A practical reliability design method considering the compound weight and load-sharing

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Abstract

Reliability design is an important work in the early design stage of offshore wind turbines. Due to the incomplete considerations and poor feasibility of the drawbacks for existing methods, a set of the practical reliability design method is proposed in this paper. The time characteristics and many influential factors of units are considered in the design process. The influential factors of the system's units are scored by several experts with extensive engineering experience. Based on this, the reliability allocation and the maintainability prediction of the repairable system are performed using different methods. To realistically evaluate the reliability level of each unit obtained by three different methods, a fuzzy reliability evaluation method is developed to rank the reliability level of each unit with considerations of the mean time between failure (MTBF), mean time to repair (MTTR), failure frequency and availability using the compound weight and fuzzy membership function. Following this, redundant design is used to eliminate weaknesses to keep the system reliability at a high level. Using the reliability data obtained above, a time-dependent reliability model of the system considering load sharing is built to explore the influences of reliability allocation on the system reliability in the 20-year service life. The effectiveness and feasibility of the proposed approaches are demonstrated with a 5MW offshore wind turbine.

Keywords: Offshore wind turbine; Reliability design; Fuzzy reliability assessment; Maintainability prediction; Load sharing; Compound weight

1. Introduction

Offshore wind turbines have been widely installed around the world. However, improving the reliability of offshore wind turbines is still a challenge for the wind power industry. Reliability design is critical to the safe operation and maintenance of offshore wind turbines in the 20-year service life, which is also a

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practical way to improve system reliability at the early design stage [1, 2]. Performing reliability design at the early stage and taking actions to eliminate weaknesses to ensure reliable and safe operation of offshore wind turbines are now even more important [3].

The reliability allocation problem is widespread in offshore wind turbines. In reality, reliability allocation is used to allocate the reliability index of each unit after the system's reliability target is determined. Based on this, designers can specify the requirements of the reliability design and estimate the manpower, time and sources required for the design, which can ensure that the system reliability meets the requirements of specified reliability indexes. System reliability allocation problem has traditionally been based on weighting factors [4, 5]. Some allocation methods considering different weighting factors have been studied in the past. David et al. [6] discussed the system reliability allocation method and developed a computational algorithm using dynamic programming to obtain the optimal solution. John [7] proposed a practical method of maintainability allocation considering the basic factors for the product at the conceptual design stage. Tian et al. [8] performed the reliability allocation of a software system using fault tree analysis (FTA) and the genetic algorithm. Zhang et al. [9] developed a reliability allocation method based on the exponential distribution and compared the results calculated by three different methods. Kyungmee et al. [10], Om and Zhuang [11] studied the reliability allocation weight considering the failure severity of subsystems and its relative frequency. Zhou et al. [12] used a transformed function to perform the reliability allocation of computer numerical control (CNC). Gianpaolo and Antonio [13] used the analytic critical flow method to perform the reliability allocation considering the weight of each factor. But this method can not take the mission time into account, and only a few factors are considered. Chang [14] considered the hesitant fuzzy linguistic term sets and minimal variance OWGA (Ordered weighted geometric averaging) to flexibly allocate system reliability. Yu et al. [15] developed a fuzzy allocation method considering failure effects and reliability costs. Hao et al. [16] performed the fuzzy maintainability allocation on the numerical control machine using interval analysis with considerations of main influential factors. The ARINC (Aeronautical Radio Incorporation) method is based on historical failure data to perform reliability allocation and does not consider the system composition and characteristics case [17, 18, 19]. According to the ARINC and the failure mode and effect analysis (FEMA), Liu et al. [20] developed an approach for reliability goal with consideration of the improvement of the components. Hu et al. [21] and Wang et al. [22] developed a reliability allocation method for CNC turrets considering related influencing factors. Zhang et al. [23] and Liu et al. [24] studied the engineering weighted method considering the multiple influences of two-layer factors, which was applied in engineering. AGREE method is developed by the Advisory Group on Reliability of Electronic Equipment (AGREE). Wang [25] and Du [26] introduced an improved AGREE method with considerations of the importance, which was verified through a series-parallel connection system. However, AGREE can only take the importance factor into consideration, which is not suitable to deal with the reliability allocation problem of complex systems. Reliability-redundancy allocation is also widely applied in the reliability design in engineering practice [27, 28, 29]. However, this method has strict requirements of the system's space and structure and can only be used in the redundant system.

The major drawback of the weight-based reliability allocation is that it has to rely on weight coefficients. The commonly used methods can not consider the mission time of units, and the influential factors considered are limited. Moreover, the results of reliability allocation can not be evaluated. The purpose of this paper is to overcome the limitation of traditional reliability design methods and improve the accuracy and effectiveness of the allocated reliability index. To reflect time characteristics in the reliability allocation and take more influential factors into account, we therefore propose an improved reliability allocation method based on the engineering weighted allocation method to overcome the drawbacks of existing methods and perform the improved method on both the non-repairable system and the repairable system. To verify the reliability level of each unit obtained by the improved method, we develop a fuzzy reliability evaluation method to assess units' reliability level, which is one contribution of this paper. According to the results of the fuzzy reliability evaluation, units with low-reliability levels are determined. Following this, we adopt the redundancy design to improve units with a low-reliability level. Redundant units are treated as load-sharing systems in the reliability assessment of the overall system, which is another contribution of this paper.

The rest of this paper is organized as follows. In Section 2, we first provide a brief introductory overview of the concept of reliability allocation, fuzzy reliability evaluation, and load sharing. In Section 3, we perform reliability allocation and evaluation of the non-repairable system and the repairable system. Section 4 presents the reliability model of the system of offshore wind turbines based on the reliability allocation considering load sharing. Following this, results and discussion are presented. We end the paper with some concluding remarks in Section 5.

2. Methodology

2.1. Improved reliability allocation method

The reliability needs to be allocated to each component and subsystem according to the system's reliability target. The reliability allocation method has a great influence on the reliability allocation results of offshore wind turbines. To realistically reflect the reliability level of each unit (components or subsystems), we develop an improved reliability allocation method based on the engineering weighted allocation method (EWM) [30]. Assuming a series-parallel connection system, the jth unit's reliability using EWM can be expressed as follows

$$R_j = R_s^{\frac{\prod_{i=1}^{n} K_{ji}}{\sum_{j=1}^{N}\prod_{i=1}^{n} K_{ji}}} \tag{1}$$

where K_{ji} is the ith weighting factor of the jth unit in the system, such as the technical level, the environmental condition, the importance, the complexity, etc. R_s means the system's reliability that designers want to achieve, n and N represent the number of the weighting factors and the number of units in the system, respectively.

For a series connection system with m components or subsystems, the system's reliability can be expressed as $R_s = \prod_{j=1}^{m} R_j$. Hence, Eq. (1) can be rewritten as

$$R_j = \exp\left(\frac{K_0 \cdot \ln R_s^{'}}{1 - K_0}\right) \tag{2}$$

where $K_0 = \prod_{i=1}^{n} K_{ji} / \sum_{j=1}^{N} \prod_{i=1}^{n} K_{ji}$ and $R_s^{'} = \prod_{i=1, i \neq j}^{m} R_i \approx R_s$.

If the lifetime of units and the system follows a Weibull distribution $w(\lambda, \gamma)$, let $R_j = e^{-(\lambda_j t_j)^{\gamma_j}}$ and $R_s = e^{-(\lambda_s t_s)^{\gamma_s}}$. Then taking the logarithm of both sides of Eq. (2), the improved reliability allocation formula can be derived as follows

$$\lambda_j = \left(\frac{K_0}{1 - K_0}\right)^{1/r_j} \cdot \frac{(\lambda_s t_s)^{r_s/r_j}}{t_j} \tag{3}$$

where λ_j and γ_j are the scale parameter and the shape parameter of the j^{th} unit, respectively; λ_s and γ_s are the scale parameter and the shape parameter of the system, respectively; t_j and t_s express the operating time of the j^{th} unit and the system ($t_j \leq t_s$). If the lifetime of units and the system follows an exponential distribution (λ), let $R_j = e^{-\lambda_j t_j}$ and $R_s = e^{-\lambda_s t_s}$. The improved reliability allocation formula can be derived in the same way, as follows

$$\lambda_j = \frac{K_0}{1 - K_0} \cdot \frac{\lambda_s t_s}{t_j} \tag{4}$$

Assuming a system with more than one type of lifetime distributions, two possible cases are existing: (i) if the unit's lifetime follows a Weibull distribution and the system's lifetime follows an exponential distribution, the failure rate of the unit can be obtained by $\lambda_j = \frac{1}{t_j}\left(\frac{K_0(\lambda_s t_s)^{1/r_j}}{1-K_0}\right)^{1/r_j}$; (ii) if the unit's lifetime follows an exponential distribution and the system's lifetime follows a Weibull distribution, the failure rate of the unit can be obtained by $\lambda_j = \frac{K_0(\lambda_s t_s)^{\gamma_s}}{(1-K_0)t_j}$.

2.2. Fuzzy reliability evaluation

To objectively reflect the uncertainty of information, we propose to adopt the entropy weight method combined with the expert weights to improve the reliability evaluation. The improved approach can improve the sensitivity of the entropy weight on the factor importance and reduce the impact of subjective factors in the expert assessment process.

2.2.1. Compound weight

Considering a multi-state system with m evaluating indicators and n states, and assuming that the initial matrix of evaluating indicators is $\mathrm{Y} = \left[y_{ij}\right]_{m\times n}$, the information entropy of the j^{th} evaluating indicator can be expressed as follows [31]

$$H_j^{fh} = -\sum_{i=1}^{m} f_{hi} \cdot \ln f_{hi} \tag{5}$$

where $f_{hi} = \sum_{j=1}^{n} \frac{p_{ij}}{n}$, and p_{ij} means the proportion of the i^{th} state indicator value under the j^{th} indicator, whose formula can be expressed by $p_{ij} = y_{ij} / \sum_{i=1}^{m} y_{ij}$.

The entropy weight w_{Hj} of the j^{th} indicator is

$$w_{Hj} = \frac{1 - H_j^{fh}}{\sum_{j=1}^{n}(1 - H_j^{fh})} \tag{6}$$

Then the entropy weight matrix W_H can be obtained from Eq. (6), which can be expressed as $\mathrm{W}_H = [w_{H1},\ w_{H2},\ \cdots,\ w_{Hn}]$. Taking the historical failure data and the expert experience into consideration, the matrix of the expert weight can be obtained as $\mathrm{W}_Z = [w_{z1},\ w_{z2},\ \cdots\ , w_{zn}]$.

The compound weight matrix can be derived from W_H and W_Z

$$\mathrm{W} = [w_1, w_2, \cdots, w_n] \tag{7}$$

where $w_j = (w_{Hj} \cdot w_{zj}) / \sum_{j=1}^{n} w_{Hj} w_{zj} \quad (j = 1, 2, \cdots, n)$.

2.2.2. Reliability evaluation model

In order to mitigate the risk of incorrectly concluding effectiveness, it is necessary to perform the quantitative analysis of the evaluation results of the reliability allocation of each unit at the early design stage. For a multi-state system with n evaluation indexes, the matrix of evaluation indexes of the system is defined as follows

$$\mathrm{X} = [X_1, X_2, \cdots, X_n] \tag{8}$$

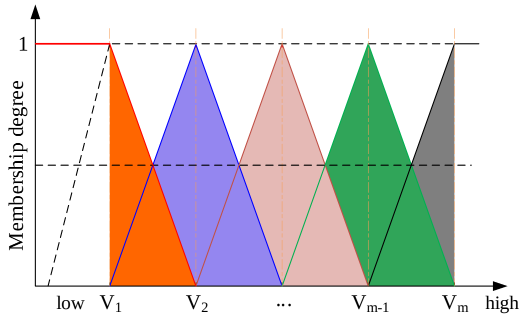


Figure 1: Fuzzy triangular membership function of reliability evaluation

According to the operation and reliability data of the system, the system reliability level is divided into m levels that can be expressed as $\mathrm{V}_{level} = [V_1, V_2, \cdots, V_m]$. The threshold values of each indicator in different levels are selected based on the actual operational experience and the reliability status.

To realistically obtain the evaluation set of a single factor, we adopt the triangular membership function to analyze the initial evaluation indicator matrix. The evaluation set of unit k can be calculated by

$$\mathrm{R}_k = \begin{array}{c} \text{index} \\ X_1 \\ X_2 \\ \vdots \\ X_n \end{array} \begin{array}{c} \begin{array}{cccc} V_1 & V_2 & \cdots & V_m \end{array} \\ \begin{bmatrix} \tilde{p}_{1,1} & \tilde{p}_{1,2} & \dots & \tilde{p}_{1,m} \\ \tilde{p}_{2,1} & \tilde{p}_{2,2} & \dots & \tilde{p}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{p}_{n,1} & \tilde{p}_{n,2} & \dots & \tilde{p}_{n,m} \end{bmatrix} \end{array}, 0 \leq \tilde{p}_{i,j} \leq 1 \tag{9}$$

where $\tilde{p}_{i,j}$ means the membership degree of the indicator X_i in the evaluation set with respect to the reliability level V_j. The membership degree $(\tilde{p}_{i,j})$ can be obtained by Eq. (10). The graphic representation of the fuzzy triangular membership function of reliability level evaluation is shown in Fig. 1.

$$f(X_i) = \begin{cases} \left(\frac{X_2 - X_i}{X_2 - X_1}, \frac{X_i - X_1}{X_2 - X_1}\right) & \text{if } X_1 \leq X_i < X_2 \\ \left(\frac{X_3 - X_i}{X_3 - X_2}, \frac{X_i - X_2}{X_3 - X_2}\right) & \text{if } X_2 \leq X_i < X_3 \\ \dots & \dots \\ \left(\frac{X_m - X_i}{X_m - X_{m-1}}, \frac{X_i - X_{m-1}}{X_m - X_{m-1}}\right) & \text{if } X_{m-1} \leq X_i < X_m \\ 1 & \text{if } X_m \leq X_i \ or \ X_i < X_1 \end{cases} \tag{10}$$

Combined with the evaluation matrix and the compound weight, the units' evaluation matrix of the system can be obtained as follows

$$\mathrm{T}_k = [w_1, w_2, \cdots, w_n] M(\bullet, \oplus) \begin{bmatrix} \tilde{p}_{1,1} & \tilde{p}_{1,2} & \cdots & \tilde{p}_{1,m} \\ \tilde{p}_{2,1} & \tilde{p}_{2,2} & \cdots & \tilde{p}_{2,m} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{p}_{n,1} & \tilde{p}_{n,2} & \cdots & \tilde{p}_{n,m} \end{bmatrix} \tag{11}$$

Finally, the reliability evaluation matrix of the system can be obtained as follows

$$\mathrm{T} = [\mathrm{T}_1; \mathrm{T}_2; \cdots; \mathrm{T}_n] \tag{12}$$

2.3. Load sharing

The quantification of the reliability of redundancy systems, are determined previously, is treated as parallel systems that, when a redundant unit fails, the failure rate or the reliability of the surviving units does not change during the mission. In reality, however, the failure rates of the surviving units will increase, because the surviving units will takes the full load during the mission. The concept of load sharing is therefore proposed to correctly determine the reliability of redundancy systems with considerations of the change of the failure rate of the surviving units [32, 33].

To realistically reflect the failure process of the redundancy system, we consider a two-unit redundant system with the lifetime of mechanical units following a two-parameter Weibull distribution and the lifetime of electronic units following an exponential distribution. There are three system success function modes for a system of two load-sharing redundant units: both units function, unit A fails while unit B functions, and unit A functions while unit B fails. The state transition diagram of a two-unit redundancy system is depicted in Fig. 2. In the state one, two units function and share the full load L_1. Unit 1 and unit 2 take the load $k_1 L_1$ and $k_2 L_1$, respectively. One unit will fail at state two where the surviving unit will suffer the full load L_1. The entire system will fail when two units go bad at state three. Therefore, there are three situations of system success function where at least one unit functions during the mission.

The system's reliability function at time t can be quantified by

$$P(T_s > t) = R_1^r(t) \cdot R_2^r(t) + \int_0^t R_2^r(t_1) \cdot R_2(t|t_1) \cdot f_1^r(t_1) dt_1 + \int_0^t R_1^r(t_2) \cdot R_1(t|t_2) \cdot f_2^r(t_2) dt_2 \tag{13}$$

where $R_i(t) = 1 - F_i(t)$ is the reliability function of unit i at time t being $i = 1, 2$, $F_i(t)$ is the lifetime distribution

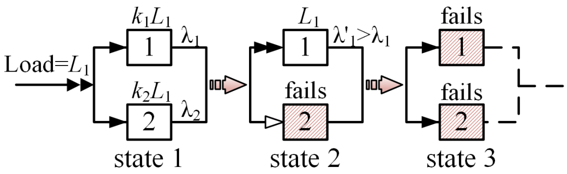


Figure 2: Load-sharing with two redundancy units ($k_1 + k_2 = 1$)

function of unit i at time t, $F_i(t) = 1 - e^{-(\lambda t)^{\gamma}}$; $R_i^r(t)$ is the reliability function of unit i taking the reduced load at time t; $R_i(t|u) = P(T > t|T > u)$ means the reliability of unit i taking the full load switched from the reduced load at time u; $f_i^r(t)$ represents the probability density function of unit i taking the reduced load at time t.

Calculating each term of Eq. (13), we can obtain the formula of the system's reliability for a mission of duration t. Therefore, Eq. (13) can be written as follows

$$\begin{aligned} R_{sys}(t) &= e^{-(\lambda_1 t)^{\gamma_1} - (\lambda_2 t)^{\gamma_2}} + \int_0^t \gamma_1 \lambda_1^{\gamma_1} t_1^{\gamma_1 - 1} e^{-\left((\lambda_1 t_1)^{\gamma_1} + \left[\lambda_2' \left(t - t_1 + \frac{1}{\lambda_2'} e^{(\lambda_2 t_1)^{\gamma_2/\gamma_2'}} \right) \right]^{\gamma_2'} \right)} dt_1 \\ &+ \int_0^t \gamma_2 \lambda_2^{\gamma_2} t_2^{\gamma_2 - 1} e^{-\left((\lambda_2 t_2)^{\gamma_2} + \left[\lambda_1' \left(t - t_2 + \frac{1}{\lambda_1'} e^{(\lambda_1 t_2)^{\gamma_1/\gamma_1'}} \right) \right]^{\gamma_1'} \right)} dt_2 \end{aligned} \quad (14)$$

In addition, if the lifetime distribution of units follows an exponential distribution, the formula of the system's reliability for a mission at time t is derived as follows

$$R_{sys}(t) = e^{-(\lambda_1+\lambda_2)t} + \int_0^t \lambda_1 e^{-(\lambda_1+\lambda_2)t_1 - \lambda_2'(t-t_1)} dt_1 + \int_0^t \lambda_2 e^{-(\lambda_1+\lambda_2)t_2 - \lambda_1'(t-t_2)} dt_2 \quad (15)$$

where λ_i is the rate parameter of unit i being $i = 1, 2$, λ_i' means the rate parameter of the surviving unit i while the other unit fails, t_i represents the time when the unit i fails.

3. Reliability design of offshore wind turbines

In this paper, a 5MW doubly-fed offshore wind turbine that is complex hydro-mechatronics integration equipment is taken as an example to conduct the reliability design. It is a typical three-bladed, upwind, variable-speed, variable blade-pitch-to-feather-controlled turbine. The rated wind speed and the rated rotor speed are 12.6 m/s and 11.34 rpm, respectively. This doubly-fed offshore wind turbine consists of blades, hub, main shaft, main-shaft bearing, gearbox, brake, generator, hydraulic system, and electrical system, etc. Each component and subsystem function throughout a prescribed operating period. The reliability design of offshore wind turbines involves the reliability allocation, fuzzy reliability level assessment, reliability rank of critical units, reliability redundant design, and system reliability assessment. The technical flowchart of the system reliability is given in Fig. 3. Therefore, the reliability design needs to allocate the reliability indicators to each unit of the repairable and non-repairable systems of offshore wind turbines based on the influential factor, which is scored by experienced experts according to the scoring criteria.

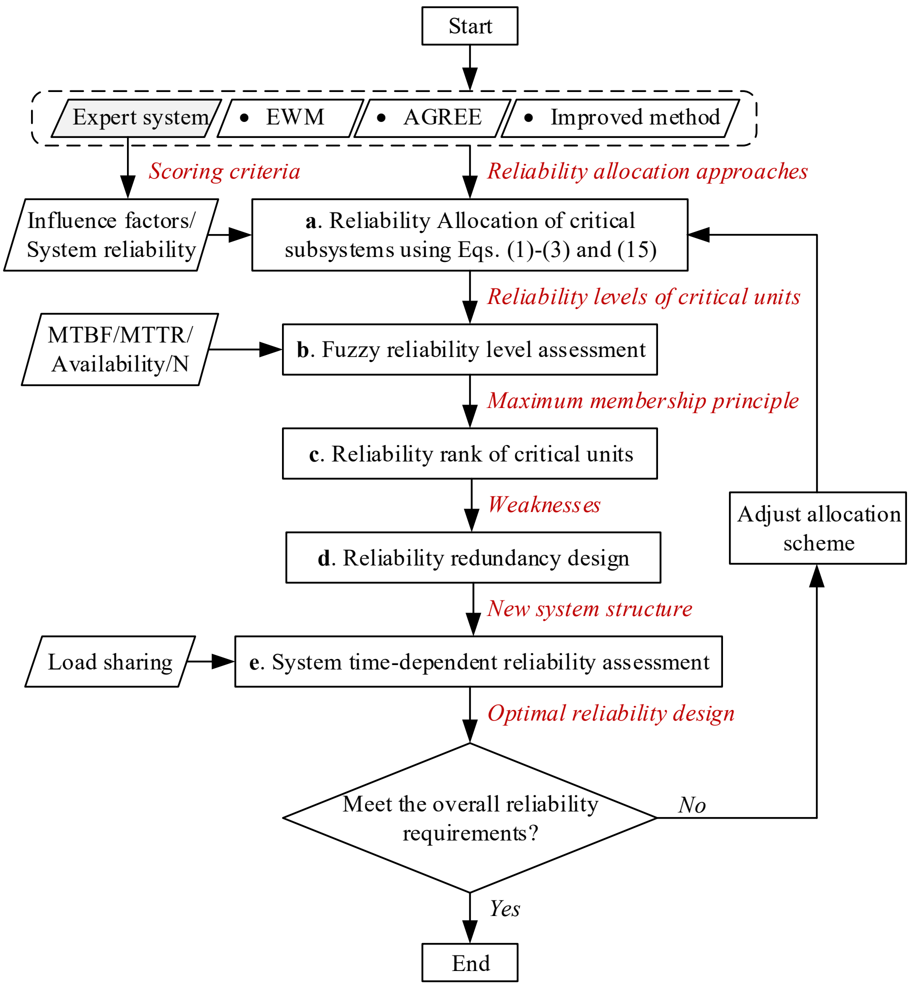


Figure 3: The technical flowchart of the reliability design method

3.1. Non-repairable system

A non-repairable system is one for which individual units that fail are removed permanently from the system by the large lifting equipment. The non-repairable system of offshore wind turbines includes the hub, main shaft, main-shaft bearings, base frame, back base frame, blades, tower, generator, gearbox, yaw bearing, pitch bearing, main transformer, etc. The reliability block diagram of non-repairable systems is shown in Fig. 4. Once one subsystem fails, the whole wind turbine has to shutdown. Moreover, the repair and replacement cost is much high. Their failures are therefore prevented. The reliability of the non-repairable system in 20-year service life is not less than 0.95, which means that the probability that the non-repairable system will perform the specified function within 20 years in the given conditions is 0.95.

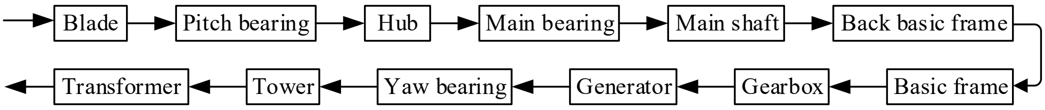


Figure 4: Reliability block diagram of the non-repairable system

Three reliability allocation methods are adopted for the reliability allocation of the non-repairable system considering the complexity, technique level, importance and environmental conditions in this paper. The scoring criteria for each factor are shown in Table 1.

Table 1: Scoring criteria of the system of offshore wind turbines

Factor	Scoring criteria
Technique level	Considering the technological level and maturity of each unit, score varies between 1 for the unit with the lowest level and 10 for the unit with the highest level.
Environmental condition	Considering the environmental conditions, units working in less difficult environmental conditions will obtain lower scores (more reliability), and vice versa ($[1, 10]$).
Importance factor	The index is evaluated based on the impact of the unit failure on the system failure. The unit with the least impact is scored 10 points and The most influential unit is scored one point.
Complexity factor	Based on the number of modules and the complexity of assembly, 10 points is allocated to the most complex units and 1 point for the simplest units.
Environment factor	Consider the environment that the unit functions, 10 points for the unit functioning in the harsh environment and 1 point for the unit functioning in the good environment.
Standardization factor	Non-standard parts and new design parts are scored 10 points, and standard parts are scored 1 point.
Maintainability factor	The more difficult the units are repaired and maintained, the higher the score units obtain (score $\in [1, 10]$).
Quality factor	The higher the unit's quality is, the lower score the unit obtains (score $\in [1, 10]$).

For units of the non-repairable system, the jth unit's failure rate obtained by the improved method using Eqs. (3) and (4). Besides, the failure rate of the ith unit using AGREE method can be obtained by Eq. (16) [26]

$$\lambda_i = -\frac{1}{t_i} \ln\left(1 - \frac{1 - R_s(t)^{q_i/Q}}{\omega_i}\right) \tag{16}$$

where ω_i is the probability that the system will fail given component i has failed (importance index), q_i means a complexity number, Q represents the total number of units in the system, t and t_i are the system operating time and the operating time of ith component, respectively ($t_i \le t$, $i = 1, 2, \cdots, n$).

According to the scoring criteria in Table 1, each unit's score of the non-repairable system can be obtained

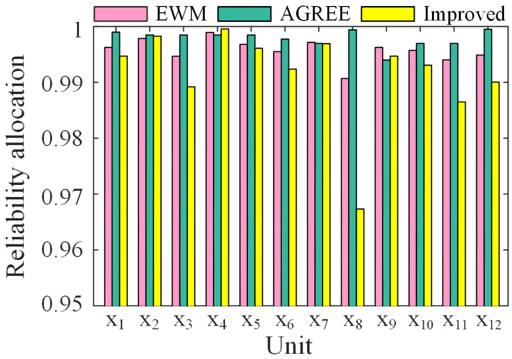


Figure 5: Reliability allocation of the non-repairable system

using the engineering experience of experts. The statistical analysis is performed on the score data of the non-repairable system to obtain the reliability index allocated to each unit. The scores of each unit are shown in Table 2. As it is shown in Table 2, ω_{j1} is the complexity index, ω_{j2} means the technique level index, ω_{j3} represents the importance index, and ω_{j4} is the environment index.

Table 2: Reliability allocation of the non-repairable system

Symbol	Name	Index			
		ω_{j1}	ω_{j2}	ω_{j3}	ω_{j4}
x_1	Hub	2	5	3	7
x_2	Main shaft	2	5	2	6
x_3	Main bearing	5	6	2	5
x_4	Back basic frame	2	3	2	5
x_5	Basic frame	3	6	2	5
x_6	Blade	3	3	4	7
x_7	Tower	4	5	1	8
x_8	Generator	7	3	5	5
x_9	Main gearbox	7	3	2	5
x_{10}	Yaw bearing	4	6	2	5
x_{11}	Pitch bearing	4	6	2	7
x_{12}	Main transformer	4	3	6	4

Fig. 5 shows the results of the reliability allocation of each non-repairable unit using different allocation methods. In this paper, three reliability allocation methods are performed on the non-repairable system, such as EWM, AGREE method and the improved method [34]. As it is shown in Fig. 5, the allocation results obtained by the improved method are almost identical to the results calculated using EWM and AGREE. For some units, the results obtained by the improved method are a little smaller than that of EWM and AGREE.

3.2. Repairable system

Compared with the non-repairable system, the repairable system is easier to repair and replace. The maintenance cost is much lower than that of the non-repairable system. Moreover, the maintenance cost and replacement cost are much lower than that of systems within a 20-year service life.

3.2.1. Reliability allocation

According to the design requirement, the availability (A_s) of the repairable system of offshore wind turbine needs to be greater than 97%, and the MTBF of the repairable system has to be greater than 8760 h. The availability of the repairable system can be calculated by [35]

$$A_s = \frac{MTBF_s}{MTBF_s + MTTR_s} \tag{17}$$

From Eq. (17), the obtained MTTR is less than or equal to 270.93 h. The reliability block diagram of the repairable system of offshore wind turbines is shown in Fig. 6. It is a series connection system that one subsystem's failure will lead to the failure of the whole wind turbine.

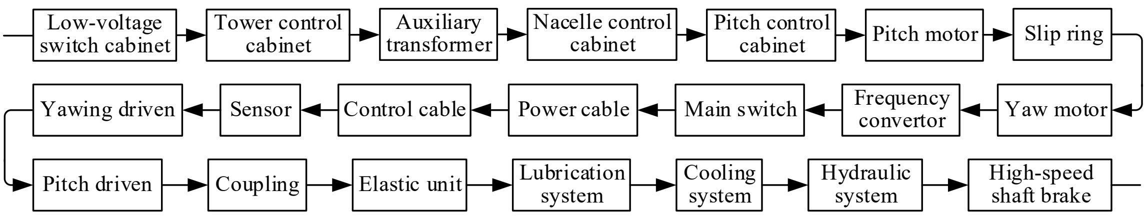


Figure 6: Reliability block diagram of the repairable system

According to the design requirements and the engineering experience of offshore wind turbines, the scoring criteria of the repairable system are developed, which are given in Table 1. The score interval of each factor is [1, 10]. The lower the score of the unit, the higher is the reliability allocated to the corresponding unit, and vice versa.

Considering the importance, complexity, operating environment, standardization degree, maintainability and component quality of each unit of the repairable system, combined with years of engineering experience, these factors are scored according to the principles of Table 1. Statistical analysis is performed on the score data, and the system's MTBF$_s$ is allocated to each unit. The comprehensive processing and allocation results of each unit's scores of the repairable system are given in Table 3. In Table 3, c_{j1}, c_{j2}, c_{j3}, c_{j4}, c_{j5}, and c_{j6} express the score of the importance factor, the complexity factor, the environment factor, the standardization factor, the maintainability factor and quality factor of the j^{th} unit, respectively.

Table 3: Reliability allocation of the repairable system

Symbol	Name	Scores of influential factors					
		c_{j1}	c_{j2}	c_{j3}	c_{j4}	c_{j5}	c_{j6}
y_1	Low-voltage switch cabinet	4.8	4.5	2.2	2.2	3.3	3.3
y_2	Tower control cabinet	4.3	6.7	3.5	2.8	3.7	3.7
y_3	Auxiliary transformer	4.2	3.3	2.2	1.7	4.7	2.5
y_4	Nacelle control cabinet	4.2	7.3	4.0	3.5	5.5	5.3
y_5	Pitch control cabinet	1.3	8.2	5.7	3.5	6.2	5.8
y_6	Pitch motor	2.8	4.2	5.3	3.7	5.7	4.2
y_7	Slip ring	2.0	5.8	4.4	4.6	6.6	6.4
y_8	Yaw motor	5.2	3.8	3.3	2.0	4.3	3.0
y_9	Frequency converter	1.3	9.2	4.2	4.2	6.8	6.5
y_{10}	Main switch cabinet	4.0	3.7	2.5	2.3	4.5	3.2
y_{11}	Power cabinet	5.2	2.5	5.7	2.3	3.8	2.3
y_{12}	Control cabinet	5.2	1.8	4.2	1.8	1.8	2.4
y_{13}	Sensor	5.0	2.5	6.2	2.8	1.7	4.2
y_{14}	Yawing driven	4.7	5.8	4.2	3.0	5.3	3.3
y_{15}	Pitch driven	2.8	6.3	6.3	3.0	6.5	3.7
y_{16}	Coupling	3.3	4.8	3.7	3.8	4.5	2.8
y_{17}	Elastic unit	5.2	3.0	3.8	4.2	5.0	3.2
y_{18}	Lubrication system	6.8	3.7	4.2	3.2	4.5	4.7
y_{19}	Cooling system	4.3	5.0	4.8	3.3	4.7	4.2
y_{20}	Hydraulic system	3.2	6.0	4.2	3.8	5.0	5.5
y_{21}	High-speed shaft brake	8.3	2.5	4.0	2.7	2.5	1.7

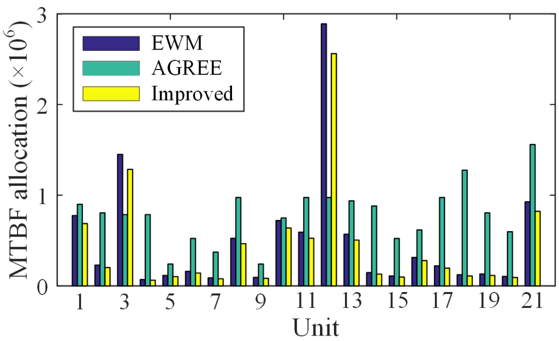


Figure 7: MTBF allocation of the repairable system

Fig. 7 shows the results of the MTBF allocation of the repairable system. From Fig. 7, we can see that the results obtained by the improved method are very close to those calculated by EWM. However, the results calculated by AGREE are much larger than that of the EWM and the improved method, which means that using the AGREE method may lead to a higher reliability allocation than others.

3.2.2. Maintainability allocation and prediction

To quantify maintainability and develop the maintenance strategy, the MTTR must first be defined. For a type of offshore wind turbines at the early design phase, no failure data and maintenance records are available. Therefore, maintainability allocation and prediction can only be conducted using design

Table 4: Scoring criteria of the repairable system considering maintainability

Factor	Type	Score	Description
Fault detection and isolation	Automatic	1	Circuitry providing automatic fault isolation
	Semi-automatic	3	Circuitry controlled manually
	Manual inspection	5	Manually inspect using portable test equipment
	Labor	10	Staffs find fault one by one
Accessibility	Very simple	1	No need to remove the cover
	Simple	2	Can remove the cover quickly
	Difficult	4	Need to remove screws before taking off the cover
	Very difficult	8	Need to remove screws with more than two people
Replaceability	Pluggable	1	Pluggable components
	Buckle	2	Replacements are modules with buckles
	Screw	4	Need to remove screws before replacement
	Weld	6	Need to weld during replacement
Adjustability	No adjustments	1	Replace failed units without de-bugging
	Fine adjustments	3	De-bugging using internal adjustment units
	Joint debugging	5	De-bugging with other circuits

parameters.

According to years of the engineering experience of experts, we take the mode of fault detection and isolation, accessibility, replaceability, and adjustability into account for the maintainability allocation of offshore wind turbines. The scoring criteria of the repairable system are given in Table 4. For the MTTR allocation of the repairable system, two points are considered in this paper: (i) Considering the MTBF level of each unit. The higher the MTBF level is, the longer the MTTR will be allocated to the unit, and vice versa; (ii) MTTR indicators are allocated to each unit with considerations of influential factors of the maintainability including fault detection and isolation, accessibility, replaceability, and adjustability.

According to years of the design and engineering experience, all influential factors are scored using the scoring criteria in Table 4. The results of maintenance factor evaluation of repairable systems are obtained in Table 5, where k_{j1}, k_{j2}, k_{j3}, and k_{j4} represent the mode of fault detection and isolation factor, the accessibility factor, the replaceability factor, and the adjustability factor, respectively.

Units' MTTR of the repairable system can be calculated in two conditions [36]: (i) Considering the relative probability of MTTR_i distributed to each unit. The MTTR allocation function can be expressed as follows

$$\overline{M}_{cti} = \frac{k_i \sum_{i=1}^{n} \lambda_i}{\sum_{i=1}^{n} k_i \lambda_i} \cdot \overline{M}_{ct} \tag{18}$$

where $k_i = \sum_{j=1}^{m_i} k_{ij}$ is the maintenance weighting factor of the i^{th} unit, k_{ij} means the j^{th} weighting factor of the i^{th} unit, m_i expresses the number of influential factors of the i^{th} unit. (ii) Considering all maintenance means and units' reliability, units with high failure rates need to be repaired quickly [37]. The MTTR

Table 5: Maintenance factor evaluation of the repairable system

Symbol	Name	Maintenance factors			
		k_{j1}	k_{j2}	k_{j3}	k_{j4}
y_1	Low-voltage switch cabinet	5	2	4	3
y_2	Tower control cabinet	5	1	4	5
y_3	Auxiliary transformer	5	8	4	3
y_4	Nacelle control cabinet	5	2	4	5
y_5	Pitch control cabinet	5	8	2	5
y_6	Pitch motor	5	8	4	5
y_7	Slip ring	5	4	4	5
y_8	Yaw motor	5	8	4	3
y_9	Frequency converter	5	4	4	5
y_{10}	Main switch cabinet	5	2	4	3
y_{11}	Power cable	10	8	4	1
y_{12}	Control cable	10	2	2	1
y_{13}	Sensor	3	2	4	3
y_{14}	Yawing driven	10	8	4	3
y_{15}	Pitch driven	10	8	4	3
y_{16}	Coupling	10	8	4	3
y_{17}	Elastic unit	10	8	4	3
y_{18}	Lubrication system	5	4	4	1
y_{19}	Cooling system	5	8	4	3
y_{20}	Hydraulic system	10	8	4	3
y_{21}	high-speed shaft brake	1	2	4	1

allocation function can be expressed as follows

$$\overline{M}_{cti} = \frac{K_i \cdot \overline{\lambda}}{\overline{K}\lambda_i} \cdot \overline{M}_{ct} \tag{19}$$

where $\overline{K} = \frac{\sum_{i=1}^{n} K_i}{n}$ is the mean of all weighting factors, K_i means the maintenance weighting factor of the ith unit.

Fig. 8 presents the results of the maintainability prediction of the repairable system using two methods. From this figure, we can see that the results obtained by Method one are very different to that of Method two. Compared with Method one, MTTRs allocated to each unit using Method two are very different. According to the engineering experience, the results of reliability allocation and predication calculated by Method one are closer to reality, which is therefore accepted and used in fuzzy reliability evaluation.

3.2.3. Fuzzy reliability evaluation

To obtain a realistic reliability evaluation of offshore wind turbines, we treat MTBF, MTTR, the number of shutdown and availability of each unit as evaluation indicators. Therefore, the evaluation indicator matrix is expressed as T=[MTBF, MTTR, N, A], where N is the number of the shutdown, and A means the unit's availability. According to the operation data of same level wind turbines and engineering experience, the

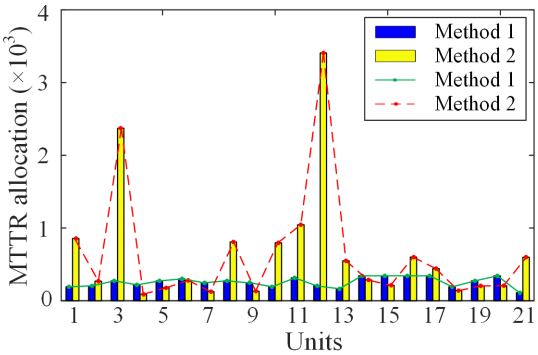


Figure 8: Maintainability allocation and predication of the repairable system

reliability levels of units can be categorized into five classes: very low (V_{vl}), low (V_l), normal (V_n), high (V_h) and very high (V_{vh}). The threshold values of each indicator of different reliability levels are determined based on the actual operational experience and the reliability data of wind turbines. The threshold values of each indicator at different reliability levels are shown in Table 6.

Table 6: Threshold values of each indicator at different reliability level

Class	MTBF/h	MTTR/h	N/year	A/%
very low	62000	340	0.143	0.996
low	692000	280	0.108	0.9969
normal	1322000	220	0.073	0.9978
high	1952000	160	0.038	0.9987
very high	2582000	100	0.003	0.9996

The evaluation set of the k^{th} unit can be obtained from Eq. (9)

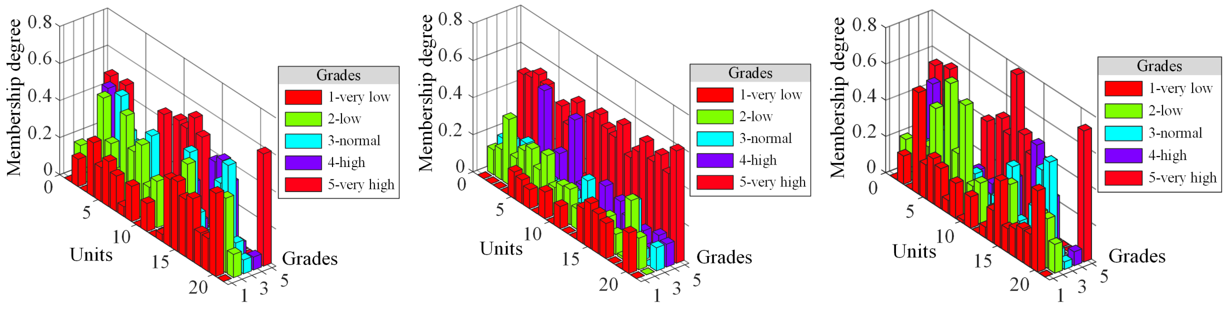
$$\mathrm{R}_k = \begin{array}{c} \text{indicator} \\ MTBF \\ MTTR \\ N \\ A \end{array} \begin{array}{c} \begin{array}{ccccc} V_{vl} & V_l & V_n & V_h & V_{vh} \end{array} \\ \begin{bmatrix} \tilde{p}_{1,1} & \tilde{p}_{1,2} & \tilde{p}_{1,3} & \tilde{p}_{1,4} & \tilde{p}_{1,5} \\ \tilde{p}_{2,1} & \tilde{p}_{2,2} & \tilde{p}_{2,3} & \tilde{p}_{2,4} & \tilde{p}_{2,5} \\ \tilde{p}_{3,1} & \tilde{p}_{3,2} & \tilde{p}_{3,3} & \tilde{p}_{3,4} & \tilde{p}_{3,5} \\ \tilde{p}_{4,1} & \tilde{p}_{4,2} & \tilde{p}_{4,3} & \tilde{p}_{4,4} & \tilde{p}_{4,5} \end{bmatrix} \end{array} \tag{20}$$

The compound weight matrix W can be obtained using Eq. (7). Following this, the reliability evaluation matrix T of an offshore wind turbine can be obtained from Eqs. (11), (12) and (20). The reliability evaluation matrix T is presented in Table 7. The reliability level of each unit can be determined by the maximum membership principle. For the reliability allocation index of the repairable system calculated by the EWM and AGREE method, the reliability evaluation matrix can be obtained in the same way. Fig. 9 shows the reliability levels of repairable units of offshore wind turbines obtained by different allocation methods. As it is shown in Fig. 9b, most units' reliability levels obtained by the AGREE method are the highest than that of units obtained by the EWM and improved method. The classes of most units' reliability levels are 'very high', which are too generous. On the contrary, some results obtained the EWM shown in Fig. 9a are conservative that some units' reliability levels are underestimated, such as the nacelle control cabinet (y_4), the pitch control cabinet (y_5), the pitch motor (y_6) and the yawing driven (y_{14}). This is because the EWM can not take time characteristics into consideration. According to experts' experience and reliability requirements, results of reliability allocation of units obtained by the improved method presented in Fig. 9c are accepted and adopted for the next stage of the reliability design.

Table 7: Reliability evaluation matrix of offshore wind turbine

Unit	V_{vl}	V_l	V_n	V_h	V_{vh}	Class
y_1	0.0013	0.1987	0.1074	0.1482	0.5444	very high
y_2	0.1554	0.0446	0.1832	0.4905	0.1264	high
y_3	0	0.1936	0.2064	0.0218	0.5782	very high
y_4	0.5597	0.2403	0.1990	0.0010	0	very low
y_5	0.1872	0.4777	0.3351	0	0	low
y_6	0.2482	0.1518	0.5027	0.0973	0	normal
y_7	0.2207	0.6698	0.1095	0	0	low
y_8	0.0719	0.3101	0.0180	0.1747	0.4253	very high
y_9	0.1930	0.6031	0.2039	0	0	low
y_{10}	0.0168	0.1832	0.1074	0.1538	0.4947	very high
y_{11}	0.1722	0.2278	0	0.1672	0.4328	very high
y_{12}	0	0	0.1532	0.0557	0.7911	very high
y_{13}	0.0593	0.1407	0.0159	0.2660	0.4852	very high
y_{14}	0.1783	0.2114	0.3773	0.0331	0.4000	very high
y_{15}	0.3677	0.3277	0.1045	0	0.4000	very high
y_{16}	0.1311	0.0689	0	0.5306	0.0694	high
y_{17}	0.1573	0.0427	0.2346	0.3654	0	high
y_{18}	0.1849	0.0552	0.4686	0.2913	0	normal
y_{19}	0.1827	0.2796	0.5377	0	0	normal
y_{20}	0.4483	0.2733	0.0784	0	0	very low
y_{21}	0	0.1587	0.0413	0.0766	0.7234	very high

The results of Fig. 9c show that the reliability levels of the nacelle control cabinet and the hydraulic system are very low, and the reliability levels of the pitch control cabinet, the slip ring, and the frequency converter are low. In engineering practice, the redundancy design is widely used to greatly improve the reliability level of units. We therefore adopt the redundancy design to improve the reliability of the hydraulic system and the frequency converter. It means that the hydraulic system and the frequency converter need to be allocated one more unit to keep them working smoothly. However, the nacelle control cabinet, the pitch control cabinet and the slip ring are not suitable for the redundancy design, and their reliability can only be improved by the high-quality manufacturing. Meanwhile, preventive maintenance is also adopted



(a) The engineering weighted method (b) AGREE method (c) The improved method

Figure 9: Units' reliability level of the repairable system obtained by different methods

to improve the availability and reliability of the units with the low-reliability levels.

4. Reliability analysis of offshore wind turbines

4.1. Calculation of failures rates

For an offshore wind turbine at the early design stage, no failure data is available in reality. To obtain the failure rate of each unit, we therefore transform units' MTBF into the distribution parameters. In engineering practice, we assume that the lifetime of mechanical units follows a Weibull distribution, and the lifetime of electronic units follows an Exponential distribution [38, 39].

For a Weibull distribution $w(\lambda, \gamma)$ with the scale parameter λ and shape parameter γ, the pdf of the Weibull distribution is

$$f(t) = \lambda\gamma(\lambda t)^{\gamma-1} \cdot e^{-(\lambda t)^{\gamma}}, \quad t > 0 \tag{21}$$

The rth moment $E(T^r)$ of the distribution is[40]:

$$E(T^r) = \frac{\Gamma(1 + \frac{r}{\gamma})}{\lambda^r} \tag{22}$$

where $E(T^r) = \text{MTBF}$,

$$\Gamma(k) = \int_0^{\infty} u^{k-1} e^{-u} du \tag{23}$$

is the gamma function, $k = 1 + \frac{r}{\gamma} > 0$.

For a lifetime distribution function following an Exponential distribution with the failure rate λ, the MTBF is defined as the expected value of the lifetime before a failure occurs, that is, $MTBF = \int_0^\infty e^{-\lambda \cdot t} dt = \frac{1}{\lambda}$. Therefore, the failure rate of the i^{th} unit is

$$\lambda_i = \frac{1}{MTBF_i} \tag{24}$$

Assuming a load-sharing system with n_t units, the failure rate of ith unit of the load-sharing system at time t can be calculated by

$$\lambda_i(t) = \frac{\lambda_s}{n_t} + \lambda_i \tag{25}$$

where n_t is the number of functioning components in load-sharing at time t, λ_s is the total failure rate related to the load that can be shared, λ_i is the further failure rate applying to component i.

According to the improved method above, the parameters of Weibull distribution and Exponential distribution of each unit can be obtained from Eqs. (22)-(24).

4.2. System reliability analysis

Reliability function of the ith unit that whose lifetime follows a Weibull distribution is $R_i^M(t) = e^{-(\lambda_i t)^{\beta_i}}$. For the electronic units that whose lifetime follows an exponential distribution, the reliability function of the jth unit can be expressed as $R_j^M(t) = e^{-\lambda_j t}$.

An offshore wind turbine system can be treated as a series-parallel connection system. The system reliability of offshore wind turbines is the product of the reliability of the non-repairable system and the reliability of the repairable system, which can be calculated by

$$R_{sys}^M(t) = R_{nrs}^M(t) \cdot R_{rs}^M(t) \tag{26}$$

where $R_{sys}^M(t)$ is the system reliability using the reliability allocation method M (M=EWM, AGREE and the improved method), $R_{nrs}^M(t)$ means the reliability of the non-repairable system, and $R_{rs}^M(t)$ represents the reliability of the repairable system.

According to the minimal cut set of the fault tree of the system, the reliability function of the non-repairable system and the repairable system can be derived as follows

$$R_{nrs}^{M}(t) = \prod_{i=1}^{N=12} R_{x_i}^{M}(t) \tag{27}$$

$$R_{rs}^{M}(t) = \prod_{i=1}^{N_1=8} R_{y_i}^{M}(t) \cdot R_{y_9}^{M,LS}(t) \cdot \prod_{j=10}^{N_2=19} R_{y_j}^{M}(t) \cdot R_{y_{20}}^{M,LS}(t) \cdot R_{y_{21}}^{M}(t) \tag{28}$$

where $R_{y_i}^{M,LS}(t)$ represents the reliability of the unit y_i using reliability allocation method M with consideration of the load-sharing at time t. The formulas of $R_{y_9}^{M,LS}(t)$ and $R_{y_{20}}^{M,LS}(t)$ can be derived from Eqs. (14) and (15)

$$R_{y_9}^{M,LS}(t) = e^{-(\lambda_9+\tilde{\lambda}_9)t} + \lambda_9 \int_0^t e^{-(\lambda_9+\tilde{\lambda}_9)\mu-\tilde{\lambda}'_9(t-\mu)} d\mu + \tilde{\lambda}_9 \int_0^t e^{-(\lambda_9+\tilde{\lambda}_9)\nu-\lambda'_9(t-\nu)} d\nu \tag{29}$$

$$\begin{aligned} R_{y_{20}}^{M,LS}(t) \quad = \quad & e^{-(\tilde{\lambda}_{20}\cdot t)^{\tilde{\gamma}_{20}}} e^{-(\lambda_{20}\cdot t)^{\gamma_{20}}} + \tilde{\gamma}_{20}\tilde{\lambda}_{20}^{\tilde{\gamma}_{20}} \int_0^t \mu^{\tilde{\gamma}_{20}-1} e^{-\left\{\left[\lambda'_{20}(t-\mu)\right]^{\gamma'_{20}}+(\tilde{\lambda}_{20}\mu)^{\tilde{\gamma}_{20}}\right\}} d\mu \\ & +\gamma_{20}\lambda_{20}^{\gamma_{20}} \int_0^t \nu^{\gamma_{20}-1} e^{-\left\{\left[\tilde{\lambda}'_{20}(t-\nu)\right]^{\tilde{\gamma}'_{20}}+(\lambda_{20}\nu)^{\gamma_{20}}\right\}} d\nu \end{aligned} \tag{30}$$

where λ_i and $\tilde{\lambda}_i$ represent the distribution parameters of the original unit and the redundant unit taking the sharing-load, respectively; λ'_i and $\tilde{\lambda}'_i$ means the distribution parameters of the original unit and the redundant unit taking the full load, respectively.

According to the results of the reliability allocation of the non-repairable system, the reliability of the non-repairable system is $R_{sys}^{test}(T) = \prod_{i=1}^{12} R_{x_i}^{M}(T) \geq 0.95$, which means that the reliability allocation of the non-repairable system meets the design requirements. For the repairable system, the units' reliability is allocated using three methods. To verify the results of reliability allocation, we perform the fuzzy reliability evaluation to rank the reliability levels of each unit of the repairable system. From Fig. 9c and Table 7, we can see that the reliability levels of the nacelle control cabinet, pitch control cabinet, the slip ring, the frequency converter, and the hydraulic system are relatively low, especially nacelle control cabinet and the hydraulic system. In engineering practice, the redundancy design is widely used to improve the units with low-reliability level, which is suitable for the frequency converter and the hydraulic system. Therefore, the frequency converter and the hydraulic system are treated as two redundancy systems in the reliability analysis of the system of the offshore wind turbine.

To realistically reflect the changes in the failure rates of redundant units, we propose the load-sharing to analyze the reliability of the redundancy system in this paper. For newly developed offshore wind turbines at the early design stage, we can not obtain the failure data and operating data from wind farms. Due to this reason, we use the results of reliability allocation to conduct the reliability analysis. MTBF of each unit can be transformed into the failure rate by the improved method in Section 4.1 considering the load-sharing properties.

Fig. 10 provides the system reliability of offshore wind turbine obtained from different modeled scenarios. The results show that the load-sharing based reliability model can get the largest value of the system reliability, and the reliability values of the parallel system and the non-redundant system are second and third. The graphs in Fig. 10 indicate that the reliability of the redundancy system treated as the load-sharing system and the parallel system is greater than that of the non-redundant system. Therefore, we can conclude that the redundancy design of the frequency converter and the hydraulic system can significantly improve system reliability. A comparison of the system reliability in different modeled scenarios reveals that the units with low-reliability levels have a large impact on system reliability. Improving low-reliability units can improve system availability and decrease the failure frequency of the system.

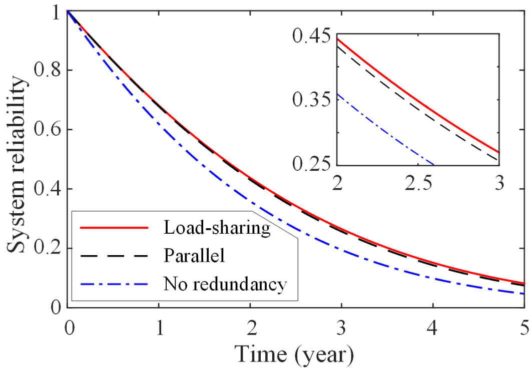


Figure 10: Comparison of system reliability during each modeled scenario

The reliability analysis of the overall system using three different methods is performed in this paper. Fig. 11 presents the reliability of the offshore wind turbine under different allocation methods. The results of Fig. 11 show that the system reliability obtained by AGREE is much higher than that of EWM and the improved method. AGREE method only takes the importance factor into account, which leads to the overestimation of the system reliability. From Fig. 7, we can see that the units' MTBF obtained by AGREE is much greater than that calculated by the EWM and the improved method, which means that the AGREE method is a risk-taking approach. The system reliability obtained by the improved method is a little smaller than that calculated by EWM because the improved method considers more influential factors than EWM and the mission time of units. Moreover, the improved method of reliability allocation is developed based on the EWM, for which the system reliability obtained by the improved method is close to that of EWM at time *t*.

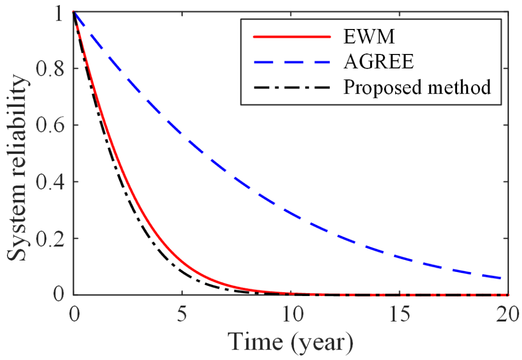


Figure 11: System reliability of offshore wind turbine under different allocation methods

5. Conclusions

The reliability design is difficult to be performed without the failure rates and the operation data using traditional methods in the early design stage of a new wind turbine. In this paper, we propose reliability allocation schemes for both the non-repairable system and the repairable system with considerations of main influencing factors. Following this, we conduct the reliability allocation and predication of the repairable system based on the scores obtained by each unit. It is crucial that the maintainability information can be used in the fuzzy evaluation of the reliability level, and also can contribute to developing the maintenance strategy.

To verify the results of the units' reliability allocation, we propose the fuzzy evaluation method of the reliability that is based on the compound weights and the fuzzy triangular membership function. We consider the MTBF, MTTR, number of failures per year and availability in the matrix of evaluation indexes. The results of fuzzy reliability evaluation show that the reliability of the nacelle control cabinet, pitch control cabinet, slip ring, frequency converter, and the hydraulic system needs to be improved, especially the nacelle control cabinet and the hydraulic system. Following this, according to the reliability level of each unit, the redundancy design is adopted to improve the reliability of units with low-reliability levels. To realistically reflect the function of redundant units, we implement the load-sharing redundancy that was introduced by Li and Coolen [33] in this study. The results of Fig. 10 indicate that the redundancy design of units with low reliability can significantly improve system reliability. Therefore, operators of wind farms should pay more attention to units with low reliability, especially frequency converters and hydraulic systems. In addition, the reliability of redundant systems is underestimated if it is treated as parallel systems, which will increase the manufacturing cost.

The time-dependent reliability analysis of the offshore wind turbine is also performed. The results show that the reliability allocation approach proposed in this paper is conservative, which can help obtain the most secure reliability allocation scheme. The practical reliability design method proposed in this paper can be easily applied to reasonably allocate the reliability of each unit, whose effectiveness and feasibility are proved in engineering practice.

In the future, the research will focus on developing the maintenance strategy of offshore wind turbines based on the MTBF of each unit at the early design stage.

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Declaration of competing interest

We declare that we do have no commercial or associative interests that represent a conflict of interests in connection with this manuscript. There are no professional or other personal interests that can inappropriately influence our submitted work.

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