Fault diagnosis of vibration signal of synchronous condenser based on wavelet model

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Abstract. A large synchronous condenser has a complex structure and many parts, which is very prone to failure. However, the regular electrical quantity generally does not change significantly at the initial stage of failure, and may not reflect the fault characteristics. Some non-electrical quantities, such as vibration characteristics, can be used to diagnose and predict faults in a timely manner. Based on this, a multilayer-perceptron based wavelet model is proposed for fault diagnosis. Vibration signals are taken in real time at different positions on the surface of the condenser, and the energy eigenvalues are calculated by fast Fourier transform of the data, and the wavelet neural network model is input for training to obtain the nonlinear mapping relationship between the vibration signals and the fault types of the condenser, so as to realize the fault diagnosis of the condenser. Experimental results show that this method can effectively detect and diagnose the fault of the synchronous condenser in the early stage.

1. Introduction
With the large-scale construction of long-distance dc transmission, the demand for reactive power compensation capacity of converter stations is increasing, and the problem of insufficient reactive power support capacity becomes more and more prominent in the dynamic adjustment of power grid[1]. Since the inherent reactive output characteristic of the tuner meets the demand of the power system for dynamic reactive power during the fault period[2], a large synchronous condenser can be used as a reactive power source in the converter station to solve the problem of dynamic reactive power compensation[3]. The application of fault diagnosis method of synchronous condenser based on vibration signal is of great significance to ensure the safe operation of synchronous condenser units and improve the stability and reliability of power grid in long-term operation.

At present, it is still widely used for real-time detection and related fault diagnosis of the synchronous condenser. However, in general, the electrical capacity of a large synchronous condenser will change significantly only after the failure occurs for a period of time or the situation deteriorates. In the early stage of the failure, the electrical capacity can hardly give back effective information, and it is difficult to avoid some serious accidents[4]. In the field operation of a large synchronous condenser, some minor faults or initial faults will not affect the operation of the system. However, by analyzing some non-electrical quantities, such as vibration and temperature, these minor faults can be detected in time, and relevant treatments can be carried out to prevent them from becoming more serious[5]. Therefore, better results will be achieved in fault diagnosis of the tuner by vibration method.

Vibration method was only proposed in the 1980s, but a large number of experiments later proved that for some faults, the accuracy rate of this method was significantly higher than other methods[6]. The
process of vibration detection is mainly to install the vibration sensor in the appropriate position of the synchronous condenser, and then monitor the vibration signal transmitted to the motor surface by windings, air gap gaskets and iron cores in real time. Through various algorithms and data comparison, the fault can be reflected immediately. Vibration signal detection can be used for online monitoring to avoid the impact on the normal operation of the power system, and there is no electrical connection with the equipment in practice, which has great security and economic advantages over conventional monitoring methods.

2. Vibration characteristics of fault synchronous condenser

Synchronous condenser unit is a high-speed rotating machine, because it is difficult to completely eliminate the influence of external interference and its own many unbalanced factors, the unit will inevitably produce vibration in the process of operation. For the synchronous condenser itself, the source of vibration is the stator core and the rotor itself.

The synchronous condenser is essentially a synchronous motor, so the vibration characteristics of the tuner can be analyzed by analogy with the turbo generator and its related literature. Vibration state is one of the important indicators to measure the continuous and reliable operation of the synchronous condenser[7]. Bending vibration (radial vibration) and torsional vibration are two types of shafting vibration. If the vibration of the stator core, base or shafting exceeds the allowable vibration value, the shafting of the unit will fail to work normally. Make the brush and rotor slip ring wear violently and produce ring fire; Then the connecting parts of the synchronous condenser base are relaxed due to the increasing stress. In severe cases, the sealing system of the unit will be damaged, causing disastrous consequences to the phase modulation unit and the surrounding buildings.

2.1. Vibration analysis of air gap eccentricity fault of synchronous condenser

Due to the process quality of the motor manufacturer and the problem of switching back and forth between various operating conditions, the long operation of the synchronous condenser under such conditions will affect the air gap distribution between the stator and the rotor to some extent, and once the distribution is uneven, the air gap eccentricity will be formed. In particular, the long and thin shaft type motor is more likely to cause air gap eccentricity. Air gap eccentricity will directly cause abnormal magnetic field distribution in the synchronous condenser and affect the operation safety of the whole unit. Meanwhile, air gap eccentricity can be divided into dynamic eccentricity and static eccentricity[8].

Through the analysis of air gap flux density, the force on the rotor of the synchronous condenser can be obtained when the fault of dynamic and static eccentricity occurs[9]:

\[
\begin{align*}
F_{ax} &= \frac{LRF^2 \pi}{4\mu_0} \left[2\Lambda_0\Lambda_s + \Lambda_0\Lambda_x \cos(2\omega t - 2\beta)\right] \\
F_{ay} &= \frac{LRF^2 \pi}{4\mu_0} \Lambda_0\Lambda_s \sin(2\omega t - 2\beta) \\
F_{dx} &= \frac{LRF^2 \pi}{4\mu_0} \left[\Lambda_0\Lambda_x \cos\omega t + \Lambda_0\Lambda_s \cos(\omega t - 2\beta)\right] \\
F_{dy} &= \frac{LRF^2 \pi}{4\mu_0} \left[2\Lambda_0\Lambda_s \sin\omega t + \Lambda_0\Lambda_x \sin(\omega t - 2\beta)\right]
\end{align*}
\] (1)

In the equation above, \( L \) represents the length of the rotor, \( R \) represents the radius of the rotor, \( \omega \) represents the angular frequency, \( \Lambda_0 \) represents the constant of the magnetic conductivity of the synchronous condenser, \( \Lambda_s \) represents the magnetic conductivity in the case of static eccentricity fault, and \( \Lambda_d \) represents the magnetic conductivity in the case of dynamic eccentricity fault.

It can be seen from equation (1) that the rotor of the synchronous condenser produces radial vibration when the static eccentricity fault occurs, and the vibration frequency is twice the frequency. The force on the shaft also contains a constant, which will cause the radial deformation of the iron core. As can be
seen from equation (2), the rotor of the synchronous condenser produces radial vibration when the
dynamic eccentricity fault occurs, and the vibration frequency is the fundamental frequency. The
experimental results show that the amplitude of vibration signal will increase with the increase of the
degree of eccentricity.

2.2. Vibration analysis of stator fault of synchronous condenser

The integral calculation and analysis of the magnetic pull of the synchronous condenser stator windings
when they are short-circuited can be obtained

\[
\begin{align*}
F_x &= LR \int_0^{2\pi} q(\alpha_n, t) \cos \alpha_n d\alpha_n = 0 \\
F_y &= LR \int_0^{2\pi} q(\alpha_n, t) \sin \alpha_n d\alpha_n = 0
\end{align*}
\]  

When the stator windings have a short circuit fault, its iron core appears radial vibration and the
vibration frequency is two, four and six times of frequency. According to equation (3), it can be found
that the rotor of the synchronous condenser does not produce additional vibration. It is proved that the
rotor is not affected when the stator short-circuit fault occurs, but the vibration of the fundamental
frequency will change.

2.3. Fault vibration analysis of synchronous condenser rotor

When the rotor winding of the synchronous condenser is short-circuited, the integral calculation and
analysis can be made

\[
\begin{align*}
F_x &= LR \int_0^{2\pi} q(\alpha_n, t) \cos \alpha_n d\alpha_n = \frac{\pi LR F_{Ld} \lambda_0^2}{2\mu_0} \cos(\omega t + \beta) \\
F_y &= LR \int_0^{2\pi} q(\alpha_n, t) \sin \alpha_n d\alpha_n = \frac{\pi LR F_{Ld} \lambda_0^2}{2\mu_0} \sin(\omega t + \beta)
\end{align*}
\]  

When there is a short circuit fault in the rotor windings of the synchronous condenser, the magnetic
tension analysis shows that the stator appears radial vibration, with the vibration frequency ranging from
1 to 4 times, and the core also appears radial deformation due to its constant value. It can be found from
equation (4) that the rotor also appears radial vibration at this time, and its vibration frequency is the
fundamental frequency.

3. Wavelet model based on multilayer perceptron

According to the literature data collected, there are two main methods to combine the wavelet analysis
with the neural network: one is to first process the vibration signal by wavelet analysis, and then send
the result to the neural network for analysis; Another kind is to use wavelet neurons to replace wavelet
neural networks of neurons, while maintaining the structure of the neural network itself unchanged, thus
combining the two, greatly improving the calculation efficiency, and this way has different resolution,
namely in the use of high resolution data, where the small amount of data using low resolution, wavelet
analysis to data at the same time, the various factors and timely adjustments to improve the effect of
classification of pneumatic[10]. The wavelet model designed in this paper is the latter.

According to the propagation process of the multilayer perceptron, the wavelet model is divided into
three layers: the input layer, the hidden layer and the output layer. Three feedforward networks
concentrated in a hidden layer can make the network model approach any function with any accuracy
(nonlinear mapping is taken here). Figure 1 is a structural diagram of a three-layer wavelet model.
Through multiple modeling comparisons, the Morlet wavelet function is the basis function that can make the model training complete the fastest, so it is selected as the excitation function in the hidden layer of the model, that is:

$$\psi_{a,b}(x) = \frac{1}{\sqrt{a}} \psi\left(\frac{x-b}{a}\right)$$

(5)

$$\psi(t) = \cos(1.75x)e^{-\frac{x^2}{2}}$$

(6)

In equation (5), $a$ represents the stretching factor of Morlet wavelet function and $b$ represents the translation factor of Morlet wavelet function.

Suppose the sample of the $m$ write corresponding to the $i$ node is $x_{im}$, $O_{im}$ represents the output of the $i$ node of the input layer (layer I) for the $m$ write to the sample, $O_{jm}$ represents the output of the $j$ node of the hidden layer (layer J), $O_{km}$ represents the output of the $k$ node of the output layer (layer K), to sum up, the output of the $i$ node in layer I is

$$O_{im} = x_{im}$$

(7)

The output value of the $j$ node in layer J is:

$$O_{jm} = \psi(\frac{\sum_{j=1}^{N_j} a_{ij}O_{im} - b_j}{a_j})$$

(8)

In the equation above, $N_i$ represents the number of nodes in the input layer.

The output value of the $k$ node in layer K is:

$$O_{km} = \sum_{k=1}^{N_k} a_{ik}O_{jm}$$

(9)

In the equation above, $N_J$ represents the number of nodes in the hidden layer.

Then the energy function, namely the error, can be obtained:

$$E = \frac{1}{2} \sum_{m=1}^{M} \sum_{k=1}^{N_k} (Y_{km} - O_{km})^2$$

(10)

In the equation above, $Y_{km}$ represents the actual output of the corresponding sample, $N_k$ represents the number of nodes in the output layer, and $M$ represents the capacity of the corresponding sample.
4. Fault diagnosis of synchronous condenser based on wavelet model
The basis function of the wavelet model designed above is Morlet wavelet function, which is used as the excitation in the hidden layer. The Morlet wavelet function is partial to time-frequency localization, and its continuous differentiable expression is simplified, so the traditional neural network algorithm is still used. The following is the specific data processing process after the vibration signal is collected:

Step 1: the model needed for the training sample is initialized first, then the vibration signals obtained from the synchronous condenser for fast Fourier transform, and then it has the characteristics of fault signal in the frequency, collection and its amplitude, and the per-unit value square after the multiplication, finally, the results are normalized to hasn't been to the training samples. The various runtime states of the synchronous condenser are coded and then the code is used as the target value of the model training output.

Step 2: initialize the model and its related parameters, the training rate $\eta$, the upper limit number of model training $k_{\text{max}}$, the weight of the initial test stage of the model $\omega$, the translation factor $b$ and the stretching factor $a$. Here the threshold value is understood as the special weight of the input value of 1.

Step 3: train the wavelet model and add the momentum factor according to the gradient descent method. After repeated calculation, the momentum factor $\alpha$ is set to 0.74 and the training rate $\eta$ is set to 0.02.

Step 4: model calculation convergence conditions, according to the equation (10) computational energy function $E$, namely the calculation error, and to determine the error function in the convergence of the target $\epsilon$, if $E < \epsilon$ (convergence condition), then cease to model of training. or in the number of model training and training times model haven't converge at the same time, the largest which add the node number of hidden layers, and repeat step 2, step 3 and step 4, until the convergence condition is met.

In this paper, the wavelet model has an input layer, a hidden layer and an output layer. Measurement point first from the synchronous condenser surface vibration signals were collected to extract the characteristics of the normalized processing, then the data as the input values into the input layer, output layer is set to synchronous condenser run four types of running state, $O_{K1}$ represents normal, $O_{K2}$ represents air-gap eccentric fault, $O_{K3}$ represents stator faults, $O_{K4}$ represents rotor fault, so the model for the output of the expression is $O_k = [O_{K1} \ O_{K2} \ O_{K3} \ O_{K4}]$. Set the synchronous condenser to run in the $i(i \in \{1, 2, 3, 4\})$ way, $O_{ki} = 1$, $O_{kj} = 0 (j \neq i, j \in \{1, 2, 3, 4\})$. In the actual calculation process of the model, let $O_{ki} = 0.95, O_{kj} = 0.05$, to ensure that the calculation will not overflow, as shown in table 1.

| Virtual condition | $O_{K1}$ | $O_{K2}$ | $O_{K3}$ | $O_{K4}$ |
|-------------------|----------|----------|----------|----------|
| Normal            | 0.95     | 0.05     | 0.05     | 0.05     |
| Air-gap           | 0.05     | 0.95     | 0.05     | 0.05     |
| Stator fault      | 0.05     | 0.05     | 0.95     | 0.05     |
| Rotor fault       | 0.05     | 0.05     | 0.05     | 0.95     |

Matlab was used for the construction of the wavelet model. Due to the limitation of conditions, 40 groups of data entry models were selected for the four operating states of the synchronous condenser for training, and another 10 groups of data of these four operating states were selected for the test of the model. Table 2 shows two sets of output results of each model in four operating states of the synchronous condenser. According to table 2, when the synchronous condenser is running in the $i(i \in \{1, 2, 3, 4\})$
mode, the theoretical output value $O_i$ is around 1 with a small error, while the theoretical output value $O_j$ is around 0 with a small error. The theoretical output value in table 2 is almost equal to the ideal output value in table 1, which indicates that the wavelet model has a high recognition rate when the synchronous condenser is running in some typical working states.

After calculation, the average error of the wavelet model reached 6.4295×10^{-5} after 459 training sessions, indicating that the model has a higher training rate and strong adaptability to fresh samples. To sum up, the training speed of the model is fast, the accuracy is high, the generalization ability is strong, and the different operating states of the synchronous condenser can be identified.

| $O_{k1}$ | $O_{k2}$ | $O_{k3}$ | $O_{k4}$ | Virtual condition | Model output |
|---------|---------|---------|---------|---------------|-------------|
| 0.9994  | 0.0041  | -0.0118 | 0.0001  | Normal        | Normal      |
| 1.0173  | 0.0054  | 0.0013  | 0.0580  | Normal        | Normal      |
| 0.0007  | 1.0012  | -0.0061 | 0.0012  | Air-gap       | Air-gap     |
| 0.0004  | 1.0083  | -0.0098 | 0.0002  | Air-gap       | Air-gap     |
| 0.0019  | 0.0043  | 1.0021  | 0.0013  | Stator fault  | Stator fault|
| 0.0033  | 0.0019  | 1.0157  | -0.0019 | Stator fault  | Stator fault|
| 0.0009  | 0.0025  | 0.0035  | 1.0017  | Rotor fault   | Rotor fault |
| 0.0021  | 0.0048  | -0.0017 | 1.0231  | Rotor fault   | Rotor fault |

Table 3. The output of the traditional BP model is compared with the actual situation

| $O_{k1}$ | $O_{k2}$ | $O_{k3}$ | $O_{k4}$ | Virtual condition | Model output |
|---------|---------|---------|---------|---------------|-------------|
| 0.9998  | 0.0028  | -0.0268 | -0.0008 | Normal        | Normal      |
| 1.0773  | **0.1957** | 0.0015  | 0.0280  | Normal        | Normal      |
| 0.0019  | 1.0016  | -0.0018 | 0.0002  | Air-gap       | Air-gap     |
| -0.1075 | 0.9883  | 0.0021  | 0.1152  | Air-gap       | Air-gap     |
| -0.0011 | 0.0003  | 1.0011  | 0.1013  | Stator fault  | Stator fault|
| 0.0013  | 0.0089  | 0.9477  | 0.0018  | Stator fault  | Stator fault|
| 0.0024  | 0.0014  | 0.0321  | 1.0017  | Rotor fault   | Rotor fault |
| **0.2741** | 0.0029  | 0.0316  | 1.0231  | Rotor fault   | Rotor fault |

In order to reflect the advantages of the designed wavelet model in fault diagnosis of the synchronous condenser, and because the gradient descent method was applied in the design of the wavelet model, the same sample data and target output were brought into the BP model based on the gradient method for learning and training. When the input data and the target output are the same, the operation results of the tuner obtained by the BP neural network based on the gradient method are shown in table 3. After calculation, the average error of the BP model based on gradient method reached 6.4916×10^{-5} after 1164 training times. The training speed was slow, and uncertain values such as 0.2741 and 0.1957 appeared in the output results, which had a great influence on the final fault discrimination of the synchronous condenser. In the process of calculation, the BP model also appears the local minimum value in advance, and the convergence rate decreases. It can be seen that the wavelet model is better than the traditional BP model in terms of fault diagnosis rate and accuracy of synchronous condenser.

5. Conclusion
This paper raises the synchronous condenser air-gap eccentric short circuit, stator winding and rotor winding short circuit through the analysis of magnetic force, it is concluded that the vibration characteristic of the related, and base the simulated failure and collected the related failure the initial
phase of the vibration data, input after pretreatment wavelet design in this paper and the integration of neural network model, through the Matlab arithmetic to solve. Finally, the same input data and target output values are substituted into the traditional BP model based on gradient method to solve the problem. The comparison results show that the wavelet model designed in this paper has faster training rate and higher accuracy.

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References
[1] Wang Yi. Research on synchronous modulation camera control system for uhvdc transmission [D]. Beijing: north China electric power university, 2017.
[2] Shi Xiangjian, Mou Wei, Han Jiao, et al. Control strategy research of large synchronous condenser [J]. China electric power. 2017,50 (12) : 44-50.
[3] Rao Hong, Zhang Donghui, Zhao Xiaobin, et al. Practice and analysis of uhvdc power transmission [J]. High voltage technology, 2015,41 (8) : 2481-2488.
[4] Dai Qingzhong. Characteristics and application of synchronous condenser [J]. Dongfang electric review, 2016(4):47-51.
[5] Li Weijun, Wu Wenjian, CAI Wenfang. Abnormal vibration treatment and analysis of a 350MW double-water internally cooled steam turbine generator set [J]. Zhejiang electric power.2017(01)
[6] Wang Jifeng, Tang Wenhu, Ji Tianyao. Monitoring of SF6 operation mechanism based on vibration signal [J]. High voltage electrical appliances.2017(09)
[7] Jiang Botao, Zhang Bo, Huang Xinbo. Review of motor fault diagnosis methods based on support vector machine [J]. Micromotor, 2018,57(7):58-67.
[8] Bao Xiaohua, Lu Qiang. Research review and prospect of induction motor air-gap eccentrics [J]. Chinese journal of electrical engineering,2013,33(06):93-100.
[9] He Yuling. Analysis of mechanical and electrical characteristics of generator air gap eccentricity and winding short-circuit combined fault [D]. North China electric power university,2012.
[10] Yu Shengbao, He Jianlong, Wang Ruijia, etc. Electromagnetic three-level converter fault diagnosis method based on wavelet packet analysis and probabilistic neural network [J]. Journal of electrical engineering, 2016,31 (17):102-111.