Priority analysis of equipment failures for a hydraulic turbine generator unit

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Abstract: Ensuring the safety operation of hydropower stations is one of the key challenges for electric generation. Clearly the safety operation of such systems can only be archived with proper and effective maintenance scheduling. The objective of this study is to analyze, rank and prioritize electromechanical equipment failures of hydraulic turbine generator units based on operating data and expert elicitation. A simple qualitative risk evaluation model is proposed able to consider equipment failures. The weights and risk indexes with respect to these failures are formulated to identify their priorities. The proposed tool is applied for the risk prioritization equipemnt failure e.g. lower rigidity, misalignment, rotating parts, axis bend, runner blade, water guide, and mass distributor of a hydropower station in China. The results have been compared against the actual statistics of component failures of the hydropower station, considered showing show good agreement.

Key words: hydraulic turbine generator unit; risk priority; equipment failures; analytic hierarchy process;

1. Introduction

According to 2018 International Hydropower Association report, hydropower plants have been built more than 160 countries, with a total number of 11000 hydropower plants equipped with 27000 hydro-turbine generator units [1]. China is leading this hydropower boom, followed by India, Europe, the United States and Japan. This huge amount of electrical energy produced via hydropower plants represents a sustainable, affordable and secure energy supply [2, 3].

However, the accelerating expansion of hydropower plants and their strategic importance as energy storage facilities require a safety operation of such plants and the abaility to cope and manage equipment failures [4, 5].
The general solution to reduce the risk of equipment failure is by performing regular maintenance [6, 7,42]. More specifically, the frequent demand of hydraulic turbine generator units (HTGUs) for maintenance that involves complex bureaucratic procedures, high cost and an enormous amount of repair time, makes this maintenance activity vulnerable and costly for hydropower companies [8-10].
One method used to decrease the expected maintenance costs is by performing fatigue failure analysis, which allows hydropower operators to predict the remaining useful life of components of HTGUs [11-16].

Fault diagnosis can be divided into two categories: data-driven diagnosis methods and model-based diagnosis methods [19-21]. The data-driven diagnosis relays on the huge failure data collected from among different hydropower stations that allows to identify weak components and derive risk features. For example, in ref. [16], the authors performed the failure analysis of bolts used to connect a hydraulic turbine to the shaft of a hydroelectric power generator, using data measured on the turbine shaft at different power levels and the actual power generation history identifying an expected useful of of only 16.4 years. This data driven methodology depends on the availability of a large data set of failure data. Unfortunately, failure data from HTGUs are limited, especially for those hydropower stations constructed in 1990s [17, 18].
The data-driven diagnosis methods have been widely studied for the application of HTGUs, such as the developed fault diagnosis model on the basis of EMD fusion [22], support vector machine diagnosis theory [23], and the fuzzy network diagnosis method [24].
Model-based diagnosis methods are not based on past data and statistics, instead based on phenomenal principles they have the ability to predict the failure of HTGUs [25-27]. For example, in ref. [28], the authors developed a fluid-structure model of the Francis hydro turbine in normal operation condition, with the aim of predicting crack failures. Recently developed models include fractional-order model to predict the misalignment fault [29], electromagnetic and hydraulic model to predict torsional vibration fault [30, 31], hydro-turbine governing system model to predict frequency reliability [32]. These models show a good performance in predicting dynamic characteristics, which is helpful to fault diagnosis, but not fully adopted in engineering practice.
Numerical models able to create a digital replica of physical components allow to take optimal decision wth the aim of improving the safety and reliability of the HTGUs and at the sime time minimizing the overall costs. This trend is highlighted defined in 2018 IHA’s report [1]. A typical example, the Portugal’s electricity operators EDP, ~~one of Europe’s largest electricity operators~~, has begun a program of implementing digitalization to optimize maintenance strategies of HTGUs. However, difficulties remain using digital devices with respect to the identification and reduction of equipment failure risks in HTGU’s [33]. One of the main challenge is due to the number of different factors that are able to produce the failure of the equipment and the complex interaction of hydraulic, mechanical, and electric subsystems, which poses an obstacle for digital device to make a reliable prediction that can be adopted by decision-makers [34, 35]. Hence, identifying and ranking the most important factors that contribute to the equipment failure is fundamental to the development of credible decision making tools [36, 37].
Another challenge in the evaluation and identification of risk factors is due to the number of standards that need to be investigated in order to meet the requirements of specific equipment.

Hence, multi-standard analysis is mandatory to use in the evaluation of the risk factor and priority analysis. Analytic Hierarchy Process is one of the most widely used decision-making method, with the aim of evaluating complex social, political, economic, and technological issues [38, 39] but not yet applied for the risk analysis of hydraulic turbine generator units

In this paper, Analytic Hierarchy Process is adopted to identity and prioritize risk factors on component failure of hydraulic turbine generator units.

The aim of the proposed study is to priority the factors responsible for equipment failures in order to provide a maintenance guidance for HTGUs. Focusing only on the most important factors, it will be then feasible to construct a credible digital replica of HTGUs.

This study is structured as follows. Section 2 presents the proposed methodology and the risk evaluation model of HTGU. The calculated process of weights and risk indexes with detailed analysis is shown in Section 3. Conclusions are given in Section 4.

2. Methodology

The priority analysis in the Analytic Hierarchy Process is composed of four separate calculation procedures for the analysis of equipment failures as shown in Fig. 1.

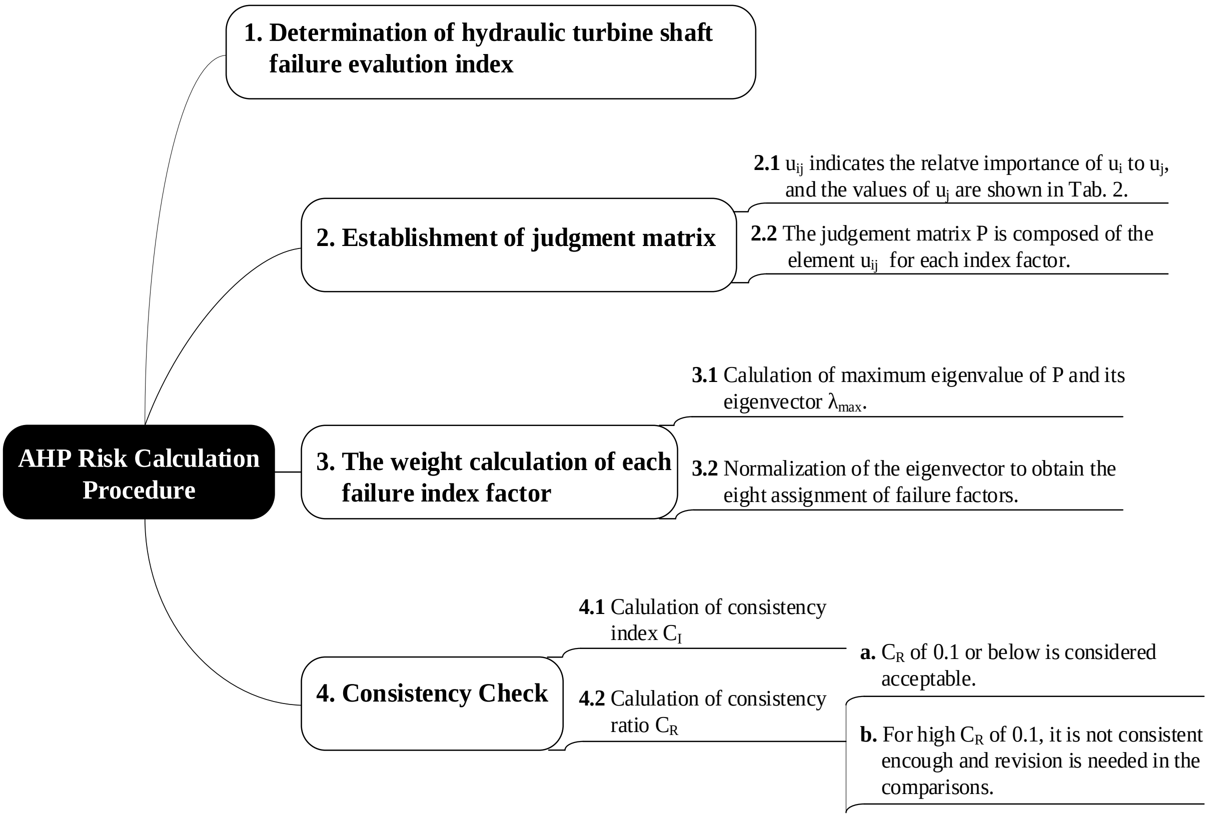

Fig. 1 Calculation procedure of analytical hierarchy process for hydraulic turbine generator units.

2.1 Hierarchical structure model

The first step establishes a hierarchical structure model (as shown in Fig. 2). This model aims at identifying relationships between the objective (at the top of the hierarchy model) and all the failures considered and to present them in a logical order within the decision process [40].

In the priority analysis, the initial step is to form a multi-level hierarchical structure model containing all the criteria (as equipment failures) and alternatives (used in this study as meaning “the factor or process of causing equipment failures in a HTGU. Criteria of one level have effects on the alternatives of the last level, but also controlled by the last level of the alternatives. After obtaining the relationships between these criteria and alternatives, the hierarchical structure model is established for a specific system (the established example model of HTGU is shown in Section 3). The levels (including criteria and alternatives) are defined as the comparison set (*U*), where

$$\vec{U} = (\vec{u}_1, \vec{u}_2, \cdots, \vec{u}_i, \cdots, \vec{u}_n) = \begin{cases} \vec{u}_1 = (u_{11}, u_{12}, \cdots, u_{1j}, \cdots, u_{1n}) \\ \vec{u}_2 = (u_{21}, u_{22}, \cdots, u_{2j}, \cdots, u_{1n}) \\ \vdots \\ \vec{u}_i = (u_{i1}, u_{72}, \cdots, u_{ij}, \cdots, u_{1n}) \end{cases}. \quad (1)$$

The rows, *i*, indicated the equipment failure while the columns, *j*, are used to represent the reasons causing these failures, respectively.

The importance of each failure is rated from 1 to 9 as shown in Tab. 1, as based on literature [41].

Tab. 1 Rating scores of the criteria and alternatives in the hierarchical structure model.

Rating	Implication
1	Equal importance between levels u_i and u_j.
3	Moderate importance of level u_i than u_j.
5	Rather importance of level u_i than u_j.
7	Quite importance of level u_i than u_j.
9	Essential importance of level u_i than u_j.
2，4，6，8	A suitable compromise importance between levels u_i than u_j.

2.2 Construction of judgment Matrix

In the second step, the judgment matrix is constructed on the basis of historical data estimated by station experts, using score ratings (as shown in Tab. 10) of equipment failures. The judgement matrix is defined as

$$P = \begin{bmatrix} p_{11} & p_{12} & \cdot\cdot & p_{1n} \\ p_{21} & p_{22} & \cdot\cdot & p_{2n} \\ \vdots & \vdots & \cdot\cdot & \vdots \\ p_{n1} & p_{n2} & \cdot\cdot & p_{nn} \end{bmatrix} \quad (2)$$

where the values of the matrix elements (p_{ij}) are computed on the basis of the comparison of importance degree (see Tab. 1) in relation to criteria and all alternatives.

2.3 Calculation of criteria weights

The importance (priority significance) of different type of failure is identified and represented by means of weights associated to each failure and its obtained by solving the following eigenvalue problem:

$$P\omega = \lambda_{\max}\omega, \quad (3)$$

where λ represents an eigenvalue and ω an eigenvector.

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2.4 Consistency Check

In the final step, the consistency is checked allowing to verify the rationality of the priority results for the equipment failures.

Tab. 2 Values of the consistency index R_I for the judgment matrix order between 1and 9.

Order n	1	2	3	4	5	6	7	8	9
R_I	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45

The formulation of consistency check is defined as

$$\begin{cases} C_i = \dfrac{\lambda_{\max} - n}{n - 1} \\ C_R = \dfrac{C_i}{R_I} \end{cases}, \tag{4}$$

where n is the order of the judgment matrix; C_i is the consistency index; C_R is the average random consistency rate; R_I is the average random consistency index, and the values are listed in Tab. 2, as based on literature [40].

The judgment matrix P meets the consistency check when one the following conditions is satisfied:

1. R_I<0.1
2. λ_{max}=n and C_I=0,

Otherwise it is necessary to adjust the matrix element in P to have a satisfactory consistency.

3. Case study

A HTGU is a key facility in the hydropower station containing a large number of sub-systems and components. The main components are: the hydraulic turbine, the synchronous generator, the rotational shafts with the coupling flange, the guide bearing, and the guide vane auxiliary equipment. The main equipment of synchronous generator involved in the HTGU is the stator, the rotor, the magnetic pole, and the fixed part locked into the station house. The hydraulic turbine and the guide vane auxiliary are mainly within the control systems [25], and include the turbine runner, the flow passage components (such as spiral case), the guide vane, the servomotor, and the oil-gas-water auxiliary equipment.

This case study focuses only on the main equipment and the reasons causing equipment failures. Data of equipment failure have been collected from China's maintenance company of *The Yellow River Electric Power Maintenance Engineering Co Ltd*. Seven equipment and forty fault reasons are placed at the central and bottom of the hierarchical structure model and shown in Fig. 3

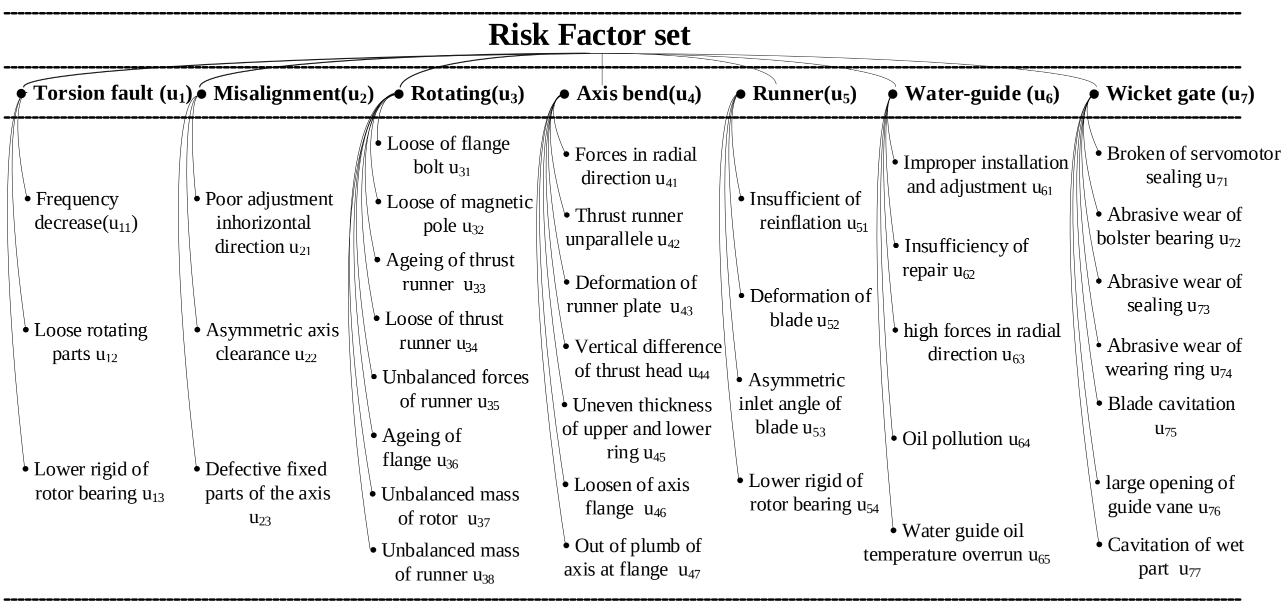

Fig. 2 Hierarchical structure model for the hydraulic turbine generator unit.

The seven equipment failures and the forty fault reasons include:

(1) Axis torsion fault u_1: u_1=(u_{11}, u_{12}, u_{13});

(2) Rubbing fault u_2: u_2=(u_{21}, u_{22}, u_{23});

(3) Rotating parts failure u_3: u_3=(u_{31}, u_{32}, u_{33}, u_{34}, u_{35}, u_{36}, u_{37}, u_{38});

(4) Axis bend fault u_4: u_4=(u_{41}, u_{42}, u_{43}, u_{44}, u_{45}, u_{46}, u_{47});

(5) Turbine runner fault u_5: u_5=(u_{51}, u_{52}, u_{53}, u_{54});

(6) Water guide bearing fault u_6: u_6=(u_{61}, u_{62}, u_{63}, u_{64}, u_{65});

(7) Wicket gate Failure u_7: u_7=(u_{71}, u_{72}, u_{73}, u_{74}, u_{75}, u_{76}, u_{77}).

The details of the fault reason (u_{ij}) are shown in Fig. 2. In light of the above analysis, the seven equipment and forty fault reasons expressed by symbols U=(u_1, u_2, u_3, u_4, u_5, u_6, u_7).

The hierarchy structure model is established as

$$level\text{-}1.\ U \leftarrow (u_1,u_2,u_3,u_4,u_5,u_6,u_7)\quad level\text{-}2.\ \begin{cases} u_1 \leftarrow (u_{11},u_{12},u_{13}) \\ u_2 \leftarrow (u_{21},u_{22},u_{23}) \\ u_3 \leftarrow (u_{31},u_{32},u_{33},u_{34},u_{35},u_{36},u_{37},u_{38}) \\ u_4 \leftarrow (u_{41},u_{42},u_{43},u_{44},u_{45},u_{46},u_{47}) \\ u_5 \leftarrow (u_{51},u_{52},u_{53},u_{54}) \\ u_6 \leftarrow (u_{61},u_{62},u_{63},u_{64},u_{65}) \\ u_7 \leftarrow (u_{71},u_{72},u_{73},u_{74},u_{75},u_{76},u_{77}) \end{cases} . \tag{5}$$

Using the values shown in Tab. 1 and Eq. (2), the judgment matrix is obtained (Table 2).

Tab. 3 Judgment matrix u_i of the seven equipment for the hierarchical structure model.

j i	1	2	3	4	5	6	7
1	1	3	1/2	1/3	3	1/4	3
2	1/3	1	1/4	1/4	2	1/5	1/2
3	2	4	1	1/2	4	1/3	4
4	3	4	2	1	4	1/2	4
5	1/3	1/2	1/4	1/4	1	1/5	1/2
6	4	5	3	2	5	1	5
7	1/3	2	1/4	1/4	2	1/5	1

From Eq. (3) and Tab. 3, the normalized maximum eigenvalue and its eigenvector are calculated as λ_{max}=7.33 and ω=(0.1108, 0.05, 0.17, 0.23, 0.04, 0.34, 0.06), respectively. From Eq. (4), the value of the average random consistency rate C_R is 0.0416 (<0.1), indicating that the obtained judgment matrix is reasonable. Therefore, the eigenvector of ω=(ω_1, ω_2, ω_3, ω_4, ω_5, ω_6, ω_7) is used as the criteria weights for the equipment failure, i.e. U=(0.1108, 0.05, 0.17, 0.23, 0.04, 0.34, 0.06).

From the analysis described above, the calculation results of the alternatives (i.e. reasons causing these equipment failures) are summarized in Tables. 4–10.

Tab. 4 Judgment matrix $u_{1\text{-}ij}$ of the fault reasons for the torsion fault.

j i	1	2	3	$\omega_{1\text{-}ij}$	$\lambda_{1\text{-}max}$	$C_{1\text{-}R}$
1	1	1/6	1/5	0.0811	3.0291	0.0251
2	6	1	2	0.5769		
3	5	1/2	1	0.3420		

Tab. 5 Judgment matrix $u_{2\text{-}ij}$ of the fault reasons for the misalignment fault.

j i	1	2	3	$\omega_{2\text{-}ij}$	$\lambda_{2\text{-}max}$	$C_{2\text{-}R}$
1	1	2	5	0.5591	8.8806	0.0462
2	1/2	1	5	0.3522		
3	1/5	1/5	1	0.0887		

Tab. 6 Judgment matrix $u_{3\text{-}ij}$ of the fault reasons for the rotating parts fault.

j i	1	2	3	4	5	6	7	8	$\omega_{3\text{-}ij}$	$\lambda_{3\text{-}max}$	$C_{3\text{-}R}$
1	1	2	6	2	5	1/3	1/3	1/3	0.0969	8.8806	0.0892
2	1/2	1	6	1/2	5	1/3	1/3	1/4	0.0675		
3	1/6	1/6	1	1/6	1/2	1/8	1/8	1/8	0.0180		
4	1/2	2	6	1	5	1/3	1/3	1/3	0.0821		
5	1/5	1/5	2	1/5	1	1/7	1/7	1/7	0.0237		
6	3	3	8	3	7	1	1	2	0.2273		
7	3	3	8	3	7	1	1	2	0.2273		
8	3	4	8	3	7	2	2	1	0.2571		

Tab. 7 Judgment matrix $u_{4\text{-}ij}$ of the fault reasons for the axis bend fault.

j i	1	2	3	4	5	6	7	$\omega_{4\text{-}ij}$	$\lambda_{4\text{-}max}$	$C_{4\text{-}R}$
1	1	2	1/3	2	2	1/3	1/2	0.1102		
2	1/2	1	1/3	2	2	1/3	1/2	0.0899		
3	3	3	1	3	4	1/2	2	0.2361		
4	1/2	1/2	1/3	1	2	1/4	1/2	0.0702	7.15	0.0189
5	1/2	1/2	1/4	1/2	1	1/4	1/2	0.0549		
6	2	3	2	4	4	1	3	0.3037		
7	2	2	1/3	2	2	1/3	1	0.1350		

Tab. 8 Judgment matrix $u_{5\text{-}ij}$ of the fault reasons for the runner fault.

j i	1	2	3	4	$\omega_{5\text{-}ij}$	$\lambda_{5\text{-}max}$	$C_{5\text{-}R}$
1	1	1/7	1/5	1/3	0.0536		
2	7	1	4	5	0.5954	4.1776	0.0658
3	5	1/4	1	3	0.2379		
4	3	1/5	1/3	1	0.1130		

Tab. 9 Judgment matrix $u_{6\text{-}ij}$ of the fault reasons for the water guide fault.

j i	1	2	3	4	5	$\omega_{6\text{-}ij}$	$\lambda_{6\text{-}max}$	$C_{6\text{-}R}$
1	1	1/2	1/2	1/2	1/2	0.1065		
2	2	1	2	2	2	0.3229		
3	2	1/2	1	2	2	0.2447	5.1947	0.0435
4	2	1/2	1/2	1	1/2	0.1405		
5	2	1/2	1/2	2	1	0.1854		

Tab. 10 Judgment matrix $u_{7\text{-}ij}$ of the fault reasons for the wicket gate fault.

j i	1	2	3	4	5	6	7	$\omega_{7\text{-}ij}$	$\lambda_{7\text{-}max}$	$C_{7\text{-}R}$
1	1	3	2	1/3	1/5	1/2	1/3	0.0752		
2	1/3	1	1/3	1/5	1/7	1/2	1/5	0.0329		
3	1/2	3	1	1/3	1/5	2	1/3	0.0702		
4	3	4	3	1	1/4	4	2	0.1910	7.1701	0.0215
5	5	7	5	4	1	6	4	0.4268		
6	1/2	2	1/2	1/4	1/6	1	1/4	0.0480		
7	3	4	3	1/2	1/4	4	1	0.1559		

Finally, from the values reported in Tables 3–10, it is possible to calculate the scoring…. TO BE COMPLETED

$$\begin{cases} \omega_{1-ij} = (0.0811, 0.5769, 0.3420) \\ \omega_{2-ij} = (0.5591, 0.3522, 0.0887) \\ \omega_{3-ij} = (0.0969, 0.0675, 0.0180, 0.0821, 0.0237, 0.2273, 0.2273, 0.2571) \\ \omega_{4-ij} = (0.0969, 0.0675, 0.0180, 0.0821, 0.0237, 0.2273, 0.2273, 0.2571) \\ \omega_{5-ij} = (0.0536, 0.5954, 0.2379, 0.1130) \\ \omega_{6-ij} = (0.1065, 0.3229, 0.2447, 0.1405, 0.1854) \\ \omega_{7-ij} = (0.0752, 0.0329, 0.0702, 0.1910, 0.4268, 0.0480.0.1559) \end{cases} \cdot \quad (6)$$

The scoring method is defined to develop a clear rating criterion, aiming to make an effective risk assessment of the equipment failures for the HTGU, which is summarized in Tab. 11. In this study, the scores corresponding to equipment are based on expert judgment (i.e. obtained with the discussions of engineers worked in *The Yellow River Electric Power Maintenance Engineering Co Ltd*,) and shown in Tab. 12.
Each equipment is ranked on the basis of the hierarchical structure model (see Fig. 3), and the scores of the investigated equipment are averaged. Compared with the equipment fault statistics over the years, the consistent results are the final scores of these equipment, and inconsistent results lead to the increasing number of sample surveys to re-score and adjust the score results. SEE MY COMMENT

From the hierarchical structure model, the scoring result of each fault reason corresponding to the criteria weight (as obtained in Eq. (6)) are added to the calculated results after multiplying the weights. The obtained added results (see Fig. 3) refer to the priority results of the rating criterion of equipment failures for the hydraulic turbine generator unit.

Tab. 11 Rating criterion of Equipment risks for the hydraulic turbine generator unit.

Score	State of Equipment for HTGU	Malfunction level
0~49	Operate with good quality	Ⅰ
50~69	Operate with fair quality	Ⅱ
70~84	Operate with a certain fault risk	Ⅲ
85~94	Operate with high fault risk	Ⅳ
95~100	Overhaul suggestion	Ⅴ

Tab. 12 Scores of the equipment failures for the hydraulic turbine generator unit

Subject	failure	Score
Hydraulic turbine generator unit	Axis torsion fault	80
	Rubbing fault	65
	Rotating parts fault	90
	Axis bend fault	85
	Turbine runner fault	65
	Water guide bearing fault	91
	Wicket gate fault	68

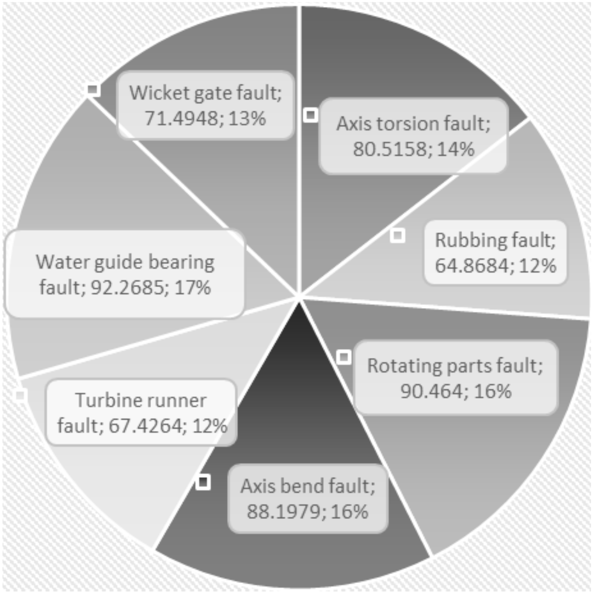

Fig. 3 Priority significance ratio of the five equipment failures for the hydraulic turbine generator unit.

From Fig. 3, the water guide bearing (17%) is the most important equipment for HTGU, followed by the axis bend (16%), the rotating parts (16%), the axis torsion (14%), the wicket gate (13%), the turbine runner (12%), and the rubbing (12%). These scores (as shown in Fig. 3) are consistent with the results shown in Tab. 12, which verifies that the analytic hierarchy process method and the obtained results are effective, feasible, and reliable. It is clear that these results are engineer dependent and are likely to be different when applied to other operation data of HTGU. These results might also be affected by different score engineers. It is important to notice that these results are qualitative and only used to rank the equipment failures and associated fault reasons. Quantitative approaches require to consider explicitly all the uncertainty associated with different parameters of the model (see e.g. [43]).

The results of all the equipment failures and the corresponding fault reasons are shown in Fig. 4.

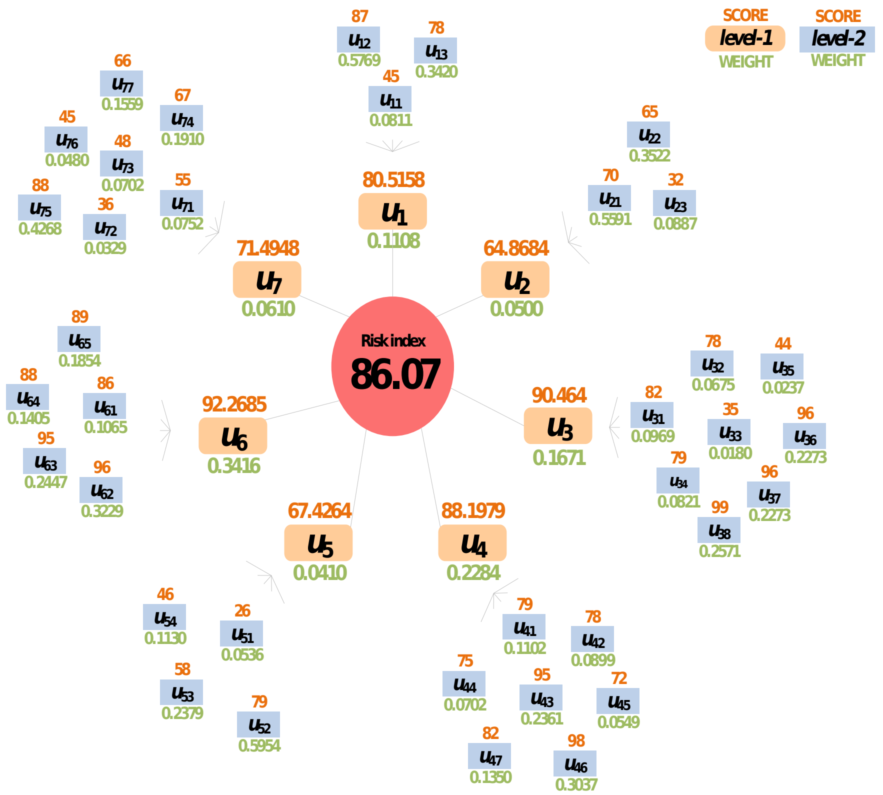

Fig. 4 Priority significance ratio of the seven equipment failures and forty fault reasons for the hydraulic turbine generator unit. Variable in the shape ▬ with orange color refers to the equipment failure (level 1), Variable in the shape ▬ with cyen color refers to the fault reason (Level 2). The values above the colored boxes indicates the score while the values reported under the box represents the criteria weight.

From Fig. 4, the loose rotating parts (u_{12}), the misalignment in horizontal direction (u_{21}), the unbalanced mass of turbine runner (u_{38}), the loosen of axis flange (u_{46}), the deformation of blade (u_{52}), the insufficiency of repair (u_{62}), and the blade cavitation (u_{75}) are seen as the most important parts causing the torsion fault, misalignment, rotating, axis bend, runner, water guide bearing, and wicket gate, respectively. The criteria weights of these equipment failures are very high. So, the maintenance workers should focus on these parts of the safety issues. The main reason is that these components involve the long-term operation of the machine, the presence of fuel and oil, and the exchange of heat. Several other fault reasons of criteria weights are also higher, such as the axis bend and the runner failures. In general, the risk index of turbine equipment failure is quite significant. This is also an indicator of the great importance to the maintenance of different part of the hydro-turbine equipment unit of hydropower.

4. Conclusions

This study presented and analyzed the causes of equipment failures of electromechanical equipment of a Chinese hydropower station based on operating data. The proposed methodology based on Analytic Hierarchy Process allows to prioritize and rank the different reasons of equipment failures of hydraulic turbine generator units. The proposed qualitative methodology is simple and allows to use historical failure data of components as well expert judgments. The proposed analysis contributes to the safety operation of of hydraulic turbine generator units allowing the hydropower operators to prioritizing the maintenance efforts, assess the quality of the fault risks of the component parts which can provide guidance for the subsequent dynamic modeling of the hydraulic turbine generator unit. This is instrumental for obtaining a robust and economical maintenance strategy allowing a safe operation of hydropower stations.

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