# Time Series Application on Reliability Evaluation of Power Systems Including Wind Turbine Generators

Saeed Karimi Mahmood Fotuhi Ali Abasspour

Sharif University of technology

**Abstract**

Because of intermittent characteristic of wind speed the reliability evaluation of power systems including wind turbine generators (WTG) is not easy and it needs specific approach. In this paper time series model used for wind speed modeling and the hourly wind speeds are simulated using an Autoregressive Moving Average model. The Roy Billinton Test System (RBTS) and the IEEE Reliability Test System (IEEE-RTS) Load Model were used as capacity and load model respectively. Monte Carlo simulation used for evaluation of power system reliability.

## I. Introduction

The application of renewable energy in electric power systems is growing rapidly due to enhanced public concern for adverse environmental impacts and escalation in energy costs, shortage of fossil fuels associated with the use of conventional energy sources throughout the world. A realistic evaluation of the monetary benefits associated with these energy sources also requires an assessment of the level of system reliability that can be obtained when using these sources. Unlike other renewable energy sources, wind energy has become competitive with conventional power generation sources and therefore application of wind turbine generators (WTG) has the most growth among other sources.
The behavior of wind energy sources is different from conventional energy sources. The wind speed is very variable in time and because of that its reliability is very low. Most of the reported work on modeling wind power generation and on the use of such models for reliability evaluation is in the analytical domain .The most obvious deficiency of analytical methods is that the chronological characteristics of wind velocity and its effects on wind power output cannot be considered. Then Monte Carlo simulation has been proven to be a more effective approach to incorporate these considerations in the adequacy assessment of systems including WTG. Time series modeling used for wind speed model. The loss of load expectation (LOLE) and loss of energy expectation (LOEE) indices is used for system reliability evaluation.[1]
The basic system structure is shown in figure 1.

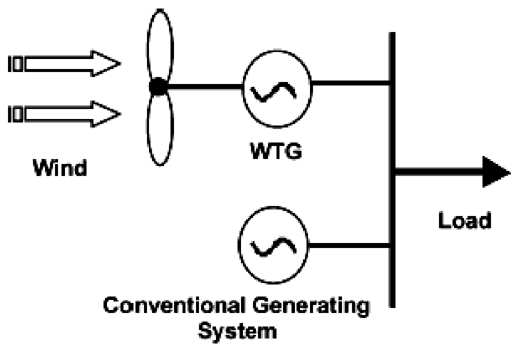


Figure1-Overall system configuration

## II. Wind Speed Model

The proposed wind speed model can be defined in terms of the following variables: [2]
Let:

$$y_t = \frac{(ow_t - \mu_t)}{\sigma_t} \qquad (1)$$

$ow_t$ : is the observed wind speed at hour t,

$\mu_t$ : is the mean observed wind speed at hour t,

$\sigma_t$ : is the standard deviation of observed wind speed at hour t.

SWt: is the simulated wind speed at hour t.
Then data series set yt can be used to establish the wind speed time series model

$$y_t = \phi_1 \times y_{t-1} + \phi_2 \times y_{t-2} + ... + \phi_n \times y_{t-n}$$
$$+ \alpha_t - \theta_1 \times \alpha_{t-1} - \theta_2 \times \alpha_{t-2} - .... \_ \theta_m \times \alpha_{t-m} \qquad (2)$$

Where $\phi_n$ و $\theta_m$ are the Autoregressive and Moving Average parameters of the model respectively and $\alpha_t$ is a normal white noise with zero mean and a variance of $\sigma_a^2$ .

The hourly wind speed $SW_t$ at time t is obtained from the mean wind speed $\mu_t$ , its standard deviation $\sigma_t$ and the time series value $y_t$ , as shown in:

$$SW_t = \mu_t + \sigma_t y_t \qquad (3)$$

### III. Output of Wind Turbine Generators

There is a nonlinear relationship between the power output of the WTG and the wind speed. The relation can be described by the operational parameters of the WTG. The commonly used parameters are the cut-in, rated, and cut-out wind speeds. The hourly power output can be obtained from the simulated hourly wind speed using

$$p_t = \begin{cases} 0 & 0 \le SW_t \le V_{ci} \\ (A + B \times SW_t + C \times SW_t^2) & V_{ci} \le SW_t \le V_r \\ p_r & V_r \le SW_t \le V_{CO} \\ 0 & V_{CO} \le SW_t \end{cases} \qquad (4)$$

Where $V_{ci}$ ، $V_r$ ، $V_{co}$ , $P_r$ are the cut-in speed, the rated speed, the cut-out speed, and the rated power of a WTG unit, respectively. The constants A, B, and C are presented in [3].

### IV. Capacity Model (Supply)

The Roy Billinton Test System (RBTS was used in the studies presented in this paper. The RBTS consists of 11 conventional generating units with a total capacity of 240 MW. The generating unit ratings and reliability data for the RBTS are shown in Table I. [4]

Table-1 units' specification of RBTS

| Rated power (MW) | TYPE | Fauiure Rate (failure/year) | Repair Time (hours) | (FOR) |
|---|---|---|---|---|
| 40 | thermal | 6 | 45 | 0.0299 |
| 40 | thermal | 6 | 45 | 0.0299 |
| 10 | thermal | 4 | 45 | 0.02013 |
| 20 | thermal | 5 | 45 | 0.02013 |
| 5 | hydro | 2 | 45 | 0.01017 |
| 5 | hydro | 2 | 45 | 0.01017 |
| 40 | hydro | 3 | 60 | 0.02013 |
| 20 | hydro | 2.4 | 55 | 0.01484 |
| 20 | hydro | 2.4 | 55 | 0.01484 |
| 20 | hydro | 2.4 | 55 | 0.01484 |
| 20 | hydro | 2.4 | 55 | 0.01484 |

### V. Load Model (Demand)

The IEEE-RTS chronological load profile on a per unit basis consisting of 8736 load points for a year was used in RBTS. The annual peak load for the RBTS is 185MW. The annual hourly load is developed by multiplying the load model per unit values by the annual peak load. This load model with 185kw peak load is shown in figure-2.

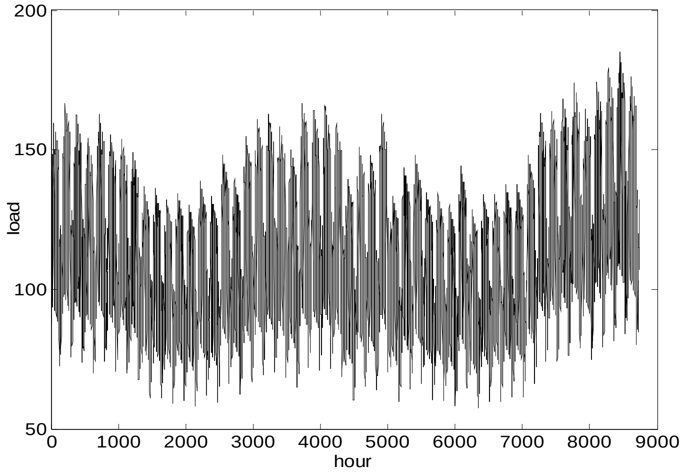


Figure2-RBTS load model

### VI. Monte Carlo Simulation

The simulation procedure for generating capacity adequacy assessment including the WTG is briefly described as follows [5].

a) Create a capacity model for the conventional generating facilities using chronological simulation. This simulation is done by using MTTF (Mean Time To Failure) and MTTR (Mean Time To Repair) parameters and the equations 5, 6.With these two equations we produce a sequence of up and down times. $X_1$, $X_2$ are uniformly distributed random variables over the interval (0, 1) and MTTR, MMTF are given as repair and failure rates in table-1.

$$T_{up} = \frac{1}{MTTR} \ln(X1) \qquad (5)$$

$$T_{down} = \frac{1}{MTTF} \ln(X2) \qquad (6)$$

Figure-3 shows sample of the RBTS capacity model for one year that it is summation of 11 units in hourly manner, so for creating capacity model for any unit equation 5, 6 are used.

b) Construct a capacity model for the WTG units using the time-series ARMA model and the WTG power output.

c) Create the total system generating capacity model by combining the capacity models obtained in steps a) and b).

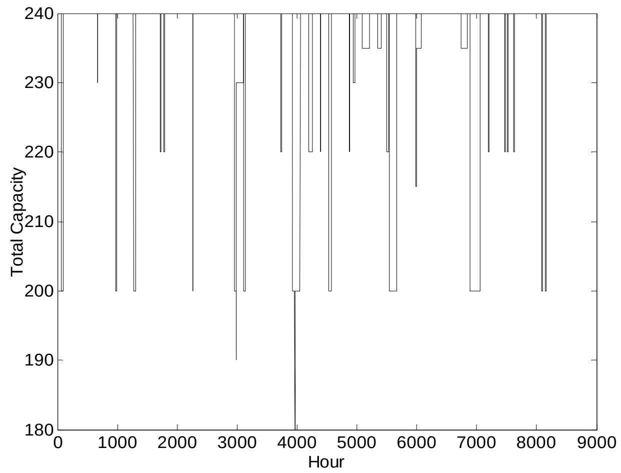


Figure-3 The sample of the RBTS capacity for one year

d) Form the required reliability indices by observing the system capacity reserve model over a long time period.

The simulation can be terminated when a specified degree of confidence has been achieved. The stopping criterion used in these studies is

$$\frac{\sigma(x)}{E(x)*\sqrt{N}} \leq .05 \qquad (6)$$

Where X is the LOLE, N is the number of sampling years, E(x) is the function mean value, and $\sigma(E)$ is the function standard deviation.

The WTG units are considered to be base loaded in that energy is supplied whenever the wind is sufficient.

## VII. Case Study

In this section at first, wind speed at one windy site in Iran is modeled then we suppose that the RBTS system have annual load growth equal to 3 percent so that it will reach to 190 KW in first year(from 185 KW) so if we do not increase capacity, the reliability of system decrease (LOLE increase)

We have to increase the system capacity in a way that the system reliability remains constant and to do this we use WTG.

### a) Wind Speed Model

Because the data of sample wind power plant was only available for three years the precision of $\mu_t$ is low.

In spite of that, we used equation (1) to produced $y_t$.

After the calculation of $y_t$ the correlogram of $y_t$ is drawn. The autocorrelations decline with increasing lags, but there are relative peaks at lag 24, 48, 72. This pattern suggests an Autoregressive and Moving Average Multiplicative Seasonal model (SARMA).

By using the Unit Root Test we observe that $y_t$ is stationary.

We examine various orders of AR and MA and at last elect the orders of AR and MA that has the least AIC (Akaike info criterion). This model includes ARMA (5, 4), SAR (24) and SMA (24).

The result for final model that is fitted to the observation is list in table2.

Table2-Specifications of evaluated ARMA model for wind speed

| | |
|---|---|
| R-squared | 0.499076 |
| Adjusted R-squared | 0.49852 |
| S.E. of regression | 0.576072 |
| Sum squared resid | 2692.041 |
| Log likelihood | -7040.15 |
| Durbin-Watson stat | 2.000344 |
| Mean dependent var | 0.013639 |
| S.D. dependent var | 0.813486 |
| Akaike info criterion | 1.736063 |
| Schwarz criterion | 1.744684 |
| F-statistic | 898.0073 |
| Prob(F-statistic) | 0 |

We examine the residuals to have normal distribution. For residuals test we first test autocorrelations of residuals .These are shown show in figure-4.

By considering this figure we can observe that residuals autocorrelations are in the permissible band approximately.

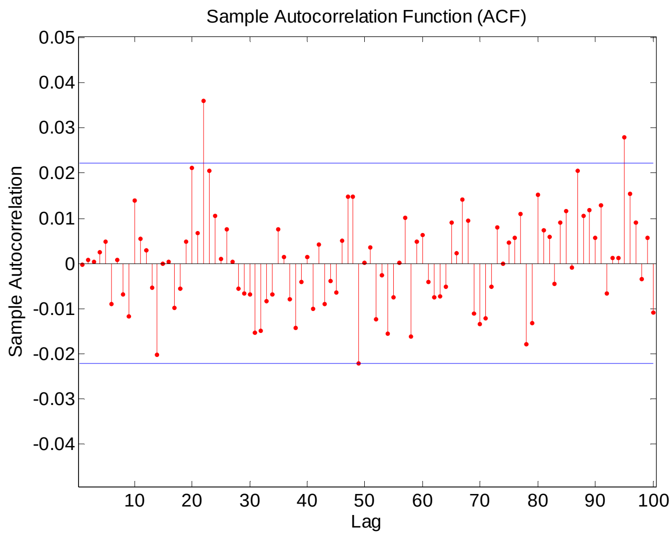


Figure4- Autocorrelations of residual for 100 lags

Also we perform Q-statistic at the 95 % probability level for differed K and its results are shown in table3.

Table3- Q-static test results

| K | 21 | 41 | 61 | 81 |
|---|---|---|---|---|
| Q | 12.265 | 36.21 | 53.144 | 69.282 |
| $\chi^2(K-11)$ | 18.30704 | 43.77297 | 67.5 | 90.5 |

#### b) Reliability Index

The LOLE index is the most applicable index to evaluate power system reliability and it is defined as the total expected time duration that load exceeds supply for one year.

For calculating this index for one system with specific load and capacity models (i.e. RBTS system) we should compute total time that demand (load) exceeds supply (capacity).

To create a capacity model including wind turbine generators we should first calculate wind speed and the output power of wind turbines from equations 3,4,5 and after that we have to adds output of these turbines to conventional units in hourly manner .

Monte Carlo simulation is used for evaluating LOLE index.

In this approach we first calculate time duration that demand (load) exceed the supply for one year and then we calculate LOLE. This process is repeated until satisfying equation-6. In this equation X is LOLE index. At last the LOLE index is calculated as total time that load exceed the capacity divided in repeating years. Figure-5 shows the sample of convergence for this index for long process.

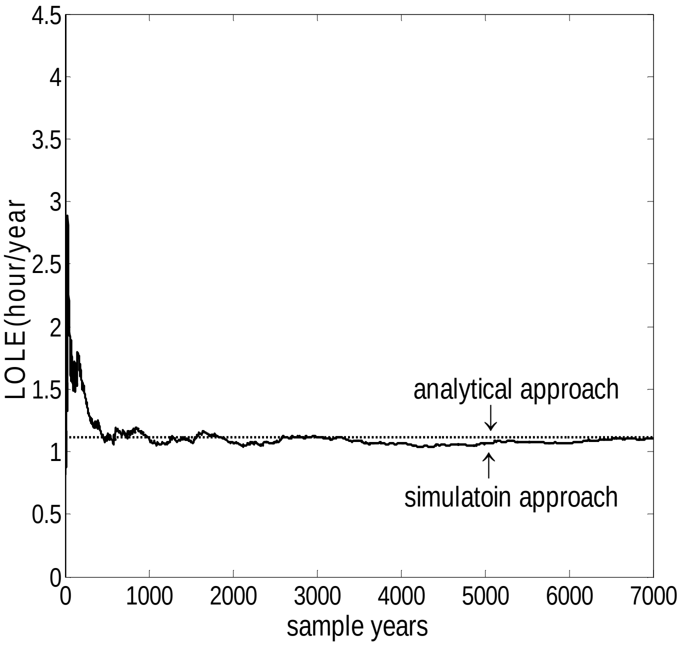


Figure5-Comparison of calculating LOLE index from analytical and simulation approach

#### c) Result

As it is mentioned, we suppose that the peak load of the RBTS reaches to 190 KW in first year. Now we want to see how much wind capacities needed in related to conventional units to maintain the LOLE index constant. Figure-6 shows load growth against the LOLE index versus load growth before and after adding wind units. As it can see from this figure, 11.25 MW wind capacity is needed for compensation of the load growth whereas only 5 MW conventional capacity need for it. Another noticeable point is that low penetration of wind units are more effective than high penetration of them that it means increasing in capacity of wind turbines in power system decrease the effect of them.

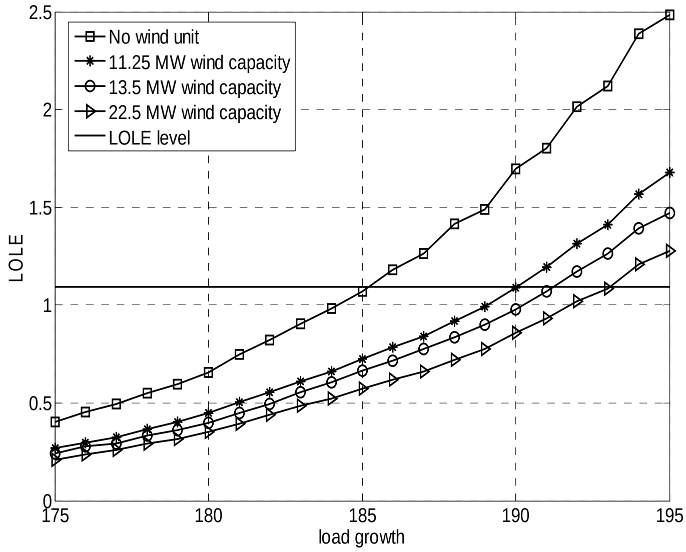


Figure-6 LOLE changes against the load growth.

### Average of Wind Speed

In this section the previous assumptions are considered and we add 50 wind units (11.25 MW) to system for various average wind speed.

Figure-7 shows the effects of increase in average wind speed on system reliability.

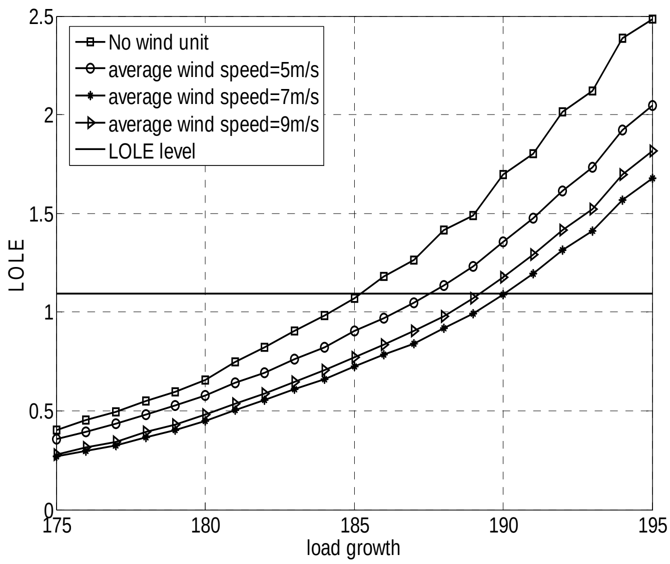


Figure7-Effects of average wind speed in reliability (addition of 11.25MW wind capacity to system)

## Conclusion

Wind power units in related to conventional units have the lower reliability. Additions of these units to power system in low among have the more effects and with increasing the per cent penetration of this unit to system the effects of them decrease. The higher average wind speed result to the more increasing in system reliability.

## References


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[2] R. Billinton, Hua Chen and R.Ghajar, "Time-series models for reliability evaluation of power systems including wind energy", Microelectronics and Reliability, Vol. 36, No. 9, 1996, pp.1253-1261.

[3] P. Giorsetto and K.F.Utsurogi, "Development of a new procedure for reliability modeling of wind turbine generators", IEEE Trans. PowerApparatus and Systems, Vol. 102, No. 1, January 1983, pp. 134-143.

[4] R. Billinton, S. Kumar, N. Chowdhury, et. al, "A reliability test system for educational purposes - basic data", IEEE Transaction on Power Systems, Vol. 4,No. 3, 1989, pp. 1238-1244.

[5] Roy Billinton, ‚Guang Bai' Generating Capacity Adequacy Associated With Wind Energy' IEEE TRANSACTIONS ON ENERGY CONVERSION, VOL. 19, NO. 3,