# Evaluation of Loss of Load Expected in an Integrated Energy System

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*Abstract: The main objective of work presented in this paper is about the prediction of power availability in advance from Energy Sources. The wind is a highly variable energy source and behaves quite different than conventional energy sources. The participation of wind energy with conventional sources of generation is increasing rapidly and it is treated as integrated energy system. In the case of wind energy, velocity predictions are important to assess the power generation in future. The prediction of wind velocity in this paper is further helpful to estimate the reliability analysis of the system. The reliability analysis is done by evaluating the Loss of Load Expected (LOLE). The reliability analysis of complete system with incorporation of wind power along with conventional plants is achieved through prediction of wind power. Hence the loss of load expected to happen in future is helpful to take decisions. The wind velocity predictions are validated with the actual data collected from MOSDAC (Metrological and Oceanographic Satellite Data Archival Centre).*

Keywords— *Reliability, Loss of Load Expected (LOLE), Wind Power, Integrated Energy System, Normal Distribution, Probability density function.*

## 1. Introduction

Every country is looking for renewable energy sources as an alternative source of generation with increasing demand for electrical power. The development and utilization of renewable resources is becoming a serious consideration due to fast reduction of fossil fuels and environmental considerations [1]. New technologies for electrical power from sun and wind have been developed and considerable research is going on to enhance the performance and also to understand their effect on the operation and economics of electrical power system. Many utilities and researchers consider the wind to be a promising and encouraging alternative for power generation because of the increasing environmental and social benefits [2].

Reliability is a main aspect of power system design and planning [3]-[6]. The economic and social effects of electric supply have significant impacts on both the generation side and the consumers. The power system operation is affected due to system abnormalities such as control failures, disturbances, lightning, faults and human operational errors. Therefore the reliable power supply to the consumers is disturbed [7]. As the wind units are being included along with the conventional power plants, the varying nature of wind makes it difficult to assess the future power output. The prediction of wind velocity is therefore helpful to find the power generation from the complete system including wind units [8]-[15]. The wind velocity predictive models are validated with the data collected from MOSDAC (Metrological and Oceanographic Satellite Data Archival Centre).

This paper presents a method to predict the wind velocity day ahead in advance. It is based on the past one week data. So the power availability of the future is estimated in advance and the reliability analysis is done in terms of Loss of Load Expected (LOLE) [16]-[20]. The probabilistic methods for operating reserves in power system are available in [21]-[22]. The average power availability at load buses through Electrical Circuit Approach is available in [23].

## 2. Modeling Considerations

The power available in the wind flowing through an area $A$ is given by

$$P_{wind} = \frac{1}{2} \rho V_w^3 A \tag{1}$$

where A is the area swept by the turbine blades, $\rho$ is the air density, $V_w$ is the velocity of the wind. According to the design of wind turbines about 40% of this energy can be extracted [7]-[10].

## 3. Methodology

The relationship between the power output of the Wind turbine generator and the wind speed is always non linear in nature. The relation can be analyzed by the operational parameters which are the cut-in, rated and cut-off wind speeds. The power out per hour is obtained from the known hourly average wind speed using the following equations [11]-[12].

The power output from the wind plant is given by,

$$P_g = A + BV + CV^2 \tag{2}$$

Where

$$A = \frac{1}{(v_i - v_r)^2} \left[ V_i(V_i + V_r) - 4(V_i V_r) \left[ \left( \frac{v_i + v_r}{2v_r} \right)^3 \right] \right] \quad (3)$$

$$B = \frac{1}{(v_i - v_r)^2} \left[ 4(V_i + V_r) \left( \frac{v_i + v_r}{2v_r} \right)^3 - 3(V_i + V_r) \right] \quad (4)$$

$$C = \frac{1}{(v_i - v_r)^2} \left[ 2 - 4 \left( \frac{v_i + v_r}{2v_r} \right)^3 \right] \quad (5)$$

Where

$V_i$= Cut-in Speed
$V_r$= Rated Speed
V= Actual velocity of wind

The complete generation system is divided into two sub systems as conventional and wind units. The integrated energy system comprising of conventional and wind generation is shown in Fig.1. The power output from wind units will partially meet the total demand. In this paper the availability of the power from the wind units is achieved by the prediction of wind velocity. This will give a chance to predict the power availability in future. The power output of conventional units is equal to their rated capacity and is assumed to be constant.
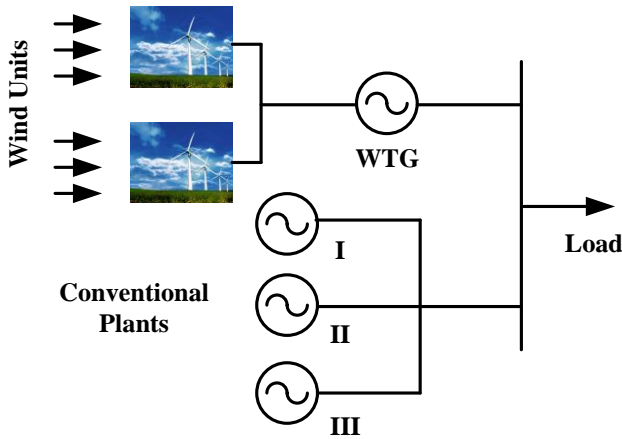


Fig.1. Integrated Energy system configuration

The hourly average wind velocity for a particular hour over the week is given in Table I. In order to predict the wind velocity on the 8th day based on the past seven days hourly data, the hourly wind velocity, $V_n$ on any day is calculated from the average wind velocity $V_0$ for the particular hour in the previous week, its standard deviation, $\sigma$ and constant $A_n$, as given by.

$$V_n = V_o + \sigma A_n \quad (6)$$

Where $V_n$= Wind velocity on the $n^{th}$ day
$V_o$= Weekly average wind velocity
$\sigma$ = Standard deviation of velocity
$A_n$= Constant

Table I
Wind Velocity data for one week in a particular hour

| S. No | Day | Wind Velocity (km/hour) |
|---|---|---|
| 1 | Mon | 13.5 |
| 2 | Tue | 15.0 |
| 3 | Wed | 16.5 |
| 4 | Thus | 16.0 |
| 5 | Fri | 14.7 |
| 6 | Sat | 16.5 |
| 7 | Sun | 16.3 |

Here one week hourly wind velocity is used to obtain the weekly average and the standard deviation of the velocity. The wind velocities in a particular hour of the day changes with the constant $A_n$, which is assumed to follow a second order polynomial as given in Eq (7). The constant An in Eq (6) is given by

$$A_n = m_o + m_1 X + m_2 X^2 \quad (7)$$

Where the n and X constant correspond to the day number and $m_o, m_1, m_2$ are the constants. The profile of the wind velocity in a particular hour of the day is shown the Fig. 2. From which $V_O$ and $\sigma$ are obtained.
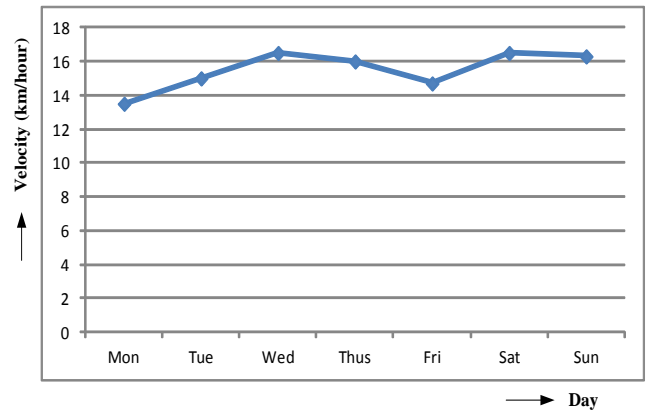


Fig.2. Profile of wind velocity

From Eq (6), the constants $A_0$ to $A_7$ for the particular hour in the week are calculated and using Eq (7) constants $m_0, m_1, m_2$ are evaluated by minimizing the error in the calculation of $A_n$. The average wind

velocity and standard deviation computed for the week are 15.5 km/hour and 0.01 respectively. From this data using the previously calculated constants $m_0, m_1, m_2$ the wind velocity of the 8th day for the hour under consideration is computed one day ahead. It is assumed that the weekly average wind velocity $V_O$, and the standard deviation $\sigma$ calculated from the past one week remain same for the day ahead prediction of wind velocity and the constant $A_8$ for the 8th day is obtained from Eq (7). From the computed wind velocity, the power availability from the wind unit is calculated using the Eq (2). For the conventional generators the power availability is assumed to be equal to their capacity multiplied by the availability index.

Similar procedure is used for predicting the load for a particular hour on the 8th day based on the load data available over the last week. The load profile for the particular hour during the past one week is shown in Fig.3. From this the weekly average load and its standard deviation are obtained as $P_0 = 495.2MW$, $\sigma = 0.06$. For the predicted load on the 8th day, the same parameters are used. The wind power generation and load are variable in nature. The predicted wind power generation and the load on 8th day are the hourly average values and their variation over the hour is assumed to follow normal distribution as shown in Fig.4. The Fig.5 shows the cumulative distribution function. Where X is the variable and $X_{average}$ is the average value over the hour. So $X_O$ is equal to 1 and $\sigma$ is taken from the past one week hourly data of the variable.
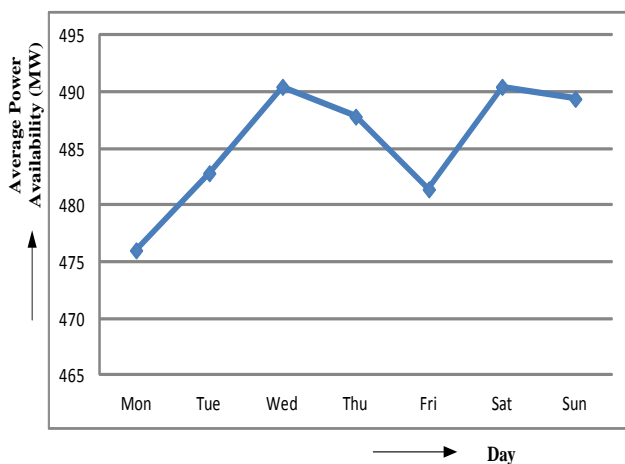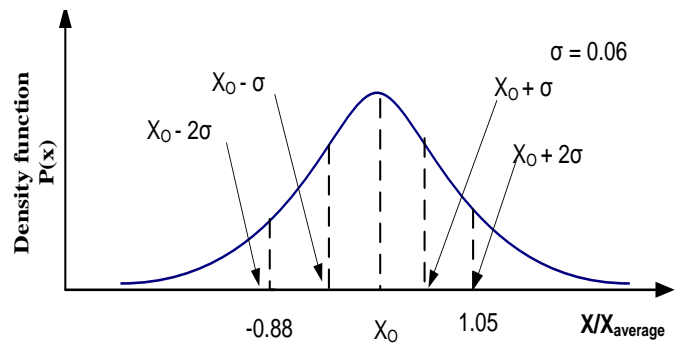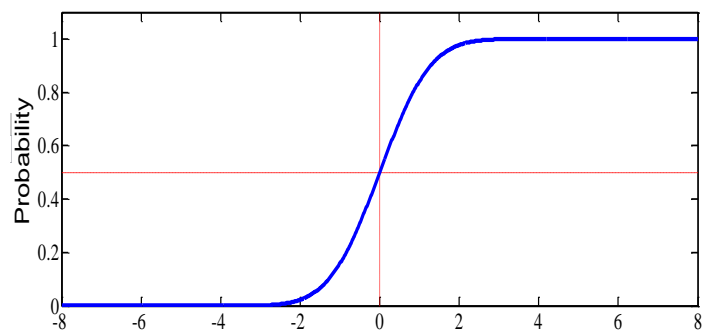


Fig. 4. Normal distribution density function



Fig.5. Cumulative distribution function

Based on the probability theory for normal distribution the variable, $\frac{X}{X_{average}}$ will stay between the limits $(1 - 2\sigma)$ and $(1 + 2\sigma)$ with a confidence level of 95%. The variable X represents wind generation / load on 8th day for the specified hour with respective average values and standard deviation.

The total power generation includes conventional power ($P_{CG}$) and wind power ($P_{WG}$). $P_{CG}$ is assumed to be constant and $P_{WG}$ has the normal distribution, Fig.6 represents the probability distribution of the wind generation and the total generation. To obtain the probability density for the wind generation the value of $X_0$ is the average wind power.



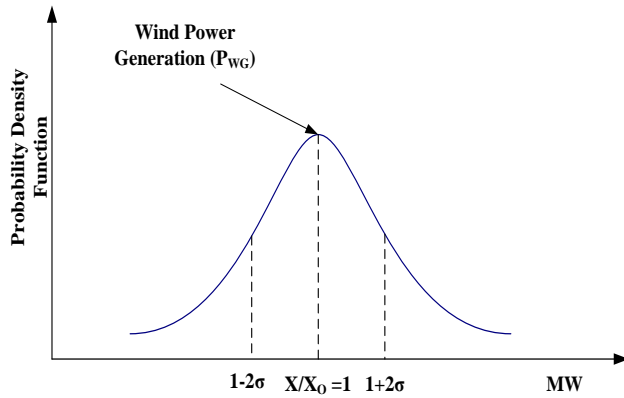Fig.3. Load profile for the particular hour over the week

Fig.6. Wind and Conventional power generation variation

The loss of load expected (LOLE) is calculated as follows. The Fig.7 shows the variation of both generation and load. In the Fig.7, $P_{LO}$ is the average load for the specified hour and $P_{GO}$ is the average total generation for the specified hour. The variable X represents the quantity, which has the variable nature like load and wind power. That variation is assumed to follow normal distribution. The shaded area in the Fig.7 gives the loss of load with $\dfrac{X}{X_{Average}}$ for load varying from 0.88 to 1.05, because in this region the probability of available total generation is lower than that of the load. Hence the loss of load is expected to happen and LOLE is calculated as per Eq (8).

$$LOLE = \int_{0.88}^{1.05} P(x)(P_1 - P_2)dx \qquad (8)$$

Where $P_1$, $P_2$ are the probabilities of load and generation.

Beyond the intersecting point the probability of power generation is more than load demand, hence there will be no expected loss of load.
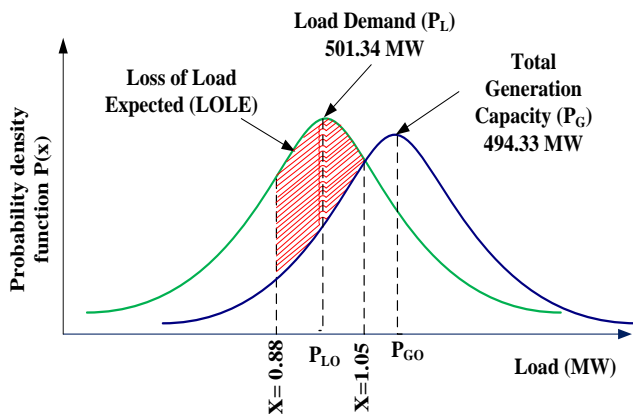


Fig.7. LOLE calculation

## 4. Results and discussion

The availability of the power for the 8th day is estimated by the above mentioned method using the following data. The complete system contains the three conventional generators units and two wind generator units shown in Fig.1.

The total estimated demand for the system is 600 MW for the particular hour on the 8th day. The total power generation capacity from the conventional plants is 450 MW and power capacity from the wind units is 150 MW at the rated wind speed $V_r$ of 21 km/hour and cut-in speed $V_i$ of 12 km/hour.

To obtain the probabilistic estimate of the available power from the conventional and wind generator units the failure and repair rates ($\lambda$ & $\mu$) are assigned for each unit. The data for the estimation of probability of loss of load is given below. The failure rate and repair time of the each unit are given in the following Table II and III.

Table II
Reliability data for the Conventional Units

| Parameter | Unit I | Unit II | Unit II |
|---|---|---|---|
| **Rated Power (MW)** | 100 | 150 | 200 |
| **Failure Rate $\lambda$ (Fails/Year)** | 6 | 5 | 4 |
| **Repair Rate $\mu$ (Hours/ Year)** | 45 | 45 | 45 |
| **Availability** | 0.88235 | 0.9 | 0.91836 |
| **Unavailability** | 0.11764 | 0.1 | 0.081632 |

Table III
Reliability data for the Wind Units

| Parameter | Unit I | Unit II |
|---|---|---|
| **Rated Power (MW) at rated wind velocity** | 75 | 75 |
| **Failure Rate $\lambda$ (Fails/Year)** | 3 | 3 |
| **Repair Rate $\mu$ (Hours/ Year)** | 40 | 40 |
| **Availability** | 0.93023 | 0.93023 |
| **Unavailability** | 0.06976 | 0.06976 |

The constants $m_o$, $m_1$, $m_2$ in the Eq (7) for the wind velocity are -0.3587, -1.19485, 0.25691 respectively. The constants in the Eq (6) are given in Table IV. These constants are calculated using the past available data. These constants are useful in the further calculations of the second order polynomial.

Table IV
Constants in the equation (6)

| Constants | Value |
|-----------|---------|
| $A_1$ | -5.01924 |
| $A_2$ | -1.2548 |
| $A_3$ | 2.50962 |
| $A_4$ | 1.2548 |
| $A_5$ | -2.00769 |
| $A_6$ | -2.5096 |
| $A_7$ | 2.0076 |

The Graphical representation of availability of conventional generating units is given in Fig.8.
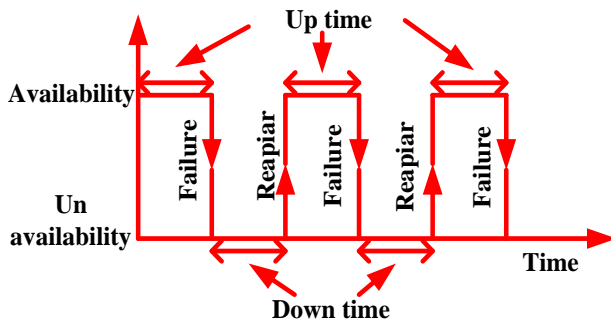


Fig.8. Availability of Conventional Generating Units

Based on the weekly wind data given above and adapting the procedure discussed above, the 8th day wind velocity is obtained as 18.168 km/hour and using the Eq (2) wind generated power is 93.99MW. The generation capacity is 600MW.

The power availability from the conventional generators is given by
Probability of availability * Capacity= 406.907MW ($P_{CG}$).

Similarly for the average power available from the wind units is 87.43MW ($P_{WG}$). The probability of power availability for the conventional and wind units are calculated from the failure and repair rates of the corresponding unit [23].

Therefore the power available from the Conventional and wind generator units is 494.33MW ($P_{Go}$) and this generation varies between the limits $P_{CG} + P_{WG}(1 - 2\sigma_1)$ to $P_{CG} + P_{WG}(1 + 2\sigma_1)$, Where $\sigma_1$ is the standard deviation of the average wind velocity equal to 0.01. Similarly the average load on the 8th day is $P_{Lo}$ and varies between $P_{Lo}(1 - 2\sigma_2)$ to $P_{Lo}(1 + 2\sigma_2)$, where $\sigma_2$ is the standard deviation for the average load. The average load demand on 8th is 501.34 MW.

The expected loss of load during the specified hour of the 8th day is 5.6 MW from the area calculated in Fig.7. Similar procedure can be adapted for the other hours of the day. The daily loss of load probability can

then be estimated.

In the present study, $X_{average}$ is the average load (Q) at the specified hour on the 8th day. Its standard deviation $\sigma_2$ is assumed to be same as that calculated from the past seven days data which is equal to 0.06. Based on the confidence level of 95% the available power at load will lie between the limits 0.87Q and 1.15Q. So the load varies between 397.24 MW to 571.93 MW with a confidence limit of 95% shown in Fig.9. The variation of LOLE on 8th day at each hour is plotted in Fig.10.
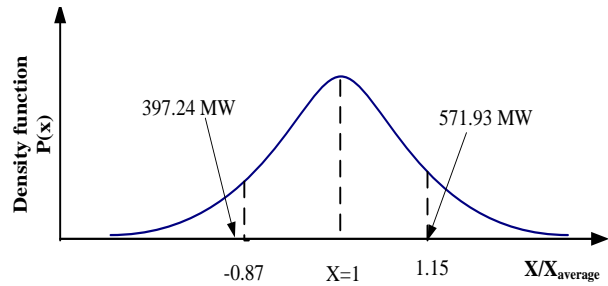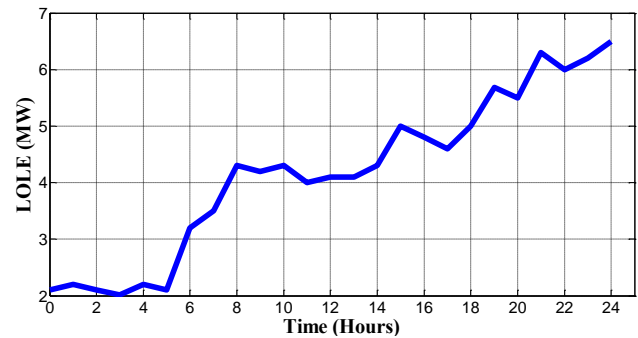


Fig.9.Variation of load and Limits



Fig.10. Variation of LOLE on 8th day

## 5. Conclusion

Evolution of loss of probability of load in an integrated energy system has been presented in this paper where some wind units and conventional units are considered to study. The probabilistic availability of power generated from the wind units is evaluated by considering the hour wind velocity data. The Loss of load expected (LOLE) is predicted in advance through the proposed methodology. The reliability index LOLE is estimated in advance and it will help to take decisions for power system planers. The velocity predictions are validated by MOSDAC.

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