Mathematical model and diagnosis of rotor fault in synchronous condenser

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Abstract. With the application of new energy in grid-connected system and the development of UHV DC transmission, the grid's requirements for reactive power regulation have gradually increased. Considering that, large-scale synchronous condensers have been put into use again. However, it is difficult to extract the characteristic signal of the inter-turn short-circuit fault in rotor windings of synchronous motors. In order to improve the stability of condensers, a certain relationship between the excitation current and the number of turns is derived using the Parker equation in the dq0 coordinate system, and the differential equation simulates the excitation current. Then the characteristic energy value of the fault signal is extracted through wavelet packet decomposition and reconstruction, and it is input to the RBF neural network for fault diagnosis. It is proved by MATLAB simulation that the diagnostic method proposed in this paper can effectively detect the degree of short-circuit faults between the turns of the rotor in condensers.

1. Introduction
With the application of new energy in grid-connected system and the development of UHV DC transmission, the grid's requirements for reactive power regulation have gradually increased. Currently, as the voltage level becomes higher and higher, the overall stability and security of the system are increasingly significant. As a large-scale reactive power adjusting equipment, a synchronous condenser can both increase and absorb reactive power, improving dynamic adjustment of voltage in the power grid [1-4]. For example, in the UHV substation, a synchronous condenser effectively avoids the sudden increase in the voltage. Moreover, it can absorb a large amount of reactive power generated by the failure of commutation quickly in the power grid while greatly increasing reactive power, speeding up the system’s recovery after the failure [5]. Therefore, a large-scale synchronous condenser represents an important part in the power grid for adjusting reactive power.

For a large condenser, the problem of excitation winding inter-turn short circuit is not very serious at the beginning. Usually, there is just a little contact between the winding, but it brings instability. In some ways, it makes the exciting winding current become larger, reactive power decline, and the bearing vibrate violently. Generally, the generator run properly when exciting winding inter-turn short circuit just begins. Even with problems such as asymmetric three-phase load, the generator can also run properly. But when that happens, there will be a negative-sequence rotating magnetic field in the condenser. The rotor winding with short circuit will then produce double frequency electromotive force, leading to the forming of a loop. As the short-loop current becomes bigger, the temperature at the short-circuit point becomes higher accordingly, which accelerates the aging of the adjacent
winding insulating part. Such a situation is always repeated\textsuperscript{[6-7]}. Therefore, some minor faults that are not detected in time will eventually lead to serious faults if the generator continues to run for a long time. When there are serious problems inside the condenser, or the condenser even breaks down, to repair the equipment involves a great deal of money and work due to its complicated structure and high cost. The stability and security of the whole power system will be affected, and huge economic losses and social impact are to be caused during the process.

Not until recent years have synchronous condensers been reinstalled and operated. Although there are few relevant identification methods for the short-circuit between turns of the rotor winding, actually synchronous condensers are synchronous motors without prime motor and mechanical load, which means the analog analysis of synchronous condensers can be carried out according to current research on large turbo-generators and other synchronous motors. In this article, the corresponding relationship between the exciting current and the number of turns is deduced by analyzing synchronous motor mathematical model, and fault diagnosis simulation analysis is carried out on the inter-turn short circuit by combining the wavelet packet analysis and RBF neural network, offering mathematical simulation model for reference for other relevant experimental analysis.

2. The excitations current model of synchronous condensers

When there is an inter-turn short-circuit fault between rotor winding in the synchronous condenser during operation, the number of effective excitation winding turns decreases. Given the unchanged condition for synthesis of magnetic flux in the air gap, excitation current increases, with a short-circuit loop added in the short-circuit turns\textsuperscript{[8-11]}. This is how to calculate the excitation current: taking the output between turns of rotor winding after a short circuit in the synchronous condenser as the normal output without a short circuit, introducing it into reverse calculation to figure out the excitation current. Then the difference between the calculated value and the actual measured value can be used to identify the short-circuit fault between turns of rotor winding, and the level of fault can be determined.

In the dq0 coordinate system, the parker expression of synchronous motor can be obtained by reverse reasoning using parker expression. Supposing the motor runs in the symmetrical steady state with no load, $\delta$ represents the power angle, then the boundary condition is $i_d=0$, $i_q=0$, $i=(i_d+i_q+i_r)/3$, $u_d=U\sin \delta$, $u_q=U\cos \delta$, and $\psi_d$, $\psi_q$ are constant value. Introducing the boundary conditions above into the parker equation:

\[
\begin{cases}
    u_d = -\psi_d - ri_d = x_d i_d - ri_d, \\
    u_q = \psi_q - ri_q = E - x_q i_q - ri_q, \\
    i_d = -ri_d + x_d (E - u_d) \quad r^2 + x_d x_q \\
    i_q = x_d i_d + r (E - u_d) \quad r^2 + x_d x_q \\
    \frac{i_d}{x_d} = \frac{(E - U \cos \delta)}{x_d} \\
    \frac{i_q}{x_q} = \frac{U \sin \delta}{x_q}
\end{cases}
\]  

The resistance value of the stator in the synchronous motor is very small, so $r$ can be ignored to simplify equation (2). The results are as follows:

\[
\begin{align*}
    i_d &= \frac{(E - U \cos \delta)}{x_d} \\
    i_q &= \frac{U \sin \delta}{x_q}
\end{align*}
\]  

Formula (3) can be introduced into the parker equation of the synchronous motor to obtain the active and reactive power outputs as follows:
\[
\begin{align*}
P &= u_{d} i_{d} + u_{q} i_{q} = \frac{E}{x_{d}} \sin \delta + \left( \frac{1}{x_{d}} \frac{1}{x_{q}} \right) U^{2} \sin 2\delta \\
Q &= u_{d} i_{q} - u_{q} i_{d} = \frac{E}{x_{d}} \cos \delta - \left( \frac{1}{x_{d}} \frac{1}{x_{q}} \right) U^{2} \cos 2\delta
\end{align*}
\]
(4)

Since it is a non-salient pole synchronous motor, \(x_{d} = x_{q}\). Introducing that into the equation above:
\[
\begin{align*}
P &= \frac{E}{x_{d}} \sin \delta \\
Q &= \frac{E}{x_{d}} \cos \delta - \frac{U^{2}}{x_{d}}
\end{align*}
\]
(5)

For a synchronous motor, its no-load electromotive force formula is:
\[
\begin{align*}
E &= x_{ad} I_{d} ; x_{ad} = L_{ad} = M_{ad} \\
M_{qad} &= \frac{M_{ad} \sin \delta}{L_{qad}} ; k_{qad} = \frac{i_{qd}}{I_{qd}} \\
M_{qad} &= \frac{16\pi l_{p}}{a_{qd} a_{qd} \lambda_{d}} (\omega_{qd} k_{qad} \lambda_{d})(\frac{\omega_{qd}}{2p} k_{qad}) \lambda_{d}
\end{align*}
\]
(6)

\[
E = x_{d} I_{d}
\]
(7)

In the equation above, \(I_{d}\) represents the stator’s self inductance value, \(\tau\) the polar distance of the condenser, \(l\) the effective length of the stator core, \(p\) the polar logarithm of the condenser, \(a_{qd}\) the number of turns of condenser’s rotor winding, \(a_{ad}\) the number of stator winding’s branches, \(a_{qd}\) the number of excitation winding branches. \(k_{qad}\) represents the winding coefficient, \(k_{ad}\) the coefficient for fundamental wave winding of the stator winding, \(\omega\) the number of winding turns, and \(\lambda\) represents the permeability coefficient of the air gap.

In the synchronous motor without an inter-turn short circuit, the excitation current is:
\[
I_{d} = \frac{a_{ad} a_{ad} \tau L_{d} k_{qad}}{8 \omega_{d} k_{qad} \lambda_{d} a_{d} \lambda_{d} a_{d} \lambda_{d}} \sqrt{x_{d}^{2} S^{2} + 2Q x_{d} + U^{4}}
\]
(8)

If there is an inter-turn short circuit in the rotor winding, \(\Delta n\) representing the number of turns, then the number of turns after the failure is \(\omega_{d} = \omega_{d} - \Delta n\). Add that into equation (8):
\[
I_{d} = \frac{a_{ad} a_{ad} \tau L_{d} k_{qad}}{8 \omega_{d} k_{qad} \lambda_{d} a_{d} \lambda_{d} a_{d} \lambda_{d}} \sqrt{x_{d}^{2} S^{2} + 2Q x_{d} + U^{4}}
\]
(9)

Assuming that the active and reactive outputs remain unchanged after the inter-turn short circuit between rotor winding in the condenser, then dividing equation (8) and (9):
\[
\frac{I_{d}}{I_{q}} = \frac{\omega_{d} - \Delta n}{\omega_{qd}}
\]
(10)

According to formula (10), there is a corresponding relationship between the excitation current and the number of turns before and after the generator’s rotor winding short-circuit, and it has nothing to do with the active and reactive output. Therefore, the excitation current can be regarded as a metric to judge whether there is a short circuit and the extent of short circuit.
3. Simulation of inter-turn short circuit in the synchronous condenser

Based on analysis above, considering the change of exciting current, whether there is an inter-turn short circuit in rotor winding could be recognized. Therefore the level of inter-turn short circuit and waveform when the generator runs properly are needed to be obtained by simulation, which benefits the next step to apply neural networks to diagnose the fault. MATLAB is applied to establish the inter-turn short-circuit problem model of the rotor winding. Some parameters of the motor are as follows: the resistance value of the stator winding in the condenser: \( r = 2.9069 \); the resistance value of the excitation windings: \( R_{\nu} = 5.9013E - 01 \), \( R_{\mu} = 11.900 \); \( R_{n} = 20.081 \); the excitation voltage: \( U_{\omega} = 24 \); the number of turns of the winding: \( \omega = 377 \).

According to the condenser’s basic structure and parameters, resistance coefficient matrix and inductance matrix are formed, and process voltage differential equation is formed in the dq0 system equation. Use the multi-step algorithm with variable order in MATLAB, the ode113 (Adams) to solve the differential equation, and the curve of the change of the excitation current can be obtained. Taking the level of the condenser’s operation and inter-turn short circuit as 20% and 50% to implement simulation respectively, excitation current curve are respectively shown in figure 1, figure 2 and figure 3.

![Figure 1. Excitation current in start-up operation](image1)

![Figure 2. The winding turns short The excitation current by 20%](image2)

![Figure 3. The winding turns short The excitation current by 50%](image3)

4. Fault signal feature extraction

The characteristic data of the excitation current signal are decomposed and reconstructed by wavelet packet, and the energy value of each part can be obtained after acquiring the distribution of
corresponding time-domain frequency band. For the excitation current signal, the characteristic value extraction process is as follows:

1. The decomposition waveforms of each layer of the excitation current signal in the condenser by utilizing three-layer wavelet packet decomposition, and signal waveforms of 23 frequency bands can be obtained in the third layer.

2. The decomposed waveforms in each frequency range are reconstructed according to the wavelet packet decomposition coefficient, from low to high.

3. Calculate the energy value within each frequency range $E_{ij}$, and the calculation process is as follows:

$$E_{ij} = \int S_y(t) dt = \sum_{k=1}^{n} |x_k|^2$$  \hspace{1cm} (11)

In equation (11), $S_y$ represents the reconstructed signal, and $x_k$ represents the amplitude of each discrete point of $S_y$.

4. Normalize the calculated energy values. If the characteristic values of the input neural network are too large, the network will become saturated. Therefore, it is necessary to normalize the energy values calculated based on the excitation current signal of the condenser. The normalization process is as follows:

$$E_{sum} = \sum_{j=1}^{z} E_{ij}$$  \hspace{1cm} (12)

$$E_{ij}' = \frac{E_{ij}}{E_{sum}}$$  \hspace{1cm} (13)

Where, $E_{ij}$ represents the energy value of each frequency segment, $E_{sum}$ represents the total energy of all frequency segments, and $E_{ij}'$ represents the normalized energy value.

5. These parts are normalized to form the feature vector through energy value:

$$T = (E_{ij1}, E_{ij2}, \ldots, E_{ijn})$$  \hspace{1cm} (14)

By decomposing rotor winding excitation current with different level of short-circuit faults in the condenser according to wavelet packet decomposition, the energy value of each frequency segment and total energy value are obtained and normalized, thus a sample database of final fault characteristics is formed and sent to the neural network for fault diagnosis.

5. Fault diagnosis using RFB neural network

1. With MATLAB, the excitation current of the rotor winding in the condenser is simulated when there is an inter-turn short circuit, and wavelet analysis is used for feature extraction, which is then used as the input vector of the neural network. Due to conditionality, only 40 groups of sample characteristics are extracted in this paper, and these sample data are sent to RBF function neural network and BP neural network to calculate and compare.

2. The RBF function neural network model is established. There were 4 nodes in the input layer and 5 nodes in the output layer.
Figure 4. Convergence of RBF neural networks

Figure 5. Convergence of BP neural networks

(3) The same training samples are sent to the RBF and BP neural networks respectively for model training. The convergence of the network is shown in figure 4 and figure 5.

After calculation, it is found that when the RBF neural network model is iterated for 30 times, the training mean square error would reach 2.40541e-30, with a faster convergence rate. After several times of optimization, the BP neural network model finally converges to 6.6316e-15 through 345 iterations. Compared with the previous RBF neural network, the accuracy and speed are reduced.

(4) After completing network model training, the test sample is sent to the radial basis function neural network to test whether the model can accurately identify the fault of rotor winding inter-turn short circuit. The output of the model is shown in table 1.

Table 1. RBF Neural network model output

| Level of fault         | The model output |
|------------------------|------------------|
| proper operation without load | 0.9998 0.0001 0.0004 0.0009 0.0008 |
| Inter-turn short circuit 5%  | 0.0004 0.9987 0.0003 0.0003 0.0015 |
| Inter-turn short circuit 10% | 0.0005 0.0007 0.9986 0.0012 0.0002 |
| Inter-turn short circuit 20% | 0.0004 0.0010 0.0009 0.9996 0.0003 |
| Inter-turn short circuit 50% | 0.0008 0.0006 0.0011 0.0007 0.9989 |

According to the output results in table 1, it can be found that the outputs of RBF neural network are very close to the expected with a fast convergence speed, showing the advantages of RBF function neural network for motor fault diagnosis.

6. Conclusion

In this paper, the mathematical model of excitation current in a synchronous condenser is established, the relationship between rotor winding inter-turn short circuit and excitation current is deduced by using the parker equation in the dq0 coordinate system, and the differential equation of the synchronous motor is solved by MATLAB to simulate the excitation current in the condenser with different fault levels. The characteristics of excitation current signals are extracted by wavelet packet decomposition and reconstruction, and the fault diagnosis is carried out by input them to RBF neural network, proving high convergence rate, high accuracy and other advantages of the diagnosis for rotor winding inter-turn short circuit fault in a synchronous condenser. However, the sample database for fault diagnosis simulation in this paper is too small, so a large amount of data needs to be collected on site to expand the sample database and improve the diagnosis model.
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