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Reliability analysis of wind turbine with feed-forward structure based on GO-FLOW method

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Abstract

Considering the multi-state characteristics, shared signals and dynamic change (time sequence), a reliability analysis method for a wind turbine (WT) with feed-forward structure based on GO-FLOW is proposed. Firstly, a GO-FLOW reliability model is constructed based on the schematic diagram of the WT with feed-forward structure. Secondly, considering the multi-state characteristics of WT components and shared signals, the output signal flows of the WT system with time sequence are obtained based on the historical fault data and the GO-FLOW arithmetic rules, and the influence of the shared signal modification on the system reliability is also studied. The results are compared and verified with those obtained by the GO method for verification. Finally, the exponential fitting method is applied to derive the variation rule of WT system reliability with time sequence. The research results show that a reliability analysis method of WT with feed-forward structure proposed in our study is effective. Only one calculation is required to obtain the output signal flows of each state of the system at all time points, which can effectively analyze the change rule of the system reliability with the time sequence. The proposed method can provide important reference for the risk assessment of WT operation.

Keywords: wind turbine, GO-FLOW method, GO method, shared signal, reliability analysis

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1. Introduction

With the in-depth implementation of strategic policies, such as the Paris Agreement and carbon peaking and carbon neutrality goals, the global energy system is accelerating its transition to low-carbon and zero-carbon [1, 2]. A high requirement for the development of renewable energy has been put forward. As deep-sea exploration advances and extreme land resources are utilized efficiently, wind turbines (WTs) have been widely deployed in oceans, deserts and swamps [3]. As an important carrier of renewable energy implementation, the reliability of WTs is a major concern for developers and users [4].

Scholars at home and abroad have achieved many results in WT reliability. Perez *et al* [5] compared the failure rate and downtime of different configurations for WT in actual operation. Wang *et al* [6] analyzed the WT reliability based on the Gibbs and layered Bayesian algorithm. Slot *et al* [7] solved the problem of uncertainty quantification in WT reliability assessment based on polynomial chaos expansion and Kriging method. Arabian *et al* [8] proposed a reliability analysis method of WT based on Markov frequency balance.

The above results mainly focus on the study of WT static (a specific moment) reliability from multiple perspectives. But WT is a complex mechatronic-hydraulic integrated system with multi-state (advance state, success state and failure state), shared signal, and dynamic change (time sequence). How to analyze the reliability of WT comprehensively considering multi-state, shared signal and dynamic change (time sequence) still need further research.

The GO-FLOW method is a success-oriented, graph-deductive system reliability analysis method [9], and has been applied in many fields. For instance, Zhang *et al* [10] proposed an improved GO-FLOW method to solve the problem of inaccurate reliability assessment caused by the performance degradation of nuclear power equipment. Fan *et al* [11] investigated the reliability of nuclear power plant electrical system by the improved GO-FLOW method. Lan *et al* [12] introduced Boolean algebra into the GO-FLOW model to study the reliability of the aircraft electrostatic-hydraulic actuator. Li *et al* [13] proposed an improved fuzzy GO-FLOW method to solve the uncertainty in the reliability analysis of on-board system. Wei *et al* [14] conducted a reliability risk assessment of aviation cold chain logistic system based on GO-FLOW method. Li *et al* [15] predicted the reliability of energy storage system based on GO-FLOW method. The application of the GO-FLOW method to study WT reliability has not yet been seen, but the above literature can provide a useful reference for the study of WT reliability.

Based on the above analysis, a reliability analysis method for WT with feed-forward structure based on GO-FLOW is proposed considering multi-state, shared signal and dynamic change (time sequence). The main content and innovations of our study are as follows:

(1) A reliability analysis method for WT with feed-forward structure based on GO-FLOW is proposed;

(2) Considering multi-state of WT component and shared signal, the output signal flows of WT system with time sequence are obtained based on the historical fault data and the GO-FLOW arithmetic rules, and the influence of the shared signal modification on the system reliability is also researched.

(3) The research results obtained by the GO-FLOW method are compared and verified with the results obtained by the GO method.

This paper is organized as follows: in section 2, the principal analysis of WT system with the feed forward structure is presented. In section 3, WT reliability analysis based on GO-FLOW method is proposed in which WT reliability model is established and the system reliability of the modified shared signal is obtained. In section 4, GO method is introduced to analyze the reliability of WT system to verify the validity of GO-FLOW method. Dynamic change (time sequence) analysis of system reliability is elaborated in section 5. In section 6, conclusions are given.

2. WT system principle analysis

The WT is a complex electromechanical-hydraulic integrated system, which can be classified into various types according to the rated power, transmission mechanism, and generator type. The research object of our study is the mainstream equipment for wind farms, namely, a large horizontal-axis doubly-fed asynchronous WT, and its system usually consists of blades, hubs, low-speed shafts (including mechanical brakes), pitch mechanism, gearbox (speed booster), high-speed shafts (including mechanical brakes), yawing systems, generators, converters, etc [16] as shown in figure 1.

The corresponding working principle is as follows: the wind blows to the wind wheel at a certain speed, and the resulting torque drives the wind wheel to rotate and converts wind energy into mechanical energy. The wind wheel hub is fixed on the main shaft of the WT, and the mechanical energy is converted into the electrical energy through the gearing system and the generator system. In addition, WTs are equipped with a feed forward structure. On the one hand, the variable pitch control system measures wind speed in real time through its internal wind speed sensors and regulates the pitch angle accordingly, fulfilling the functions of power control, load optimization, and safety protection for wind power generation. On the other hand, the yaw system detects wind direction in real time via its internal direction sensors, aligning the rotor to face the main wind direction to maximize wind energy capture. Finally, the electrical energy is transmitted to the grid system through an inverter.

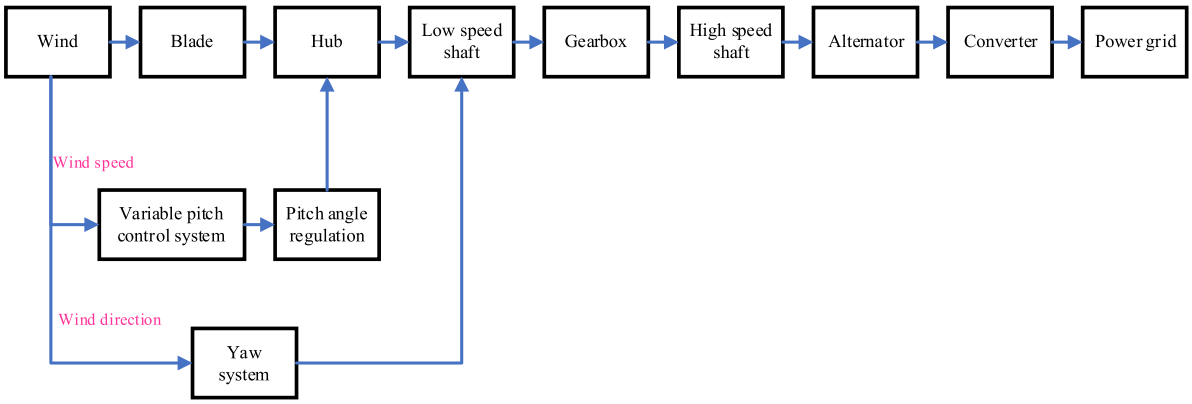


Figure 1. Schematic diagram of WT system with feed-forward structure.

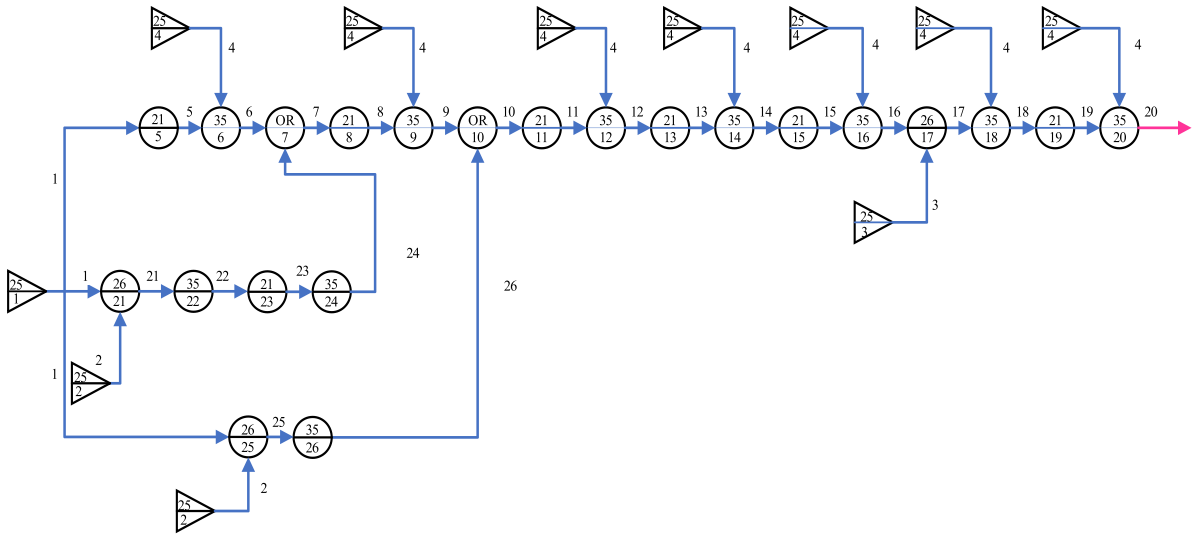


Figure 2. GO-FLOW reliability model for wind turbine with feed-forward structure.

3. Reliability analysis of WT with feed-forward structure based on GO-FLOW method

3.1. Reliability model of WT with feed-forward structure based on GO-FLOW method

In reliability analysis, the GO-FLOW model consists of operators and signal flows, and more details of GO-FLOW can be found in [17]. In our study, the GO-FLOW reliability model of WT is constructed according to the WT system principle analysis and figure 1, as shown in figure 2.

In figure 2, there are 26 operators and 26 signal flows in which the operators represent components and signal flows represent inputs and outputs of the WT system with feed-forward structure.

In WT system, the power signal, control command signal, and motor operation signal can be represented by the operator 25 signal generators. And the corresponding serial numbers are 1, 2, and 3, respectively. The time interval signal of operator 35 can be represented by operator 25, and the corresponding serial number is 4.

Blade, hub, low-speed shaft, gearbox, and high-speed shaft, converter are assumed as two states, namely, success or failure states. They can be represented by operator 21. Component failures over time can also be represented by operator 35. Consequently, function and failure characteristics of blade, hub, low-speed shaft, gearbox, and high-speed shaft, converter can be described by using operator 21 and operator 35. Their corresponding serial numbers can be seen table 1 and figure 2.

Generator, yaw system, and pitch control system are components that operate with excitation. But they may start in advance due to short circuits and other reasons. Consequently, they have not only success or failure states, but also an advance state, which can be represented by operator 26. The failure of their components over time can be represented by operator 35. Consequently, function and failure characteristics of generator, yaw system, and pitch control system can be described by using operator 26 and operator 35. Their corresponding serial numbers can be seen in table 1 and figure 2.

Branch signal flows 6 and 24 are connected by operator 22 to obtain signal flow 7, and signal flows 9 and 26 are connected by operator 22 to obtain signal flow 10. As can be seen

Table 1. GO-FLOW operators and their corresponding parameters.

Serial number	Type	Parameters	Meaning
1	25	$R(1) = 0, R(t) = 1(t \neq 1)$	Power signal
2	25	$R(2) = 0, R(t) = 1(t \neq 1)$	Control command signal
3	25	$R(3) = 1, R(4) = 1, R(t) = 0(t \neq 3, t \neq 4)$	Motor operation signal
4	25	$R(4) = 500\ h, R(t) = 1(t \neq 4)$	Time interval signal
5,6	21, 35	$P_{g5} = 0.9929654, \lambda_6 = 2.698 \times 10\ h$	Blade
7,10	22	—	Or gateway
8,9	21,35	$P_{g8} = 0.999\ 33\ 57, \lambda_9 = 2.664 \times 10\ h$	Wheel
11,12	21,35	$P_{g11} = 0.994\ 55\ 19, \lambda_{12} = 8.7139 \times 10\ h$	Low speed shaft
13,14	21,35	$P_{g13} = 0.999\ 27\ 55, \lambda_{14} = 1.2938 \times 10\ h$	Gearbox
15,16	21,35	$P_{g15} = 0.994\ 55\ 19, \lambda_{16} = 8.7139 \times 10\ h$	High speed shaft
17,18	26,35	$P_{p17} = 0.000\ 01\ 20, P_{g17} = 0.996\ 28\ 89, \lambda_{18} = 1.4840 \times 10\ h$	Generator
19,20	21,35	$P_{g19} = 0.998\ 85\ 93, \lambda_{20} = 4.0068 \times 10\ h$	Converter
21,22	26,35	$P_{p21} = 0.000\ 00\ 11, P_{g21} = 0.999\ 94\ 67$	Variable pitch control system
23,24	21,35	$P_{g23} = 0.999\ 79\ 89$	Pitch adjustment
25,26	26,35	$P_{p25} = 0.000\ 00\ 10, P_{g25} = 0.999\ 45\ 95$	Yaw system

Table 2. Definition of time points.

Point in time	Meaning of representation
Time point 1	WT system is in initial time point, and this has no action in the shutdown state.
Time point 2	The wind enters the wind turbine and the drive blades begin to rotate.
Time point 3	The generator and system start working.
Time point 4	500 h after time point 3.

in figure 2, signal flow 20 is the final output signal of the WT system, which represents the WT system reliability.

The data in our study are sourced from [5, 18] and German wind farm data in Windstats Newsletter, as shown in table 1. And the time-to-failure of each wind-turbine component is assumed to follow an exponential distribution with a constant hazard rate λ [19, 20].

In table 1, $R(t)$ is the output signal of the operator at time *t;* P_p, P_g and λ are the probability of advance state, success state, and failure state of the WT system component, respectively.

In table 1, $R(t)$ is the output signal of the operator at time *t;* P_p, P_g and λ are the probability of advance state, success state, and failure state of the WT system component, respectively.

To study the WT reliability analysis with time sequence (dynamic change), four working time points of WT are defined based on the GO-FLOW method, as shown in table 2.

3.2. GO-FLOW arithmetic operation

In the GO-FLOW diagram, if a signal is connected to two or more operators as its input signals, the signal is defined as the shared signal [21–23]. In order to make reliability analysis result more accurate, the probability expression of each state containing the shared signal is expanded, and the high-order term of the shared signal is modified to linear term, when using probability formula algorithm. And the modified state probability expression represents the modified state probabilities [17, 24].

According to figure 2, signal 1 is the shared signal. Taking the signal 7 and signal 10 as examples, the necessity of signal modification can be illustrated by the equations (2) and (5). And $I_i(t)$ and $R_i(t)$ represent the signal strength of signal i and the output signal of the operator of signal i at time point t, respectively. The strength of the output signal at each time point characterizes the reliability of WT system.

(1) Signal flow 7

From figure 2, it can be seen that both signal 6 and signal 24 contain signal 1, which is the shared signal and needs to be modified, as shown in equation (1). The modified expression of $R_7(t)$ is shown in equation (2),

$$\begin{aligned} R_6(t) &= R_1(t) P_{g5} P_{\lambda 6}(t) \\ R_{24}(t) &= R_1(t) P_{g24} R_{21}(t) \\ R_7(t) &= R_6(t) + R_{24}(t) - R_6(t) R_{24}(t) \\ R_7(t) &= R_1(t) \left[P_{g5} P_{\lambda 6}(t) + P_{g24} R_{21}(t) \right. \\ &\quad \left. - R_1(t) P_{g24} R_{21}(t) P_{g5} P_{\lambda 6}(t) \right] \end{aligned} \tag{1}$$

$$\begin{aligned} R_7(t) = R_1(t) \Big[& P_{g5} P_{\lambda 6}(t) + P_{g24} R_{21}(t) \\ & - P_{g24} R_{21}(t) P_{g5} P_{\lambda 6}(t) \Big] \end{aligned} \tag{2}$$

(2) Signal flow 10

From figure 2, it can be seen that both signal 9 and signal 26 contain the signal 1, as shown in equation (3). When calculating signal 10, signal 1 is the shared signal and needs to be modified, as shown in equation (4), and the modified expression is as shown in equation (5),

Table 3. Calculation results of signal flows 7 and 10.

	Intensity at each point in time			
Signal flow number	1	2	3	4
7 (unmodified)	0.0	1.0	1.0	1.0
7 (modified)	0.0	0.999 99 82	0.999 99 86	0.999 99 59
10 (unmodified)	0.0	0.9999999	1.0	1.0
10 (modified)	0.0	0.999 99 96	0.999 99 98	0.999 99 99

$$\begin{aligned} R_9(t) &= R_7(t) P_{g8} P_{\lambda 9}(t) \\ R_{26}(t) &= R_1(t) P_{26}(t) \\ R_{10}(t) &= R_9(t) + R_{26}(t) - R_9(t) R_{26}(t) \end{aligned} \tag{3}$$

$$\begin{aligned} R_{10}(t) = {} & R_1(t) P_{g8} P_{\lambda 9}(t) \left[P_{g5} P_{\lambda 6}(t) + P_{g22} R_{21}(t) \right. \\ & \left. - P_{g22} R_{21}(t) P_{g5} P_{\lambda 6}(t)\right] + R_1(t) P_{26}(t) \\ & - R_1(t)^2 P_{g8} P_{\lambda 9}(t) P_{26}(t) \left[P_{g5} P_{\lambda 6}(t) \right. \\ & \left. + P_{g22} R_{21}(t) - P_{g22} R_{21}(t) P_{g5} P_{\lambda 6}(t)\right] \end{aligned} \tag{4}$$

$$\begin{aligned} R_{10}(t) = {} & R_1(t) \left\{P_{g8} P_{\lambda 9}(t) \left[P_{g5} P_{\lambda 6}(t) + P_{g22} R_{21}(t) \right. \right. \\ & \left. - P_{g22} R_{21}(t) P_{g5} P_{\lambda 6}(t)\right] + P_{26}(t) \\ & - P_{g8} P_{\lambda 9}(t) P_{26}(t) \left[P_{g5} P_{\lambda 6}(t) + P_{g22} R_{21}(t) \right. \\ & \left. \left. - P_{g22} R_{21}(t) P_{g5} P_{\lambda 6}(t)\right]\right\}. \end{aligned} \tag{5}$$

The calculation results of the modified signal flows 7 and 10 are shown in table 3. To determine the impact of shared signal at each point in time for signal flows 7 and 10, the calculation results of unmodified signal flows 7 and 10 are also obtained as shown in table 3.

(3) Signal flow 26

$$\begin{aligned} O(1) &= P_{p25} = 0.0000010 \\ I_{26}(1) &= I_1(1) \cdot O(1) = 0.0 \\ O(2) &= O(1) + [1 - O(1)] \cdot I_2(2) \cdot P_{g25} = 0.9994595 \\ I_{26}(2) &= I_1(2) \cdot O(2) = 0.9994595 \\ O(3) &= O(2) + [1 - O(2)] \cdot I_2(3) \cdot P_{g25} = 0.9999997 \\ I_{26}(3) &= I_1(3) \cdot O(3) = 0.9999997 \\ O(4) &= O(3) + [1 - O(3)] \cdot I_2(4) \cdot P_{g25} = 1.0 \\ I_{26}(4) &= I_1(4) \cdot O(4) = 1.0. \end{aligned} \tag{6}$$

(4) Signal flow 19

$$\begin{aligned} I_{19}(t) &= I_{18}(t) \cdot P_{g19} \\ I_{19}(1) &= 0.0 \\ I_{19}(2) &= 0.0000118 \\ I_{19}(3) &= 0.9836265 \\ I_{19}(4) &= 0.9652108. \end{aligned} \tag{7}$$

(5) Signal flow 20

$$I_{20}(t) = I_{19}(t) \cdot \exp\left\{-\lambda \cdot \sum_{k \leqslant t} I_4(k) \cdot \min\left[1.0, I_{19}(k)/I_{19}(t)\right]\right\}. \tag{8}$$

From table 1, it can be seen that $I_4(1) = I_4(2) = I_4(3) = 0.0$ in equation (8).

$$\begin{aligned} I_{20}(1) &= I_{19}(1) = 0.0 \\ I_{20}(2) &= I_{19}(2) = 0.0000118 \\ I_{20}(3) &= I_{19}(3) = 0.9836265. \end{aligned} \tag{9}$$

When $I_4(4) = 500$ h, it is obtained:

$$I_{20}(4) = I_{19}(4) \cdot \exp\left\{-\lambda \cdot I_4(4) \cdot \min\left[1.0, I_{19}(4)/I_{19}(4)\right]\right\}. \tag{10}$$

To investigate the effect of shared signal on the system reliability, the system reliability without considering and disregarding shared signal modification with time sequence are solved, respectively, and the results are shown in table 4.

In table 4, the system reliabilities with and without shared signal modification are both 0.0 at time point 1 and 0.000 01 18 at time point 2, respectively. The system reliability of unmodified shared signal is 0.984 59 67, 0.098 64% higher than the system reliability of modified shared signal at time point 3. At time point 4, the system reliability of unmodified shared signal is 0.949 03 47, 0.3138% higher than the system reliability of modified shared signal. The obtained signal flow strength of the system is shown in table 5.

According to figure 2 and table 5, signal flow 20 represents the reliability of the WT system. And the system reliabilities of WT system are 0.9836265 and 0.9460662 at time point 3 and at time point 4, respectively.

4. Comparison with the GO method

To verify the validity of the GO-FLOW method, the GO method is introduced to analyze the reliability of WT with feed-forward structure. The specific modeling method can be found in [17, 25]. The GO reliability model of WT system is established, as shown in figure 3.

In GO reliability modeling, the WT system is considered to have three states, where 0 represents the advance state, 1 represents the success state, and 2 represents the failure state. According to table 1 and the GO arithmetic rule, the probability of each state for all output signal flows of the WT system can be obtained, as shown in table 6.

From figure 3, the reliability characteristic of signal flow 12 represents the reliability characteristic of the WT. The state probability of signal flow 12 can be obtained, in which the advance state probability is $P_p = 0.000\,00\,00$, the success state probability is $P = 0.983\,63\,78$, and the failure state probability is $\lambda = 1 - P_p - P = 0.016\,36\,22$.

Analyzing figures 2 and 3, as well as tables 5 and 6, it becomes evident that:

(1) Because the GO method does not take into account the dynamic change in the system reliability over time, the system reliability results obtained by GO method corresponds to the system reliability result at the moment of

Table 4. System reliability with time sequence.

Point in time	The final output signal flow of the WT system	
	Considering shared signals modification	Disregarding shared signals modification
Time point 1	0.0	0.0
Time point 2	0.000 01 18	0.000 01 18
Time point 3	0.983 62 65	0.984 59 67
Time point 4	0.946 06 62	0.949 03 47

Table 5. Calculation results of signal flow of WT system.

Operator		Signal flow		The output signal flow strength at each time point			
Serial number	Type	Input	Output	1	2	3	4
1	25		1	0.0	1.0	1.0	1.0
2	25		2	0.0	1.0	1.0	1.0
3	25		3	0.0	0.0	1.0	1.0
4	25		4	0.0	0.0	0.0	500
5	21	1	5	0	0.992 96 54	0.992 96 54	0.992 96 54
6	35	5,(4)	6	0.0	0.992 96 54	0.992 96 54	0.979 66 02
7	22	6,(22)	7,(1)	0.0	0.999 99 82	0.999 99 86	0.999 99 59
8	21	7	8	0.0	0.999 33 39	0.999 33 43	0.999 33 16
9	35	8(4)	9	0.0	0.999 33 39	0.999 33 43	0.998 00 14
10	22	9, 23	10,(1)	0.0	0.999 99 96	0.999 99 98	0.999 99 99
11	21	10	11	0.0	0.994 55 15	0.994 55 19	0.994 55 19
12	35	11,(4)	12	0.0	0.994 55 15	0.994 55 19	0.990 22 81
13	21	12	13	0.0	0.993 83 10	0.993 83 13	0.989 51 07
14	35	13,(4)	14	0.0	0.993 83 10	0.993 83 13	0.983 13 02
15	21	14	15	0.0	0.988 41 65	0.988 41 69	0.977 77 40
16	35	15,(4)	16	0.0	0.988 41 65	0.988 41 69	0.973 52 32
17	26	16,(3)	17	0.0	0.000 01 19	0.984 74 98	0.973 50 98
18	35	17,(4)	18	0.0	0.000 01 19	0.984 74 98	0.966 31 31
19	21	18	19	0.0	0.000 01 18	0.983 62 65	0.965 21 08
20	35	19,(4)	20	0.0	0.000 01 18	0.983 62 65	0.946 06 62
21	26	1,(2)	21	0.0	0.999 94 67	1.0	1.0
22	21	21	22	0.0	0.999 74 56	0.999 79 89	0.999 79 89
23	26	1,(2)	23	0.0	0.999 45 95	0.999 99 97	1.0

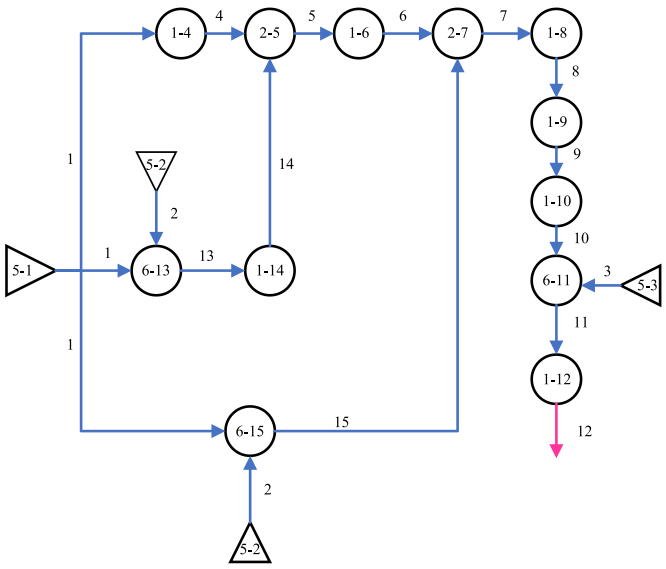


Figure 3. GO reliability model of WT with feed-forward structure.

Table 6. Signal flows calculation results of GO method.

Serial number	Type	Input signal	Output signal	Output signal state probability		
				State 0	State 1	State 2
1,2,3	5		1,2,3	0.0	1.0	0.0
4	1	1	4	0.0	0.992 96 54	7.0346×10^{-3}
5	2	4,14	5	0.0	0.999 99 82	1.8×10^{-6}
6	1	5	6	0.0	0.999 33 39	6.661×10^{-4}
7	2	6,15	7	0.0	0.999 99 96	4×10^{-7}
8	1	7	8	0.0	0.994 55 15	5.4485×10^{-3}
9	1	8	9	0.0	0.993 83 09	6.1691×10^{-3}
10	1	9	10	0.0	0.988 41 64	0.0115836
11	6	10,3	11	0.0	0.984 76 11	0.0152389
12	1	11	12	0.0	0.983 63 78	0.0163622
13	6	1,2	13	0.0	0.999 94 78	5.22×10^{-5}
14	1	13	14	0.0	0.999 74 67	2.533×10^{-4}
15	6	1,2	15	0.0	0.999 46 05	5.395×10^{-4}

the generator and system start working (Time point 3). It can be seen that the research result obtained by GO-FLOW method is only $0.1\%_{00}$ lower than research results obtained by GO method, and both research results are basically the same.

(2) The system reliability obtained by GO method is 3.9713% higher than that obtained by GO-FLOW method at time point 4. The system reliability obtained by GO-FLOW method at time point 3 is 3.9700% higher than that obtained at time point 4. These verify the necessity of dynamic change analysis of system reliability.

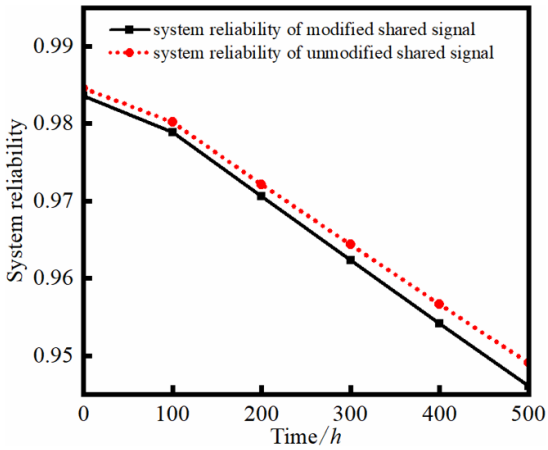


Figure 4. The unmodified and modified system reliability change over time.

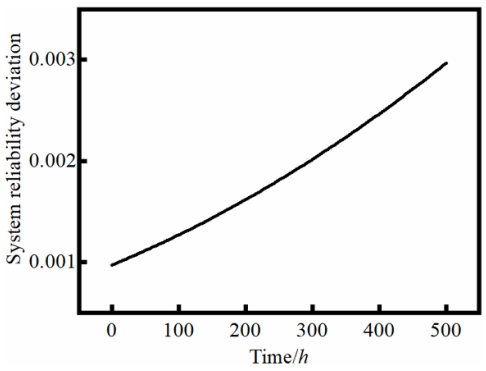


Figure 5. The system reliability deviation caused by unmodified shared signal.

5. Dynamic change (time sequence) analysis of system reliability

To study the influence of the shared signal on the WT reliability, qualitative analysis and quantitative calculation are executed, 4 time points are inserted between time point 3 and time point 4 with the time interval of 100 h, and the unmodified and modified system reliabilities are obtained, respectively, as shown in figure 4. The system reliability deviation caused by unmodified signal is also obtained, as shown in figure 5.

From figures 4 and 5, the differences between the system reliability with unmodified and modified shared signal are 9.702×10^{-4} at time point 3 and 2.9685×10^{-3} at time point 4, respectively. The deviation of system reliability caused by the unmodified shared signal increases over time, showing a nonlinear relationship.

To study the change rule of WT system reliability over time considering the modified shared signal, 4 time points are inserted between time point 3 and time point 4, with a time interval of 100 h. The signal flows at each time point from 0 to 500 h can be calculated. To increase the readability and conciseness of our study, only a few key signal flows are listed, as shown in table 7.

Based on the signal flow results in table 7, the reliability of the WT system can be described by an exponential distribution with a constant hazard rate:

$$R_{\mathrm{sys}}(t) = R_{\mathrm{sys}}(0) \times \exp(-\lambda_{\mathrm{eq}} t)$$

where $R_{\mathrm{sys}}(t)$ is the reliability at operating time t, $R_{\mathrm{sys}}(0)$ is the initial reliability, and λ_{eq} is the equivalent failure rate of the WT system.

Table 7. The output signal flow at each time point of the WT system.

	Signal strength of each operator						
Times(h)	6	7	9	12	14	16	20
0	0.992 96 54	0.999 99 86	0.999 33 43	0.994 55 19	0.993 83 13	0.988 41 68	0.983 62 65
100	0.990 29 00	0.999 99 80	0.999 06 75	0.993 68 56	0.991 68 18	0.985 41 99	0.978 89 27
200	0.987 62 18	0.999 99 75	0.998 80 09	0.992 82 01	0.989 53 70	0.982 43 22	0.970 58 08
300	0.984 96 08	0.999 99 70	0.998 53 44	0.991 92 66	0.987 36 81	0.979 42 51	0.962 33 95
400	0.982 30 69	0.999 99 64	0.998 26 78	0.991 09 14	0.985 26 13	0.976 48 40	0.954 16 81
500	0.979 66 02	0.999 99 59	0.998 00 14	0.990 22 81	0.983 13 02	0.973 52 32	0.946 06 62

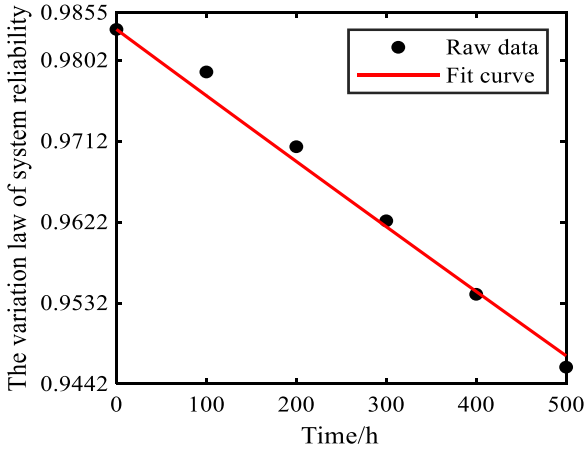


Figure 6. Reliability curve of wind turbine system.

According to table 7, $R_{sys}(0) = 0.983\ 62\ 65$. By fitting the reliability data from 0 h to 500 h, the equivalent failure rate is obtained as:

$$\lambda_{eq} = 7.52 \times 10^{-5} h^{-1}.$$

Thus, the reliability model of the WT system is:

$$R_{sys}(t) = 0.983\,62\,65 \times \exp\left(-7.52 \times 10^{-5} t\right).$$

As shown in figure 6, the WT system reliability decreases from 0.983 62 65 at 0 h to 0.946 06 62 at 500 h. The reliability of the WT system over time sequence can be quickly obtained by the function expression $R_{sys}(t)$, and the reliability of WT with dynamic change (time sequence) can be analyzed effectively.

6. Conclusions

Considering the multi-state characteristics, shared signals and dynamic change (time sequence), a reliability analysis method for a WT with feed-forward structure based on GO-FLOW is proposed in our study. The research results are compared and verified based on the GO method, and show that:

(1) A reliability analysis method for WT with feed-forward structure proposed in our study is verified, which can fully take into account the multi-state (advance state, success state, and failure state), shared signal, and dynamic change (time sequence) of WT system.

(2) Compared with the other reliability model, a reliability analysis method of WT with feed-forward structure proposed in our study only requires one calculation to derive the strength of the output signals of each state of the system at all time points, which can effectively and accurately analyze the change rule of the system reliability with the time sequence.

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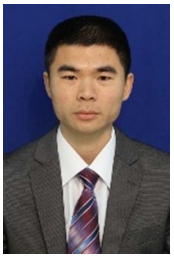
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