Fuzzy Fault Tree Analysis of a Gas Turbine Fuel System

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Abstract: This paper mainly explores the common faults of the fuel system in gas turbine and establishes the corresponding fault tree model, and also analyzes the fuzzy fault tree based on the fault tree and the fuzzy information feedback from the staff. Certain components of the fuel system and the reliability of the fuel system in gas turbine are improved according to the results of the fuzzy analysis. Thus, this paper provides a certain theoretical basis for designers to improve the performance and reliability of gas turbine.

1. Introduction
The gas turbine system on the ship is mainly composed of a fuel system, an ignition system, an electronic control system, a lubricating oil system, a starting system, etc., hence the composition of the gas turbine system is quite complicated, and each system above has inseparable connections, and especially the fuel system is the source of energy to guarantee the output power of the gas turbine. Weijun Zhu [1] conducted a detailed discussion on the possible faults of the gas turbine according to its characteristics of star-up, and further brought out the issues that should be paid much attention to in the stage of gas turbine start-up management. Xuejun Shi [2] analyzed the causes and treatment methods of MS6001 starting faults in four aspects: starting system fault, compressor efficiency drop, fuel control system fault and atomization system fault. Yu Qin [3] conducted a simulation study and diagnosis of the fault of the fuel system of the marine gas turbine. Moreover, this paper establishes a fault tree model in terms of common faults of fuel system in gas turbine on a certain type of ships, and carries out fuzzy fault analyses and came to improved methods based on analytical results to improve the reliability of the fuel system in gas turbine, which provides some ideas for the designer to improve the performance of the gas turbine and also boasts a guiding significance for the ships’ staff to check the maintenance faults.

2. Fuel System

2.1. Fuel System descriptions
The fuel system regulates and distributes the fuel to the combustion chamber of the gas generator to control the speed of the gas generator. The working principle is shown in figure 1.
The fuel flows into the fuel pump booster component through the ships’ oil supply system, and passes through the pump’s high-pressure components and the filter installed on the pump and into the fuel controller, and then enters the fuel manifold through the action of fuel booster valve, and finally it’s sprayed into the combustion chamber through the fuel nozzle. This process can only be carried out when both series-connected electrically operated fuel shut-off switches are opened. While if the two switches are closed, the fuel will be vented and not allowed to exist in the manifold, nozzle and vent pipe, thus the fuel in the nozzle will be inserted into the combustion chamber through the rear of the compressor to provide atomized fuel to for combustion chamber. It can be seen from the working principle figure of fuel system that there are many components in the fuel system, so it is very necessary to figure out the structure and working principle of the fuel system, which are also the prerequisite of establishing the fault tree model for the fuel system.

2.2. The common faults of fuel system and establishment of the fault tree model
Common faults in the fuel system are that fuel manifold pressure is excessively high or low at start-up or no pressure and the fault of rotor guide vane system. Hence we build a fault tree model by analyzing the causes of above common faults to make problems clearer, and the fault tree model of the fuel system is shown below:

![Fault Tree Model of Fuel System](image-url)
In this figure, the fault tree model is established with the “fuel system fault” as the top event T1. Three common faults are intermediate events. \( X_i(i=1\cdots10) \) are used to represent basic events. The specific names of the basic events are shown in table 1.

2.3. Fuzzy fault reliability analysis

The reliability analysis of fault tree requires that the probability of occurrence of top event and basic events are certain values, which is difficult to achieve in real life for various reasons. And this paper analyzes the reliability of fault trees based on fuzzy mathematics and the uncertainty of the probability of occurrence of basic events, that is, fuzziness.

In the fuzzy fault tree analysis, the fuzzy number \( P \) is introduced to describe the probability of event occurrence, and the membership function \( P(x) \) is used to represent the fuzziness of the fault. Besides, \( P_{T(i)}, P_{G(i)}, P_{X(i)} \) are adopted to indicate the fault rate of top events, intermediate events and basic events. A ternary array \((m, \alpha, \beta)\) is commonly used in engineering applications to represent fuzzy numbers. \( m \) corresponds to a function with a membership degree of \( \mu = 1 \), namely, an average value, which is based on the experience of the staff. \( \alpha \) and \( \beta \) are the left and right distributions of the fuzzy number \( P \), which represents the fuzzy degree. The narrower the interval, the more reliable the value of \( m \). The two values \( \alpha \) and \( \beta \) are determined by the membership function are taken.

Combined with the actual situation, L-R triangle membership function is chosen in this paper. Its function forms are:

\[
\mu_{P_i} = \begin{cases} 
0 & \text{if } x \leq m, \alpha > 0, \text{L}(m-x)/\alpha] = \max\{0,1-(m-x)/\alpha\}; \\
\frac{(x-m)}{\alpha} & \text{if } m-\alpha \leq x < m; \\
\frac{(x-m)}{\beta} & \text{if } m \leq x < m+\beta; \\
0 & \text{if } x \geq m+\beta.
\end{cases}
\]

Simplify the above formula:

\[
\mu_{P_i} = \begin{cases} 
1 - \frac{(x-m)}{\alpha} & \text{if } m-\alpha \leq x < m; \\
\frac{(x-m)}{\beta} & \text{if } m \leq x < m+\beta.
\end{cases}
\]

Based on users’ feedback and the fuzzy data provided by the staff’s experience, the basic events and their fuzzy data are shown in table 1:

| Code | Basic events                                | Fuzzy number |
|------|---------------------------------------------|--------------|
| T1   | Fuel system fault                           |              |
| G1   | Fuel mainfold pressure is too low or no pressure at start-up |              |
| G2   | Rotor guide vane system fault                |              |
G3: Fuel manifold pressure is too high at start-up
X1: Fuel supply system fault (0.00196, 0.00271, 0.00346)
X2: Constant pressure valve fault in fuel booster pump removal system (0.00152, 0.00261, 0.00349)
X3: Oil leakage of vent port (0.00182, 0.00267, 0.00352)
X4: Fuel manifold pressure gauge and sensor fault (0.00132, 0.00242, 0.00341)
X5: Gas generator fuel system fault (0.00217, 0.00320, 0.00421)
X6: Rotor guide vane feedback cable installation error (0.00105, 0.00228, 0.00332)
X7: Feedback cable strapping is not firm (0.00121, 0.00238, 0.00339)
X8: Static blade installation at all levels is incorrect (0.00142, 0.00255, 0.00347)
X9: The system is unstable (0.00184, 0.00319, 0.00454)
X10: Fuel flow is too high (0.00189, 0.00315, 0.00441)

According to the fault tree model and fuzzy data, we can obtain the fault rate of the intermediate events and top event:

\[ P_{G_1} = P_{s_1} + P_{s_2} + P_{s_3} + P_{s_4} + P_{s_5} = (0.00879, 0.01361, 0.01809); \]
\[ P_{G_2} = P_{s_4} + P_{s_7} + P_{s_8} + P_{s_9} = (0.00552, 0.01040, 0.04595); \]
\[ P_{G_3} = P_{s_1} + P_{s_4} + P_{s_6} = (0.00517, 0.00828, 0.01128); \]
\[ P_{G_4} = P_{s_1} + P_{s_2} + P_{s_3} = (0.01948, 0.03229, 0.07532). \]

According to the literature [7], when a confidence level \( \lambda \) is given, we are capable of getting a confidence interval for the top event to occur based on the following expression:

\[ P_{T}^\lambda = [m_T - \alpha_T \lambda \beta_T, m_T + \alpha_T \beta_T, m_T]. \]

When \( \lambda = 0 \), \( P_{T}^{0\lambda} = (0.01948, 0.07532) \); When \( \lambda = 1 \), \( P_{T}^{1\lambda} = (0.03229, 0.03229) \).

In summary, the fault rate range of the fuel system is \( (0.01948, 0.03229) \).

3. The reduction of fault rate of fuel system in gas turbine

This method based on fuzzy fault tree analysis is to reduce the fault rate of the basic event through improving some components of the gas turbine fuel system or to increase the frequency of its maintenance, and finally to improve the reliability of fuel system. In the fault tree model of figure 2, it can be seen that the basic events X1, X4 are in critical positions in the fault tree model, and any occurrence of those events will lead the intermediate event G1 or G3 to occur, which results in a fuel system fault. Therefore, it is of great significance for improving the reliability of fuel system to reduce the fault rate of two basic events. For the fault of fuel supply system, we can consider whether the oil supply pipe is blocked or leaked, and the ways such as clean the filter regularly, check the tightness of the oil pipe and periodically replace the gasket can be adopted. For fuel manifold pressure gauges and sensor faults, we are required to periodically correct errors and increase the number of inspections. After adopting the above methods, according to the feedback of users and the experience of technicians, a new set of fuzzy numbers of the basic events X1 and X4 is obtained:

\[ P_{X_1} = (0.00106, 0.00239, 0.00334); \quad P_{X_4} = (0.00068, 0.00132, 0.00196). \]
Substitute the new fuzzy number into the formula in Section 2.3 to get the fault rate of the new intermediate events and top event:

\[
P_{Gi} = (0.00741, 0.01248, 0.01694); \quad P_{Gi} = (0.00379, 0.00715, 0.01013);
\]

\[
P_{T} = (0.01672, 0.03003, 0.07302).
\]

According to the literature [7], the fuel system fault rate range is (0.01672, 0.03003). Compared with the fault rate range in Section 2.3, the latter fault rate of the fuel system has been reduced to some extent, and the reliability has been improved.

4. Conclusion

In this paper, the working principle and common faults of the fuel system in the gas turbine are introduced. The fuzzy fault analysis is carried out on the top event by establishing the fault tree model, and some measures are taken to reduce the fault rate of key events in the fault tree model. We can safely draw the following conclusions through the above work:

1. Through the fuzzy fault analysis, the fault rate interval of each event is obtained, which provides a theoretical basis for the maintenance personnel to eliminate the fault and boasts guiding significance for the fault can be eliminated in time. Also, it provides a theoretical basis for designers to improve the reliability of gas turbines.

2. Certain protective and maintenance measures are taken to reduce the fault rate by establishing a fault tree model to find key events, and finally to improve fuel system reliability. This provides a new idea for the fault research of gas turbine systems, and also has reference significance for the maintenance work of maintenance personnel.

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