Evaluating the Power Systems Reliability by Developing Reliability Network Equivalent Techniques

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Received: May 2017 Revised: June 2017 Accepted: June 2017

ABSTRACT

Due to the importance of providing reliable electricity for consumers in today's power networks, the need for studies in the field of power systems reliability is feeling increasingly considering inherent uncertainties of renewable sources. Therefore, the main challenge of this study is to provide an efficient technique for evaluating reliability of power systems considering economic transactions between generative companies and load sources and review the impact of renewable sources on system reliability. In this article, a solution is improved based on equivalent techniques of power system reliability considering the effect of changes in wind speed for producing wind power in the network. In addition, a new method has been provided for reliability assessment of transmission network to check the adequacy of transmission lines corresponding to each load point based on the maximum power that can be transferred. In this study, we have avoided to do iterative calculation for computing adequacy of transmission lines in load point indices when the load and generation level are variable. Finally, RTS IEEE is used as the sample network in order to evaluate the efficiency of the proposed algorithm. The results indicate the high efficiency of the proposed method for reducing reliability of computation time.

KEYWORDS: Uncertainty of renewable sources, Reliability, Bilateral contracts, Network equivalent techniques.

1. INTRODUCTION

Given the importance of electricity in the world and in developed countries compared with developing countries, there are appropriate supports from the power industry and removing its' challenges. For this reason, extensive studies have been conducted or are in progress to determine the challenges and how troubleshoot them. One of these studies is the reliability of the electricity industry. Studies on the reliability of power systems have become increasingly important in the world [1].

Electrical power systems in recent decades have made many new enhancements. Their first emphasize is on providing a reliable and economical source of electrical energy for consumers. Excess capacities and storage in generation and network equipment are predicted in case of occurring error and mandatory withdrawals of power plant and outage with network plan for maintenance, there would be the possibility to supply continuous energy. The capacity redundancy amount must be in accordance with the needs and the source has to be economic as much as possible [2]. Therefore, according to the importance of electricity reliable supply of consumers in today's power networks, there should be more studies in the field of reliability in power systems. In the meantime, power systems are shifted towards the use of renewable sources due to increasing environment concerns especially in the last two decades. On the other hand, exploitation of these sources is complex due to high uncertainty of input energy and totally, it makes the network utilization to face challenge. Hence, by the influence of renewable sources in the network, it is essential to provide new techniques to evaluate network reliability considering market clearing transactions of energy. Various studies have been done in this area. In [3], a framework is provided for electricity market analysis in long-term to evaluate the effect of performing load response and smart measurement structure on market price fluctuations and system reliability. In [4], influence of wind and water resources on the reliability of power systems is discussed and evaluated using Monte Carlo simulation method. Markov equivalent model is used for modeling water resources. In [5], a probabilistic model is presented for assessing the reliability of the power system dominated by renewable sources. Considering the demand-side programs is noteworthy in this study.

In [6], according to the random behavior of the wind, a method is presented for modeling wind energy resources in reliability studies. A combination of analytical and simulation methods is used in the provided model. In [7], a new algorithm is proposed to study the effect of solar cells and renewable sources on the reliability of the power system. In this article, a structure is provided for supplying sensitive loads when solar cells are not able to feed all loads. In [8] a model is provided based on equivalent methods of network reliability. One innovation of this study is providing a new method to obtain a multi-phase model in wind farm with non-uniformed wind turbines. In contrast, many hypotheses make the issue away from real exploitation condition such as considering the effect of withdrawal of generation units of a company on the performance of generation units of adjacent power generation companies; this makes the proposed model inefficient practically.

In the context of market risk in [9] that a combination of market risk and generation risk is considered, we need to develop an appropriate risk management plan due to competitive markets and also uncertainty related to the g unit of restructured systems. In addition to the above studies, reliability network of equivalent technique (RNET) is provided to consider new aspects of power networks. In these methods, power network is divided into several categories of equivalent multistate generation provider (EMGP), equivalent multistate transmission provider (EMTP) and equivalent bulk load point (EBLP). In this method, the effect of power plants and transmission lines is determined on reliability of each load point separately. It is simple to determine parameters and effects of EMGP; this is while the evaluation of the effects of EMTP on evaluation indices of reliability of each of points is much more complex and requires AC load shedding and performing load outage methods. In addition, regarding the load changes and generation of renewable sources, the volume of conducted calculations will be increased. Therefore, in this article, we have tried to reduce the volume and time of studies by improving reliability network equivalent techniques. Some capabilities of the proposed model are mentioned bellow:

- Considering structure and network topology
- Considering equation of AC load flow and observing the limit of buses voltage range and thermal limits of transmission lines
- Uncertainty of the withdrawal of thermal generation resources
- Uncertainty of generative power of wind sources and uncertainty of wind resource withdrawal due to defects in mechanical system
- Bilateral transactions of Genco companies with subscribers
- Ability to calculate financial risks of Genco companies due to uncertainty of renewable and generative resources withdrawal

The proposed method has high ability in implementing load time model and generation in reliability studies. It is so that repeated studies of load flow in each hour are avoided in the proposed method. Total listed items cause high efficiency of the model and the proposed method is for studies of reliability assessment in this article.

2. RELIABILITY MODEL

Power system reliability evaluation can be done in each of the main areas of generation, transmission and distribution in each hierarchical level (HL). Reliability assessment at sequential level II (HL-II) returns to the ability of transmission network equipment and generation sources for requested load supply [10]. In this article, according to the study of adequacy of transmission and generation networks in power systems, reliability studies are conducted at HL-II level. Then, reliability of generation network equivalent and transmission network is discussed in two parts.

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2.1. Generation network equivalent model

Equivalent multistate generation provider is used for modeling internal generation sources. The internal system is provided in the form of EMGP which is shown in figure 1. The structure of an EMGP is provided as Available Capacity Probability Table (ACPT). The corresponding ACPT table is provided in the form of an EMGP based on the possible modes of generation units and availability or unavailability of internal generation units. To calculate ACPT, first, the Capacity Outage Probability Table (COPT) model of each of internal generation sources is calculated based on the average exit rate and the average time of repair corresponding to them. Generative sources model is presented in detail as follows.

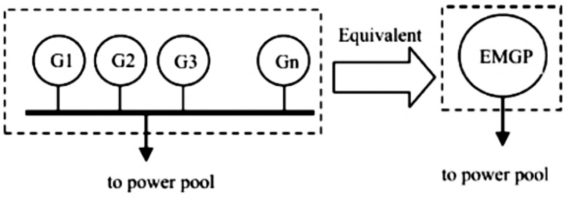


Fig. 1. The EMGP model of internal generation sources.

2.1.1. Thermal sources model

A two-state COPT model is used for modeling thermal resources. The multistate mode of COPT is one of the most useful models for planning studies which is widely used in the studies of power systems. This table includes the probability of occurring possible modes of each of heat and power sources available in each possible mode. Assuming the two-state model (availability / unavailability) for existing thermal sources in the studied network and also adherence of resources withdrawal from exponential probability distribution function, probability of unavailability and availability of thermal generative unit is provided as equations (1) and (2) [10].

$$UA = \frac{\lambda}{\lambda + \mu} \tag{1}$$

$$A = 1 - UA \tag{2}$$

In above equations, UA is probability of unavailability of a unit, A is availability of a unit and λ is withdrawal rate provided as fail/year. Also, μ is maintenance rate as repair/year. This indicator shows the ability of network operator in repairing the lost resources. Both mentioned rates can be obtained using statistical information of recorded withdrawals of the system of thermal resources in the past. Having the withdrawal rate and repair rate of each of generative sources, the withdrawal probability of each of them is calculated via equation (3). This probability is considered as the probability of mandatory withdrawal of unit. Thus, COPT model of each of thermal sources is provided as below:

$$COPT \quad Model = \begin{pmatrix} P_G & UA \\ 0 & A \end{pmatrix} \tag{3}$$

In above model, P_G is generative capacity of sources.

2.1.2. Modeling uncertainty of wind resources

The power-speed feature of a wind unit is calculated via equation (4) [11].

$$G(V_q) = \begin{cases} 0 & 0 \le V_q < V_{cut} \\ \frac{1}{2}\rho A V_q{}^3 C_p & V_{cut} \le V_q < V_{nominal} \\ P_r & V_{nominal} \le V_q < V_{out} \\ 0 & V_q \ge V_{out} \end{cases} \tag{4}$$

In equation (4), Cp is the power coefficient of the rotor or rotor gain. Also, the effective level of rotor blades (A), wind speed (v_q), wind current density (ρ), turbine nominal speed ($V_{nominal}$) and cut speed and out speed are respectively (V_{cut}) and (V_{out}).By statistical analysis of wind speed in the region, at an altitude of turbine blades deployment, the probability of different speeds is calculated as a function of Weibull distribution. The number of considered modes for expected powers of a wind farm has an important role in assessing wind turbine reliability. Certainly, the more considered modes for expected power of wind farm output, the more accurate assessment will be done. But the volume of calculations will be increased as well. Usually, in different studies on wind farm, the six-state model is appropriate and acceptable. Initially, the reliability model of wind units is provided in form of an accessibility matrix for all events. This matrix is defined as follows [8].

$$AM = [a_{ij}]_{S \times W} \tag{5}$$

$$a_{ij} = \begin{cases} 1, & ifWTG_j \ available \\ 0, & ifWTG_j \ not \quad available \end{cases} \tag{6}$$

In equation (5), a_{ij} indicates the status of being in the circuit or not of j wind unit in i exploitation mode. In this equation, s and w are respectively the possible modes of wind farm and the number of wind farm turbines. For N power plant unit with M lost unit, the probability of occurring i mode is obtained via equation (7) [8].

$$p_i = \prod_{j=M+1}^{N} A_j \times \prod_{j=1}^{M} U_j \tag{7}$$

In above equation, A_j and U_j are respectively probability of availability and withdrawal of j unit. Values of A_j and U_j are calculated using the equations (1) and (2). Also, M indicates the number of turbines out of circuit and N indicates the number of wind units of the wind farm. The past information of wind should be classified in n range of speed. In this study, n is considered equal to 6. According to this classification and equation (4) that shows the speed power characteristic of wind units, WM matrix is provided as the matrix of output power of wind units. Output power of each unit in each wind speed regardless of reliability of wind units can be provided as WM matrix.

$$WM = \begin{bmatrix} G_1(V_1) & G_1(V_2) & ... & G_1(V_n) \\ G_2(V_1) & G_2(V_2) & ... & G_2(V_n) \\ ... & ... & ... & ... \\ G_w(V_1) & G_w(V_2) & ... & G_w(V_n) \end{bmatrix}_{W \times n} \tag{8}$$

Output power of wind farm in different events regarding reliability of wind units can be provided as Cap matrix [8].

$$cap_{S \times n} = AM_{S \times W} \times WM_{W \times n} \tag{9}$$

Probability matrix of Prob mode is formed considering different modes of wind speed and reliability of wind units.

$$\Pr ob_{S \times n} = [p_i]_{S \times 1} \times [p_v]_{1 \times n} \tag{10}$$

COPT of wind units is obtained from Cap matrix and the probability corresponding to every power of Prob matrix based on the matrix of generative capacity mode of wind farm [8]. The final model of EMGP as EMGPN which is shown in figure 2 is obtained through combination of multistate model of COPT of wind farm with EMGP model of internal network generation source.

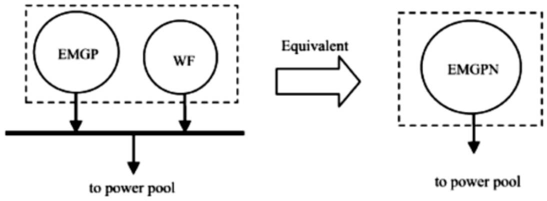


Fig. 2. The EMGPN model of internal generative sources.

2.2. Transmission network equivalent model

Existing methods are proposed in order to consider deliverable capacity of transmission networks between EMGP and load points of EBLP as RNET. Figure 3 has indicated the equivalent model for reliability assessment of power network.

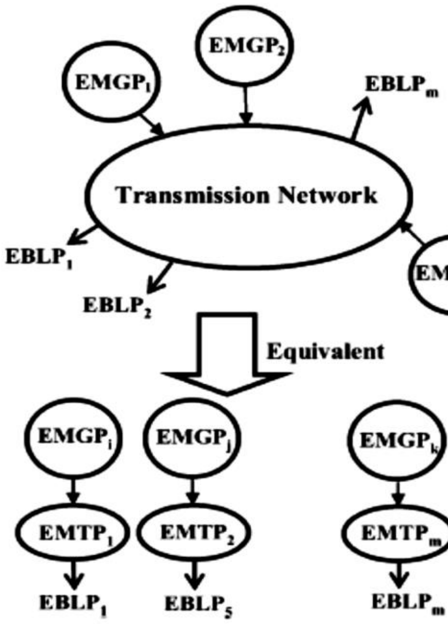


Fig. 3. The Equivalent model of EMTP for assessing adequacy of transmission network.

The proposed method based on obtaining Deliverable Capacity Probability Table (DCPT) is one EMTP. Two important parameters in DCPT are probability of occurring each mode and Deliverable Generation Capacity (DGC) to each of load points in each mode. in current methods, GDC for each of probability modes of transmission network is obtained using AC power flow considering constraints of network utilization. One problem of this method is iterative calculations to obtain DGC despite changing load in different hours. On the other hand, in a big system, despite the large number of transmission lines and consequently the high number of possible modes of transmission lines using common methods, calculation volume will be increased severely. Therefore, using existing methods in order to obtain indexes of load point reliability in real networks seems to be very time consuming.

The process of probabilistic assessment of reliability is divided into three main parts: modes sampling, modes assessment and indices calculation. Each sampled mode includes the status of being in the circuit or withdrawal of transmission lines that some are in active condition and some are in disable mode. Assessment of modes aims to evaluate the success or failure in sampled modes and determine the severity of system inefficiency in failure modes. After stopping the sampling process, indexes of system adequacy are calculated by the information resulting from assessment of modes based on predetermined relations.

2.2.1. Sampling process

All possible modes of the studied system transmission lines are created to review the adequacy of transmission network and calculate EMTP in sampling part. According to the withdrawal rate and repair rate of each transmission line, probability of availability or unavailability of each transmission line is calculated via equations (1) and (2). So, probability of occurring each of transmission lines mode is calculated via equation (11).

$$p_k = \prod_{j=N_{Fail}+1}^{L} A_j^{line} \times \prod_{j=1}^{N_{Fail}} UA_j^{line} \qquad (11)$$

In above equation, p_k is probability of occurring the k event, N_{Fail} is the number of lines out of the circuit, A_j^{line} is probability of accessibility of j line and UA_j^{line} is probability of inaccessibility of j line. Hence, we can say that the proposed method in this article is based on the method of counting for calculating EMTP.

2.2.2. Assessment of modes

In the second part of probabilistic evaluation process of the events of transmission lines which was mentioned as the assessment of modes, the rate of adequacy of transmission network is calculated in supply of network loads in each of created modes in sampling part.

The proposed method aims that the rate of maximum deliverable power of MDC be transmitted between EMGPs and load points for each of events considering stability and thermal limits of lines. In this method, the rate of network deviations is examined in each mode by AC load flow. In case of deviations, the network parameters with load increase or reduce and generation level efforts are made to put the exploitation mode in normal position. finally, the amount of MDC for each of EMTP events is the maximum load supplied in each load point so that the network constraints and parameters be in allowable range. The below optimization problem is solved to obtain MDC for each possible mode of transmission network. The purpose of the transmission network operator at the withdrawal time of each of transmission lines in power system is to minimize the off time and reduce damages due to load off of consumers. Hence, to calculate MDC in each mode of transmission network, maximizing the total power deliverable to the network buses (equivalent to minimize the off rate in the network events) is considered as target function of the problem in form of equation (12).

$$\max \quad f = \sum_{k=1}^{N} P_{Dk} \tag{12}$$

The constraints of the reviewed problem in calculating MDC are provided as below relations:

- Load flow

Basic constraints of load flow extracted from load flow equations are given below:

$$P_{Gi} - P_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \cos(\delta_i - \delta_j) \ldots + B_{ij} \sin(\delta_i - \delta_j)) \tag{13}$$

$$Q_{Gi} - Q_{Di} = V_i \sum_{j=1}^{N} V_j (G_{ij} \sin(\delta_i - \delta_j) \ldots - B_{ij} \cos(\delta_i - \delta_j)) \tag{14}$$

In above equation, P_{Gi} and P_{Di} are respectively generative and consuming actual power in i bus of network. Also, Q_{Gi} and Q_{Di} are generative and consuming reactive power in i bus of network. B_{ij} and G_{ij} are respectively virtual and actual division of admittance between the two buses of i and j. also, δ_i and δ_j are voltage phase of network buses.

- Limit constraint of generative power of thermal units

The generative power of units varies between their minimum and maximum producible power. Minimum and maximum producible power of thermal units is depended on the unit technical parameters and is determined while designing the unit. The mathematical relation of this constraint is given in equation (15):

$$P_{\min}^{Th} \le P_i^{Th} \le P_{\max}^{Th} \tag{15}$$

- Limit constraint of reactive power generation of thermal units

The heat due to stimulating flow in network generators leads to impose constraints of reactive power generation in the network generative units. So we have:

$$Q_{\min}^{Th} \le Q_i^{Th} \le Q_{\max}^{Th} \tag{16}$$

- Security constraints of network bus voltage

Appropriate utilization of power system requires fixing voltage profile in the network buses. This constraint is formulated as follows:

$$V_{\min}^{i} \le V^{i} \le V_{\max}^{i} \tag{17}$$

- Security constraints of thermal limit of transmission lines

Thermal limit of transmission lines due to flow pass from the lines is shown by the following equation:

$$\left| S_{Li} \right| \le S_{Li,\max} \tag{18}$$

In above equation, S_{Li} is the flow passing from i line and $S_{Li,\max}$ is sustainable limit of i line.

3. THE PROPOSED METHOD

3.1. Assessment of generation network adequacy

In this part, the model used for evaluating the effect of reliability of network generative companies on reliability indices of the system load points is provided. A multistate model of generation is used for system Genco modeling. A Genco is provided in form of EMGP as shown in figure 1. Structure of a EMGP is provided in form of available capacity probability table. According to possible modes of generative units and availability or unavailability of units of each Genco, the EMGP table corresponding to its' Genco is provided as a ACPT. To calculate ACPT, first the COPT model of each generative source under the cover of a Genco based on the average of withdrawal rate and the average of repair time of each of network units is calculated according to their reliability in previous section. Genco is calculated through combination of the model of the units of a ACPT. EMGP models is used in the study period for each Gecno in order to calculate reliability indices of load points under the cover of its' Genco.

3.1.1. Calculating financial risk of generative companies

In each bilateral agreement between Genco companies with load points, a fine will be considered equivalent to the energy spot price for Genco in case of the breach of contract on the maturity date from each Genco caused by unavailability of units and inability to supply the contracted amount on the maturity date. Naturally, according to integrity of power systems and dominance of load flow equations on the way of transmission line flow, the load of the parties to the contract may not be turned off necessarily in case of withdrawal of a Genco capacity and inability of Genco in contracted power supply. In such condition, other Genco of network supply the power in case of having power and load off happens only if the total system face generative power shortage.

So, in order to calculate indexes of load points reliability due to inadequacy of generation system, the obtained EMGP model of each Genco of network are merged and EMGP model of total system is applied. in contrast, we can use the damages caused by generation inadequacy to each Genco using EMGP model of each of Genco of network and specificity of contracted loads. Below equation is suggested to calculate the expected damage to each Genco due to power shortage.

$$ED^k = \sum_{t=1}^{T} \sum_{i \in LC} p_i \times RP_t \times \left(P_L^t - P_{G,i}^{ava} \right) \qquad (19)$$

In above equation, ED^k is expected damage of k Genco, T is study hours and LC is set of modes of k Genco EMGP; the rate of available generation is lower than total contracted loads in t hour. Also p_i, RP_t, P_L^t and $P_{G,i}^{ava}$ are respectively the possibility of i event, momentary market price in t hour based on $/MWh, total loads under contract in t hour based on MW and available power rate in i mode.

So, EMGP model of each Genco of network is an efficient model for asset management of each Genco. So that each Genco of network with its' EMGP model can calculate the rate of its' expected damage (due to withdrawal of generative units and beneficiary fine) per accepting each of bilateral transactions and use it as a tool for making decisions about bilateral agreements.

3.2. Assessment of transmission network adequacy

MDC of each of network loads is calculated in order to evaluate the adequacy of transmission network after sampling in accordance with optimization problem posed in section 1.1.4. Direct search method is used to find the amount of MDC for each mode of transmission network. This method is given below in short:

Step 1) Calculate the probability of i mode

Step 2) Set the initial load and initial power of each PV buses

Step 3) Run the AC load flow

Step 4) If P_{Gk} was over the limit in floating buses, a part of load is reduced and we will return to step 3.

Step 5) If $P_{Gk} < 0$ and network constraints are not observed, then we will reduce the power of PV buses and return to step 3.

Step 6) If $P_{Gk} < 0$ and network constraints are observed, we will increase the amount of load slightly and return to step 3.

Step 7) If $P_{Gk} > 0$ and network constraints are observed, we will increase the load slightly and return to step 3.

Step 8) Proper amount of load is selected in buses and AC load flow is run.

Step 9) If network constraints are observed, we will go to step 8.

Step 10) Selected amount for load of each load point is considered as MDC for that mode.

Step 11) If the information of all modes is obtained for DCPTs, the program is finished, otherwise, we will return to step 1.

Increasing and decreasing amount of Δ should be selected properly to select MDC correctly, because the buses voltage shows much sensitivity to the load changes. In other provided methods, the amount of interruptible load with aim of network voltage stability is obtained using P-V and Q-V curves. The load outage programs are used in actual systems for voltage stability. When the voltage of each of system buses reduces from its' limit amount, a part of load is cut in order to reduce deviations of network parameters. This amount is usually between 5 to 20% of network load peak. So the amount of Δ in conducted studies is selected 5% of peak load for correct network exploitation.

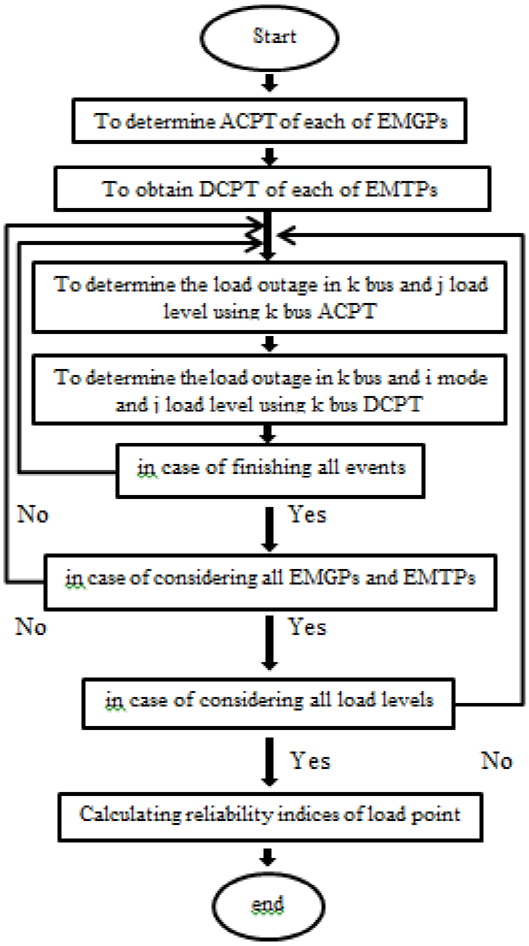
It should be noted that the amount of MDC for each EMTP in each network condition depends on how to select method for balancing load and generation. Many load shedding methods have been used in assessment calculations of power network reliability. In this study, we have used both regional and partial load shedding methods for presenting the proposed method. If the load flow is diverged in each of events, this divergent is considered as a deviation of network and load shedding program will be run for it.

3.3. Reliability indices

The DCPT of each of EMTPs is used in order to obtain reliability assessment indices in network load points in different load and generation levels. The load outage amount in each mode of network load comparison and MDC is obtained by below equation:

$$L_k = P_{Lk} - MDC_k \tag{20}$$

DCPT of each EMTP can be used for other load levels. The current method for obtaining reliability indices of load points is obtained via using the following algorithm:



Simultaneous events of transmission lines and generation units are ignored for obtaining reliability indices of load point. Given that the studies of reliability assessment are done considering second order events, the possibility of losing a line and a generating unit at the same time in an actual network is very low. So, the considered approximation is evaluated as a good one. Having calculated the power system equivalent model, reliability assessment indices of LOLE (loss of load expected) and EENS (expected energy not supplied) in conducted study are calculated via equations (21) and (22).

$$LOLE_k = \sum_{j=1}^{N_t} \sum_{i \in LC_j} p_i \qquad \left(\frac{Hours}{Period} \right) \tag{21}$$

$$EENS_k = \sum_{j=1}^{N_t} \sum_{i \in LC_j} p_i . L_{kij} \qquad \left(\frac{MWh}{Period} \right) \tag{22}$$

In above equations, L_{kij} is interruptible load of k bus for j load level in i event mode. LC_j are a set of events in which load shedding has been done for observing network exploitation constraints. Also, N_t is the number of load levels in network. Given that in the conducted study, a one-day study period has been considered, thus, the number of load levels in this period is 24.

4. NUMERICAL STUDIES

4.1. The studied network

The RTS IEEE test network was applied to evaluate the performance of the proposed method. The structure of this network is indicated in figure 3. As shown in this figure, this network has totally 24 buses including 10 buses of 138 kV and 14 buses of 230 kV, 32 generative units and 38 transmission lines. Table 1 has indicated the information of generative units including mandatory withdrawal rate and the average repair time of generative units. Other information of the studied network includes features of transmission lines, network buses load, hour profile of load and … are available in reference [12].

Table 1. The information of wind turbine.

Manufactory	Vestas
Type	V47-660 kW
Nominal Power	660 kw
Rotor Diameter	47 m
Sweet Area	1.735 m^2
V cut	4 m/s
V out	25 m/s
Nominal V	15 m/s
λ	6
μ	130

Table 2. Reliability information of generative units.

Unit	Capacity (MW)	Type	FOR	MTTE (Hour)	MTTR (Hour)
U12	12	Steam	0.02	2940	60
U20	20	Fossil	0.10	450	50
U50	50	Water	0.01	1960	20
U76	76	Steam	0.02	1960	40
U100	100	Steam	0.04	1200	50
U155	155	Steam	0.04	960	40
U197	197	Steam	0.05	950	50
U350	350	Steam	0.06	1150	100
U400	400	Nuclear	0.12	1100	150

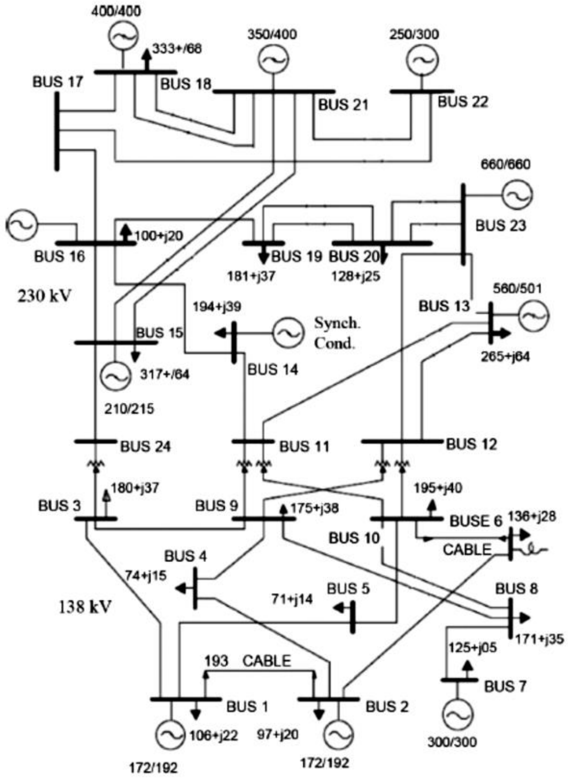


Fig. 4. The structure of RTS IEEE network.

Considering uncertainties of wind sources, a wind farm with ten 660 kW wind turbines has been added to the network. Table 2 has indicated the information of wind turbines taken from [13].

4.2. Numerical results

1.1.6. Results of adequacy assessment of generation network

In this article, according to the proposed model in section 2.1, we have used a 6-state model of wind speed. We used the information of anemometer station in Loutak located in Zabol for calculating the 6-state model. Table 3 has indicated the number of considered modes along with the probability of corresponding event of each of these modes.

Table 3. The Six-state wind model according to the anemometer information of Loutak, Zabol.

Wind speed m/s	Probability
6.016	1.52777e-1
6.850	1.73611e-1
7.683	1.59722e-1
8.516	2.22222e-1
9.350	2.15277e-1
10.183	7.63880e-2

A model equal to 10-state has been provided for the wind farm which is combined with the six-state model of wind speed. Finally, the reliability model of wind farm is provided in table 4 by combination of ten-state model of wind farm with six-state model of wind speed.

Table 4. The Ten-state model of wind farm.

Output power (MW)	Probability
2.050	4.86491e-2
2.456	2.24533e-2
2.908	1.41765e-1
3.361	6.38514e-2
3.814	1.54713e-1
4.267	8.06365e-2
4.720	1.50345e-1
5.173	1.21659e-1
5.626	1.60334e-1
6.070	5.55854e-2

In order to study the effect of generation adequacy on reliability indices of load points of EMGP model in each calculated Genco company, EMGP model of total system is calculated by integration of Genco models of network EMGPs. It should be noted that the EMGPN model of companies with wind turbine is calculated via integration of ten-state model of wind farm with its' EMGP model. The sample network of RTS IEEE is divided into three Genco to demonstrate the superiority of the equivalent network reliability method for a couple of EMGP and bilateral market. Genco1 includes 11 generating units common in buses 1, 2 and 7 and a wind farm in bus 1. Genco 2 includes 6 generating units connected to buses 13 and 23. Genco 3 contains generators connected to buses 15, 16, 18, 21 and 22. Bilateral agreement has been established between companies and load points to evaluate the damages of

Genco companies due to adequacy of generative sources. It is assumed that the loads 1, 2, 4, 5 and 7 have bilateral contract with Genco 1. Also, the loads 3, 6, 8, 9, 10 and 13 have bilateral contract with Genco 2 and the loads 14, 15, 16, 18, 19 and 20 have bilateral contract with Genco 3. A limit number of ACPT 1 modes for Genco 1 are provided in table 5. Tables 6 and 7 have provided similar information for Genco 2 and Genco 3 respectively.

Table 5. ACPT 1 table for EMGP1.

Available capacity (MW) EMGP1	Probability	Mode number
688.076	2.604e-2	1
608.076	3.971e-6	50
564.001	1.653e-3	100
487.623	6.261e-5	200
432.076	4.012e-8	300
384.076	4.512e-9	400
344.021	1.594e-7	500
296.002	2.91e-10	600
156.452	21.0e-10	745

Table 6. ACPT2 table for EMGP2.

Available capacity (MW) EMGP2	Probability	Mode number
1251	7.269e-1	1
1069	6.060e-2	2
1054	1.148e-1	3
941	1.300e-3	4
704	1.001e-2	10
547	1.048e-5	15
350	1.841e-7	20
155	7.682e-7	23

Table 7. ACPT 3 table for EMGP 3.

Available capacity (MW) EMGP3	Probability	Mode number
1470	6.07e-1	1
1384	3.12e-6	10
1303	5.20e-3	20
1253	3.13e-4	30
1165	1.04e-6	40
1103	7.0e-10	50
724	2.44e-8	100
310	1.18e-6	150
210	3.0e-10	155

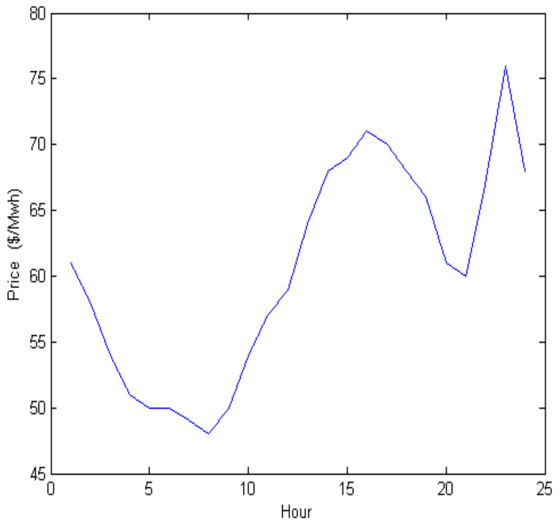


Fig. 5. Energy price in sales market.

As can be seen in table 5 to table 7, ACPT for Genco 1 has 745 modes, it has 24 modes for Genco 2 and 155 modes for Genco 3. Hence, it can be seen that considering uncertainty of wind sources will rise the possible modes of ACPT table and volume of calculations will also be increased corresponding to it. According to the energy price in the sales market indicated in figure 5, the rate of financial risk of each Genco of network in case of withdrawal of generative units are given in tables 6 to 8.

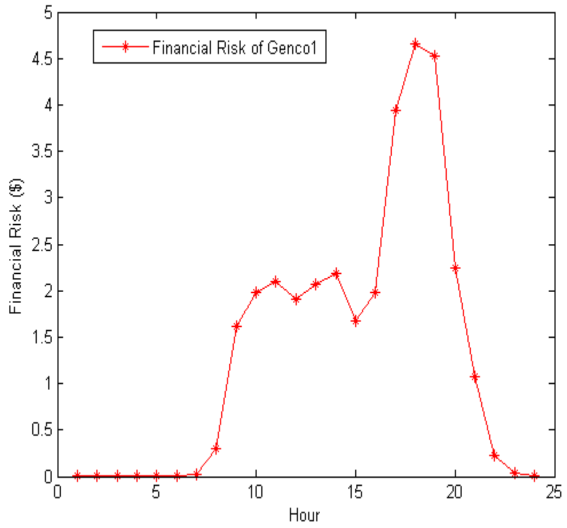


Fig. 6. Financial risk of Genco 1.

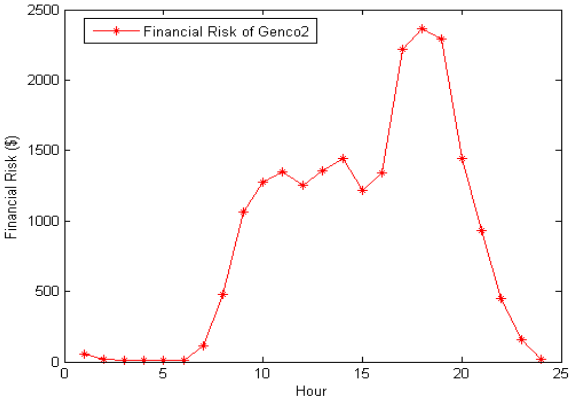


Fig. 7. Financial risk of Genco 2.

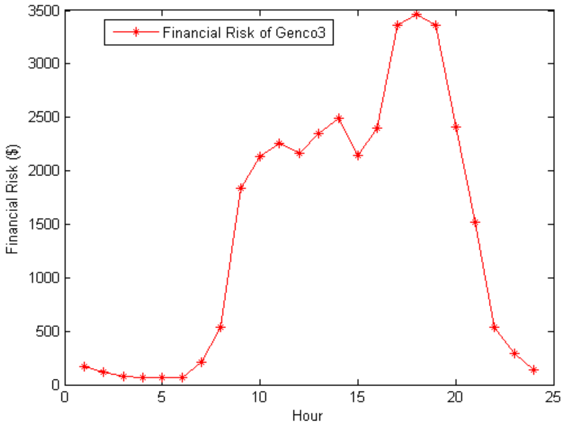


Fig. 8. Financial risk of Genco 3.

As can be seen, the financial risk of Genco 1 arising from customers' outage in bilateral contract is much less than Genco 2 and Genco 3 due to several generative units and high excess energy. At peak time, the load from total loads to the contract of Gecno 1 is 745 MW; this is while the total capacity of Genco 1 generative units according to ACPT1 is 688.07 MW. While in peak time, the loads to the contract of Genco 2 and Genco 3 are respectively 1122 and 1253 MW. However, according to ACPT2 and ACPT3, the maximum capacity available for Genco 1 and Genco 2 is respectively 1251 and 1450 MW.

Therefore, the sideline of low spinning reserve in Genco 2 and 3 imposes high financial risk to these companies due to lack of supplying loads to the contract. Another reason of high financial risk of Genco 2 and 3 can be the existence of generative units with high capacity (including nuclear generative units). According to low reserve sidelines of these two companies, withdrawal of each of their big units leads to lack of supplying the contracted load. So, conclusion of bilateral contracts requires careful and thoughtful studies on capacities and conditions of generative units and calculation of financial risk. Table 8 has provided a comparison between total financial risk of generative companies and their reserve level.

Table 8. Financial risk of the network Genco in bilateral contracts in whole day.

Genco name	Financial risk ($)	Day sideline (MW)
Genco1	32.537	213.07
Genco2	20873	129
Genco3	34163	197

At last, the EMGP model obtained from the network Genco is merged and EMGP model of total system is applied in order to review the impact of generation adequacy on load points indices. On this basis, in each hour of day, the shortage modes of generative power are determined according to the amount of network load and indices of load points caused by generation adequacy are calculated. Values of LOLE and EENS created by EMGP of the system are given in table 9.

Table 9. Reliability indices of load points due to generation network adequacy.

Load points	LOLE (Hours/Day)	EENS (MWh/Day)
1	0.022476	0.135751
2	0.022476	0.121924
3	3.400808	65.63693
4	0.022476	0.093014
5	0.022476	0.089243
6	3.400808	49.59235
7	0.022476	0.157119
8	3.400808	62.35509
9	3.400808	63.81368
10	3.400808	71.10668
13	3.400808	96.63215
14	3.579136	121.9026
15	3.579136	199.1915
16	3.579136	62.83644
18	3.579136	209.2453
19	3.579136	113.7339
20	3.579136	80.43064

4.3. Adequacy assessment of transmission network

Studies on generation adequacy assessment show that in regional load shedding, only the loads in the network regions are removed that their parameters have been deviated in each mode of transmission network. In contrast, in partial load shedding, the total load of the network is removed to compensate the voltage deviations. DCPT for each load points of EBLP3 and

EBLP20 is provided in tables 10 and 11 by applying partial and regional load shedding methods.

Table 10. DCPT for EMTP20 and EMTP3 by partial load shedding method.

EMTP20		EMTP3	
MDC (MW)	probability	MDC (MW)	probability
151	9.767e-1	212	9.76701e-1
150	1.881e-2	211	1.83397e-2
149	4.118e-6	210	4.76878e-4
148	1.091e-6	209	1.337e-6
147	1.253e-6	208	8.581e-7
146	1.725e-6	207	1.253e-6
143	7.800e-7	206	8.156e-6
140	6.995e-6	205	9.09e-7
139	1.770e-7	201	6.25e-7
138	1.980e-7	200	1.55e-7
135	1.502e-6	197	6.99e-7
133	1.721e-3	196	1.77e-7
132	4.862e-6	194	1.98e-7

Table 11. DCPT for EMTP20 and EMTP3 with partial load shedding method.

EMTP20		EMTP3	
MDC (MW)	Probability	MDC (MW)	Probability
183	3.90e-7	249	2.33e-7
172	1.18e-6	227	1.75e-7
171	2.99e-6	212	9.93e-1
170	1.61e-6	211	2.13e-3
169	8.30e-7	210	4.20e-6
167	1.52e-6	208	1.80e-6
164	8.50e-7	207	1.11e-6
159	3.40e-7	201	3.89e-7
157	2.30e-7	197	4.41e-7
151	9.89e-1	196	1.77e-7
150	6.11e-3	194	1.98e-6
149	3.52e-6	190	1.50e-6
148	1.14e-6	189	9.37e-7
147	1.78e-6	187	1.72e-3
146	3.90e-6	186	4.56e-6
145	2.99e-6	185	5.99e-6
143	3.90e-7	183	2.55e-6

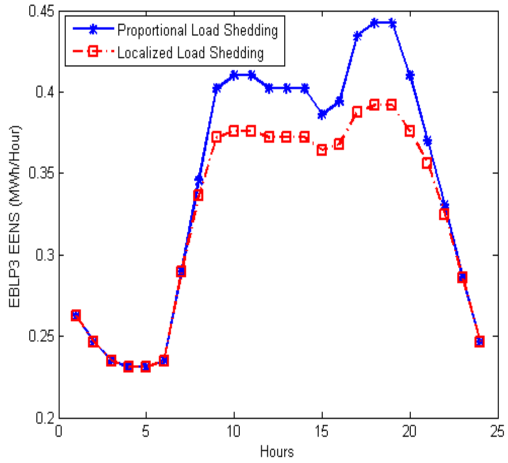


Fig. 9. EENS load point of EBLP3 in each hour of a day.

As expected, MDC values for each of load points in each network point have different values compared to the partial load shedding. Figures 9 and 10 have shown the hourly EENS of EBLP3 and EBLP20 respectively.

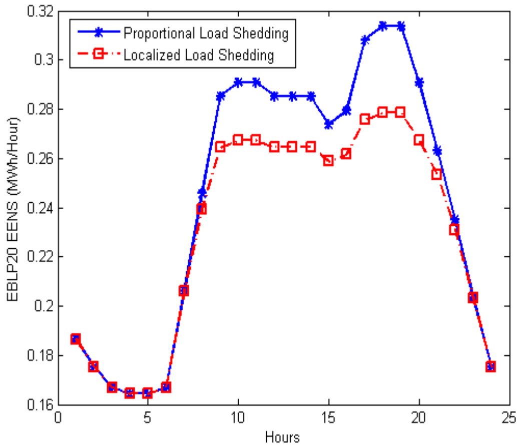


Fig. 10. EENS load point of EBLP20 in each hour of a day.

According to above figures and tables, DCPT tables are calculated for each of load points and the off rate and the network reliability indices are calculated based on hourly load of load points.

At the end, the final results of the study are recorded in table 12 for calculating adequacy assessment of transmission network as EENS and LOLE of load points for both partial and regional load shedding methods in each load point.

Table 12. Reliability indices of load points due to transmission network adequacy.

	Partial load shedding		Regional load shedding	
EBLP	LOLE (Hour/day)	EENS (MWh/day)	LOLE (Hour/day)	EENS (MWh/day
1	8.553e-2	4.86313	5.218e-2	4.49131
2	8.553e-2	4.36781	5.231e-2	4.03509
3	8.379e-2	7.92495	5.237e-2	7.48943
4	8.552e-2	3.33188	5.239e-2	0.07897
5	8.378e-2	3.12570	5.227e-2	2.95303
6	8.378e-2	5.98725	5.833e-2	5.67408
7	8.378e-2	5.50299	5.218e-2	5.19829
8	8.378e-2	7.52809	5.233e-2	7.11318
9	8.553e-2	7.88007	5.235e-2	7.28118
10	8.378e-2	8.58467	5.222e-2	8.11020
13	8.552e-2	11.9317	5.223e-2	11.0205
14	8.379e-2	8.54134	5.224e-2	8.06931
15	8.378e-2	13.9555	5.226e-2	13.1832
16	8.553e-2	4.50289	5.219e-2	4.15863
18	8.552e-2	14.9934	5.228e-2	13.8488
19	8.379e-2	7.96898	5.223e-2	7.52772
20	8.378e-2	5.63506	5.223e-2	5.32347
Total	1.43654	126.625	8.946e-1	118.556

5. CONCLUSION

According to the importance of reliable supply of consumers' electricity in today's power networks, the necessity of reliability studies in power systems is felt more than before. Considering market-clearing transactions of energy and inherent uncertainties of renewable sources, it seems to be necessary to provide new techniques for network reliability assessment by influencing renewable sources in the network. Hence, the main challenge of this article was to provide an efficient technique for systems reliability assessment considering economic transactions between generative companies and load resources and also evaluate the effect of renewable sources on system reliability. In this article, a solution was improved based on power system reliability equivalent methods considering the effect of wind speed changes in wind power plant in the network. The proposed model can include features such as, uncertainty of withdrawal of thermal generative resources, uncertainty of wind source generative power due to uncertainty of wind speed, uncertainty of wind sources withdrawal caused by defects in mechanical system, bilateral transactions of Genco companies with customers and possibility of calculating risks of Genco companies due to uncertainty of withdrawal of generative and renewable resources. According to the studies, the proposed method has the ability to efficiently implement the load and generation time model in reliability studies; so that the repeated studies of load flow in each hour have been avoided in the proposed model.

Finally, the RTS IEEE network was used as the sample network to evaluate the efficiency of the proposed algorithm. The results indicate the high efficiency of the proposed model in calculating financial risks of generative companies in bilateral contracts and assessment of generation adequacy of new systems.

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