

Reliability Analysis of Gas Turbine Based on Analytic Hierarchy Process and FTA

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Abstract—Gas turbine generator sets have complex structures and poor operating conditions, which place high demands on the reliability of components. Aiming at the structural characteristics of gas turbine generator sets, combined with the latest theory of reliability analysis development, based on the characteristics of the hierarchical structure of fault tree model, the combination of hierarchical analysis method and fault tree model is proposed to analyze the reliability of complex mechanical systems. In this paper, combined with the gas turbine startup failure, this method is applied to the analysis of the fault. The results show that this method is feasible and effective.

Keywords—reliability analysis; analytic hierarchy process; FTA

I. INTRODUCTION

The gas turbine power generation system consists of compressor, combustion chamber and turbine. In the gas turbine power station, the fuel is natural gas or heavy oil, and its combustion products are carbon dioxide and water, so it is a clean energy power generation method. Under the current situation that the air quality in northern China is not optimistic, the application of clean energy power generation mode is gradually promoted, which plays an important role in improving air quality. Although China's proven natural gas reserves are limited due to the limitation of China's primary energy structure, in recent years, breakthroughs have been made in the utilization of coalbed methane and the exploitation of combustible ice, providing the possibility of large-scale applications for gas turbine power generation systems in China. However, the structure of the gas turbine generator set is complex, the operating temperature is high, the operating conditions are complex, thus the system has many failure modes. In order to improve the reliability of the system and ensure the safe and stable operation of the system, it is very important to analyze the reliability of the system.

The diagnosis of gas turbine failure began in the 1960s. L. A. Urban [1] proposes a diagnostic method for multiple faults in gas turbine gas path components. M. Rychetsky[2] proposes the application of neural network technology in gas turbine vibration fault detection. In this paper, based on statistical analysis and neural network filtering, a gas turbine fault diagnosis expert system is established. From the perspective of fault detection and fault diagnosis of rotating machinery, the wavelet analysis of the vibration signal of the shafting rotor is analyzed by the combination of neural network. A. J. Volponi[3] explores the Kalman filtering method and the neural network method for gas turbine fault diagnosis. C.A. Plamer[4] proposes

the application of Bayesian evidence in gas turbine gas path fault diagnosis. Based on historical data, H.Lipowsky[5] proposes a new Bayesian prediction statistical method to predict the performance of gas turbines.

Although many research methods and implementations for gas turbine fault diagnosis technology have been proposed, some gas turbine fault diagnosis systems have been introduced. However, in practical engineering applications, due to the lack of comprehensive capabilities of fault diagnosis methods and theoretical applications, there is still a lack of a full-featured mature system to solve many problems in gas turbine fault diagnosis.

II. GAS TURBINE FAILURE MODE ANALYSIS

When the gas turbine starts to ignite, the turbine exhaust gas temperature rises to the temperature control line during the speed increase process, and the gas turbine is transferred from the speed control to the temperature control, which suppresses the increase rate of the fuel quantity and affects the gas turbine speed increase and extension. When the gas turbine starts, in severe cases, the gas turbine is maintained in the temperature control state so that the gas turbine cannot rise speed and is in a "hot hanging" state.

If the fuel is not completely burned or the combustion of the individual combustion chamber is poor, the outlet temperature is not uniform, and the maximum exhaust temperature difference at the turbine outlet exceeds the allowable value, and a combustion failure alarm is issued.

In addition to the above failure modes, there are failure modes such as startup system failure, compressor surge, blade failure, cooling system failure, and control system failure.

III. RELIABILITY ANALYSIS BASED ON FTA AND AHP

The fault tree analysis method analyzes various triggering factors of the research object's faults, and extracts the fault events that may occur from the top layer to the bottom layer. In the fault tree, list all the events that might cause the top event to occur. By analyzing the cause of a fault event, the weakest event can be found.

The main purpose of the fault tree qualitative analysis is to find all failure modes that have the potential to cause the top event to occur. For the most undesired events occurring in the object system, the probability of occurrence is calculated, which is the minimum cut set finding process of the fault tree. Look for all source events that caused the top event to occur and

identify all failure modes that caused the top event to occur. It helps to analyze potential failures, improve and optimize the deficiencies in the design.

By the quantitative analysis of fault trees, the parameters are calculated based on the probability of occurrence of the bottom event. The probability of occurrence of the top event can be

calculated based on the structure, probability, and critical importance of the bottom event.

In this paper, the fault tree of startup failure is built as figure 1. Based on the FMEA analysis, the middle events and bottom events are found which are listed in Table 1.

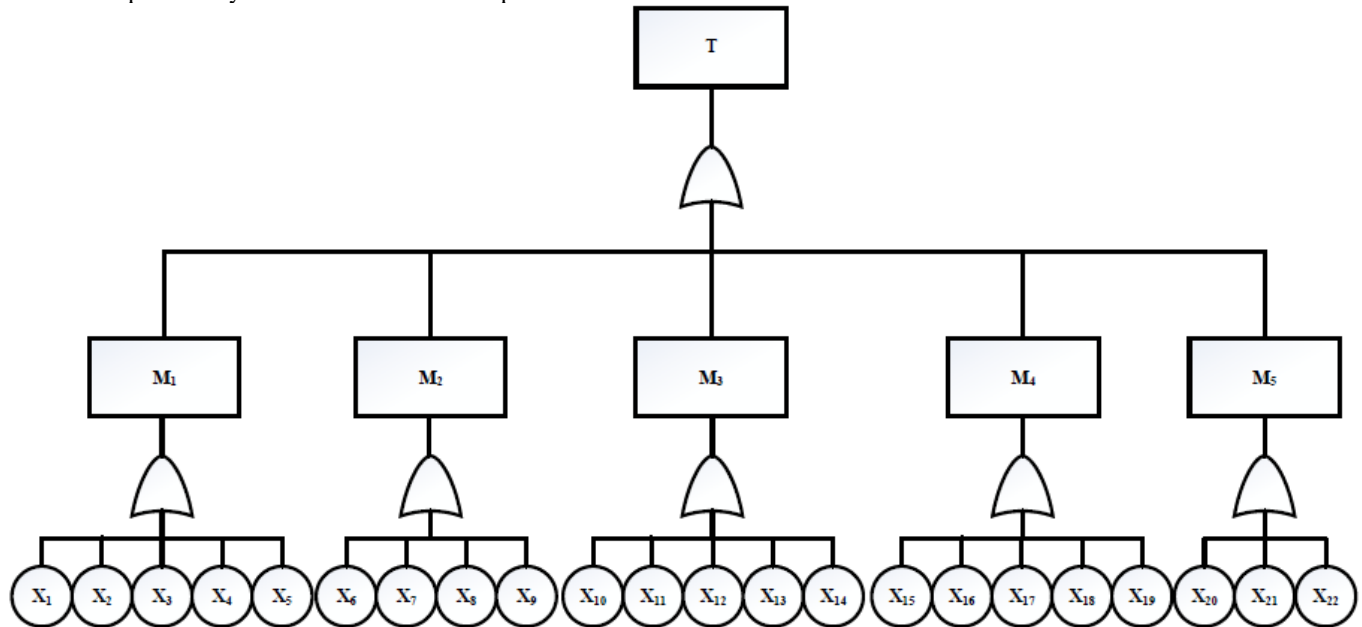


FIGURE 1. THE FAULT TREE OF GAS TURBINE STARTUP FAILURE

TABLE I. THE EVENT DESCRIPTION IN THE FAULT TREE

| Notation | Event description |
|-----------------|------------------------------------|
| T | Top event |
| M ₁ | Startup system failure |
| M ₂ | Ignition failure |
| M ₃ | Combustion failure |
| M ₄ | Hot hanging |
| M ₅ | Compressor surge |
| X ₁ | Start motor burned out |
| X ₂ | Motor control box burned out |
| X ₃ | Motor stall |
| X ₄ | Motor bearing failure |
| X ₅ | Overspeed switch can not be opened |
| X ₆ | Ignition fault |
| X ₇ | Fuel failure |
| X ₈ | Atomizing air failure |
| X ₉ | Fuel nozzle coke blockage |
| X ₁₀ | Uneven fuel intake |
| X ₁₁ | Poor atomization |
| X ₁₂ | Fuel nozzle fault |

TABLE I. CONTINUE

| | |
|-----------------|--|
| X ₁₃ | Compressor failure |
| X ₁₄ | Turbine failure |
| X ₁₅ | Problem with startup system |
| X ₁₆ | Compressor intake filter blockage |
| X ₁₇ | Control system failure |
| X ₁₈ | Poor fuel atomization |
| X ₁₉ | Insufficient turbine output |
| X ₂₀ | Deviation from design condition |
| X ₂₁ | Anti-surge deflation valve is not open at startup |
| X ₂₂ | Anti-surge deflation valve is not open at shutdown |

According to the gas turbine fault tree analysis, the faults are hierarchically divided according to the affiliation between the factors affecting the fault and the relationship between the factors. The gas turbine index system consists of a target layer and a criteria layer, where the criterion layer is the influencing factor layer. The top-down hierarchical sub-domination structure is the fault-grading model of the gas turbine. It is shown in figure 2.

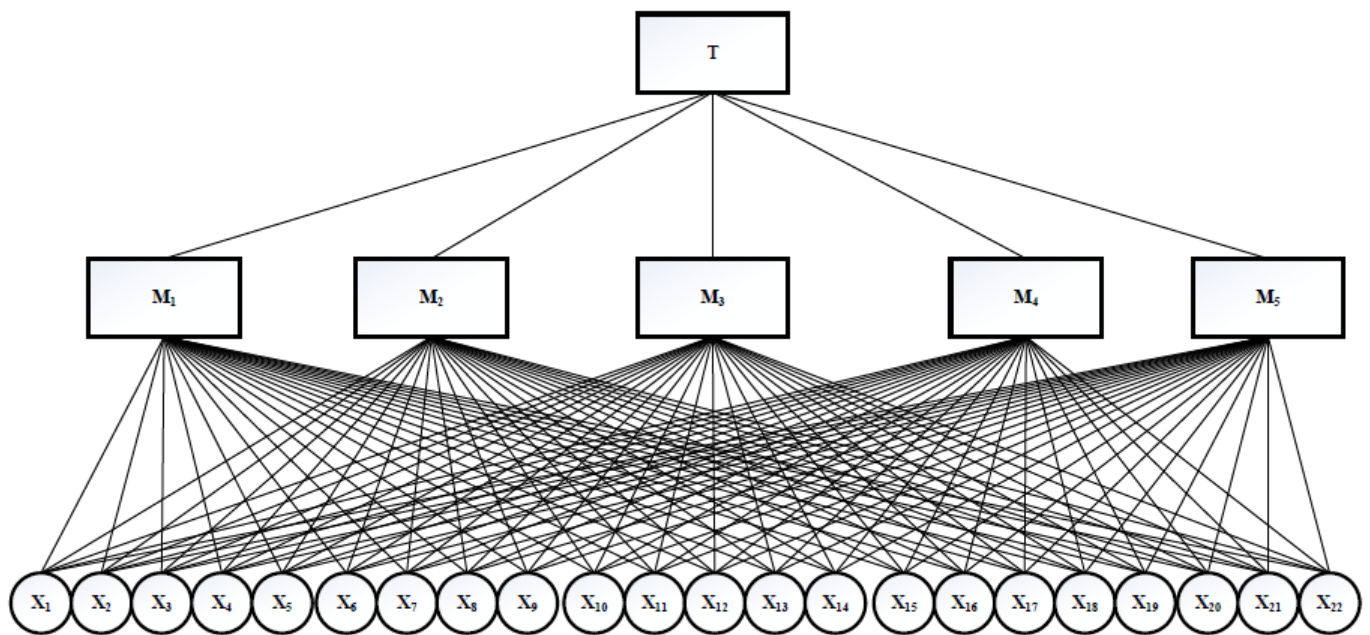


FIGURE II. THE HIERARCHICAL MODEL FOR THE STARTUP FAULT

Any system analysis is based on certain information. The information foundation of AHP is mainly the judgment given by people on the relative importance of each factor at each level. These judgments are represented by numerical values, and the matrix form is the judgment matrix. Judgment matrix is the starting point of AHP work. Constructing judgment matrix is a key step of AHP.

After the relationship between the upper and lower layers is determined, it is necessary to determine the proportion of the lower elements associated with an upper element in the upper element.

Through the relative comparison between the importance of the related events of this level event and the previous level event, the analytic hierarchy process judges the matrix elements. The analytic hierarchy process quantifies the analysis process by judging the numerical value of the matrix. The relative degree of importance between events is achieved through qualitative comparisons.

The evaluation process is as follows: 1 Compare the evaluation indicators in pairs, and form a pairwise comparison matrix according to the above metric scales; 2 select an appropriate ranking method, and normalize the above pairwise comparison matrix to obtain the evaluation index. The relative weight and weight vector; 3 the public design scheme in the same evaluation index layer to compare the two, and obtain their relative weight; 4 the design of the pros and cons of the design is equal to the product of the two.

TABLE II. EVALUATION SCALE OF ANALYTICAL HIERARCHY PROCESS[6]

| Scale value | Value description (a_{ij}) |
|-------------|---|
| 1 | i has the same effect as j |
| 3 | i is slightly stronger than j |
| 5 | i is stronger than j |
| 7 | The effect of i is better than j |
| 9 | i is definitely stronger than j |
| 2,4,6,8 | The effect of i and j is between the above two levels |

Based on the scale value, the pairwise comparison matrix can be obtained as followings:

TABLE III. PAIRWISE COMPARISON MATRIX AMONG M LEVEL

| | M1 | M2 | M3 | M4 | M5 | w_i |
|----|-----|-----|-----|-----|----|-------|
| M1 | 1 | 2 | 3 | 4 | 4 | 0.41 |
| M2 | 1/2 | 1 | 3 | 3 | 4 | 0.29 |
| M3 | 1/3 | 1/3 | 1 | 2 | 2 | 0.14 |
| M4 | 1/4 | 1/3 | 1/2 | 1 | 2 | 0.10 |
| M5 | 1/4 | 1/4 | 1/3 | 1/2 | 1 | 0.07 |

TABLE IV. PAIRWISE COMPARISON MATRIX B-X

| B1 | x1 | x2 | x3 | x4 | x5 | x6 | x7 | x8 | x9 | x10 | x11 | x12 | x13 | x14 | x15 | x16 | x17 | x18 | x19 | x20 | x21 | x22 | w_i |
|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| x1 | 1 | 3 | 3 | 2 | 2 | 4 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 0.13 |
| x2 | 1/3 | 1 | 2 | 1/2 | 1/3 | 3 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 0.09 |
| x3 | 1/3 | 1/2 | 1 | 1/2 | 1/3 | 3 | 2 | 2 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 0.08 |
| x4 | 1/2 | 2 | 2 | 1 | 1/2 | 4 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 0.11 |
| x5 | 1/2 | 3 | 3 | 2 | 1 | 4 | 3 | 3 | 4 | 5 | 5 | 5 | 5 | 5 | 6 | 6 | 6 | 6 | 6 | 7 | 7 | 7 | 0.12 |
| x6 | 1/4 | 1/3 | 1/3 | 1/4 | 1/4 | 1 | 1/3 | 1/2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 0.05 |
| x7 | 1/3 | 1/2 | 1/2 | 1/3 | 1/3 | 3 | 1 | 1/2 | 1/3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 0.05 |
| x8 | 1/3 | 1/2 | 1/2 | 1/3 | 1/3 | 2 | 2 | 1 | 1/3 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 0.06 |
| x9 | 1/4 | 1/3 | 1/3 | 1/4 | 1/4 | 1/2 | 3 | 3 | 1 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 0.06 |
| x10 | 1/5 | 1/4 | 1/4 | 1/5 | 1/5 | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 2 | 2 | 3 | 3 | 4 | 4 | 4 | 4 | 4 | 5 | 5 | 5 | 0.04 |
| x11 | 1/5 | 1/4 | 1/4 | 1/5 | 1/5 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1 | 1/2 | 2 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 0.03 |
| x12 | 1/5 | 1/4 | 1/4 | 1/5 | 1/5 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 2 | 1 | 3 | 2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 0.03 |
| x13 | 1/5 | 1/4 | 1/4 | 1/5 | 1/5 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1/3 | 1 | 1/2 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 0.02 |
| x14 | 1/5 | 1/4 | 1/4 | 1/5 | 1/5 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1/2 | 2 | 1 | 3 | 3 | 3 | 3 | 3 | 4 | 4 | 4 | 0.03 |
| x15 | 1/6 | 1/5 | 1/5 | 1/6 | 1/6 | 1/4 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 1/2 | 2 | 1/2 | 2 | 3 | 3 | 3 | 0.01 |
| x16 | 1/6 | 1/5 | 1/5 | 1/6 | 1/6 | 1/4 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 2 | 1 | 2 | 2 | 3 | 3 | 3 | 3 | 0.02 |
| x17 | 1/6 | 1/5 | 1/5 | 1/6 | 1/6 | 1/4 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1/2 | 1 | 1/2 | 2 | 3 | 3 | 3 | 0.01 |
| x18 | 1/6 | 1/5 | 1/5 | 1/6 | 1/6 | 1/4 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 2 | 1/2 | 2 | 1 | 2 | 3 | 3 | 3 | 0.02 |
| x19 | 1/6 | 1/5 | 1/5 | 1/6 | 1/6 | 1/4 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1/3 | 1/2 | 1/2 | 1 | 3 | 3 | 3 | 0.01 |
| x20 | 1/7 | 1/6 | 1/6 | 1/7 | 1/7 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1 | 2 | 2 | 0.01 |
| x21 | 1/7 | 1/6 | 1/6 | 1/7 | 1/7 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1 | 2 | 0.01 |
| x22 | 1/7 | 1/6 | 1/6 | 1/7 | 1/7 | 1/5 | 1/5 | 1/5 | 1/5 | 1/5 | 1/4 | 1/4 | 1/4 | 1/4 | 1/3 | 1/3 | 1/3 | 1/3 | 1/3 | 1/2 | 1/2 | 1 | 0.01 |

The pairwise comparison matrix on the relationship between the bottom events and the middle events can also be obtained. After a consistent test, we were able to obtain a ranking of the risk of each fault event. This provides more evidence for future design and maintenance.

IV. CONCLUSION

Reliability analysis of gas turbine startup failure was developed based on the combination of fault tree and analytic hierarchy process, which opens up a new way for fault analysis of gas turbine systems. A hierarchical analysis of typical compressor start failures is based on the hierarchical differences in events in the fault tree. Based on the hierarchical relationship of the fault tree, a gas turbine fault stratification analysis model is established. Taking the starting fault of gas turbine compressor as an example, a hierarchical model of starting fault is established. The hierarchical analysis method is adopted, and the analysis results of the hierarchical index of fault events are basically consistent with the actual operation. It shows the effectiveness of the analytic hierarchy process applied to fault analysis.

REFERENCES

[1] L. A. Urban. Parameter Selection for Multiple Fault Diagnostics of Gas Turbine Engines. ASME, 1974,74-GT-82.

[2] M. Rychetsky, S. Ortmann, M. Glesner. Support Vector Machines for Spam Categorization. IEEE Trans. On Neural Networks IJCNN99., Wshington, USA, 1999, 969-974.

[3] A. J. Volponi, H. Depold, R. Ganguli, et al. The Use of Kalman Filter and Neural Network Methodologies in Gas Turbine Performance Diagnostics: A Comparative Study. Journal of Engineering for Gas Turbines and Power, 2003,125(4):917-824.

[4] C.A. Plamer. Combining Bayesian Belief Networks with Gas Path Analysis for Test Cell Diagnostics and Overhaul. ASME Paper 98-GT-168.

[5] H.Lipowsky, S. Staudacher, M. Bauer, et al. Application of Bayesian Forecasting to Change Detection and Prognosis of Gas Turbine Performance. ASME Paper GT2009-59447, 587-596.

[6] Huadong Yang, Yijing Zhang. Feeding Mechanism Design for Automatic Nail-making Machine. Chinese Journal of Construction Machinery, 2010,8(2):173-178.