Reliability Cost/Worth Analysis of Distribution System with Wind Generation as Alternate Supply using Monte Carlo Simulation

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Abstract— **A Monte Carlo simulation approach is used in this paper to evaluate the impact of intermittent wind generation on reliability evaluation of distribution system. Taking into account the fluctuating nature of wind speed, the random failures of generating units and recognized dependencies, wind speed model, wind turbine generator output model and load model are established. 2-partameter Weibull probability distribution is used to simulate hourly wind speeds values and the output of the wind farm. A specific Monte Carlo simulation procedure is described and a test system from the Roy Billinton Test System is used to illustrate the method.**

Keywords- **Monte Carlo simulation, cost/worth, reliability index, distribution system, wind generation.**

I. INTRODUCTION

Power generation techniques are highly concerned by the power engineers nowadays. Running out of conventional fuels like oil, coal, and the raw materials used in nuclear stations forced power engineers to find other to generate electricity from unconventional energy sources such as; sun, wind, tidal energy, bio mass, mini, micro hydel etc. One cannot totally depend on these renewable energy sources as primary supplies in our power networks and systems, so it is better to use them in distributed generation which have many applications; peaking power, back-up, and other ones [1]. Reliability indices which are proposed by the IEEE [2] will be used to evaluate the performance of these sources. Two ways are available to obtain these indices; analytical and simulation methods.

A wind turbine generators (WTG) system converts the wind energy to electrical energy to meet typical load demand. Wind energy varies from time to time, season-to-season and site-to-site. Factors like wind speed, location, hub height, parameters of WTGs, battery size and the load profile affect the performance and reliability of the system. In order to assess the system reliability it is essential to create reliability model for a wind farm which is compatible and consistent with grid connected or a standalone wind system. This requires reliability assessment of the wind site.

The wind speed model can be used to analyze the reliability of the electric power system including wind energy, and evaluate the wind energy resources and plan wind farm [3]. There are mainly two methods for wind speed forecasting model: Probability distribution Method and Time Series Model [3].

Wind speed variation at any site can be precisely described by appropriate wind speed probability distribution model. Various wind speed probability distribution such as Double parameters Weibull Distribution, Triple Parameters Weibull Distribution, Rayleigh Distribution and Normal Distribution are used to build wind speed models. Two Parameters Weibull Distribution is simple and fit with actual wind speed probability distribution perfectly [3]. Although the range of parameters of Weibull Distribution is small, but the wind speed model is very sensitive to the Weibull parameters. If the parameters are accurate, the wind speed forecasting model can represent the actual wind speed variation. Several methods such as mean wind speed and standard deviation; least-squares; mean wind speed and fastest wind speed can be used to estimate Weibull parameters. In this paper, 2-parameter Weibull distribution is used.

Due to uncertainty stochastic models have to be built to evaluate the reliability of distribution networks containing wind generations. The authors in [4] have proposed three probability distributions for wind speeds and solar radiations. These are Normal, Weibull, and Beta. Prediction analysis tool has been used in [5], [6], which can simulate light intensity fluctuations. A wind turbine model for reliability studies has been proposed in [7]. A probabilistic method to predict wind speeds is presented in [8], [9]

Monte Carlo simulation (MCS) is very useful in power system studies such as probabilistic power flow, economic dispatch and reliability evaluation [10], [11], [12]. Monte Carlo simulation method [13] is used to predict the value of each index after a certain number of samples. Reliability evaluation of distribution system based on MCS is very useful for complex non-linear systems. This method gives more information on the load point and system reliability indices compared to analytical method [13]. Because of the uncertainty of both wind turbine output power, it is not easy to use the analytical method to evaluate reliability of a system contains these resources [14]. However, the output power of wind turbine can be predicted by generating a large number of scenarios in desired time. Therefore, using Monte Carlo simulations to simulate the output power of wind turbine can be used to avoid complexities of the analytical method.

Modeling by using comprehensive and Sequential Monte Carlo (SMC) simulation, the influence of DG to distribution system reliability is shown in [15]. The evaluation of reliability indices and system reliability concepts are in [16]. This paper, mainly focused on reliability evaluation of radial distribution feeders in the presence of Wind generation as alternate supply located at the load side.

Section II describes reliability and system indices. System modeling and simulation procedure for analysis is included in Section III. Section IV gives the system analysis with results and Section V concludes the paper following with references.

II. RELIABILITY INDICES

Both load point and system indices assessment are included in distribution system reliability evaluation. Commonly used load point indices include the failure rate, λ_j (failures/year), average outage time r_j (hours/failure), and average annual unavailability U_j (hours/year), where j is load point. Proposed that N_i is the total number of failure events, $\sum T_{uj}$ and $\sum T_{dj}$ are the respective summations of all the up times T_{uj} and all down times T_{dj} for load point l, these indices are defined as follows[13]:

$$\lambda j = \frac{Nj}{\sum Tuj}, \qquad rj = \frac{\sum Tdj}{Nj}, \qquad Uj = \frac{\sum Tdj}{(\sum Tuj + \sum Tdj)}$$

Based on the above indices, the following system reliability indices are evaluated. System Average Interruption Frequency Index (SAIFI), System Average Interruption Duration Index (SAIDI), Customer Average Interruption Duration Index (CAIDI), Average Service Availability Index (ASAI) and Expected Energy Not Supplied (EENS).

III. SYSTEM MODELLING

A. Wind Energy System Model

A WTG machine is driven by a predominant wind speed component, such as a horizontal or vertical force, which is assumed to follow a normal distribution. So we should define a model to forecast the wind speed, and then predict the corresponding wind turbine output.

1) 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. And 2-parameter Weibull distribution, in all of these is most widely used. The function of 2-parameter Weibull distribution [3] is

$$Fw(v) = P(V \leq v) = 1 - e^{\left(-\frac{v}{c}\right)k} \tag{4}$$

where k is the form parameter, whose span is usually from 1.8 to 2.3 and, c is the scale parameter, which indicates the mean wind speed of that area. Parameters k and c can be obtained by the actual measurement of wind speed.

According to the inverse transformation method: [3] If {Xi} is a stochastic variable which submit uniform distribution in [0, 1], its distribution function is $F_1(x)$. If we want to obtain F_2 (v), the distribution function of {Yi}, we assume $x=F_2(y)$, namely $y=F_2^{-1}(x)$. Assume,

$$x = F(v) = 1 - e^{\left(-\frac{v}{c}\right)k} \tag{5}$$

Then,

$$v = c[-\ln(1 - X)]^{\frac{1}{k}} \tag{6}$$

Because x and 1-x are both stochastic variable which submit uniform distribution in [0, 1], 1-x can be replaced by x, so we get;

$$SWt = v = c[-\ln(Xi)]^{\frac{1}{k}} \tag{7}$$

We can use the Weibull-distribution stochastic variable generator, $v = c[-\ln(Xi)]^{\frac{1}{k}}$ (X_i is a stochastic variable which submit uniform distribution in [0, 1], to generate the sample of wind speed.

2-parameter Weibull distribution is used to estimate the wind speed distributions of wind. Monte Carlo simulation is used to generate random numbers. These random numbers are converted into wind speed values. The steps for getting wind speed are illustrated in the flow chart shown in Fig.1.

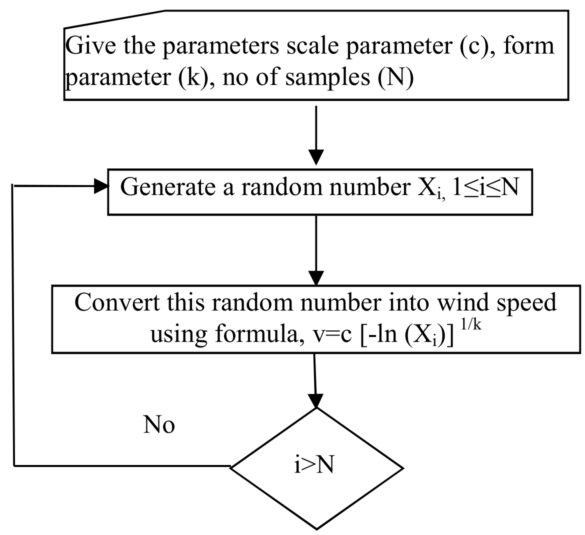

Fig 1 Flow chart for generation of wind speed.

A wind speed sample process is illustrated in Fig. 2, and wind speed distribution is presented in Fig 3.

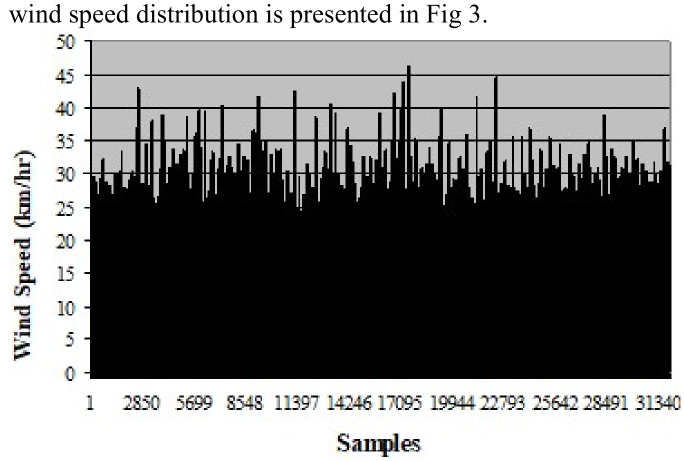

Fig 2 Wind speed sample process for 50000 samples

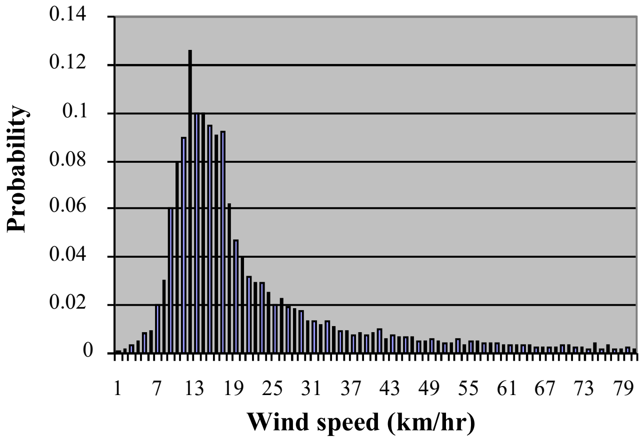

Fig 3. Wind speed probability distribution

2) Power output of WTG

A conventional generation unit is normally represented using two states. If the unit is in the up state it is capable of producing its rated capacity. If the unit is in the down state, the power output is zero. A wind turbine generation (WTG) unit can also be represented using up and down states. The main difference is that the WTG output in the up state varies with wind speed, which is a random variable which varies chronologically.

The power output of a WTG unit at hour t depends on the wind speed at that hour. After the hourly wind speed SW_t, is determined using Eq. 7, the power output Pt of a WTG is calculated using the following Eq. 8[18].

$$Pt = \begin{cases} 0 & 0 \le SW_t \le Vci \\ (\mathrm{A} + \mathrm{B} \times SW_t \ + \ \mathrm{C} \times {SW_t}^2)\mathrm{Pr} & Vci \le SW_t \le Vr \\ \mathrm{Pr} & Vr \le SW_t \le Vco \\ 0 & SW_t \ge Vco \end{cases} \quad (8)$$

where V_{ci}, V_r, V_{co} and P_r are the cut-in speed, the rated speed, the cut-out speed and the rated power of a WTG unit, respectively. Parameters A, B and C are given in Eq. 9-11

$$A = \frac{1}{(V_{ci} - V_r)^2}\left\{V_{ci}(V_{ci} + V_r) - 4V_{ci}V_r\left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right\} \quad (9)$$

$$B = \frac{1}{(V_{ci} - V_r)^2}\left\{4(V_{ci} + V_r)\left[\frac{V_{ci} + V_r}{2V_r}\right]^3 - (3V_{ci} + V_r)\right\} \quad (10)$$

$$C = \frac{1}{(V_{ci} - V_r)^2}\left\{2 - 4\left[\frac{V_{ci} + V_r}{2V_r}\right]^3\right\} \quad (11)$$

If the cut in speed is 9 km/hr, rated speed is 38 km/hr and cutoff speed is 80 km/hr and the rated power of WTG is 225 KW then the relationship between wind speed and power output is obtained using Eq. 8 to Eq.11 and it is presented by graph in Fig. 4.

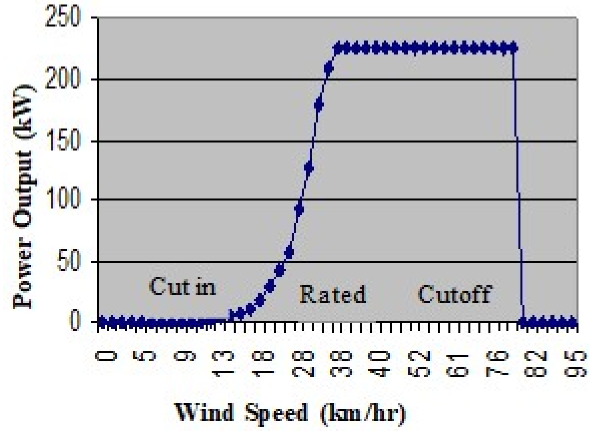

Fig. 4 Power output as a function of wind speed

B. Simulation Procedure

1) Determination of Maximum Load Capacity

Calculate the total maximum load capacity (MLC) of load points that are required to be restored by the wind distributed generation source using the following equation, where N is the number of load points.

$$\mathrm{MLC} = \sum_{k=1}^{\mathrm{N}}(\mathrm{L}_{alj}) \quad (12)$$

2) Determination of Minimum Wind Generation Capacity

Minimum wind distribution generation capacity (MWC) for each WTG that can be supplied during the total time to repair can be calculated using Eq. 8. If there is M_a numbers of WTGs supply the power to a system then total minimum capacity of wind generation can be calculated using

$$\mathrm{MWC} = \mathrm{Ma} \times \mathrm{Pt} \quad (13)$$

3) Load curtailment policy

When a fault occurs in a distribution system, a series of switching actions are usually required to isolate the failed elements. Many load points can often be restored to service through main and alternative supplies. The load to be cut is therefore based on the available wind generation capacity at that time and the switching connections. The MWC of a wind farm during the repair time and the MLC to be supplied by the wind farm are calculated. If the MWC is larger than the MLC, no load is cut. If not, some load must be cut. The curtailment policy used here for wind turbine generator (WTG) as alternative supplies is to cut the loads connected to the sub feeders first, and then the loads connected to the main feeder. Load points are isolated from the downstream feeders to the upstream feeders sequentially. Before a load cut, the switch connection is checked to see if this load can be isolated alone. If no switches exist to isolate this load point alone, the neighboring load point is considered and the switch connection is checked again. This procedure continues until the MLC exceeds or equals the MWC [18].

4) Simulation Algorithm

Algorithm developed in [19], [20] is used and extension is done with considering wind as the alternate supply. The simulation procedure used to conduct reliability worth analysis using WTGs as alternative generation sources consists of the following steps:

1. Define the system i.e. input data such as location of components, failure rate, failure duration, load connected, customer sector cost data for different type of customers of the system and rated output and wind speeds of the wind turbine generator.
2. Input number of sample years 'N', simulation period 'T'
3. Simulation starts, n = 1, t=0
4. Generate random numbers [0-1] for each element in the system and convert it into times to failure (TTF), based on the failure time distribution and the expected time to failure of each element.
   $TTF_j = (-\log(U)/\lambda) \times 8760$, Where U is random number between 0 to 1
5. Determine the element 'e' with minimum TTF.
6. Define 'e' as failed element and perform following things for event j
   a. Compute TTR and TTS using appropriate probability distribution for element repair and switching time
   b. Determine location of 'e'
   c. Find the load points L_i that are affected due to failure at 'e'
   d. Determine the load points that can be supplied by the main supply and the load points that can be supplied by WTG
   e. Calculate Maximum Load Capacity (MLC) of load points that are to be supplied by WTG
   f. Simulate the hourly time sequential wind speed for TTF+TTR hours
   g. Calculate the hourly power output Pti of WTG for each hour during TTR.
   h. Calculate the minimum wind generation capacity (MWC) that can be supplied by the available WTG units during TTR.
   i. Compare MWC and MLC to determine the load points to be supplied by WTG using the load cut policy.
   j. Determine failure duration for each affected load point L_i
   k. Evaluate the per unit interruption cost C_{ij} of load point i using r_{ij} and the load point function $f(r_{ij})$.
   $$C_{ij} = f(r_{ij}) \tag{14}$$
   l. Evaluate the energy not supply ENS_{ij} and the interruption cost $COST_{ij}$ of the load point i due to the failure event j [18].
   $$ENS_{ij} = L_i r_{ij} \tag{15}$$
   $$COST_{ij} = C_{ij} L_{ij} \tag{16}$$
   m. Add the ENS_{ij} and the $COST_{ij}$ to their total values respectively.
   n. Repeat Step g-m for all load points.
7. Generate a new random number for 'e' and convert that it into new TTF.
8. If t is less than simulation period 'T' then go to step 5.
9. Do n = n+1, if n < Sample years 'N' then go to step 4.
10. The total energy not supply ENS_i and the interruption cost $COST_i$ of the load point i for the total simulation years are[18]:

$$\mathrm{ENS}_i = \sum_{j=1}^{N_s} L_{ij} r_{ij} = L_{ij} \sum_{j=1}^{N_s} r_{ij} \tag{17}$$

$$\mathrm{COST}_i = \sum_{j=1}^{N_s} L_{aij} \mathrm{c}_{ij} = L_{aij} \sum_{j=1}^{N_s} \mathrm{c}_{ij} \tag{18}$$

where N_s is the total number of failure events in the specified simulation period. The expected energy not supplied $EENS_i$, the expected interruption cost $ECOST_i$; and $IEAR_i$ can be calculated using the following equations[18]:

$$\mathrm{EENS}_i = \frac{\mathrm{ENS}_i}{\mathrm{TST}} \tag{19}$$

$$\mathrm{ECOST}_i = \frac{\mathrm{COST}_i}{\mathrm{TST}} \tag{20}$$

$$\mathrm{IEAR}_i = \frac{\mathrm{ECOST}_i}{\mathrm{EENS}_i} = \frac{\mathrm{COST}_i}{\mathrm{ENS}_i} = \frac{\sum_{j=1}^{N_s} (\mathrm{c}_{ij})}{\sum_{j=1}^{N_s} (\mathrm{r}_{ij})} \tag{21}$$

where, TST is the total specified simulation period in years. The system EENS, ECOST and IEAR can be calculated using equations (22)-(24).

$$\mathrm{EENS} = \sum_{i=1}^{N_p} (EENS_i) = \sum_{i=1}^{N_p} (L_i) \sum_{j=1}^{N_e} (\mathrm{r}_{ij} \lambda_{ij}) \tag{22}$$

$$\mathrm{ECOST} = \sum_{i=1}^{N_p} (ECOST_i) = \sum_{i=1}^{N_p} (L_i) \sum_{j=1}^{N_e} (\mathrm{c}_{ij} \lambda_{ij}) \tag{23}$$

$$\mathrm{IEAR} = \frac{\mathrm{ECOST}}{\mathrm{EENS}} \tag{24}$$

The simulation procedure is shown in Fig. 5.

IV. SYSTEM ANALYSIS AND RESULTS

The system under study is shown in Fig. 6. It is feeder 1 from Bus 2 of Roy Billiton Test System (RBTS). This distribution system is a typical rural distribution system, with one main feeder (F1), seven load points (LP1 to LP7). A WTG farm is incorporated in the system. The total peak load is 5.934 MW and total average load is 3.645 MW. The data related to failure rate, repair time of different components are assumed to be those provided in [17].

C++ program is developed for the reliability cost/worth analysis including CG and WTG as the end of feeder as alternate supply.

Case 1 (with CG as an alternate supply)

In this case, one 11.25 MW Conventional Generation (CG) is installed at the end of feeder. The system is evaluated using sequential simulation. The results are tabulated as follows.
The load point indices for the feeder are shown in Table 1. The system indices are shown in second column of Table 3.

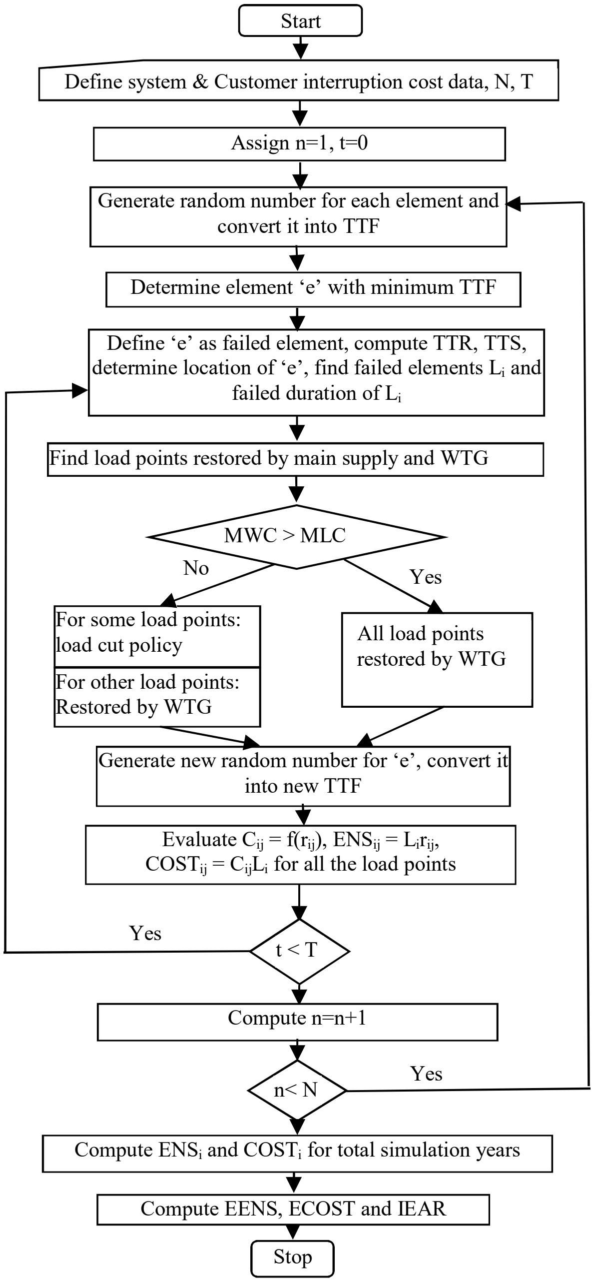

Fig. 5 Flowchart for simulation for reliability analysis including WTG

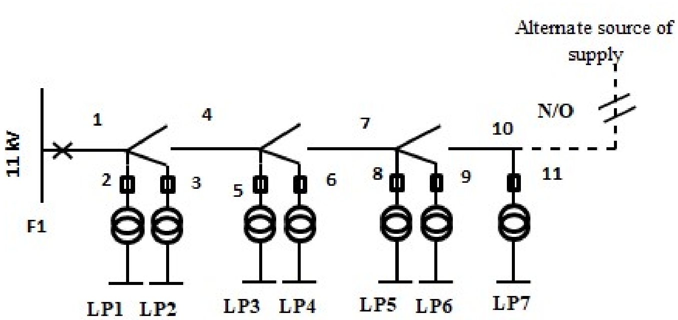

Fig. 6 Feeder 1 from Bus 2 of RBTS System

Table 1 Load point indices with CG as alternate source of supply for simple feeder

Load point	λ (fr/yr)	R (hrs/yr)	U (hrs/fr)	EENS (MWh/yr)	ECOST K$/yr	IEAR $/kWh
LP1	0.236	12.678	2.986	1.597	3.394	2.125
LP2	0.241	13.879	3.342	1.788	3.394	1.898
LP3	0.245	12.629	3.098	1.658	3.394	2.048
LP4	0.238	13.174	3.130	1.772	7.739	4.368
LP5	0.244	12.195	2.979	1.686	7.739	4.590
LP6	0.240	12.920	3.100	1.408	17.686	12.565
LP7	0.250	11.870	2.966	1.347	19.686	14.620

The probability distributions of system indices can be obtained using the developed program. Fig. 7 to Fig. 9 shows the probability distributions of Energy not supplied, Expected interruption cost, and IEAR for simple Feeder.

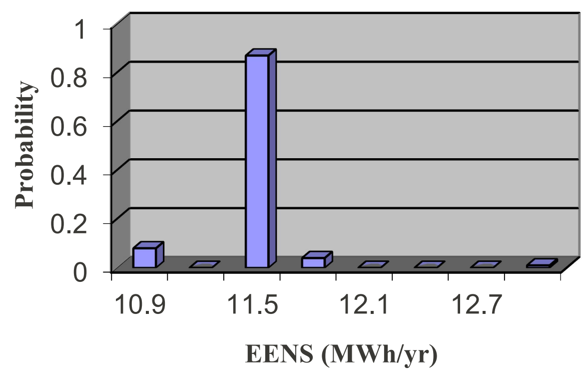

Fig.7 Histogram for EENS

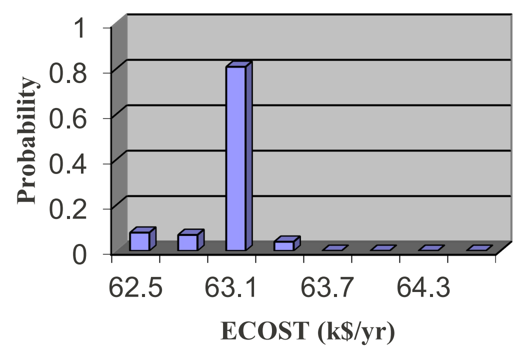

Fig. 8 Histogram for ECOST

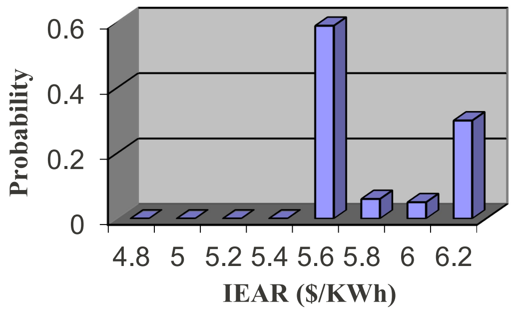

Fig. 9 Histogram for IEAR

It can be seen from figure that energy not supplied is between 11.2 and 11.5 is about 84 percent and interruption cost in between 62800 to 63100 $ is about 79 percent.

Case 2 (50 WTG as an alternate supply)

A wind farm with 50 WTG units is then integrated to the system at the end of feeder in case 2. The benefits of adding WTG depends on different parameters of wind site like wind speed, number of WTG units. The rated output of each WTG unit is 225 KW. The unit forced outage rate is 0.04. The V_{ci}, V_r and V_{co} are 9 km/h, 38 km/h and 80 km/h, respectively. The form factor k, and scale parameter c for simulation of hourly speed are assumed to be 1.8 and 12 respectively. In case 2 the system was simulated for 50000 sample years to ensure the indices convergence.

The simulation procedure is applied to a system and results are presented in following Tables. Table 2 gives load point indices and system indices obtained with 50 WTG units in the system are included in third column of Table 3.

Table 2 Load point indices with WTG as alternate source of supply for simple feeder

Load point	λ (fr/yr)	r (hrs/yr)	U (hrs/fr)	EENS (MWh/yr)	ECOST K$/yr	IEAR $/kWh
LP1	0.236	13.394	3.158	1.689	4.384	2.596
LP2	0.246	12.895	3.167	1.694	4.389	2.591
LP3	0.246	13.208	3.253	1.740	4.482	2.576
LP4	0.235	14.004	3.285	1.858	8.440	4.541
LP5	0.245	14.218	3.485	1.972	8.904	4.515
LP6	0.244	14.050	3.429	1.556	19.973	12.836
LP7	0.243	14.255	3.456	1.568	20.094	12.811

It can be seen in the Table 1 and Table 2 that with the integration of WTGs, the increase in an individual load point's reliability indices.

The probability distributions of system indices can be obtained using the developed program. Fig. 10 to Fig. 12 shows the probability distributions of Energy not supplied, Expected interruption cost, and IEAR for simple Feeder. It can be seen from figure that energy not supplied is between 13.3 and 13.6 is about 91 percent and interruption cost are larger than 72000 $ is about 90 percent.

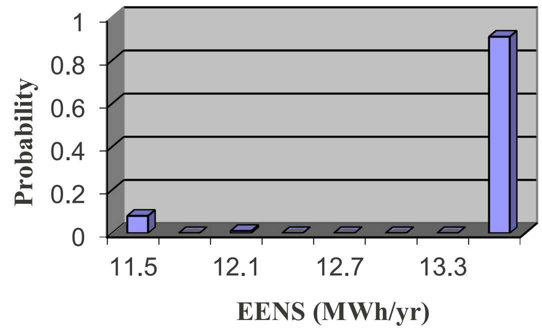

Fig. 10 Histogram for EENS

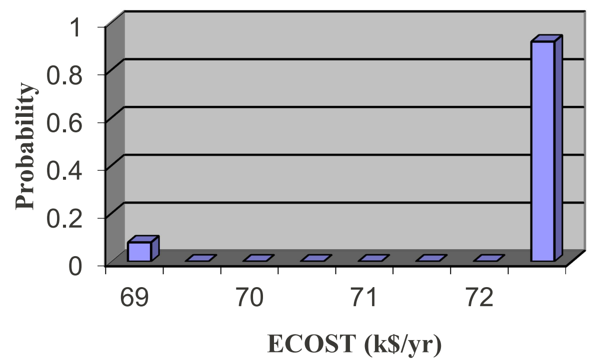

Fig. 11 Histogram for ECOST

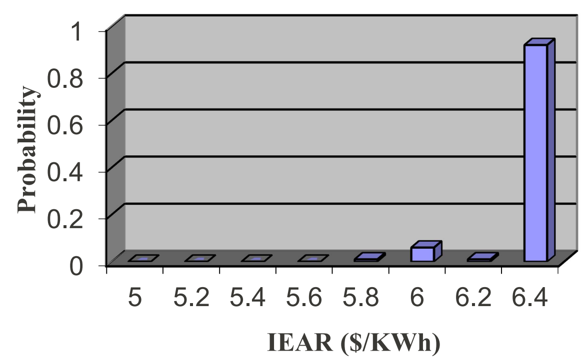

Fig.12 Histogram for IEAR

Comparative analysis of system indices for 2 cases

By comparing case (with CG as alternate supply) and case 2 (with WTG as alternate supply), it can be seen that with the integration of the CG or 50 WTG units in the system, the system indices are considerably affected. Table 5 gives the comparative analysis of system indices for different cases considered.

Table 3 System indices for 2 cases for simple feeder

Case	With CG	With 50 WTG units
SAIFI	0.241	0.243
SAIDI	3.138	3.201
CAIDI	13.040	13.196
ASAI	0.999642	0.999635
ASUI	0.000358	0.000365
EENS	11.255	12.078
ECOST	63.033	70.667
IEAR	5.601	5.851

From Table 3 it can be seen that there is no change in system failures means there is no much difference in SAIFI by the integration of CG or WTG units, but the duration (SAIDI) of interruption in the system is less with CG. So ASAI is more with the integration of CG. It can be seen from Table 3 that the system EENS and ECOST increased by addition of WTG. It is due to intermittent nature of wind.

V. CONCLUSION

The impact of wind generation on the reliability of the distribution system is presented in this paper. Stochastic models have been used to simulate the intermittency of the wind speed. A time sequential technique is used to evaluate the reliability indices including wind generation as an alternative supply is presented.

Alternate supply has a different impact on the reliability of a distribution system than does a conventional generator because of the random nature of wind speed, and the nonlinear relationship between WTG and wind velocity. In general, it can be concluded that WTG are not efficient way to improve reliability of a rural distribution system due to random nature of wind speed.

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