Shunt Reactor with Auxiliary Winding System Inter-turn Protection Based on Zero Sequence Differential Current

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SUMMARY

Shunt reactor with auxiliary winding system can compensate UHV long distance transmission line capacitive reactive power, and solve the problem of station power supply for remote and without access to electricity. For example, the switching station is built in UHV long distance transmission line usually, and shunt reactor is installed in the station for compensating line capacitive reactive power. If shunt reactor with auxiliary winding system replaces shunt reactor, power for the switching station is provided at the same time.

Inter-turn protection of shunt reactor is zero sequence power direction protection, but the protection cannot operate reliably with auxiliary winding inter-turn fault. The inter-turn fault of the auxiliary winding must be specially protected. There are two parts of the existing inter-turn protection of auxiliary winding. One part is zero sequence overcurrent protection to identify the fault, the other part is zero sequence voltage and current blocking protection of shunt reactor winding to prevent action with outside fault. The protection has the following problems. The setting value needs manual calculation work, and setting fit is difficult, sensitivity is low, protection cannot operate correctly in case of PT break.

Shunt reactor with auxiliary winding system inter-turn protection based on zero sequence differential current is proposed, according to researching equivalent circuit of shunt reactor with auxiliary winding system, and fixed relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current.

There is large air gap in the iron core, thus the coupling relationship between shunt reactor winding and auxiliary winding is weak. Its working principle is similar to the air core transformer.

For Y_0/Δ type shunt reactor with auxiliary winding system, zero sequence circuit of auxiliary winding is equivalent to a short circuit, thus there is no load in the zero sequence equivalent circuit. Figure 1 is zero sequence circuit of shunt reactor with auxiliary winding system.

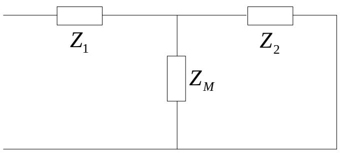

Fig.1 Zero sequence circuit of shunt reactor with auxiliary winding system

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Figure 2 is zero sequence circuit of shunt reactor with auxiliary winding system without resistance, when fault occurs outside.

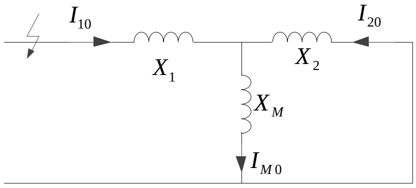

Fig.2 Zero sequence circuit when fault location is outside the zone

The positive direction is the current flowing towards the shunt reactor. The relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current is get:

$$K = \frac{-3\dot{I}_{02}}{3\dot{I}_{01}} = -\frac{X_M}{X_2 + X_M} \tag{1}$$

Since X_M and X_2 are only related to the material and structure of shunt reactor with auxiliary winding system, there is no change in the operation, *K* is a constant and represents fixed relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current. *K* can be obtained by no-load test and short circuit test of the shunt reactor with auxiliary winding system.

The criterion of zero sequence current differential protection is constructed:

$$\begin{cases} \left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| > \min\left\{\left|K3\dot{I}_{01}\right|, \left|3\dot{I}_{02}\right|\right\} \\ \left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| > k_{set} \end{cases} \tag{2}$$

$\dot{I}_{01}$ is zero sequence current of shunt reactor winding, $\dot{I}_{02}$ is zero sequence current of auxiliary winding, k_{set} is differential current setting value, which is set automatically according to rated current.

External fault: the differential criterion of zero sequence current is not satisfied, inter-turn protection of shunt reactor with auxiliary winding system don’t operate.

Shunt reactor winding inter-turn fault: the differential criterion of zero sequence current is satisfied, inter-turn protection of shunt reactor with auxiliary winding system can operate reliably.

Auxiliary winding inter-turn fault: the differential criterion of zero sequence current is satisfied, inter-turn protection of shunt reactor with auxiliary winding system can operate reliably.

Prototype protection device based on shunt reactor with auxiliary winding system inter-turn protection principle has passed the dynamic simulation test. The conclusion shows that this principle is current protection without voltage information and PT, and protection setting doesn’t need manual calculation work, and has high sensitivity.

KEYWORDS

shunt reactor with auxiliary winding system, inter-turn fault, zero sequence current differential protection, inter-turn protection

I. INTRODUCTION

Shunt reactor with auxiliary winding system can compensate UHV long distance transmission line capacitive reactive power, and solve the problem of station power supply for remote and without access to electricity[1-4]. For example, the switching station is built in UHV long distance transmission line usually, and shunt reactor is installed in the station for compensating line capacitive reactive power[5]. If shunt reactor with auxiliary winding system replaces shunt reactor, power for the switching station is provided at the same time.

The auxiliary winding is at the bottom of return path usually[6]. A part of the energy is extracted from shunt reactor with auxiliary winding system using the auxiliary winding for providing power for switching station, meanwhile, the shunt reactor with auxiliary winding system can compensate line capacitive reactive power.

Inter-turn protection of shunt reactor is zero sequence power direction protection, but the protection cannot operate reliably with auxiliary winding inter-turn fault. The inter-turn fault of the auxiliary winding must be specially protected[7-8]. There are two parts of the existing inter-turn protection of auxiliary winding[9]. One part is zero sequence overcurrent protection to identify the fault, the other part is zero sequence voltage and current blocking protection of shunt reactor winding to prevent action with outside fault[10]. The protection has the following problems. The setting value needs manual calculation work, and setting fit is difficult, sensitivity is low, protection cannot operate correctly in case of the voltage transformer disconnected.

Shunt reactor with auxiliary winding system inter-turn protection based on zero sequence differential current is proposed, according to researching equivalent circuit of shunt reactor with auxiliary winding system, and fixed relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current. The conclusion of prototype protection device dynamic simulation test shows that this principle is current protection without voltage information, and protection setting doesn't need manual calculation work, and has high sensitivity.

II. ADAPTABILITY STUDY OF THE EXISTING PROTECTION FOR SHUNT REACTOR WITH AUXILIARY WINDING SYSTEM

Analyzing fault characteristic of auxiliary winding of Y_0/Δ type shunt reactor with auxiliary winding system. Figure 1 (a) is 100% inter-turn short circuit of auxiliary winding, figure 1 (b) is interphase short circuit of auxiliary winding.

"$3I_0$" is the zero sequence current of shunt reactor winding. $3I_0 = I_A + I_B + I_C$. "$3i_0$" is the zero sequence current inside the delta. $3i_0 = i_A + i_B + i_C$ "$3i_0'$" is the zero sequence current outside the delta. $3i_0' = i_A' + i_B' + i_C'$. In both cases, the zero sequence current of shunt reactor winding is the same, and is 0. The zero sequence current inside the delta is synthesized from three phase current. It is not 0 with 100% inter-turn short circuit of auxiliary winding. The inter-turn fault of shunt reactor with auxiliary winding system has following characteristics:

- When inter-turn fault is occurred on auxiliary winding, there is zero sequence current in auxiliary winding, there is not zero sequence component in shunt reactor winding.
- When inter-turn fault is occurred on shunt reactor winding, there is zero sequence current in auxiliary winding and shunt reactor winding.

Inter-turn protection of ordinary shunt reactor is zero sequence power direction protection. Based on the characteristics, the protection is not sensitive and can't operate correctly with auxiliary winding inter-turn fault. Inter-turn protection of shunt reactor with auxiliary winding system can't use this protection.

Existing protection of shunt reactor with auxiliary winding system for auxiliary winding inter-turn fault combines the fault identification criterion for regional fault and the fault blocking criterion for external fault. The fault identification criterion is zero sequence over current criterion of auxiliary

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winding. The fault blocking criterion is zero sequence voltage and current blocking criterion of shunt reactor winding. Figure 2 is existing protection logic diagram for auxiliary winding inter-turn fault.

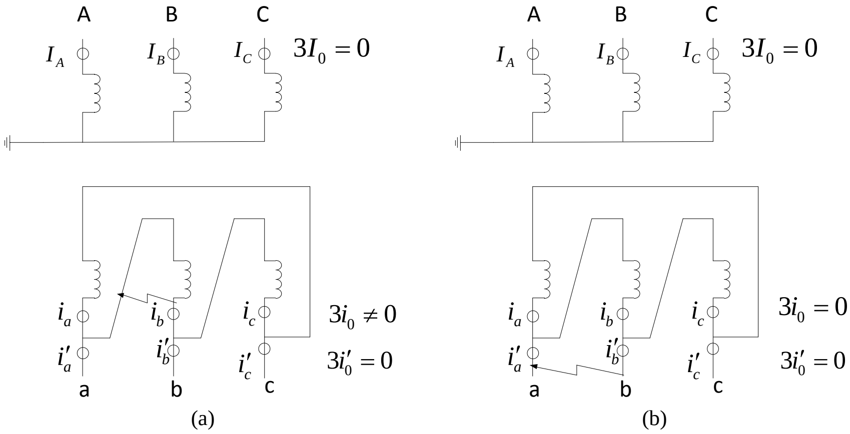

Fig.1 Zero sequence current of auxiliary winding fault
(a) 100% inter-turn short circuit of auxiliary winding
(b) interphase short circuit of auxiliary winding.

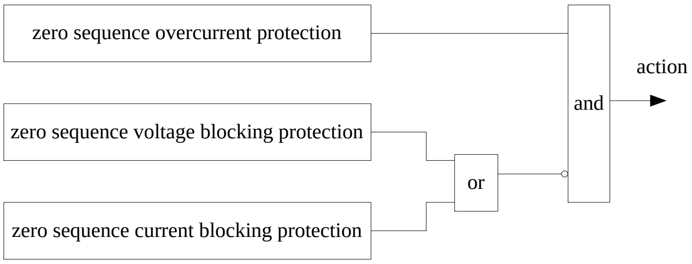

Fig.2 Logic diagram of auxiliary winding inter-turn Protection

The setting value of this protection needs manual calculation work. And setting fit value of this protection is difficult, because it could happen that the blocking protection can't operate and zero sequence overcurrent protection operate, which lead to maloperation in case of external fault. If setting value of zero sequence overcurrent protection is improved in order to prevent maloperation for external fault, the protection becomes less sensitive. In addition, zero sequence voltage blocking protection of shunt reactor winding using three phase voltage of shunt reactor winding, it can't operate when voltage transformer disconnects.

III. SHUNT REACTOR WITH AUXILIARY WINDING SYSTEM INTER-TURN PROTECTION BASED ON ZERO SEQUENCE DIFFERENTIAL CURRENT

A. equivalent circuit of shunt reactor with auxiliary winding system

There is large air gap in the iron core, thus the coupling relationship between shunt reactor winding and auxiliary winding is weak. Its working principle is similar to the air core transformer. Figure 3 is equivalent circuit of air core transformer.

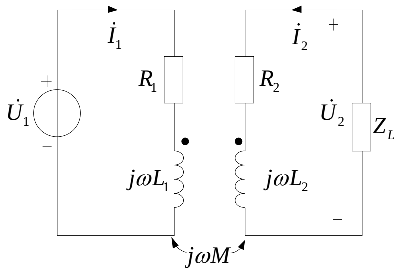

Fig.3 Equivalent circuit of Air Core Transformer

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The following equation is get:

$$\begin{cases}(R_1 + j\omega L_1)\dot{I}_1 + j\omega M\dot{I}_2 = \dot{U}_1 \\ j\omega M\dot{I}_1 + (R_2 + j\omega L_2 + Z_L)\dot{I}_2 = 0\end{cases} \quad (1)$$

In the equation, $\dot{U}_1$ and $\dot{U}_2$ are voltage of shunt reactor winding and auxiliary winding, $\dot{I}_1$ and $\dot{I}_2$ are current of shunt reactor winding and auxiliary winding, L_1 and L_2 are self-inductance of shunt reactor winding and auxiliary winding, M is mutual inductance of shunt reactor winding and auxiliary winding, R_1 and R_2 are resistance of shunt reactor winding and auxiliary winding, Z_L is load of Shunt reactor with auxiliary winding system, ω is the system angular frequency.

As $Z_{11} = R_1 + j\omega L_1$, $Z_{22} = R_2 + j\omega L_2$, $Z_M = j\omega M$, the equation (2) is get:

$$\begin{cases}Z_{11}\dot{I}_1 + Z_M\dot{I}_2 = \dot{U}_1 \\ Z_M\dot{I}_1 + (Z_{22} + Z_L)\dot{I}_2 = 0\end{cases} \quad (2)$$

To simplify the analysis, the shunt reactor with auxiliary winding system can be equivalent to the two-port network. It is shown in figure 4.

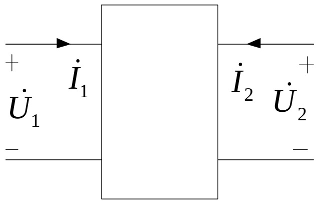

Fig.4 Two-Port Network of shunt reactor with auxiliary winding system

Based on equation (2), the following equation is get:

$$\frac{\dot{U}_1}{\dot{I}_1} = Z_{11} - Z_M^2 Y_{22} = (Z_{11} - Z_M) + (Z_{22} - Z_M) \,||\, Z_M \quad (3)$$

The two-port network internal can be equivalent to T type circuit. It is shown in figure 5.

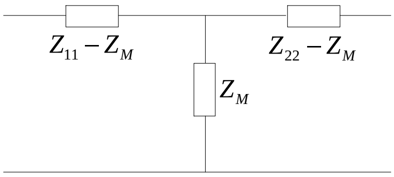

Fig.5 T-type equivalent circuit of shunt reactor with auxiliary winding system

For Y_0/Δ type shunt reactor with auxiliary winding system, zero sequence circuit of auxiliary winding is equivalent to a short circuit, thus there is no load in the zero sequence equivalent circuit. Figure 6 is zero sequence circuit of shunt reactor with auxiliary winding system.

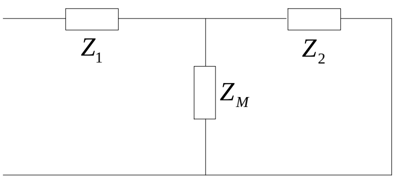

Fig.6 Zero sequence circuit of shunt reactor with auxiliary winding system

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B. Relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current

Figure 7 is zero sequence circuit of shunt reactor with auxiliary winding system without resistance, when fault occurs outside. (Ignoring the loss, and $X_1 = \omega L_1$, $X_1 \gg R_1$, $X_2 = \omega L_2$, $X_2 \gg R_2$, $X_M = \omega L_M$)

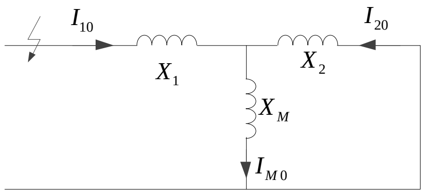

Fig.7 Zero sequence circuit when fault location is outside the zone

The positive direction is the current flowing towards the shunt reactor. The relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current is get:

$$K = \frac{-3\dot{I}_{02}}{3\dot{I}_{01}} = -\frac{X_M}{X_2 + X_M} \tag{4}$$

Since X_M and X_2 are only related to the material and structure of shunt reactor with auxiliary winding system, there is no change in the operation, *K* is a constant and represents fixed relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current. *K* can be obtained by no-load test and short circuit test of the shunt reactor with auxiliary winding system.

C. Inter-turn protection of shunt reactor with auxiliary winding system

The criterion of zero sequence current differential protection is constructed:

$$\begin{cases} \left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| > \min\left\{\left|K3\dot{I}_{01}\right|, \left|3\dot{I}_{02}\right|\right\} \\ \left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| > k_{set} \end{cases} \tag{5}$$

In the equation, $\dot{I}_{01}$ is zero sequence current of shunt reactor winding, $\dot{I}_{02}$ is zero sequence current of auxiliary winding, k_{set} is differential current setting value, which is set automatically according to rated current.

1) External fault

The relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current with external faults.

$$\left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| = 0 \tag{6}$$

The differential criterion of zero sequence current is not satisfied, inter-turn protection of shunt reactor with auxiliary winding system don't operate.

2) Shunt reactor winding inter-turn fault

Shunt reactor winding zero sequence current and auxiliary winding zero sequence current are not 0, when fault occurs shunt reactor winding, and they are in the same direction.

$$\left|K3\dot{I}_{01} + 3\dot{I}_{02}\right| = \left|K3\dot{I}_{01}\right| + \left|3\dot{I}_{02}\right| > \min\left\{\left|K3\dot{I}_{01}\right|, \left|3\dot{I}_{02}\right|\right\} \tag{7}$$

The differential criterion of zero sequence current is satisfied, inter-turn protection of shunt reactor with auxiliary winding system can operate reliably.

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3) Auxiliary winding inter-turn fault

Shunt reactor winding zero sequence current is 0, when fault occurs auxiliary winding.

$$|K3\dot{I}_{01} + 3\dot{I}_{02}| = |3\dot{I}_{02}| > |K3\dot{I}_{01}| = 0 \quad (8)$$

The differential criterion of zero sequence current is satisfied, inter-turn protection of shunt reactor with auxiliary winding system can operate reliably.

IV. Simulation Verification

Prototype protection device based on shunt reactor with auxiliary winding system inter-turn protection principle has passed the dynamic simulation test. Figure 8 is the model. The shunt reactor with auxiliary winding system is installed on the bus of 500kV system, and it is Y_0/△ type, and auxiliary winding lead wire is connected to the 10kV bus. Table 1 is parameter of shunt reactor with auxiliary winding system parameter.

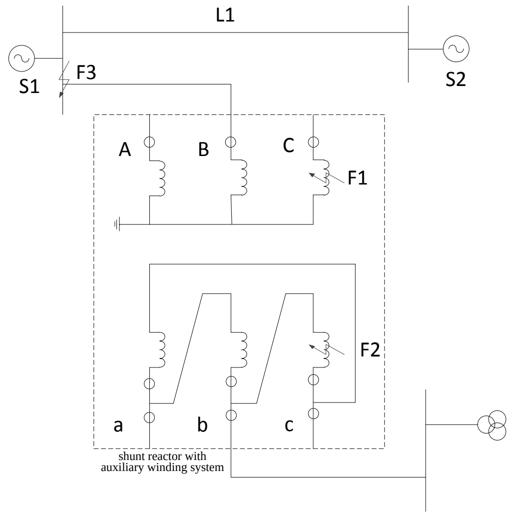

Fig.8 The model of shunt reactor with auxiliary winding system dynamic simulation test

TABLE I Shunt reactor with auxiliary winding system parameter table

NAME	ORIGINAL	MODEL
TV ratio	500kV/100V	1000V/100V
TA ratio of shunt reactor winding	300:1	1:1
TA ratio of auxiliary winding	75:1	1:1

1) Simulation of shunt reactor winding inter-turn fault

Figure 9 is simulation of zero sequence current differential criterion, when 3% inter-turn fault occurred in shunt reactor winding. The differential current is greater than the restraint current, the operation condition is satisfied, the protection can operate reliably.

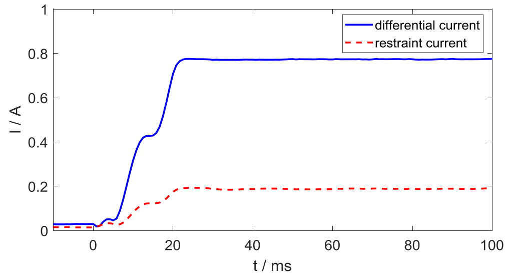

Fig.9 Simulation result of shunt reactor winding 3% inter-turn fault

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2) Simulation of auxiliary winding inter-turn fault

Figure 10 is simulation of zero sequence current differential criterion, when 3% inter-turn fault occurred in auxiliary winding. The differential current is greater than the restraint current, the operation condition is satisfied, the protection can operate reliably.

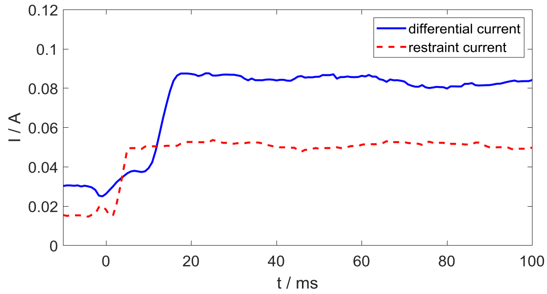

Fig.10 Simulation result of auxiliary winding 3% inter-turn fault

3) Simulation of external fault

Figure 11 is simulation of zero sequence current differential criterion with external fault. The differential current is less than the restraint current, the operation condition is not satisfied, the protection can't operate reliably.

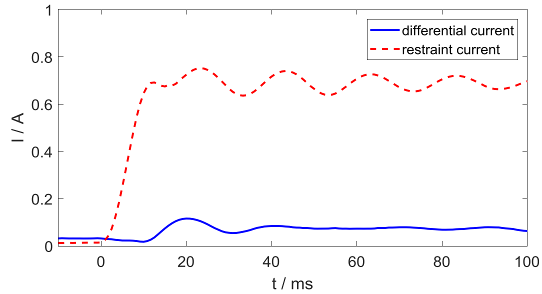

Fig.11 Simulation result when fault location is outside the zone

V. CONCLUSION

Equivalent circuit of shunt reactor with auxiliary winding system is researched in this paper. According to relationship between shunt reactor winding zero sequence current and auxiliary winding zero sequence current, the shunt reactor with auxiliary winding system inter-turn protection based on zero sequence differential current is proposed. The protection has following characteristics:

- The protection principle is current principle, without the influence of PT break.
- The protection setting doesn't need manual calculation work, the problem is solved, which is setting value of inter-turn fault and external fault blocking cooperation
- The protection can operate reliably with shunt reactor winding inter-turn fault or auxiliary winding inter-turn fault. Protected redundant configuration is avoided.
- The protection has high sensitivity, and can identify slight inter-turn fault.

The protection device based on the shunt reactor with auxiliary winding system inter-turn protection principle has been applied in practical engineering, and the problem of protection maloperation is solved effectively.

End of text

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