

# Condition Analysis of Steam Turbine DEH Control System based on Data Fusion

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**Abstract**-Aiming at the problem that the system of digital electro-hydraulic(DEH) regulation system is complex and difficult to analyze its condition, a method based on characteristic extraction and information fusion is proposed. By making RCM analysis, the indexes for quantitative risk evaluation of fault modes are determined, and the fuzzy rule base for risk evaluation is built. Using fuzzy inference, the system fault modes are ranked according to their risk level. Then, the condition characteristic parameters are extracted according to the pivot fault modes. Using the extracted characteristic parameters, an information fusion method based on evidence theory is put forward to evaluate the system's condition. It is shown by the instance that this method is feasible and effective and the condition analysis results can be used as a support for next maintenance decisions.

## INTRODUCTION

With the rapid developing of electric power industry in our country, the maintenance mode is changing from planned maintenance to condition-based maintenance. The pivotal task of condition-based maintenance is to evaluate the equipment condition synthetically and arrange maintenance times and items reasonably. DEH regulation system is complex and includes many components. Meanwhile, the relations between subsystems have strong relationships. In condition analysis, reasonable condition characteristic extraction method and accurate condition evaluation model are two pivotal aspects. But, in most methods<sup>[1]</sup>, condition characteristics are extracted just using qualitative analyzing and expert opinion, and the condition evaluation model is just linear integration. The accuracy of condition evaluation results is weakened greatly. So based on RCM analysis, fuzzy theory and evidence theory, a method of condition analysis is put forward for DEH system.

In the paper, take DEH regulating system as an example, all subsystems are analyzed in RCM method based on system division and the fault modes and their risk evaluation indexes are determined. Then based on fuzzy theory, the risk levels of all fault modes are evaluated quantitatively using fuzzy inference method and the characteristics are extracted by analyzing the fault modes with higher risk levels. Finally, the system condition is analyzed by information fusion arithmetic based on D-S theory.

## RCM ANALYSIS ON POWER STATION EQUIPMENT

### A. System division of DEH regulating system

According to the principle of function correlation, the system division is shown in Fig.1

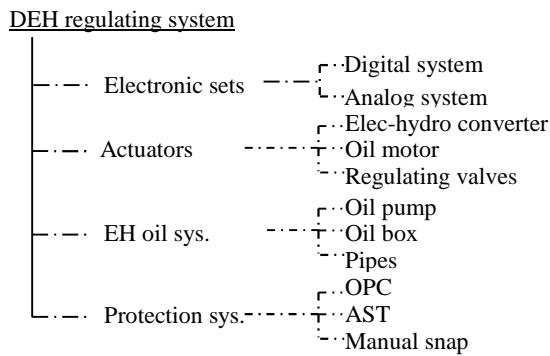


Fig.1 The division of DEH regulating system

### B. FMEA on DEH regulating system

In the process of fault mode and effective analysis, the possible fault modes and their effects of subsystem or components are listed in the form of table<sup>[2,3]</sup>. In the same time, the risk evaluation indexes of fault modes are also determined. Based on the actual operation condition of DEH regulating system, the components prone to fail are selected to be analyzed. The possible fault modes of the components are determined. In Tab.1, the fault modes and their risk evaluation factor values of oil motor are listed.

Tab.1 Oil motor' failure modes and linguistic descriptions

FM no.	Failure modes	Severity	Occ Freq.	Dete.
F1	Inlet jammed	Mod	Vlow	Mod
F2	Outlet jammed	Mod	Low	Low
F3	Spring rapture	Mod	Low	Mod
F4	Unfit preload	Mod	Low	Low
F6	Piston jammed	Mod	High	Low
F7	Piston wear	Mod	High	Low
F8	Sealing ring bad	Mod	Mod	Mod
F9	LVDT break	Mod	Low	High

### C. Quantitative indexes of failure mode risk analysis

During the risk evaluating of failure mode, the 3 indexes of failure severity, probability of occurrence and detectability should be considered. The evaluation criterions of the there indexes are shown in table 2, table 3 and table 4. In addition, the risk evaluation index of failure mode is shown in table 5.

Tab.2 The scale for severity

Severity	Rating
Very low	1
Low	2
	3
Moderate	4
	5
	6
High	7
	8
Very high	9
	10

Tab.3 The scale for probability of occurrence

Probability of occurrence	Failure rate(day)	Rating
Very low	<1:20000	1
Low	1:20000	2
	1:10000	3
Moderate	1:2000	4
	1:1000	5
	1:200	6
High	1:100	7
	1:20	8
Very high	1:10	9
	1:2	10

Tab. 4 The scale for detectability

Detectability	Probability of detection(%)	Rating
Very high	85 -100	1
High	75-85	2
	65-75	3
Moderate	55-65	4
	45-55	5
	35-45	6
Low	25-35	7
	15-25	8
Very low	5-15	9
	0-5	10

Tab.5 The scale for risk evaluation

Risk	None	Elow	Vlow	Rlow	Low
Rating	1	2	3	4	5
Risk	Mod	High	Rhigh	Vhigh	Ehigh
Rating	6	7	8	9	10

## RISK ANALYSIS ON FAILURE MODES BASED ON FUZZY INFERENCE

### A. Fuzzy membership function<sup>[4,5]</sup>

Depending on the table 2~5 and the experiences of domain experts, the fuzzy membership functions for the severity, the probability of occurrence, the detectability and risk of failure mode is set up, and shown in figure2~5.

In the figures, the scope of abscissa is between 1 and 10. Using figures of fuzzy membership function, the corresponding fuzzy membership value can be gained when input the evaluation value of a certain index. The value of a certain index can be decided by the there evaluation criterion tables.

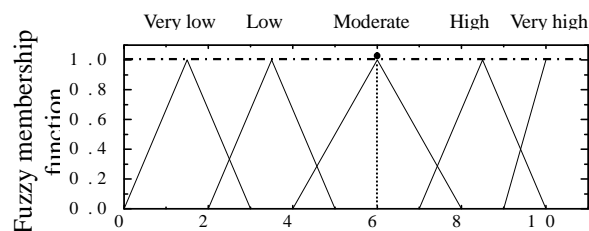


Fig. 2 The severity

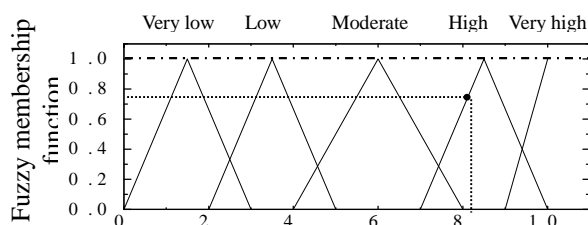


Fig. 3 The probability of occurrence

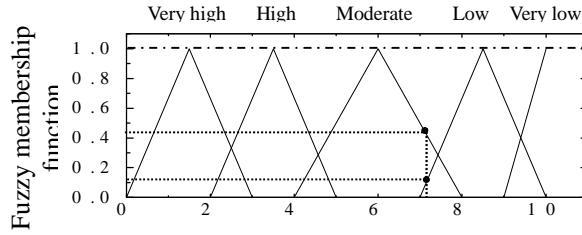


Fig. 4 The detectivity

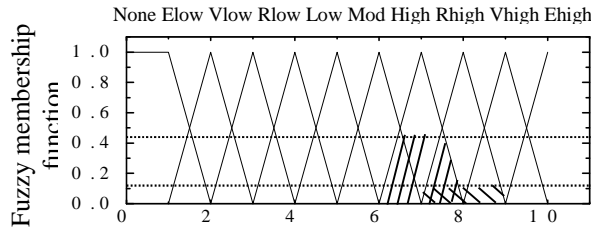


Fig. 5 The risk level

### B. Fuzzy rule base development

Fuzzy inference systems are knowledge-based or rule-based systems constructed from human knowledge in the form of fuzzy *IF-THEN* rules. In fuzzy inference systems, the rule base describes the synthetic risk caused by input variables with different combination. The rules usually are described by natural language, and in the form of *IF-THEN*. The *IF-THEN* rule consists two parts, one is precondition which can compares with input, the other is the result under the precondition. In this paper, the input of rule base is severity, probability of occurrence and detectability, the output is a linguistic variable, that is, the criterion of fault mode risk evaluation.

### C. Principle of fuzzy inference

The min-max fuzzy inference form is used in the paper<sup>[6,7]</sup>, there are 3 important formulas as follows.

According to the fact “ $x_0$  and  $y_0$ ” and the inference of rule “ $A_i \text{ and } B_i \Rightarrow C_i$ ” ( $i=1, 2, \dots, n$ ), the fuzzy membership grade of  $C_i$  can be got using formula (1)

$$m_{C_i}(z_i) = m_{A_i}(x_0) \wedge m_{B_i}(y_0) \quad (1)$$

Suppose a certain fact  $x_1, y_1$ , from  $m$  rules, a same inference result  $C_i' (i=1, 2, \dots, L, m)$  is obtained. The  $m$  rules correspond to  $m$  fuzzy membership  $m_{C_{i1}}, m_{C_{i2}}, \dots, m_{C_{im}}$ . The fuzzy membership grade of result  $C_i'$  can be calculated using formula (2)

$$m_{C_i'}(z_i) = m_{C_{i1}}(z_i) \vee m_{C_{i2}}(z_i) \vee \dots \vee m_{C_{im}}(z_i) \quad (2)$$

According to the fact  $x_0, y_0$ , the fuzzy membership grade of  $C_1', C_2'$  is  $m_{C_1'}(z_1), m_{C_2'}(z_2)$ . Then, a method of weighted averaging can be used to get the numeral value of the fuzzy result  $C'(C_1', C_2')$ , and the representative value  $z_0$  is obtained.

$$z_0 = \frac{\sum_{i=1}^2 z_i m_{C_i'}(z_i)}{\sum_{i=1}^2 m_{C_i'}(z_i)} \quad z_i \in Z \quad (3)$$

Thus, using formula (1)~(3), the fuzzy inference from fact “ $x_0$  and  $y_0$ ” to the result representative point  $z_0$  can be realized.

## CONDITION ANALYSIS BASED ON INFORMATION FUSION

### A. Decision tree information fusion model

Typical decision tree information fusion model is as follow<sup>[8]</sup>.

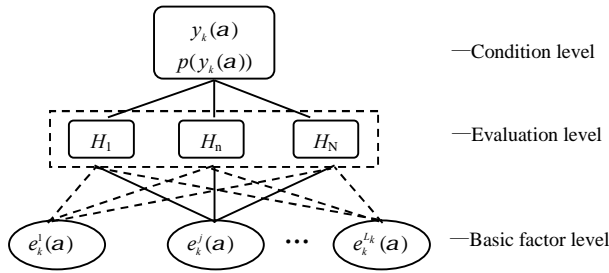


Fig.6 A representative decision tree information fusion model

In evaluation level,  $H_n$  is called an evaluation grade ( $n=1, \mathbf{L}, N$ ). A set of evaluation grades for condition attribute  $y_k$  is denoted by

$$H = \{H_1, \mathbf{L}, H_n, \mathbf{L}, H_N\} \quad (4)$$

where  $N$  is the number of evaluation grades.  $H_1$  and  $H_N$  are set to be the worst and the best grades, respectively, and  $H_{n+1}$  is preferred to  $H_n$ .

The qualitative evaluation is difficult to give, as it is subjective and sometimes incomplete. In order to quantify these evaluation grades and eventually to quantify subjective judgments with uncertainty, the concept of preference degree was introduced. A preference degree takes values from the close interval  $[-1, 1]$ , the set of evaluation grades may thus be quantified by

$$p\{H\} = [p(H_1), \mathbf{L}, p(H_n), \mathbf{L}, p(H_N)]^T \quad (5)$$

where  $p(H_n)$  is the scale of  $H_n$  and satisfies the following basic conditions:

$$p(H_1) = -1, \quad p(H_N) = 1$$

$$p(H_{n+1}) > p(H_n), \quad n = 1, \mathbf{L}, N-1 \quad (6)$$

In basic factor level, the factor set connecting with condition attribute evaluation is as follow:

$$E_k = \{e_k^1, e_k^2, \mathbf{L}, e_k^{L_k}\} \quad (7)$$

where  $e_k^i (i=1, \mathbf{L}, L_k)$  denotes the factors affecting the evaluation on  $y_k$ , the evaluation of  $e_k^i$  can be determined by connected condition characteristic parameters,  $e_k^i = e_k^i(a)$ . A larger preference degree value is interpreted as a higher evaluation grade. So the preference degree for the state of an condition attribute  $y_k$  through the direct evaluations of the relevant factors  $e_k^i$  can then be generated and integrated by using the D-S evidence theory presented follow.

### B. Condition analysis arithmetic based on information fusion

D-S evidence theory is a kind of information fusion classification arithmetic based on statistic, the Dempster rule combining multiple information is as follow:

In the decision tree information fusion model, evaluation grade  $H_n$  can be regarded as a basic hypothesis of D-S evidence theory, factor  $e_k^i$  as a piece of evidence, and a basic probability assignment may be obtained from a confidence degree. All of the evaluation grades in  $H$  are defined as distinct grades. With this in mind, the frame of discernment may be defined by

$$\Theta = H = \{H_1, \mathbf{L}, H_n, \mathbf{L}, H_N\} \quad (8)$$

Let  $M(H_n/e_k^i(a))$  express a basic probability assignment to which  $e_k^i$  supports a hypothesis that the state of  $y_k$  is conform to  $H_n$ , also let  $b(e_k^i(a))$  be a confidence degree to which the decision maker considers that the state of  $e_k^i$  is confirmed.

If there is only one factor  $e_k^i$  in  $E_k$ ,  $m(H_n/e_k^i(a))$  should be equal to  $b(e_k^i(a))$ ; if there are multiple factors in  $E_k$ , then:

$$M(H_n/e_k^i(a)) = I_k^i b(e_k^i(a)) \quad (9)$$

in which,  $I_k^i$  are the weights of all factors  $e_k^i$  in  $E_k$ .

After gained the basic probability assignments, the overall probability assignment can be calculated by using the following evidence reasoning arithmetic.

Define a factor subset  $e_{L_k(i)}(a)$  and a combined probability assignment  $MM_{r,i}^C(a)$  as follow:

$$e_{L_k(i)}(a) = \{e_k^1(a), L, e_k^i(a)\}, \quad 1 \leq i \leq L_k \quad (10)$$

$$MM_{r,i}^C(a) = M\left(\frac{C}{e_{L_k(i)}(a)}\right) = M_{r,i}^C(a) \quad (11)$$

Then, initial condition:

$$MM_{r,1}^n = M_{r,1}^n; \quad MM_{r,1}^H = M_{r,1}^H \quad (12)$$

iterative formula:

$$MM_{r,i+1}^n = K_{r,i+1} (MM_{r,i}^n M_{r,i+1}^n + MM_{r,i}^n M_{r,i+1}^H + MM_{r,i}^H M_{r,i+1}^n) \quad (13)$$

$$n = 1, L, N$$

$$MM_{r,i+1}^H = K_{r,i+1} MM_{r,i}^H M_{r,i+1}^H \quad (13)$$

$$\text{in which, } K_{r,i+1} = \left[ 1 - \sum_{t=1}^N \sum_{s=1, s \neq t}^N MM_{r,i}^t M_{r,i+1}^s \right]^{-1},$$

$$i = 1, L, L_k - 1, \quad r = 1, L, R$$

Then the overall preference degree can be calculated as follow:

$$p_{rk} = p(y_k(a_r)) = \sum_{n=1}^N MM_{r,L_k}^n p(H_n) + MM_{r,L_k}^H p(H) \quad (14)$$

$$\text{where, } p(H) = \sum_{n=1}^N \frac{p(H_n)}{N}.$$

### C. Condition analysis example of the DEH regulation system

Took a 300MW steam turbine unit DEH regulation system as example. Using the results of section 3, the condition characteristic parameter values of a certain running time is listed as tab.9.

In this example, the condition space is defined as follow:

$$H = \{H_1, H_2, H_3, H_4, H_5\} = \{\text{serious}, \text{fault}, \text{general}, \text{good}, \text{best}\} \quad (15)$$

Tab.6 Condition characteristic parameter values of DEH regulation system

Parameter names		Threshold ; normal values	Actual values	units
Actua-t ors	Ratio of flutter	>0.5; 1	0.84	—
	Oil pressure difference between in and out	<1; 0.2	0.42	Mpa
	Down oil pressure of oil motor	<1.5; 1	1.16	—
	Worn scraps in oil	<5; -	1.6	—
	Flux warp of valve	<0.2; 0	0.042	—
	Power attenuation time	<1.5; 1	1.16	—
	EH oil pump swing	<50; -	16	μm
EH oil system	EH oil pump current	<30; 21	25.5	A
	Oil temperature	<57; 43	46	°C
	EH oil main pipe pressure	11-16; 14.5	13	Mpa
Protect ion sys	OPC oil pressure	>1; 1.96	1.78	Mpa
	AST oil pressure	>1; 1.96	1.86	Mpa

After making unitary treatment and fuzzy transform, the results are listed in tab.10, which

are used as the input for system condition analysis.

Tab.7 Input data for system condition analysis

Parameter names	Weight	$H_1$	$H_2$	$H_3$	$H_4$	$H_5$
Ratio of flutter	0.18	(0,0,0.1,0.53,0)				
Oil pressure difference between in and out	0.21	(0,0,0,0.83,0)				
Down oil pressure of oil motor	0.23	(0,0,0.1,0.53,0)				
Worn scraps in oil	0.19	(0,0,0.1,0.53,0)				
Flux warp of valve	0.11	(0,0,0,0.73,0)				
Power attenuation time	0.08	(0,0,0.1,0.53,0)				
EH oil pump swing	0.24	(0,0,0.1,0.53,0)				
EH oil pump current	0.27	(0,0,1,0,0)				
Oil temperature	0.23	(0,0,0,0.76,0)				
EH oil main pipe pressure	0.26	(0,0,0.65,0,0)				
OPC oil pressure	0.5	(0,0,0,0.6,0.1)				
AST oil pressure	0.5	(0,0,0,0,1)				

Put above data into the iterative formula, the condition analysis results of subsystems and system can be gained as follow:

Tab.8 Condition analysis results

System	Weight	$H_1$	$H_2$	$H_3$	$H_4$	$H_5$	Preference degree
Actuators	0.46	(0,0,0,0.29,0.57)					0.686
EH oil system	0.28	(0,0,0.33,0.19,0)					0.076
Protection system	0.26	(0,0,0.032,0.41,0)					0.164
DEH system	-	(0,0,0.06,0.23,0.22)					0.312

The above data indicate that the three subsystems are in “best”, “general” and “good” condition respectively, and the whole DEH system is in “good” condition. Analyzing the preference degrees of the three subsystem, the EH oil system is in relatively poor condition. Based on this condition analysis, caution should be exercised and measure be taken in appropriate opportunity.

the condition analysis results can denote the system condition more accurately, and provide an effective support for next maintenance decision

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