On-line Monitoring Technology of Interturn Short Circuit in Dry Reactor Based on Impedance Micro-incremental Identification

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Abstract. Dry-type air-core reactor has frequent faults due to insulation aging in long-term operation, among which the inter-turn short circuit fault rate is the highest. Firstly, the equivalent circuit model of reactor inter-turn short-circuit fault is established, and the characteristics of reactor power angle change caused by inter-turn short-circuit fault are analyzed. Based on this, an on-line monitoring technology of dry air-core reactor inter-turn short-circuit based on impedance micro-incremental identification is proposed. The power factor angle of the reactor is obtained by impedance micro-incremental analysis. The test results show that the proposed technology can effectively monitor the short circuit fault of the reactor with less turn-to-turn insulation.

1. Introduction
Dry-type reactor is an important equipment in power system. It is widely used in power system because of its stable parameters, good linearity, low noise and low loss[1]-[3]. With the annual increase of the number of dry-type reactors and the increase of their operation life, the product quality defects gradually appear due to the immature technology or inadequate process control in the early products. At the same time, due to its use of air heat dissipation and poor operating environment, it is easy to cause insulation damage after a long period of operation, which further causes inter-turn short circuit and other faults, and even causes reactor burnout in serious cases, thus affecting the safe and stable operation of the power grid. According to relevant research, 95% of reactor faults are caused by insulation faults and inter-turn short circuit, but the existing monitoring methods have some problems, such as low sensitivity and poor reliability, which can not detect faults in time and lead to the burning of reactor. Therefore, it is particularly important to study more effective monitoring methods and find faults in time[4]-[5].

At present, the on-line monitoring methods of dry-type reactor at home and abroad mainly include temperature monitoring method, partial discharge monitoring method, magnetic induction detection coil method and so on[6]. However, neither of them can accurately and reliably reflect the insulation and slight inter-turn short-circuit faults of the reactor, and the method based on impedance micro-incremental identification can accurately and quickly reflect the two faults. Normally, the equivalent resistance of the reactor is basically unchanged, and the impedance angle is basically a certain value.
Interturn short circuit fault will cause the change of the equivalent resistance and the equivalent reactance of the reactor. The increase of the equivalent resistance is more obvious, and the impedance angle also changes, so it can be changed according to the equivalent resistance of the dry reactor and the power factor power angle[7]-[9]. The characteristic realizes the monitoring and diagnosis of internal insulation fault and turn-to-turn short circuit fault, discovers faults in time, ensures the safe operation of dry-type reactor, and serves for the further diagnosis system of the Internet of Things.

In this paper, a CKDGKL-2.5/10-1 series reactor is taken as the research object. Firstly, the inter-turn short circuit fault model of reactor is established, and the characteristics of power angle decreasing when the inter-turn short circuit fault occurs are obtained through theoretical analysis. On this basis, the improved median filter algorithm and the modified ideal sampling frequency method are used to analyze the data. The power angle of the reactor is obtained by harmonic analysis method. Finally, a test platform is built to study the characteristics of the power angle variation when the reactor has different turns and different positions of the inter-turn circuit fault, and to verify the effectiveness and feasibility of the proposed method.

2. Turn short circuit fault model
The dry-type air-core reactor is equivalent to several shunt inductance branches. It is assumed that the k-turn short circuit of the m-turn winding of the S-layer shunt winding occurs. Fig. 1 is the equivalent circuit model. In Fig. 1, the short circuit loop forms a separate closed loop. The m-layer winding is divided into two windings in series. Its equivalent resistance is \( R_{S+1} \) and self-inductance is \( L_{S+1} \).

![Figure 1. Equivalent circuit of dry-type air-core reactor inter-turn short circuit](image)

When the reactor has inter-turn short circuit, the equation is as follows:

\[
\dot{U} = M \cdot \dot{I}
\]
Distribution currents $I_1, I_2, I_3, ..., I_S$ of reactor branches are obtained from Formula (1) and Formula (2). The total current $I$ flowing through the reactor is obtained. The resistance $R$ and reactance $X$ are obtained according to Ohm's law, and then the power angle $\theta$ is calculated.

3. Principle of Interturn Short Circuit Monitoring

When the inter-turn short circuit fault occurs, the short-circuit part can be regarded as the secondary winding, which is equivalent to the short-circuit fault of the secondary side of single-phase autotransformer. As shown in Fig. 2 (a), the equivalent circuit is shown in Fig. 2 (b). $N_1$ is the number of turns per phase winding (series winding); $N_2$ is the number of turn-to-turn short circuit (common winding); $K_a$ is the ratio; $X_{1a}$ is the leakage reactance of series winding; $X_{2a}$ is the leakage reactance of public winding; $X_m$ is the excitation reactance; $I_{1a}$ and $I_{2a}$ are the primary and secondary current of fault respectively; $I_0$ is the excitation current.

In normal operation, the main active power losses of reactor are resistance loss $P_R$ and additional loss $P^*$. When the frequency is fixed, it is generally considered that the additional loss is a fixed value, and its value does not exceed 35% of the resistance loss, then the active power loss of reactor in normal operation is:

$$P = UI \cos \theta = P_R + P^* = i^2 + P^*$$

Among them, $i$ is the total current flowing through the reactor.

In the initial stage of reactor failure, the change of equivalent reactance $X'$ can be neglected. A large amount of energy is consumed in the short circuit instantaneous, which makes the total active power
loss $P$ increase sharply, while the current $i$ hardly changes, the equivalent resistance $R$ increases, and changes to $R^*$. At this time, the power angle of reactor is $\theta'$. When the number of short-circuit turns is greater than 8 turns, the inductance change cannot be ignored. Figure 2 (b) shows that when the inter-turn short-circuit fault occurs, the equivalent reactance $X$ consists of two parts, one is the parallel connection of leakage inductance and excitation reactance of the public winding part, the other is the leakage reactance of the series winding and part of the leakage reactance of the public winding, in which the leakage reactance of the series winding and part of the leakage reactance of the public winding are composed. In the first part, the shunt reactance is lower than the normal value of the reactor. At this time, the equivalent reactance is $X''$ and the short-circuit current is larger. When the equivalent resistance becomes $R''$ the power angle changes to $\theta''$, as shown in Fig. 3.

![Figure 3. Power angle variation of reactor inter-turn short circuit](image)

### 4. Monitoring Technology of Dry Air-core Reactor

#### 4.1 Acquisition of power angle

In this paper, the power angle of the reactor is obtained by harmonic analysis method. The terminal voltage of the reactor is $U(t)$, and the total current flowing through the reactor is $I(t)$. The Fourier series decomposition method is used to decompose the power angle of the reactor.

$$
U(t) = a_0 + \sum_{k=1}^{\infty} A_k \sin(2k\pi f_0 t + \varphi_k)
$$

$$
I(t) = a_0 + \sum_{k=1}^{\infty} A_k \sin(2k\pi f_0 t + \varphi_k)
$$

Among them, $f_0$ is the fundamental frequency; $a_0$ and $a_0$ are the DC components of voltage and current; $A_k$ and $A_k$ are the amplitudes of $k$-th harmonics of voltage and current; $\varphi_k$ and $\varphi_k$ are the initial phases of $k$-th harmonics of voltage and current respectively. After processing the signal, the discrete sequence is obtained. The real and imaginary parts of the voltage signal are as follows:

$$
X_{Re}(k) = \sum_{n=0}^{N-1} x(n) \cos(2\pi kn / N)
$$

$$
X_{Im}(k) = \sum_{n=0}^{N-1} x(n) \sin(-2\pi kn / N)
$$

The phase of the voltage signal is calculated by the real part and the imaginary part of the voltage signal.

$$
\varphi_k = \arctan\left(\frac{X_{Im}(k)}{X_{Re}(k)}\right)
$$

#### 4.2 Hardware Design of Monitoring Device

The on-line monitoring device of dry air-core reactor adopts the structure of complex programmable logic device and digital signal processor (CPLD + DSP), as shown in Fig. 4. Among them, CPLD achieves high-precision system frequency measurement, and DSP achieves high-speed data processing, analysis and transmission. Electric quantity is collected by high precision voltage transformer (TV) and current transformer (TA); after signal conditioning, signal is converted into digital signal and
input to MCU by AD7656, data processing and fault logic judgement are realized, and the reactor operation state and electrical parameters are separated by optical fiber communication. Do not upload to the host computer and remote monitoring center to realize real-time monitoring of reactor operation status.

5. Test Verification and Analysis

5.1 Fault simulation experiment of shunt reactor

In order to simulate the inter-turn short-circuit fault of reactor, on the basis of not destroying the original structure of reactor, after encapsulating and solidifying the product, several coils with different turns are added at different positions on the outer surface of phase A reactor. Each coil is connected by knife-gate, and the knife-gate of different coils is closed to simulate the short-circuit fault of different turns. After the equipment is put into operation, adjusting booster makes the bus voltage rise to 0.12KV, and the current flowing through the reactor is 19.2A. When the equipment is stable on power, manual initialization is carried out to obtain the characteristic value of the equipment in normal operation, and then the two-turn coil in the middle of phase A reactance is closed to simulate the inter-turn short circuit fault. The power factor of the reactor varies as shown in Figure 4.

![Figure 4. Power factor change of one turn short circuit](image)

From Figure 4, it can be seen that the power of C-phase reactor is quite different from A and B under normal conditions. This is because Three-phase Reactors A, B and C are not products of the same batch. There are certain differences in the electrical parameters of each reactor itself. Therefore, when applying the same voltage to Three-phase Reactors A, B and C, the power and power of each reactor are equal. There are differences in phase angles.

| Phase | \( \theta \) /° | \( P \)/kW | \( Q \)/kvar | Powerfactor |
|-------|----------------|------------|-------------|-------------|
| A     | 88.591         | 0.030      | 0.814       | 0.02457     |
| B     | 89.145         | 0.034      | 0.745       | 0.03221     |
| C     | 86.358         | 0.034      | 0.776       | 0.05020     |

5.2 Short-circuit Fault Simulation Experiments with Different Turns

The inter-turn short-circuit fault of reactor is caused by the decrease of the insulation performance of reactor. The multi-turn short-circuit fault is the result of the development of single-turn short-circuit fault. With the increase of the number of short-circuit turns, the short-circuit current in the short-circuit ring increases, the active power consumed increases, the equivalent resistance of reactor increases, the power angle decreases, and the power factor increases. Big. Therefore, the author simulates the inter-turn short-circuit faults of the reactor in different degrees by closing the coil groups of different turns on the A-phase reactor.

6. Conclusion

This paper designs an on-line monitoring system for inter-turn insulation of dry-type air-core reactor, and takes the parallel reactor monitoring as an example to test and verify it. The power factor variation
characteristics of dry-type air-core reactor with different turns, the same turns and different positions of inter-turn short circuit fault are obtained.

1. By modeling the dry air-core reactor interturn short-circuit fault, it is found that the power angle of the reactor decreases and the power factor increases when the reactor interturn short-circuit fault occurs.

2. When the reactor has inter-turn short-circuit fault, the impedance variation is the largest. The experimental study provides a basis for on-line monitoring of dry reactor internal insulation fault and minor inter-turn short-circuit based on impedance micro-increment.

3. The experimental results show that the device can quickly detect the early small turn-to-turn short-circuit faults of the reactor, and the variation of the power angle before and after the reactor short-circuit faults is related to the number of short-circuit turns and the location of short-circuit faults. With the increase of the number of short-circuit turns or the location of short-circuit faults between turns moves from both ends to the middle, the reactor competes for power. The power factor increases as the power factor decreases.

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