Reliability assessment of wind turbine generators by fuzzy universal generating function

Tudi Huang\textsuperscript{a,}, Tangfan Xiahou\textsuperscript{a,}, Yan-Feng Li\textsuperscript{a,}, Hua-Ming Qian\textsuperscript{a,}, Yu Liu\textsuperscript{a,}, Hong-Zhong Huang\textsuperscript{a,}\textsuperscript{*}

\textsuperscript{a}Center for System Reliability and Safety, School of Mechanical and Electrical Engineering, University of Electronic Science and Technology of China

Sichuan, 611731, P. R. China

Abstract

Wind power has been widely used in the past decade because of its safety and cleanness. Double fed induction generator (DFIG), as one of the most popular wind turbine generators, suffers from degradation. Therefore, reliability assessment for this type of generator is of great significance. The DFIG can be characterized as a multi-state system (MSS) whose components have more than two states. However, due to the limited data and/or vague judgments from experts, it is difficult to obtain the accurate values of the states and thus it inevitably contains epistemic uncertainty. In this paper, the fuzzy universal generating function (FUGF) method is utilized to conduct the reliability assessment of the DFIG by describing the states using fuzzy numbers. First, the fuzzy states of the DFIG system’s components are defined and the entire system state is calculated based on the FUGF. Second, all components’ states are determined as triangular fuzzy numbers (TFN) according to experts’ experiences. Finally, the reliability assessment of the DFIG based on the FUGF is conducted.

Highlights

- The fuzzy states of the DFIG systems are provided.
- All components’ states are given as triangular fuzzy number based on experts’ experience.
- The reliability assessment of the DFIG based on the FUGF is performed.

Keywords

Reliability assessment, double fed induction generator, multi-state system, fuzzy universal generating function.

1. Introduction

Energy is closely connected with our human beings. With the increasing crisis on energy and environmental problems, wind energy has gained significant attention in recent years due to its safety and cleanness. Consequently, technologies related to wind energy developed fast in the past decade. With the increasing capacity of wind turbine generators, wind turbine generator systems are becoming more and more compounded and complicated, especially for the megawatt-scale wind turbine generator systems. For a large complex equipment such as wind turbine generator systems, much attention should be paid to their reliability assessment besides considering their capacity. In general, the designed life span of a wind turbine generator is 20 years. Thus, it is very difficult to have an accurate reliability assessment of the wind turbine. Due to the external working environments and internal failure dependence, the double fed induction generator (DFIG), as a typical type of wind turbines, inevitably deteriorates with the usage. Once the deterioration beyond the acceptable level, it is deemed as failure. The failure of the DFIG will not only cause energy loss but also create damage to the entire wind farm. Therefore, reliability assessment for the DFIG is of great significance. In the literature, many works on reliability assessment of the DFIG have been reported. Carroll et al. [1] studied the reliability of wind turbines with the DFIG and permanent magnet generator (PMG) drive trains. Zhou et al. [34] conducted a certain amount of research on reliability and performance improvement of the DFIG. Note that most of the existing studies assumed the DFIG system and its components as a binary-state system or components, i.e., the working state and the failure state. However, the DFIG is typically made up of five main components, i.e., blades, gearboxes, generators, converters and transformers. Blades and gearboxes are mecha-
2. Overview of Wind Turbine Generators

2.1. Background and Structure of Wind Turbine Generators

As a significant new energy, wind power plays an indispensable role in both industry and our daily lives. In China, for example, wind power increases quickly in recent years, and it is ranked the third in the country’s power equipment capacity. More information about Chinese power equipment capacity [3, 4] is shown in Fig. 1.

The wind turbine generator is the vital device to convert wind energy into electric energy. According to the output capacity of wind turbine generations, wind turbine generations can be divided into small, medium, large, and megawatt-scale. With the increase of the capacity, double-fed wind induction generator (the DFIG) gradually becomes the mainstream of wind turbine generation market due to its good performance and operation stability. As for DFIG, there are five main parts, i.e., the blade, the gearbox, the generator, the converter and the transformer. The structure of DFIG is shown in Fig. 2. The blade can rotate with the wind and then the torque forming. This is the first step that the wind power transforms into mechanical energy. The forming torque will be transmitted to the gearbox for acceleration. The output shaft of gearbox with high-speed rotating is connected with the generator and then the mechanical energy will be transmitted into electric energy. The converter of DFIG is used to excite the rotor of the DFIG. The amplitude, frequency, and phase of the output voltage at the stator side of the DFIG are the same as those of the grid. Without the converter, the generator cannot work normally [30].

In this paper, we consider a typical type of wind turbine generator systems, i.e., the DFIG, and model the DFIG as an MSS. As the DFIG is a system with high reliability and few test/event data, traditional reliability assessment methods based on large amount of failure data with rigorous statistical models are incapable of handling such a challenge. Moreover, specifying the component states of the DFIG, such as the states of the blades and gearboxes, often relies on experts’ knowledge. Due to the vague judgements of experts, the determination of component states often contains epistemic uncertainty and it is suitable to be modelled as fuzzy numbers [21]. In this work, first, the fuzzy states of the DFIG systems are defined and the entire system state is calculated based on system structure function. Secondly, the performance rates and probabilities of all components’ states are determined as triangular fuzzy number (TFN) based on experts’ experiences. TFNs are chosen rather than other types of fuzzy numbers due to the easy concept and wide applications to reliability engineering. what’s more, if the imprecise component state probability elicited by experts is naturally modelled by the TFNs, the experts only have to decide the most possible values of component state probability and the uncertainty associated with this decision. For other types of fuzzy numbers, such as Trapezoidal fuzzy number, the experts have to decide at least four values associated with the component state probability. It, therefore, introduces additional challenges to the expert elicitation process. Finally, the reliability assessment of the DFIG based on the FUGF is conducted.

The remainder of this paper is organized as follows. Section 2 introduces a brief overview of the turbine generators. The introduction on the MSS and the UGF are given in Section 3. Section 4 conducts the fuzzy reliability assessment for the DFIG system based on FUGF. Finally, a brief conclusion is given in Section 5.

2.2. Reliability Modeling of a Wind Turbine Generator

According to the physical connections of the five components in DFIG, the reliability block diagram of a DFIG is shown in Fig. 3. In
the DFIG, two separate systems with a generator and converter connected in series are used as redundancy. They are connected in series with the blade, the gearbox and the transformer.

![Reliability block diagram of the DFIG.](image)

The components of a DFIG can be categorized into two types, i.e., the mechanical type and the electrical type. The former includes the blade and the gearbox whose failures are mainly caused by wear. Whereas, the latter includes the generator, the converter and the transformer, whose failures are mainly caused by the damage of IGBT modules. For the former type of components, the mechanical performance will deteriorate into different levels with the development of wear and tear. When the performance reaches a certain threshold, components will be failure. For the latter type of components, the damage of IGBT modules can also make the degradation of performance due to the backup. Therefore, the system of the DFIG can be considered as an MSS whose components have multi-state as well. According to the experts’ experiences, the states of every component of the DFIG is defined and given in Table 1. As we can see from Table 1, there are 4 states of blade and gearbox, 3 states of generator, converter and transformer.

| Component       | State division                        |
|-----------------|---------------------------------------|
| Blade           | perfect, mild wear, severe wear, failure (4 states) |
| Gearbox         | perfect, mild wear, severe wear, failure (4 states) |
| Generator       | perfect, middle, failure (3 states)    |
| Converter       | perfect, middle, failure (3 states)    |
| Transformer     | perfect, middle, failure (3 states)    |

Based on the structure function of the entire system, there are totally 482 states of the DFIG. Thus, it is difficult to accurately assess the system state parameters and an efficient method for reliability assessment is strongly needed.

3. UGF-Based Reliability Assessment of MSS

3.1. Overview of MSS

For an MSS, it could have a finite number of performance rates (levels). For each component, they could have a finite number of performance rates (levels) as well. In order to conduct the reliability assessment of an MSS, the characteristics of its components should be determined first. Components can have different states with corresponding performance rates (levels). The performance rates (levels) of every states of any components can be represented as:

\[ g_j = \{g_{j1}, \cdots, g_{jk}, \cdots \}, \]

(1)

where \( i \) indicates the \( i \)th (1 \( \leq i \leq k_j \)) state of component and \( g_{ij} \) is the performance rate (level) of \( j \). Then the probabilities associated with different states of component \( j \) can be represented as:

\[ P_j = \{p_{j1}, \cdots, p_{jk}, \cdots \} \]

(2)

After determining the performance rates and corresponding probabilities, the probability distribution (PD) of the system can be determined if the system structure function \( \phi(*) \) is known. The probability of system state \( i \) can be calculated as follows:

\[ P_i = \prod_{j=1}^{n} p_{ij} \]

(3)

The performance rate (level) of MSS for state \( i \) is:

\[ g_i = \phi(g_{i1}, \cdots, g_{in}) \]

(4)

The PD of the MSS can be represented as:

\[ g_i = \phi(g_{i1}, \cdots, g_{in}), p_i = \prod_{j=1}^{n} p_{ij} \]

(5)

3.2. UGF Method

The UGF is an effective method to conduct the reliability assessment of MSSs. Boolean model, stochastic process method, Monte Carlo simulation and UGF method are common methods used for reliability analysis of MSS. In engineering practice, the UGF method can be applied to the system with complex structure and function, meanwhile, the calculation is small and the implementation is flexible. Most importantly, reliability assessment via the UGF method can be done by decomposing the calculation of system UGF into a combination of two component UGF. It, therefore, dramatically reduces the computational burden of system reliability assessment for complex systems with many components. As the performance rates and PD of the MSS have been determined, the \( z \) – transform of random variable \( g_j = \{g_{j1}, \cdots, g_{jk}, \cdots \} \), \( p_j = \{p_{j1}, \cdots, p_{jk}, \cdots \} \) is defined as:

\[ u(z) = \sum_{j=1}^{k_j} p_{jj} \cdot z^{g_{jj}} \]

(6)

Equation (6) represents the PD of the component \( j \). This form is the UGF representation of multi-state component \( j \). The output PD with \( z \) – transform representation of the entire system can be represented as:

\[ U(z) = \Omega_g \{u_1(z), \cdots, u_n(z)\} \]

\[ = \Omega_g \left\{ \sum_{i=1}^{k1} p_{i1} \cdot z^{g_{i1}}, \cdots, \sum_{i=1}^{kn} p_{in} \cdot z^{g_{in}} \right\} \]

\[ = \sum_{i=1}^{k1} \cdots \sum_{i=1}^{kn} \left( \prod_{j=1}^{n} p_{ij} \cdot z^{g_{ij}} \right) \]}

(7)

where \( \Omega_g \) is a general composition operator. The UGF method is based on the general composition operator and individual universal \( z \) – transform representations. Therefore, the PD of the MSS can be easily obtained through the PDs of each component if the structure function \( \phi(*) \) is known. The structure function \( \phi(*) \) is defined according to the structure of the system. A system with different structures, such as series, parallel, series-parallel or bridge structures, will have different \( \phi(*) \). The states of an MSS can be divided into two subsets depending on whether the state is acceptable by the system function. Whether a state is accepted or not depends on the system demand \( w \). Suppose that the index \( \gamma \) represents \( g_j - w \), the state \( i \) is an acceptable state.
if and only if \( \eta \geq 0 \). The availability of an MSS is the probability the system staying in the subset of acceptable states:

\[
A(w) = \sum_{\eta \geq 0} p_{\eta} = \sum_{i=1}^{K} p_{i} \cdot \alpha_{i},
\]

where:

\[
\alpha_{i} = \begin{cases} 
1, & \eta \geq 0 \\
0, & \eta < 0
\end{cases}
\]

(9)

Herein, a subsystem of the DFIG is taken as an example to illustrate the UGF-based reliability assessment for MSSs.

![Fig. 4. Structure of the subsystem of DFIG](image)

As shown in Fig. 4, there is a subsystem of DFIG with five components. This subsystem can be treated as a flow transmission system whose performance rate (level) is defined by its transmission capacity. Suppose that there are 3 states of generator (component 1) and converter (component 2) and 2 states of the transformer (component 3). The performance rates (levels) of the states of generator are \( g_{11} = 1.7 \), \( g_{12} = 1.2 \), \( g_{13} = 0.5 \) with the corresponding probabilities being \( p_{11} = 0.7 \), \( p_{12} = 0.2 \), \( p_{13} = 0.1 \), respectively. The performance rates (levels) of the states of the converter are \( g_{21} = 0.8 \), \( g_{22} = 0.2 \), \( g_{23} = 0 \) and the corresponding probabilities are \( p_{21} = 0.4 \), \( p_{22} = 0.3 \), \( p_{23} = 0.3 \). The performance rates (levels) of the states of transformer are \( g_{31} = 1 \), \( g_{32} = 0 \) and the corresponding probabilities \( p_{31} = 0.5 \), \( p_{32} = 0.5 \). The UGF for each component based on the PD is defined as:

\[
u_{1}(z) = p_{11} \cdot z^{g_{11}} + p_{12} \cdot z^{g_{12}} + p_{13} \cdot z^{g_{13}} = 0.7 \cdot z^{1.7} + 0.2 \cdot z^{1.2} + 0.5 \cdot z^{0.5},
\]

\[
u_{2}(z) = p_{21} \cdot z^{g_{21}} + p_{22} \cdot z^{g_{22}} + p_{23} \cdot z^{g_{23}} = 0.4 \cdot z^{0.8} + 0.3 \cdot z^{0.2} + 0.3 \cdot z^{0},
\]

\[
u_{3}(z) = p_{31} \cdot z^{g_{31}} + p_{32} \cdot z^{g_{32}} = 0.5 \cdot z^{1} + 0.5 \cdot z^{0}.
\]

According to the structure as shown in Figure 4, the system structure function is expressed as:

\[
\phi(G_{1}(t), G_{2}(t), G_{3}(t)) = \min \{ \phi(G_{1}(t)), \phi(G_{2}(t)), \phi(G_{3}(t)) \},
\]

and the PD of the entire system can be obtained as:

\[
\phi(\nu_{1}(z), \nu_{2}(z), \nu_{3}(z)) = \Omega_{\phi}[\phi(\nu_{1}(z), \nu_{2}(z), \nu_{3}(z))],
\]

\[
= \Omega_{\phi} \left[ 1.1296 \cdot z^{0.5} + 0.0288 \cdot z^{1.3} + 0.2176 \cdot z^{1} + 0.216 \cdot z^{0.8} - 0.024 \cdot z^{0.7} \right],
\]

\[
= 0.188 \cdot z^{1} + 0.108 \cdot z^{0.8} + 0.012 \cdot z^{1.3} + 0.012 \cdot z^{0.5} + 0.045 \cdot z^{0.4} + 0.09 \cdot z^{0.2} + 0.545 \cdot z^{0}.
\]

Therefore, the system availability is calculated as:

\[
A(0.5) = \sum_{i=1}^{4} p_{i} \cdot \alpha_{i} = 0.188 + 0.108 + 0.012 + 0.012 + 0.045 + 0.09 + 0.545 - 0.32.
\]

The result of 0.32 can be considered as the system availability corresponding to the demand \( w = 0.5 \), and the reliability of the system can be assessed if the reliability demand is a set.

4. FUGF Method for Reliability Assessment of the DFIG

4.1. FUGF

Fuzzy reliability theory is a combination of fuzzy mathematics and reliability theory. Conventional UGF technique is based on two fundamental assumptions. Firstly, the probabilities of each state of each component can be fully characterized by probability measures. Secondly, the performance rate of each component can be precisely determined. However, since the performance rates and probabilities cannot be obtained precisely in practical engineering, the FUGF technique is developed. Therefore, the values in UGF cannot be represented as crisp numbers and the values can be considered around a crisp number. In this situation, the fuzzy set and fuzzy number are proposed to describe such epistemic uncertainty.

A fuzzy number is different from a crisp number because it is a subset defined by its membership function. For example, \( X \) is a fuzzy subset, and is defined by its membership function \( \mu_{X}(x) : U \rightarrow [0,1] \).

The values of \( \mu_{X}(x) \) are in the range of 0 to 1, and the value of \( \mu_{X}(x) \) indicates the probability that the fuzzy number can be obtained as a specific value \( x \). There are different kinds of fuzzy numbers with different kind of membership functions. In this paper, the TFN is considered. The membership function of a typical TFN parameterized by the triplet is defined as:

\[
\mu_{TFN}(x) = \begin{cases} 
\frac{x-a}{b-a}, & a \leq x \leq b \\
1, & x = b \\
\frac{x-c}{b-c}, & b < x \leq c \\
0, & \text{otherwise}
\end{cases}
\]

(10)

And the function can be plotted as Fig. 5.

![Fig. 5. Membership function of TFN](image)

If fuzzy values exist in the UGF, it can be considered as FUGF. In this paper, both the performance rates and the probabilities are treated as fuzzy numbers. Furthermore, all the fuzzy numbers in this paper are considered as TFNs.

For a fuzzy MSS with \( n \) components, the component \( j(1 \leq j \leq n) \) can have \( k_{j} \) different states, the corresponding PD can be represented as ordered fuzzy sets \( \tilde{g}_{j} = \{ \tilde{g}_{j1}, \tilde{g}_{j2}, ..., \tilde{g}_{jk_{j}} \} \) and
\[ \tilde{p}_{ij} = \{ \tilde{p}_{ij1}, \tilde{p}_{ij2}, \ldots, \tilde{p}_{ijt} \} \], so the fuzzy performance rates (levels) and probabilities of each state are:

\[
\tilde{P}_{ij} = \{ P_{ij1}, \bar{P}_{ij}(P_{ij1}), \alpha_{ij1} \} \quad \text{and} \quad \tilde{G}_{ij} = \{ G_{ij1}, \bar{G}_{ij}(G_{ij1}), \alpha_{ij1} \} \in G_{ij}
\]

where \( \bar{P}_{ij} \) and \( \bar{G}_{ij} \) are membership functions of fuzzy numbers \( \tilde{P}_{ij} \) and \( \tilde{G}_{ij} \), respectively.

The operation of fuzzy number follows the extension principle, the performance of system state \( i \) can be evaluated as:

\[
\tilde{g}_{i} = \bar{g}_{i} = \tilde{g}_{i} = \{ g_{i1}, \bar{g}_{i}(g_{i1}), \alpha_{ij1} \} = \{ g_{i1}, \bar{g}_{i}(g_{i1}), \alpha_{ij1} \}, g_{i1} \in G_{ij}
\]

where \( \bar{g}_{i} = \sup \{ \bar{g}_{i}(g_{i1}), \alpha_{ij1} \} \) and \( \tilde{g}_{i} = \sup \{ \tilde{g}_{i}(g_{i1}), \alpha_{ij1} \} \) are the structure function of FMSS.

The probability of system state \( i \) represented by fuzzy numbers can be calculated as:

\[
\tilde{p}_{i} = \{ p_{i1}, \bar{p}_{i}(p_{i1}) \} = \sup_{j=1}^{n} \{ p_{ij1}, \bar{p}_{ij}(p_{ij1}) \} \in P_{ij}
\]

where \( \bar{p}_{i} = \sup_{j=1}^{n} \{ \bar{p}_{ij}, \alpha_{ij1} \} \).

The PD of a FMSS can be calculated as:

\[
U(z) = \Omega \{ \sum_{k=1}^{h} \tilde{p}_{k1} \cdot z^{k} \cdot \bar{g}_{i} \} = \sum_{k=1}^{h} \sum_{k=2}^{h} \tilde{p}_{k1} \cdot z^{k} \cdot \bar{g}_{i}(g_{i1})
\]

Since system demand is represented as a fuzzy number, the availability assessment for a fuzzy MSS is re-defined in this paper. If the performance rate (level) \( g \) for the state \( i \) is represented as a TFN parameterized by a triplet \( (a, b, c) \) and the system demand \( w \) is represented as a TFN parameterized by a triplet \( (x, y, z) \), there would be different kinds of relationship between them.

If \( a \geq x \), state \( i \) is a reliable state.

If \( x < c \), state \( i \) is a failure state.

If there is an overlapping between \( (a, b, c) \) and \( (x, y, z) \), the availability of a FMSS can be represented as:

\[
\tilde{A} = \sum_{i=1}^{k} \tilde{p}_{i} \cdot |ar|_{rel}
\]

where \( |ar|_{rel} \) is the relative cardinality of fuzzy set \( ar \) and \( \tilde{A} = \{ ar_{1}, \bar{A}(ar_{1}), \alpha_{ij1} \} \in AR_{ij} \).

4.2. Reliability Assessment of the DFIG by FUGF

From the state definitions of DFIG in Table 1, there are 4 states of the blade and the gearbox, and 3 states of the generator, the converter and the transformer, respectively. The degradation forms of components are different, for instance, the blade will have a slower speed of rotation but the gearbox will have a lower speed of the output shaft during degradation. Due to limited reliability testing resources (e.g., time, budget, manpower), the amount of collected reliability-related data from the components of the DFIG are extremely small. It, therefore, becomes difficult to estimate the precise values of the state probabilities of the DFIG and its components [28], [29]. Alternatively, imprecise information with respect to the DFIG and its components, i.e., the performance rates (levels), and the corresponding state probabilities can be gathered from experts. In this work, the performance rates (levels) of all components are treated as TFNs under the fuzzy set theory, as tabulated in Table 2. The data in Table 2 are collected from real industry according to cooperation with wind turbine enterprises.

Based on the given values, the reliability assessment based on FUGF can be conducted as follows:

\[
u_i(z) = \sum_{j=1}^{l} p_{ij1} \cdot z^{j1} + \bar{
u}_i(z) \cdot z^{j2} + \bar{p}_{ij1} \cdot z^{j1} \cdot z^{j2} = 0.7226 \cdot 0.7 \cdot 0.72 = 0.7226 \cdot 0.7 \cdot 0.72
\]

\[
u_i(z) = \sum_{j=1}^{l} p_{ij1} \cdot z^{j1} + \bar{
u}_i(z) \cdot z^{j2} + \bar{p}_{ij1} \cdot z^{j1} \cdot z^{j2} = 0.7226 \cdot 0.7 \cdot 0.72
\]

According to Fig. 3, components 3 and 4 are connected in parallel. Therefore, the operator \( \tilde{\Omega}_{pp} \) is applied between \( u_i(z) \) and \( u_j(z) \):

\[
\tilde{\Omega}_{pp}(u_i(z), u_j(z)) = (0.6237, 0.7221, 0.7912) \cdot z^{0.7} + (0.0972, 0.1305, 0.1840) \cdot z^{0.7}
\]

\[
\tilde{\Omega}_{pp}(u_i(z), u_j(z)) = (0.6237, 0.7221, 0.7912) \cdot z^{0.7} + (0.0972, 0.1305, 0.1840) \cdot z^{0.7}
\]

\[
\tilde{\Omega}_{pp}(u_i(z), u_j(z)) = (0.6237, 0.7221, 0.7912) \cdot z^{0.7} + (0.0972, 0.1305, 0.1840) \cdot z^{0.7}
\]

\[
\tilde{\Omega}_{pp}(u_i(z), u_j(z)) = (0.6237, 0.7221, 0.7912) \cdot z^{0.7} + (0.0972, 0.1305, 0.1840) \cdot z^{0.7}
\]

\[
\tilde{\Omega}_{pp}(u_i(z), u_j(z)) = (0.6237, 0.7221, 0.7912) \cdot z^{0.7} + (0.0972, 0.1305, 0.1840) \cdot z^{0.7}
\]
Firstly, the reliability block diagram of DFIG is built according to the system structure function. Secondly, the component states are defined. Specifically, there are four (perfect, mild wear, severe wear and failure) states for the blade, 3 states (perfect, middle and failure) for the gearbox, 3 states (perfect, middle and failure) for the generator, 3 states (perfect, middle and failure) for the converter, and 3 states (perfect, middle and failure) for transformer. Finally, the FUGF method is used to calculate the fuzzy availability of the entire DFIG system based on the reliability block diagram, fuzzy states and the corresponding probabilities. The results show that given the system demand of (0.78, 0.85, 0.92), the availability of the DFIG system is (0.2397, 0.4719, 0.7315). If the system demand increases to a higher level, the availability of system will decrease and vice versa. Triangular fuzzy number is a special category of trapezoidal fuzzy number, which is the most widely studied fuzzy number. Most fuzzy concepts and fuzzy information in real life, especially some fuzzy judgments of decision-makers or experts’ experience, can be expressed by triangular fuzzy numbers. It is noteworthy that the proposed constrained optimization model for reliability assessment is not restricted to the TGF. It can be readily implemented to other types of fuzzy numbers because at any cut levels, we can find the interval of the component state probability of any type of fuzzy numbers. Therefore, the proposed method is a generalized method for reliability assessment under fuzzy set theory. However, for reliability assessment of MSS, UGF method is convenient, but it is not equal to that UGF method is the most accurate one. In the future, we need to further compare the accuracy of the results with other methods. This is the direction we will focus on in the future.

5. Conclusions

In this paper, the reliability assessment of the DFIG, a typical wind turbine generator, is conducted under the fuzzy set theory. The DFIG, which consists of a blade, a gearbox, a generator, a converter, and a transformer is treated as an MSS. The FUGF method is used to evaluate the reliability of the DFIG with fuzzy states and probabilities. Firstly, the reliability block diagram of DFIG is built according to the system structure function. Secondly, the component states are defined. Specifically, there are four (perfect, mild wear, severe wear and failure) states for the blade, 4 states (perfect, mild wear, severe wear and failure) for the gearbox, 3 states (perfect, middle and failure) for the generator, 3 states (perfect, middle and failure) for the converter, and 3 states (perfect, middle and failure) for transformer. Finally, the FUGF method is used to calculate the fuzzy availability of the entire DFIG system based on the reliability block diagram, fuzzy states and the corresponding probabilities. The results show that given the system demand of (0.78, 0.85, 0.92), the availability of the DFIG system is (0.2397, 0.4719, 0.7315). If the system demand increases to a higher level, the availability of system will decrease and vice versa. Triangular fuzzy number is a special category of trapezoidal fuzzy number, which is the most widely studied fuzzy number. Most fuzzy concepts and fuzzy information in real life, especially some fuzzy judgments of decision-makers or experts’ experience, can be expressed by triangular fuzzy numbers. It is noteworthy that the proposed constrained optimization model for reliability assessment is not restricted to the TGF. It can be readily implemented to other types of fuzzy numbers because at any cut levels, we can find the interval of the component state probability of any type of fuzzy numbers. Therefore, the proposed method is a generalized method for reliability assessment under fuzzy set theory. However, for reliability assessment of MSS, UGF method is convenient, but it is not equal to that UGF method is the most accurate one. In the future, we need to further compare the accuracy of the results with other methods. This is the direction we will focus on in the future.

Acknowledgement

The authors extend sincere gratitude to the National Natural Science Foundation of China for financial support under contract number 51775090.
6. Ding Y, Lisianski A. Fuzzy universal generating functions for multi-state system reliability assessment. Fuzzy Sets and System 2007; 159: 307-324, https://doi.org/10.1016/j.fss.2007.06.004.
7. Dong W, Liu S, Zhang Q, Mierzwiak R, Fang Z, Cao Y. Reliability assessment for uncertain multi-state systems: an extension of fuzzy universal generating function. International Journal of Fuzzy Systems 2019; 21, 945-953, https://doi.org/10.1007/s40815-018-0552-x.
8. Eryilmaz S. Reliability analysis of multi-state system with three-state components and its application to wind energy. Reliability Engineering & System Safety 2017; 172: 58-63, https://doi.org/10.1016/j.ress.2017.12.008.
9. Gao H, Zhang X. A novel reliability analysis method for fuzzy multi-state systems considering correlation. IEEE Access 2019; 7: 153194-153208, https://doi.org/10.1109/ACCESS.2019.2948492.
10. Gao P, Xie L, Hu W, Liu C, Feng J. Dynamic fuzzy reliability analysis of multistate systems based on universal generating function. Mathematical Problems in Engineering 2018; 2018: 1-8, https://doi.org/10.1155/2018/6524629.
11. Huang HZ. Reliability analysis method in the presence of fuzziness attached to operation time. Microelectronics Reliability 1995; 35: 1483-1487, https://doi.org/10.1016/0026-2714(94)00173-L.
12. Huang HZ, Tong X, Zuo MJ. Postbist fault tree analysis of coherent systems. Reliability Engineering & System Safety 2004; 84: 141-148, https://doi.org/10.1016/j.ress.2003.11.002.
13. Huang HZ, Zuo MJ, Sun Z. Bayesian reliability analysis for fuzzy lifetime data. Fuzzy Sets and System 2006; 157: 1674-86, https://doi.org/10.1016/j.fss.2007.06.004.
14. Jaiswal N, Negi S, Singh S. Reliability analysis of non-repairable weighted k-out-of-n system using belief universal generating function. International Journal of Industrial and Systems Engineering 2018; 28: 300-318, https://doi.org/10.1050/IJISE.2018.089741.
15. Khaniev T, Baskir M B, Gokpinar F, Mirzayev F. Statistical distribution and reliability functions with type-2 fuzzy parameters. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2019; 21(2): 268-274, https://doi.org/10.17531/ein.2019.2.11.
16. Leviin G. The universal generating function in reliability analysis and optimization. London: Springer, 2005.
17. Li Y, Ding Y, Zio E. Random fuzzy extension of the universal generating function approach for the reliability assessment of multi-state systems under aleatory and epistemic uncertainties. IEEE Transactions on Reliability 2014; 63: 13-25, https://doi.org/10.1109/TR.2014.2299031.
18. Li YF, Huang HZ, Mi J, Peng W, Han X. Reliability analysis of multi-state systems with common cause failures based on Bayesian network and fuzzy probability. Annals of Operations Research 2019; https://doi.org/10.1007/s10479-019-03247-6.
19. Li YF, Liu Y, Huang T, Huang HZ, Mi J. Reliability assessment for systems suffering common cause failure based on Bayesian networks and proportional hazards model. Quality and Reliability Engineering International 2020; 36(7): 2509-2520, https://doi.org/10.1002/qre.2713.
20. Li YF, Huang HZ, Mi J, Peng W, Han X. Reliability analysis of fuzzy multi-state systems. Reliability Engineering & System Safety, 2020, 198: 106900, https://doi.org/10.1016/j.ress.2020.106900.
21. Liu Y, Huang HZ. Reliability assessment for fuzzy multi-state systems. International Journal of Systems Science 2009; 41: 365-379, https://doi.org/10.1080/0020772090342939.
22. Mi J, Li YF, Liu Y, Yang YJ, Huang HZ. Belief universal generating function analysis of multi-state systems under epistemic uncertainty and common cause failures. IEEE Transactions on Reliability 2015; 64(4): 1300-1309, https://doi.org/10.1109/TR.2015.2419620.
23. Mi J, Li YF, Peng W, Huang HZ. Reliability analysis of complex multi-state system with common cause failure based on evidential networks. Reliability Engineering & System Safety 2018; 174: 71-81, https://doi.org/10.1016/j.ress.2018.02.021.
24. Mlyinarski S, Pilch R, Smolnik M, Szybka J, Wiazania G. A method for rapid evaluation of k-out-of-n systems reliability. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2019; 21(1): 170-176, https://doi.org/10.17531/ein.2019.1.20.
25. Negi S, Singh S. Fuzzy reliability evaluation of linear m-consecutive weighted-k-out-of-r-from-n: F systems. International Journal of Computing Science and Mathematics 2019; 10: 606-621, https://doi.org/10.1504/IJCSM.2019.104027.
26. Qin JL, Niu YG, Li Z. A combined method for reliability analysis of multiple-state system of minor-repairable components. Eksploatacja i Niezawodnosc - Maintenance and Reliability 2016; 18(1): 80-88, https://doi.org/10.17531/ein.2016.1.11.
27. Wu H. Fuzzy reliability estimation using Bayesian approach. Computers and Industrial Engineering 2004; 46: 467-93, https://doi.org/10.1016/j.cie.2004.01.009.
28. Xiahou T, Liu Y. Reliability bounds for multi-state systems by fusing multiple sources of imprecise information. IEEE Transactions 2020; 52(9): 1014-1031, https://doi.org/10.1109/24725854.2019.1680910.
29. Xiahou T, Zeng Z, Liu Y. Remaining useful life prediction by fusing experts' knowledge and condition monitoring information. IEEE Transactions on Industrial Informatics 2020, https://doi.org/10.1109/II.2020.2998102.
30. Xiao H, Cao M. Joint Optimization of redundancy and preventive maintenance of a power grid system considering economic cost. Energy 2020; 201: 118470, https://doi.org/10.1016/j.energy.2020.118470.
31. Xiao H, Cao MH, Kou G, Yuan XJ. Optimal element allocation and sequencing of multi-state series systems with two levels of performance sharing. Proceedings of the Institution of Mechanical Engineers, Part O: Journal of Risk and Reliability, 2019, https://doi.org/10.1177/1748006X20947846.
32. Xiao H, Yi XK, Kou G, Xing LD. Reliability of a two-dimensional demand-based networked system with multistate components. Naval Research Logistics (NRL), 2020, 67(6): 453-468, https://doi.org/10.1002/nav.21922.
33. Xiao H, Zhang YY, Xiang YS, Peng R. Optimal design of a linear sliding window system with consideration of performance sharing. Reliability Engineering & System Safety, 2020, 198: 106900, https://doi.org/10.1016/j.ress.2020.106900.
34. Zhou D, Blaabjerg F, Lau M. Cost on reliability and production loss for power converters in the doubly fed induction generator to support modern grid codes. Electric Power Components and Systems 2016; 44: 152-164, https://doi.org/10.1080/15325008.2015.1102990.