Research on Fault Diagnosis Method of Switch Machine Based on KFCM

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Abstract—as one of the most important equipment in railway system, the failure of switch machine has a great impact on the safety and benefit of railway transportation. In order to realize the rapid fault diagnosis of switch machine, according to the power curve of switch machine detected by centralized monitoring system of railway signal, a new fault diagnosis method of switch machine based on variational mode decomposition (VMD) and improved fuzzy clustering algorithm is proposed. Firstly, VMD decomposition method is used to preprocess the collected fault data to remove the outliers and noise; then, the kernel fuzzy c-means clustering algorithm is used to classify different fault types into classes, and the classification results are obtained according to the dynamic clustering graph, so as to realize fault diagnosis. Through simulation analysis and experimental data verification, the algorithm can accurately extract fault features and support multiple fault detection at the same time, which effectively improves the accuracy and efficiency of S700K switch machine fault diagnosis.

1. INTRODUCTION

Switch machine, signal machine and track circuit are the three major outdoor parts of railway signal equipment, which are the key control equipment of railway transportation, in which the switch machine is used to switch the turnout and change the train operation line. After the switch is in place, through the gap inspection, it is necessary to confirm whether the switch rail and the stock rail reach the specified degree of closeness, so as to ensure the safety of the train when passing through the turnout. With the development of China's railway towards high-speed and heavy load, S700K speed-up switch machine has been widely used in railway lines. Since it is installed outdoors, it is greatly affected by natural conditions such as sand, rain and cold, train impact, rail crawling, lateral movement and other external factors. It has always been a railway signal equipment with high failure rate. The development of high-speed railway puts forward higher requirements for the electrical service system. Maintenance personnel must accurately and quickly remove equipment faults. At
present, the maintenance of switch machine in our country still uses the traditional maintenance method, which can not meet the needs of railway development.

Railway signal centralized monitoring system will collect a large number of data every day, import them into the fault diagnosis model, use the fault diagnosis function to analyze the data comprehensively, and extract fault feature points from the data, which can be used for fault diagnosis. In the fault records of switch machines in the electrical department, most of the faults are caused by mechanical reasons, and it is not practical to analyze the circuit faults only. Therefore, it is of practical significance to comprehensively analyze the mechanical faults and circuit faults in this paper. At present, the intelligent fault diagnosis methods of S700K electric switch machine have been studied, but each method has its limitations. Wang Siming[1] and others proposed a diagnosis method based on support vector machine, which has strong reasoning and interpretation ability, but it is difficult to acquire knowledge and has poor fault tolerance ability; Xue Yanqing et al.[2] used expert system to analyze the change law of electrical parameters of switch machine, but it is difficult to establish a large number of expert knowledge base. Eker et al.[3] used support vector mechanism to build empirical model for fault diagnosis of S700K switch machine. Wang Ruifeng et al.[4] used neural network and its improved algorithm to identify the fault type of switch machine. When the network model is large, the calculation amount may increase exponentially. Xiao Meng et al. [5] used Bayesian network for fault diagnosis, the prior probability is difficult to determine, and if the number of samples is small, the fault diagnosis effect is not ideal. The method based on wavelet packet decomposition by Chunlan et al.[6] needs to set parameters such as basis function and decomposition scale in advance, and the selection of wavelet parameters directly affects the diagnosis results.

The fault diagnosis model is based on the centralized signal monitoring system, which provides real-time data support by the monitoring system, and realizes the fault diagnosis function of switch machine combined with model logic. The action power curve of S700K switch machine is nonlinear and non-stationary, and the action power curve of each fault type has its own characteristics. Considering that the variational mode decomposition (VMD) algorithm has been successfully applied in bearing fault monitoring[7-8], it can accurately extract the bearing fault information, and the application of fuzzy clustering algorithm in fault diagnosis has increased significantly. In this paper, a new intelligent fault diagnosis method of switch machine based on VMD and KFCM is proposed by using the action power curve collected from microcomputer monitoring system. Firstly, VMD algorithm is used to eliminate noise and outliers, then VMD modal components are determined, and KFCM algorithm is used for fault classification, so as to determine the running state of switch machine.

2. ANALYSIS OF SWITCH MACHINE ACTION POWER CURVE

In the process of one action of the switch machine, the power of the switch machine can directly reflect its output pull force, and the operation state of the switch machine can be obtained by processing and analyzing the power curve. At present, TJWX-2006 signal microcomputer monitoring can monitor the power of S700K switch machine and generate curves. Through the obtained power curve, the electrical characteristics, mechanical characteristics and time characteristics of the turnout can be judged. Figure 1 shows the normal action power curve of S700K AC electric switch machine.
3. VARIATIONAL MODE DECOMPOSITION (VMD)

3.1 Principle

VMD is an adaptive and incomplete recursive signal decomposition algorithm[9], which has a solid mathematical theoretical foundation and can reduce the nonstationarity in time series. Variational mode decomposition (VMD) uses alternating direction multiplier (ADMM) to optimize the center frequency of each modal component. Its core idea is to construct and solve the variational model. The input signal is decomposed into k intrinsic mode function (IMF) components with finite bandwidth:

\[
\min_{\{u_k, \omega_k\}} \sum_k \left\| e^{j\omega_k t} * [\delta(t) + \frac{j}{\pi t}] * u_k(t) \right\|^2 \\
\text{s.t. } \sum_k u_k = f
\]  

(1)

Where: \(t\) is the time, \(a_t\) is the partial derivative of \(T\), \(\{u_k\}\) is the kth mode component, \(\{\omega_k\}\) is the central frequency, and \(j\) is the imaginary unit.

By introducing Lagrange multiplier \(\alpha\) and quadratic penalty factor \(\lambda\), equation (1) can be transformed into an unconstrained optimization problem. The augmented Lagrange function model is as follows:

\[
\sum_k \left\| e^{j\omega_k t} * [\delta(t) + \frac{j}{\pi t}] * u_k(t) e^{-j\omega_k t} \right\|^2 + \left\| f(t) - \sum_k u_k(t) \right\|^2 + \left\langle \lambda(t), f(t) - \sum_k u_k(t) \right\rangle
\]  

(2)

The center frequency of each modal component is obtained by using alternating direction multiplier algorithm.

3.2 Determination of K value in VMD by means of instantaneous frequency

For the variational mode decomposition, the number of decomposition levels is determined by solving the instantaneous frequency mean value. Firstly, the K value is set to decompose the original signal circularly, and the instantaneous frequency mean value of the components with different K values is calculated to obtain the optimal decomposition level. Finally, the component is selected and processed, and the corresponding fault frequency is observed for fault diagnosis. The calculation formula of instantaneous frequency \(f\) is as follows:

\[
f = \frac{\text{angle}\{-x(t+1)[x(t-1)]^*\} + \pi}{4\pi}
\]  

(3)
Specific steps: given the K value range of decomposition level, do cyclic decomposition; calculate the mean value of instantaneous frequency for different K value components. The K value is determined by observing the relationship between instantaneous frequency and VMD components. The critical value of K is the optimal decomposition number k when the instantaneous frequency curve bends downward. The flow chart is shown in Figure 2.

4. FAULT IDENTIFICATION BASED ON KFCM

4.1 Principle and algorithm of KFCM
Fuzzy c-means clustering algorithm (FCM) is a clustering method based on the optimization of the objective function. The output result is the membership degree of the sample to the cluster center. Fuzzy clustering algorithm can be used to classify different fault samples of S700K switch machine. This method has rigorous theory and good clustering effect, and has been successfully applied in many fields [10-11].

KFCM is a kernel fuzzy c-means clustering algorithm. As shown in Figure 3, since the cluster samples cannot be linearly divided in the original space, it is mapped to a higher dimensional space to realize the division of cluster samples in the high-dimensional space. Compared with FCM, KFCM improves the clustering performance, and has better anti-interference ability to noise and outliers.
KFCM changes the distance function of fuzzy c-means clustering by kernel function:

$$J_{cm}(U,V) = \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ij}^{m} \| x_j - \Phi(v_i) \|^{2m} \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ij}^{m} [1 - K(x_j, v_i)]$$  (4)

Where: $v_i$ is the clustering center of the clustering data; $c$ is the number of clusters; $n$ is the number of samples participating in clustering; $u_{ij}$ is the membership degree of the class $i$ corresponding to the $j$-th sample, and $0 < u_{ij} < 1$; $m$ is the fuzzy index; $K(v_i, v_j)$ is the Gaussian radial basis function.

According to the necessary conditions of Lagrange extremum, the iterative formula of membership degree and cluster center is deduced as follows:

$$u_{ij} = \frac{\sum_{k=1}^{c} \sum_{j=1}^{n} u_{ik}^{m} [1 - K(x_j, v_i)]^{\frac{1}{m}}}{\sum_{k=1}^{c} \sum_{j=1}^{n} u_{ik}^{m} [1 - K(x_j, v_i)]^{\frac{1}{m}}}$$  (5)

$$v_i = \frac{\sum_{j=1}^{n} u_{ij} K(x_j, v_i) x_j}{\sum_{j=1}^{n} u_{ij} K(x_j, v_i)}$$  (6)

The membership matrix is as follows:

$$U(i, j) = u_{ij}$$  (7)

The specific steps of the algorithm are as follows:

1. Initialization $u$; Gaussian radial basis function parameter $\delta$; number of clusters $c$ (in this paper, $c = 8$); fuzzy index $m = 2$; convergence accuracy $\varepsilon = 0.0001$; iteration times $k = 0$; initial cluster center matrix $V$;
2. Calculate $U^k$ with formula (5) and (7);
3. Calculate with $V_i$ equation (6);
4. Repeat steps 2 and 3 until the termination conditions are met $\| U^k - U^{k-1} \| < \varepsilon$.

### 4.2 Diagnosis method flow

The specific steps of S700K switch machine fault diagnosis algorithm based on improved VMD and KFCM are as follows:

1. The improved VMD algorithm is used to decompose the power data of a switch machine collected by the railway microcomputer monitoring system, and some modal components $u_d(t)$ are obtained.
2. Each modal component is analyzed, and the center frequency is calculated to determine the number of decomposition layers $K$. The singular values of each $u_d(t)$ component are extracted as eigenvalues, and the eigenvalue parameter matrix is formed as clustering samples.
3. KFCM method is used to cluster the samples, and the final fuzzy membership matrix $U$ is obtained. The clustering is completed by the maximum membership method.

4. Judge the unknown fault type. The fault types of the samples which are divided into one class with the labels of the known samples are consistent with the fault types of the known samples. The specific process is shown in Figure 4:

5. EXAMPLE

In order to verify the feasibility of this algorithm, the power curve corresponding to S700K switch machine failure at two different times is selected as the sample to be tested. In order to facilitate the operation with fuzzy clustering algorithm, the two curves are called curve 1 to be inspected and curve 2 to be inspected, which are recorded as $d_1$ and $d_2$ respectively. The VMD algorithm is used to calculate the eigenvalues of the sum of curves in Figure 5, as shown in Table 1. In order to reduce the information loss caused by too many decomposition modes, the optimal decomposition mode number $k = 6$ is selected to ensure the fidelity of the actual signal decomposition.

| Features | $Es_1$ | $Es_2$ | $Es_3$ | $Es_4$ | $Es_5$ |
|----------|--------|--------|--------|--------|--------|
| $D_1$    | 1.973  | 0.660  | 0.096  | 0.055  | 0.072  |
| $D_2$    | 0.063  | 0.006  | 0.006  | 0.038  | 0.109  |

Figure 4. Fault diagnosis process

TABLE 1 FAULT CHARACTERISTIC VALUE OF CURVE TO BE TESTED
According to the obtained data, the feature matrix $X$ is constructed, and the feature pattern matrix $X$ is calculated by fuzzy clustering algorithm. When $\lambda$ is in the range of $[0,1]$, the dynamic clustering results of S700K switch machine fault diagnosis system can be obtained. The results show that when $\lambda=0.688$, the operation curve $D_1$ of the current switch machine is similar to the fault curve of the switch machine which is stuck by foreign matters and the switch cannot be converted normally. Therefore, it is classified into one category. When $\lambda=0.890$, the current operation curve $D_2$ of the switch machine is the most similar to the fault curve indicating circuit diode damage. This is consistent with the results of manual detection.

In order to verify the recognition performance of the algorithm for S700K switch machine fault type, 36 groups of S700K switch machine action power data are obtained from the microcomputer monitoring system as the samples to be tested. The test results show that the accuracy rate is 94.2%, and the missing report rate is 0.12%.

6. CONCLUSION
In this paper, the improved variational mode decomposition (VMD) is used to decompose the power signal. The modal function components can be obtained and the characteristic parameters can be extracted to form fault samples, which can fully reflect the characteristics of fault signals.

The kernel fuzzy c-means clustering algorithm (KFCM), which is used in fault classification method, can achieve better classification effect by adding kernel function. Different classification situations can be obtained according to different threshold values, which is conducive to rapid fault diagnosis and can support multiple fault detection at the same time. Accuracy and efficiency.
ACKNOWLEDGMENT
2019 China National Railway Group Co., Ltd. Science and Technology Research and Development Program Project Number: N2019G017 Research on Key Technologies of Railway Signal Interlocking Engineer Training System.
Lanzhou Talent Innovation and Entrepreneurship Project of Gansu Province in 2019 No.: 2019-RC-107
The author is very grateful to Teacher He Tao for providing valuable advice in the writing of the thesis.

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