Research on Fault Location of SF6 Circuit Breaker Relay Coil Based on Traveling -Wave Reflection Method

Shuaiwei Qian\textsuperscript{a*}, Lu Wang\textsuperscript{b*}, Jianxi Chen\textsuperscript{c*}, Yanjun Peng\textsuperscript{d*}, Ningbo Pan\textsuperscript{e*}, Yongqiang Huang\textsuperscript{f*}, Xiong Zhou\textsuperscript{g*}

\textsuperscript{1}Guangxi Power Grid Co., Ltd., Guilin Power Supply Bureau, Guilin 541002, China

\textsuperscript{a*}2367517690@qq.com, \textsuperscript{b*}2919767651@qq.com, \textsuperscript{c*}3218916881@qq.com, \textsuperscript{d*}2297865012@qq.com, \textsuperscript{e*}172507844@qq.com, \textsuperscript{f*}360873409@qq.com, \textsuperscript{g*}864152159@qq.com

Abstract—The traveling wave-reflection method is proposed to locate the short circuit fault of the opening/closing coil of the circuit breaker, the capacitance and inductance matrix of the opening/closing coil are calculated by finite element simulation, and the wave impedance model of the coil is established based on ATP-EMTP. A low-voltage square wave pulse signal is injected into the head end of the winding to detect the characteristic curve of the reflected wave when an inter-turn short-circuit fault occurs. The generalized fractal dimension of reflection wave characteristic curve was calculated and its variation as the position of short circuit change was analysed. Compared with box dimension, the variation of information dimension and correlation dimension are more obvious, thus information dimension and correlation dimension are selected as inputs, and the evaluation model of inter-turn short circuit position is established based on probabilistic neural network.

1. Introduction

As one of the important equipment of power system, circuit breaker not only plays a role in controlling the normal load current, but also plays a protective role in carrying, breaking and closing abnormal current within the specified time\cite{1}, which is of great significance to ensure the safe and reliable operation of power system. As an important component in secondary control loop of switch equipment, the relay coil greatly affects the reliability of circuit breaker operation. For the circuit breaker in operation, due to the influence of electricity, heat and environment and other factors, the insulation paint of the relay coil gradually aging, resulting in the decline of insulation performance, may lead to inter-turn short circuit fault and inter-layer short circuit fault. In the case of slight short-circuit fault, even if the circuit breaker can still operate normally, the decrease of resistance of the coil will lead to the increase of current passing through the coil at work, the coil heating is serious, and the coil burning is caused in serious cases, which affects the on-off function of the circuit breaker and leads to the rejection, thus affecting the stable operation of the power grid\cite{2}. Therefore, it is of great significance to find the insulation failure of the relay coil in time and take corresponding maintenance measures to improve the reliability of circuit breakers. In engineering practice, the measurement of dc resistance of coil is used to determine whether the coil has inter-turn short circuit fault\cite{3}. 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 was first used for fault location on transmission lines, and has been widely used due to its high reliability and accurate location. In paper\cite{4}, traveling wave method is applied to locating inter-turn short circuit fault of transformer windings. By analyzing the propagation
characteristics of traveling wave on transformer windings, it is concluded that the voltage amplitude of reflected wave corresponding to short-circuit turns is greater than that corresponding to no-fault turns, so as to realize the location of inter-turn short circuit fault.

In this paper, the travelling-wave reflection method is introduced into the fault location of SF6 circuit breaker turning coil short circuit. The model of relay coil was established by finite element calculation software, and its inductance and capacitance parameters were calculated. Then based on ATP-EMTP, the wave impedance model of relay coil is established. A high frequency low voltage pulse was injected into the front end of the model and the reflected wave curve was detected. The characteristic curve was obtained by differentiating the reflected wave curve before and after the short circuit. The generalized fractal dimension of the characteristic curve is calculated, and the fault diagnosis model of inter-turn short circuit of relay coil is established based on probabilistic neural network.

2. Traveling -Wave Reflection Method

The traveling-wave reflection method is proposed based on the single terminal traveling wave location method of transmission line fault. Inject dc low voltage pulse signal into the fault winding, and the reflected wave generated by the pulse is measured to locate and identify the fault.

Since the length of single relay coil is much larger than the distance between the adjacent turns, the electromagnetic boundary is discontinuous at the transposition of the online turns, and the wave impedance at the transposition of the adjacent turns changes significantly. Therefore, each turn of the coil can be equivalent to a transmission line, corresponding to a wave impedance value. A low-voltage pulse signal is applied to one end of the winding. As the equivalent wave impedance value of each turn of the coil is different, refraction and reflection occur when the pulse wave passes through each turn of the coil, and the reflected wave is refracted several times until it returns to the signal input end, as shown in Fig.2 (a). When interturn short circuit fault occurs, short-circuited turn wave impedance does not exist, the wave impedance values after fault location point changes, the reflection coefficient is changed as well, the reflection wave amplitude changes. As shown in Fig.2 (a), (b) shown below, when wave impedance $Z_{n+1}$ is short-circuited, the reflection coefficient of node A change from $k_b$ to $k'_b$, the amplitude of reflected wave $u_{1n}$ here also changes. Detect the reflect wave in input end, the first $n-1$ reflected wave is the same as that without failure, while the $n$th reflected wave $u_{nb}$ changes suddenly. Therefore, the reflected wave curve detected at the input end is different from that detected without the fault when the inter-turn short-circuit fault occurs. The characteristic curve is obtained by differentiating the reflected wave curve before and after the fault, and the information containing the short-circuit fault location exists in the characteristic curve.

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

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

Fig.1 Diagram of traveling-wave reflection in winding
3. Model establishment

3.1 Finite element model of relay coil
Relay coil is continuously wound 300 layers, and each layer has 300 turns. Due to the excessive number of turns, so the 300 turns of each layer is equivalent to 3 turns. Based on finite element software, the model of relay coil is established and its inductance and capacitance parameters are calculated. Considering its axisymmetric characteristics, it is simplified into a two-dimensional axisymmetric model to reduce the amount of calculation while ensuring the calculation accuracy, as shown in Fig.3.

![Fig.2 Two-dimensional axisymmetric model](image)

3.2 Wave impedance model of relay coil
The equivalent wave impedance circuit model of relay coil is established based on ATP-EMTP as shown in Fig.4. A 10-V voltage square wave pulse signal with a rising edge and a falling edge of 0.05μs and a pulse width of 0.15μs was applied at the input end of the circuit. Short circuit fault was set by connecting the corresponding turns directly through the wire.

![Fig.3 Wave impedance circuit model](image)

4. Analysis of reflection-wave characteristic curve

4.1 Reflection-wave characteristic curve
The single-turn short-circuit faults at different positions were set up respectively, and the reflected wave curves were measured at the input end. The characteristic curves were obtained by making the subtraction between the reflected wave curves at the input end and that without short-circuited faults. Typical characteristic curves of different short-circuit positions are shown in Fig.5. It can be seen that when the short-circuit position is close to the input end, the characteristic curve is very dense. When the
short-circuit position is far from the input end, the curve becomes sparse and the waveform start time is delayed.μs

![Typical characteristic curves of different short-circuit positions](image)

(a) In the front  (b) In the middle  (c) In the rear

Fig.4 Typical characteristic curves of different short-circuit positions

4.2 Generalized fractal dimension analysis

The original meaning of fractal is irregular, fractional and fragmented objects, which can be understood as the similarity between the part and the whole in a certain aspect[5]. Fractal dimension is a very important concept in fractal theory, which can quantify the disorder and complexity of the object, so as to effectively describe the behavior characteristics of complex nonlinear and non-stationary systems[6]. The numerical form of fractal dimension describes the changes of irregularity of the research object, thus reflecting the operating status of the system. It is simple and intuitive, and has been widely used in the judgment of abnormal state of equipment based on vibration signals, identification and classification of equipment faults, and early prediction of equipment faults[7].

It can be seen from Fig.5 that the reflected-wave characteristic curves are nonlinear and non-stationary, and have certain self-similar characteristics in geometry. At the same time, the irregularity of reflection wave characteristic curves also changes significantly with the change of short-circuit position. Therefore, the generalized fractal dimension is applied to extract the characteristic information of reflected-wave characteristic curve.

The covering method is applied to calculate the generalized fractal dimension. \( N \) hypercubes of scale \( l \) are used to cover the research object. The probability of a point falling into the ith box is set as \( p_i(l) \). Given the value of \( q \), the general information entropy can be calculated as below:

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

(3)

Change the value of \( L \), calculate the corresponding \( K_q(l) \), and make \( \lg l \) as a function of \( K_q(l) \), the absolute value of slope within the existence range of the scale is the value of \( D_q \) the given parameter \( Q \). When \( q=0 \), the generalized fractal dimension is box dimension. When \( q=1 \), it is the information dimension, which can better reflect the dynamic behavior of the system. When \( q=2 \), it is the correlation dimension, which reflects the strength of the correlation between points in the point set, and is described by the distance and proximity between points. The box dimension, information dimension and correlation dimension of the reflected-wave characteristic curve of interturn short circuit at different positions of the relay coil are calculated, and their variation with the short-circuit position is shown in Fig.6. It can be seen that as the distance between the short-circuit position and the input end increase, the box dimension does not show an obvious change trend, while the information dimension and correlation dimension gradually decrease.
5. Fault location evaluation model based on probabilistic neural network

Probabilistic neural network (PNN) is an artificial neural network based on statistical principle. It is based on Bayesian minimum risk criterion, even if the expected risk of misclassification is minimal. It has the advantages of fast training, rapid convergence, good expansion performance, easy hardware implementation, and suitable for real-time processing, and has significant advantages compared with traditional feedforward neural network in mode classification [8]. It consists of input layer, mode layer, summation layer and output layer, and its topology is shown in Fig. 7.

The main steps of designing probabilistic neural network are as follows:
1) Determine the input feature vectors that can reflect the characteristics of the problem.
2) Process sample data to form training set and test set.
3) Set the Spread value and use the training set to train the probabilistic neural network.
4) Use test sets to evaluate the accuracy of probabilistic neural networks.

Choose the information dimension and correlation dimension of characteristics curve as the input of the net. And according to the position of short circuit, the fault is divided into three categories: front, middle and rear, which are numbered 1, 2, and 3 in sequence. 30 samples were selected from 60 samples as training sets to train the probabilistic neural network, and the remaining 30 samples were used as test sets to verify the evaluation accuracy of the network. When Spread is 0.1, the short-circuit position classification results of test sets are shown in Fig. 8. It can be seen that only sample 10 and sample 20 are wrongly classified, and the accuracy rate of position assessment of inter-turn short circuit fault is 93.3%.
6. Conclusion
In this paper, the travelling-wave reflection method is applied to evaluate the short-circuit position of circuit breaker relay coil. The wave impedance model was established based on ATP-EMTP, and the reflected wave characteristic curves of different short-circuit positions were analysed. The conclusions were as follows:

1) With the increase of the distance between the short-circuit position and the input end, the start time of the characteristic curve is delayed, and the information dimension and correlation dimension decrease.

2) Based on the probabilistic neural network, the evaluation model of interturn short-circuit position was established, and the accuracy of test set evaluation was 93.3%, which indicated that this method was feasible.

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