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Reliability Modeling of Various Type of Wind Turbines

A. Ghaedi[1,]*, R. Sedaghati[2], M. Mahmoudian[3]

[1] Department of Electrical Engineering, Dariun Branch, Islamic Azad University, Dariun, Iran.
[2] Department of Electrical Engineering, Beyza Branch, Islamic Azad University, Beyza, Iran.
[3] Department of Electrical and Electronic Engineering, Shiraz University of Technology, Shiraz, Iran.

ABSTRACT: Various wind turbines have been manufactured for converting wind power into electric energy. They are fixed speed concepts with squirrel cage induction generators, limited variable speed concepts with wound rotor induction generators, variable speed concepts with double fed induction generators, direct-drive concepts with electrically excited synchronous generators and gearbox-free concepts with permanent magnet induction technologies. The composed components and the power curve of these technologies are different and to select an appropriate wind turbine for a wind site, in addition to the economic parameter, reliability criterion must be considered. To address this, a reliability model is developed in this paper that considers both component failure and the unpredictable nature of wind speed for different types of wind turbines. The optimal state number of reliability presentations is determined using XB index calculation and fuzzy c-means clustering method to create multi-state presentations for wind turbines. The proposed approach can be used to determine the most reliable wind turbine for a given wind site by assessing the adequacy of the electric network containing various types of wind turbines. The approach's effectiveness is demonstrated through adequacy assessments of the RBTS and IEEE-RTS, which contain various types of wind turbines.

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1- Introduction

Power plants using fossil fuels are held responsible for environmental problems such as greenhouse gas emissions, change of climate, and global warming. Due to volatility in price and resource depletion problems, many countries are turning to renewable energy. Due to its advanced technology, abundant resources, and availability, wind power is the best choice for generating electricity in electrical systems. Large wind farms are being built all over the world; The top ten wind farms are constructed in China, India, the United States, and the United Kingdom. Wind energy is converted into electricity using various wind turbines, such as the high-speed concept of squirrel-cage asynchronous generators, the limited-speed concept of wound-rotor asynchronous generators, the variable-speed main octet of double-fed induction generators, electrically excited Synchronous generators, and gearbox-free techniques using permanent magnet synchronous technologies. Reliability and financial considerations are important when choosing wind turbines for wind farms because these turbines have different power and different characteristics. This study uses reliability models to compare different wind turbine types [1].

Given the advanced understanding of wind energy, significant research has been done to explore how wind turbines affect energy. For example, time-dependent reliability models related to wind farms have been developed to assess the reliability of generators at short and medium duration time with large-power wind access. In addition, back up many case models for conventional generators, fast-start generators, and hybrid generation, and others for wind farms [2]. In another study, a new classification-based approach was developed to analyze wind farm adequacy considering the relationship between wind velocity and turbine reliability. The main aim of the study is to better understand how changes in wind velocity affect the failure of turbines and therefore wind farm's reliability. In addition, there are problems in integrating wind energy into the grid. In addition to ensuring the cohesion and flexibility of the electricity supply, the diverse and interconnected nature of wind power can affect the stability and adequacy of the electric network. To overcome these problems and to ensure the integration of wind energy into energy, advanced control strategies, and energy storage should be developed and deployed. The difficulty of integrating wind energy into electrical energy is reduced by using various control strategies and energy storage [3]. One strategy for managing differential and interconnected power generation is to use advanced control strategies. For example, grid control systems such as power control, power control, and frequency control can help control the output power of wind turbines and increase their grid-compatible efficiency. An additional solution to the diverse and interconnected nature of wind energy is the integration of multiple wind

*Corresponding author's email: amir_ghaedi_63@yahoo.com

turbines. Using energy storage devices to store excess air and release it as needed is another way.

Energy storage systems such as batteries, flywheels, and compressed air energy storage are used as backup power sources when wind energy is insufficient and help to solve the interaction problem of wind energy. Additionally, these facilities can improve grid compatibility by controlling the power output of wind turbines. Additionally, other techniques, such as estimating wind power output and integrating wind power into a variable power mix, can reduce the problems associated with mixing wind power into electrical power. Wind power forecasting can provide accurate estimates of wind power resources and allows utility users to adjust their power operations as needed. By integrating wind energy into a mix of different energy sources, a stable and reliable power supply can be achieved, which helps to balance the differential and interdependent interaction of wind energy with other energy sources.

There are many studies related to the reliability of wind turbines. The diversity and interdependence of wind energy, which can be unstable and affect the overall reliability of the electric power system, is a major challenge for plate integration. To manage the diverse and interconnected nature of wind power generation, many studies have proposed control strategies for cutting and energy storage. These studies also develop reliability models that take into account factors that have an impact on wind turbine operation, such as wind fluctuations, expected outages, wind turbine failures, and failure rates. For example, the framework in [4] shows a reliable model for wind farms used in and extracted from wind turbines, while the model in [5] selects the best layout for an offshore wind farm based on reliability and economy. In addition, while determining the safety limit, the model in [6] suggests a novel idea for examining wind sensor generators' reliability. To accurately predict the behavior of wind speed, other studies (such as [7]) have developed measurement models. The authors in [8] proposed a method to select the best battery energy store based on the wind speed model for improving the reliability of energy. Authors of the paper [9] suggest a novel method for assessing the reliability of external wind farms, including weather forecasting. This approach is according to the Markov-chain Monte Carlo technique. Besides, the model in [9] proposed a novel technique according to the Markov-chain Monte Carlo technique to assess the reliability of western agricultural systems considering extreme weather conditions. Finally, the authors in [10] developed several state reliability models for wind farms using dual generators that take into account both failures and other costs and instability of power generation. The proposed model, which provides important recommendations for the development, management, and maintenance of wind farm electricity, is used to calculate the adequacy of the electric network including wind farms.

In this paper, the comparison among different types of wind turbines from the reliability point of view is performed. For this purpose, a multi-state reliability model is developed for these wind turbines. The contributions of this paper would be:

- Different large-scale wind energy conversion systems are introduced. The basis of operation, composed components, and the generated power of them are studied.
- A multi-state reliability model considering both the failure of composed components and variation in the generated power arising from the variation in the wind speed is developed for different types of wind turbines.
- To determine the optimum number of states in the reliability model of different types of wind energy conversion systems, the XB index is calculated.
- To determine the probability of reduced states in the reliability model of different types of wind energy conversion systems, the fuzzy c-means clustering method is applied.
- The adequacy of the power system containing large-scale wind turbines is performed and a comparison among different types of large-scale wind energy conversion systems based on the reliability criterion is performed.

The organization of this research is as follows for examining how different wind energy conversion systems affect the dependability of power systems: different technologies for wind units are introduced in the second section. Various wind units' reliability models are run in the third section. A method for evaluating a power system's suitability with wind energy conversion systems is illustrated in the fourth part. Numerical simulations are described in the fifth part to compare different kinds of large-scale wind energy conversion systems from a reliability perspective. The conclusion of the paper is illustrated in the sixth part.

2- Different Types of Wind Turbines

Wind, as a renewable resource, can be used by the power system to produce electricity. The power generated by an air mass moving at *v* velocity is obtained using equation (1) [11]:

$$P = \frac{1}{2} C_P \rho A v^3 \tag{1}$$

In the equation above, C_P stands for the Betz factor, A for the square area of the wind turbine, *K* for air density in kilograms per cubic meter. The generated power can be determined using the wind turbine's power curve. Fig. 1 illustrates a typical power curve for wind turbines [12]. The electric produced power of the turbine, as depicted in the figure, is zero for speeds greater than the cut-out velocity (v_{co}) and less than the cut-in velocity (v_{ci}). For velocities between cut-in velocity and rated velocity (v_{rat}), the generated power of the wind turbine can be calculated as (1). The wWind turbine's output is fixed and equal to its nominal capacity (P_{rat}) for wind speeds between nominal velocity and cut-out velocity.

Various wind turbine technologies have been developed to take advantage of wind energy, each with different characteristics and efficiency. This technology includes ideas of direct drive with excited synchronous generators, ideas of

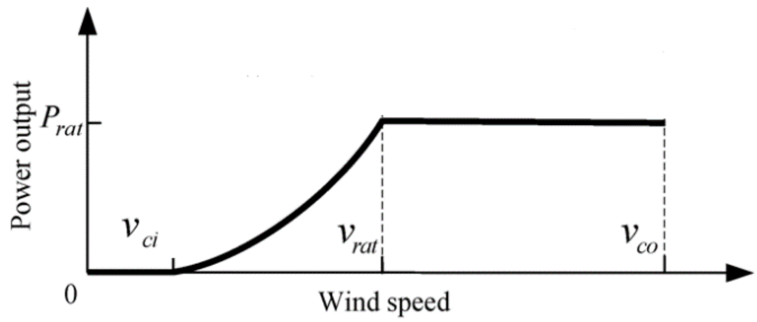

Fig. 1. Typical power curve of wind turbine [12]

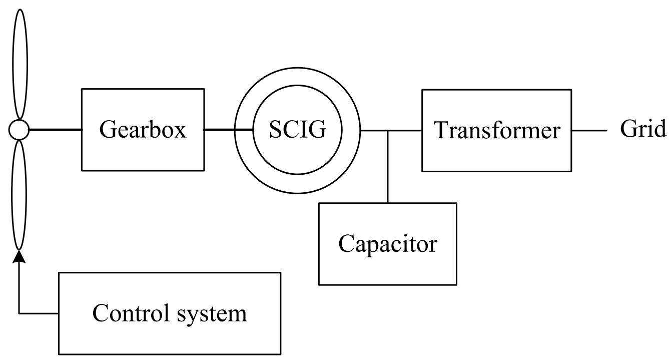

Fig. 2. The structure of the fixed speed concept equipped to the squirrel cage induction generator [13]

direct drive with excited synchronous generators, fixed speed points with electrically excited synchronous generators, different speed concepts with wound rotor asynchronous generators limited to different speed elements, equipped with a two-fed induction generator, etc. Because of these changes, reliability standards are specifically designed for each wind turbine. This model takes into account the unique curve and installation process of each generator. Based on the failure of the assembly and the difference in power generation due to the difference in wind speed, this study presents several reliability cases for each type of wind turbine. In the proposed model, more reliable and usable wind turbines are estimated by considering the effect of various faults on the overall performance.

2- 1- Fixed speed concept equipped to the squirrel cage induction generator

The wind turbine illustrated in Figure 2 uses a constant velocity concept equipped with Squirrel Cage Induction Generator (SCIG) technology. A wind turbine has many components such as cables, control systems, capacitors, transformers, SCIGs, and wind turbine rotors. The technology's reliability, availability, and affordability make it ideal for mass production. In addition, this technology allows control centers to operate at high speed while connected to a large network providing stable control. In addition to station control, station control or sound control techniques can be used to control the output of wind turbines [13].

One of the most used wind turbine types today, especially in onshore wind farms, is SCIG's high-speed wind turbine machine. Wind generator manufacturers consider it an alternative due to its simplicity, low cost, and reliability. SCIG technology is particularly useful for wind turbines operating in unstable conditions, as it is less affected by changes in wind speed and direction. However, the continuous use of SCIG wind turbines has some disadvantages. One of the main problems is its inability to adjust to wind changes, which reduces its capture power and efficiency. Active and slope control technologies have been developed for controlling output of wind turbines and increase efficiency for overcoming this limitation.

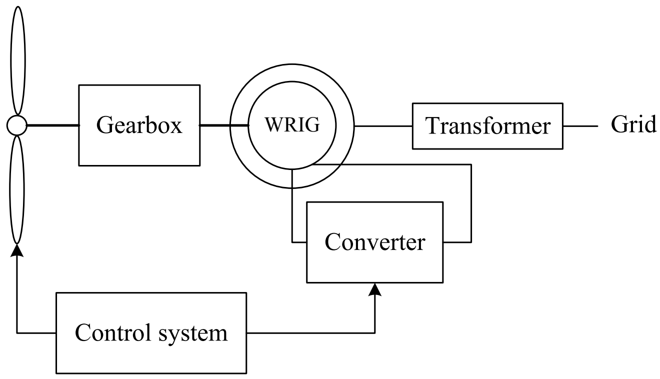

Fig. 3. Structure of limited variable speed concept equipped to the wound rotor induction generator [13]

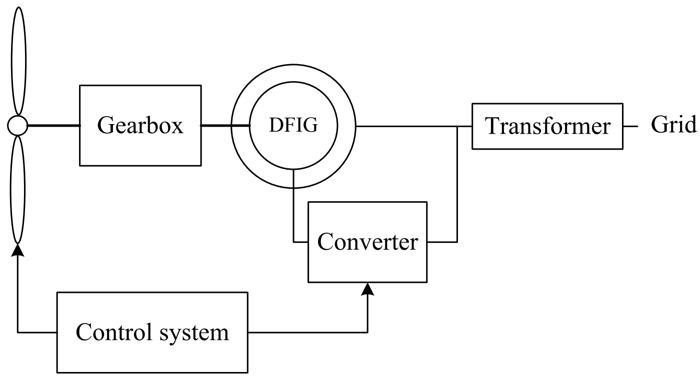

Fig. 4. The structure of the variable speed concept equipped to the double-fed induction generator [13]

2- 2- Limited variable speed concept equipped to the wound rotor induction generator

Figure 3 shows a wind turbine containing a wound-rotor asynchronous generator (WRIG) that uses a different concept with its structure and components. The wind turbine has many elements including transformer, cable, gearbox, WRIG, converter, and wind turbine rotor. The machine connects the electric power switch and the voice control path to the WRIG's variable rotor resistor. Stator windings of the generator are directly attached to the network, unlike rotor windings attached by control. Most of the power from the rotor is dissipated in an external resistor to stabilize the mains frequency. Thus the generator can run at high velocity [13]. A popular option for wind turbines used in on-shore and off-shore wind units is the variable velocity wind turbine concept with WRIG technology. Thanks to this technology, better control of wind turbine output is possible, which can increase energy capture and efficiency. Because it can adjust wind speed and direction, WRIG technology is particularly useful in areas with variable winds. However, the limited velocity variable velocity wind unit concept based on WRIG technology has some limitations. One of the main problems is the need to dissipate too much energy in external resistors, resulting in loss of efficiency and power loss. To overcome this limitation, advanced electrical equipment and control systems have been developed, thereby increasing the efficiency and performance of WRIG-based wind units.

2- 3- Variable speed concept equipped to the double-fed induction generator

Using a Double Feed Induction Generator (DFIG), Figure 4 shows the structure and characteristics of a wind turbine with a different concept. Gearboxes, DFIGs, power converters, transformers, cables, control systems, and wind turbine rotors are some of the components that make up a wind turbine system. With this technology, a local generator is mounted on the rotor of the generator and WRIG is attached to the differential of the wind turbine. The transformer

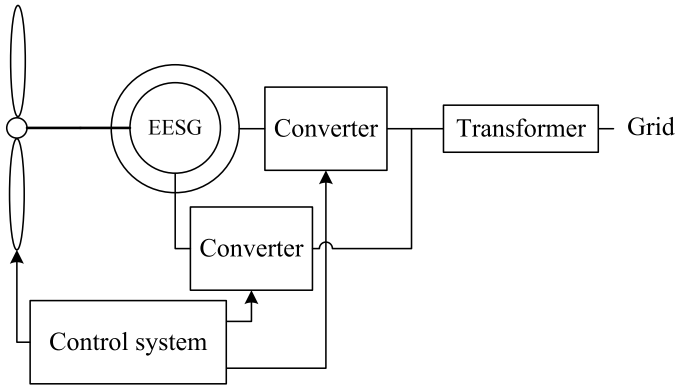

Fig. 5. The structure of the direct-drive concept equipped to the electrically excited synchronous generator [13]

controls rotor frequency, which affects rotor speed. The transformer is used as a direct connection between the stator and the grid [13]. For on-shore and off-shore wind units, the variable velocity wind turbine concept with DFIG technology is a popular choice. The technology provides better control of the wind turbine's power output, increasing energy capture and efficiency. Because DFIG technology can adapt to changes in wind speed and direction, it is particularly useful in environments where the wind is changing. The power converter applied in DFIG based wind unit controls the rotor speed and rotor frequency which controls the output of the wind unit. Thanks to this control, wind turbines can operate at different speeds, which allows them to use more energy and work better.

2- 4- The direct-drive concept equipped with the electrically excited synchronous generator

The structure and the composed components of the wind turbine based on the direct-drive concept equipped to the electrically excited synchronous generator (EESG) are presented in Figure 5. As can be seen in the figure, this wind generation unit consists of the wind turbine, EESG, two power electronic converters including converters connected to the rotor and stator, control system, transformer, and cable. The voltage and frequency can be controlled using the power electronic converter connected to the stator. To control the flux for loss minimization the power electronic converter connected to the rotor can be utilized to control the excitation current [13]. Due to the mechanical complexity and maintenance problems associated with the gearbox, direct drive technologies that remove the gearbox, are frequently used in the wind turbines. These wind turbines have several advantages including high efficiency, low maintenance, and high reliability. The electrical power converters used in the direct drive wind turbines equipped with the electrically excited synchronous generator can provide high-level control of generated power. To enhance the performance and efficiency of the wind unit, this technology, the field current, and magnetic flux are controlled through a power converter connected to the rotor. Besides, the voltage and frequency of the wind unit are controlled by the electrical converters attached to the stator. Thus, the wind unit can generate the output power in the stable manner.

2- 5- The direct-drive concept equipped to the permanent magnet synchronous generator

The structure and components of PMSG gearbox-free wind turbine are described in Figure 6. Wind turbine rotors, PMSGs, power converters, control systems, transformers, and cables are some of the goods. Combination of wind turbine systems. PMSG technology is superior to other generator technologies in many ways, including high efficiency, reliability, and efficiency. This device is one of the best choices for wind power generators as its price is lower than in previous years [13]. In wind energy, direct-drive wind turbines using PMSG technology have gained popularity. By replacing the transmission with PMSG, mechanical complexity and maintenance should be reduced. The advantages of PMSG for wind power generators include its high efficiency, reliability, and efficiency. In direct drive wind turbines with PMSG technology, wind unit output is better controlled using energy conversion and quality control techniques. The power converter makes it possible to adjust the voltage and frequency of output, which can increase the output of wind turbines.

2- 6- The multiple-stage geared concept equipped with the permanent magnet synchronous generator

Figure 7 describes the structure and characteristics of a wind turbine using a multiphase gear mechanism coupled to a PMSG. An electric generator has many parts, including wind turbines, gearboxes, PMSG, power transformers, control

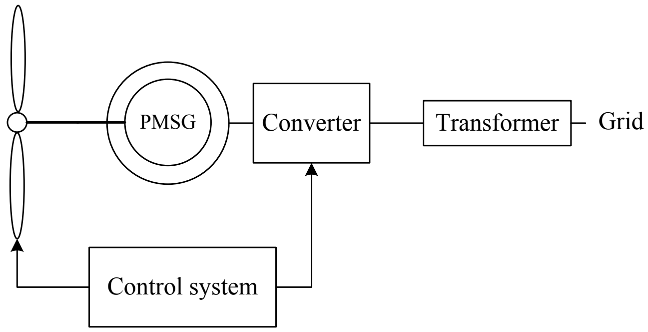

Fig. 6. The structure of the direct-drive concept equipped to PMSG [13]

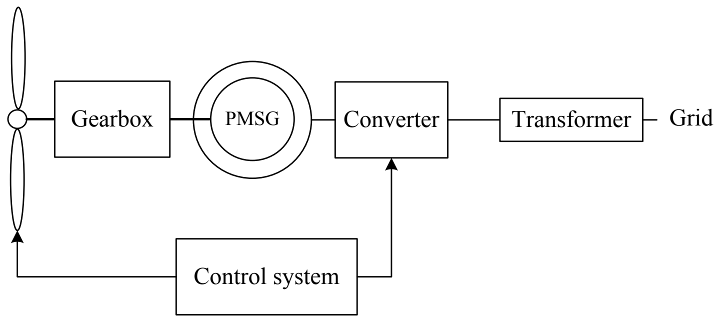

Fig. 7. The structure of the multiple-stage geared concept equipped to the permanent magnet synchronous generator [13]

systems, transformers, and cables. Together, these elements can capture wind energy and convert it into electricity [13]. The application of multistage gear and PMSG technology in power generation is increasing. Wind turbine torque is increased using multistage gears, resulting in more power and increased efficiency. PMSG technology has many advantages over other generators such as high efficiency, reliability, and efficiency. In a wind turbine with PMSG technology, the output of the device can be better managed using a converter and efficient control strategy. This converter makes it possible to control the voltage and frequency of output so that the output of the power generator can be completed.

2- 7- The multiple-stage geared concept equipped with the squirrel cage induction generator

Figure 8 shows the multistage gear concept as a wind turbine connected to SCIG with its design and components. Wind turbines, gearboxes, SCIGs, power converters, control systems, transformers, and cables are the main components of this technology as shown in the figure [13]. Other wind turbine technologies that are less common on the market are brushless double-feed induction generators (BDFIG), switched reluctance generators, claw shaft generators, and linear induction generators [13].

3- Reliability modeling of different wind turbines

To develop reliability models for various wind turbines, this section considers changes in turbine power due to wind variations and the effects of component failures on the overall performance of wind turbines.

3- 1- Fixed speed concept equipped to the squirrel cage induction generator

In this paper, a Markov model with 2 states (up and down) is applied to model the reliability of elements. The hazard rate denotes the transition from perfect to failed state. Any one of the component parts that make up a fixed velocity wind unit-based SCIG technology, such as wind turbine, gearbox, SCIG, capacitor, transformer, control system, and cable, fails, leading to the failure of the entire system and the end

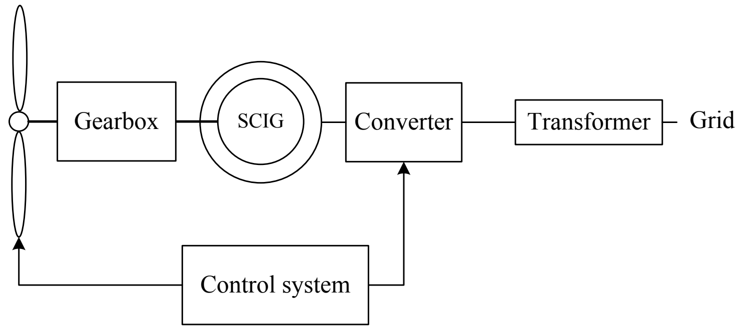

Fig. 8. The structure of the multiple-stage geared concept equipped to the squirrel cage induction generator [13]

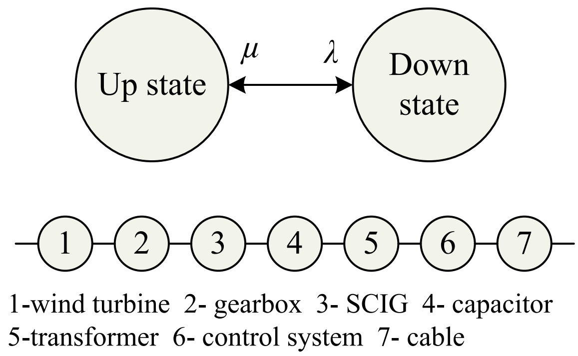

Fig. 9. The reliability model of the fixed speed concept equipped to the SCIG

of wind turbine production. Therefore, from the standpoint of reliability, the equivalent hazard rate (λ) and repair rate (μ) of device with n series elements are calculated as follows [14]:

$$\lambda = \sum_{k=1}^{n} \lambda_k , \mu = \frac{\lambda}{\sum_{k=1}^{n} \frac{\lambda_k}{\mu_k}} \quad (2)$$

Therefore, Fig. 9 can be used to demonstrate the fixed speed concept-based reliability presentation of a wind unit fitted to SCIG. You can calculate the availability (A) and unavailability (U) of this wind turbine using the formulas below [14]:

$$A = \frac{\mu}{\lambda + \mu}, U = 1 - A = \frac{\lambda}{\lambda + \mu} \quad (3)$$

Wind farms consisting n wind units are represented by the reliability model in Figure 10. Each of the ($n+1$) states in this model has (k-1) wind turbines that have failed. These numbers can be used to calculate the likelihood of state k:

$$P_k = \binom{n}{k} A^{n-k+1} U^{k-1} \quad (4)$$

In northern of Iran, at the Manjil site, Fig. 11 shows hourly wind velocity for 2017. Using hourly wind velocity and the power curve of the wind unit wind turbine's hourly generated power is calculated. Because the generated power varies due to variations in wind speed, we decrease the state's number of wind turbine outputs to construct a multi-state reliability presentation for these turbines.

The references [15–20] use a reliability model for renewable power plants, including wind farms, PV systems, run of the river units, stream-kind tidal units, and barrage-type

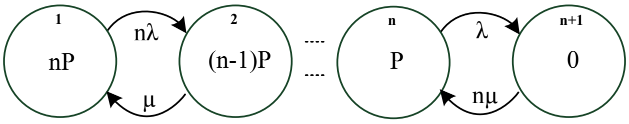

Fig. 10. Reliability presentation of the wind farm

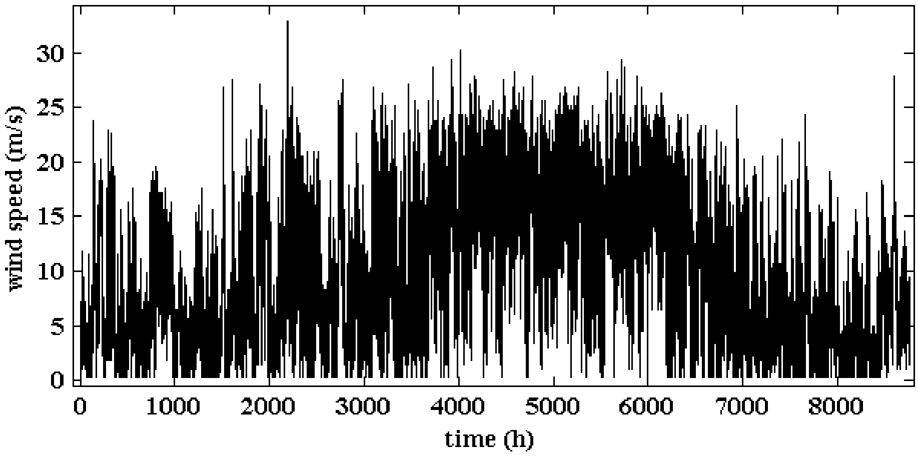

Fig. 11. The hourly wind speed

tidal power plants; a robust technique is used for reducing the number of states. The fuzzy c-means clustering technique requires known state numbers number in order to reduce total state numbers. This paper calculates optimal cluster numbers in the reliability presentation of wind units using *XB* index. The formula used to calculate the *XB* index is [21]:

$$XB = \frac{J_m(U,v)}{n \times \min_{i \neq j}\left(\left|v_i - v_j\right|^2\right)} \tag{5}$$

The objective function connected to *FCM* is $J_m(U,v)$ in this instance. When there are right cluster number, *XB* is minimal. Initial output power data are divided into c clusters by FCM technique [22] when following objective function is minimized.

$$J = \sum_{i=1}^{c}\sum_{k=1}^{n} u_{ik}^{m}\left|x_k - v_i\right| \tag{6}$$

Where u_{ik} is the fuzzy degree to which x_k depends on i_{th} cluster and m is the fuzzification parameter, which in this paper is considered to be 2. Wind turbine output power for hour k is given by x_k, the center of i_{th} cluster by v_i, number of decreased cluster is given by c, and the number of initial power data is given by n. The reliability presentation of wind turbine's states is reduced using *XB* index to calculate the ideal number of reduced clusters. Thus x_k is the wind turbine output power related to hour k, v_i is the center of i^{th} cluster, c is the number of decreased clusters, n is the number of initial wind unit output data, m is the fuzzification factor, and u_{ik} is fuzzy degree between x_k and i_{th} cluster. To reduce the number of output states in the reliability presentation of wind turbines, we calculate *XB* index, and the ideal number of reduced clusters is established. FCM technique is then used to determine the capacities and probabilities associated with these clusters. For illustration, the probability of cluster i can be calculated as follows:

$$P_i = \sum_{k=1}^{n} u_{ik} \tag{7}$$

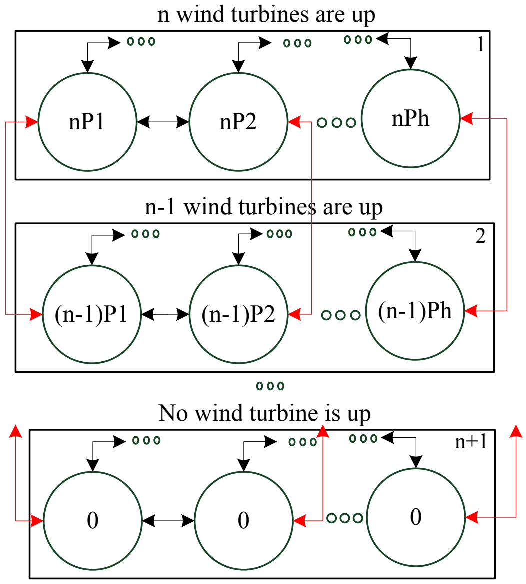

Fig. 12. The complete reliability presentation of the wind farm

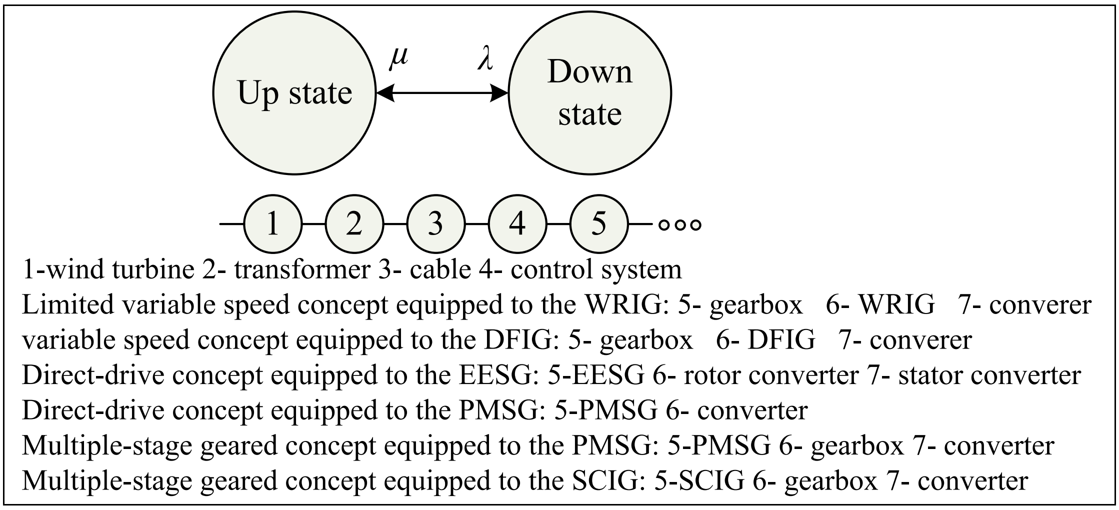

Fig. 13. Reliability presentation of different wind turbines considering the hazard of composed elements

The reliability presentation of the wind farm is the result of combining reliability presentation linked to the impact of component failure with reliability presentation linked to the change of wind unit output, and it is depicted in Fig. 12 as the finished product. In this model, it is assumed that we install *n* wind units in the farms. Variation in the output of wind unit is described by *h* clusters with the corresponding power levels of *P1*, *P2*, ..., and *Ph*.

3- 2- Reliability modelling of other wind turbines

The method for figuring out reliability for the fixed speed concept used with the SCIG that was described in the previous subsection is the same as the proposed method for developing the multi-state reliability presentation for other wind units. However, different wind energy conversion systems have unique power curves, component compositions, and reliability models. Figure 13 shows a reliability presentation that considers the hazard of assembled elements for a variety of wind turbines. Failure of any wind energy conversion system's primary constituents, as shown in the design of these wind turbines, leads to hazards of entire unit.

To determine the multi-state reliability model of each winding unit through the proposed method introduced in the paper, the steps of the flowchart shown in Fig. 14 must be followed.

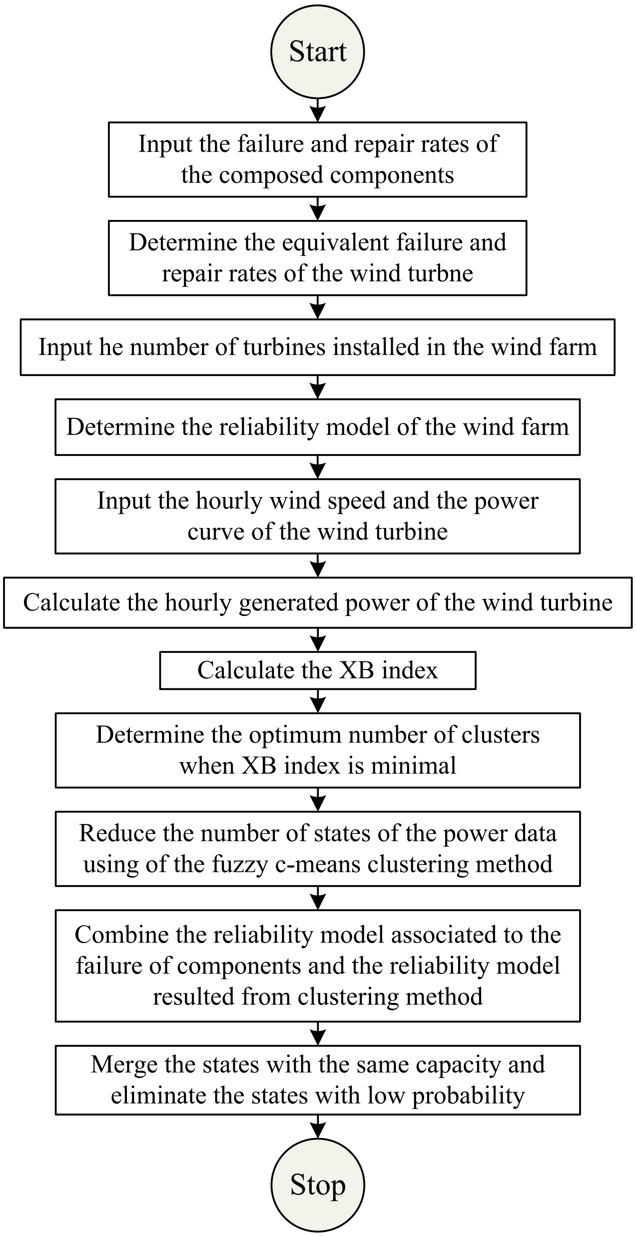

Fig. 14. The flowchart of multi-state development for the wind farms

4- Adequacy assessment of power systems including wind units

According to Fig. 15, for studying the dependability of the electric networks with wind units based on sufficiency indices, all generation power plants and the system load are attached to a common bus, and the transmission network is disregarded.

For each conventional generation unit, we construct a capacity outage probability table (COPT) for determining sufficiency indices of large-capacity wind units in the power system. These power plants can be displayed in two different states: up (at full capacity) and down (producing no power). The COPT of the wind farms can be reached, as was mentioned in the previous section, and by adding all COPTs, the system's overall COPT can be reached. The generation system model, which consists of the total COPT and the load model, can be convolved to calculate important reliability indices like average time of interruption (LOLE) and average interrupted energy (EENS).

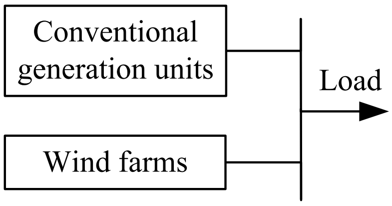

Fig. 15. Adequacy assessment of electric network including wind units

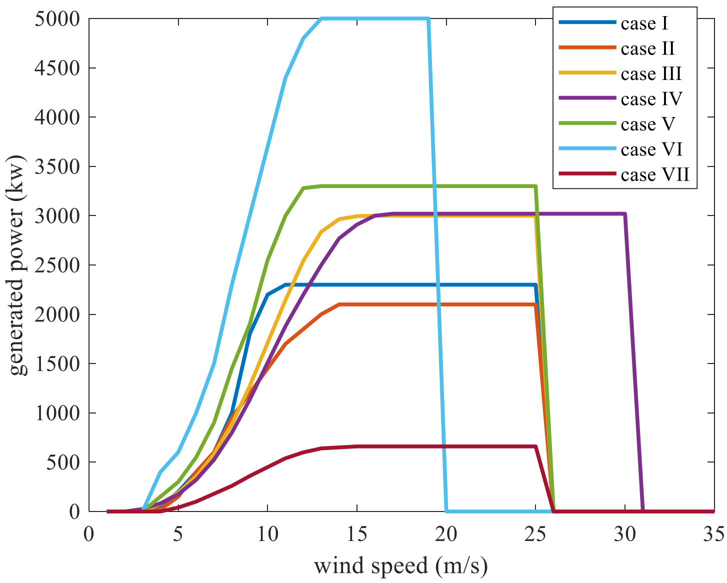

Fig. 16. Power curve of different wind farm situations

5- Numerical results

Here, the suitability of the Roy Billinton Test Network (RBTS) and IEEE Reliability Test Network (IEEE-RTS) is assessed, and the influence of various wind turbines on important reliability indices of these electric networks is investigated. Thus, the seven wind farms listed below are taken into account:

Case I: A constant velocity concept wind turbine containing a squirrel cage asynchronous generator, the SWT108 technology is used in Farm I, a 29.9 MW wind farm with 13 sets of 2.3 MW wind turbines.

Case II: 14 sets of 2.1 MW S88 wind turbines with wound rotor induction generators make up Wind Farm II, a 29.4 MW wind farm. The concept of restricted variable speed wind turbines is the foundation for this wind farm's capacity.

Case III: A 30MW wind farm as farm III with 10 sets of 3MW wind turbines based on the V90 technology, which is a wind unit with a variable velocity concept and double-fed induction generator, is built.

Case IV: A 30MW wind farm as farm IV with 10 sets of 3MW wind turbines based on the E82E3 technology, which is the direct-drive concept wind turbine coupled with an electrically excited synchronous generator.

Case V: Based on the V112 technology, a gearbox-free wind unit with permanent magnet synchronous technology, this 29.7MW wind farm as farm V consists of nine turbines, each rated at 3.3MW.

Case VI: A 30MW wind farm as farm VI with 6 wind turbines based on G128 technology, each of which has a 5MW capacity and is based on the multiple-stage geared concept. A synchronous generator with permanent magnets is connected to these turbines.

Case VII: A 29.7MW wind farm as farm VII with 45 wind turbines, each with a 0.66MW capacity, based on the V47 technology, wind unit that employs squirrel cage asynchronous generator in addition to multiple stages of gearing.

The power curve of wind technologies installed in these seven wind farms is shown in Fig. 16. As can be seen, because these turbines use different working principles for

Table 1. Failure rates (FR) and repair rates (RR) (times per year) associated with different wind turbine components

Cases/Components		Turbine	Transformer	Cable	Control system	Gearbox	Generator	Converter	Capacitor
Case I	FR	0.08	0.02	0.05	0.04	0.09	0.06	0	0.02
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case II	FR	0.08	0.02	0.05	0.04	0.09	0.06	0.05	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case III	FR	0.08	0.02	0.05	0.05	0.09	0.07	0.05	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case IV	FR	0.08	0.02	0.05	0.05	0	0.07	0.1	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case V	FR	0.08	0.02	0.05	0.04	0	0.05	0.05	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case VI	FR	0.08	0.02	0.05	0.04	0.09	0.05	0.05	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5
Case VII	FR	0.08	0.02	0.05	0.05	0.09	0.06	0.05	0
	RR	73	121.7	121.7	182.5	73	121.7	182.5	182.5

converting wind kinetic energy to electricity, their cut-in, nominal, and cut-out velocities as well as the dependency of electric produced power on wind velocity are different. Cases I through VII are used to illustrate each of the seven technologies that are discussed in the research.

5- 1- Reliability models of different wind turbines

Reliability data parameters of the composed components of different wind units including hazard and repair rates of the turbine, transformer, cable, control system, gearbox, generator, and capacitor used in wind energy conversion systems are displayed in Table 1 [23]. Every component that makes up a distinct wind turbine is connected in series from the standpoint of reliability. Therefore, based on (2) and (3), the hazard and repair rates of these wind technologies and associated availabilities are calculated and displayed in Table 2. Equation (4) can be used to establish the understudied farms' reliability model.

The power curves of various wind turbines and hourly wind velocity are applied to calculate the hourly generated power associated with these seven wind farms. The XB index for these technologies is calculated and shown in Fig. 17. According to the figure, the ideal number of clusters for Cases I through VII of these seven wind turbine technologies would be 3, 3, 7, 4, 7, 6, and 5.

Generated power data from each wind turbine is subjected to FCM method based on the ideal cluster number. Table 3 verifies the capacities of the clusters and the corresponding probabilities.

The full reliability presentation of various wind technologies can be determined by combining the reliability presentation of these wind technologies with the reliability model obtained from the clustering method. Multi-state reliability presentation of these wind farms is used to evaluate the sufficiency of power systems including wind units, allowing for reliability comparison of various energy conversion systems.

5- 2- Adequacy analysis of RBTS

The RBTS is subjected to reliability analysis with various wind energy conversion systems in this subsection. The characteristics of the RBTS generation unit are given in [24]. Cases I through VII in this section refer to the RBTS integrated with wind farms based on technologies I through VII. The original RBTS and the RBTS combined with the standard 30MW unit with the availability of 0.98 are cases VIII and IX, respectively. The load duration curve can be viewed as a line sketch 100% to 60% of peak demand. Reliability indices, which account for peak loads and are calculated and shown in Figures 18 and 19, include the average time of interruption and average interrupted energy associated with these cases. The graphs show how the RBTS's reliability indices are enhanced by the inclusion of units from a new generation. However, the addition of conventional units improves the power system's reliability indices more than the incorporation of wind units. The generated power of wind turbines fluctuates due to variations in wind speed, and as a result, it is frequently less than the rated capacity. According to wind velocity data on

Table 2. Equivalent hazard and repair rates and associated availability of different wind technologies

Cases	Equivalent failure rate (times per year)	Equivalent repair rate (times per year)	availability
Case I	0.36	96.6225	0.9963
Case II	0.39	100.2540	0.9961
Case III	0.41	101.8107	0.9960
Case IV	0.37	120.5927	0.9969
Case V	0.29	112.6182	0.9974
Case VI	0.38	99.7913	0.9962
Case VII	0.40	101.3964	0.9961

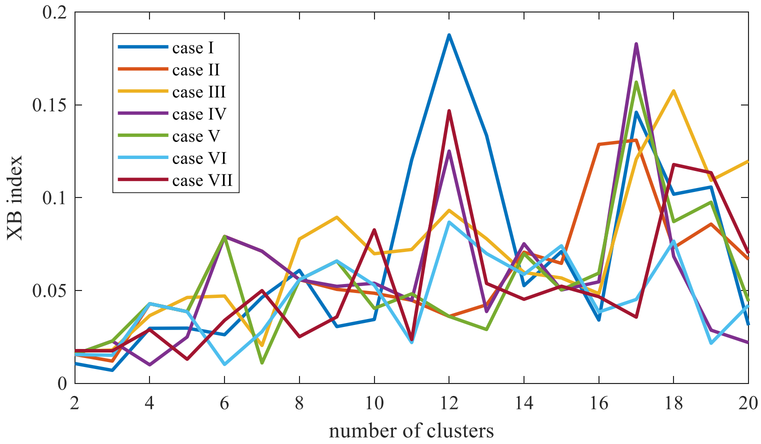

Fig. 17. XB considering cluster number

the site, the top technologies among the various wind energy conversion systems, from a reliability point of view, are listed below.

Order 1: Farm I, a 29.9 MW wind farm with fixed speed gearing for the SCIG.

Order 2: Farm V, a 29.7MW wind farm with direct-drive technologies fitted with PMSG equipment.

Order 3: Farm II, a 2.9.4MW wind farm that is equipped with the WRIG's limited variable speed technologies.

Order 4: Farm VII is a 29.7MW wind farm with multiple-stage gearing systems attached to the SCIG.

Farm IV, Order No. 5, is a 30MW wind farm with direct-drive technologies attached to the EESG.

Order 6: Farm III, a 30MW wind farm that is equipped with DFIG-compatible variable speed technologies.

Order 7: Farm VI, a 30MW wind farm with multiple-stage gearing and PMSG-equipped technology.

5- 3- Adequacy analysis of IEEE-RTS

Here, the efficiency of the IEEE-RTS integrated various types of wind turbines is evaluated. The characteristics of the IEEE-RTS generation unit are provided in [25]. Cases I through VII in this section refer to wind farms that have been integrated with the IEEE-RTS using technologies I through VII. Cases VIII and IX are, respectively, the original test network and test network combined 30MW conventional unit with the availability of 0.98. The load duration curve is represented as a line sketched 100% to 60% of peak demand. Reliability indices are calculated and displayed in Table 4 at a peak demand of 2850 MW. These indices include the average time of interruption and average interrupted energy associated with these cases. The inferences made from this table are in line with those made from the RBTS's adequacy assessment, i.e. considering wind velocity data at the site, top technologies for wind energy conversion systems in terms of

Table 3. The capacities and probabilities of the clusters associated to different wind turbines

Case I	Capacity (MW)	29.5	0.8	9.5				
	Probability	0.4903	0.3946	0.1151				
Case II	Capacity (MW)	1.1	28.6	14.8				
	Probability	0.4300	0.4288	0.1412				
Case III	Capacity (MW)	24.6	7.2	0.25	0.3	18.9	12.8	29.8
	Probability	0.0561	0.0645	0.3169	0.1139	0.0471	0.0515	0.3500
Case IV	Capacity (MW)	20.2	9.2	0.9	29.6			
	Probability	0.1097	0.1160	0.4283	0.3460			
Case V	Capacity (MW)	2.7	24.1	17.5	12.2	6.8	29.6	0.2
	Probability	0.1206	0.0493	0.0421	0.0442	0.0677	0.4067	0.2694
Case VI	Capacity (MW)	15.7	29.7	3.4	8.3	0.1	23.2	
	Probability	0.0680	0.2955	0.1549	0.0801	0.3381	0.0635	
Case VII	Capacity (MW)	23.2	15.0	6.8	29.4	0.4		
	Probability	0.0744	0.0693	0.1006	0.3808	0.3749		

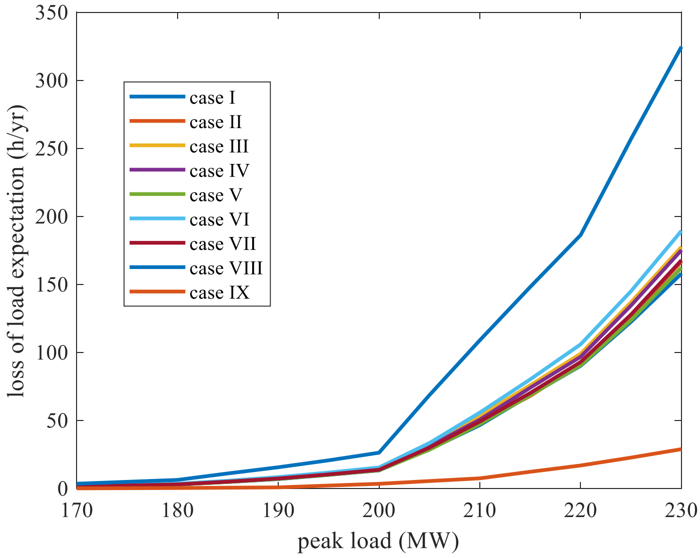

Fig. 18. Average time of interruption versus demand

reliability are I, V, II, VII, IV, III, and VI.

To present the effectiveness of the suggested method based on the analytical approach explained in the fourth section, the reliability indices of Table 4 are calculated by well-known numerical methods, i.e. Monte Carlo simulation technique. According to the Monte Carlo method, for adequacy assessment of the power system including wind units, at each hour, for composed components of the wind turbines, random numbers are generated. If the generated number is less than the availability of the component, the associated components are up. Thus, the situation of the wind turbine (up or down) is determined. Then, based on the wind velocity at the understudied hour, and according to the power curve of the wind unit, the hourly generated power of the wind unit is computed. For other conventional generation units, random numbers are generated to determine the situation and produced power of them. Thus, at each hour, the generated power of the power system is calculated. By comparing the hourly generated power and hourly peak load, the value of the curtailed load at each hour is computed. By

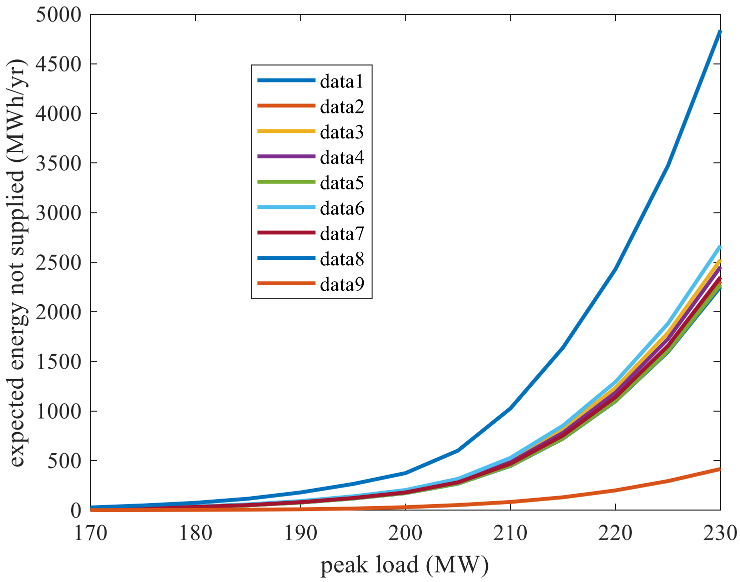

Fig. 19. Average interrupted energy versus demand

Table 4. The reliability indices of different cases

Cases	Loss of load expectation (h/yr)	Expected energy not supplied (MWh/yr)
1	103.0596	15330
2	103.6644	15431
3	104.2367	15529
4	104.2303	15527
5	103.3627	15381
6	105.0934	15671
7	103.6951	15437
8	112.9085	16984
9	94.7670	13944

repeating the Monte Carlo simulation method during a year, the value of curtailed load and the number of hours with load curtailment in a year are determined. The Monte Carlo simulation approach is repeated for several years and the reliability indices including LOLE and EENS are calculated by averaging the number of hours with load curtailment and curtailed load, respectively. The reliability indices of Table 4 are calculated through the Monte Carlo simulation method with a repetition of 100 years and presented in Table 5. As can be seen in the table, the computation error in the reliability indices calculated by the two methods is low. Thus, the proposed analytical approach with good accuracy can calculate the adequacy indices of the power system containing wind units.

6- Conclusion

The reliability criteria implemented in this study are used to compare different wind energy conversion systems. Several technologies of wind units are developed for accomplishing this, including fixed-speed concepts containing squirrel-cage asynchronous generators, limited variable speed concepts

Table 5. The reliability indices of different cases calculated by the Monte Carlo simulation method and the computation error

Cases	Loss of load expectation (h/yr)	Expected energy not supplied (MWh/yr)
1	103.0596	15330
2	103.6644	15431
3	104.2367	15529
4	104.2303	15527
5	103.3627	15381
6	105.0934	15671
7	103.6951	15437
8	112.9085	16984
9	94.7670	13944

containing wound-rotor asynchronous generators, variable speed concepts equipped with double-fed asynchronous technologies, gearbox-free concepts equipped with permanent magnet synchronous technologies, and multiple-stage geared concepts. Multi-state reliability presentation for these wind turbines is developed. When developing a multi-state reliability presentation for these wind farms, we consider the hazard of assembled elements and change in produced electric power due to changes in wind velocity. It is believed that variations in the structure of these turbines' power curves are what distinguish different wind technologies. For creating a reliability model for these wind turbines, FCM is applied to decrease the number of states in generated power data and the XB index is calculated to determine the ideal state number. Multi-state reliability presentation of these various wind energy conversion systems is used to assess the reliability of electric networks including these enormous wind technologies. 29.9MW wind farm with fixed speed technologies equipped to the SCIG, the 29.7MW wind farm with the direct-drive technologies equipped to the PMSG, and the 2.9MW wind farm with the fixed speed technologies equipped to the SCIG are determined to be the top technologies from a reliability standpoint at wind velocity data of the understudied site. A 4MW wind farm with limited variable speed technologies installed on the WRIG, 29.7MW wind farm with multiple-stage geared technologies installed on the SCIG, 30MW wind farm with direct-drive technologies installed on the EESG, 30MW wind farm with variable speed technologies installed on the DFIG, and 30MW wind farm with multiple-stage geared technologies installed on the PMSG. Besides, it is deduced from the numerical results that the integration of conventional units into the power system improves the reliability indices of the power system more than the integration of wind farms. It is due to the variation in the wind speed leads the generated power of wind turbines changes and consequently the generated power of the wind farms is less than the rated capacity in the most of time.

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