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A Grey Relation Analysis Method to Vibration Fault Diagnosis of Hydroelectric Generating Set

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Abstract

Aiming to the complexity of vibration fault cause, the great many of fault parameters in hydroelectric generating set, and the superiority of grey relation analysis for its no strict requirement to fault sample capacity and regularity, the weighted grey relation model is built to look for the vibration fault type. The fuzzy matrix's transformation arithmetic is used to obtain the weight vectors of the grey relation coefficient, thus the weighted coefficient is the weighted grey relation model. The relation coefficient between reference sequence and compare sequence in vibration fault sample is provided by synthetic arithmetic of fuzzy weight to diagnose the vibration fault type. The grey relation coefficient weighted by fuzzy synthetic arithmetic, which is not only made the established weight be a scientific basis, but also can "sensitive" highlight the vibration fault type of hydroelectric generating set. Thus the problem of looking for every fault types is better resolved. By analyzing the practical example, it proved that the weighted grey relation model in the paper can effectively diagnose the vibration fault type of hydroelectric generating set and it has definite applicability.

Keywords: *hydroelectric generating set, vibration, fault diagnosis, grey relation analysis, matrix transformation arithmetic by fuzzy relationship, fuzzy synthetic arithmetic*

1. Introduction

Hydroelectric generating set is the most important power equipment of power station. Whether it can run safely or not, will directly concern the normal operation of the power station and the power system. The vibration of hydroelectric generating set is inevitable, but the excessive vibration will have a great influence on normal run life of the unit, even can lead to great destructive accidents [1]. In order to be able to quickly and accurately diagnose the vibration fault, enough vibration fault characteristic parameters and fault types data of hydropower generating set are needed collect, and the samples collected should be actual measured data from some a actual unit. When the vibration fault is diagnosed, a scientific and reasonable analysis method is required, so that the diagnosis conclusion can be practical [2-3]. Because the cause of the vibration is very complicated, and the mutual coupling between varieties of fault types, the vibration fault diagnosis itself carries a lot of ambiguity. When the vibration fault type is looking for, if all kinds of possible fault types are not accurately taken into account, the cause diagnosed may be wrong. Thus the unnecessarily additional work to the troubleshooting can be brought, and even the stable operation condition of the power station itself and the whole power system will be affected.

Grey relation analysis is to measure the close extent of different factors by their development trend. The method about the sample capacity and regularity are not strict required, and the percent of contact area between the conclusion obtained and the actual situation is very high [4]. Usually, in applying the method of grey relation analysis, the algebraic average of the correlation coefficient between the various factors is used to determine their each other closeness, which does not consider the relative importance of the factors and whose conclusions are not convincing enough. This paper, by using the fuzzy and weighted average model which is generalized fuzzy synthetic arithmetic [5] to diagnose the vibration fault types,

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according to t matrix transformation arithmetic by fuzzy relationship [6] to obtain the weights of every grey relation coefficient, which is in order to increase the credibility of diagnosis.

2. Matrix Transformation Arithmetic by Fuzzy Relationship

Assumed in n indexes or parameters among m targets, a data matrix is expressed with **X**= $(x_{ij})_{m\times n}$:

$$\boldsymbol{X}=(x_{ij})_{m\times n}=\begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix} \quad (1)$$

The relative importance of every indexes or parameters can be showed with the weight, whose calculation process is as follows:

(1) The distance of every indicator or parameter relative to the optimal and the worst possible target:

The distance of every indicator or parameter relative to the optimal possible target:

$$\lambda_{ig}=\sqrt{\sum_{j=1}^{n}(g_j-x_{ij})^2} \quad (i=1, 2, \dots, m; j=1, 2, \dots, n) \quad (2)$$

The distance of every indicator or parameter relative to the worst possible target:

$$\lambda_{ib}=\sqrt{\sum_{j=1}^{n}(x_{ij}-b_j)^2} \quad (i=1, 2, \dots, m; j=1, 2, \dots, n) \quad (3)$$

In the formulas: the optimal target set g : $g=(g_j)$= $\left(\max_i r_{i1}, \max_i r_{i2}, \cdots, \max_i r_{in}\right)$ (i=1, 2, …, m, j=1, 2, …, n) ; the worst target set b : $b=(b_j)$= $\left(\min_i r_{i1}, \min_i r_{i2}, \cdots, \min_i r_{in}\right)$ (i=1, 2, …, m, j=1, 2, …, n).

(2) The closeness of every indicator or parameter relative to the optimal target set λ_i :

$$\lambda_i=\lambda_{ib}/(\lambda_{ig}+\lambda_{ib}) \quad (i=1, 2, \dots, m) \quad (4)$$

(3) Judgment matrix S:

$$\mathbf{S}=(s_{lj})_{n\times n}=\lambda_j/\lambda_l \quad (l, j=1, 2, \dots, n) \quad (5)$$

(4) Normalize judgment matrix to matrix V:

$$\mathbf{V}=(v_{lj})_{n\times n}=s_{lj}\Big/\sum_{k=1}^{n}s_{lk} \quad (l, j, k=1, 2, \dots, n) \quad (6)$$

(5) The weight of every indicator or parameter:

From the matrix V=$(v_{lj})_{n\times n}$ to the matrix U:

$$\mathbf{U}=(u_1, u_2, \dots, u_n) \quad (7)$$

In the formula: $u_j = \sum_{l=1}^{n} v_{lj}$, which is from the matrix V after the matrix V is added according to the column.

The matrix U=(u1, u2, …, un) is normalized and then the matrix ω is obtained:

$$\boldsymbol{\omega}=(\omega_j)_{1\times n}=(\omega_1, \omega_2, \cdots, \omega_n) \tag{8}$$

In the formula: $\omega_j = u_j \Big/ \sum_{f=1}^{n} u_j$, (j=1, 2, …, , n). The vector $\omega = (\omega_1, \omega_2, \cdots, \omega_n)$T is the weight of every indicator or parameter.

3. Grey Relation Analysis

The problem of "large sample and uncertainty" that is the large sample and a lot of data but the lack of obvious regularity can be solved by using the theory of probability and mathematical statistics. The problem of "cognitive uncertainty" which is the uncertainty of priori knowledge about the human experience and cognitive can be processed by fuzzy mathematical theory. The problem of "little data and uncertainty" which has no experience and little data can use the gray system theory to be settled [7].

The grey system theory is that any system in a certain range and time, some information is known, some information is unknown. Grey relation theory is put forward by Professor Deng Julong [4], which is one of the important parts of grey system theory. Grey relation analysis is widely used in such fields as natural science, social science and economic management and so on [8-10]. The basic principle of grey relation analysis is to distinguish the relational extent of many parameters or indicators by comparing the geometrical relationship of data sequences in the system. If the geometrical shape of the data sequences curve in system is closer, it suggests that the relation extent between them is greater, whereas the smaller [8-10]. Grey relation degree is used to describe the degree of the close relationship between the factors in system, to measure the change extent of system, and can distinguish the relation degree between various factors in system. The analysis method compared with other correlation analysis method such as mathematical statistics, it is not only intuitive, has simple and convenient calculation process, but also not too high about the typicality of distribution regularity and the data capacity in compare sequence.

3.1. Grey Relational Degree

Ordinary, grey relation degree is used grey relation coefficient to express. Grey relation degree analysis is to assess the grade of the reference sequence by analyzing the relation extent between the reference sequences data and the compare sequences data. The calculation formula of relation coefficient is:

$$\xi_i(j) = \frac{\min_i \min_j \Delta_i(j) + \varepsilon \max_i \max_j \Delta_i(j)}{\Delta_i(j) + \varepsilon \max_i \max_j \Delta_i(j)} \tag{9}$$

In the formula: ξ_i is the relation degree between the reference sequences data $X_0 = \{X_0(j) / j = 1,2,\cdots,n\}$ and the compare sequences data $X_i = \{X_i(j) / j = 1,2,\cdots,n\}$, and $\Delta_i(j) = |X_0(j) - X_i(j)|$, *i*=1, 2, …, *m*, *j*=1, 2, …, *n*. ε is the resolution coefficient which is in the [0 , 1]. ε is smaller, the resolution power is stronger, conversely, the resolution power is weaker, but the resolution coefficient has no effect on the conclusion of the analysis. In the paper ε = 0.5.

3.2. The Weighted Grey Relation Degree

To avoid missing some a single parameter information, and consider the effect of all parameters as far as possible, the "weighted average model *M* (o, +)" which is the fuzzy synthetic arithmetic generalized in engineering fuzzy mathematics is for synthetic computing in the paper to weight the relation coefficient. The algorithm compared with other model of fuzzy synthetic computing generalized such as $M[\wedge,\vee]$、$M[\circ,\vee]$ and $M[\wedge,\oplus]$, the advantage is that the weighted average model is relative " sensitive ". The synthetic algorithm is not only "main factors highlighted", but also taken into account the other factors [6]. Furthermore, the conclusion computed is more coincident with the vibration characteristic of hydroelectric generating set.

The comprehensive value of weighted grey relation degree between the reference sequences data and the compare sequences data is expressed with Y, whose calculation formula is:

$$\boldsymbol{Y}=\boldsymbol{\omega}\circ\boldsymbol{\xi}^{T} \tag{10}$$

In the formula: "o"is the synthetic computing in "weighted average model *M* (o，+)".That is $y_i=\sum_{j=1}^{n}\omega(j)\xi_i(j)$.$\omega(j)$ is the weight of the *j* grey relation coefficient that is equal to the *j* fault characteristic parameter.

According to the maximum of the relational degree weighted, the corresponding fault type can be identified which is the most likely fault type.

4. The Vibration Fault Diagnosis of Hydroelectric Generating Set Based on Grey Relational Degree Analysis

4.1. The Generation and Handling of Sample Set

The fault sample set is from the representative characteristic parameter of vibration fault in the various fault types when vibration fault occurs. Fault types and characteristic parameters collected must have definite universality and practicability, and can accurately identify the fault types of hydroelectric generating set. In sample set, characteristic parameters include vibration amplitude parameters, also vibration frequency parameters, and even the fluctuating pressure parameters. Because these parameters have different physical dimensions, in order to ensure that the fault diagnosis analysis can be accomplished successfully, all of the parameters have to be normalized.

The n fault characteristic parameter data in the m fault type is supposed, which can use the following formula to be normalized becoming the data in the [0, 1]:

$$r_{ij}=\frac{g_j-x_{ij}}{g_j-b_j} \tag{11}$$

In the formula: the "x_{ij}" is from the formula (1), the "g_j" is from (2) and the "b_j" is from (3). At the same time, *i*=1，2，…，*m*；*j*=1，2，…，*n*.

4.2. The Weight Distribution of Fault Characteristic Parameters

The relative important extent of fault characteristic parameters can be expressed in weight. After all of the characteristic parameters are normalized, their weight can be allocated through the following calculation.

The distance of the fault characteristic parameters relative to the most likely fault type is obtained though using the formula (2) and the distance relative to the least likely fault type though using the formula (3). The closeness of the fault characteristic parameters relative to the most likely fault type can be obtained by the formula (4) and then the judgment matrix can be from the formula (5). After the judgment matrix is processed by the formula (6) and (7), and is normalized by the formula (8), the weight distribution vector of every fault characteristic parameters can be gotten.

4.3. The Weighted Grey Relation Degree between the needing Diagnosis Fault Samples and Characteristic Parameters

Vibration fault characteristic parameters in the common fault type are chosen, which constitute a compare sequence. The needing diagnosis fault samples are selected as the reference sequence. Both of the sequences are normalized by the formula (11) and then the relation coefficient between the needing diagnosis fault samples and the compare sequence is gotten. The relation coefficient is weighted by using the formula (10), and then the weighted grey correlation value is obtained. From the weighted grey relation numerical value, the fault types of vibration unit can be judged.

5. Example Analysis

Frequent fault of hydro-generator units is chosen as the fault type set. The set include the rotor imbalance F_1, the rotor misalignment F_2, dynamic or static scratches F_3, deflected vortex band in draft tube F_4 and Karman vortex street F_5. Rotational frequency of unit is supposed f_0. Standard sample of vibration spectrum such as $(0.18\sim0.20)f_0$、$(1/6\sim1/2)f_0$、f_0、$2f_0$ and $3f_0$ are chosen as fault parameters, standard sample of vibration amplitude are the relationship between vibration amplitude and rotate speed expressed in C_1, the relationship between vibration amplitude and the load expressed in C_2, the relationship between vibration amplitude and the pressure of the spiral case expressed in C_3 and the relationship between vibration amplitude with the flow expressed in C_4. Both of the samples constitute a compare sequence after they are normalized, which is shown in the Table 1. The needing diagnosis sample [2-3] from a hydropower station unit constitutes the reference sequence, which is shown in the Table 2.

Table1. Standard Sample Parameters of Vibration Fault

if **Vibration fault type is**	***And*** **Vibration fault characteristic parameters are**								
	And **Standard sample of vibration spectrum is**					***And*** **standard sample of vibration amplitude is**			
	$(0.18\sim0.20)f_0$	$(0.18\sim0.20)f_0$	f_0	$2f_0$	$3f_0$	C_1	C_2	C_3	C_4
F_1	0.01	0.11	0.95	0.04	0.13	0.96	0.12	0.07	0.03
F_2	0.01	0.03	0.70	0.96	0.81	0.98	0.96	0.52	0.46
F_3	0.06	0.07	0.91	0.53	0.49	0.97	0.02	0.03	0.14
F_4	0.09	0.96	0.06	0.02	0.01	0.09	0.95	0.02	0.08
F_5	0.95	0.05	0.12	0.09	0.04	0.03	0.04	0.01	0.97

Table 2. Needing Diagnoses Sample Parameters of Set Vibration Fault

$(0.18\sim0.20)f_0$	$(0.18\sim0.20)f_0$	f_0	$2f_0$	$3f_0$	C_1	C_2	C_3	C_4
0.01	0.02	0.94	0.05	0.10	0.89	0.13	0.15	0.09

The distance of every fault characteristic parameter relative to the most likely fault type:

$$\lambda_{ig} = [1.8517 \quad 1.8115 \quad 1.2707 \quad 1.6427 \quad 1.6479 \quad 1.2808 \quad 1.5727 \quad 1.9216 \quad 1.6120]^T$$

The distance of every fault characteristic parameter relative to the least likely fault type:

$$\lambda_{ib} = [0.9443 \quad 0.9576 \quad 1.4719 \quad 1.0817 \quad 0.9361 \quad 1.6591 \quad 1.3413 \quad 0.5137 \quad 1.0695]^T$$

The closeness of every fault characteristic parameter relative to the most likely fault type set:

$$\lambda_i = [0.3377 \quad 0.3458 \quad 0.5367 \quad 0.3970 \quad 0.3623 \quad 0.5643 \quad 0.4603 \quad 0.2109 \quad 0.3988]$$

The judgment matrix of every fault characteristic parameter:

$$S=\begin{bmatrix} 1.0000 & 1.0240 & 1.5891 & 1.1756 & 1.0727 & 1.6710 & 1.3629 & 0.6246 & 1.1810 \\ 0.9766 & 1.0000 & 1.5519 & 1.1481 & 1.0475 & 1.6319 & 1.3310 & 0.6100 & 1.1533 \\ 0.6293 & 0.6444 & 1.0000 & 0.7398 & 0.6750 & 1.0515 & 0.8577 & 0.3931 & 0.7432 \\ 0.8506 & 0.8710 & 1.3517 & 1.0000 & 0.9124 & 1.4214 & 1.1593 & 0.5313 & 1.0045 \\ 0.9323 & 0.9546 & 1.4815 & 1.0960 & 1.0000 & 1.5578 & 1.2706 & 0.5823 & 1.1010 \\ 0.5984 & 0.7513 & 0.9510 & 0.7035 & 0.6419 & 1.0000 & 0.8156 & 0.3738 & 0.7067 \\ 0.7337 & 0.7513 & 1.1660 & 0.8626 & 0.7870 & 1.2261 & 1.0000 & 0.4583 & 0.8665 \\ 1.6010 & 1.6394 & 2.5442 & 1.8822 & 1.7173 & 2.6753 & 2.1821 & 1.0000 & 1.8907 \\ 0.8468 & 0.8671 & 1.3456 & 0.9955 & 0.9083 & 1.4150 & 1.1541 & 0.5289 & 1.0000 \end{bmatrix}$$

After the judgment matrix is normalized, the weight distribution vector of every fault characteristic parameter is expressed:

$$\boldsymbol{\omega}=\left[0.12230\ \ 0.11934\ \ 0.07690\ \ 0.10394\ \ 0.11392\ \ 0.07494\ \ 0.08966\ \ 0.19564\ \ 0.10347\right]$$

The grey relation coefficient between the standard sample and the needing diagnosis sample is expressed:

$$\xi_i=\begin{bmatrix} 1.0000 & 0.8393 & 0.9792 & 0.9792 & 0.9400 & 0.8704 & 0.9792 & 0.8545 & 0.8868 \\ 1.0000 & 0.9792 & 0.6620 & 0.3406 & 0.3983 & 0.8393 & 0.3615 & 0.5595 & 0.5595 \\ 0.9038 & 0.9038 & 0.9400 & 0.4947 & 0.5465 & 0.8545 & 0.8103 & 0.7966 & 0.9038 \\ 0.8545 & 0.3333 & 0.3481 & 0.9400 & 0.8393 & 0.3701 & 0.3643 & 0.7833 & 0.9792 \\ 0.3333 & 0.9400 & 0.3643 & 0.9216 & 0.8868 & 0.3534 & 0.8393 & 0.7705 & 0.3481 \end{bmatrix}$$

The weighted grey relation degree:

$$y_i=[0.918471\quad 0.633394\quad 0.790307\quad 0.679241\quad 0.666227]^{T}$$

It can be seen from the numerical value in the weighted relation degree, the vibration fault or the vibration fault cause of the power plant unit is diagnosed as "rotor imbalance", whose conclusion is consistent with the literature [3], and consistent with the actual fault cause of the power station. The diagnosis conclusion shows that the diagnosis method described in the paper can effectively judge the vibration fault type from the fault type set, also shows that the method can be applied to fault diagnosis of hydroelectric generating set.

6. Conclusion

(1) By collecting common or typical vibration fault of hydroelectric generating set as sample, normalizing the characteristic parameters data in the sample and the needing diagnosis sample, both of the fault samples become the bigger the possible, thus it is easy to find the grey relation coefficient.

(2) The weight of vibration fault characteristic parameters can be gotten through the method of fuzzy matrix transformation, which can not only show that vibration fault is fuzziness, but also the conclusion is more persuasive if it is compared with the traditional analytic hierarchy process for its rigorous mathematical calculation.

(3) Vibration fault cause of hydroelectric generating set is very complex, vibration fault parameters is a great many. The paper select the weighted grey relational analysis, which can effectively reflect relative importance of fault characteristic parameters, can take into account all of the fault parameters as many as possible, can also indicate that the method of weighted grey

relational analysis based on fuzzy synthetic used in fault diagnosis of hydroelectric generating set is more practical.

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