Research on current imbalance law of bus-bar caused by inter-turn short circuit of dry-type air-core reactor

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Abstract. Dry-type Air-core Reactor is widely used in power system. It is an important reactive power compensation equipment in power system. In recent years, the dry air reactor has suffered a number of failures in operation. The failure occurred most frequently in the dry-type air-core reactor and we cannot detect the inter-turn short circuit faults in neither single wire winding nor multiple wire windings. The research and protection of reactor faults is almost in the blank at present. This paper presents the method of collecting the unbalanced current between bus-bars to detect the winding inter-turn short circuit faults. The numerical simulation of short circuit model between different windings of the reactor is carried out. Current-differential analyzed on the unbalanced current data of experiment are used to determine whether an inter-turn short circuit occurs. The results indicated that the closer the short-circuit is to the end of the reactor, the greater the unbalance current is. The changes of collecting current between bus-bars are much larger than the total current. Short-circuit current redistribution only occurs between two windings after the short circuit. The circuit in other windings is almost unchanged.

1. Introduction

Dry hollow reactor is an important machine to guarantee the security and stable operation of electric power system because it has technical advantages, such as lower price, simple structure, light weight, lower linear loss of reactance value, and easy maintenance, which are widely used in modern power systems [1-3]. These technical advantages play a part in reactive compensation, suppress harmonics, neutral grounding, impact current, suppression of short circuit current [4-13]. However, in recent years, the reactor accidents are frequent, so the research of reactor protection has been paid more and more attention.

At present, the protection of the reactor includes differential protection and zero sequence differential protection, the turn-to-turn protection is protected by Phase to phase fault, ground fault, interturn fault back-up current protection and zero sequence over current protection [14]. Among them, Single-phase ground fault and interturn short circuit fault are main faults, and sensitivity of interturn fault protection and misoperation problem. As to turn-to-turn fault, traditional method is zero sequence current direction protection. When there is interturn short circuit, smaller current of three phase unbalance current, which is because of fewer turns of short circuit, leads to early low sensitivity of reactor protection in [15]. In [16], with the zero sequence current protection with compensation, the sensitivity of the interturn protection of the reactor has been improved, but the problem of compensation is difficult to fix. Xin [17] based on traditional methods, adaptive zero-sequence power direction
protection is put forward. This method makes compensation to the zero sequence voltage when there is short circuit. Besides that, with the help of auxiliary criteria for mutation and steady-state criterion, the sensitivity of the turn-to-turn protection has been improved. However, there is still a hidden danger in the incomplete phase operation. In [18], in addition to the compensation to the zero sequence voltage, the zero sequence impedance element, the fault open element, the harmonic locking element, and the protection starting element of the fluctuation threshold of the work frequency change are added. These elements improve the reliability and sensitivity of interturn protection, but the protection principle and process are complicated. Protection of reactor includes zero sequence current, zero sequence voltage or zero sequence impedance, but all of them are based on unbalance of three phase. The matter is that three phase unbalance is greatly influenced by power grid. Compensation can improve the reliability, but did not fundamentally solve the problem. Zhang [19] calculate the current, voltage and impedance, but the number of short circuits used in different winding short circuit is exactly the same. In fact, the number of short circuit turns is a quarter of a turn on four bus reactors, and a sixth of a turn on the six bus reactors. In addition, there are some rules about the interturn faults in different locations of the same layer of different winding in the same layer of the reactor. At present, it is almost in the research blank, and the reactor accidents still occur frequently. Therefore, to improve the performance of the interturn short circuit protection and improve the sensitivity, it is urgent to further study the regularity of short circuit and the method of interturn short circuit protection. This paper will introduce a method which use unbalance current of single-phase reactor bus to judge interturn short circuit. It starts from the interturn short circuit between the internal winding of the reactor, researching the regularity of unbalanced current of interturn short circuit in different winding. In this way, whether there is interturn short circuit is clear. At the same time, comparing unbalanced current with total current, analyzing the root cause of the insensitivity of interturn short circuit protection are both significant for the safe and stable operation of power system and the reactor manufacturing.

2. Simulation analysis of unbalanced current between turns.
When there is interturn short circuit, the internal resistance, self-inductance and mutual inductance of the hollow reactor will change along it. Thus, the first step is calculating the internal resistance, self-inductance and mutual inductance before and after the short circuit. The following is the derivation.

2.1. Basic principle

![Figure 1. The geometrical dimensions of the two windings.](image-url)
The geometric dimensions of the two windings of a single wire are shown in figure 1. In the figure, \(n_1\), \(n_2\) are used to show unit height of two windings, \(h_1\), \(h_2\) are used to show radius of two windings and \(s\) is used to show Center distance. Cui, Ma, and Shen [20], according to the Biot Savart law and Feng. Neumann formula, mutual inductance calculation formula can be worked out between single turn metal ring at \(x_1\) of winding 1 and that one at \(x_2\) of winding 2. The following is the formula.

\[
M_0 = \frac{\mu_0}{4\pi} \int_{l_1} \int_{l_2} \frac{dl_1 dl_2}{r}
= \mu_0 \int_0^\pi \frac{rr_d d\theta}{\sqrt{r_1^2 + r_2^2 + (x_1 - x_2)^2 - 2rr_1\cos\theta}}
\]

In formula (1), \(\mu_0\) is the vacuum permeability, \(l_i\) is the integral curve of the circumference along the circumference of winding 1, \(l_2\) is the integral curve along the circumference of winding 2, \(r\) is the distance between the winding 1 and the winding 2, \(\theta\) is the angle, which is projected from \(r\) to the middle between the plane of \(dl_1\) and the plane of \(dl_2\). The mutual inductance \(M\) between the two windings can be obtained by integrating the mutual inductance and the height.

\[
M = \mu_0 r_1 r_2 n_1 n_2 [F(r_1, r_2, z_1) - F(r_1, r_2, z_2) + F(r_1, r_2, z_3) - F(r_1, r_2, z_4)]
\]

\[
F(r_1, r_2, z_i) = \rho_1 r_1 \int_0^\pi \frac{\sqrt{r_1^2 + r_2^2 + z_1^2 + 2rr_1\cos\theta}}{r_1^2 + r_2^2 - 2rr_1\cos\theta} \sin^2\theta d\theta
\]

When \(h_1\) is equal to \(h_2\), \(r_1\) is equal to \(r_2\), \(n_1\) is equal to \(n_2\), and \(s\) is zero, and they are used in (2), self - sense of each winding can be worked out. DC resistance of winding in temperature \(T\) is showed following.

\[
R = 8n\rho(1 + \alpha T) / d^2
\]

In the formula, \(r\) is average radius, \(n\) are turns of winding, \(\rho\) is resistivity, \(\alpha\) is coefficient of temperature, \(d\) is diameter of wire.

### 2.2. Equivalent model of turn-to-turn short circuit

The turn-to-turn short-circuit model of the reactor windings is shown in figure 2. In it, \(R_1 - R_6\) is reactor, \(u_i - u_6\) is internal resistance of each winding, \(L_1 - L_6\) is the self-sense of each winding. They are respectively corresponding with the voltage at both ends, \(i_i - i_k\) are each winding input and output current, and the black dot is the mutual sense end.
Before the short circuit

\[ i_1 R_{/2} L_{1} \] \[ i_2 R_{/2} \]

\[ i_3 R_{/2} L_{2} \]

\[ i_4 R_{/2} L_{3} \]

\[ i_5 R_{/2} L_{4} \]

\[ i_6 R_{/2} L_{5} \]

\[ i_7 R_{/2} L_{6} \]

\[ i_8 \]

After the short circuit

\[ i_1 R_{1} L_{1} \]

\[ i_2 R_{2} \]

\[ i_3 R_{3} L_{3} \]

\[ i_4 R_{4} L_{4} \]

\[ i_5 R_{5} L_{5} \]

\[ i_6 R_{6} \]

\[ i_7 \]

\[ i_8 \]

Figure 2. Equivalent model of inter-turn short circuit.

According to Kirchhoff’s law, the system of voltage and current of the node after short-circuit is listed as follows:

\[ z \times i = u \]

\[ z = \begin{bmatrix} R_1 + jwL_1 & jwM_{12} & \cdots & jwM_{16} \\ jwM_{21} & R_2 + jwL_2 & \cdots & jwM_{26} \\ jwM_{31} & jwM_{32} & \cdots & jwM_{36} \\ jwM_{41} & jwM_{42} & \cdots & jwM_{46} \\ jwM_{51} & jwM_{52} & \cdots & jwM_{56} \\ jwM_{61} & jwM_{62} & \cdots & R_6 + jwL_6 \end{bmatrix} \]

\[ u = [u_1, u_2, u_3, u_4, u_5, u_6]^T \]

(4)

\[ i = [i_1, i_2, i_3, i_4, i_5, i_6]^T = z^{-1} u \]

Meanwhile, there is a relation between the two winding short circuit as following.

\[ u_1 = u_3 \] (5)

\[ u_2 = u_4 \] (6)

\[ i_1 + i_3 = i_2 + i_4 \] (7)

\[ u_3 + u_2 = u_5 = u_6 \] (8)

The current theoretical value of each winding before and after the short circuit can be worked out by bringing equations (5)-(8) to equation (4). The result is shown in table 1.
2.3. Analysis of numerical simulation

The distribution of the current numerical simulation results before and after the short circuit of each winding is shown in figure 3. When there is short circuit between winding 1 and winding 2, current in windings is newly distributed to winding 1 and winding 2. The current of the winding 3 and the winding 4 are nearly the same as the current of the windings before the short circuit. At short-circuit point F1, there is the biggest difference of current between winding 1 and winding 2, and the smallest one between winding 1 and winding 2 at short-circuit point F4. From Short-circuit points F1 and F4, current of winding 1 is becoming smaller and smaller, and current of winding 2 is becoming bigger and bigger.

![Figure 3. Distribution of calculated values of current in each short - circuit location.](image)

The total current of dry air reactor before short circuit is 10.2012. At different places, the total current is 10.203. Total current amplitude changes are 0.0001 amps. Little amplitude change is the reason of the lack of sensitivity and reliability. At short circuit F1, the maximum unbalance current amplitude of winding 1 and winding 2 is 0.063 amps, which is as 630 times as total current. They prove the feasibility and superiority of unbalanced current method.

3. Analysis of experimental data

3.1. The experimental principle

This experiment used the same reactor parameters as simulation. As is shown in figure 4, the power supply is transmitted by a large current generator to the reactor and then back to the large current generator. By measuring current of four windings $I_1, I_2, I_3, I_4$ and total current $I$ when there is short circuit between windings at $F_1, F_2, F_3, F_4$, the regularity of current change can be found. $F_1, F_2, F_3, F_4$
is one tenth, two tenths, three tenths and four tenths of the total length.

Figure 4. Experimental circuit diagram.

The black dots in the figure indicate the mutual sense of the same name. $l_1 - l_4$ represents the inductance of each winding, CH1-CH4 represent the four windings of the single-layer reactor, $i_1 - i_4$ represent the current of four windings. And the digital power meter model is YOKOGAWA WT1600, T1 is a self-coupling adjustable transformer, T2 is liter current transformer. T1 and T2 are large current generators.

3.2. Analysis of the experimental result

According to the experimental schematic diagram, the current amplitude of each winding is shown in table 1, and the current of each winding in different fault points is shown in figure 5. It can be seen from figure 5 that the current of each winding is unchanged from the short circuit point F1 to the short-circuit point F4 before the failure, but the current difference exists between the four windings before the failure, and there is an unbalanced current.

![Figure 5](image-url)

Figure 5. The current in the short-circuit position of the winding before the fault.

In order to eliminate the influence of the unbalance current on the measurement method, the relationship between the total current and the four winding current is studied by changing the total current of the reactor. In the case of 45°C, change the total current of the reactor from 1 to 15A increase by 1A per time. The change rule of each winding current with the total current is shown in figure 6. It can be seen that with the increase of the total current, the current of each winding will increase linearly, which means that the current of the four windings becomes a constant linear relationship before the failure. Therefore, the unbalance current in itself can be offset by multiplying the linear coefficients.

After the failure, the current change trend of each winding current with the total current is shown in figure 7. As shown in figure 7, when the winding 1 and winding 2 are short-circuited in F1, the
winding current of dry air reactor still changes linearly with the total current. Only the linear coefficients of winding 1 and winding 2 have changed. In other words, the linear coefficient between the bus bars is measured before the unbalanced current is calculated, and the linear coefficient is multiplied. Then the unbalanced current can be close to and zero before the failure, after the failure, the same linear coefficient is used to process the experimental data, and the fault detection is realized by calculating that the unbalance current between the short circuit winding is not equal to zero. Therefore, the method of unbalanced current cannot be used because of the imbalance of the reactor itself.

![Figure 6. Winding current with the total current change map.](image)

![Figure 7. The current in the short-circuit position of the winding after the fault.](image)

3.3. Experimental data processing

In order to eliminate the influence of the unbalanced current on the measurement method, the linear coefficients between the bus bars of the dry air reactor were obtained:

\[
K_{21} = I_2 \div I_1, \quad K_{31} = I_3 \div I_1, \quad K_{41} = I_4 \div I_1,
\]

According to the experimental values given in table 1, the values of \(K_{21}, K_{31}, K_{41}\) before failure are calculated as shown in table 2.

| Short circuit position | \(K_{21}\)     | \(K_{31}\)     | \(K_{41}\)     |
|-----------------------|---------------|---------------|---------------|
| F1                    | 1.005801      | 1.011053      | 1.004586      |
| F2                    | 1.005812      | 1.011113      | 1.004673      |
| F3                    | 1.005783      | 1.011094      | 1.004603      |
| F4                    | 1.005756      | 1.011117      | 1.004612      |

Take the average of the linear coefficients of different positions, get the value of \(K_{21} = 1.0058, K_{31} = 1.0111, K_{41} = 1.0046\)

The calculation Formula of the unbalance current between the bus bars.

\[
\begin{align*}
I_{21} &= I_2 - K_{21} \cdot I_1 \\
I_{31} &= I_3 - K_{31} \cdot I_1 \\
I_{41} &= I_4 - K_{41} \cdot I_1 \\
I_{32} &= I_3 + K_{31} \cdot I_1 - K_{31} \\
I_{42} &= I_4 + K_{41} \cdot I_1 - K_{21} \\
I_{43} &= I_4 + K_{41} \cdot I_1 - I_2 + K_{21}
\end{align*}
\]

According to table 2, it not only eliminates the influence of the unbalanced current on the measurement method, but also can find out the unbalanced current between the bus bars after the short circuit. According to the data, the change trend of the imbalance current of the bus after the short circuit is shown in figure 8.
It can be seen from figure 8 that the unbalance current of bus no. 1 and bus no. 2 is the largest in the unbalanced current after the short circuit, while the unbalance current of Bus no. 3 and Bus no. 4 is almost zero. In addition, as the short-circuit position is closer to the output end of the reactor, its unbalanced current is also increasing.

Figure 8. The unbalance current change trend chart of each busbar after the fault.

Figure 9. The current in the short-circuit position of the winding after the fault.

Figure 9 is the current of each short-circuit point winding after the fault (excluding the unbalance current interference). It can be found that the current amplitude difference between winding 3 and winding 4 in different short-circuit positions is basically unchanged. And the winding 1 and the winding 2 caused the current to be redistributed due to the short circuit, resulting in a large imbalance current. and at short circuit point F1, the imbalance current is the largest, while the unbalanced current is the minimum at the short-circuit point F4. And from the short-circuit point F1 to the short-circuit point F4 unbalanced current decreases in turn, consistent with the trend of theoretical derivation. and the unbalance current variation between the short circuit winding is 50 times that of the single phase total current. When the short circuit position is at the end, the unbalance current variation between the windings is 124 times of the change of single phase total current. It can be found that the change of unbalanced current is much higher than that of the total current. In other words, the method of measuring the unbalance current of the bus bars to detect the short-circuit fault is greatly improved compared with the method of detecting total current.

3.4. The theoretical value of current is compared with the experimental value of current

Figure 10. Comparison between theoretical and experimental values.
The comparison between the theoretical value of current and the measured value of the experiment is shown in figure 10. It can be seen from the figure that the trend of the theoretical and actual value of unbalanced current is the closer to the short-circuit point F1 unbalanced current is larger, the closer to the short-circuit point F4 unbalanced current is smaller.

As can be seen from figure 8, the unbalanced current is much larger than the total current, whether it is theoretical simulation or experiment, and the closer to the end of the reactor the greater the change. This indicates that the detection of the imbalance current in the bus bars is more sensitive than the detection of total current. And when the reactor is working normally, the bus bars current by multiplying the linear coefficient is approaching to 0, which is the result of the internal calculation of the single-phase reactor, it will not be affected by the unbalanced fluctuations of the power grid, compared with zero sequence protection, it greatly improves the reliability of anti-interference ability.

4. Conclusion
This experiment verifies the validity of the method of measuring the unbalance current of the bus bars to detect the turn-to-turn short circuit of the winding, and the following conclusions are obtained:

- The closer the short-circuit position of the reactor winding to the end, the greater the imbalance current, the better the effect of the interturn short circuit fault of the measuring reactor.
- Whether there is a short circuit between the winding, the short-circuit position is in the middle, the short-circuit position occurs at the end or in the middle-upper part. Compared with the three phase zero sequence unbalanced current induced by the single phase total current variation, the current sensitivity is higher.

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