Simulation on Transient Characteristics of Inter-Turn Short Circuit Fault of Dry-type Air-Core Reactor Based on ANSYS Maxwell

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\textbf{Abstract.} Transient characteristic analysis of inter-turn short circuit fault has been done which is paramount for detecting the earlier fault of dry-type air-core reactor. Dynamic physical process of inter-turn short circuit is theoretically analyzed for dry-type air-core reactor from normal running condition to inter-turn short circuit fault condition. Using ANSYS Maxwell, transient field circuit coupling calculation model is set up and the transient characteristic of inter-turn short circuit fault is simulated, which is also verified by experiments. The study shows that the short circuit ring causes a sudden change of magnetic field at the position of short circuit which can be detected by the detecting coils installed on the package of reactor. Inter-turn short circuit fault can be detected in the earlier fault period by the method proposed in this paper.

\textbf{Introduction}

Dry-type air-core reactor has been widely used in power system for limiting over current, filtering harmonic wave and compensating reactive power, etc [1-3]. Because of being used in the harsh outdoor environment, accidents occur frequently in which inter-turn short circuit is the most common one and accounts for more than 50\% of the total faults occurring in the reactor. Short circuit may cause local overheating which would result in the acceleration of insulation ageing, and even damage the reactor, thus endanger the safe operation of the power system [4-7]. So far online detection methods for inter-turn short circuit are usually based on the steady characteristic of the reactor and not sensitive to small turn short circuit [8-9]. Actually, the earlier detection and warning are expected to avoid any harm to power system. It is paramount to study the transient characteristic of inter-turn faults for the earlier detection.

In this paper, dynamic physical process of inter-turn short circuit is analyzed in detail based on the electromagnetic theory for dry-type air-core reactor from running normal condition to inter-turn short circuit fault condition. Based on ANSYS Maxwell, transient field circuit coupling calculation model is set up. And, the transient characteristic of inter-turn short circuit fault is simulated, which also is verified by experiment. The research will provide theoretical and experimental basis for the earlier fault detection of inter-turn short circuit of the dry-type air-core reactor.

\textbf{Dynamic Physical Process of Inter-Turn Short Circuit in the Reactor}

The dry-type air-core reactor is constructed of several packages in parallel with cooling airway between two adjacent ones supported by spacers, and each package is made up of several winding layers also in parallel, as shown in Fig.1(a). The corresponding circuit of the reactor is shown in Fig.1.
(b) where \( u(t) \) and \( i(t) \) are the voltage and current of the reactor, respectively. \( i_k(t), R_k \) and \( L_k \) \((k=1, 2, \ldots, n, n \) is the number of winding layers\) are the branch current, resistance and self inductance of the \( k \)th winding layer, respectively, \( M_{kj} \)(\( j=1, 2, \ldots, n, j \neq k \)) is the mutual inductance between the \( k \)th layer and the \( j \)th layer.

Three stages can be included in the dynamic physical process of inter-turn short circuit in the reactor: normal running period, early fault period and failure period [10-11].

During the running period, two adjacent turns are connected in series and have the same current, as shown in Fig.2 (a). The current of the \( m \)th turn is the same as the one of the \( m+1 \)th turn. According to Ampere’s force law, both adjacent turns attract each other but not short circuit because of good insulation between them.

When failure occurs in inter-turn insulation, the two turns in the insulation failure will be touched to form a short circuit ring by the electromagnetic attractive force, but will separated immediately after their collision by the electromagnetic repulsive force because that the direction of the short circuit current is opposite to the one of normal turns according to electromagnetic induction law, as shown in Fig.2 (b), the \( m \)th turn is a short circuit ring. This can be called early fault period during which the two adjacent turns repeat collision and separation.

The large induced current of the short circuit ring may cause local high temperature and aggravate the insulation damage, which leads to metal wire being welt into integer. This is called failure period during which the touched turns will not be separated any more and a steady short circuit ring will be formed which can cause more severe short circuit, even burn the reactor.

![Figure 1. Structure and circuit model of dry-type air-core reactor.](image)

![Figure 2. Current of the dry-type air-core reactor.](image)
Transient field Circuit Coupled Model of the Reactor

Dynamic process of the inter-turn short circuit of the reactor can be simulated with the “Transient” modular of ANSYS Maxwell. The rated electrical parameters and structural parameters are shown in Table 1 and Table 2, respectively [11].

| Capacity[kVar] | Voltage[V] | Current[A] | Inductance[mH] | Frequency[Hz] |
|----------------|------------|------------|----------------|----------------|
| 4.4            | 110        | 40         | 8.76           | 50             |

Table 2. Structure parameters of the reactor.

| Layer number | Winding diameter[mm] | Winding height[mm] | Number of turns | Wire diameter[mm] |
|--------------|----------------------|--------------------|-----------------|------------------|
| 1            | 606.22               | 525.30             | 147.50          | 3.15             |
| 2            | 612.66               | 512.91             | 144.00          | 3.15             |
| 3            | 675.48               | 524.99             | 131.75          | 3.55             |
| 4            | 682.68               | 523.31             | 131.50          | 3.55             |

Finite Element Geometry Model

According to the structure of the reactor, a two-dimensional axisymmetric finite element model in cylindrical coordinates (Cylindrical about Z) can be set up, as shown in Fig.3, where short circuit winding consists of three sub winding: upper winding, short circuit ring and lower winding. Besides, the detective coil and the solution domain (Region) are also built.

![Figure 3. The finite element geometry model of dry-type air core reactor.](image)

Boundary and Excitation Loading

Since the solution domain is infinite, boundary loading can be done by assigning balloon boundary condition on the boundary of “Region”.

Excitation loading can be done by importing external circuit to the winding port after the port and turn are assigned to the winding.

External Circuit Model

External circuit models are built by ANSYS Maxwell Circuit Editor, as shown in Fig.4. In the early period of the inter-turn short circuit, the circuit structure of the reactor is changing, this can be achieved by a controlled switch S_18, as shown in Fig.4 (a), where ModelV is the switch model of...
S_18, Lwinding1, Lwinding2 and Lwinding3 are the 1th to 3th winding. Assume that inter-turn short circuit occurring in the 4th winding, Lwinding6 represents short circuit ring, Lwinding4 and Lwinding7 the upper winding and lower winding, respectively. R9, R10 and R11 are the resistance of the 1th to 3th winding, respectively, R6 is the resistance of the short circuit ring, and R4 and R7 are the resistance of the upper winding and lower winding, respectively. The controlled circuit of the switch is shown in Fig.4 (b), where V21 is pulse voltage source, R22 current-limiting resistance and IVc voltmeter. In Fig.4(c), Lwinding5 represents detective coil, R13 is open circuit resistance, $10^6 \Omega$.

**Simulation and Experiment Results**

**Simulation Results and Analysis**

Inter-turn short circuit has been set at a distance of 100mm from the center of the reactor along an axial direction in the 4th winding. The simulation current of the short circuit ring is shown in Fig.5, and the induced voltage of the detective coil is shown in Fig.6 by which the transient characteristic of the magnetic field can be detected.

![Main circuit model](image)

![Control circuit of Switch](image)

![Loop of detective coil](image)

**Figure 4.** Transient simulation circuit model of inter-turn short circuit of reactor.
We see from Fig.5 that the current of a normal turn will get to a large value while it becomes to be a short circuit ring which can cause a significant change to the magnetic field of the reactor, and accordingly, the induced voltage will change apparently, as shown in Fig.6. Therefore, we can easily detect the early short circuit fault by the induced voltage of the detective coil.

**Experimental Results**

An experimental platform has been set up to obtain the practical induced voltage of detective coil during the dynamic process of inter-turn short circuit arranged artificially. NI PCI-6221 is selected and the sampling rate is 30 kHz/s. The induced voltage is shown in Fig.7, where we can observe that the induced voltage has a prominent change at the instant of short circuit. Experimental results and simulation results show excellent agreement, which indicates correctness of the simulation computation.
Conclusions

The dynamic physical process of the dry-type air-core reactor from normal running condition to inter-turn short circuit fault condition based on the electromagnetic field theory, in which three stages are included: normal running period, early fault period and failure period. The transient characteristic of inter-turn short circuit has been obtained by simulation based on ANSYS Maxwell as well as by experiment. Both simulation results and experimental results show that in the early period of inter-turn short circuit, the large current in the short circuit ring can cause a prominent change of the magnetic field of the reactor. Therefore, we can detect the inter-turn short in the early fault period by the induced voltage of the detective coil installed on the package.

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