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Search Method for Wind Turbine Gearbox Failures Based on Grey and Fuzzy Fault Tree Analysis

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Abstract: According to the characteristics of complicated structure as well as failure probability for shortage, failure mechanism is not clear, the fault degree are grey and fuzzy properties in Wind turbine gearbox transmission system. The grey and fuzzy theory were introduced into fault tree analysis method and the fault tree analysis method of Wind turbine gearbox transmission system was proposed based on grey and T-S fuzzy fault tree analysis. The method used fuzzy Numbers to describe system failure probability to solve the failure probability of uncertainty. Using T-S logic fuzzy gate to solve the connections and using grey correlation degree to get fault search order. Example of fault tree analysis of the Wind turbine gear-box system was given for illustration. Results show that the method is feasible.

Key words: Fault tree, fuzzy number, grey theory, wind turbine, fault diagnosis, gearbox

INTRODUCTION

With the increasing shortage of energy and more serious environmental issues, wind power as a clean and renewable energy has developed on a large scale (Hameeda *et al*., 2009). Fault rate of wind turbines is much higher as the installed capacity and scale increase much more. Therefore, monitoring and fault diagnosis of wind turbines have become more important. The inherent uncertainty and changeability of wind power bring enormous challenge to the operation and control of transmission system. As a result, fault diagnosis of transmission system which core is the gearbox has been an important problem to be not neglected on that of mechanical system in wind turbines. And it has become a burning issue of wind power (Long *et al*., 2012).

For the complex structure and the incomplete fault information, gearbox transmission system of wind turbines can be regarded as a grey system. What's more, it is fuzzy because of the indeterminate failure mechanism and probability. The gearbox fault diagnosis can provide technical support for the equipment and provide convenience for the maintenance. Vibration signal can mostly reflect the running state of the equipment of gearbox's various monitoring signals (Gao *et al*., 2011), set vibration signal as the research object and draw whether the gearbox operation is normal after the time and frequency domain analysis (Gao *et al*., 2011; Hong-Shan *et al*., 2012; Yang *et al*., 2011).

Considering the gray characteristic and fuzziness, this study applies the theory of grey system and fuzzy mathematics and combines that with the method of fault tree analysis to find the failure probability and grey correlation of minimal segmental sets. Then the correlation sequence and the relative approach degree of ideal solution of fault search are obtained, so as to determine the order of fault search.

BASIC T-S FUZZY THEORY

Trapezoidal subordinate function: In the analysis of system, fuzzy numbers and linguistic values are always used to represent the state of the system or components. The trapezoidal subordinate function of fuzzy number is shown in Fig. 1 and its expression is:

$$\mu_F = \begin{cases} 0 & 0 \le F \le F_0 - a - b \\ \dfrac{F - (F_0 - a - b)}{b} & F_0 - a - b \le F \le F_0 - a \\ 1 & F_0 - a \le F \le F_0 + a \\ \dfrac{(F_0 + a + b) - F}{b} & F_0 + a \le F \le F_0 + a + b \\ 0 & F \ge F_0 + a + b \end{cases} \quad (1)$$

where, F_0 the center of fuzzy number supporting set is, a is the supporting radius and b is fuzzy region. As a is equal to 0, trapezoidal subordinate function becomes into a triangle. While b equals zero, the fuzzy number is some definite value.

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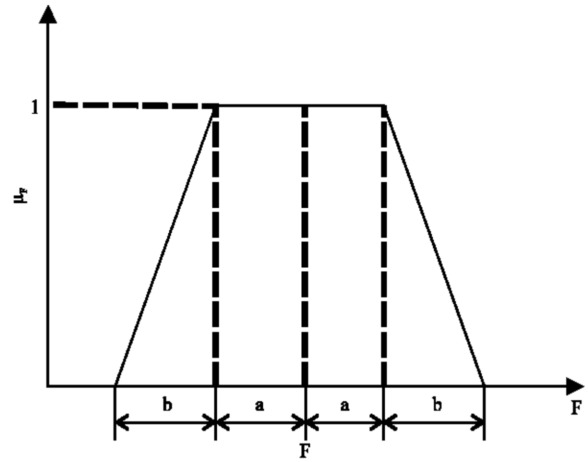

Fig. 1: Fuzzy subordinate function

T-S fuzzy gate algorithm: T-S fuzzy gate is composed of IF-THEN rules. Assume that the failure degree of bottom events $x_1, x_2, \ldots, x_k$ and top event y are represented in fuzzy numbers as, $(x^1_1, x^1_1, \ldots, x^{n1}_1)$, $(x^1_k, x^1_k, \ldots, x^{nk}_k)$ and $(y^1, y^2, \ldots y^{ny})$ where:

$$\begin{cases} 0 \le x_1^1 < x_1^2 < \cdots x_1^{n1} \le 1 \\ 0 \le x_2^1 < x_2^2 < \cdots x_2^{n2} \le 1 \\ \vdots \\ 0 \le x_k^1 < x_k^2 < \cdots x_k^{ny} \le 1 \end{cases} \quad (2)$$

If the rule $l(l = 1, 2, \ldots, m)$ is known and the fault fuzzy probability of the bottom events are $p(x_1^{i1}), p(x_2^{i2}), \ldots, p(x_k^{ik})$, the execution probability of the rule l is:

$$p_0^l = p(x_1^{i1}),\ p(x_2^{i2}) \cdots p(x_k^{ik}) \quad (3)$$

And fuzzy probabilities of superior events are:

$$\begin{cases} p(y^1) = \sum_{l=1}^{m} p_0^l p^l(y^1) \\ p(y^2) = \sum_{l=1}^{m} p_0^l p^l(y^2) \\ \vdots \\ p(y^k) = \sum_{l=1}^{m} p_0^l p^l(y^k) \end{cases} \quad (4)$$

If the bottom events are known as $x' = (x'_1, x'_2, \ldots, x'_k)$, the fault fuzzy probabilities of superior events can be estimated by T-S model as followed:

$$\begin{cases} p(y^1) = \sum_{l=1}^{m} \beta_l^*(x') p^l(y^1) \\ p(y^2) = \sum_{l=1}^{m} \beta_l^*(x') p^l(y^2) \\ \vdots \\ p(y^k) = \sum_{l=1}^{m} \beta_l^*(x') p^l(y^k) \end{cases} \quad (5)$$

$$\beta_l^*(x') = \frac{\prod_{j=1}^{k} \mu_{x_j^{ij}}(x'_j)}{\sum_{l=1}^{m} \prod_{j=1}^{k} \mu_{x_j^{ij}}(x'_j)} \quad (6)$$

where, $\mu_{x_j^{ij}}(x'_j)$ is the fault degree of the component j in the rule l which also referred to as the membership of fuzzy sets x'_j.

GREY SYSTEM THEORY

Grey system theory is a new method to study the issues of uncertainty and lack of data or information. Through the main relationship in various elements (or subsystems) of systems, the important factors affecting the target value is found out which promotes and guides the coordinated development of system rapidly, efficiently and healthy.

Correlation degree is referred to correlation changing with time between two systems or two factors of the same system. Grey correlation grade is the index of the similarity between two grey systems.

In a case with two series $\{X_i(t), X_j(t)\}$, as t equals k, correlation degree is:

$$r_{ij} = \frac{1}{n} \sum_{k=1}^{n} \varepsilon_{ij}(k) \quad (7)$$

Where:

$$\varepsilon_{ij}(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij}(k) + \rho\Delta_{max}} \quad (8)$$

$$\Delta_{ij}(k) = |X_i(k) - X_j(k)| \quad (9)$$

where, $\varepsilon_{ij}(k)$ is the correlation coefficient and $\Delta_{ij}(k)$ is absolute difference of the two series at the moment k. Δ_{max} is the maximum absolute difference Δ_{min} and is the minimum one. ρ is the distinguishing coefficient.

FAULT SEARCH ALGORITHM BASED ON GREY THEORY AND FUZZY FAULT TREE

Based on grey theory and fuzzy fault tree, fault search steps are illustrated as following:

- Minimal segmental sets are found out according to the system fuzzy fault tree
- Based on the T-S fuzzy algorithm, the critical importance of every bottom event is calculated and the pattern vector to be tested is determined

- Fault feature matrix is established
- Dimension of the original data is eliminated and the data is converted into comparable data columns
- Grey difference, $\Delta_{oi}(k)$, is calculated. $\Delta_{oi}(k)$ is the absolute difference of two comparing series at the moment k, i.e., $\Delta_{oi}(k) = |x_O(k)-x_i(k)|$
- Correlation coefficient, $\varepsilon_{ij}(k)$, is calculated:

$$\varepsilon_{ij}(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij}(k) + \rho\Delta_{max}},$$

  where, ρ is the distinguishing coefficient, generally taking 0.5
- Correlation degree, γ_i, is calculated:

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_i(k)$$

  where, γ_i is correlation degree of series x_i and x_0 series. Its value is greater and the relationship between x_i and x_0 is more closely
- Correlation order is arranged. The fault search order is obtained by comparing the failure occurring probability of bottom events as the failure occurs in the top events

EXAMPLE ANALYSIS

Establishment of T-S fuzzy fault tree of gearbox transmission system in wind turbines: Data shows that the failure ratio of gear to the gearbox reaches up to 60% (Tavner *et al*., 2007; Ribrant and Bertling, 2007). Consider the wind turbines of a wind farm in a Zhangbei County, Zhangjiakou City. Without regard to work environment and human factors, the T-S fuzzy fault tree is established in which the top event is that the gear transmission system can not operate normally, as shown in Fig. 2.

In Fig. 2, the top event, y4, is the output of T-S gate 4 which represents that the gear transmission system can not run. Intermediate event, y1, is the output of T-S gate 1 representing the gear teeth failure. The event y2 as the output of T-S gate 2 is represented the gear wheel failure. The output of T-S gate 3 is the intermediate event y3 and it is the bearing failure. X1, X2, X3, x4, x5, x6, x7 and x8 are the components' partial failures of gear transmission system while y1, y2, y3 and y4 represent the system partial failures of gear transmission system. Consider that the common fault degree is (0, 0.5, 1). In this case, 0 represents no failure which means that the system can work normally. 0.5 means half fault or mild fault which means that the system can work partially. 1 which represents the complete failure or serious fault, means that the system does not work. Names of the events are shown in Table 1.

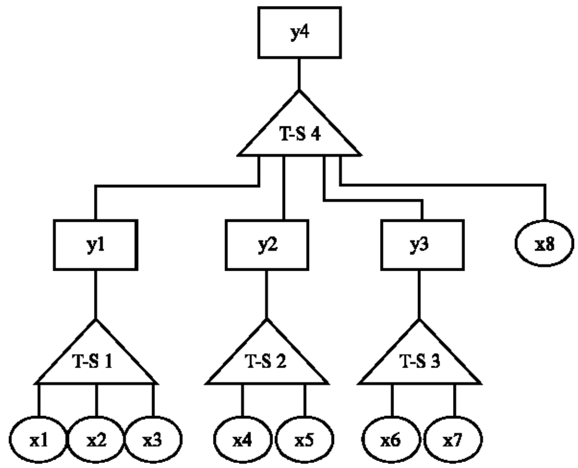

Fig. 2: Tree of T-S fuzzy fault

Table 1: Names of the events

Event code	Event name
y4	The gear transmission system can not operate
y1	Gear tooth failure
y2	Gear wheel body failure
y3	Bearing failure
x1	Broken teeth
x2	Gluing
x3	To enter the debris
x4	Ring gear breakage
x5	Deformation damage
x6	Burn
x7	Roller off
x8	Sources of power failure

Table 2: T-S gate 1 of the rules

				y1		
Rule	x1	x2	x3	0	0.5	1
1	0	0.0	0.0	1.0	0.0	0.0
2	0	0.0	0.5	0.1	0.2	0.7
3	0	0.0	1.0	0.0	0.0	1.0
4	0	0.5	0.0	0.1	0.3	0.6
5	0	0.5	0.5	0.2	0.3	0.5
6	0	0.5	1.0	0.0	0.0	1.0
7	0	1.0	0.0	0.0	0.0	1.0
-	-	-	-	-	-	-
27	1	1.0	1.0	0.0	0.0	1.0

Considering the trapezoidal subordinate function shown in Fig. 1, let the parameter a equal 0.1 and the parameter b equal 0.3. According to the relevant data of the Dali wind field in Inner Mongolia and the Zhangbei wind field in Zhangjiakou (Ming-Ming, 2009), the T-S gate rules are established with the combination of expert experience and human estimation.

Each row in Table 2-5 represents a fuzzy rule. As shown in Table 2, the first row represents that if x2, x3 and x4 are all 0, the possibility that y5 equals 0 is 1 while the possibility y5 being 0.5 or 0 is 0 and so on.

Table 3: T-S gate 2 of the rules

Rule	x4	x5	y2: 0	0.5	1
1	0.0	0.0	1.0	0.0	0.0
2	0.0	0.5	0.3	0.2	0.5
3	0.0	1.0	0.0	0.0	1.0
4	0.5	0.0	0.2	0.3	0.5
5	0.5	0.5	0.1	0.2	0.7
6	0.5	1.0	0.0	0.0	1.0
7	1.0	0.0	0.0	0.0	1.0
8	1.0	0.5	0.0	0.0	1.0
9	1.0	1.0	0.0	0.0	1.0

Table 4: T-S gate 3 of the rules

Rule	x6	x7	y3: 0	0.5	1
1	0.0	0.0	1.0	0.0	0.0
2	0.0	0.5	0.7	0.2	0.1
3	0.0	1.0	0.0	0.0	1.0
4	0.5	0.0	0.3	0.4	0.3
5	0.5	0.5	0.2	0.4	0.4
6	0.5	1.0	0.0	0.0	1.0
7	1.0	0.0	0.0	0.0	1.0
8	1.0	0.5	0.0	0.0	1.0
9	1.0	1.0	0.0	0.0	1.0

Table 5: T-S gate 4 of the rules

Rule	y1	y2	y3	x8	y4: 0	0.5	1
1	0	0	0.0	0.0	1.0	0.0	0.0
2	0	0	0.0	0.5	0.1	0.3	0.6
3	0	0	0.0	1.0	0.0	0.0	1.0
4	0	0	0.5	0.0	0.3	0.4	0.3
5	0	0	0.5	0.5	0.2	0.3	0.5
6	0	0	0.5	1.0	0.0	0.0	1.0
7	0	0	1.0	0.0	0.0	0.0	1.0
8	0	0	1.0	0.5	0.0	0.0	1.0
-	-	-	-	-	-	-	-
54	1	1	1.0	1.0	0.0	0.0	1.0

Table 6: Importance degree of each bottom event

Bottom event	Criticality importance	Bottom event	Criticality importance
x1	0.0744567	x5	0.1913793
x2	0.2233701	x6	0.1381771
x3	0.0372284	x7	0.1381771
x4	0.0956897	x8	0.1015014

Analysis of fuzzy importance degree: An important index of fault tree analysis is importance degree, in which critical importance can reflect not only the status of bottom events in the fault tree of the system, but also the uncertainty of the event itself. What's more, it can reflect more objectively the impact of components on the system fault tree (Yao *et al*., 2011; Yao and Zhao, 2009) and calculating method of critical importance is illustrated in the reference (Song *et al*., 2005; Ni *et al*., 2008; Yong-Jian *et al*., 2010). The importance degree of each bottom event is given in Table 6.

Failure searching based on the grey theory and fuzzy fault tree:

- **Finding out the minimum cut set:** According to the fault tree shown in Fig. 2 and the ascending method, the minimum cut set is found out as following:

$$T_{k1} = \{1\},\ T_{k2} = \{2\},\ T_{k3} = \{3\},\ T_{k4} = \{4\},\ T_{k5} = \{5\},\ T_{k6} = \{6\},\ T_{k7} = \{7\},\ T_{k8} = \{8\}$$

- **Determination of the pattern vector to be tested:** On the basis of the critical importance of each bottom event, the test pattern vector is:

$$X_n = \{0.0744567, 0.2233701, 0.0372284, 0.0956897, 0.1913793, 0.1381771, 0.1381771, 0.1015014\}$$

- **Establishment of fault feature matrix:** The number of bottom events is 8, i.e., n = 8. In the feature matrix, let the bottom events comprising the minimal cut set equal one and the others equal zero. Then:

$$T_k = \begin{vmatrix} T_{k1} \\ T_{k2} \\ T_{k3} \\ T_{k4} \\ T_{k5} \\ T_{k6} \\ T_{k7} \\ T_{k8} \end{vmatrix} = \begin{vmatrix} 1\,0\,0\,0\,0\,0\,0\,0 \\ 0\,1\,0\,0\,0\,0\,0\,0 \\ 0\,0\,1\,0\,0\,0\,0\,0 \\ 0\,0\,0\,1\,0\,0\,0\,0 \\ 0\,0\,0\,0\,1\,0\,0\,0 \\ 0\,0\,0\,0\,0\,1\,0\,0 \\ 0\,0\,0\,0\,0\,0\,1\,0 \\ 0\,0\,0\,0\,0\,0\,0\,1 \end{vmatrix}$$

- **Initialization of original data:** The original data is initialized as following, considering the test pattern vector, X_n, as the maternal factor and the minimum cut set, T_{ki}, as the sub-factor:

$$T_{ki} = \{1, 3, 0.5, 1.2851725, 2.5703436, 1.8558048, 1.8558048, 1.3632272\}$$

- **Calculation of the difference sequence $\Delta_{zki}(k)$:** Difference sequence is defined as the absolute difference between the two comparison series

$$\Delta_{zki}(k) = |X_n(k)-T_{ki}(k)|$$

where, i = 1, 2...8 and k = 1, 2...8. Then the biggest difference is 3 and the smallest difference is 0

- **Calculation of the correlation coefficient:**

$$\varepsilon_{ij}(k) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{ij}(k) + \rho\Delta_{max}}$$

Table 7: Grey correlation coefficient

	k = 1	k = 2	k = 3	k = 4	k = 5	k = 6	k = 7	k = 8
i = 1	1.0	0.333333	0.75	0.500000	0.3685192	0.4469867	0.4469867	0.5238844
i = 2	0.6	0.428571	0.75	0.538566	0.3685192	0.4469867	0.4469867	0.5238844
i = 3	0.6	0.333333	0.75	0.538566	0.3685192	0.4469867	0.4469867	0.5238844
i = 4	0.6	0.333333	0.75	0.840254	0.3685192	0.4469867	0.4469867	0.5238844
i = 5	0.6	0.333333	0.75	0.538566	0.4885447	0.4469867	0.4469867	0.5238844
i = 6	0.6	0.333333	0.75	0.538566	0.3685192	0.6367251	0.6367251	0.5238844
i = 7	0.6	0.333333	0.75	0.538566	0.3685192	0.4469867	0.4469867	0.5238844
i = 8	0.6	0.333333	0.75	0.538566	0.3685192	0.4469867	0.4469867	0.8050548

where, ρ = 0.5, the grey correlation coefficient is shown in Table 7

- **Calculation of the correlation degree:**

$$\gamma_i = \frac{1}{n}\sum_{k=1}^{n}\xi_{ij}(k)$$

Then:

$$\gamma_{k1} = 0.546214,\ \gamma_{k2} = 0.512939,\ \gamma_{k3} = 0.501035,$$
$$\gamma_{k4} = 0.538746,\ \gamma_{k5} = 0.516038,\ \gamma_{k6} = 0.548469,$$
$$\gamma_{k7} = 0.501035,\ \gamma_{k8} = 0.536181$$

- **Arrangement of correlation order and obtaining of fault search order:** The correlation order of X_{ki} to X_n is:

$$\gamma_{k6}>\gamma_{k1}>\gamma_{k4}>\gamma_{k8}>\gamma_{k5}>\gamma_{k2}>\gamma_{k3} = \gamma_{k7}$$

As a result, eight failure modes leading to the abnormal operation of gear transmission system in wind turbines have the sequence of occurring possibility as (from high to low, no comma meaning same) {X_6}, {X_1}, {X_4}, {X_8}, {X_5}, {X_2}, {X_3} {X_7}. That is the fault search order.

CONCLUSION

According to the fuzzy and gray characteristics of the gear system fault in wind power gearbox, the uncertainty of fault probabilistic is determined effectively by the description of system failure probability with fuzzy number; and the fuzzy characteristics caused by the ambiguous relationship between events and failure mechanism are solved instead of the traditional fault tree with T-S fuzzy logic gates. Using grey system and fuzzy theory and combined with the fault tree analysis method, grey correlation degree of the minimum cut sets is calculated and correlation sequence is obtained on the basis of the failure analysis of the abnormal operation of gear transmission system in wind turbine gearbox. Thus the fault search order is determined. And the research provides a theoretical basis for the order dealing with accidents, control of accidents occurrence and improvement of system reliability.

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