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Evaluation of Reliability Indices and Cost Worth Analysis for Generating Power Plants

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***Abstract* -- Recent research and development of alternative energy sources have shown excellent potential as a form of contribution to conventional power generation systems. The main objective is to study the concept of Capacity Availability of Wind Turbine for maximum utilization of resources. Since wind speeds vary from month to month and second to second, the amount of electricity wind can produce varies constantly. Using wind turbine model and probability theory, the Capacity Availability of wind power is estimated which forms an important input to proper resource utilization along with the probability of wind power.**

The most commonly used are the Loss-of-load probability (LOLP), the Loss-of-load expectancy (LOLE) and Loss of Energy Expected (LOEE). The Capacity Outage Probability Table (COPT) and Markov Process, an Analytical method is used for calculating reliability indices. This method is one of the simplest and straightforward ways of estimating reliability. Another method for evaluation of reliability indices is Monte Carlo Simulation (MCS) method. The advantages of MCS over analytical method are discussed in detail when analysis is done on IEEE RTS and Laboratory – based micro grid (LMD) system. Customer interruption costs (CIC) are used as substitute in the assessment of reliability worth in electric power systems. In order to determine an optimal and reliable level of customer service, reliability cost/worth is to be assessed by calculating the costs associated with different system configurations and assessing the corresponding reliability worth at the respective system load points.

***Index Term* -- Reliability Indices, Capacity Availability, Wind Turbine, Resources Utilization, Cost & Worth Analysis.**

1. INTRODUCTION

The next generation of power systems must change and adapt to environmental factors, customer concerns, and reliability issues. Using Matlab, Mathematical wind turbine model is established. The various values of the wind speed are provided as input to this model. The random numbers are generated using Matlab programming and these are further converted into wind speed using suitable expressions.

The wind power is calculated by using these wind speed. For n wind speed samples, n wind power is obtained. The capacity availability of wind power refers to the capability of wind power to increase the reliability of the power system. The number of occurrence of wind power is shown with the help of graphical representation. The probability for the same is also shown. The proposed approach will be of immense help to the user for deciding the capacity available for the utilization of the resources.

In order to make a consistent appraisal of economics and reliability, it is necessary to combine the reliability criteria with certain cost considerations. Reliability cost/worth assessment provides the opportunity to incorporate cost analysis and quantitative reliability assessment into a common structured framework. Reliability cost refers to the investment needed to achieve certain level of adequacy. Reliability worth is the benefit derived by the utility, consumer and society because of higher reliability due to more investment in system.

2. WIND TURBINE DATA SIMULATION

The classical horizontal axis wind turbine with three rotor blades is predominantly used in most of the wind farms. The disadvantage of vertical axis turbine is that the tower is in the way of wind and wind swirls. About 90% of the installed wind turbines today have three rotor blades [1].

A. Turbine Swept Area (A):

This refers to the area in square feet of the rotor. It is also called the 'capture area'. The power output of a wind turbine is directly related to the area swept by the blades. The larger the diameter of its blades, the more power it is capable of extracting from the wind. It is given in m^2.

Pi x Radius^2 = Area Swept by the Blades.

B. Performance Coefficient (Cp):

Not all the energy can be recovered from a wind stream. The theoretical maximum value for the coefficient of performance is 0.593. In practice the value of the maximum values of coefficient is in the range 0.25 to 0.50.

C. Tip Speed Ratio (λ):

The Tip Speed Ratio (TSR) is an extremely important factor in wind turbine design. TSR refers to the ratio between the wind speed and the speed of the tips of the wind turbine blades. The λ - Cp characteristic of the turbine is illustrated in fig: 1

$$\text{TSR } (\lambda) = \frac{\text{Tip Speed of Blade}}{\text{Wind Speed}}$$

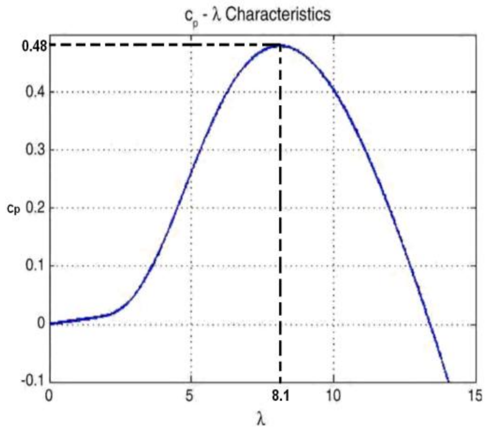

Fig.1. Cp – TSR Characteristic of Wind Turbine

D. Blade Pitch Angle (β):

Blade pitch control is a feature of nearly all large modern horizontal-axis wind turbines. While operating, a wind turbine's control system adjusts the blade pitch to keep the rotor speed within operating limits as the wind speed changes.

Blade Pitch Control = Control of the rotor blades angle.

E. Wind speed (ms^{-1}) and Air Density [Kg $(m^3)^{-1}$]:

Wind speed is the speed of wind, the movement of air or other gases in an atmosphere. In our case, we have taken 10 m/s and 7 m/s. Air density here taken is 1.225 kg/m³ [1].

3. WIND SPEED MODEL

The speed of wind is random; hence probability theory is used to understand the behavior of wind speed. The probability of occurrence of a particular wind speed can be described by 2-parameter Weibull distribution, Rayleigh distribution, Gamma distribution, Gulton distribution and Gumbel distribution etc [2]. And 2-parameter Weibull distribution, in all of these is most widely used. The function of 2-parameter Weibull distribution is

$$F_W(v) = P(V \leq v) = 1 - \exp\left[-\left(\frac{v}{c}\right)^k\right] \quad \text{...... (1)}$$

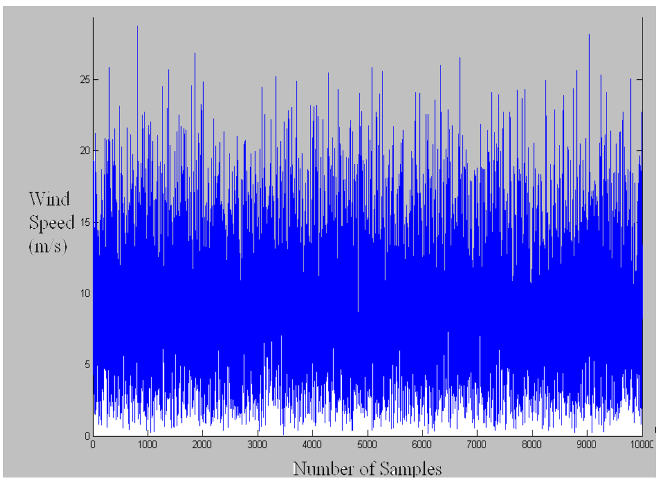

Fig.2. Wind speed sample process for 10000 samples.

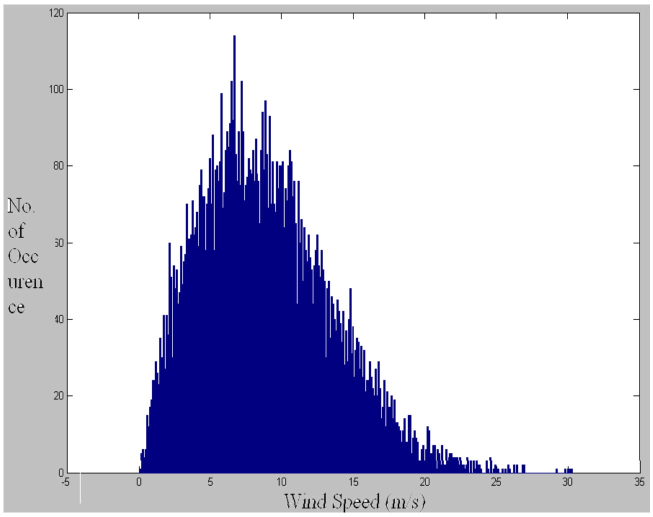

Fig.3. Wind speed probability distribution.

4. ELECTRICAL POWER OUTPUT MODEL OF WIND TURBINE

Power curve of a wind turbine describes the relationship between input wind speed and output electrical power of a wind turbine generator. The simplest model would use a straight line to describe the variation in output power between cut-in and rated wind speeds. For more accurate results, output power is assumed to vary as *v* between cut-in and rated wind speeds, where *k* is the

Weibull shape parameter. A power curve of a wind turbine is shown in Fig.4 [3] Electrical power output of a model wind turbine can be defined as:

Pt = 0, v<vci
Pt = (a + (b*v)), vci<=v<=vr
Pt = Pr, vr<=v<=vco
Pt = 0, v>vco ...... (2)

Where parameters *a* and *b* is defined as:

a= (Pr*Vci)/(Vci-Vr);
b= (Pr)/(Vr-Vci);

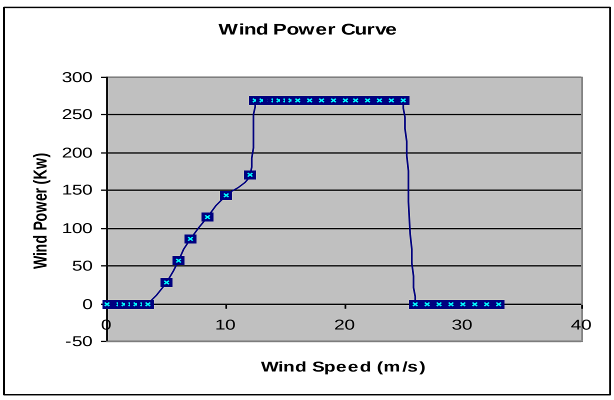

Fig.4. Power curve of a wind turbine.

5. SIMULINK MODEL OF WIND TURBINE

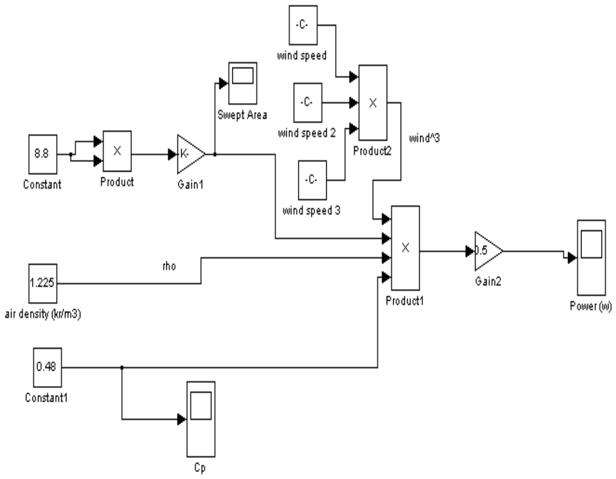

Fig.5. Mathematical Simulink model of Wind Turbine

Figure.5. represents the Simulink model of wind turbine. All the necessary values has to given to get the final mechanical output (Tm) which is to fed to the Induction Generator to get the electrical output. The parameters used in the mathematical modeling of the wind turbine are as follows:

A = Turbine swept area [m^2]
Cp = Performance coefficient of the turbine
Cp_pu = per unit (p.u.) value of the performance coefficient cp
Kp = Power gain for Cp_pu = 1 and Vwind _pu = 1 p.u., kp <=1
Pm = mechanical output power of the turbine [W]
Pm_pu = power in p.u. of nominal power for particular values of ρ and A
β = blade pitch angle [°]
λ = tip speed ratio of the rotor blade tip speed to wind speed
ρ = air density [kg/m^3]
Vwind = wind speed [m/s]
Vwind_pu = p.u. value of the base wind speed. The based wind speed is the mean value of the expected wind speed in (m/s).
The output power of the wind turbine is given by

$$Pm = cp(\lambda, \beta)\frac{\rho A}{2}v_{wind}^{3} \quad \text{..... (3)}$$

After getting all the parameters for the above equations (Cp (λ, β) = 0.48, ρ = 1.2 kg (m3) −1,
r = 8.8m, v^3wind = 10m/s).

$$c_p(\lambda, \beta) = c_1\left(\frac{c_2}{\lambda_i} - c_3\beta - c_4\right)e^{(c_5/\lambda_i)} + c_6\lambda \quad \text{...... (4)}$$

Where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1}.$$

The coefficients values used are: $c1$ = 0.5176, $c2$ = 116, $c3$ = 0.4, $c4$ = 5, $c5$ = 21 and $c6$ = 0.0068. The maximum value of cp, (cp = 0.48) is achieved for β = 0° and λ= 8.1. This particular value of λ is defined as the nominal value [1].

6. CAPACITY AVAILABILITY

The wind power is computed for 100 wind speed samples with the help of the Simulink model. The capacity availability of wind power refers to the capability of wind power to increase the reliability of the power system. Capacity factor is one element in measuring the productivity of a wind turbine or any other power production facility. It compares the plant's actual production over a given period of time with the amount of power the plant would have produced if it had run at full capacity for the same amount of time [4][5]. To calculate the capacity factor, take the total amount of energy the plant produced during a period of time and divide by the amount of energy the plant would have produced at full capacity.

Availability factor (or just "availability") is a measurement of the reliability of a wind turbine or other power plant. It refers to the percentage of time that a plant is ready to generate [4] [5]. The maximum capacity availability of wind power has been calculated. The table shows the value for maximum available capacity.

Table.1. Availability of Wind Power

Sr.No	Available Capacity (kW)	No. of Occurrence
1	0-50	45
2	50-100	18
3	100-150	13
4	150-200	7
5	200-250	6
6	250-300	11

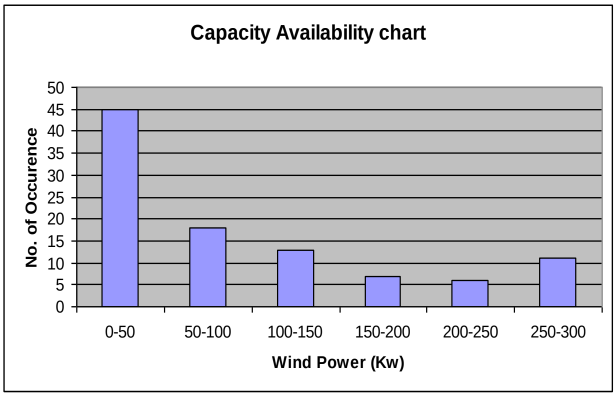

Fig.6. Capacity Availability Chart

The probability for the availability of wind power is shown below [6] [7].

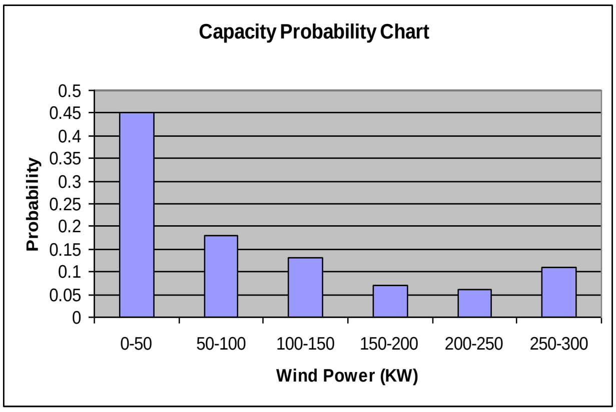

Fig.7. Capacity Probability of Wind Power

7. POWER SYSTEM RELIABILITY

Power systems have evolved over decades. Their primary emphasis has been on providing a reliable and economic supply of electrical energy to their customers. Overinvestment can lead to excessive operating costs, which impact the tariff structure and lead to high customer costs. Power system reliability evaluation, both deterministic and probabilistic, can be divided into the two aspects such as system adequacy and system security. The reliability indices for generation system such as LOLE, LOLP, LOEE and COPT have been calculated. For calculating these reliability indices, conventional hydro power plant from IEEE RTS and wind power plant from one of the reference papers has been considered [11] [12].

Reliability indices can be calculated by analytical and simulation methods. Markov Process is used as the analytical method and Monte Carlo simulation method is been used. Both the methods is been compared and shown in table.2.

Table.2. Comparison of the System

Plant	Indices	Analytical (A)	Simulation (S)
Hydro 400MW	LOLE	0.1119	0.1200
	LOLP	12.77e10-4	10e10-4
Wind 270kW	LOLE	0.1950	0.2000
	LOLP	22.29e10-4	20.2e10-4

The results in Table 2 from both simulation and analytical approaches are very close. The analytical approach provides a direct and practical technique system evaluation and is quite adequate. The result obtained by analytical method gives only a single average value. This method does not take into account the uncertainty in the behavior of the system. The Monte Carlo simulation (MCS) method gives the results close to the results obtained by analytical method.

8. COST WORTH ANALYSIS

The function of a power system is to supply electricity economically and with a reasonable assurance of continuity and quality [8]. However, due to the integrated nature of power systems, failures in any part of the system can cause service disruptions. The method is illustrated in Fig.9. The investment and operating costs can be represented by curve RC, function of any suitable reliability index. Outage costs, represented by curve OC, decrease as reliability increases. The total cost curve TC is the sum of the individual cost curves RC and OC. Total cost presents a minimum at R*, which determines the optimal level of reliability.

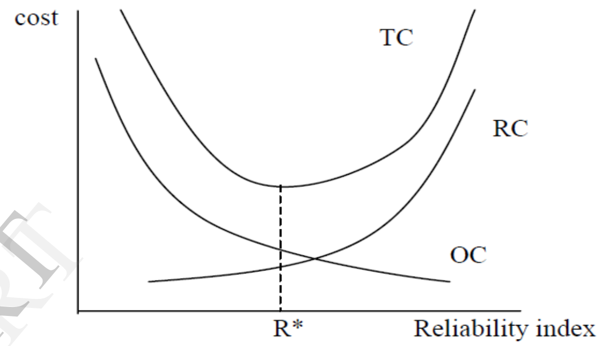

Fig.8. Total Reliability Cost.

The reliability cost/worth indices of expected energy not supply (EENS) can be calculated using the three basic load point indices and customer interruption costs. The equations used to calculate these indices are described in a generalized Analytical Approach. The outage energy, or expected energy not supplied (EENS), provides the severity associated with capacity deficiencies in terms of the energy not supplied when demand exceeds the available capacity [10].

Table.4. Two Unit Capacity Outage Probability Table

Sr. No	Capacity Out (kW)	Capacity In (kW)	Probability
1	**0**	**540**	**0.9216**
2	**270**	**270**	**0.0768**
3	**540**	**0**	**0.0016**

To illustrate the calculation of reliability indices we will use the generation model of Table.4. We will combine that model with the load shown in fig.9 representing a simplified load duration curve.

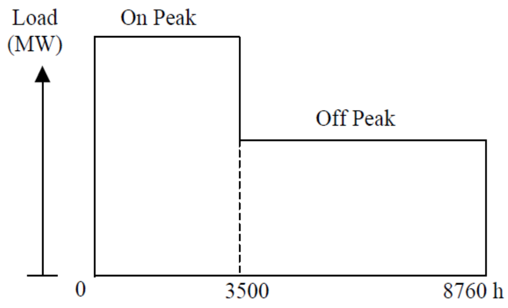

Fig.9. Load model for Calculation

The loss-of-energy method is a variation of the loss-of-load method. Here the measure of interest is the ratio of expected non-served energy to total energy demand over a period of time. The total energy demanded by the system is:

E = 500KW x 3500h + 300KW x (8760h - 3500h)
= 3.328 kWh

If E_k is the energy not supplied due to a capacity outage O_k, and E is the total energy demand during the period of study, the Loss-of-Energy Probability (LOEP) or expected energy not supplied (EENS) is given by the following ratio:

$$LOEP = \sum_{k} \frac{E_k \cdot p_k}{E} \qquad (5)$$

Equation.5. is also known as the Loss-of-Energy Expectation LOEE. The simplest case is when the load is constant and known. From the above equation the LOEE can be calculated, and the value is

LOEE = (270 x 3500)(0.0768) + 540 x (87603500)(0.0016) / 3.328

LOEE = 23173.23 kWh/year

Customer Interruption Cost Model:

Customer interruption costs can be easily represented by customer damage functions (CDF). The CDF for a specific customer sector is called a sector customer damage function (SCDF). The survey data have been analyzed to give the SCDF for each of the seven customer sectors used in this chapter. The data for different customer sectors and different failure durations are shown in Table.5. [9]

Table.7.Sector Interruption Cost (Rs/kW)

User sector	Interruption duration (Min) and cost (Rs. /kW)				
	1 min	20 min	1 hr	4 hr	8 hr
Industrial	1.050	2.455	6.005	18.125	37.250
Commercial	0.125	0.985	3.850	16.125	42.750
Residential	0.0005	0.048	0.250	2.809	9.750
Govt. and Inst.	0.015	0.145	0.725	4.985	19.150
Office and bldg.	1.025	2.119	6.450	22.250	40.250

Table.7. gives the interruption costs for five discrete outage durations. In the case of durations greater than 8 hours, a linear extrapolation with the same slope as that between 4 and 8 hour values was used to calculate the interruption cost [10].

Interruption cost for 270kW Wind Power Plant is calculated.

LOEE for one year = 23173.26kWh

LOEE for one hour = 2.645kWh

Table.8. Customer Damage Function (Rs/kW)

Interruption Duration (For8 Hours)	Customer Damage Function (Rs /kW)
Industrial	37.250x2.645 = 98.526
Commercial	42.750x 2.645 = 113.073
Residential	9.750x2.645 = 25.788
Govt. and Inst.	19.150x2.645 = 50.651
Office and Building	40.250x2.645 = 106.461

Reliability Cost/Worth indices provide an opportunity to include customer concerns into system planning, operation and expansion.

9. CONCLUSION

Wind power for different wind speed is been calculated. From the wind power data capacity availability for different wind power is shown. The capacity availability is crucial information for decision makers. Further the probability of wind power is calculated. Reliability assessment can be done by analytical methods or by simulation methods. Each approach has its own advantages and disadvantages. Studies are performed on the test systems known as IEEE RTS. Markov process Analysis and Monte Carlo Simulation method are used for calculating reliability indices such as LOLE (Loss of Load Expectation), LOLP (Loss of Load Probability), COPT (Capacity Outage Probability Table) and LOEE (Loss of Energy Expectation) is calculated. Markov process is the simplest and straight forward way of estimating reliability. The Monte Carlo Simulation (MCS) technique makes it possible to incorporate the time varying and random nature of failures in the reliability evaluation. This simulation technique can also provide wide range of indices and their probability distributions. The MCS approach is more advantageous.

A simplified load duration curve is been taken for the calculation of the wind power plant for which capacity in/out probability table (COPT) is shown. Customer surveys indicate the interruption costs as a function of duration.

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11. BIOGRAPHIES

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