

# Adequacy Assessment of Wind Energy Conversion System through Simulating Wind Speed using Weibull Distribution

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**Abstract**—In the electrical power market, nowadays wind energy is becoming a popular alternative to the conventional sources to meet the ever-increasing cumulative power demand due to its eco-friendly, communal and commercial benefits. Unlike conventional, the electrical power generated from wind energy conversion system (WECS) acts differently as it is solely relying on the wind speed and site-specific. This paper focuses on simulating the behavior of the wind speed using Weibull distribution and calculates the power in associating the power speed characteristic of the wind turbine. The output power of the WECS is segregated to create multi-state WECS model. Adequacy assessment demands two state reliability model to estimate the adequacy of the generating system. Thus the multi-state model is reduced to 2 state model using apportioning method and assess the reliability of the WECS. 15 MW wind farm is considered as the case study to validate the efficacy of the proposed methodology.

**Keywords**— Adequacy; apportioning method; Weibull distribution; wind energy conversion system

## I. INTRODUCTION

Electrical power is dominated by the conventional sources like fossil fuel since the dawn of the commercialization electricity. Power generated from wind energy is gaining potential as an alternative with environmental, social and economic benefits [1] owing to the hazardous impact on the environment of dwindling fossil fuel. But in the assessment of the adequacy of generating units, wind energy conversion system behaves differently unlike conventional sources as it is solely dependent on random wind speed, and also site-specific [1, 2]. So a proper care is to be undertaken to survey the behavior of the wind speed for the adequacy assessment.

The conversion of wind potential to electrical energy by WECS considers certain factors. One of them is the randomness of the wind characteristic that must be modelled to include in the reliability calculation. Another one is the relation between wind speed and turbine characteristic resulting in the output power of WECS [2].

Literature is available to simulate the intermittent behavior of wind speed using time series ARMA model [2, 3]. Here, two parameters Weibull distribution is chosen to simulate wind behavior [4, 5]. Statistical analysis like Weibull distribution is

quite convenient in the frequency domain. So the collected data are converted to frequency format by segregating the wind speed in different classes with their frequency of occurrence [5]. The distribution parameters are calculated using the popular methods like maximum likely hood method, power density method and graphical method [6-8]. Maximum likely hood method is preferred here with its superiority over other two. The effective fitting of the theoretical distribution is checked through statistical tests like mean percentage error, mean absolute percentage error, root mean square error and chi-square test [4-7].

The output power of WECS is the combination of the available resources at the plant location and the turbine characteristics [1]. The power output is then segregated into different output states, and each state has the probability calculated from the number of occurrences of that state. The multistate represent the derated states of the WECS which will lead to capacity outage profile of the WECS [2]. The multistate model can't be included on the adequacy assessment as it demands the two-state model either fully available or unavailable [9]. Therefore, apportioning method is used to reduce the multistate model to reduced two-state model to be incorporated in the reliability analysis [10].

## II. SIMULATING WIND SPEED USING WEIBULL DISTRIBUTION

### A. Weibull Distribution

Generally the analysis using Weibull distribution is done in the frequency domain as it is quite convenient as compared to time series. Thus the collected wind speed data are first converted to frequency format [5]. To do so, the collected wind speed data are segregated into different classes or bins and represented using histograms. The relative frequency associated with each bin can be calculated from the ratio of the total number of data falls into that bin with the width of the bin. The characteristic of wind speed is simulated using Weibull distribution through two function probability distribution and cumulative probability distribution function [4-8]. These functions are given as

$$f(v) = \frac{k}{c} \left(\frac{v}{c}\right)^{k-1} e^{-\left(\frac{v}{c}\right)^k} \quad (1)$$

where  $f(v)$  is probability density function of the measured wind speed;  $v$  is wind speed in m/s;  $c$  is scale parameter, measured using the same unit of the wind speed and  $k$  is shape parameter which is unitless.  $c$  is generally associated with average wind speed through  $k$  to decide the range of variation of the wind speed at a considered plant location [7].

$$F(v) = 1 - e^{-\left(\frac{v}{c}\right)^k} \quad (2)$$

where  $F(v)$  is the cumulative distribution function which is the additive relative frequency of each bin.

### B. Determination of Weibull Parameters

There are considerable approaches are available to find the parameters of the Weibull distribution. Some popular methods are maximum likely hood method (MLM), power density method (PDM) and graphical method [4-7]. As per some literature, graphical method is not giving the accurate result as compare to other methods [6]. Again MLM and PDM are giving almost coinciding results [5, 11]. Therefore, here MLM is followed to estimate the desired parameters of the distribution. In this method of estimation, numerical analysis like Newton Raphson method is used [4, 11]. The parameters are determined as

$$k = \left[ \frac{\sum_{i=1}^n v_i^k \ln(v_i)}{\sum_{i=1}^n \ln(v_i)} - \frac{\sum_{i=1}^n v_i^k}{n} \right]^{-1} \quad (3)$$

$$c = \left( \frac{1}{n} \sum_{i=1}^n v_i^k \right)^{1/k} \quad (4)$$

The theoretical statistical Weibull distribution is adopted here to fit with the observed data. To check how well it is fitted to the collected data, statistical tests are performed. The tests will determine the errors in determination like mean percentage error ( $MPE$ ), mean absolute percentage error ( $MAPE$ ), root mean square error ( $RMSE$ ) and chi-square error ( $\chi^2$ ) [4, 7].

Mean percentage error

$$MPE = \frac{1}{N} \sum_{i=1}^N \left( \frac{x_{i,w} - y_{i,m}}{y_{i,m}} \right) \times 100 \quad (5)$$

that determines the average proportionate deviation of the Weibull values from the observed values. Mean absolute percentage error is just the absolute value of the  $MPE$ .

Root mean square error

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^N (y_{i,m} - x_{i,w})^2 \right]^{1/2} \quad (6)$$

Chi-square error

$$\chi^2 = \sum_{i=1}^N \left( \frac{(x_{i,w} - y_{i,m})^2}{x_{i,w}} \right) \quad (7)$$

that judges the adequate fitting of the theoretical distribution to the observed samples. Here  $N$  is the total number of measurement,  $y_{i,m}$  is the number of observation or  $i^{\text{th}}$  measured value from the observed data,  $x_{i,w}$  is the frequency of Weibull or  $i^{\text{th}}$  measured value from the Weibull distribution.

### III. IMPACT OF HOURLY WIND SPEED ON POWER OUTPUT OF WIND TURBINE GENERATOR

The yield of the WTG is strongly relying on the hourly wind pattern for a horizon, so the output behavior of a WECS are absolutely contrasting from those of typical thermal generating units [1, 2, and 12].

Once the hourly pattern is achieved, then the power output of the WECS is to be estimated as a function of the wind speed [1, 2, & 13]. It is determined with the knowledge of the cut in speed ( $V_{ci}$ ), the rated speed ( $V_r$ ), and the cutout speed ( $V_{co}$ ) specified for a turbine [14]. The hourly yield of the WECS is obtained as

$$PP(SW_t) = \begin{cases} 0 & 0 \leq SW_t < V_{ci} \\ (A + B \times SW_t + C \times SW_t^2) \times P_r & V_{ci} \leq SW_t < V_r \\ P_r & V_r \leq SW_t < V_{co} \\ 0 & V_{co} \leq SW_t \end{cases} \quad (8)$$

where  $P_r$  is the graded power of the WTG and the parameters  $A$ ,  $B$ , and  $C$  depending on wind turbine characteristics (i.e. the speed limits of the turbine) are presented in [13].

### IV. MULTI-STATE REPRESENTATION OF WECS

The hourly wind speed is simulated according to the Weibull distribution and the generated power of the WTG unit is calculated using the power speed characteristic, respectively. At each instant of the wind speed, it generates an output power. Thus, WTG model can be regarded as WECS with two basic components wind resources and the actual wind turbine generator (WTG) unit as it is shown in the Fig. 1 for a single unit as well as multi-unit systems [2, 3]. The available rated output powers are first of all segmented into different output states. The frequency of wind speed generating a power output, coming under any one of the states are counted. The probabilities of each states are determined by taking ratio of the occurrence of each output state to the whole sum of observation [2, 3]. Thus, WTG outputs are residing in many derated states like large conventional generating unit [2, 10].

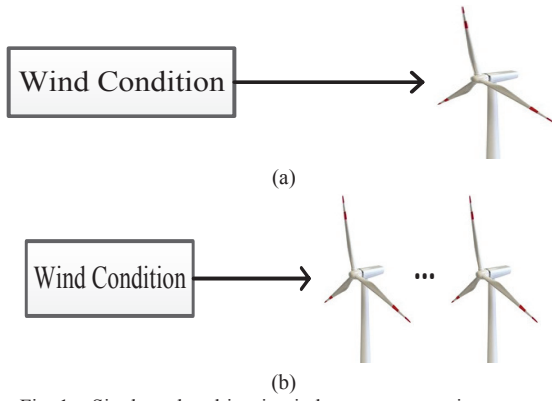


Fig. 1. Single and multi-unit wind energy conversion system

TABLE I. WIND TURBINE SPECIFICATION

Model used	Leitwind LTW77
Capacity (MW)	1.5
$V_{ci}$ (m/s)	3
$V_r$ (m/s)	12
$V_{co}$ (m/s)	25
Rotor diameter (m)	76.6
Generator	Permanent Magnet Direct Drive Synchronous Machine
Hub Height (m)	80
Tower type	Hybrid (steel and concrete)

## VII. RESULT & DISCUSSIONS

### A. Weibull Distribution

The comparative probability plot of the observed wind speed with the resulted one from the Weibull distribution fitting with the observed wind speed is shown in the Fig. 3. It is observed from the Fig. 3; the simulated one is quite coinciding to the observed one that validates the efficacy of the Weibull distribution function in fitting with the observed data.

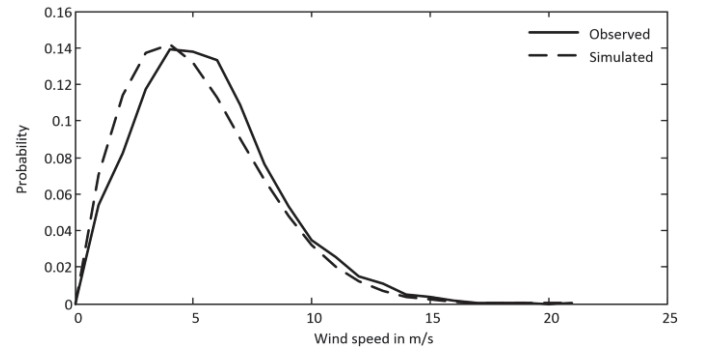


Fig. 3. Comparative probability plot of the wind speed

## V. ADEQUACY ASSESSMENT OF WIND TURBINE GENERATOR

The reliability assessment demands curtail the number of derated states generally two states, i.e., either fully up or down. Thus, the multi-derated states are to be reduced to two states [9]. For example, a three states model is reduced to two states model as shown in Fig. 2 [10]. The probability of residing in fully downstate is called the derated adjusted force outage rate (DAFOR) that will estimate the system adequacy [10]. The DAFOR is calculated using apportioning method as

$$DAFOR = P_{DN} + \sum_{i=1}^n \frac{Cap.Cur_i}{Cap} \times P_{DEi} \quad (9)$$

where  $DAFOR$ =Derating-adjusted forced outage rate

$P_{DN}$ =Probability of the generator in downstate

$Cap.Cur_i$ =Curtailed generation of the generating unit in the  $i$ th derated state (MW)

$P_{DEi}$ =Probability of the generator in the  $i$ th derated state

$n$ =number of derated states.

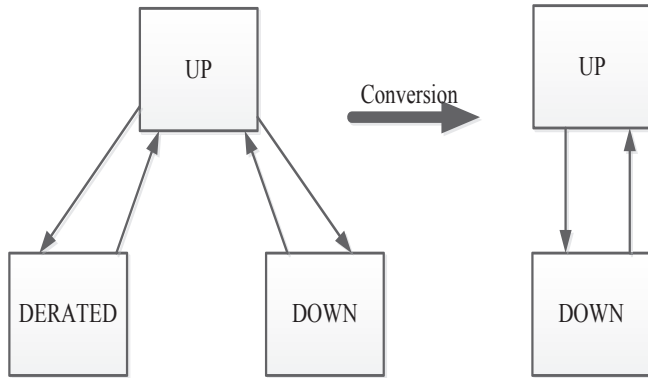


Fig. 2. Conversions of multi-state to 2 state model [9].

## VI. CASE STUDY

15 MW of wind generating capacity comprising of 10 1.5 MW units is considered as case study to validate the proposed methodology. The wind speed data are collected at a latitude  $8^{\circ}94'$  and longitude  $77^{\circ}77'$  near Kayathar real wind farm using Homer Pro software [12]. The specification of the wind turbine used here are specified in the table I [14, 15].

The parameters of the distribution are determined using MLM as 1.85 and 5.75. Shape parameter generally determines the variation of wind speed and scale parameter determines the mean wind speed. How well the distribution is fitted to the observed data are checked through statistical tests. The different error values like MPE, MAPE, RSME and chi-square are found as -0.0819, 0.1218, 0.478 and 0.0324 respectively.

### B. Power Curve of WECS

The parameters  $A$ ,  $B$  and  $C$  are determined with the knowledge of the wind turbine characteristics specified in the table I. The power output of WECS is estimated using the above parameters and the simulated data. Wind speed vs turbine output power is shown in Fig. 4. The speed power characteristic just looks like the general power curve of the wind turbine.

### C. Multi-state Representation

Each hourly wind speed will generate hourly output power from the WTG as per the power speed characteristic of the wind turbine. The output power is segregated into different states to find the multi derated states. The probability of individual state will be determined by the frequency of occurrence of that state. The multi-state representation of 15

MW wind farm is represented graphically in Fig. 5 and is tabulated as the capacity outage profile as given in Table II.

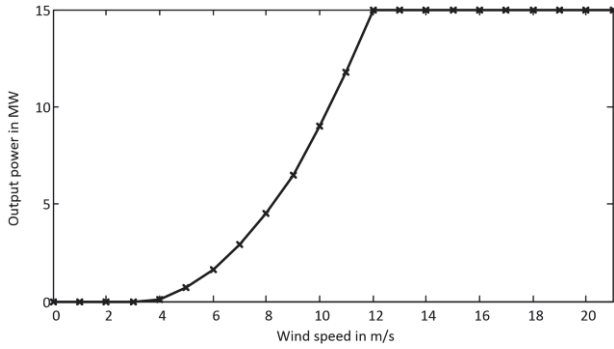


Fig. 4. Power speed characteristic of the wind turbine

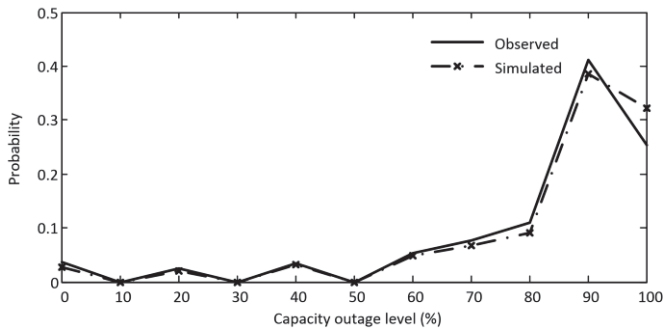


Fig. 5. Capacity outage probability profile

TABLE II. MULTISTATE MODEL

Capacity outage (%)	Observed probability	Simulated probability
0	0.036644	0.027221
10	0	0
20	0.025457	0.020311
30	0	0
40	0.034703	0.031954
50	0	0
60	0.053311	0.047731
70	0.07637	0.067512
80	0.10879	0.09009
90	0.410502	0.386061
100	0.254224	0.32091

#### D. Reliability Assessment of the WECS

To assess the reliability of any generating unit, it must be represented in two states either fully available or unavailable [9]. So the multi-state representation of the considered wind farm has to be reduced to 2 state representation using apportioning method. The fully down state is found out as the DAFOR using the equation 9 as 0.83, and the reduced 2-state model is given in Table III. Once the knowledge of unavailability rate is available, it's quite easy to estimate the adequacy of any generating unit.

TABLE III. REDUCED 2-STATE MODEL

Capacity outage in %	Probability
0	0.17
100	0.83

## VIII. CONCLUSION

The comparative probability plot of the measured wind speed and the simulated wind speed resulting from the Weibull distribution seems to be quite promising in analysing the behavior of the wind speed. The statistical tests are justifying the fitting of the theoretical probability distribution to the observed data. The dependency of the generated power of the WECS on the wind speed can be realised from power curve. Capacity outage profile of the WECS can be represented using the multi derated states by segmenting the power output in different states. The multi derated states are reduced to 2 state model for adequacy assessment using apportioning method.

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