Research on Risk Assessment of Turbine Regulation System Based on Markov State Model and Entropy Weight Fuzzy Comprehensive Evaluation Method

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Abstract. In recent years, the hydropower unit is developing towards high power, and large-scale, which increases the adjustment difficulty of the turbine regulation system. In addition, the turbine regulation system itself is a complex nonlinear system. The risk of system operation and risk assessment has become more complicated. This paper proposes a method to evaluate the operational safety risk of Turbine Regulation System by combining Markov State Model and Entropy Weight Fuzzy Comprehensive Evaluation Method. Firstly, the full-state operation model of the turbine regulation system is established. The Markov model is used to calculate the probability of fault occurrence. Secondly, the Entropy Weight Fuzzy Comprehensive Evaluation Method is introduced to evaluate the severity of the fault. Finally, a risk assessment system is established based on the probability of failure and the severity of the failure.

1. Introduction

The Turbine Regulation System is combined into a complex system by linear and nonlinear subsystems. The safe and stable operation of the Turbine Regulation System directly determines the safety and stability of the hydropower station it controls [1,2]. In the actual operation of the System, there are many typical operating conditions such as unit vibration and grid connection. At the same time, it is affected by the random uncertainty factors and power load [3]. Failure affecting the normal operation of the hydroelectric generating unit, causing certain losses [4]. Therefore, it is an important issue to evaluate the operational safety risk of the turbine regulating system. Therefore, this paper combines the Markov State Model and the Entropy Weight Fuzzy Comprehensive Evaluation Method to evaluate the operational risk of the Turbine Regulation System, make up for the blank in the field of risk assessment of the Turbine Regulation System, and establish risk assessment system that can be applied to the actual.
2. Markov State Model of Turbine Regulation System

2.1 Full state model of Turbine Regulation system

The Turbine Regulation System mainly includes five parts: Turbine, Generator, Governor, Water Diversion system and Load. According to the relevant literatures [5-8], the full state model of the Turbine Regulation System shown in figure 1.

Figure 1. Whole state model diagram of Turbine Regulation System.

2.2 Application of Markov Process in Turbine Regulation System

The Markov process [9] describes the probability of occurrence of a state transition from one state to another in a stochastic process [10].

\[ P \{ X(t + \Delta t) = j \mid X(t) = i \} = P \{ X(\Delta t) = j \mid X(0) = i \} = P_{ij}(\Delta) \]  

Equation (1)

\[ P_{ij} \] represents the probability that state \( i \) is converted to state \( j \) at the time \( \Delta t \). In the above formula, when \( \Delta t \to 0 \), we can get follow formula:

\[ P \{ X(t + \Delta t) = j \mid X(t) = i \} = P_{ij}(\Delta t) = \lambda_{ij} \Delta t \]  

Equation (2)

\( \lambda_{ij} \) represent the transfer rate between states \( i \) and \( j \) per unit time.

Since the transfer rate is constant and does not change with time, the failure rate and repair rate of each device of the Turbine Regulation System can be taken as the transfer rate of the Markov process. The probability the System is in the normal operating state is \( P_{0} \), and the subsystems are at the probability of the fault state is \( P_{i} (i = 1, 2, 3, 4, 5) \), and the failure rate and repair rate are \( \lambda_{i} \) and \( \mu_{i} \). Combined with the fault full-state model, the turbine regulation system can be sorted out as figure 2. In the repairable system of the Turbine Regulation System, we can find the matrix \( P \) at \( \Delta t \to 0 \), The state transition matrix of the Turbine Regulation System formed by \( n \) states.

\[
P = \begin{bmatrix}
1 - \sum \lambda_{i} \Delta t & \lambda_{1} \Delta t & \lambda_{2} \Delta t & \lambda_{3} \Delta t & \lambda_{4} \Delta t & \lambda_{5} \Delta t \\
\mu_{1} \Delta t & 1 - \mu_{1} \Delta t & 0 & 0 & 0 & 0 \\
0 & 1 - \mu_{2} \Delta t & 0 & 0 & 0 & 0 \\
\mu_{2} \Delta t & 0 & 1 - \mu_{2} \Delta t & 0 & 0 & 0 \\
0 & 0 & 0 & 1 - \mu_{3} \Delta t & 0 & 0 \\
\mu_{3} \Delta t & 0 & 0 & 0 & 1 - \mu_{3} \Delta t & 0
\end{bmatrix}
\]  

Equation (3)

State transition density matrix can also be get

\[ A = \lim_{\Delta t \to 0} \frac{P(\Delta t) - E}{\Delta t} \]  

Equation (4)
Solving the equations can determine the probability that the system is in each state:

$$\begin{align*}
P(i=0) &= \sum_{j=1}^{5} P_i \\
\sum_{i=0}^{5} P_i &= 1
\end{align*}$$

(5)

Finally, using equation 5 to calculate the linear equations of the Turbine Regulation System with the matrix, the probability of each state of the Turbine Regulating System can be obtained.

$$\begin{align*}
P_i &= \begin{bmatrix}
1 & 1 & 1 & 1 & 1 \\
\lambda_1 & -\mu_1 & 0 & 0 & 0 \\
\lambda_2 & 0 & -\mu_2 & 0 & 0 \\
\lambda_3 & 0 & 0 & -\mu_3 & 0 \\
\lambda_4 & 0 & 0 & 0 & -\mu_4 \\
\lambda_5 & 0 & 0 & 0 & 0
\end{bmatrix} \\
\begin{bmatrix}
1 \\
\lambda_1 \\
\lambda_2 \\
\lambda_3 \\
\lambda_4 \\
\lambda_5
\end{bmatrix} &= \begin{bmatrix}
1 \\
0 \\
0 \\
0 \\
0 \\
0
\end{bmatrix}
\end{align*}$$

(6)

In the above formula, $P_i (i=0,1,2,3,4,5)$ respectively indicate the normal operation state of the water wheel regulating system, turbine failure, generator failure, speed system failure, water diversion system failure, generator port side The probability of six failure states of load failure.

3. Entropy Weight Fuzzy Comprehensive Evaluation

3.1 Identify evaluation metrics and reviews

The risks failures are expressed as equipment loss risk, system loss risk, and social loss risk[11]. Therefore, we determine the Turbine Regulation System evaluation index set as $U = \{u_1, u_2, u_3, u_4, u_5, u_6\}$

=\{ Maintenance cost, Maintenance time, Direct economic loss, Adjustment time, Overshoot, Peak time\}. The failure severity we assume $A = \{a_1, a_2, a_3, a_4, a_5\} = \{Mild, General, Heavier, Heavy, Extremely heavy\}$, using the membership function to characterize the fault corresponding to the comment in the comment set.

3.2 Establish a hydropower turbine regulation system evaluation matrix

Through the determination of the evaluation index of the turbine regulation system, and the system evaluation matrix can be established for the system.

$$A = \begin{bmatrix}
A_1 & A_2 & A_3 & A_4 & A_5 & A_6 \\
A_{11} & A_{12} & A_{13} & A_{14} & A_{15} & A_{16} \\
\vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\
A_{51} & A_{52} & A_{53} & A_{54} & A_{55} & A_{56}
\end{bmatrix}$$

(7)

In the above formula, $A_{ij} = (i=1,2,\ldots,5; j=1,2,\ldots,6)$ indicates the $j$-th evaluation index of the $i$-th part of the Turbine Regulation System. The evaluation matrix is standardized by the following formula.

$$A' = \max_{i=1,2,\ldots,5} A_{ij} - \min_{j=1,2,\ldots,6} A_{ij}$$

(8)

In the above formula, $A'_{ij} (i=1,2,\ldots,5; j=1,2,\ldots,6)$ indicates the value of the evaluation index.
after normalization is calculated.

The Entropy Weight Fuzzy Comprehensive Evaluation Method determine the weight vector of the evaluation index by the entropy weight method. The principle is to determine the respective weight vector according to the degree of change of each target value function value. The first is to find the entropy from the normalized matrix, and the solution process uses formula (9).

\[ H_j = -K \sum_{j=1}^{n} P_j \ln P_j \]  

(9)

\( H_j \) (j = 1, 2...6) represents the entropy value of the j-th evaluation index. \( K = \ln n \), where \( n \) represents the \( n \)-th fault assessment site of the evaluation system, and \( P_{ij} \) represents the state probability, \( P_{ij} = \frac{A'_{ij}}{\sum A'_{ij}} \). Thus the index weight \( \omega_j \) can be calculated.

\[ \omega_j = 1 - H_j / \left( m - \sum_{j=1}^{n} H_j \right) \]  

(10)

Solving the weight vector of six evaluation indicators by solving equations (11).

\[ \left\{ \omega_j = 1 - H_j / \left( m - \sum_{j=1}^{n} H_j \right) \right\} \]  

(11)

Finally calculate the evaluation index weight vector \( \omega = [\omega_1 \ \omega_2 \ \omega_3 \ \omega_4 \ \omega_5 \ \omega_6] \).

For the fault comment of each evaluation index, we can use the membership function to determine. We choose the isosceles triangle function distribution as the membership function, and set the base length of the isosceles triangle to 1.6. According to the following formula, we can take each indicator according to the following formula. The degree of membership to get the corresponding comment.

\[ r_{ij}(a_l) = \begin{cases} \frac{\lambda_{ij}-0.2}{0.8} & (0.2 \leq \lambda_{ij} \leq 1) \\ 0 & \text{Other} \end{cases} \]  

(12)

\[ r_{ij}(a_2) = \begin{cases} \frac{\lambda_{ij}+0.05}{0.8} & (0 \leq \lambda_{ij} \leq 0.75) \\ 0 & (0 \leq \lambda_{ij} \leq 0.75) \end{cases} \]  

(13)

\[ r_{ij}(a_3) = \begin{cases} \frac{\lambda_{ij}+0.3}{0.8} & (0 \leq \lambda_{ij} \leq 0.05) \\ \frac{1.3-\lambda_{ij}}{0.8} & (0.5 \leq \lambda_{ij} \leq 1) \end{cases} \]  

(14)

\[ r_{ij}(a_4) = \begin{cases} \frac{\lambda_{ij}+0.55}{0.8} & (0 \leq \lambda_{ij} \leq 0.25) \\ 0.8 & (0.25 \leq \lambda_{ij} \leq 1) \end{cases} \]  

(15)

\[ r_{ij}(a_5) = \begin{cases} \frac{0.8-\lambda_{ij}}{0.8} & (0 \leq \lambda_{ij} \leq 0.8) \\ 0 & \text{Other} \end{cases} \]  

(16)

By bringing the elements in each evaluation matrix into the above five formulas, the fuzzy evaluation matrix of the faults of the five parts of the system can be obtained, and the i-th part is faulty by \( R_i \) (i=1, 2...5). A matrix of membership degrees for each of the six evaluation indicators for each review.

\[ R_i = \begin{bmatrix} r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \\ r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \\ r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \\ r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \\ r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \\ r_{i1}(a_1) & r_{i1}(a_2) & r_{i2}(a_1) & r_{i2}(a_2) & r_{i3}(a_1) & r_{i3}(a_2) \end{bmatrix} \]  

(17)

The final comment for each part can be found below. Assuming that the final fuzzy evaluation set is \( B_i \), the formula for obtaining \( B_i \) is as follows

\[ B_i = \omega_i R_i = [b_{i1} \ b_{i2} \ b_{i3} \ b_{i4} \ b_{i5}] \]  

(18)
In the above formula, $\omega$ refers to the entropy weight vector of each index, $R_i$ corresponds to the fuzzy evaluation matrix of the fault of the $i$-th part with respect to the severity of the six evaluation indicators, and the $j$ bounded and multiplied calculation is performed. The formula is as follows.

$$b_k = \sum_{j=1}^{6} \omega_j R_{i} K = 1,2,3,4,5$$ (19)

In the above formula, each element in $b_i$ indicates the degree of failure of the $i$-th part failure relative to the membership of the comment set, and the larger the value, the greater the comment on the severity of the part. According to the principle of maximum membership degree, the maximum value is selected.

### 4. Turbine Regulation System risk assessment system

Based on the above probabilities of various states and the severity of system failures, we consider both to establish a risk assessment matrix for Turbine Regulation Systems. First, define the fault occurrence probability and establish a risk assessment matrix as shown in table 1 and table 2. We establish the risk assessment matrix of the turbine regulation system by using the fault occurrence probability level as the abscissa and the comment on the seriousness of the fault as the ordinate, as shown in Table 3, which characterizes the fault according to different probability levels and the severity of different levels to determine their risk value. The meanings of the different risk values showed in table 4.

| Table 1. Occurrence probability level |
|--------------------------------------|
| Failure probability level | Probability level value $P$ |
|--------------------------|---------------------------|
| Negligible | $P < 0.001$ |
| Lower | $0.001 \leq P \leq 0.01$ |
| Medium | $0.01 \leq P \leq 0.05$ |
| Higher | $0.05 < P \leq 0.1$ |
| High | $P > 0.1$ |

| Table 2. Definition of severity of fault severity |
|--------------------------------------|
| Failure comment | Definition |
|----------------|----------------|
| Mild | Cause low economic loss, repaired in short time, the adjustment time is short, the overshoot is small, the system can return to the original operation state in short time. |
| General | Cause certain economic loss, repaired in allowed time, the adjustment time is long, the overshoot is large, can return to the original operation state within the allowed time. |
| Heavier | Cause large economic loss, repaired in long time, the adjustment time is long, the overshoot is large, need long adjust time to enter the new stable operation state. |
| Heavy | Cause large economic loss, long troubleshooting time, difficult maintenance, long adjustment time, large overshoot, If necessary, stop the entire system. Running. |
| Extremely heavy | Severe economic losses, long troubleshooting time, difficult maintenance, long adjustment time, large overshoot, must be stopped immediately. |
Table 3. Risk assessment matrix

| Failure severity | Negligible | Lower | Medium | Higher | High |
|------------------|------------|-------|--------|--------|------|
| Mild             | I          | I     | II     | II     | III  |
| General          | I          | II    | II     | III    | III  |
| Heavier          | II         | III   | III    | IV     | IV   |
| Heavy            | III        | III   | IV     | V      | V    |
| Extremely heavy  | III        | IV    | IV     | V      | V    |

Table 4. Risk assessment risk of hydraulic turbine governing system

| Risk value | Definition                                                                 |
|------------|-----------------------------------------------------------------------------|
| I          | Failure this part will not have much impact on the system. You can observe it first and then decide whether to take maintenance measures. |
| II         | The failure has a low impact on the turbine regulation system, and the fault location should be recorded in real time to find the problem in time. If the fault occurs, the turbine control system will have a medium impact. Positive measures should be taken to find out the cause of the fault and deal with the fault problem in time. |
| III        | The failure has a great impact on the turbine regulation system. The unit should be trouble-checked as soon as possible to find problems in time to avoid the expansion of the problem. The failure has a great impact on the turbine regulation system, and immediately carries out the general inspection of the fault, if necessary, the unit is disengaged from the power system. |
| IV         |                                                                 |
| V          |                                                                 |

5. Example

Take the LuDiLa hydropower station as an example. Evaluation index adjustment time, overshoot, peak time[12] and then according to the expert experience, the evaluation index maintenance cost, maintenance time and direct economic loss values are as follow table5. The failure rate $\lambda_k$ and repair rate $u_k$ of the turbine regulation system are shown in table 6. Finally, the risk assessment of each subsystem of the turbine regulation system is carried out in table7.

Table 5. Evaluation table of fault severity of hydraulic turbine governing system

| Fault location      | Maintenance cost (Thousand) | Inspection time (h) | Direct economy loss(Thousand) | Peak time (s) | Adjustment time (s) | Overshoot (%) |
|---------------------|-----------------------------|---------------------|-------------------------------|---------------|---------------------|---------------|
| Turbine             | 130                         | 122.8               | 552                           | 3.89          | 273                 | 4.17          |
| Generator           | 122                         | 14.2                | 1062                          | 4.74          | 179.1               | 5.23          |
| Speed control system | 155                         | 28.7                | 2865.7                        | 3.22          | 445.16              | 3.07          |
| Water diversion system | 160                   | 41                  | 365                           | 8.8           | 328.9               | 5.97          |
| Load                | 30                          | 22                  | 150                           | 11.1          | 214.5               | 6.39          |

Table 6. Failure rate and repair rate of Turbine Regulation System

| Fault location      | $\lambda_k$ | $u_k$   |
|---------------------|-------------|---------|
| Turbine             | 0.13221     | 8.839   |
| Generator           | 0.11348     | 51.022  |
| Speed control system | 0.08775     | 102.33  |
| Water diversion system | 0.01072   | 144.37  |
| Load                | 0.11668     | 26.25   |
Table 7. Risk assessment results of Turbine Regulation System.

| Fault location          | Probability level value | Failure severity | Risk value |
|-------------------------|-------------------------|-----------------|------------|
| Turbine                 | Medium                  | Heavy           | IV         |
| Generator               | Lower                   | Heavier         | III        |
| Speed control system    | Negligible              | Extremely heavy | III        |
| Water diversion system  | Negligible              | Mild            | I          |
| Load                    | Lower                   | General         | I          |

6. Conclusion

Aiming at the problem of lack of operational risk assessment method for Turbine Regulation System operation, this paper proposes a risk assessment system for Turbine Regulation system based on Markov State Model and Entropy Weight Fuzzy Comprehensive Evaluation. The system can accurately evaluate each subsystem, not only can evaluate the overall operation of the system, but also evaluate the state of the system. By analyzing the risk assessment results, it provides a basis for formulating the corresponding maintenance strategy. Applying the risk assessment system to the Turbine Regulation System can evaluate the actual system operation, and the system has certain practicability.

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