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FUZZY LOADS WITH DEMAND SIDE CONTINGENCY MANAGEMENT FOR RELIABILITY ASSESSMENT OF RESTRUCTURED POWER SYSTEMS

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ABSTRACT

This paper introduces fuzzy elements in loads in the reliability evaluation of hybrid power markets. The resultant reliability indices provide useful information about the range of variation of the indices due to an unpredictable, or a fuzzy, variation of load. The change in reserve management due to system restructuring is introduced in the reliability evaluation technique by using supply and demand side contingency management model. A non-sequential Monte Carlo simulation technique based on this framework has been proposed to evaluate the customer reliability of restructured power systems with the hybrid market model. The modified IEEE Reliability Test System (RTS) is used to illustrate the proposed technique. This approach provides a useful tool for the ISO to study the impact of load uncertainties and market transactions on customer reliability indices.

KEY WORDS

Customer Reliability, Contingency Management, Monte Carlo Simulation, Reserve, Load Curtailment bids.

Nomenclature

h index for Genco
k index for customer
v index for generating units
i index for sampling state
j index for system contingency state
m number of Gencos
p number of customers
x number of units in Genco to supply energy
y number of units in Genco to provide reserve
s index for spot market (superscript)
b index for bilateral contract (superscript)
g index for generator (superscript)
d index for customer (superscript)
N number of Monte Carlo samples

For unit v, Genco h and customer k
P_{hv} Capacity of the unit
P_h Total generation scheduled by Genco
R_{hv} Capacity of reserve unit
T_h^{gs} Power sold by Genco in the spot market
T_k^{ds} Power purchased by customer in the spot market
T_{hk}^{b} Power sold through bilateral contract
T_h^{g} Total power sold by Genco
T_k^{d} Total power purchased by customer
ρ_{hv} Reserve bid price
ORR_{hv} Outage replacement rate
λ_{hv} Failure rate
θ_{hk}^{b} willingness to curtail bilateral transaction
θ_{k}^{ds} willingness to curtail spot transaction
ϑ curtailment cost for every MW load curtailed

For sample i
S_{hvi} Sampling state of unit
S_{hi} Sampling state of Genco
P_{hi}^{avl} Available capacity of energy units of genco
R_{hvi}^{avl} Available capacity of reserve unit

For contingency state j
R_{hvj} Reserve dispatched
C_{kj}^{ds} Load curtailed for customer in the spot market
C_{hkj}^{b} Load curtailed for bilateral customer
$EENS_k^d$ EENS of customer k
ERD Expected reserve dispatch

1. Introduction

Restructuring of Power Systems has given an opportunity for the generators and customers to trade electricity and reserve based on their price, reliability offers and reliability requirements. Generators and customers can trade for power in either spot or bilateral markets. The choice of bilateral and spot market trading of the Generators and customers depends on their willingness to take risk. Risk-averse players will chose bilateral contracts as the prices are stable for a long-term. Risk prone players will trade in the spot market with half hourly fluctuating prices. In restructured power systems both Generators and customers participate in reliability management. In order to maintain system reliability, reserve offers are procured from both the generators and customers. Generators provide their reserve generation capacity and are paid the reserve price when their reserves are utilized during contingency states. Similarly customers can offer Interruptible loads for system reliability by participating in Interruptible load programs[1]as in Singapore, NYISO, Alberta power pool in Canada and demand relief program in California that give financial incentives to the customers for reducing their demand. Customers express their willingness to curtail their load based on their ability to change their load profile. In case of contingency, if the customers are willing to curtail their load then ISO will activate the customers' curtailment and pay the load curtailment price fixed by the ISO. Reserve provisions from both supply side and demand side [1, 2] has changed the mechanism of reliability management.

Reliability evaluation techniques are mostly based on probabilistic theory. The two main probabilistic techniques are the analytical techniques and Monte Carlo simulation techniques [3,4]. Reliability indices obtained by these techniques are expected single point values. In practical real life, input data for reliability assessment such as forced outage rate (FOR) of generators, load forecasted etc are uncertain in nature. Therefore reliability indices contain uncertainty due to lack of sufficient or accurate data. In [5] a fuzzy based analytical reliability evaluation technique is proposed to deal with uncertainties in load data, generator failure and repair rate data. In [6] Fuzzy arithmetic operations and Fuzzy clustering algorithm based analytical reliability evaluation technique, is proposed to manage the uncertainty in reliability input data. In [7] a Monte Carlo Simulation based reliability evaluation technique considering fuzzy loads is presented. In [8] fuzzy theory is used to find the fuzzy Forced Outage Rate of generators. In [9] fuzzy logic based method is proposed to calculate the reliability indices by considering uncertainties in FOR and forecasted load.

Reliability evaluation techniques for conventional systems are well developed and widely in use. In conventional power systems customers and generators do not trade electricity and reserve based on their price, reliability offers and reliability requirements. The techniques developed for conventional power systems as in [3-4] cannot be directly used for restructured power systems [10]. In [11] a framework to implement supply and demand side contingency management in the reliability assessment of hybrid power markets is presented. This model enables the Independent System Operator (ISO) to coordinate reserve and load curtailment bids for contingency states to balance reliability worth and reliability cost. The spot market, bilateral and reserve transactions are considered in [11]. However uncertainties in reliability input data is not handled in [11]. In [5-9] uncertainties are handled but are developed for conventional systems.

The technique developed for restructured power systems in [11] has been extended and improved so that it can handle the uncertainty in forecasted load data. In this paper a combined Fuzzy and probabilistic load model is incorporated with the supply and demand side contingency management model for the reliability assessment of hybrid power markets. The reserve generators bid their price and quantity. Customers express their willingness to curtail and are paid a fixed load curtailment price announced by the ISO. In case of contingency the ISO clears the reserve and load curtailment bids based on reserve price and the combination of customers' willingness to curtail and load curtailment price fixed by ISO. The load curtailments and generation re-dispatch for a contingency state are determined based on minimizing the market interruption cost using the optimization technique. A non-sequential Monte Carlo simulation technique based on this framework has been proposed to evaluate the customer reliability of restructured power systems with the hybrid market model. Market model and contingency management are described in Section III. In Section IV, Fuzzy and probabilistic load model is described. The proposed Monte Carlo simulation based reliability evaluation technique is discussed in Section V. In Section VI, the modified IEEE Reliability Test System (RTS) is used to illustrate the proposed technique. This approach provides a useful tool for the ISO to study the impact of load uncertainties and market transactions on customer reliability indices.

2. Market Transactions and Contingency Management

A hybrid market consisting of m Gencos and p customers with spot, bilateral and ancillary services (AS) market for reserve and load curtailment bidding is considered as in reference [11].

The total power sold by Genco *h* through the spot market and bilateral contracts is:

$$T_h^g = T_h^{gs} + \sum_{k=1}^{p} T_{hk}^b \tag{1}$$

A Genco will schedule its units to meet the aggregated spot and bilateral demand T_h^g. The total power supplied by Genco h with x scheduled units to meet the spot and bilateral demand is:

$$P_h = \sum_{v=1}^{x} P_{hv} = T_h^g \tag{2}$$

The total power purchased by customer *k* from the hybrid market is:

$$T_k^d = T_k^{ds} + \sum_{h=1}^{m} T_{hk}^b \tag{3}$$

The total reserve in AS market is equal to the sum of all the scheduled reserve units.

Customers express their willingness to curtail their bilateral load θ_{hk}^{b} and spot market load θ_k^{ds} on a scale of 1 to 6 where 1 denotes more willingness to curtail and 6 denotes less willingness to curtail. A flat rate of ϑ is the curtailment cost for every MW load curtailed. In cases of contingency when the customers are called to interrupt they are paid based on the curtailment cost and the load curtailed.

After the market settlement, the total number of units scheduled for providing energy and reserves from each Genco, the associated reliability data and installed capacity for each unit, and the load curtailment cost data from customers are provided to the ISO for contingency management of the system as in reference [11].

The contingency management problem by the ISO is formulated as an optimal DC power flow problem with an objective to minimize the total cost which includes the curtailment costs of bilateral customers, the curtailment costs of the spot market customers and the cost of the reserve dispatched.

The objective function is to

$$Min\left(\begin{array}{c}\sum_{k=1}^{p}\sum_{h=1}^{m} C_{hkj}^{b} \times \vartheta \times \theta_{hk}^{b} + \sum_{k=1}^{p} C_{kj}^{ds} \times \vartheta \times \theta_{k}^{ds} \\ + \sum_{h=1}^{m}\sum_{v=1}^{y} R_{hvj} \times \rho_{hv}\end{array}\right) \tag{4}$$

Subject to the power balance constraints, reserve constraint of the spot market**,** the curtailment limits for the bilateral transactions, the curtailment limits for Gencos in the spot market, the curtailment limits for the customers in the spot market, the limits for the available generation from the Gencos, the limits for reserve and the transmission limits as described in [11]. The contingency state transactions are determined by subtracting the curtailments from the original transactions.

3. Load Modeling

The load at a dispatch hour used in reliability assessment is usually a single value obtained from historical data. The hourly load is obtained as a percentage of the peak load. There are many uncertainties such as weather, different load components, change in customers consumption etc which are usually not incorporated while load forecasting. In order to incorporate the uncertainties in load forecasting the peak load is modeled as fuzzy sets.

3.1 Fuzzy peak load model

Fuzzy peak load set L_{pk} in the universe of W is defined as a set of ordered pairs of peak load l_{pk} and its membership function value $\mu(l_{pk})$

$$L_{pk} = \{\, (l_{pk}, \mu(l_{pk})) \mid l_{pk} \in W \} \tag{5}$$

The peak load $l_{pk}$is forecasted by the most probable peak load l_{mp} and its upper bounds $l_{up}$and lower boundsl_{lp} and hence it can be modeled as a triangular membership function [9]. The membership function is described as

$$\mu(l_{pk}) = \begin{cases} 0, l_{pk} \le l_{lp} \\ \frac{l_{pk} - l_{lp}}{l_{mp} - l_{lp}}, l_{lp} \le l_{pk} \le l_{mp} \\ \frac{l_{up} - l_{pk}}{l_{up} - l_{mp}}, l_{mp} \le l_{pk} \le l_{up} \\ 0, l_{up} \le l_{pk} \end{cases} \tag{6}$$

In equation 6, it can be seen that the membership value is 1.0 to forecast the peak load l_{pk} as the most probable peak load l_{mp} and the membership value is 0.0 to forecast the peak load l_{pk} beyond the upper bound $l_{up}$and lower boundl_{lp}.

3.2 Probabilistic load model

The annual/monthly/daily load curve is the load levels at different time points. Reliability evaluation for large number of load points increases the computation time. In order to reduce the computation time the annual/monthly/daily load curve is represented by probabilistic load model [4, 12]. In the discrete probabilistic load model [4] the load curve is represented by n number of l_a load levels and their corresponding probabilities φ_a.

$$\varphi(l_a) = \varphi_a \qquad \forall a = 1, \dots, n \tag{7}$$

where each load level l_a is a percentage,$l_{a\%}$, of the peak load l_{pk}.

$$l_a = l_{ak} \times l_{pk} \quad (8)$$

The load level l_a is the total power bought by customers from the market. In restructured power systems the market transactions can be different for the same load level. For simplicity it is assumed that the market transactions are same for a particular load level.

4. Reliability Evaluation Methodology

A state enumeration technique that incorporates the fuzzy and probabilistic load model in the reliability evaluation of restructured power systems with hybrid market model is developed. A two-state model of generating units is used in the simulation. Exponentially distributed times to failure are assumed for each unit, and the outage replacement rate (ORR) [3] is used.

The procedure to incorporate fuzzy and probabilistic load model in reliability evaluation is as follows:

Step 1: Input transactions, reserve and curtailment bids, forecasted load and reliability data determined from the hybrid market.

Step 2: Select from the fuzzy peak load set L_{pk}, the ordered pair (l_{pk}, $\mu(l_{pk})$)

Step 3: Initialize $a - 1$.

Step 4: Select from the probabilistic load model (l_a, φ_a).

Step 5: Initialize the index for sampling state $i = 1$.

Step 6: Generate the sample state of all the units scheduled in the market by using

$$S_{hvi} = \begin{cases} 1 & (Operating\ state) \quad if \quad U_{hvi} \geq ORR_{hv} \\ 0 & (Failure\ state) \quad if \quad 0 \leq U_{hvi} < ORR_{hv} \end{cases} \quad (9)$$

U_{hvi} is a uniformly distributed random number between zero and one and is generated for each unit scheduled in the energy and reserve market to determine the state of the unit.

Step 7: Determine the state of Genco h with x +y units based on the state of each unit of the Genco by using

$$S_{hi} = (S_{h1i}, \ldots, S_{hvi}, \ldots S_{hxi}, \ldots, S_{h(x+y)i}) \quad (10)$$

Step 8: Determine available generation from Genco h, P_{hi}^{avl} by using

$$P_{hi}^{avl} = \sum_{v=1}^{x} P_{hv} \times S_{hvi} \quad (11)$$

Step 9: Determine the available reserve from each unit in the primary reserve market, R_{hvi}^{avl} by using

$$R_{hvi}^{avl} = R_{hv} \times S_{h(v+x)i} \quad (12)$$

Step 10: Check the state of the gencos and transmission lines to determine system state. If $P_{hi}^{avl} = T_h^g$ for sample *i* and there are no transmission outages, then the system is in normal state and all curtailments are equal to zero. Go to step 12. If $P_{hi}^{avl} < T_h^g$, for sample *i*, or if there is transmission congestion the system is in contingency state *j*. Go to step 11. If sample *i* results in a contingency state *j* then all the symbols with subscript *i* are represented by subscript *j*.

Step 11: Determine C_{ki}^{ds}, C_{hki}^{b}, C_{hi}^{gs} and R_{hvi} using the optimization technique for the contingency state.

Step 12: Set $i = i + 1$, if $i < N$ go to step 6 else go to step 12.

Step 13: Calculate the expected load not supplied (ELNS) for customer k by using

$$ELNS_k^d(l_a) = \frac{1}{N} \times \sum_{i=1}^{N} \left[C_{ki}^{ds} + \sum_{h=1}^{m} C_{hki}^{b} \right] \quad k=1,\ldots..p \quad (13)$$

Step 14: Calculate the expected reserve dispatched (ERD) from the reserve market by using

$$ERD(l_a) = \frac{1}{N} \times \sum_{i=1}^{N} \left[\sum_{h=1}^{m} \sum_{v=1}^{y} R_{hvi} \right] \quad (14)$$

Step 15: Set $a = a + 1$, if $a < n$ go to step 4 else go to step 16.

Step 16: Calculate ELNS of the customers by using

$$ELNS_k^d(l_{pk}, \mu(l_{pk})) = \sum_{a=1}^{n} ELNS_k^d(l_a) \times \varphi_a \quad (15)$$

Step 17: Calculate the expected reserve dispatch by using

$$ERD_k^d(l_{pk}, \mu(L_{pk})) = \sum_{a=1}^{n} ERD_k^d(l_a) \times \varphi_a \quad (16)$$

Step 18: If all the ordered pairs of fuzzy peak load set L_{pk} are considered obtain the membership function of all the customers $ELNS$ and ERD. Else go to step 2.

5. System Analysis

The IEEE reliability test system (RTS) was analyzed to illustrate the proposed technique. The single line diagram of the test system and the system configuration data are given in [3,4]. The modified failure rate data of the generating units is given in Table A.1 of the Appendix. The test system is modified into a restructured power system with three Gencos (G1, G2 and G3) and four bulk customers (D1, D2, D3 and D4). The generators at buses 1, 2 and 7 belong to G1, generators at buses 13, 15, 16 & 23 belong to G2 and generators at buses 18, 21 and 22 belong to G3. The load at buses 1 to 6 is D1, at buses 7 to 10 is D2, at buses 13 to 15 is D3 and at buses 16 and 18 to 20 is D4.

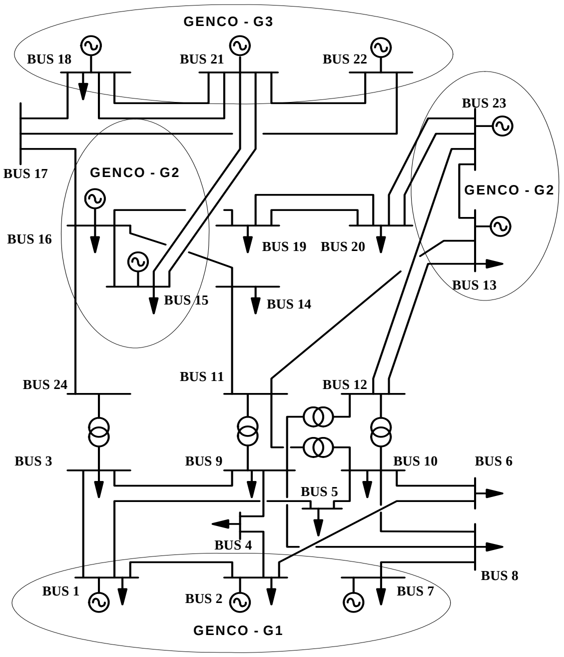

Fig. 1. IEEE RTS Test System.

Two sets of peak load transactions (Set 1 and Set 2) are given in Tables A.2 and A.3 respectively of the Appendix. The time varying market transactions for each hour of the day are taken as a percentage of the peak load transactions. The second day of week 51 of the IEEE load model is considered as a typical day of a hybrid market for the study. The curtailment bids submitted by the customers and the reserve market price are shown in Table A.4.The unit commitment for the day is shown in Table A.5. The reserve units are the 76-MW unit of G1, 155-MW unit of G2 and 50-MW unit of G3. The lead-time is assumed to be 4 hours and the market transactions are assumed to be as in Set 1.

5.1 Evaluation of customer reliability indices with crisp hourly loads

The customer reliability indices and the expected reserve dispatch for different hours of the day using crisp load values are presented in Table 1. The solutions converge after 2500 Monte Carlo samples.

Table 1. ELNS and ERD with Hourly Load Model

	ELNS (MW)				
Hour	D1	D2	D3	D4	ERD (MW)
1	8.6905	3.7273	0.0182	0.0000	49.5260
3	8.1131	3.7972	0.0419	0.0000	43.0310
5	8.4639	3.9686	0.1975	0.0183	45.1010
7	10.3331	2.1884	0.0481	0.0000	57.8731
9	17.6080	0.4810	0.2144	0.0000	73.6690
11	18.3280	0.0922	0.0444	0.0000	75.6720
15	17.2790	0.3754	0.1265	0.0000	74.7930
17	21.6330	0.4102	0.2065	0.0091	79.3850
18	20.9610	0.3216	0.1008	0.0000	78.2210
21	15.8540	0.4782	0.0918	0.0019	69.3560
22	14.0220	1.0224	0.0761	0.0000	66.6920
23	9.2184	2.2311	0.0196	0.0000	55.5250
24	7.4892	3.6316	0.1686	0.0000	46.3100

5.2 Evaluation of customer reliability indices with probabilistic load

In order to reduce the computational time instead of an hourly load model a discrete probabilistic load model is employed in reliability evaluation. Reliability indices for the discrete probabilistic load model of Table A.6 with peak load of 2650.5 MW are given in Table2.

Table 2. ELNS and ERD with Probabilistic Load Model

	ELNS (MW)				ERD
Peak load	D1	D2	D3	D4	(MW)
2650.5	11.2464	2.0486	0.0529	0.0001	59.3029

5.3 Evaluation of customer reliability indices with combined probabilistic and fuzzy load

The most probable forecasted peak load for a typical hour is taken as 2650.5 MW with the lower bound at 2365.5 MW and higher bound at 2850 MW.

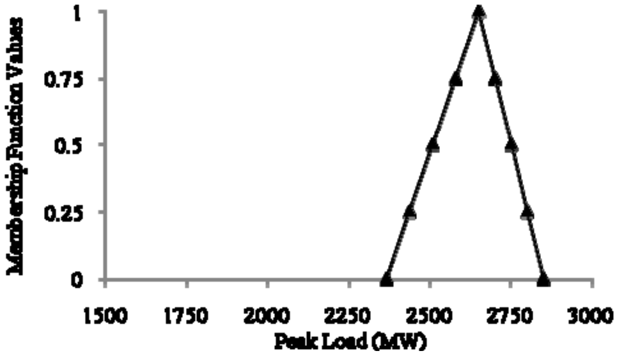

Fig. 2. Fuzzy load model

The forecasted load is used to build the fuzzy load model for the peak load as in Figure 2, in which the most probable peak load is 2650.5 MW with the membership value of 1.0 and the lower and upper bounds are 2365.5 and 2850 MW, respectively, with a membership value of zero.

The combined discrete probabilistic load model of Table A.6 and Fuzzy load model of Figure 2 is used for the study. The Expected reserve dispatch corresponding to the five membership values of 0, 0.25, 0.5, 0.75 and 1.0 is obtained using the proposed method and is shown in Figure 3.

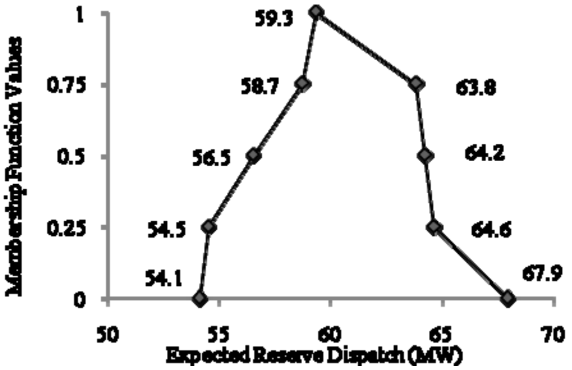

Fig. 3. Membership Function of Expected Reserve Dispatch

The ELNS of customers using combined fuzzy and probabilistic load is shown in Figure 4. The ELNS of customers with fixed peak load can be obtained by α cut values. The 1.0 α cut value of the fuzzy ELNS represents the ELNS of customers with no uncertainty in peak load. The 0.0 α cut value of the fuzzy ELNS represents the ELNS of customers for higher and lower bound peak loads. The advantage of this method is that it can show the range of all possible ELNS values under peak load uncertainties.

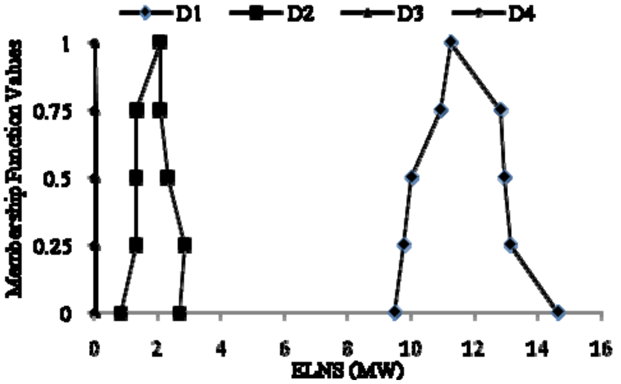

Fig. 4. Membership Function of the ELNS of customers

The ELNS of customer D1 in spot market and in bilateral contracts market using the proposed technique is shown in Figure 5. The uncertainty range for different transactions is different.

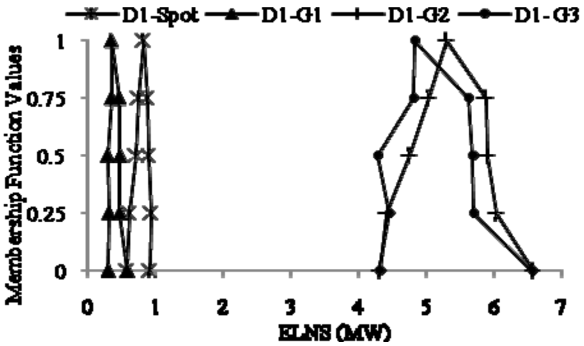

Fig. 5. Membership Function of the ELNS of D1

5.4 Influence of transactions on customer reliability indices

The ELNS of D1 for Set1 and Set2 market transactions are presented in Table 3. The results in Table 3 are for the discrete probabilistic load model of Table A.6 with peak load of 2650.5 MW. The mix of spot market and bilateral contracts are different for both the Sets but the total demand and supply quantities of the individual customers and Gencos are the same. The interruption cost data and unit commitment schedule are shown in Table A.4 and A.5 respectively for both the market transaction Sets.

The ELNS for a customer also depends on the quantities it negotiates with different Gencos. The ELNS for D1 in Set 1 is lower than that in Set 2. This is because the quantity bought by D1 from G2 is more in Set1 than in Set 2, and from G3 is less in Set1 than in Set2. The reliability provided by G2 is better than that provided by G3. The reliability performance of G2 and G3 can be explained by an example. In Set 2 D1 has bought 200 MW from G2 and G3. The reliability index for D1 is higher for the bilateral contract with G3 than with G2.

Table 3. ELNS (MW) of D1

Transactions	D1	D1-Spot	D1-G1	D1-G2	D1-G3
Set 1	11.246	0.802	0.334	5.281	4.828
Set 2	12.428	0.821	1.619	4.233	5.755

The Membership function of ELNS of D1 for Set1 and Set2 market transactions were obtained using the proposed method and are presented in Figure 6. It can be observed from the graph that ELNS index for Set 1 has a larger uncertainty range than Set2. The percentage ratio of ELNS of D1 at lower bound peak load and upper bound peak load with respect to the ELNS of D1 at most probable peak load are calculated. The uncertainty range for set 1 is 84.1% to 129.9%. The uncertainty range for set 2 is 96.3% to 118.2%.

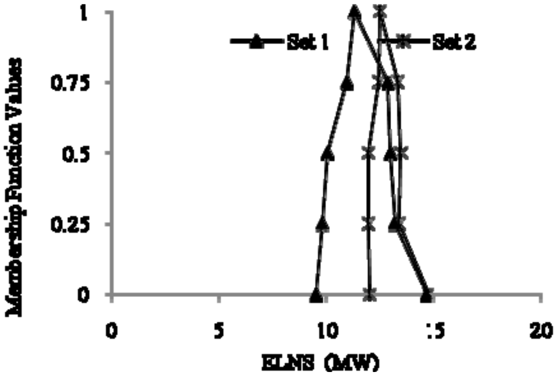

Fig. 6. Membership Function of the ELNS of D1

6. Conclusion

This paper presents a non sequential Monte Carlo simulation based reliability evaluation technique for reliability assessment of restructured power systems with hybrid market model. In this technique Fuzzy load model is incorporated with the supply and demand side contingency management model to obtain fuzzy reliability indices. The changes brought about by restructuring of power systems in reliability management is handled by the supply and demand side contingency management model. The uncertainties in load forecasting are handled by the fuzzy load model. The reliability indices obtained by this technique are fuzzy numbers and provides better information regarding the uncertainties of customer reliability indices. In case of multiple generator and transmission outages the computational effort for Monte Carlo technique is less, as opposed to analytical technique. Therefore this approach provides a useful tool for the ISO to study the impact of load uncertainties and market transactions on customer reliability indices. The modified IEEE Reliability Test System (RTS) is used to illustrate the proposed technique.

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Appendix

Table A.1 Failure Rate of the Generating Units

Unit size (MW)	Failure rate (f/hr)	Unit size (MW)	Failure rate (f/hr)
12	0.0034	155	0.01042
20	0.0222	197	0.01053
50	0.00505	350	0.0087
76	0.0051	400	0.00909
100	0.00833		

Table A.2 Transactions (MW) in a hybrid market – Set 1

Set1	D1	D2	D3	D4	spot
G1	75	50	75	100	200
G2	225	150	200	267	466
G3	166	200	151	225	300
spot	200	266	350	150	

Table A.3 Transactions (MW) in a hybrid market – Set 2

Set2	D1	D2	D3	D4	spot
G1	100	100	100	100	100
G2	200	100	200	142	666
G3	200	166	176	100	400
spot	166	300	300	400	

Table A.4 Interruption Cost Data in a Hybrid Market

Curtailment cost & Willingness to curtail & Reserve Price					
Curtailment cost ($/Mwh)	D1	D2	D3	D4	Reserve ($/Mwh)
100	3	4	5	6	200

Table A.5 Unit Commitment Schedule for the Hybrid Market

Unit Rating	Time Periods (1-24 Hours)
Genco 1	
76	111111111111111111111111
76	111111111111111111111111
76	111111111111111111111111
100	1**11111**11111111111111111**1**
100	**1**00000**1**11111111111111**11**0
100	0000000**11111111111111**000
20	000000000000000000000000
20	000000000000000000000000
20	000000000000000000000000
20	000000000000000000000000
Genco2	
350	111111111111111111111111
155	111111111111111111111111
155	111111111111111111111111
155	11**1111**111111111111111111
197	**11**0000**1**111111111111111**11**
197	0000000**1**111111111111**11**00
197	00000000**111111111111**0000
12	000000000000000000000000
12	000000000000000000000000
12	000000000000000000000000
12	000000000000000000000000
12	000000000000000000000000
Genco3	
50	111111111111111111111111
50	111111111111111111111111
50	111111111111111111111111
50	111111111111111111111111
50	111111111111111111111111
400	11**1111**111111111111111111
400	**11**0000**111111111111111111**

Table A.6 Probability Distribution of the Load

% of peak load	Probability
1	0.00777
0.95	0.08002
0.9	0.17648
0.85	0.34955
0.8	0.2452
0.75	0.14098

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