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Reliability Evaluation of Wind Turbine Systems' Components

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Abstract

The increasing use of wind generation requests modifications in the electric power systems planning conception, because it includes one more uncertainty component, which needs to be studied properly and modeled. Understanding the failures rates and downtimes of wind turbines is difficult not only because of the considerable range of designs and sizes that are now in service worldwide but also since studies are conducted independently under various operating conditions in different countries. The fault tree method (FTA) has been used to study the reliability of many different power generation systems. This paper now applies that method to a wind turbine system to estimate the reliability of wind turbines. In the implementations, several types of wind turbines were considered in order to analyze the system's reliability. The effectiveness of the proposed method is revealed through several case studies.

***Keywords**: Reliability, wind turbine, fault tree method*

1. Introduction

Over the last few decades, the usage of renewable energies in electric power generation systems has been increased dramatically. Wind power is the fastest growing renewable energy sources which their penetration in the near future and present will have a few effects on their operation, planning, and reliability. Industry developers and operators prefer the most reliable wind generation system. Lone-term reliability analysis of wind turbine will result in better wind turbine structure. The reliability performance of wind turbine has been assessed in a number of references [1]-[5]. Such studies considered the wind generation as a stochastic process based on the Markov method. Additionally, several studies considered design improvements on wind turbine technologies [6]-[10]. Among these, reliability evaluation of power systems incorporating wind energy systems has widely been studied (see [11]-[15] as examples). The intermittent nature of wind energy systems with the probabilistic behavior of wind turbine outages makes their output variable. Therefore, assessing a comprehensive reliability model of wind turbines can be counted as a major dilemma in wind energy integration projects and seems inevitably necessary to be included in reliability assessment of power systems.

In the literature, some efforts have been proposed analytical reliability evaluation of wind system generation availability [16]. For instance, Ref. [17] proposed an analytical model of wind turbines' production aimed at evaluating reliability indices as well as frequency. The main drawback of this model is that the component failures of the wind turbine have been not taken into account in the reliability model. This paper proposed a new method for estimating the reliability of the wind turbine components. The fault tree method (FTA) is used to analyze the reliability of the wind generation systems. In the implementations, different types of wind turbines are considered. The rest of the paper is organized as follows. In Section 2, the electrical structure of wind turbines are introduced. Section 3 presents the reliability framework based on the FTA. Section 4 is concerned with the implementation process of the proposed technique through two case studies. The conclusion is drawn in Section 5.

2. Wind Turbine Structure

For issues such as operating better, increasing power and the most compatibility with power network, different configurations of wind turbine with innovative technology have been

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developed during the last few years. In this section, the main wind turbine components, which can significantly affect the wind turbine reliability, are presented.

Typical wind turbines and DFIG wind turbines are discussed below, which are the most common configuration can be used with different combinations of rotational speed, power control, drive train configuration and generator.

A DFIG wind turbine consists of the following components [18]:
1. Tower structure.
2. Rotor (blades and pitch control).
3. Mechanical gear.
4. Electrical generator.
5. Yaw mechanism.
6. Sensors and control.
7. Brake system.
8. Transformer.

The description for each component is presented as follows [19].
1. Blades and Pitch Control: The turbine blades are manufactured of high-density wood or glass fiber and epoxy composites. The steady mechanical stress due to centrifugal forces and tiredness under continuous vibrations makes blade the weakest mechanical link in a turbine. Thus, the foremost effort in the design stage of wind turbines is employed to avoid premature fatigue failure of the blades which causes mechanical failure. The output regulation of a wind turbine can be achieved via pitch control by feathering the blades in order to control the power or by aerodynamic design of the rotor blades. When wind speeds higher than the rated velocity of the wind turbine, the maximum power output will be restricted and a portion of the available energy will be wasted. Therefore, the pitch control is used for speed controlling of the wind turbine. If it fails, the blades may be broken since there are no control devices for speed controlling.
2. Yaw System: The yaw system constantly orients the rotor in the direction of wind speed. Theoretical works mainly consider a free yaw system for turbines as much as possible. The yaw system might fail because of the failure in its component (e.g. control system failure or drive motor). Consequently, the blades will become unable to track the direction of the wind and the output power will be dramatically declined. Moreover, if the yaw system is in the failure mode, the blades might be break down because of the wind which is in the opposite direction in comparison with the blades direction. Thus, it was assumed that any failure in the yaw system causes the wind turbine outage.
3. Gearbox: A gearbox in the drive train of a turbine ensures the DFIG operation in facing wind speeds more than the acceptable speed range of 10-25 rpm. For a turbine, 20% of the overall failures come from the gearbox failures which the repair time will take almost 256 hours. So, the gearbox has been considered as the most critical component in the wind turbine generation systems.
4. DFIG: Turbine's generator can be failed because of either the internal or external failures. Internal failures mainly occur because of the insulation failures, mechanical parts failures, and turn-to-turn connections. External failures usually happen due to the failure in other parts connected to the generator. A short circuit which can be occurred in the electrical grid might increase the rotor's current as well as stator winding in which the overheating might fails the turbine.
5. Converters: The rotor energy can be efficiently fed into the electrical grid by the power electronic converters. Moreover, the converter can cover the reactive power, for example, the grid-side converter can control its reactive power without considering the generator operation. The output power generated from the turbine is rectified by a six-pulse rectifier incorporated to dc bus from one side and to the rotor from the other side. Following this, an inverter converts the dc power to the ac power and transmitted to the electrical grid.
6. Control System: The inverter and rectifier valves switching are determined by the control system of frequency, voltage, reactive and active power regulation of wind turbine. Therefore, any failure in the control system will cause the turbine outage.
7. Sensors: In a wind turbine, different kinds of sensors are considered for controlling and protecting. Thus, any failure in these sensors will disturb the control and protection system.

8. Brake System: In emergency situations, the brake system can stop the rotor by using the brake disk electrically, mechanically, and hydraulically. The brake system should be repaired after any failures which might be caused in its structure.
9. Transformer: Any failure in the transformer cuts off the connection of the turbine with the grid which subsequently interrupts the produced power to the grid.

Figure 1 depicts the DFIG-based wind turbine structure. The electrical structure of a typical wind turbine is shown in Figure 2.

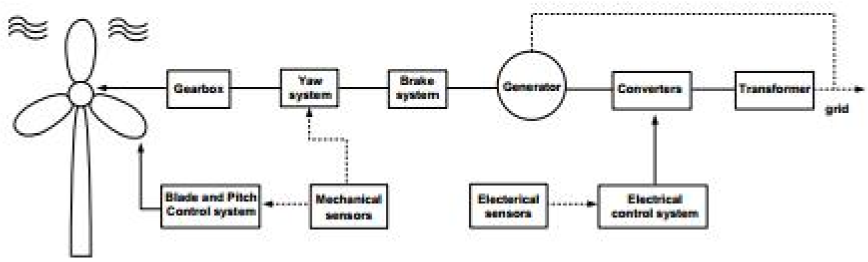

Figure 1. DFIG-based wind turbine structure

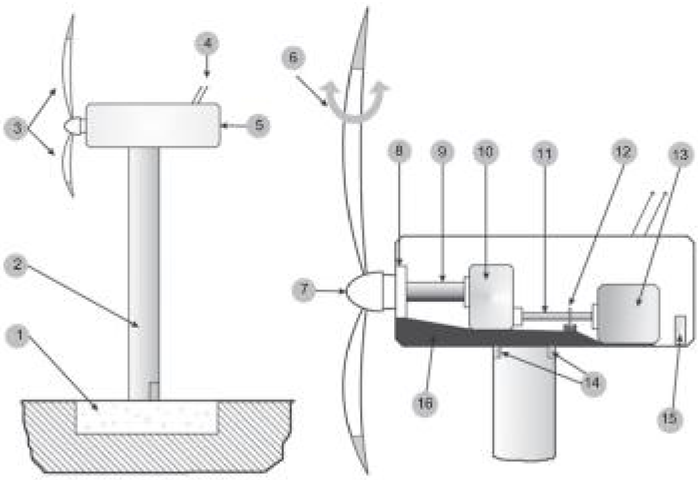

Figure 2. Electrical structure of a typical wind turbine.
Components: 1- base/foundations; 2- tower; 3- blades; 4- meteorological unit (vane and anemometry); 5- nacelle; 6- pitch system; 7-hub; 8- main bearing; 9- low speed (main) shaft; 10- gearbox; 11- high speed shaft; 12- brake system; 13- generator; 14- yaw system, 15- converter, 16- bedplate.

3. A Brief Summary of Fault Tree Method

Reliability is defined in quantitative terms as the probability of a component performing its function adequately.The reliability function is the probability that a system will be successfully operating without any failure in the given time t:

$$R(t) = P(T > t) \quad (1)$$

The unreliability or failure probability can be also expressed as:

$$F(t) = P(T \leq t) = 1 - R(t) \quad (2)$$

Equations (1) and (2) with a density function $f(t)$ could be written as:

$$R(t) = \int_t^{\infty} f(t)dt \quad (3)$$

$$R(t) = \int_t^{\infty} f(t)dt$$
$$F(t) = \int_0^{t} f(t)dt \quad (4)$$

The mean time to failure (MTTF) of a component can be expressed as:

$$MTFF = \int_0^{\infty} t f(t)dt = \int_0^{\infty} R(t)dt \quad (5)$$

Equation (5) represents the reliability of a component. In the real world, systems are complex and consist of a large number of components that may be connected in series, in parallel or in a combination of series and parallel. When connected in series, the failure of one component interrupts the overall system, whereas all components must fail in the parallel system to interrupt the overall system.
The reliability of a series system with n components can be calculated as:

$$R_{system} = P(E_1 \cap E_2 \cap \ldots \cap E_i) \quad (6)$$

If the n components are independent, thus:

$$R_{system} = P(E_1) \times P(E_2) \ldots \times P(E_i) \quad (7)$$

Assuming the system is not repairable, the overall system reliability can always be derived by Boolean techniques. Thus, system reliability performance can be expressed as a function of components reliability as follows:

$$R_{system} = R_1 \times R_2 \ldots \times R_n \quad (8)$$

Thus

$$R_{system} = \prod_{i=1}^{n} R_i \quad (9)$$

Where $R_i = P(E_i)$ is the reliability of component i.

The system reliability of x series units with M parallel components in each unit can be obtained using:

$$R_{system} = 1 - (1 - R_x)^M \quad (10)$$

The fault tree analysis (FTA) has been widely employed as a useful tool to estimate the safety and reliability of complex systems by many scholars [20]-[24]. There are two main approaches for analyzing the reliability of the system (i.e. analytic, and simulation approach). Analytical approaches mainly consist of fault-tree analysis and Markov modeling. Also, simulation methods include Monte Carlo simulation. FTA offers a simple cause and effect relation to determine the system's reliability. This method was developed by H.A. Watson in 1961 in the aviation industry and has been used extensively in the nuclear industry and other engineering and control system applications. Several methods such as failure mode effect analysis (FMEA), reliability block diagram, and event tree analysis are used in the reliability analysis. FTA is a logic diagram consists of a top event and a structure delineating the ways in which the top event might occur. It is a useful tool for analyzing coherent systems. FTA is a computationally efficient and powerful technique for predicting and analyzing system reliability. FTA allows identifying and then quantifying the initiating failure causes in order to maintain system reliability at the required level with particular attention given to aggressive environmental factors. The process involves two stages:

1. Selection of the various components that are to be considered for analysis.
2. Assessment of how the component states affect the condition variables.

Both are critical and have a significant impact on the accuracy of the model.

By definition, a minimal cut set causes the system to be unavailable because of component failures. If all components are unavailable, a minimal cut set will cause the top event to occur. If all components are available, then the top event will not occur. The minimal cut set for any fault tree is finite and can be achieved easily. For instance, the three component minimal cut sets show that all three components must fail in order for the top event to occur. For an n component minimal cut set, all n components must be unavailable.

The minimal cut set expression for the top event can be obtained as

$$TopEvent = ((((((((((PV + CON + BD) + DCS) + CC) + (SPD + BS)) + INV) + (CBac + SPD)) + GP) + ACS) + DCB) \quad (11)$$

It is also assumed that SPDs are flawless and have no failure rates; therefore, Equation (11) is reduced to

$$TopEvent = PV + CON + BD + DCS + CC + BS + INV + CBac + GP + ACS + DCB \quad (12)$$

Equation (12) indicates that the fault tree in this study had 11 minimal cut sets. The analysis of the FTA can be categorized into the two kinds of qualitative and quantitative analysis. The qualitative analysis is obtained from minimal cut sets (the combinations of events which can cause system failure) and quantitative fault tree evaluation deals with calculating the top event probability according to the bottom events. The probability of failure for top event can be calculated on qualitative analysis as follows:

$$P_{TOP} = \sum_{i=1}^{n} P_{MCSi} - \sum_{i<j} P_{MCSi \cap MCSj} + \sum_{i<j<k} P_{MCSi \cap MCSj \cap MCSk} - \cdots + (-1)^{m-1} P \bigcap_{i=1}^{m} MCS_i \quad (13)$$

The probability of occurrence of MCS_i can be expressed as:

$$P_{MCSi} = P_{B1} \times P_{B2|B1} \times P_{B3|B1 \cap B2} \times \ldots \times P_{Bn|B1 \cap B2 \cap \ldots \cap Bn-1} \quad (14)$$

It was assumed that the components are independent. Thus,

$$P_{MCSi} = \prod_{i=1}^{n} P_{B_i} \quad (15)$$

Using probability theory and the minimal cut set, the probability of failure of the top event can be obtained from Equation (12), and the reliability probability can be expressed as:

$$Pr(TopEvent) = Pr(E_1 + E_2 \ldots En) \quad (16)$$

$$1 - Pr(TopEvent) = [1 - Pr(E_1)] \text{ x } [1 - Pr(1 - E_2)] \ldots [1 - Pr(1 - E_n)] \quad (17)$$

It is assumed that the components are independent, so the total system reliability can be calculated as:

$$R_{tot} = \prod_{i-1}^{n} = R(PV) \text{ x } R(CON) \text{ x } R(BD) \text{ x } R(DCS) \text{ x } R(CC) \text{ x } R(BS) \quad (18)$$

x $R(INV)$ x $R(CBac)$ x $R(GP)$ x $R(ACS)$ x $R(DCB)$

Using exponential distribution and Equation (9), the total system reliability can be shown as:

$$R_{tot} = \exp\left(\sum_{i=1}^{n} m_i \lambda_i t_i\right) \quad (19)$$

where m_i is the total number of components, λ_i is the failure rate of component i, n is the total number of different components, and t is the study time of the reliability analysis.

4. Case Study

In this section, various studies have been conducted in order to estimate the reliability of wind turbines. The average failure rates for different wind turbine components are given in Tables 1 and 2. Considering the cumulative failure rate of each component, the control system has the highest value, followed by the blades/pitch and then the electric system. Gears yaw system, hydraulic, brake, generator, sensor and others form a group with medium cumulative failure rate. Hubs, drive trains and structures all have low rates. The components of the turbines are in a series combination as shown in Figure 3.

Table 1. Components failure rates for the DFIG wind turbine

Components	Failure rate (occ/yr)
Blade and pitch control system	0.052
Yaw system	0.026
Gearbox	0.045
Brake system	0.005
Generator	0.021
Converters	0.067
Control system	0.050
Sensors	0.054
Transformer	0.020

Table 2. Components failure rates for the typical wind turbine systems

Components	A0 Failure rate (occ/yr)	A1 Failure rate (occ/yr)	DDE Failure rate (occ/yr)	B Failure rate (occ/yr)
Blades	0.22	0.38	0.24	0.17
Pitch	0	0	0.3	0.1
Generator	0.18	0.18	0.35	0.09
Electric	0.27	0.28	0.54	0.34
Inverter and electronics	0.2	0.14	0.31	0.27
Shaft/bearing	0.06	0.02	0.08	0
Sensors	0.12	0.07	0.12	0.08
Gearbox	0.1	0.2	0	0.18
Brake system	0.15	0.18	0	0.01
Hydraulics	0.07	0.18	0.02	0.26
Yaw system	0.06	0.18	0.11	0.1
Other	0.27	0.34	0.32	0.26

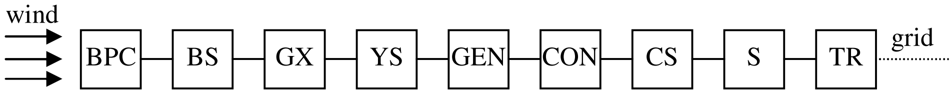

Figure 3. Wind turbine components

Using the aforementioned proposed method, the fault tree can be drawn for the wind turbines as shown in Figure 4. The FTA method serves as a useful tool to evaluate the reliability of wind turbines. The results of this study are summarized in Tables 3 and 4. As shown in tables, blades, control systems and electrics are most frequently cited in connection with failure rates; gearboxes, generators and blades feature most in consideration of downtime. In addition, the most problematic are components such as gears, blades or hydraulics with combinations of failure rate and downtime per failure that result in high downtime (hours lost per turbine per year). The trend is towards three blades, power control by pitch system and variable rotational speed. Moreover, direct drive (DD) wind turbines have more frequent electrical and electronic failures than indirect types (A, B, C, DI) but, for these, gearbox failures cause the most downtime. Larger wind turbines tend broadly to suffer more failures than smaller ones although this is confounded by type and differences between manufacturers.

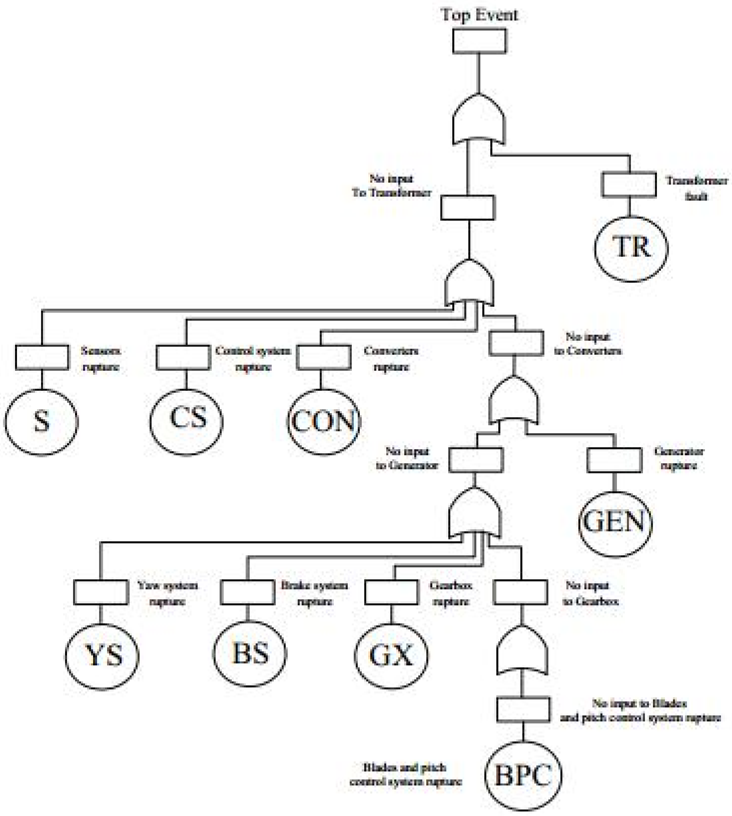

Figure 4. Fault tree for the wind turbine

Table 3. Reliability

Turbine type	Reliability per 1 year (occ/yr)	Reliability per 10 years (occ/yr)
DFIG	99.7026	97.0655
A0-Micon M1500	98.5218	86.1638
A1-Tacke TW600	98.1342	82.8333
DDE-Enercon E40	97.9281	81.1100
B-Vestas V30/V4x	98.3838	84.9646

Table 4. Unavailability

Turbine type	Unavailability per 1 year (occ/yr)	Unavailability per 10 years (occ/yr)
DFIG	0.2974	2.9345
A0-Micon M1500	1.4782	13.8362
A1-Tacke TW600	1.8658	17.1667
DDE-Enercon E40	2.0719	18.8900
B-Vestas V30/V4x	1.6162	15.0354

5. Conclusion

The use of wind generation systems is ever-increasing which follows a few modifications in theelectric power systems planning concepts. The wind generation systems consist of several uncertainty components which need to be studied properly and modeled. Understanding the downtimes and the failures rates of wind turbine is difficult not only because of the considerable range of designs and sizes that are now in service worldwide but also since studies are conducted independently under various operating conditions in different countries. Larger wind turbines tend broadly to suffer more failures than smaller ones although this is confounded by type and differences between manufacturers. This paper developed a novel method based on the FTA for estimating the reliability of wind turbines. The developed model considered several types of wind turbines including typical ones and DFIG. Moreover, it has been shown that the proposed method serve as a preliminary failure rate prediction tool. Additionally, the implementations revealed that the proposed method could be a useful tool for predicting failure rates in new turbine designs as well as an applicable took for designers to identify weak points in the wind turbine design. It is worth noting that the main principles of the analytical model proposed in this paper can also efficiently be used for the other wind turbines' technologies.

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