_k \tilde{X}_L + \sum_{j=1}^{NS} {}_k X_{oj} \quad (1)$$

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  
 ${}_k X_{oj}$ : 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 occurred 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).

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

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

${}_i\tilde{\Phi}_o$  = 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

### III. NODAL FUZZY PROBABILISTIC RELIABILITY EVALUATION AND PRODUCTION COST SIMULATION

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

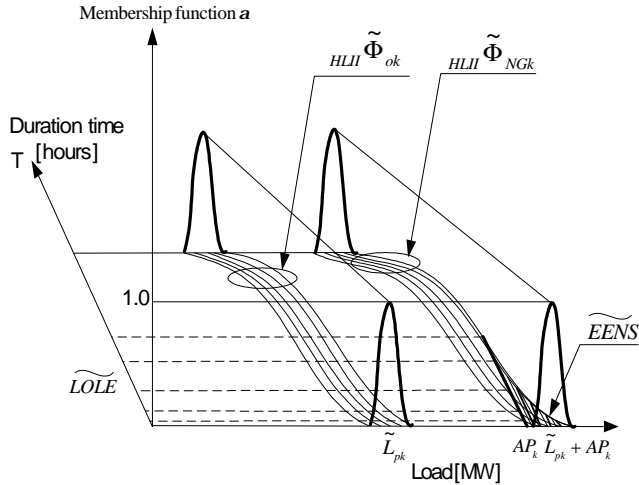


Fig. 3. Fuzzy reliability indices and fuzzy ELDC at load point #k.

In this Figure,  $\tilde{L}_{pk}$  and  $\tilde{AP}_{ik}$  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 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  $\tilde{AP}_{ik}$  has noncoherence characteristics and that the CMELDC can not be recursively obtained as unlike that at HLI because of capacity limitations of the transmission system[8].

$$FLOLE_{ik} = \int_{x=\tilde{AP}_{ik}} {}_k\tilde{\Phi}_i(x) dx \quad (\text{hours}) \quad (3)$$

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

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  $FEENS_{i-1k}$  after loading the generator system without the generator and the  $FEENS_{ik}$  after loading the generator system with the generator as Eq.(5). The probabilistic production cost  $\Delta P\tilde{C}_{ik}$  of generator #i at the load point #k can be also obtained as Eq.(6).

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

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

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

### IV. FUZZY AND PROBABILITY DISTRIBUTION FUNCTIONS ( $\tilde{f}_{os}$ ) OF THE SYNTHESIZED FICTITIOUS GENERATORS

#### 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 being failed 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.

$${}_k q_j = \begin{cases} \sum_{j \in \bar{e}_j} [P(B_j) P_{lj}] & n(\bar{e}_j) \leq 5 \\ 0 & n(\bar{e}_j) > 5 \end{cases} \quad (7)$$

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  $B_j$   
 $P_{lj}$ : loss of load time probability at state #j

#### Fuzzy Arrival Power Evaluation

Reliability indices of HLLI can be obtained differently

according to objective function of optimal power flow in order to evaluate probability distribution function of outage capacity of 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 under assuming that transmission line losses are ignored and effective power only is considered as following Eqs.

### 1) Objective function

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

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

$B_L$  : set of loads buses

$max$  : abbreviation of *maximum*

### 2) Constraints

(a) constraint of incident circuit

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

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

$$-CT_{lmax} \lesssim x_l \lesssim CT_{lmax} \quad l \in B_T \quad (10)$$

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 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).

*Minimize*  $\mathbf{g}$

*Subject to*

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

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  $\mathbf{m}(\mathbf{B}(\mathbf{x}))$  has linear characteristics as like as eq.(12), the eq.(11) can be formulated as eq.(13). Where, the  $d^{(i)}$  means the permissible width of a i-th fuzzy constraint equation.

$$\mathbf{m}(\mathbf{B}(\mathbf{x})) = \left\{ \begin{array}{ll} 1 & (\mathbf{B}(\mathbf{x}))_i \leq b'_i \\ 1 - \{(\mathbf{B}(\mathbf{x}))_i \leq b'_i\} / d^{(i)} & b'_i < (\mathbf{B}(\mathbf{x}))_i \leq b'_i + d^{(i)} \\ 0 & b'_i + d^{(i)} < (\mathbf{B}(\mathbf{x}))_i \end{array} \right\} \quad (12)$$

### Equivalent Linear Programming

The Eq.(11) can be formulated equivalently to conventional linear programming with introducing parameter  $\lambda$  as like as Eq.(13). Where,  $\gamma^*$  an presents aspiration level of the outage power rate at the load point(bus) which the maximum outage power rate shall be supposed.

$$\begin{aligned} &\text{Maximize} && \mathbf{I} \\ &\text{Subject to} && \\ &\sum_{j=1} a_{ij} x_j \leq CG_i && i \in B_B \\ &x_l + d_l \mathbf{I} \leq CT_l + d_l && l \in B_T \\ &-x_l + d_l \mathbf{I} \leq CT_l + d_l && l \in B_T \\ &x_k + \tilde{L}_{pk} \mathbf{g} \geq \tilde{L}_{pk} && k \in B_L \\ &\mathbf{g} + d_r \mathbf{I} \leq \mathbf{g}^* + d_r && \end{aligned} \quad (13)$$

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

$$A\tilde{P}_k = x_k^* \quad k \in B_L \quad (14)$$

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

## V. MEMBERSHIP FUNCTIONS

### A. Membership function of fuzzy load

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

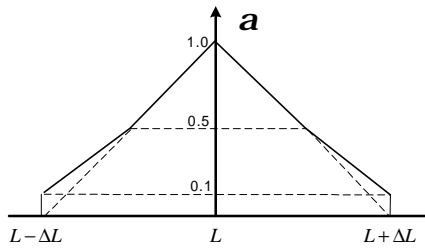


Fig. 4. Membership function of fuzzy load.

### B. Membership function of fuzzy capacity of transmission line

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

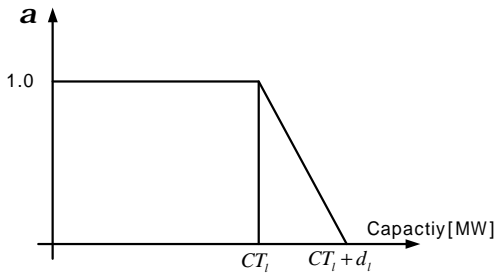


Fig. 5. Membership function of capacity of transmission line.

## VI. EXAMPLE

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

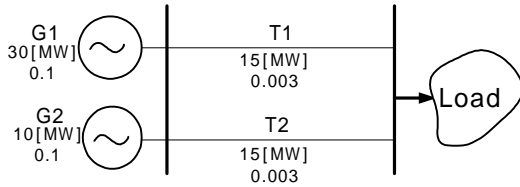
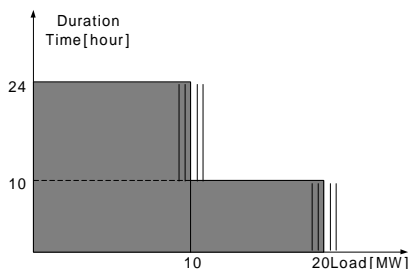


Fig. 6. Simple system for case study.

### A. Case 1(Fuzzy Load)

Load duration curve has been assumed fuzzily as shown in Figure 7 for case 1. Permission width of membership function of fuzzy load,  $\Delta L$  is assumed as 5(MW) and 10(MW) for two cases in case 1 study.

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

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

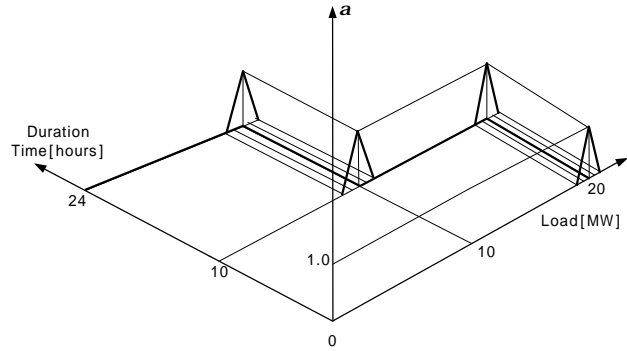


Fig. 8. Membership function of fuzzy load for case study.

Fuzzy CMELDC considering fuzzy load has been obtained three dimensional curve with membership grade. Results of crisp and fuzzy load is 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]
<b>Crisp</b>	1.19	12.67
<b>Fuzzy L1 (DL=5(MW))</b>	0.1/12.49 1.0/0.05	0.1/34.70 0.5/34.83 1.0/32.35
<b>Fuzzy L2 (DL=10(MW))</b>	0.1/0.13 0.5/12.49 1.0/0.05	0.1/62.65 0.5/71.10 1.0/6.47

### B. Case 2(Fuzzy capacity of transmission lines)

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

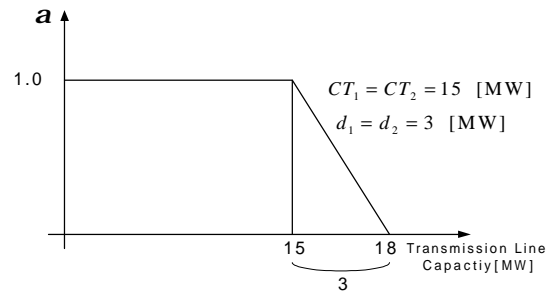


Fig. 9. Membership function of fuzzy capacity of transmission lines, T1 and T2.

The CMELDCs within 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 permission width of membership function of fuzzy capacity of transmission lines increases, the bulk reliability indices decrease because of the flexibility of flows in lines.

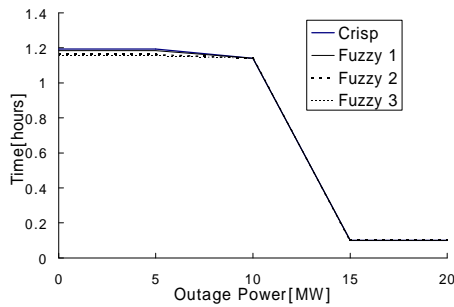


Fig. 10. CMELDCs of case studies.

TABLE 3  
COMPARISON OF RESULTS OF CRISP AND FUZZY CAPACITY OF  
TRANSMISSION LINES (HLII)

	LOLE[hours/day]	EENS[MWh/day]
<b>Crisp</b>	1.19	12.67
<b>Fuzzy T1</b> ( $d_i=1(\text{MW})$ )	1.1833	12.6183
<b>Fuzzy T2</b> ( $d_i=3(\text{MW})$ )	1.1617	12.5106
<b>Fuzzy T3</b> ( $d_i=5(\text{MW})$ )	1.1556	12.4799

$$(\gamma^*=0.0, d_r=0.1)$$

## VII. CONCLUSIONS

This paper illustrates 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 nodal and decentralized operation and control philosophy of electrical power systems under competition electricity market. 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 first step and inquire for the more studies for real system application in future.

## VIII. ACKNOWLEDGEMENT

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## X. BIOGRAPHIES

**Jaeseok Choi**(M'88) was born at Kyeongju, Korea in 1958. Obtained B.Sc., M.Sc. and Ph.D. degrees from Korea University in 1981, 1984 and 1990 respectively. His research interest includes Expansion Planning, Probabilistic Production Cost Simulation, Reliability Evaluation Outage Cost Assessment and Fuzzy Applications, of Power Systems. He has been a Post-Doctor at University of Saskatchewan in Canada on 1996. Since 1991, he has been a faculty of Gyeongsang National University where is now an Associate Professor.

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