Generation Reliability Assessment in Power Market Using Fuzzy Logic and Monte Carlo Simulation

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Abstract—Deregulation policy has caused some changes in the concepts of power systems reliability assessment and enhancement. In this paper, generation reliability is considered, and a method for its assessment using fuzzy logic is proposed. Monte Carlo Simulation is used for reliability evaluation. Since generation reliability, merely focuses on interaction between generation complex and load, therefore in this paper, transmission and distribution systems are considered reliable. In this research, based on market type and its concentration, a fuzzy logic is proposed for modeling the market which is valid for all kinds of power pool markets. The proposed method is assessed on IEEE-Reliability Test System with satisfactory results. In all case studies, generation reliability indices are evaluated with different reserve margins and various load levels.

Index Terms—Power market - Fuzzy logic - Power generation reliability - Monte Carlo methods.

I. INTRODUCTION

Power systems have evolved over decades. Their primary emphasis has been on providing a reliable and economic supply of electrical energy to their customers [1]. A real power system is complex, highly integrated and almost very large. It can be divided into appropriate subsystems or functional zones that can be analyzed separately [2]. This paper deals with generation reliability assessment (Hierarchical Level I-HLI) in power pool market, and transmission and distribution systems are considered reliable and adequate as shown in Fig. 1.

Most of the methods used for HLI reliability evaluation, are based on the “loss of load or energy” approach. One of the suitable indices that describes generation reliability level is “Loss Of Load Expectation” (LOLE); that is the time in which load is more than available generation.

Generally, the reliability indices of a system can be evaluated using one of two basic approaches [3]:

• Analytical techniques.
• Stochastic simulation.

Simulation techniques, estimate the reliability indices by simulating the actual process and random behavior of the system. Since power markets and generators’ forced outages have stochastic behavior, Monte Carlo Simulation (MCS) which is one of the most powerful methods for statistical analysis of stochastic problems, is used for reliability assessment in this research.

HLI reliability depends absolutely on generating units specifications. The main function in traditional structure for Unit Commitment (UC) of generating units is generation cost minimization. Since beginning 21st century, many countries have been trying to deregulate their power systems and create power markets [4]-[8]. In power markets, the main function of players, is their own profit maximization; which severely depends on type of the market. As a result, reliability assessment in HLI, completely depends on market type and its characteristics.

Generally, economists divide the markets in four groups which vary between perfect competition market and monopoly market [9]. This paper deals with evaluation of generation reliability in different kinds of power pool markets based on characteristics of demand.

In [10], independent power producers’ impact on reliability and associated costs of existing power systems under deregulation environment has been presented. This paper has used “Expected Unserved Power” (EUP) as reliability index and economic dispatch problem is solved under some reliability and system constraints.

Reference [11] has used “Effective Load Duration Curve” (ELDC) for evaluation of “Loss Of Load Expectation” (LOLE) and “Expected Energy Not Served” (EENS) as reliability indices in HLI.

Reference [12] has presented some reliability models for different players in a power system. Generation system is represented by an equivalent multi-state generation provider (EMGP). The reliability parameters of each EMGP are shown by an available capacity probability table (ACPT) which is determined using conventional techniques. Then, the equivalent reliability parameters for each state (including state probability, frequency of encountering the state and the equivalent available generation capacity) are determined.

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Reference [13] has presented generation operational cost minimization problem under system constrains and load uncertainty for evaluation of “Expected Unserved Power” (EUP) as reliability index.

This paper considers HLI reliability assessment in power pool market using fuzzy logic. Also, sensitivity of reliability index to different reserve margins and future times will be evaluated. In section-II fundamental of power pool market is discussed. In section-III, the algorithm for HLI reliability assessment in power pool market will be proposed and finally in section-IV case study results are presented and discussed.

II. POWER POOL MARKET FUNDAMENTALS

Market demand curve has negative gradient. Amount of demand decrease is explained by “price elasticity of demand”. This index is small for short term, and big for long term; because in longer term, customers can better adjust their load relative to price [14]. Demand function, generally, is described as \( P = a - bQ \). Therefore, price elasticity of demand is explained as indicated in (1).

\[
Ed = \left| \frac{dQ}{dP} \right| = \frac{1}{b} \quad (1)
\]

Let’s suppose forecasted load by dispatching and control centers is an independent power from price and it equals \( Qn \). Therefore, price of electrical energy is zero. As a result, demand function can be obtained as (2).

\[
P = a - bQ = bQn - bQ = \frac{Qn}{Ed} - \frac{Q}{Ed} \quad (2)
\]

Typically as shown in Fig. 2, price elasticity in power markets, is 0.1-0.2 for 2-3 future years and 0.3-0.7 for 10-20 future years [14]. In short term, costumers can’t completely adjust their consumption with price, and price elasticity is small and in long term it is big.

![Image](Fig. 2. Price elasticity of demand for various times)

![Image](Typical total offer and demand exponent curves)

III. PROPOSED METHOD FOR HLI RELIABILITY ASSESSMENT USING FUZZY LOGIC

In power markets, Hirschman-Herfindahl Index (HHI) which is obtained from (6), is used for market concentration measurement [16]:

\[
HHI = \sum_{M} q_i^2 
\]

Where: \( MR = a - 2bQ = bQn - 2bQ = \frac{Qn}{Ed} - \frac{2Q}{Ed} \quad (4)

Comparison (2) and (4) produces a result that if there is no any market power, offer curve of industry for each market (from perfect competition to monopoly) will equal marginal cost; but negative gradient of Demand Exponent curve (DE) varies between b (for demand function in perfect competition market) and 2b (for marginal revenue in monopoly market). Therefore, generally demand exponent curve can be expressed as (5); where \( K \) varies between 1 and 2.

\[
DE = a - KbQ = \frac{Qn}{Ed} - \frac{KQ}{Ed} \quad (5)
\]
If market shares are measured in percentages, \( HHI \) will vary between 0 (an atomistic market) and 10000 (monopoly market). In one usual grouping, the US merger guidelines stipulates an assumption that markets with a \( HHI \) below 1000 is unconcentrated, a \( HHI \) between 1000 and 1800 is moderately concentrate, and a \( HHI \) above 1800 is highly concentrated [17].

As mentioned before, according to type of market and \( HHI \) value, negative gradient of demand exponent curve, varies between \( b \) and \( 2b \). Therefore in this paper, for modeling the market, a fuzzy number is proposed for estimate of demand exponent curve gradient coefficient (\( K \)) based on \( HHI \) value. Membership functions of unconcentrated, moderately concentrated and highly concentrated markets fuzzy sets and the equation to estimate gradient coefficient are shown in Fig. 4 and (7) respectively.

\[
K = (MFU + 1.5MFM + 2MFH)
\]  

(7)

As can be seen from Fig. 4 and (7), while proposed coefficient (\( K \)) covers all kinds of markets with different degrees, at the same time, the change of degrees is not sudden, rather it is gradual and continuous. Also, the proposed method and fuzzy logic are valid for all power pool markets.

Generation reliability of a power system depends on many parameters. One of these parameters which has an important role, is reserve margin which is defined as (8) [18].

\[
RM\% = \frac{Installed \; Capacity - Peak \; Demand}{Peak \; Demand} \times 100
\]  

(8)

Algorithm of HLI reliability assessment in power pool markets using fuzzy logic and MCS is shown in Fig. 5. Steps of proposed algorithm are as following:

1- Calculation of total offer curve of power plants.

2- Based on characteristic of market, \( HHI \) is obtained. Using Fig. 4 and (7), gradient coefficient of demand exponent curve (\( K \)) is calculated.

3- Determinations of a day and related load (\( Q_n \)) randomly, and demand exponent curve using (5).

4- The power plants which are selected for generation in the selected day are determined from intersection of power plants’ total offer curve and demand exponent curve with regards to reserve margin.

5- For each selected power plant in previous step, a random number between [0-1] is generated. If the generated number is more than power plant’s Forced Outage Rate (\( FOR \)), the power plant is considered available in mentioned iteration; otherwise it encounters forced outage and can’t generate power. This process is performed for all power plants using an independent random number generated for each one of them. Finally, sum of the available power plants’ generations is calculated. If the sum becomes less than intersection of power plants’ total offer curve and demand exponent curve, we will have interruption in the iteration, and therefore, \( LOLE \) increases one unit; otherwise, we go to the next iteration. Steps 3 to 5 are repeated for calculation of \( LOLE \).

IV. NUMERICAL STUDIES

IEEE - Reliability Test System (IEEE-RTS) is used for case studies. Data for IEEE-RTS can be found in [19]. In various case studies following assumptions are applied:
1- All studies are simulated for second half of year, based on daily peak load of mentioned test system.
2- All simulations in MCS are done with 5000 iterations.
3- Each study is simulated for two different times (present time and 2nd future year), and with two different reserve margins (0%, 9%).
4- Annual growth rates of power plants’ generation capacity and consumed load are considered 3.4% and 3.34% respectively.
5- Annual growth rates of oil and coal costs are considered 4% and 1% respectively. Nuclear fuel cost (including uranium, enrichment and fabrication) is considered as a fixed rate. Also, annual growth rate of variable O&M cost is considered 1%.

In first study, each power plant is assumed as an independent company. Therefore, $HHI = 634$, and the market will be unconcentrated. Using Fig. 4 and (7), $K$ is calculated as 1. Based on this assumption and using the proposed algorithm, $LOLE$ values are obtained versus different times and reserve margins as shown in Fig. 6.

In second study, all power plants based on their types (including: oil, coal, nuclear and water plants), are classified. Therefore, $HHI$ equals 2984, and $K$ is calculated as 1.5722. Based on this assumption and using the proposed algorithm, $LOLE$ values are obtained versus different times and reserve margins as shown in Fig. 7.

In third study, all fossil power plants (including oil and coal power plants), are classified in one company and others are as second case study. Therefore, types of power plants are fossil, nuclear and water. As a result, $HHI$ equals 5290, and $K$ is calculated as 1.7128. Based on this assumption and using the proposed algorithm, $LOLE$ are obtained versus different times and reserve margins as shown in Fig. 8.

In fourth study, it is assumed that all power plants belong to a monopolist, and the market will be fully concentrated and monopoly. Therefore, $HHI$ equals 10000, and $K$ is calculated as 2. Based on this assumption and using the proposed algorithm, $LOLE$ values are obtained versus different times and reserve margins as shown in Fig. 9.
If market becomes more concentrated or HHI becomes bigger, $K$ will find bigger value, too. Therefore, according to (5), intersection of power plants’ total offer curve and demand exponent curve occurs at less demand. This matter, leads to decrease of in service power plants’ units and therefore, reliability improves. So that in the last study (monopoly market), FOR has its least values between all studies.

In all case studies, if reserve margin increases LOLE will decrease and reliability will improve.

As mentioned before, in longer term, customers can better adjust their load relative to price. Therefore, price elasticity increases, and according to (5), demand exponent curve finds less gradient. As a result, intersection of power plants’ total offer curve and demand exponent curve occurs at less demand (Fig. 3). This matter, leads to decrease of in service power plants’ units and therefore, reliability improves. Therefore, in each study, if time increases, LOLE will decrease. Although, the annual growth rate of power plants’ capacity has its effect, too.

It is to be noted that since in IEEE-RTS available capacity of hydro plants are different in first and second half of year, therefore simulations have been done for second half of year. Evidently, the proposed method can be utilized for every single study, if time increases, LOLE will decrease. Although, the annual growth rate of power plants’ capacity has its effect, too.

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V. CONCLUSION

In this paper, HLI reliability in power pool market is evaluated using market concentration concept. Power pool markets can be divided in three groups based on their concentration which is measured by $HHI$ as an index. Since $HHI$ changes in various kinds of power markets isn’t sudden, therefore, a fuzzy logic is proposed for calculate gradient coefficient of demand exponent curve which varies in different kinds of markets. Also, because of market and generators’ FOR random behavior, MCS is used for simulations.

In this research, LOLE is used as reliability index; and following main results are obtained:

- If market becomes more concentrated, LOLE will decrease and reliability will improve.
- Whatever price elasticity of demand increases, reliability will improve.

VI. SYMBOL LIST

$MC$: Marginal cost (mills/kWh)
$MR$: Marginal revenue (mills/kWh)
$Q$: Quantity of power (kW)
$P$: Electrical energy price (mills/kWh)
$RM$: Reserve margin (%)  
$Ed$: Price elasticity of demand ($kW^2/h / mills$)
$Qn$: Forecasted load (kW)
VIII. BIOGRAPHIES

Hossein Haroonabadi was born in Tehran, Iran on 1975. He obtained B.Sc. and M.Sc. degrees from Azad University (Tehran south branch) in 1999 and 2001, respectively. He is now Ph.D. senior of power engineering at Azad University (Science and Research branch). His research interests include power system reliability, soft computing application in power systems and power system restructuring.

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