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Multi - core SVM fault diagnosis of electrical system based on dimensional determining directional factor graph

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Abstract. Binary tree support vector machine (SVM) is characterized by little repeated operation quantity, fast classification speed and no dead division zone but structural design will affect the classification accuracy. To design structure of binary tree SVM reasonably, multi-classification algorithm (AHP-BSVM) integrating analytic hierarchy process (AHP) and binary tree SVM is proposed. Establish evaluation system model through analytic hierarchy process firstly, measure numerous impact factors comprehensively and determine weight of various faults, and then rank faults according weight size, and determine structure of binary tree SVM according to fault rank order, and make fault diagnosis analysis through the algorithm finally. Simulation experiment shows that compared with other methods, the algorithm has higher recognition accuracy rate, which verifies that the method is applicable to multi-classification and has higher classification accuracy and good promotion prospect.

Key words. SVM Electrical fault Analytic hierarchy process Classification, Characteristic

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1. Introduction

SVM is new learning method based on statistical learning theory[1], mainly applied to solve two-value classification problems initially, but in reality, multi-classification problem is met mostly. Therefore, promoting two-value classification algorithm to multi-classification field is one of important contents for SVM research at present. Multi-classification extension strategy of SVM is mainly divided into 2 types: one is global optimization method, which means that all sub-classifier parameters will be optimized within one formula, it seems that the method is simple, but the solution is complex, and it is rarely applied to solve classification problems; the other is combined leaning method where SVM shall be combined into multi-classifier

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according to different strategies, such as one-to-many method, one-to-one method, decision directed acyclic graph method and binary tree method [2] etc.

Aimed at classification problems of k kinds of mode, k two-value classifiers shall be constructed in one-to-many method, and the repeated operation quantity is great and calculation speed is slow; in one-to-one method, operation speed is fast but $k(k-1)$ two-value classifiers shall be constructed, and number of classifier will be great with increase of classification; compared with former 2 methods, operation quantity of decision directed acyclic graph method is less and operation time is shorter, but decision preference problem exists, and operation accuracy is random in a certain degree; $k-1$ two-value classifiers are needed in binary tree method, the repeated operation quantity is little and calculation speed is fast, and dead division zone does not exist, and the method is a kind of multi-classification method applicable to fault diagnosis, but structure design will affect classification accuracy of binary tree SVM greatly.

Therefore, this paper makes improvement on the basis of existing binary tree SVM, proposing a kind of multi-classification algorithm (AHP-BSVM) integrating analytic hierarchy process and binary tree SVM, and the method will be applied to fault diagnosis of generator bearing.

2. Binary tree SVM

Classification principle of binary tree SVM is as follows: resolve multi-classification problem into a series of two-value classification problem firstly by constructing binary tree, and then use SVM to realize binary classification. When binary tree SVM is trained and tested, classification shall start from SVM at root node, and the tendency shall be decided according to judgment classification until classification of test sample is recognized. If there is 1, 2, ..., k kinds of mode, the classification of k kinds of mode needs $k-1$ SVMs, and the structure is as shown in Fig.1.

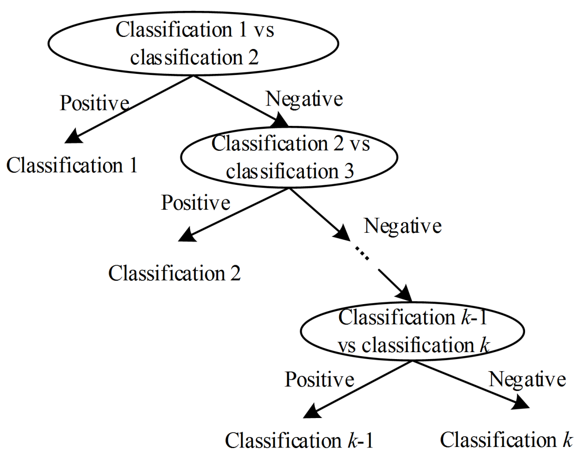

Fig. 1. Structure of binary tree SVM

In binary tree method, test sample does not need to pass all two-value classifiers, and operation can be stopped once the classification is recognized, thus saving test time. In classifier shown in Fig.1, the 1th SVM is applied to distinguish classification 1 from classification 1, classification 2, ... and classification k, and the 2th SVM is applied to distinguish classification 2 from classification 1, classification 2, ... and classification k, and so on, until the $k-1$th SVM distinguishes the last 2 classifications. Classifier shown in Fig.1 is just one kind in many classification strategies, and classification order is 1, 2, ..., k and there are $k!$ kinds of classification order in total, corresponding to $k!$ kinds of structure respectively. In mode recognition, classification accuracy of classifier can be changed by designing structure of binary tree.

At present, SVM multi-classification method based on binary tree has been researched in a certain degree. Binary tree multilayer classifier realization method that depends on fault priority and that is based on SVM can determine structure of binary tree classifier according to occurrence frequency rank of various faults, which means that condition of fault with relatively high occurrence frequency will be recognized firstly. Literature [3, 4] designs classification order according to distribution condition of various samples in high-dimensional characteristic space, dividing classification with wide distribution scope or relatively great classification interval distribution distance, which means that classification that will be divided in the easiest degree in sample space will be divided firstly.

3. SVM Binary tree being integrated with SVM

3.1. Decision preference

Structure of binary tree SVM is not unique. As described above, for k classification problem, there are $k!$ kinds of structure for binary tree in total, and different structure will cause different classification accuracy and classification result.

Take Fig.1 as example, supposed that division accuracy of each layer is $p_1, p_2, \cdots$, p_k respectively, and classification division accuracy is l, then division accuracy of all fault classifications respectively is

$$\begin{cases} l_1 = p_1\,, \\ l_2 = p_1 \cdot p_2\,, \\ \vdots \\ l_{k-1} = l_k = p_1 \cdot p_2 \cdots p_k\,. \end{cases} \tag{1}$$

Seen from above equality, it can be concluded that

$$l_1 > l_2 > \cdots l_{k-1} = l_k\,. \tag{2}$$

The lower the layer location of binary tree classifier is, the lower the corresponding classification recognition accuracy of SVM will be; recognition rate of SVM at lower layer depends on upper layer, and recognition rate of SVM at lower layer can only be guaranteed when recognition of SVM at upper layer is correct. Based on the feature of binary tree structure, if each classification is measured with one standard, then classification recognized firstly shall be classification with relatively high standard. Relatively high classification accuracy of the entire binary tree classification can only be guaranteed when relatively high correct recognition rate of high-standard classification is guaranteed, which is the reason why literature [3, 4] recognizes classification that will be divided in the easiest degree in sample space firstly, and literature [5] constructs binary tree through the maximum voting mechanism algorithm.

This paper adopts value degree as comprehensive standard to measure all classifications. In mode recognition, establish a set of evaluation system and synthesize numerous indexes to compare size of weight of various classifications. Rank all classifications according to weight size, and design structure of binary tree based on the order to recognize classification with greater weight firstly. The greater the weight is, the greater the correct recognition rate will be and the shorter the recognition time will be, which guarantees relatively high classification accuracy as a whole. Structure of binary tree determined in such way depends on weight quantity of each classification in all classifications, and compared with structure of binary tree determined randomly, the method saves time with higher correct diagnosis rate and diagnosis effect.

3.2. SVM AHP being integrated with binary tree SVM

In above content, it is proposed that structure of binary tree affects classification accuracy of the entire binary tree SVM greatly, and improvement in this paper is that structure of binary tree is designed on the basis of analytic hierarchy process. Evaluation system based on analytic hierarchy process can design important index affecting value degree and synthesize numerous indexes to measure value degree of all faults by combining with fault condition and expert experience, and it gains weight value of each fault, and weight size decides fault recognition order, and structure of binary tree can be constructed based on the order finally.

Analytic hierarchy process (AHP) is a kind of multi-objective and multi-criteria decision analysis method. The method resolves evaluation objective into a multi-level index, judging relative importance of each factor by introducing proportional scaling of 1∼9[6], and resolving complex problem into several layers and several factors simultaneously, and making simple comparison and calculation among each factor to gain weight of different scheme and provide basis for choice of the best scheme[7].

Analytic hierarchy process makes weight of each index tend to be reasonable by considering importance of each layer of factor in evaluation system comprehensively, and model of binary tree SVM based on analytic hierarchy process can be constructed mainly through following steps.

(1) Construct hierarchical structure

Model is generally divided into 3 layers, being objective layer, criterion layer and scheme layer respectively, and relationship between each layer is connected with line.

For evaluation system based on fault diagnosis, objective layer is value degree of fault, criterion layer is impact factor measuring fault, and scheme layer is fault condition. Bearing fault is common fault of generator, and normal operation of bearing will be hard because of fatigue wear caused by poor lubrication and incorrect assembly[8]. Therefore researching bearing fault diagnosis is of great importance.

Based on physical truth of generator bearing, this paper determines measurement index of criterion layer as: sample distribution scope B_1 of various faults in high-dimensional characteristic space, fault occurrence frequency B_2, diagnosis redemption loss B_3 and sample classification interval distribution distance B_4 of various faults in high-dimensional characteristic space. Therefore, weight in evaluation system is concentrated reflection of fault recognition rate, practical occurrence probability and theoretical division complexity. Normal condition, inner race fault, outer race fault, and ball fault are chosen as classification objects, and then hierarchical structure established is as shown in Fig.2.

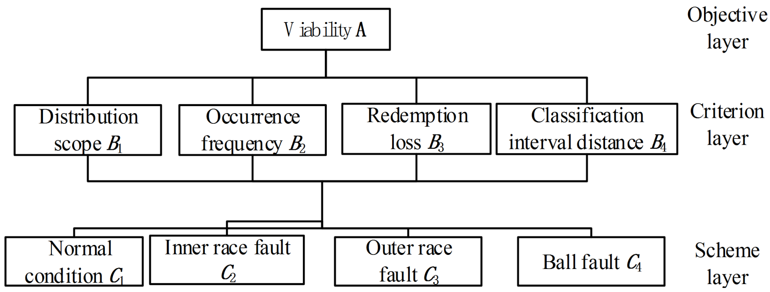

Fig. 2. Hierarchical structure based on bearing fault diagnosis

(2) Comparison matrix construction

To quantify qualitative analysis result, two-two comparison will be made aimed at importance of element at the same layer to a criterion at upper layer to construct judgment matrix, of which a_{ij} is specific value for significance of element a_i and a_j to criterion layer, and judgment matrix $\mathbf{A}$ is characterized by:

$$\begin{cases} a_{ij} > 0\,, \\ a_{ij} = 1/a_{ji}\,, \\ a_{ii} = 1\,. \end{cases} \tag{3}$$

For importance of element at the same layer, valuation is generally made based on proportional scaling of 1∼9, and its meaning is listed in Table 1.

In bearing fault of this paper, judgment matrix of criterion layer B constructed based on diagnosis experience to objective A is:

$$\mathrm{A} = \begin{bmatrix} 1 & 3 & 3 & 5 \\ 1/3 & 1 & 1 & 3 \\ 1/3 & 1 & 1 & 3 \\ 1/5 & 1/3 & 1/3 & 1 \end{bmatrix}. \tag{4}$$

Table 1. Proportional scaling and meaning of judgment matrix

Scaling	Meaning
1	The 2 factors are of equal importance.
3	When 2 factors are compared, the former is more important than the latter slightly.
5	When 2 factors are compared, the former is more important than the latter obviously.
7	When 2 factors are compared, the former is more important than the latter strongly.
9	When 2 factors are compared, the former is more important than the latter extremely.
2,4,6,8	Represent median of above adjacent judgment.

(3) Calculation of weight value according to judgment matrix

There are many kinds of method to calculate weight according to judgment matrix, including harmonization method, the minimum included angle method and characteristic vector method etc., of which characteristic vector method is adopted in this paper. Firstly, calculate the maximum characteristic value $\lambda_{\max}$ of judgment matrix **A**, and solve corresponding positive characteristic vector according to formula (6) (characteristic vector of which all components are greater than 0).

$$AW = \lambda_{\max} W \,. \tag{5}$$

Where, $\lambda_{\max}$ is the maximum characteristic value of matrix **A**, $W$is its characteristic vector, and normalization processing shall be made to it to gain weight vector.

The maximum characteristic value of judgment matrix **A** is $\lambda_{\max} = 4.043$ and weight vector is $W = (0.520, 0.201, 0.201, 0.078)$ through calculation.

(4) Consistency inspection of matrix

Consistency inspection steps are as follows:

① Calculate consistency index of judgment matrix

$$CI = \frac{\lambda_{\max} - n}{n-1} \,. \tag{6}$$

② Find average random consistency index RI in Table 2 according to matrix order.

Table 2. Average random consistency index

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

③ CR Calculate consistency ratio CR

$$CR = \frac{CI}{RI} \,. \tag{7}$$

If $CR < 0.1$, it will be considered that **A** has satisfying consistency, and **A** will be accepted; otherwise, **A** will be refused or data of **A** will be adjusted properly.

$CR = 0.016 < 0.1$ is gained after inspection, which shows that acceptable consistency is possessed.

(5) Calculate relative weight of scheme layer to total objective

What is gained through above calculation is just weight vector of each element in criterion layer B to objective A, and the final objective is to gain weight vector of each element in scheme layer C to objective A. Therefore, weight vector of each element in scheme layer C to each element in criterion layer B shall be calculated respectively according to above method, and calculation integration shall be made to weight vector that has been gained to gain total weight vector finally.

Therefore, the entire model based on analytic hierarchy process and binary tree SVM is constructed, and the model will be applied to fault diagnosis of generator bearing, and structure chart is as follows:

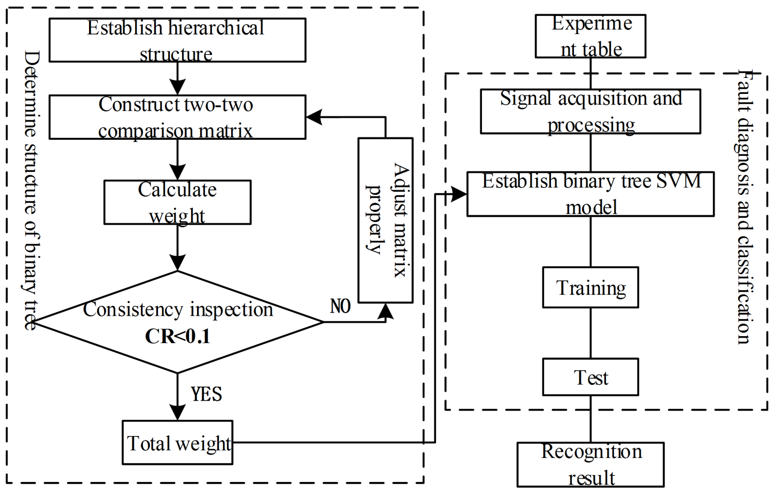

Fig. 3. Structure chart for bearing fault diagnosis

4. Simulation experiment

4.1. Data sources

To verify effectiveness of improved algorithm to diagnose generator bearing fault, bearing fault data provided by Case Western Reserve University of America is used to make simulation experiment and compare algorithm analysis data. 50 groups of sample data are sampled respectively for 4 conditions, i.e. normal condition, outer race fault, inner race fault, and ball fault with 200 groups of data in total, of which 120 groups of data are applied to training while other 80 groups of data are applied to test.

Fig.4 is a set of time domain waveform figure of vibration signal under different fault conditions, and it is normal condition, outer race fault, inner race fault, and ball fault successively from the upper part to the lower part.

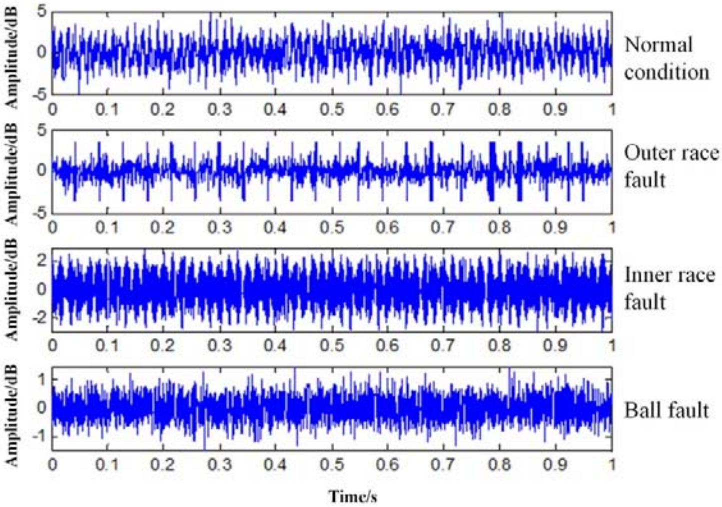

Fig. 4. Vibration time domain waveform figure

4.2. Fault feature extraction

There is noise interference at low-frequency stage in vibration signal in Fig.4, and there is corresponding harmonic wave, so it is inapplicable to direct diagnosis as fault feature, and corresponding treatment is needed. In wavelet packet entropy theory, vibration signal of fault generator can be handled, and fault feature in signal can be extracted effectively[9]. Therefore, 3 layers of wavelet packet decomposition[10] is made to vibration signal with db3 wavelet based on wavelet packet entropy theory, and signal is decomposed to 8 sub-bands at the third layer, as shown in Fig.5 which is figure on wavelet packet decomposition to outer race fault signal.

Calculate entropy value of each sub-band and gain proportion of entropy value of each sub-band in total energy of the 3th layer. Then relative energy of each band will be taken as element to construct a 8-dimensional characteristic vector as fault data sample input SVM[11].

4.3. Result and analysis

Through calculation, synthetic weight of relative objective in each scheme of bearing fault diagnosis model based on analytic hierarchy process and binary tree SVM is (0.151, 0.238, 0.210, 0.401), and $CR = 0.024 < 0.1$, which shows that synthetic weight has good consistency. Therefore, bearing fault diagnosis order is: ball fault, inner race fault, outer race fault and normal condition.

To improve calculation accuracy, for 2 important parameters affecting SVM performance, i.e. nuclear parameter and penalty parameter, genetic algorithm is

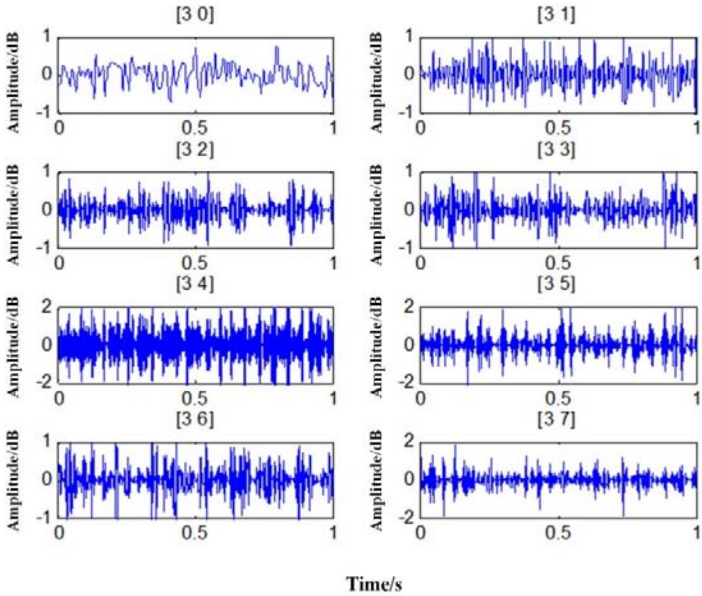

Fig. 5. Wavelet packet decomposition figure

adopted for optimization to determine that the value has quite good effect[12].

$$K(x,y) = \exp(-\frac{\|x-y\|^2}{2\delta}) \,. \tag{8}$$

After optimization is made to SVM parameter though genetic algorithm, 4 is taken as parameter δ while 224 is taken as penalty parameter C.

Characteristic vector of 120 groups of training sample shall be sent to binary tree SVM for training firstly, and 20 groups in training sample shall be extracted randomly for training to calculate training accuracy rate; 80 groups of test sample shall be chosen for test to inspect the generalization and fault-tolerant capability and count test accuracy rate. $M1$ represents algorithm in this paper, and to inspect effect of the algorithm, $M1$ is compared with $M2$, $M3$, $M4$, $M5$ and $M6$ respectively, structure of binary tree in algorithm $M2$ is designed according to fault frequency, structure of binary tree in algorithm$M3$ is designed according to sample distribution scope, and $M4$ represents one-to-many method, $M5$ represents one-to-one method, and $M6$ represents decision directed acyclic graph method, and comparison result is as shown in Table 3.

From above comparison form, it can be seen that compared with other algorithms, diagnosis accuracy rate of binary tree SVM based on analytic hierarchy process and one-to-one method is greater, and improved algorithm consumes less diagnosis time, and requires less number of SVM. Therefore, diagnosis efficiency of improved algorithm in this paper is great with good classification accuracy, and it has relatively good fault recognition capability.

Table 3. Fault diagnosis result of several multi-classification algorithms

Algorithm	Number of SVM	Diagnosis time/s	Training accuracy rate/%	Test accuracy rate/%
$M1$	3	3	100	95.9
$M2$	3	6	99.2	94.5
$M3$	3	8	98.5	94.8
$M4$	4	14	97.6	93.6
$M5$	6	7	100	96.8
$M6$	6	4	97.6	91.2

5. Conclusion

This paper proposes a kind of generator bearing fault diagnosis method based on AHP and binary tree SVM by combining with analytic hierarchy process and binary tree SVM. The algorithm considers numerous impact factors affecting classification accuracy comprehensively, calculates weight of various faults through analytic hierarchy process, and determines classification order of various faults according to the size. Simulation experiment is made to bearing fault diagnosis through different methods, and experimental result shows that diagnosis efficiency of the algorithm is high, classification accuracy is good, and the algorithm is feasible and effective in bearing fault diagnosis, which provides a new thought for bearing fault diagnosis.

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