On-line Monitoring and Analysis of Turn-to-Turn Short Circuit Fault of Reactor

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Abstract. The problem that the hidden fault between turns of reactor can not be found in time is becoming more and more obvious. In order to find out the method capable of rapidly discovering the interturn short circuit fault, a dry-type air-core reactor turn fault model is set up in this paper. Based on the relationship between magnetic signal and electrical signal, the turn-to-turn short circuit fault of reactor is monitored and analyzed online. Firstly, the principle of turn-to-turn short circuit fault monitoring is introduced. Then, the voltage value obtained from the detection coil is compared with the threshold value, and the internal integrity of the reactor is determined according to the comparison result, so as to avoid misoperation of the protection device. The experimental data shows that the method in this paper is accurate and it has important value for solving the turn-to-turn short circuit warning problem of reactors.

1. Introduction
Dry-type air-core reactor (hereinafter referred to as reactor) is the main inductive element in power system[1]. Because the reactor has the advantages of simple structure, low cost of operation and maintenance and good linearity, it is widely used in current limiting, filtering, reactive power compensation and improving line voltage distribution[2]-[3]. It is widely used in current limiting, filtering, reactive power compensation and improving line voltage distribution[4]-[7]. The statistics show that a short-circuit malfunction with the dry air reactor is more than half the number of faults in the reactor. If the turn-to-turn short circuit fault of the reactor cannot be solved in the shortest time, then the ultra-high temperature generated by the short circuit current will burn down the reactor and lead to the occurrence of power failure, which will have a bad impact on the stability and reliability of the power system.

At present, the inter-turn insulation monitoring and power direction monitoring of reactors are the main research direction of the inter-turn short circuit monitoring of reactors in China[8]. However, the power monitoring sensitivity is poor. At the same time, inter-turn insulation monitoring is a kind of off-line monitoring mode, which cannot accurately reflect the running condition of the equipment[9]. The American national standard electrical engineering association has proposed a pulsed voltage method, which can only be used for scheduled maintenance, and be monitored offline[10]-[11]. But it is also destructive and can seriously shorten the service life of reactors[12].
In view of the problems existing in the current turn-to-turn short circuit monitoring method of reactors, this paper proposed the method of adding detection coil, which solved the problem of low monitoring sensitivity, overcame the constraints of offline monitoring, and could timely and accurately judged the abnormal state and fault between turns.

2. Establishment of turn-to-turn short circuit model of reactor

It is assumed that the dry-type air-core reactor coils are of the $n$ layer, with the designation of $I:n$. The applied voltage at both ends of the dry-type air-core reactor is $U_S$, layer $i$ ac resistance is $R_i$, self-induction is $L_i$, current is $I_i$, the mutual inductance between layer $i$ and layer $j$ is $M_{ij}$. The equivalent circuit model of the reactor in normal state is shown in Figure 1.

The circuit equation is:

$$
\begin{align*}
\sum_{i=1}^{n} j\omega L_iI_i + j\omega M_{ij}I_j + \ldots + j\omega M_{in}I_n + R_iI_i &= U_S \\
\sum_{i=1}^{n} j\omega M_{ij}I_i + j\omega L_jI_j + \ldots + j\omega M_{jn}I_n + R_jI_j &= U_S \\
&\ldots \\
\sum_{i=1}^{n} j\omega M_{jn}I_i + j\omega M_{nj}I_j + \ldots + j\omega L_nI_n + R_nI_n &= U_S \\
I_1 + I_2 + \ldots + I_n &= I_{total}
\end{align*}
$$

(1)

Where, $L_i$ is the self-inductance of the winding of the $i$th coil ($i=1,2,3,\ldots,n$); $I_i$ is the current flowing through the winding ($i=1,2,3,\ldots,n$); $M_{ij}$ is the mutual inductance between layer $i$ and layer $j$ windings ($i \neq j, i=1,2,3,\ldots,n$); $U_S$ is the terminal voltage; $n$ is the total number of independent branches; $R_i$ is the resistance value ($i=1,2,3,\ldots,n$).

Assuming that turn-to-turn short circuit occurs in the $j$-layer of the reactor, and establishing the equivalent circuit model under this fault condition, as shown in Figure 2.

A closed loop is formed after a turn-to-turn short circuit in the reactor. The coil forming the closed loop is called a short circuit loop. The continuous change of magnetic field direction in the loop
promotes the formation of short circuit current in the short circuit loop. Because the current direction in the short circuit loop is opposite to the original current direction, the current in the original coil is weakened and affected. After short circuit between turns, the number of turns in the coil decreases, and the self-inductance in the original coil becomes \( L_i + L_{2i} \) and satisfies \( L_i > L_{1i} + L_{2i} \).

Supposing that the reactor turn-to-turn short-circuit fault occurs in the \( j \)-layer coil, the original inherent total coil turns are \( n_z \), and the short-circuit coil turns are 1, then after the turn-to-turn short-circuit, the number of turns in the \( j \)-layer is \( n_z - 1 \), and the mutual inductance between the \( j \)-layer short-circuit and the normal \( i \)-layer is \( M'_{iz} \). The ac resistance formed on the short circuit ring is \( R_c \), the self-inductance is \( L_r \), and the mutual inductance between the \( i \)-layer and the short circuit ring is \( M_{ir} \). Then, the equation of short-circuit fault between turns is:

\[
\begin{align*}
\sum_{j \neq i} j \omega L_j \hat{I}_j + j \omega M_{ij} \hat{I}_i + \ldots + j \omega M_{iz} \hat{I}_z + j \omega M_{ir} \hat{I}_r + R_c \hat{I}_i &= U_n \\
\sum_{j \neq i} j \omega M_{iz} \hat{I}_z + j \omega M_{ir} \hat{I}_r + R_c \hat{I}_r &= U_n \\
\ldots
\end{align*}
\]

(2)

3. Short circuit fault monitoring between turns

Under normal circumstances, the magnetic field inside the reactor is symmetrical. When an internal fault occurs, the magnetic field inside the reactor will no longer be symmetrical. Firstly, the detection coil is used to monitor its alternating magnetic field. According to the physical characteristics of the reactor, the detection coil is installed in the position of the reactor about the horizontal axis to monitor whether the magnetic field is symmetrical or not. Secondly, the magnetic field signals are converted into electrical signals by using specific magneto-sensitive electrical components and relevant mathematical knowledge. Signal conversion is mainly to convert magnetic field signal into voltage signal. Finally, a display instrument is used to display the results.

The induced voltage of different coils coil1 with respect to longitudinal symmetry is expressed as \( u_i(t) \), and the induced voltage of coil2 is expressed as \( u_z(t) \). \( u_i(t) = u_z(t) - u_c(t) \) is taken as its differential signal, and its effective value is \( U_e \). If \( U_e = 0 \), it indicates that the magnetic field is symmetrical and the dry-type air-core reactor is in normal condition. If \( U_e \neq 0 \), it indicates that the magnetic field is asymmetric and the dry-type air-core reactor has a turn-to-turn short circuit fault. The induced voltage \( u(t) \) is expressed as:

\[
\begin{align*}
u(t) &= -N \frac{d\Phi(t)}{dt} = -N \frac{dB_z(t)S}{dt} = -NS \frac{dB_z(t)}{dt} \\
\end{align*}
\]

(3)

Where, \( N \) is the number of turns of detection coil; \( S \) is the sectional area of the detection coil; \( B_z(t) \) is the Z component of magnetic flux density; \( \Phi(t) \) is the magnetic flux. The effective value \( U \) of \( u(t) \) is:

\[
U = 2\pi NSB_z
\]

(4)

According to the time of short circuit between turns of reactor, the fault is divided into two different stages, which are development stage and fault stage. In the development stage, the small fault range does little damage to the reactor. At this time, if the protection device cannot quickly disconnect the reactor, the turn-to-turn short circuit fault of the reactor will aggravate and enter the fault stage. The magnetic field formed by the fault coil during the fault period affects the symmetry of the original magnetic field, so the difference voltage value measured will rise. Therefore, it is only necessary to analyze and compare the difference voltage value to determine whether the reactor has entered the fault period.
4. Hardware device connection and voltage threshold setting

4.1. Connection of hardware devices

The detection coil is installed symmetrically on the outermost layer of the package to monitor the instantaneous change of magnetic field size and direction. The closer the installation location of the detection coil is to the fault point short-circuit ring, the larger the differential voltage value will be.

The connection sequence of relevant hardware devices is shown in Figure 3, where $U_c$ represents the differential voltage. The isolation transformer is mainly used to isolate the monitoring loop and reactor to ensure that the primary loop does not affect the monitoring results of the monitoring loop. The low-pass filter is used to ensure the clarity of the generated waveform and enable it to accurately read the measured signal.

![Schematic diagram of hardware connection](image)

**Figure 3. Schematic diagram of hardware connection**

In order to avoid damage to the data acquisition card, resistance $R_L$ and diode TVS are connected to the data acquisition card in parallel. The data acquisition card is used to transmit the collected signals to the computer. At last, the insulation degree of the interturn coil is judged to be good or not. The image signal and digital signal displayed by the computer are used for the discrimination.

4.2. Voltage threshold setting

The software detection module consists of three different parts: filter waveform, development period monitoring and failure period monitoring. There are many burrs on the waveform in the development stage, so the monitoring signal is set according to the characteristics in accordance with the general conditions, and the signal monitoring value of each extreme point position is set as 1, and the signal monitoring value of any other position is set as 0. The voltage threshold in the development period is:

$$N_{\text{max}} = N_s \frac{f_p}{f_s} + 2$$

$$U_{d_{\text{g}}} = K_{d_{\text{g}}} \sqrt{\frac{1}{N_s N_{\text{max}}}}$$

Where $N_s$ is the number of sampling points displayed each time; $f_s$ is the sampling frequency; $f_p$ is the power frequency ac frequency; $U_{d_{\text{g}}}$ is the threshold of the development period; $N_{\text{max}}$ is the maximum number of extreme points of sampling points that will appear on the display; $K_{d_{\text{g}}}$ is the corresponding safety margin parameter.

Setting the parameters of each variable in the software is as follows: $N_s = 25000$, $f_s = 50$ kHz, $f_p = 50$ Hz, $K_{d_{\text{g}}} = 1.03$. When the effective value of the collected filter signal is greater than the set threshold, the software system sends out an alarm signal through the alarm device.

According to the research on the installation position of the coil, the physical structure of the reactor coil should be taken into account in its winding, and the detection coil should be accurately installed according to the requirements of the specification. The experimental results obtained by different turns of the installed coil are different. In this experiment, the number of turns of the coil is 30. Due to the different coil technology produced by different manufacturers, there will be certain
error effects, and it is usually allowed to monitor the limit error of 10mm coil winding rather than being completely symmetric. The voltage threshold is calculated according to the following formula.

\[ U_{er} = |U_a - U_d| \]  
\[ U_{gl} = \sqrt{2} K_s U_{er_{max}} \]  

Where \( U_{er} \) is the effective value of differential voltage generated by manufacturing error; \( U_{er_{max}} \) is the maximum effective value of differential voltage; \( K_s \) is the corresponding safety margin, which is generally taken as 1.05.

Table 1. Reactor rating parameters

| Nominal Parameter | Parameter Value | Nominal Parameter | Parameter Value |
|-------------------|-----------------|-------------------|-----------------|
| Capacity \( S_n \) /kVr | 120 | Inductance \( L_n \)/mH | 3.85 |
| Voltage \( U_n \)/V | 380 | Frequency \( f_n \)/Hz | 50 |
| Current \( I_n \)/A | 315 | Number of Roots Wound \( n \) | 2 |

The actual total current in the experiment is \( I = 312.40 \), the error is less than 1%, \( L = 3.9mH \), the error is less than 2%. Considering that the coil of the limited-reactor at the production level cannot be completely symmetrical, the maximum error of 10mm is allowed within a certain error range. Then the voltage threshold on the upper induction coil is \( U_{a1} = 2.03 - 115.72i \). The voltage threshold on the lower induction coil is \( U_{d1} = 2.12 - 120.01i \). Therefore, the induced differential voltage within the process error range is \( U_{er} \leq |U_{a1} - U_{d1}| = 6.051 \). The voltage threshold is set to \( U_{gl} = K_s U_{er_{max}} = 6.354V \).

4.3. Voltage threshold setting

Because the power system often occurs resonance overvoltage, operating overvoltage and lightning overvoltage and other factors of magnetic field changes in the disturbance induction coil, it is necessary to set false alarm conditions in the software. If the effective value of the filtered signal is more than the set voltage threshold within 1.5s, the warning device will send out an alarm signal when both conditions are satisfied, and the relay will take protective measures. On the contrary, the default of the software system is the normal disturbance in the power system. The software only automatically records the disturbance, and the relay protection device does not act without sending an alarm signal, so as to avoid the misoperation of the protection device and improve the reliability of the system.

5. Conclusion

In this paper, the turn-to-turn short circuit fault model of dry-type air-core reactor is established and the protection threshold of detection device is calculated. The experiment shows that the closer the detection coil is installed from the short-circuit ring, the larger the difference voltage value will be; on the contrary, the farther the detection coil is installed from the short-circuit ring, the smaller the difference voltage value will be. The detection coil is installed in the position where short-louis occurs between turns and the position where it often occurs, which is conducive to its monitoring and improves the accuracy and sensitivity of its monitoring. Comparing the difference voltage signal value collected and the threshold value set, it is of certain application value to judge whether there is turn-to-turn short circuit in the coil of the dry type air-core reactor, so as to avoid the wrong action of the protection device.

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