



## A probabilistic model for assessing the reliability of wind farms in a power system

Mostafa HOSSEINPOUR<sup>†1</sup>, Habib RAJABI MASHHADI<sup>1,2</sup>, Mohammad Ebrahim HAJIABADI<sup>1</sup>

<sup>(1)</sup>Faculty of Engineering, Department of Electrical Engineering, Ferdowsi University of Mashhad, Mashhad, Iran

<sup>(2)</sup>Center of Excellence on Soft Computing and Intelligent Information Processing, Ferdowsi University of Mashhad, Mashhad, Iran

<sup>†</sup>E-mail: hoseinpoor\_mostafa@yahoo.com

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**Abstract:** Modeling the generation of a wind farm and its effect on power system reliability is a challenging task, largely due to the random behavior of the output power. In this paper, we propose a new probabilistic model for assessing the reliability of wind farms in a power system at hierarchical level II (HLII), using a Monte Carlo simulation. The proposed model shows the effect of correlation between wind and load on reliability calculation. It can also be used for identifying the priority of various points of the network for installing new wind farms, to promote the reliability of the whole system. A simple grid at hierarchical level I (HLI) and a network in the north-eastern region of Iran are studied. Simulation results showed that the correlation between wind and load significantly affects the reliability.

**Key words:** Wind farm, Reliability, Priority, Probabilistic model

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### 1 Introduction

Renewable energy resources play an important role in eliminating reliance on fossil fuels and reducing greenhouse gas emissions. Within the last two decades, the trends of various countries in the world toward renewable energies have led to an increase in penetration of wind farms in power systems, and it is forecasted that power generated by wind farms will be comparable to that produced by other units in the near future. Therefore, analyzing the effects of penetration of these units on the planning and operation conditions of power systems is of high significance. At the same time, studying the rate of effectiveness that these units have on the reliability of power systems is crucial due to the random nature of these units. In recent years, various models of wind farms have been introduced to evaluate the reliability of power systems.

An appropriate model should be able to integrate randomness and probably-being characteristics of wind speed for any wind unit. Most of the introduced models have strived to simulate wind speed in wind unit modeling to accomplish a reasonable evaluation for a power system including wind units. Probabilistic reliability techniques are required to model the impacts of wind energy resources on system reliability and adequacy. The energy-limited and intermittent characteristics of wind generation have been studied using the probabilistic reliability assessment techniques. The capacity state probability model of energy-limited generation has been developed by Billinton and Harrington (1978) and Billinton and Allan (1996) for probabilistic reliability assessment. In this model wind generation output is dependent on wind speed and wind turbine outage (Giorsetto and Utsurogi, 1983; Wang *et al.*, 1984). The impacts of wind generation on system reliability have been investigated based on probabilistic reliability assessment from different viewpoints (Billinton *et al.*, 1996; Karki *et al.*, 2004; Chowdhury, 2005; Zhang and

Chowdhury, 2009).

What has been considered in these models is the probability of existence in various cases for the wind farm output. In fact, the correlation between wind and load directly influences the reliability of the system, and for the installation of a new wind farm, the hourly correlation between wind and load plays a key role in supplying peak load. In the present models for wind farms, however, effect of correlation between wind and load in one area on the reliability of a network has not been analyzed.

The fundamental feature of the model presented in this paper for calculating reliability in wind farms is that it considers the effect of correlation between wind and load in one area. The main goal is to develop a probabilistic model which is more effective for reliability assessment at hierarchical level II (HLII). This model presents the effect of correlation between hourly patterns of wind and load in one area on the reliability of the network. It can also be used for identifying the priority of various points of the network for installing new wind farms, to promote the total reliability level of the system. This model is implemented on a real network, and the results are evaluated and compared to those of simulations.

## 2 Literature review

### 2.1 Wind turbine generator modeling

The output of a wind turbine is a function of wind speed. There is a nonlinear relationship between them. Fig. 1 illustrates a typical case.

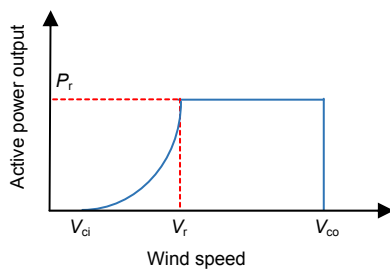


Fig. 1 Relationship between wind turbine power output and wind speed

In Fig. 1,  $V_{co}$ ,  $V_{ci}$ ,  $V_r$ , and  $P_r$  are the high cutting velocity, low cutting velocity, rated velocity, and rated power of a wind turbine, respectively. The

output power of the wind turbine generator ( $P_{WTG}$ ) in each hour can be calculated through the mathematical expression related to the power-speed curve:

$$P_{WTG} = \begin{cases} 0, & SW_t \leq V_{ci}, \\ A + B \cdot SW_t + C \cdot SW_t^2, & V_{ci} < SW_t \leq V_r, \\ P_r, & V_r < SW_t \leq V_{co}, \\ 0, & SW_t > V_{co}, \end{cases} \quad (1)$$

where  $SW_t$  is the wind speed in each hour, and  $A$ ,  $B$ , and  $C$  are calculated as follows (Haghifam and Omidvar, 2006):

$$\begin{cases} A = \frac{1}{(V_{ci} - V_r)^2} \left[ V_{ci}(V_{ci} + V_r) - 4V_{ci}V_r \left( \frac{V_{ci} + V_r}{2V_r} \right)^3 \right], \\ B = \frac{1}{(V_{ci} - V_r)^2} \left[ 4(V_{ci} + V_r) \left( \frac{V_{ci} + V_r}{2V_r} \right)^3 - (3V_{ci} + V_r) \right], \\ C = \frac{1}{(V_{ci} - V_r)^2} \left[ 2 - 4 \left( \frac{V_{ci} + V_r}{2V_r} \right)^3 \right]. \end{cases} \quad (2)$$

Note that the turbines used in this work have such specifications:  $V_{co}=25$  m/s,  $V_{ci}=4$  m/s,  $V_r=15$  m/s, and  $P_r=2$  MW.

### 2.2 Multi-state modeling

Among the methods that have been introduced for wind unit modeling, we use a multi-state model in reliability calculation.

With this method, data of wind speed in last years is used to extract the probabilistic distribution function (PDF) for a given geographical area. Then considering the power-speed characteristic of wind turbines, a wind farm is changed into a multi-state generation unit, whose corresponding probability to any state is available. Fig. 2 shows the modeling process (Chowdhury, 2005; Haghifam and Omidvar, 2006; Haghifam and Soltani, 2010; Zhang *et al.*, 2011).

### 2.3 Markov chain modeling

A Markov chain model is used in many references for modeling wind speed or power generated in wind farms. In general, to model a randomized

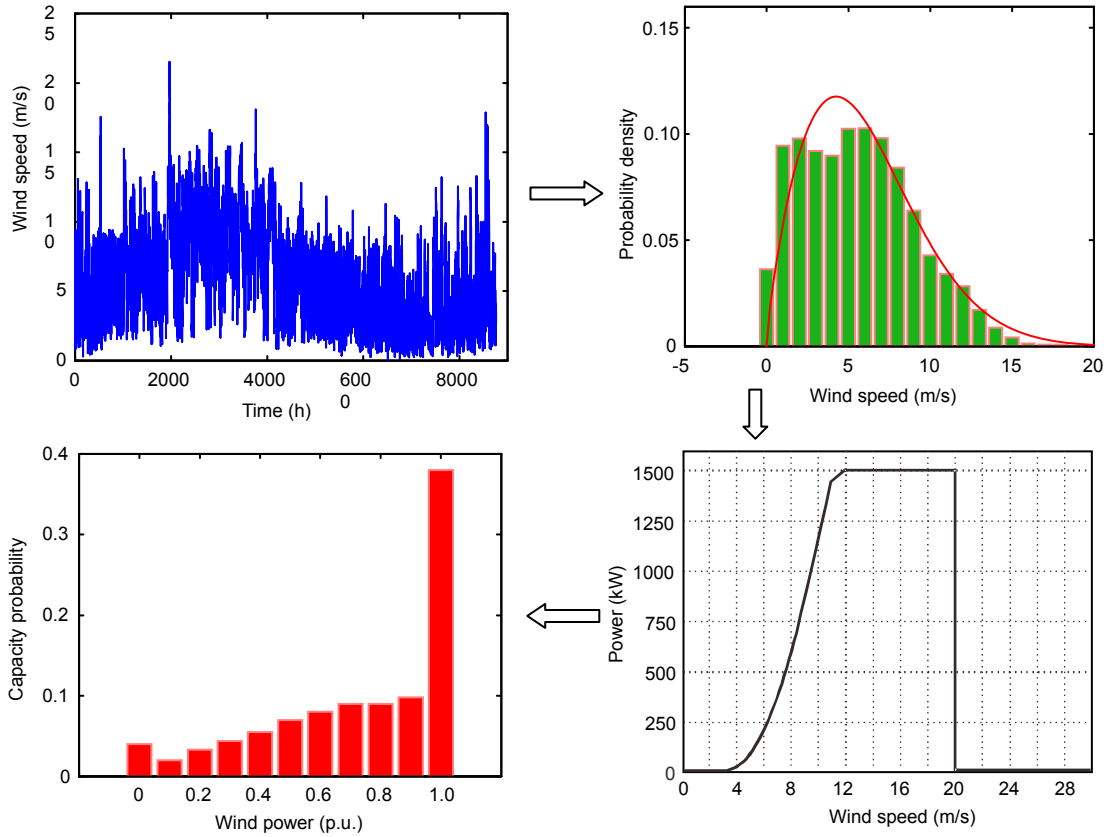


Fig. 2 Multi-state model for a wind unit

process with the Markov chain, it is necessary to calculate the transition rates in many different cases. By modeling wind speed, continuous data of wind speed is converted to discrete data. According to

$$\begin{aligned} & \Pr(X_t = j | X_{t-1} = i, X_{t-2} = 1, X_{t-3} = m, \dots, X_{t-k} = n) \\ &= \Pr(X_t = j | X_{t-1} = i), \end{aligned} \tag{3}$$

a first-order Markov model is defined as the future state of the system, related only to its last state.

Hence, in the Markov chain model the probability of transition from state  $i$  to state  $j$  is

$$\Pr(X_t = j | X_{t-1} = i) = P_{ij}. \tag{4}$$

Since the reliability studies for network planning are accomplished for a period of one year or more, the changes in wind speed can be presented by a steady Markov model, which has a fixed transition rate. In fact, the exponential distribution of the transition

rate is considered as a constant. This fixed transition rate is achieved by

$$\lambda_{ij} = N_{ij} / D_i, \tag{5}$$

where  $N_{ij}$  is the number of iterations in which state  $i$  transmits to state  $j$  within the period.  $D_i$  is the duration of the past states in the whole period,

$$D_i = \sum_{i=1}^n t_i. \tag{6}$$

The probability of occurrences of state  $i$  is given by

$$P_i = D_i / T_s, \tag{7}$$

where  $T_s$  is the total period of the time series of wind speed. The frequency of occurrence  $F_i$  of state  $i$  is given by the total number of occurrences of this state.

This method was extended by Leite *et al.* (2006), Papaefthymiou and Klockl (2008), and Dobakhshari and Fotuhi-Firuzabad (2009).

### 2.4 Time-series modeling

The ARMA( $n, m$ ) time-series model is a conventional model for simulating and forecasting wind speed. The general representation is as follows (Karki *et al.*, 2006; Billinton *et al.*, 2009):

$$y_t = \sum_{i=1}^n \varphi_i y_{t-i} + \alpha_t - \sum_{j=1}^m \theta_j \alpha_{t-j}, \quad (8)$$

where  $y_t$  is the time-series value at time  $t$  and  $\varphi_i$  ( $i=1, 2, \dots, n$ ) and  $\theta_j$  ( $j=1, 2, \dots, m$ ) are the autoregressive and moving average parameters, respectively.  $\{\alpha_t\}$  is a normal white noise process with zero mean and variance  $\sigma^2$ . 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  $y_t$ :

$$SW_t = \mu_t + \sigma_t y_t. \quad (9)$$

### 3 Proposed method for wind farm modeling

The principal issue of the presented model for reliability assessment of wind farms is that it considers the effect of hourly correlation between the annual wind curve and the load of an area.

Around some wind farm locations, seasonal and daily wind patterns are out of phase with the patterns of local load; i.e., heavy wind generation occurs during a low load period and poor wind generation occurs during a peak load period. The worst case scenario is that a wind project is sited where wind is rich at night during winter while the system load peak takes place in daytime during summer. Fig. 3 shows an area load profile and an aggregated wind generation of several wind farms for 24 h. It is obvious that the trends of load and wind generation deviate from each other.

One of the main goals of the system planner is to determine the time and place for installation of new equipments to maintain the reliability level or bring it to a standard rate. Therefore, peak load supply is an issue that has significant effect on network planning and directly influences system reliability. We know

that for installing a new wind farm, the hourly correlation between wind and load has a key role in peak load supply.

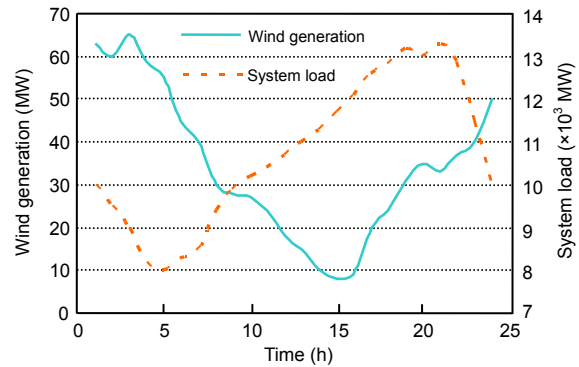


Fig. 3 Unfavorable daily wind generation pattern

Accurate simulation of wind speed in every hour is a crucial requirement for reliability assessment in systems including wind farms. Wind speed changes upon alteration in place or time. On the other hand, wind speed in every hour depends on the wind speed in recent hours. In this study we use the ARMA time-series model to simulate hour-to-hour wind speed.

In the proposed method, the equivalent generation model and equivalent load model are used. Assuming that a load and a local conventional generator exist on a bus connected to the wind farm (Fig. 4), we want to model the total power generated by the wind farm and the local load by an equivalent generator and equivalent load.

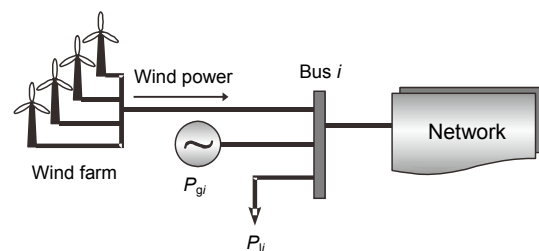


Fig. 4 Local generator and load on a bus connected to a wind farm

The power curves of local load ( $P_{li}$ ) and the conventional generator ( $P_{gi}$ ) are involved in modeling (Fig. 4). After modeling, the equivalent generator and load existing on the bus connected to the wind farm and network are considered (Fig. 5). The proposed model consists of four steps (Fig. 6).

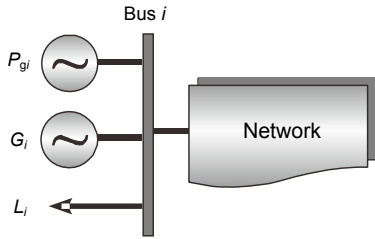


Fig. 5 Equivalent generator and load on the bus connected to a wind farm

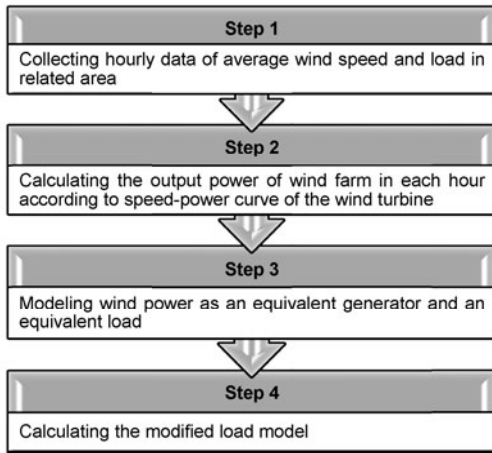


Fig. 6 Basic steps of the proposed method

Step 1: In the proposed model, the hourly load curve and the average wind speed in each hour for the entire grid are used to present the effect of correlation between wind and load. Wind speed data is extracted from the information measured by synoptic stations located in various areas whose heights are 40 m. The ARMA time-series model is used to simulate the hour-to-hour wind speed. The load curve is achieved by collecting the annual load in related areas and then calculating the average for each hour.

Step 2: Using the wind speed data for each hour and power-speed curves for wind turbines, the hourly power output is achieved for each area. Fig. 7 shows a typical power output for a 2 MW turbine.

The output power of a wind farm is

$$P=0.95AX, \tag{10}$$

where  $A$  is the total number of turbines in the wind farm,  $X$  is the capacity of a specific type of turbine, and 0.95 is the correlation coefficient of the wind

farm, which depends on the formation of wind turbines (Haghifam and Omidvar, 2006).

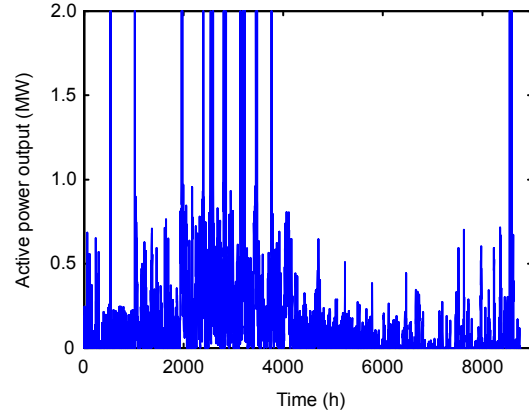


Fig. 7 Annual hourly wind power output

Step 3: This uncertainty of a wind farm in generation is modeled as a load. A wind farm is represented by an equivalent load and specified generation level. In this procedure the annual hourly load curve of each bus is also used, if available. The amount of power generated by a supposed generator is equal to the maximum power that the network absorbs from the wind farm in each hour throughout a year:

$$G_i = PW_{i,max} \tag{11}$$

Note that this generator is considered as a fully reliable generation unit. In other words, the forced outage rate (FOR) for this unit is zero.

The additional power generation to the power that a wind farm really injects to the network ( $P_w$ ) is modeled as an equivalent hourly load ( $L_{equal}$ ) (Fig. 8), calculated as

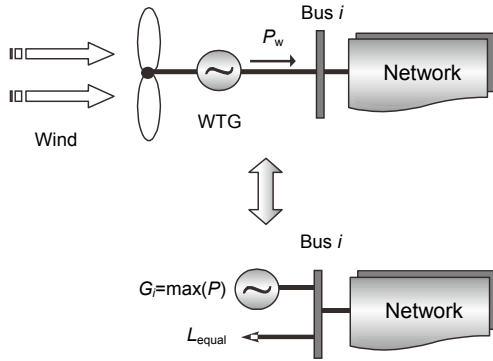
$$PW_{i,max} - L_{equal} = P_w, \tag{12}$$

or

$$L_{equal} = PW_{i,max} - P_w. \tag{13}$$

Step 4: An equivalent load model is achieved by combining the local hourly load curve for the bus connected to wind farm ( $P_{li}$ ) and the equivalent hourly load curve ( $L_{equal}$ ) in an equivalent generation model:

$$L_{modified}=L_{equal}+P_{li}. \tag{14}$$



**Fig. 8** Equivalent generator and load on the bus connected to a wind farm

According to the annual data of  $L_{\text{modified}}$ , the modified load duration curve (MLDC) is calculated, for use in reliability assessment with Monte Carlo simulation.

The equivalent generation ( $G_i$ ) and equivalent load ( $L_i$ ) in bus  $i$  are thus achieved:

$$G_i = P_{W_{i,\text{max}}} \tag{15}$$

$$L_i = \text{MLDC} \tag{16}$$

As mentioned before, the only issue that should be considered is that since a wind farm is modeled as an equivalent load along with a specific generation level, the generator which is equivalent to wind farm in bus  $i$  ( $P_{W_{i,\text{max}}}$ ) should have a zero outage rate, while the conventional generation at bus  $i$  ( $P_{g_i}$ ) has a specific outage rate. In other words, in this model the uncertainty related to wind farm generation is transformed to MLDC.

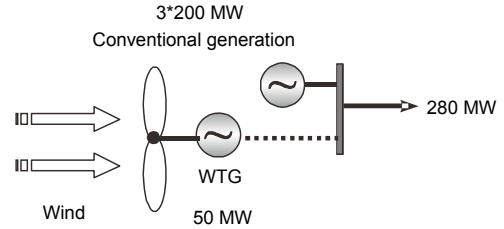
## 4 Case studies

### 4.1 Case I

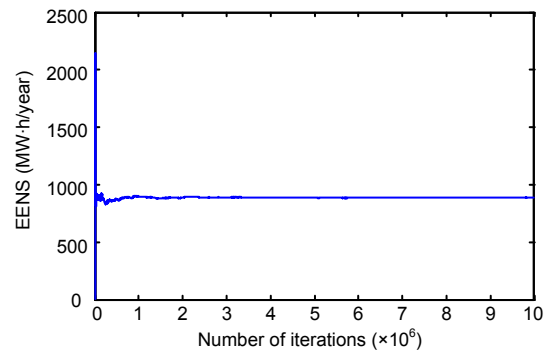
To compare the proposed model with conventional models, a simple grid at hierarchical level I (HLI) is used. This grid has three conventional generators, each having 200 MW rated power and FOR of 0.05, along with a local load, with peak load being 280 MW (Fig. 9).

This grid with its conventional generators and local load reaches an expected energy not supplied (EENS) index of 842 MW·h/year after 10 million

iterations of our reliability assessment program (Fig. 10).



**Fig. 9** Grid for the case study at hierarchical level I



**Fig. 10** The expected energy not supplied (EENS) index for case study at HLI with Monte Carlo simulation

In the following, the presumptive wind speed data in 10 districts (A to J) is used. For data of each district, a wind farm with a total capacity of 50 MW is added to the grid using the proposed model and conventional models, and the results are analyzed.

The correlation coefficient is used to analyze the effect of hourly correlation between wind and load on reliability evaluation indices. The correlation coefficient between two variables  $x$  and  $y$  is calculated as

$$R_{xy} = \frac{\text{cov}(x, y)}{\sqrt{\text{var}(x) \cdot \text{var}(y)}} \tag{17}$$

The closer the correlation coefficient  $R_{xy}$  to one, the higher the correlation between data of two variables  $x$  and  $y$  (data of wind and load in each district). The data in 10 districts is given in Table 1.

Monte Carlo simulation at the HLI level is used to measure the reliability. EENS is calculated for each bus.

$$\min \left( -\sum_{i=1}^N P_{li} \right)$$

such that

$$\begin{aligned}
 \sum P_{gi} - P_{li} - \sum_j f_{ij} &= 0, \quad i = 1, 2, \dots, N, \\
 f_{ij} - \gamma_{ij}(\theta_i - \theta_j) &= 0, \quad i = 1, 2, \dots, N, \\
 |f_{ij}| &\leq \max(f_{ij}), \\
 0 \leq P_{gi} &\leq \max(P_{gi}), \quad i = 1, 2, \dots, G, \\
 0 \leq P_{li} &\leq \max(P_{li}), \quad i = 1, 2, \dots, N.
 \end{aligned}
 \tag{18}$$

The objective function in each iteration of the Monte Carlo process is the maximum load delivered to each bus at any grid status under the operation constraints and DC load flow.  $N$  is the total number of buses.

**Table 1 Data related to wind speed of 10 presumptive regions**

Site	Wind speed (m/s)			SD	CC
	Average	Maximum	Minimum		
A	4.20	17.25	0.0	3.92	0.31
B	6.67	25.21	0.0	3.12	0.35
C	3.97	16.10	0.0	2.22	0.15
D	5.26	19.38	0.0	4.68	0.20
E	4.58	17.41	0.0	4.58	0.31
F	3.98	22.72	0.0	3.87	0.02
G	4.83	18.41	0.0	3.23	0.06
H	5.15	25.55	0.0	2.42	0.35
I	3.59	20.41	0.0	3.59	0.09
J	3.68	25.81	0.0	2.14	0.07

SD: standard deviation; CC: correlation coefficient between wind and load

After running a reliability program with Monte Carlo simulation for all the 10 districts, the priorities of locations for installing wind farms are achieved (Table 2).

This priority is based on reliability promotion, i.e., more reduction in the EENS reliability index. Also, prioritizing on the basis of annual average wind speed, correlation between wind and local load, and annual energy supply is shown in Table 3.

As can be seen, in most cases, prioritizing according to the proposed method accords with prioritizing according to correlation between wind and load. The reason for contradiction in some cases is the difference between the amounts of energy supplied in these districts. One district (for example, G) may experience a low correlation between wind and load,

but a relatively high level of annual generation energy, and thus is preferable to a district (for example, C) that has a relatively high correlation between wind and load but a lower level of annual generation energy. Therefore, the proposed model not only includes the generation level in each district, but also shows the effect of correlation between wind and load on reliability. In conventional modeling techniques such as the multi-state unit method and Markov chain model, prioritization is determined mainly due to the average wind speed in each district and the effect of correlation between wind and load is not considered. This may lead to deceptive results for the network planner, because the major objective of the network planner is to maximize the reliability level of the system.

**Table 2 Prioritizing installation locations in terms of reliability**

Proposed model	Multi-state unit model	Markov chain model
B	B	B
H	D	D
A	H	G
E	G	H
D	E	E
J	A	F
G	F	A
F	J	J
C	I	C
I	C	I

**Table 3 Prioritizing installation locations in terms of wind energy potential**

Energy generated	Average wind speed	Correlation between wind and load
B	B	B
D	D	H
A	H	A
H	G	E
E	E	D
G	A	C
J	F	I
F	C	J
I	J	G
C	I	F

Considering the importance of generation planning in power systems and new approaches toward wind farms, the prioritization of locations for installing generation units can be considered as a primary factor in power system planning. Various indexes can be studied for this reason, each prioritizing wind farm installation potential from a distinct viewpoint. From the viewpoint of network planners and operators, since analysis and evaluation of the reliability level in power system generation and transmission networks is one of crucial requirements in network planning and operating processes, system reliability is the most efficient index for determining the location and time of installation of new equipments. For this reason, accurate and correct calculation of reliability indexes is an important concern for the planners and operators. Additionally, given the requirement to install new wind farms in various points in the network, another complexity related to calculation of network reliability indexes is how to model and analyze the effect of the generation level of wind farms on such indexes. The proposed model

for use in reliability evaluation calculations of a wind farm is a new approach for modeling such units, which in contrast to other models is capable of indicating the effect of correlation between hourly load and wind patterns on reliability indexes appropriately. If in one region wind peak hours are concurrent with load peak hours, while investment costs to supply peak load decrease, the reduction of lost load during peak hours improves the system reliability level. In the proposed model, a generation equivalent model and a load equivalent model are used to model wind farms in network reliability calculations.

### 4.2 Case II

The proposed model was implemented on Khorasan's high voltage (HV) network. A vast part of the current network in Iran is used with the purpose of presenting and running the proposed model on a real network. This network consists of 63, 132, and 400 kV voltage levels. In this study the HV portion of this network having 17 buses and 19 transmission lines is used (Fig. 11). The HV portion is 2040 km in length

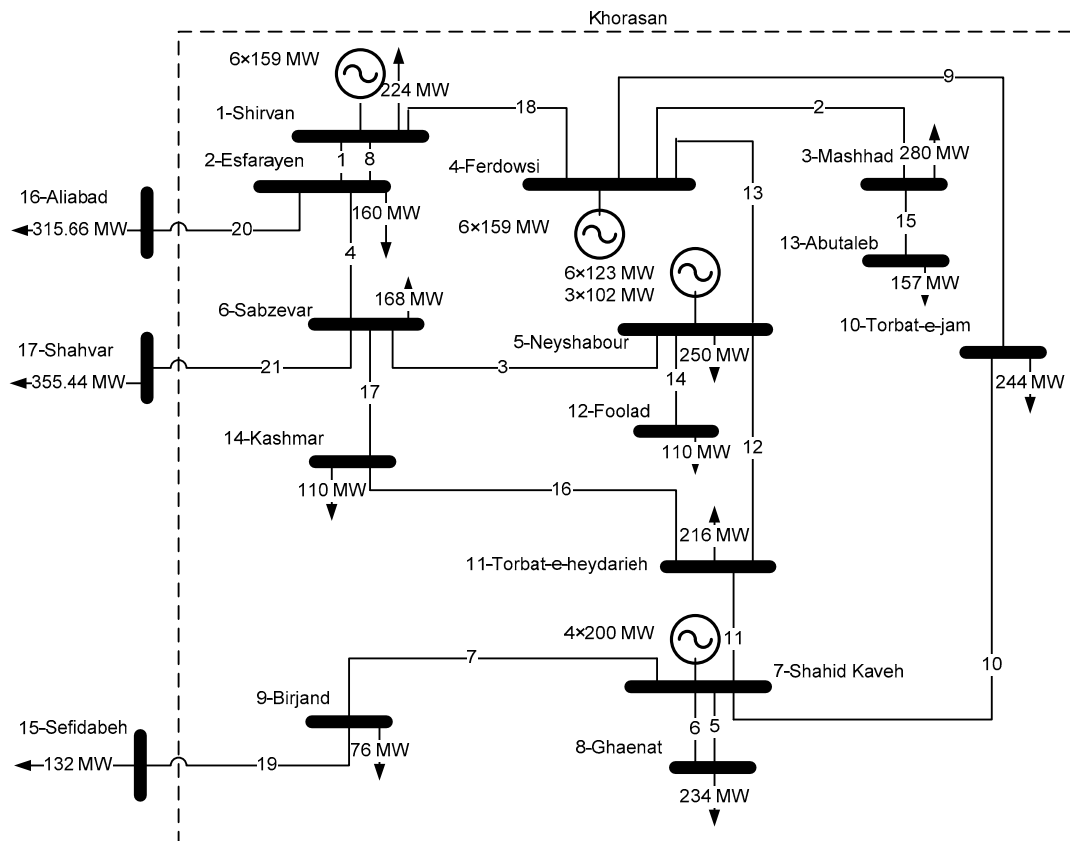


Fig. 11 Single line diagram of the Khorasan transmission network



and has 4760 MW installed capacity. This network is also vast geographically and occupies an extensive part of Iran. In some regions of this network, the wind blows intensely, while in some zones installing wind farms or connecting them to the network is not feasible. Also, in some regions wind blows less intensely.

It is assumed in calculations that a 200 MW wind farm can be placed in 10 different points of the Khorasan transmission network. In this placement, reliability assessment was accomplished using Monte Carlo simulation at the HLII level. The proposed model is used for modeling a wind farm. Also, the data for average wind speed in the past 15 years is achieved for each hour from 10 meteorological synoptic stations in Khorasan's network. In the locations of these stations the possibility to install wind farm and connect it to the power system is provided. According to the height of the towers which house wind turbines, data related to wind speed in 40 m of height is used.

Table 4 shows the nearest bus to each meteorological synoptic station for which data is used, along with data related to wind speed and the correlation coefficient between wind and load calculated in each district.

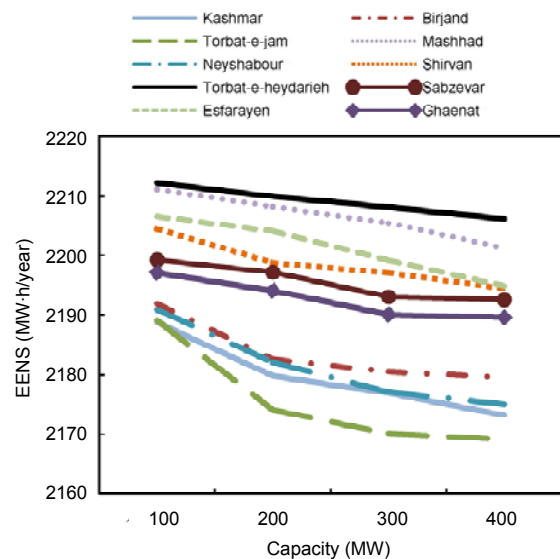
**Table 4** Data related to wind speed in 10 different buses of the Khorasan transmission network

Bus	Wind speed (m/s)			SD	CC
	Average	Maximum	Minimum		
Torbat-e-heydarieh	4.9	16.1	0.0	2.4	0.1570
Sabzevar	4.5	19.4	0.0	3.3	0.0956
Ghaenat	5.5	18.4	0.0	3.5	0.3108
Mashhad	4.9	20.7	0.0	3.1	0.0227
Neyshabour	5.1	19.2	0.0	3.9	0.3139
Torbat-e-jam	7.6	26.5	0.0	4.6	0.3509
Shirvan	5.7	18.4	0.0	3.4	0.0611
Birjand	6.1	21.6	0.0	3.4	0.3504
Esfarayen	4.6	15.9	0.0	2.9	0.0786
Kashmar	6.2	19.4	0.0	3.7	0.2017

SD: standard deviation; CC: correlation coefficient between wind and load

The results are related to the running reliability program for any distinct capacity of the wind farm located in related points of Khorasan's transmission network using the proposed model (Fig. 12). The rate

of calculated EENS for this network using this program and without adding new wind farms is 2215.7 MW·h/year. Fig. 12 shows that as the capacity of wind farms added to different buses of the network increases, the promotion in the EENS reliability index decreases. An increase in the generation level of wind farms gradually makes the decrease in reliability indices saturated. This fact can be used to determine the appropriate capacity of wind farms in different points of the network. But what has more significance is that while some locations in the network experience high average wind speed, installation of wind farms in such points does not improve the reliability level significantly. This is due to the fact that load and wind curves do not behave coordinately in each hour in those districts. Through the modeling method for wind farms in this work, this influence on reliability assessment measurements is clearly seen.



**Fig. 12** Change of the expected energy not supplied (EENS) index along with capacity increase of wind farms located in Khorasan's transmission network

Fig. 13 shows the results concluded from running the reliability program, along with the characteristics of correlation between wind and load, estimated energy generated by a 660 kW·h turbine, and average wind speed in each district of Khorasan's transmission network.

Table 5 lists the priorities of wind farm installation locations in Khorasan's network in terms of different points of view. In this evaluation, the

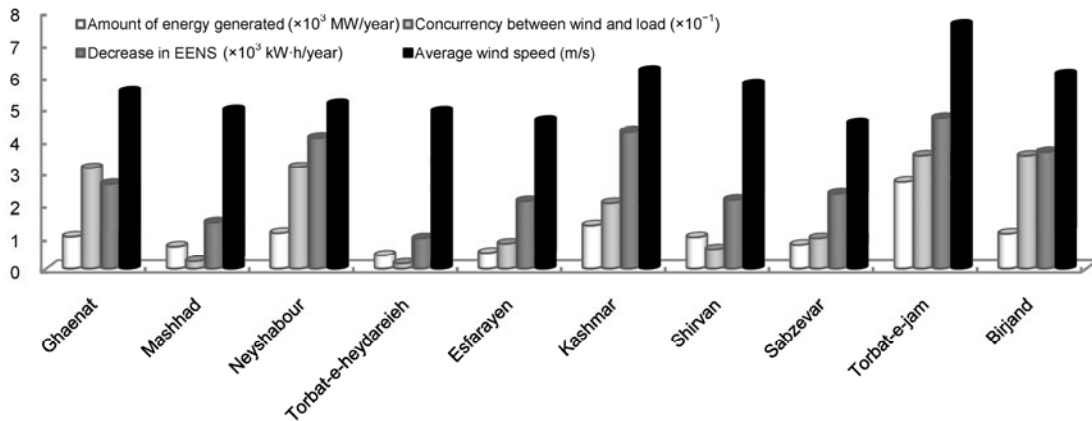


Fig. 13 Data and results related to reliability assessment measurements accomplished in the 10 districts of Khorasan’s transmission network

Table 5 Comparison between priorities of installation locations of wind farms in terms of wind energy potential and reliability level promotion in Khorasan’s transmission network

Amount of energy generated	Average wind speed	Correlation between wind and load	Reliability level promotion
Torbat-e-jam	Torbat-e-jam	Torbat-e-jam	Torbat-e-jam
Kashmar	Kashmar	Birjand	Neyshabour
Neyshabour	Birjand	Neyshabour	Kashmar
Birjand	Shirvan	Ghaenat	Birjand
Ghaenat	Ghaenat	Kashmar	Ghaenat
Shirvan	Neyshabour	Torbat-e-heydarieh	Sabzevar
Sabzevar	Mashhad	Sabzevar	Shirvan
Mashhad	Torbat-e-heydarieh	Esfarayen	Esfarayen
Esfarayen	Esfarayen	Shirvan	Mashhad
Torbat-e-heydarieh	Sabzevar	Mashhad	Torbat-e-heydarieh

installation of wind farms with different capacities in distinct locations is modeled and priorities of installation locations of such generation units are shown in terms of reliability. Not only is the energy generated in each site considered, but also the effect of the correlation between wind and load on prioritization is included for each district. To prioritize, this model considers a sort of trade-off between annual energy generated and the correlation between wind and load existing in each district.

### 5 Conclusions

Given the increasing level of wind farm presence in power systems, a method for modeling such units is presented to prioritize their installation locations in terms of reliability. Considering the limitation of other presented models which disables them from analyzing the effect of hourly correlation between wind and load on reliability characteristics and peak load supply, our approach focuses on the effects of these circumstances on reliability assessment, and uses the presented model to prioritize installation locations of wind farms in a power system.

The results of implementation of this model on Khorasan’s transmission network showed the efficiency of this approach in reliability assessments. Moreover, these results can be used to allocate appropriate capacity to wind farms located on various points of the grid.

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## Highlights

### **Detection of quantization index modulation steganography in G.723.1 bit stream based on quantization index sequence analysis**

This paper presents a method to detect the quantization index modulation (QIM) steganography in G.723.1 bit stream. We show that the distribution of each quantization index (codeword) in the quantization index sequence has unbalan...

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