Generation Planning for Interconnected Power Systems with High Wind Penetration Using Probabilistic Methods

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Abstract: *The rapid increase in the wind power penetration into power system introduces more variability and uncertainty in existing conventional power system. The variability and uncertainty factors are the key challenges to integrate large amounts of wind generation into future grid. The large scale wind integration calls for generation planning which is an important aspect in order to meet the customer demands with optimum mix of generation like thermal, hydro and renewable energy sources. Power system reliability assessment methods can be categorized into analytical or Monte-Carlo simulations. Monte-Carlo simulation methods, compute the reliability indices by simulating the random behavior of the power system, and can include any system processes which are approximated in analytical methods. In this paper wind model at regional level has been proposed using Monte-Carlo simulation approach in order to find the impact of the intermittent energy sources on generation planning for interconnected power system. In the present paper two neighboring regions in southern part of India with high wind penetration levels have been considered for analysis considering the reliability index as per regulations.*

Key words: *Generation planning, high wind penetration, interconnected system, Monte Carlo Simulation, probabilistic methods, reliability Index.*

1. Introduction

Generation planning determines the optimal size, time, and location of additional generating units for facilitating economic, secure, and reliable operations of a power grid. In isolated utility environment, the only option available for maintaining system reliability is to upgrade existing facilities or to add new generating units and transmission facilities. In interconnected environment, which is normally the case, the utility can have a mechanism for sourcing some of the reserve to maintain reliability from neighboring systems. This type of reserve sharing takes advantage of the load, generation mix and outage diversities that generally exist in interconnected systems. Consequently, each utility can maintain the desired level of reliability with lower installed reserves compared to isolated operation, i.e. reduced reserve costs.

In interconnected power systems, the coordination between the generations in connected system would become more critical as it could enhance the reliability of individual areas as well as that of the entire system. The actual interconnection benefits depend on the installed capacity in each system, total tie capacity, the forced outage rates of tie lines, the load levels and the residual uncertainties in each system and type of agreement in existence between the systems [1].

The probabilistic methods in planning phase are well developed in the literature [1]-[2]. The present tools developed to handle wind power variability and uncertainty has been discussed in [3]. The application of probabilistic approaches for interconnected power systems have been discussed in [9], [20]-[21]. The reliability analyses discussed in literature [5], [7], [16], [19] are applied to practical interconnected power systems using probabilistic methods.

In interconnected power system analysis, Monte-Carlo simulation method has been selected in the most of the literature [6], [9] for reliability analysis. A direct method using network flow algorithm has been addressed in [20]. Decomposition method for reliability analysis of interconnected power system is addressed in [10], [18].

Work has been conducted on large scale integration of wind power systems and the impact on the system reliability in planning phase for standalone systems [14]. Multistate wind energy conversion system models for adequacy assessment with wind energy are presented in [2]. The modeling of wind power presented in above literature is poised with difficulty in the practical scenario when wind penetration level increases. Further, including wind speed forecast in the modeling of each individual wind turbine operating horizon would be difficult as there would be thousands of wind turbines in the practical domain (in the considered practical case there are more than 10000 wind turbines in one system). Hence, the region wise modeling of wind generation has been incorporated in the present paper.

Also from the literature [11], [15], it is observed that wind power forecast error will follow the normal distribution function with standard deviation. Considering this regional level wind generation has been modeled as normal distribution function considering the wind power forecast values with forecast uncertainties observed in the past.

This paper proposes a new methodology to address the modeling of large scale wind generation for interconnected power system using Monte-Carlo simulation technique as individual wind turbine modeling is not feasible for large utility systems. The imports and exports between interconnected systems are considered based on surplus power from thermal generation along with tie line constraints like total tie capacity, the forced outage rates of tie lines. The implemented methodology has been applied for practical interconnected power system in southern part of India where two neighboring systems having high wind penetration levels of 46% and 17% respectively.

2. Methodology

A power system consists of three functional zones of generation, transmission and distribution. These functional zones can be combined to form hierarchical levels. Hierarchical Level I (HL-I) is concerned with only the generation facilities, while Hierarchical Level II (HL-II) includes both the generation and transmission facilities and Hierarchical Level III (HL-III) includes all the three functional zones to provide a complete system. Adequacy evaluation at HL-I involves the determination of the total system generation required to satisfy the total load requirement and the model for adequacy evaluation at HL-I is shown in Fig. 1.

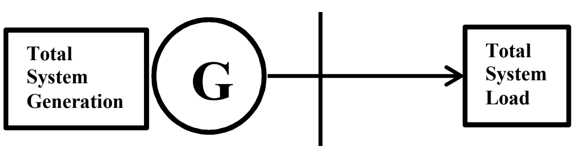

Fig. 1 Model for adequacy evaluation at HL-I

The basic approach to perform adequacy evaluation at HL-I consists of three segments as shown in Fig. 2. The generation and load models are combined to form the risk model. The risk indices obtained are overall system adequacy indices and do not include transmission constraints and transmission reliabilities.

The balance between the supply of electricity and the demand is quantified using a reliability indicator called the Loss of Load Probability (LOLP) or Loss of Load Expectation (LOLE). When this indicator is at an appropriate level namely, the generation adequacy standard specified by state regulation like GRIDCODE, the supply/demand balance is judged to be satisfactory. Once the LOLP/LOLE is calculated, any divergence from specified reliability standard is analyzed and quantified in terms of adequacy/ surplus/ deficit in MW capacity.

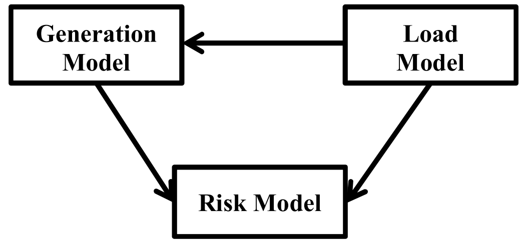

Fig. 2 Conceptual model in adequacy assessment at HL-I

In the recent time the generation planning is being increasingly carried out using probabilistic methods as the customer demand variations, generation variations (including intermittence nature of the renewable energy sources), and component failures are all probabilistic in nature. Probabilistic methods can be categorized into two types, analytical and Monte-Carlo simulation methods.

Two different approaches are reported [1] for calculating the LOLE indices in interconnected systems. They are the probability array method and equivalent assisting unit method. In the first method, a capacity model will be developed for each system and an array of simultaneous capacity outage existence probabilities will then obtained from individual models. The second method models the assisting system as an equivalent assisting unit which can be with tie line constraints and added into the existing capacity model of the assisted system as shown in Fig. 3. Later the computation of the risk in the assisted system is same as normal single system study. This paper uses the second approach, i.e. equivalent assisting unit method using Monte-Carlo simulation technique.

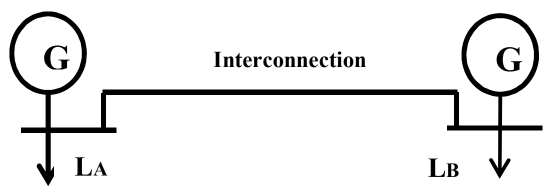

Fig. 3 Model of interconnected systems in HL-I studies

A brief description of Monte-Carlo simulation methods is presented below.

Monte-Carlo Simulation Method

Monte-Carlo Simulation methods estimate the reliability indices by simulating the actual process and stochastic behavior of the system. Probabilistic or stochastic simulation itself can be used in one of two ways: sequential or non-sequential. The sequential approach simulates the basic intervals in chronological order. The non-sequential approach simulates the basic intervals of the system lifetime by choosing intervals randomly. In this paper the generation planning model is implemented based on non-sequential approach and is applied for high wind penetration interconnected power system.

The major steps involved in Monte-Carlo simulation approach are:

- Generate operating histories for each generating unit;
- Combine the operating cycles of all units and produce total available generation capacity;
- Super imposition of the available capacity on the load curve for single area system as shown in Fig.4 ;
- Calculate the required reliability risk index;
- Verify the stopping rules.
- After calculating the surplus power in individual systems based on corresponding reliability targets, the surplus power from thermal generation from any system can be allocated to deficit system, considering the interconnection tie line constraints.

The modeling details of components in non-sequential Monte-Carlo simulation approach is described below.

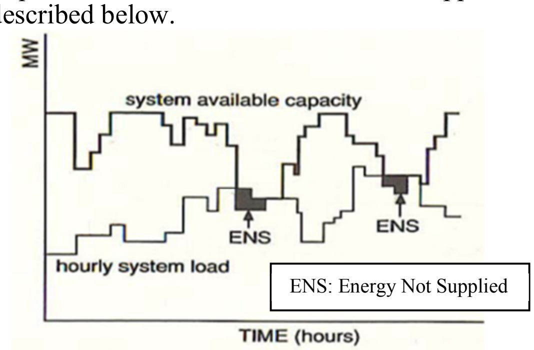

Fig. 4 Superimposition of the available capacity on the load

Base Load Generating unit Models:

The two state models for base load generating unit are shown in Fig. 5. The base load unit can also be modeled with derated or partial output state as shown in Fig. 6. This model can be expanded to include more number of derated states. However more than 3 or 4 state models are not necessary for reliability analysis as reported in the literature [1].

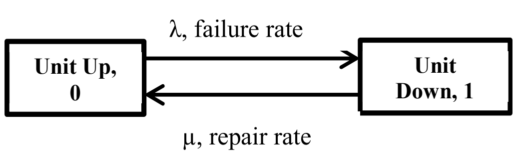

Fig. 5 Two-state model for a base load unit

$$UP\ state\ probability = P_{up} = \frac{ST}{ST + FOT}$$

$$DOWN\ state\ probability = P_{down} = \frac{FOT}{ST + FOT}$$

ST → Service Time (hours)

FOT → Forced outage Time (ours)

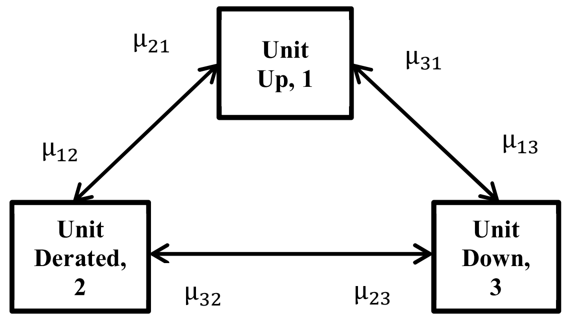

Fig. 6 Three-state model for a base load unit

$$A = \mu_{31}\,\mu_{21} + \mu_{31}\,\lambda_{23} + \mu_{32}\,\mu_{21}$$
$$B = \lambda_{13}\,\mu_{21} + \mu_{32}\,\lambda_{12} + \mu_{31}\,\lambda_{12}$$
$$C = \lambda_{12}\,\mu_{23} + \lambda_{13}\,\lambda_{12} + \lambda_{13}\,\lambda_{23}$$
$$D = A + B + C$$

$$UP\ state\ probability = P_{up} = \frac{A}{D}$$

$$DERATED\ state\ probability = P_{derated} = \frac{B}{D}$$

$$DOWN\ state\ probability = P_{down} = \frac{C}{D}$$

Peak Load or Hydro Generating Unit Modeling

Hydro units which are used for peaking units operate for relatively short times and are frequently started and stopped. The model used for base load unit is not adequate to model peaking units. The 'IEEE Task Group on Models for peaking Service Units' proposed the four-state model [12] to model the peak load units or hydro units. However, modeling of hydro units in most of the practical conditions is limited by energy constraints and unavailability of data. Hence in this approach, the status of the hydro units are simulated by considering their forced outage rate, system load level, the power output from conventional units & wind farms, and the energy limitation imposed by water availability [13]. The energy availability has been considered from past history of water availability.

Wind Generation Model

The wind power forecast error almost follows a Gaussian distribution or normal distribution [8], [15]. In this paper, the stochastic nature of the wind power forecast error has been modeled as normal distribution function with mean and standard deviation (σ) for each hour from the historical wind power data. The probabilistic methods like Monte-Carlo simulation technique can simultaneously consider the stochastic nature of this variation in wind power along with demand variation. In simulation, the normal distribution function is constructed as shown in Fig. 7 up to ±3σ using modified Box–Muller transform technique [17] from historical wind power data with Wind Forecast Uncertainty (WFU).

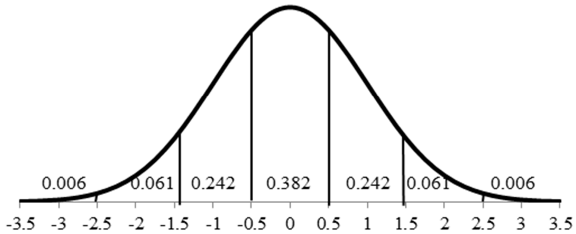

Fig. 7: Seven step approximation of the normal distribution.

Algorithm:

Step1: Generate uniform random numbers U_1, U_2 in the range of $[0, 1]$

Step 2: Generate random numbers v_1, v_2 such that,

$$v_1 = (2 * U_1) - 1;\ v_2 = (2 * U_2) - 1$$

Step 3: Calculate $r = v_1^2 + v_2^2$

Step 4: If $r \geq 1$, then go to step 1;
Otherwise Calculate ,

$$X = v_1 \left[\frac{-2 \ln r}{r}\right]^{\frac{1}{2}},\ Y = v_2 \left[\frac{-2 \ln r}{r}\right]^{\frac{1}{2}}$$

Step 5: use generated random number X or Y for hourly simulation of wind power in Monte-Carlo simulation

3. Validation of the Model

The basic models are validated with IEEE Reliability Test System (RTS) [24] [25] and the results are presented in Table 1. As stated in [24], in practice, COPT's are truncated and rounded, which, when convolved with load models, which may also be approximated, can give results with varying degrees of inaccuracy based on the computer precision. The accuracy of the Monte-Carlo simulation models depends on the stopping criteria adopted [1].

4. System Data

The studies have been performed for two high wind penetration systems in INDIA where the wind penetration levels (wind installed capacity/total installed capacity including wind) are around 46% and 17% respectively. The total installed capacity of one of the systems including wind is 15500 MW where wind installed capacity is around 7190 MW. This works out to be around 46% (7190*100/15500) of wind penetration level. The hydro units installed capacity of the system is around 2220 MW and the rest of the generation comes from coal, gas, diesel base units. The second system has the total installed capacity of 12715 MW where wind installed capacity is around 2160 MW. The wind penetration level for this system is around 17% (2160*100/12715). The hydro units installed capacity of the system is around 3670 MW and the rest of the generation comes from coal, gas, diesel base units. In addition to above installed capacity, the central share which is mainly thermal power plants for the corresponding systems has been considered for the analysis [22], [23]. Historical minute wise wind power data has been analyzed to understand the behavior of wind power variation. Fig. 8 shows the wind power availability along with demand requirements. It is clear that the maximum wind power occurrences are not at the same time of peak demand occurrences and low wind power availability during night times is in-line with demand profile. This kind of high wind penetration profile along with demand profile poised to have more system complexities during the system integration and generation schedules.

Table 1: Validation of LOLE Calculation

	Analytical method, published	**Monte-Carlo simulation, published**	**Developed Program**	
			Analytical method	***Monte-Carlo simulation***
Case 1: Two state generation model				
LOLE (days/year)	1.36886	*NA**	1.36886	1.3646
LOLE (hr's/year)	9.39418	9.34130	9.28659	9.3400
Case 2:Case 1 with multi state unit model				
LOLE (days/year)	0.88258	*NA*	0.883	0.85276
LOLE (hr's/year)	*NA*	5.13909	5.602	5.6075
Case 3: Case1 with load forecast uncertainty of 5%				
LOLE (days/year)	1.9113	*NA*	1.911315	2.026116
LOLE (hr's/year)	*NA*	*NA*	13.40174	13.56044
Case 4: units with maintenance				
LOLE (days/year)	2.66659	*NA*	2.670497	2.8118
Case 5: Case 1 with 20 MW units as hydro peaking units				
LOLE (hr's/year)	*NA*	8.71733	-----	8.72

**NA – Not available*

The Forced Outage Rates (*FOR*), planned outages and auxiliary consumption of generating units for present and future are considered from the GRIDCODE and same is presented in Table 2 and Table 3.

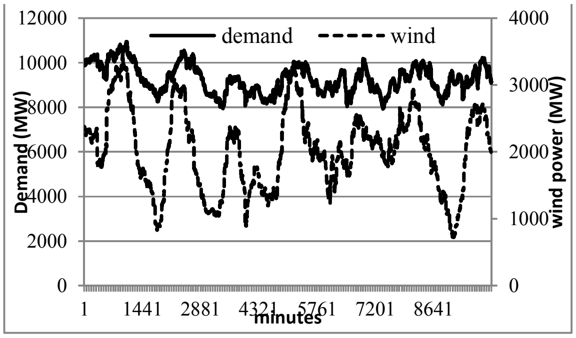

Fig. 8: Wind and demand profile for one week (high wind season, minute wise data)

The hourly demand data of previous years has been considered as base load curve based on the minimal load shedding events. Individual hydro units or energy limited units are modeled by their specific capacity and available energy estimated from the historical hydro energy availability (seven years past data has been considered) as presented in Fig. 9. Pumped storage units have been modeled by altering the load curve like dispatching the unit capacity to meet peak demands and restored the water in off peak demands.

Table 2: Generating Unit Planned Outage Rates & FORs

Unit Type	Planned Outage (POR)		Forced Outage (FOR)	
	(days/year)	(%)	(days/year)	(%)
Hydro Electric	30	8.2	16 to 37	4.5 to 10
Steam Thermal	35	10	51	14
Gas Turbine	30	8	37	10

Table 3: Generating Unit Auxiliary Consumption

		Size/Type	Auxiliary Consumption
1	Coal based Thermal Power Station	i) 200 MW ii) 500 MW	9.5% 8.0%
2	Gas Based Thermal Power Station	i) Combined cycle ii) Open cycle	3.0% 1.0%
3	Hydro Station		0.5%

The stochastic nature of the wind power forecast is modeled as normal distribution function with mean and standard deviation error for each time interval. The normal distribution function is generated from the available historical wind power data using Box–Muller transform technique.

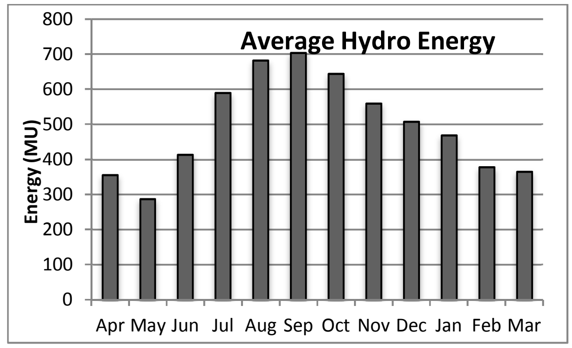

Fig. 9: Average historical energy availability (2011-12 to 2005-06)

By convolving the operating histories of all the generating units and load duration curve the reliability index, LOLE/LOLP, is evaluated for each state presented in next section. The reliability index LOLP of 2% (i.e LOLE of 175 hours/year) has been used for generation planning analysis as per present GRIDCODE. After calculating the surplus power in individual systems for each interval, the surplus power from thermal generation is allocated to deficit system considering the interconnection tie line constraints. The case studies for this interconnected system have been performed to understand the effect of tie lines on system reliability for wind rich connected systems.

4. System Analysis

The following procedure is considered to model the system for generation planning studies.

i. Generation unit availability is considered based on the unit's planned and forced outage rates as presented in Table 2.
ii. All available conventional generation up to the study year is considered. (Ex: for 2014-15 study, the generation available up to 1st, April, 2014 has been considered).
iii. *LOLP* of 2% (i.e. LOLE of 175 hours/year) is considered according to GRIDCODE.
iv. The maximum unit capacity to meet the demand is considered after the unit auxiliary consumption (called as effective capacity) as presented in Table 3.
v. Hydro units are modeled as energy limited units with its maximum installed capacity.
vi. The forecasted wind power is considered with uncertainty of 5% standard deviation. This uncertainty is modeled as seven step normal distribution function with maximum of three times standard deviation.
vii. Forecasted peak demand has been considered as per 18th EPS (Electric Power Survey) [26]. The forecasted peak demands for the year 2014-15

for two systems are 16805 MW and 11123 MW respectively.

viii. The surplus power if any (surplus power has been calculated based on reliability targets) from thermal units are allowed for export considering the other system deficiency and tie line constraints.

ix. Tie line capacity details and tie line constrains (assumed) are presented in Table 4.

x. High wind season has been considered from June to October (five months) based on the historical data and the reliability analysis has been performed with available hydro energy during this time horizon.

Table 4: Tie Line constraints for interconnected system

S. No.	Tie Line From	Tie Line To	Tie Line Capacity (MW) Min-Max	Tie Line FOR per km	Tie Line Length in km
1	1	2	0 – 2500	0.00025	400
2	2	1	0 - 200	0.000285	350

Individual System Analysis

The annual study results are presented below for the year 2014-15 considering the above presented data and methodology. The analysis is performed with wind generation in both areas and thermal unit unavailability of 14% (considering only unit FOR of 14%) and case study results are presented in Table 5 and Table 6 for individual system with wind capacity credits in respective systems.

Table 5: Annual LOLE indices for individual power system

	Annual	
	System 1	**System 2**
Total Effective Capacity without Wind Generation (MW)	14430	11260
Wind Installed Capacity for analysis year (MW)	8000	2900
Forecasted Peak Demand (MW)	16805	11123
LOLE (hours/year)	4164	366
Peak Demand Met with LOLP of 2% (LOLE = 175 hours/year) with full generation (MW)	13000	10750
Surplus (+)/deficit (-) peak power in MW	-3805	-373
Peak Demand Met with LOLP of 2% (LOLE = 175 hours/year) without wind generation (MW)	12080	10150
Wind Capacity credit (MW)	920 (11.5%)	600 (21%)

Table 6: Seasonal LOLE indices for individual power systems during High Wind Season (June-Oct)

	High Wind Season	
	System 1	**System 2**
Total Effective Capacity without Wind Generation (MW)	14430	11260
Wind Installed Capacity for analysis year (MW)	8000	2900
Forecasted Peak Demand (MW)	15700	9217
LOLE (hours/year)	461	0.09
Peak Demand Met with LOLP of 2% (LOLE = 175 hours/year) with full generation (MW)	14733	10814
Surplus (+)/deficit (-) peak power (MW)	-967	+1597
Peak Demand Met with LOLP of 2% (LOLE = 175 hours/year) without wind generation (MW)	11370	9720
Wind Capacity credit (MW)	3363 (42%)	1094 (38%)

From Table 5, it is observed that both systems are in deficit for annual basis when both systems are operated independently. From Table 6, it is observed that during high wind season, i.e. from June to October, one system is in surplus and other system is in deficit. It is also clear that the wind power capacity credit is varying in annual and seasonal studies.

Interconnected System Analysis

The variation of annual LOLE for respective systems with tie line capacity for interconnected system is presented in Table 7 and Fig. 10.

Table 7: Annual LOLE indices for interconnected system

S. No.	Tie Line Transfer Capacity (MW)	LOLE (hours) for System 1	LOLE (hours) for System 2
1	0	4164.05	366.31
2	500	3993.43	365.92
3	1000	3891.99	365.9
4	1500	3844.8	365.89
5	2000	3828.27	365.89
6	2500	3823.97	365.89

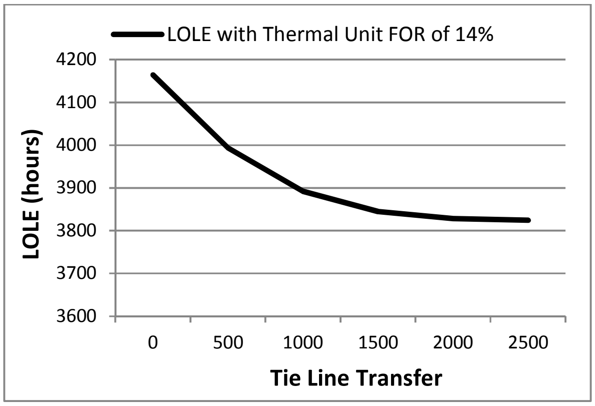

Fig. 10 Annual LOLE index verses tie line capacity for system-1

From the annual reliability studies for interconnected system it is observed that reliability of the deficit system (system-1) is improved in proportion with tie line capacity. It is also observed that there is no much benefits from annual studies because the two systems are in deficit condition as seen in Table 7 where system-1 has loss of load incidents of 4164 hours and system-2 has loss of load incidents of 366 hours. This scenario may change depending on wind/hydro season. Hence inter-connection between these two systems may help deficit system to decrease loss of load incidents in high wind scenario.

To understand high wind season scenario the analysis for interconnected system has been extended to high wind season starting from June to October. The reliability study results during high wind season are presented in Table 8 and Fig. 11.

Table 8: High Wind seasonal LOLE indices for interconnected power system

S. No	Thermal Unit un-availability	Tie Line Transfer Capacity (MW)	LOLE (hours) for System 1	LOLE (hours) for System 2
1	14 %	0	461.16	0.09
2	14 %	500	352.63	0.06
3	14 %	1000	284.49	0.06
4	14 %	1500	245.35	0.09
5	14 %	2000	224.99	0.09
6	14 %	2500	216.36	0.09
7	24 %	0	1319.8	10.11
8	24 %	500	1199.83	9.41
9	24 %	1000	1113.91	9.35
10	24 %	1500	1054.16	9.34
11	24 %	2000	1015.83	9.34
12	24 %	2500	994.52	9.34

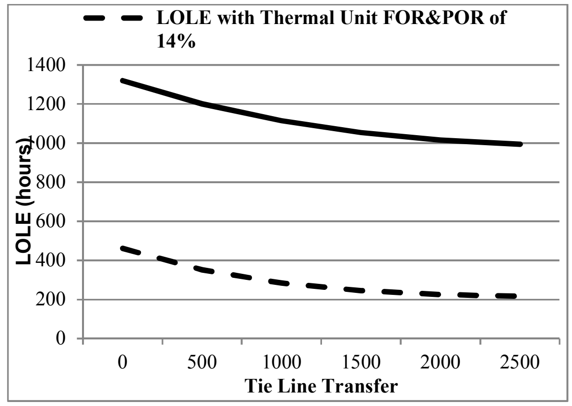

Fig. 11: LOLE verses tie line capacity for high wind season

From reliability analysis for high wind season presented in Table 8, it is observed that system-2 is in surplus and system-1 is in deficit. Hence interconnection between these two systems will help deficit system to decrease loss of load incidents. From case-1, it is seen that LOLE of the system-1 is 461 hours and it decreases with increase in tie line capacity in other cases presented. Hence the interconnection between these two systems is beneficial for deficit system during high wind season. As the interconnection tie lines between two systems are already available up to 2400 M, the deficit system can bring down the LOLE from 461 hours to 216 hours with the help of long term interconnection agreements. Hence this new methodology is beneficial for utility systems to plan for long term agreements between systems by performing the reliability planning analysis.

5. Conclusions

This paper presents a new methodology for modeling of large scale wind generation in planning studies. Probabilistic methods using Monte-Carlo simulation technique for inter-connected power system with generation mix of thermal, hydro and high penetrated wind generation has been used to find the effect of tie line capacity along with tie line forced outage rate on reliability of the interconnected system. The region wise modeling of wind generation has been proposed as normal distribution function considering the wind power forecast values with forecast uncertainties. The imports and exports between interconnected systems are considered based on surplus power from thermal generation along with tie line constraints like total tie capacity, the forced outage rates of tie lines. The new methodology has been applied for a practical interconnected power system in southern part of India where two neighboring systems are having high wind penetration levels of 46% and 17% respectively. From the results it is observed that the interconnection is beneficial to deficit system only during high wind season as both systems are deficit during low wind season. Hence this new methodology is beneficial for utility systems to plan for long term tie line agreements by performing the reliability analysis.

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