Research on inter-turn short circuit fault location of SF6 circuit breaker energy storage motor coil based on traveling wave reflection method

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Abstract—The traveling wave reflection method is proposed to locate the inter-turn short circuit fault of the circuit breaker energy storage motor coil. The capacitance and inductance matrices of the energy storage motor coil are calculated by finite element simulation, and the wave impedance model of the coil is established based on ATP-EMTP. The low-voltage square wave pulse signal is injected at the winding head to detect the characteristic curve of reflected wave when inter-turn short circuit fault occurs. The variation law of generalized fractal dimension of reflection wave characteristic curve with short circuit position is analyzed. The short-circuit position is evaluated based on BP neural network, and the evaluation accuracy is 100 %, indicating that this method is feasible.

1. Introduction

Circuit breaker is the key substation equipment to complete the control and protection of power system, and it is an important hardware support of power grid. As one of the important equipment of power system, circuit breaker plays a role of protection and control in power system. Its operation state will directly affect the stability of the whole power system and the reliability of power supply[1-2]. Circuit breaker closing requires sufficient operating energy. In the process of automatic reclosing, the energy storage can also be used to complete the rapid reclosing function after closing. For the circuit breakers in operation, under the influence of electrical, thermal and environmental factors, the insulation paint of the energy storage motor coil will gradually aging, resulting in a decline in insulation performance, which may lead to inter-turn short circuit fault and inter-layer short circuit fault. When a slight short-circuit fault occurs, the decrease of the coil resistance will lead to the increase of the current passing through the coil at work, and the coil is seriously heated. In severe cases, the coil is burned, which affects the energy storage of the energy storage motor and leads to the failure of closing or reclosing, thus affecting the stable operation of the power grid. Therefore, timely detection of insulation fault of energy storage motor coil and corresponding maintenance measures are of great significance for the stable operation of power grid.

In engineering practice, DC resistance is measured to determine whether there is inter-turn short-circuit fault in the coil. This method can only roughly determine whether there is a fault, and cannot further reveal the location of short-circuit fault and other information. Traveling wave method has the
characteristics of high reliability and accurate positioning, which is widely used in fault location of transmission lines. This method is first used for fault location on transmission lines, and is widely used due to high reliability and accurate location\textsuperscript{[3,4]} Scholars in China and abroad have carried out a large number of studies on fault traveling wave information. In Reference\textsuperscript{0}, the traveling wave method was applied to the diagnosis of inter-turn short circuit of generator rotor winding, and the fault location and fault degree were reflected by the starting time and distortion area of characteristic waveform. In Reference\textsuperscript{0}, the traveling wave method was applied to the inter-turn short-circuit fault location of transformer winding. By comparing the voltage amplitude of the reflected wave corresponding to the short-circuit turn and that without fault, the inter-turn short-circuit fault location was realized.

In this paper, the traveling wave reflection method is introduced into the fault location of inter-turn short circuit of SF6 circuit breaker energy storage motor coil. The coil model of energy storage motor is established by finite element calculation software, and the inductance and capacitance parameters are calculated. Then the wave impedance model of energy storage motor coil is established based on ATP-EMTP. The high-frequency low-voltage pulse is injected into the head of the model and the reflection wave curve is detected. The characteristic curve is obtained by subtracting the reflection wave curve before and after the short circuit. The starting time of the waveform is extracted from the characteristic curve, and the generalized fractal dimension is used as the characteristic quantity to diagnose the inter-turn short circuit fault location. Based on BP neural network, an inter-turn short circuit fault diagnosis model of energy storage motor coil is established.

2. Traveling Wave Reflection Method

Traveling wave reflection method is proposed based on the single-ended traveling wave fault location method of transmission line, which sends DC low voltage pulse signal to the fault winding and measures the reflected wave generated by the pulse to locate and identify the fault.

Because the coil turn length of the energy storage motor is much longer than the distance between adjacent turns, the electromagnetic boundary on-line turn transposition is discontinuous, and the wave impedance at the adjacent turn transposition changes significantly. Therefore, each turn coil can be equivalent to a transmission line, corresponding to a wave impedance value. A low voltage pulse signal is applied at one end of the winding. Because the equivalent wave impedance of each coil is different, the pulse wave is refracted and reflected when passing through each coil, and the reflected wave is refracted many times back to the signal input end, as shown in Fig.1 (a).

When the inter-turn short circuit fault occurs, the wave impedance of the short-circuited turn is equivalent to no existence, the wave impedance value changes after the fault location point, the reflection coefficient of the mutation point of the wave impedance is also changed, and the amplitude of the reflected wave is also changed. As shown in Figure 1 (a), (b), when the wave impedance $Z_{n+1}$ is shorted, the reflection coefficient of point A is changed from $k_b$ to $k'_b$, and the amplitude of the reflected wave $u_{1n}$ is also changed. At this time, the reflected wave is detected at the input end. The first n-1 reflected wave is the same as that without fault, and the nth reflected wave $u_{nb}$ is mutated. Therefore, when inter-turn short circuit fault occurs, the reflected wave curve detected at the input end is different from that without fault. The characteristic curve is obtained by subtracting the reflected wave curve before and after the fault, and the information containing the short-circuit fault location exists in the characteristic curve.

\[
k_b = \frac{Z_{n+1} - Z_n}{Z_{n+1} + Z_n}
\]

(1)

\[
k'_b = \frac{Z_{n+2} - Z_n}{Z_{n+2} + Z_n}
\]

(2)
3. Establishment of the Model

3.1 Finite element model of energy storage motor coil

The coil of energy storage motor adopts continuous winding mode, the rated voltage is 220 V, and the wire is a copper conductor enameled wire with a diameter of 0.355 mm. The energy storage motor is composed of iron core, shell and winding. There are two groups of windings, and each group of windings contains 103 turns of coil. The coil model of energy storage motor is established based on finite element software and the inductance and capacitance parameters are calculated. Considering its axisymmetric characteristics, it is simplified to a two-dimensional axisymmetric model to reduce the calculation amount under the condition of ensuring the calculation accuracy, as shown in Fig. 2.

![Two-dimensional axisymmetric model](image)

3.2 Calculation of inductance capacitance matrix

The capacitance is an energy storage element. The electric field energy stored by the conductor is calculated first, and then the capacitance of the conductor is calculated through the electric field energy. The inductance and capacitance matrix of the coil is calculated based on the finite element model, and the capacitance matrix is calculated through the electrostatic field module. Each time a coil is set as a terminal, and the unit voltage is applied. The electric field energy can be automatically calculated by opening the terminal scanning, so as to calculate the corresponding capacitance parameters. The calculation formulas are shown in Formulas (3) and (4).

\[
\begin{align*}
C_{ii} &= \frac{2}{V_i} \int W_e d\Omega \quad V_i = \begin{cases} 0 & j \neq i \\ V_j & j = i \end{cases} \\
C_{ij} &= \frac{1}{V_i V_j} \int W_e d\Omega - \frac{1}{2} \left( \frac{V_i}{V_j} C_{ij} + \frac{V_j}{V_i} C_{ji} \right) \quad V_i = \begin{cases} 0 & k \neq i, j \\ V_k & k = i \end{cases} \\
& \quad V_j = \begin{cases} 0 & k \neq i, j \\ V_k & k = j \end{cases}
\end{align*}
\]

\[C_{ii}\] is the self-capacitance of conductor, i.e., the ground capacitance; \(C_{ij}\) is the mutual capacitance between conductor \(i\) and conductor \(j\); \(V_i\) and \(V_j\) are the potential of conductor \(i\) and \(j\); and \(W_e\) is the energy of the whole system.
Similarly, based on the principle of magnetic field energy storage, the inductance matrix is calculated by the magnetic field module, and the calculation formula is shown in formula (5) and (6).

\[
L_{ii} = \frac{2}{I_i} \int W_m d\Omega, \quad L_{ij} = \begin{cases} 0 & j \neq i \\ I_i & j = i \end{cases}
\]

\[
L_{ij} = \frac{1}{I_i I_j} \int W_m d\Omega - \frac{1}{2} \left( \frac{I_i}{L_j} L_{ii} + \frac{I_j}{L_i} L_{jj} \right), \quad I_k = \begin{cases} 0 & k \neq i, j \\ I_i & k = i \\ I_j & k = j \end{cases}
\]

$L_{ii}$ is the self-inductance of the conductor, $L_{ij}$ is the mutual inductance between the conductor $i$ and the $j$, $I_i$ and $I_j$ are the current through the conductor, $W_m$ is the energy of the whole conductor.

3.3 Wave impedance model

Based on ATP-EMTP, the equivalent wave impedance circuit model of energy storage motor coil is established. Each coil is equivalent to one wave impedance, and the coil is connected in sequence, with a total of 206 wave impedances, as shown in Fig. 3. The low voltage square wave pulse signal with amplitude of 10V, rising edge and falling edge of 0.05μs and pulse width of 0.15μs is applied at the front of the circuit. The short circuit fault is set by directly connecting the coils through the wire.

4. Characteristic curve analysis of reflected wave

4.1 Generalized fractal dimension analysis

The fractal is an irregular, fractional and fragmented object, which can be understood as the similarity between the local and the whole in some aspects\(^6\). Fractal dimension is a very important concept in fractal theory. It can quantify the disorder and complexity of the research object, and effectively characterize the behavior characteristics of complex nonlinear non-stationary systems. Fractal dimension depicts the irregular change of the research object in the form of numerical value, which reflects the operation status of the system. It has the characteristics of simple and intuitive, and has been widely used in the field of judgment of abnormal state of equipment based on vibration signal, identification and classification of equipment faults and early prediction of equipment faults.

![Fig.3 Wave impedance circuit model](image-url)
The typical reflection wave characteristic curves under different short-circuit positions are shown in Fig.4. It can be seen that the reflection wave characteristic curve of the energy storage motor has the characteristics of nonlinear and non-stationary, and there is a certain self-similarity in geometry. At the same time, with the change of short-circuit position, the irregularity of the reflection wave characteristic curve also changes significantly. Therefore, the generalized fractal dimension is introduced into the location study of inter-turn short-circuit fault of energy storage motor coil to extract the characteristic information of reflected wave characteristic curve.

The grazing cover method is used to calculate the generalized fractal dimension. \( N \) hypercube grazing covers with scale \( l \) are used as the research objects. The probability of a point falling into the \( i \)th box is set as \( p_i(l) \), and the General information entropy is calculated by given \( q \):

\[
K_q(l) = \{ \lg \sum_{i=1}^{N} (p_i(l))^q \} (1-q)
\]

By changing the size of scale \( l \), the corresponding \( K_q(l) \) value is calculated, and the \( \lg l \cdot K_q(l) \) curve is plotted. The absolute value of the slope in the range of scale law is the \( D_q \) value of the given parameter \( q \).

Given different \( q \) values, the generalized fractal dimensions of different scale index subsets can be obtained. When \( q=0 \), the generalized fractal dimension is the box dimension; when \( q=1 \), it is the information dimension. Information dimension can better reflect the dynamic behavior of the system. When \( q=2 \), it is the correlation dimension, which reflects the correlation between the points in the point set, and is described by the distance proximity between the points.

The approximate calculation probability of frequency is generally used in the actual calculation process:

\[
p_i(l) = \frac{d_i}{\sum_i^{N} d_i}
\]

In the formula, \( d_i \) is the number of points falling into the \( i \) hypercube and \( \sum_i^{N} d_i \) is the number of points falling into all boxes.

The box dimension, information dimension and correlation dimension of the reflected wave characteristic curve of inter-turn short circuit at different positions of the winding of the energy storage motor are calculated. The curves of the box dimension, information dimension and correlation dimension of the reflected wave characteristic curve with the change of the short circuit position are shown in Fig.5. It can be seen that with the change of the short circuit position, the box dimension does not show obvious change rule, and the information dimension and correlation dimension gradually decrease.
5. Insulation fault evaluation model based on BP neural network

BP (Back Propagation) neural network is a multi-layer feed-forward network which is trained and learned based on error back propagation. It is one of the most widely used artificial neural networks, and its topological structure is shown in Fig.6. The BP neural network calculates the errors of the output layer, the hidden layer and the input layer in turn, and then continuously adjusts the weights and thresholds according to the mathematical relationship between the errors and the weights and thresholds of neurons in each layer, so that the errors of the BP neural network are gradually reduced and the accuracy of the network is improved.

The energy storage motor has two sets of coils, and the wave impedance model is divided into two sections. BP neural network is used to evaluate the position of inter-turn short circuit fault. The BP neural network with 2 neurons in the input layer, 5 neurons in the hidden layer and 2 neurons in the output layer is established. The training algorithm is L-M method. Input parameters are information dimension $D_1$ and correlation dimension $D_2$; the output parameter is the position of short-circuit fault, and the inter-turn short-circuit fault of the two coils is encoded as 1 and 2.

By ATP-EMTP simulation, 102 sets of sample data including characteristic parameters and short circuit position are obtained, and 50 sets of data are randomly selected as test sets to verify the accuracy of network evaluation after network training. The remaining 52 are training sets of training models. The maximum number of iterations is set to 1000, and the target mean square error is set to $1 \times 10^{-5}$. After the training, 50 sets of data are input into the test set to verify the accuracy of the evaluation. The BP neural network evaluation results of the degree of short-circuit fault are shown in Fig.7, which shows that the accuracy of inter-turn short-circuit fault location evaluation is 100%.
6. Conclusion

In this paper, the traveling wave reflection method is applied to the evaluation of the inter-turn short circuit fault position of the circuit breaker energy storage motor coil. The wave impedance model of winding is established by ATP-EMTP software, and the reflection wave characteristic curves under different short circuit positions are analyzed. The conclusions are as follows:

1) As the short-circuit position moves, the box dimension, information dimension and correlation dimension of the characteristic curve of the short-circuit reflection wave between turns at different positions of the energy storage motor winding are calculated. The box dimension does not show obvious variation, and the information dimension and correlation dimension gradually decrease.

2) Based on BP neural network, the evaluation model of inter-turn short circuit position of energy storage motor coil with input parameters of information dimension and correlation dimension and output parameters of inter-turn short circuit position is established. The accuracy of test set evaluation is 100%, which shows that the method is feasible.

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Fig.7 Test results of neural network