Power Based Open Phase Condition Detection Scheme

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Abstract. Open phase condition can occur in all types of power plants and substations, of which the detection and treatment measures are beginning to be required in the design standards of nuclear power plants. Operation experience shows that when open phase condition occurs on the primary side of the transformer, especially under light and no-load conditions, the traditional protection device based on sequence components cannot reliably operate, and the safety equipment that is used to isolate station auxiliary transformer will not work properly, which leads to the failure of safe bus automatically transferred to a standby power source. This situation poses great threats to the safe operation of nuclear power plants. This article systematically analyzes the difficulties in open-phase detection and the change in electrical quantities after open phase fault, and more importantly, focuses on the analysis of the power characteristics after the fault, based on which a new open phase detection scheme for nuclear power plants is proposed. It can also be applied to other types of power plants. The method and its feasibility are verified on PSCAD simulation software. The paper provides a new idea for the detection of open phase fault.

1. Introduction
Open phase condition (OPC) refers to the disconnection of one phase (or two phases) of the power supply outside the factory [1]. There are many reasons for open phase condition, such as a broken busbar connector [2]. If an OPC occurs on one side of the transformer, there will be induced voltage on both sides, the magnitude of which is affected by the winding connection and the load condition. However, the existing relay protection device cannot effectively react to the fault under all working conditions. Open phase condition can degrade the safety of nuclear power plants. Both the International Atomic Energy Agency (IAEA) and the US Nuclear Regulatory Commission (NRC) have defined open phase condition as the weakness of nuclear power plants. For example, an single OPC occurred on primary side of Byron Unit 2 station auxiliary transformer which was caused by a broken insulator stack for the phase C conductor on the 345kV power circuit, due to which the safety level was degraded, but none of the protections responded to the fault [3]. Therefore, the safe operation of nuclear power plants puts forward new requirements for the open phase condition detection technology.
2. Electrical analysis of open phase condition

2.1. Theoretical analysis
The existing open phase condition protection is based on the sequence component of voltage or current [4, 5]. Compared with single OPC, double OPC has more serious electrical imbalances which means the existing OPC protection device can operate. But when a single OPC occurs in the cases of transformer with moderate loading condition and specific transformer winding connection (such as YNd11), the unbalance of the system is very slight, which makes the negative-sequence and zero-sequence current based relay protection take more time to operate which may even cause the backup protection of the next level equipment to malfunction and expand the scope of the accident [6].

As shown in Fig. 1, the most common YNd11 winding connection of the main transformer in a nuclear power plant is analyzed. A single OPC occurs on phase A on the high-voltage side.

![Figure 1. YNd11 winding connection.](image)

1) From the voltage perspective, when the system is operating normally, the voltage on low-voltage side will be:

\[
\dot{U}_{wa} + \dot{U}_{wb} + \dot{U}_{wc} = 0
\]  

(1)

After the fault, assuming that the power grid is sufficiently stable and the voltages of phases B and C on the primary side are the same as before the fault, so the induced voltages on phases b and c on low-voltage side remain unchanged. Therefore, even if phase A is disconnected, voltage on phase a is still as follow:

\[
\dot{U}_{wa} = -\dot{U}_{wb} - \dot{U}_{wc}
\]  

(2)

2) From the perspective of flux, \(I_A = 0\), the currents of phase B and C pass through the neutral point to the ground. Therefore, the only return path for the flux of phase B and C is through the coil of phase A, so the flux of phase A can be reconstructed by the other two phases. Besides, the flux and current of phase B and C will increase by nearly 50% to provide energy for phase A, so the voltage and line current on the secondary side will remain unchanged.

2.2. Simulation analysis
Taking a nuclear power plant in Fujian province as example, the main parameters of electrical equipment are shown in the Table 1. As below.
Table 1. Main Parameters of Electrical Equipment.

| Electrical Equipment | Electrical parameters |
|----------------------|-----------------------|
| Generator G1, G2     | 1150MW, 23kV, 50Hz, 0.9(lag) |
| Main transformer T1, T2 | 1000MVA, 50Hz  |
|                      | 530/27kV, Z=20% |
|                      | YNd11 |
| Auxiliary transformer TA, TB, TC, TD | 68/34-34MVA, 50Hz |
|                      | 27/10.5-10.5kV, Z=10.5% |
|                      | Dynyn1 |
| Standby transformer TA1, TA2 | 34MVA, 50Hz |
|                      | 220/10.5kV, Z=11% |
|                      | YNyn0 |

PSCAD is used for modeling. Because the research focuses on the change of the electrical quantities after an OPC, the generator, transmission line, and loads are simplified in the modeling process, and the circuit breaker is used to simulate the open phase condition.

The OPC occurs on phase A on the primary side at 0.5s, and the transformer is under moderate loading condition (30%).

Figure 2. The voltage and current during the primary phase A open phase condition.

Figure 3. Sequence component during primary A open phase condition.

Fig. 2 shows the voltage and current on both sides of the transformer after the fault. As Fig. 2(1), (3) illustrate, when a single OPC occurs on the primary side, the magnitude of the voltage on primary side
and secondary side fluctuates slightly. Fig. 2(2), (4) show the phase A current on the high-voltage side is close to zero, and the phases B and C current increase by nearly 50%. There is only a small amount of unbalanced component in the current on low-voltage side, which is close to the theoretical analysis.

Using the FFT module in PSCAD simulation software to decompose the voltage and current on both sides of the transformer, the negative sequence and zero sequence components are illustrated as shown in Figure 3.

1) From the perspective of sequence voltage, Fig. 3(1), (3) show that after the loss of phase A, the negative sequence and the zero-sequence voltage on both sides are only about 1% of the rated value. The negative sequence voltage is even smaller than that generated by the motor starting process. So using negative sequence voltage for OPC detection is not ideal.

2) From the perspective of sequence current, comparing Fig. 3 (2) with Fig. 2 (2), we can see that after the open phase condition occurs, the zero-sequence current on the high-voltage side increases sharply, which is close to the current during normal operation. However, the problem is that asymmetrical short circuit such as single-phase-to-ground can also generate a large amount of zero-sequence current. Therefore, using zero-sequence current as an OPC detection criterion violates the reliability requirement of a relay protection. Fig. 3 (4) illustrates that on the secondary side, changes of negative sequence current are slight and cannot meet the setting value requirements.

In conclusion, the existing open phase detection scheme based on the increase of negative sequence current and zero sequence current cannot reliably operate under lightly loaded conditions of the transformer.

3. New open phase detection scheme

3.1. Power analysis during a single OPC

Because the difficulties of open phase detection under lightly loaded condition is that the amount of change in voltage and current is quite weak. Considering that power combines the characteristics of both voltage and current, the possibility of using power to detect open phase is further studied in the content below.

![Figure 4. Active power and reactive power during phase A open phase condition.](image)

Based on the analysis above, the three-phase voltage and current on the low-voltage side are almost unchanged after the fault, so the power provided to the load also remains unchanged. Fig. 4. is the simulation results of active power and reactive power transmitted by the lines on both sides which shows
that the change of the total transmitted power is very small. However, on the high-voltage side, power is transmitted only by two healthy phases. Therefore, the current of these two phases will increase by nearly 50% to ensure energy conservation. For winding $\alpha$, although the voltage is regenerated, there is only a small amount of magnetizing current and iron loss current on the winding, as shown in Fig. 5, which only accounts for about 3% of the current during normal operation. Therefore, the coil of phase $\alpha$ barely carries any power.

![Figure 5. Coil current on phase $\alpha$](image)

The active power of the windings on both sides are shown in Fig. 6, according to which the active power of phase A on the primary side drops to zero after the phase-break, and the power of phases B and C increases. Since the active power of phase A is zero, the induced active power is also zero on phase $\alpha$.

![Figure 6. Coil active power on both sides after the fault.](image)
Figure 7. Coil reactive power on both sides after the fault.

Fig. 7. shows the reactive power of the windings on both sides. There is only a small amount of reactive power generated by the magnetizing current on the winding of phase \( a \) to build the voltage, and the magnitude is also close to zero.

In summary, the electrical characteristics after a single OPC occurs on the high-voltage side with YNd11 connection are as follows

(I) Under lightly loaded condition, the voltage on both sides are quite balanced and close to the voltage before the fault

(II) The negative sequence and zero sequence components of the voltage are very small

(III) The active power and reactive power are close to zero on the fault-phase corresponding winding on the low-voltage side

By simulating other types of faults, now we explore whether the three characteristics above are unique for single OPC under lightly loaded condition.

Under the same conditions, taking phase A as example, the following 10 types of shunt faults are simulated and analyzed, where \( P_a, Q_a \) are active power and reactive power of phase \( a \) winding on the low-voltage side; \( P_0, Q_0 \) are active power and reactive power of phase \( a \) winding before the fault; \( V_2, V_1 \) are the negative-sequence voltage and positive-sequence voltage on the low-voltage side. The simulation results are shown in Table 2.

### Table 2. Electrical characteristics under different types of faults.

| Fault Types | \( P_a/P_0 \) | \( Q_a/Q_0 \) | \( V_2/V_1 \) |
|-------------|---------------|---------------|---------------|
| A→G        | -6.218        | -11.063       | 0.497         |
| B→G        | 12.417        | -2.389        | 0.497         |
| C→G        | -6.021        | 15.118        | 0.497         |
| AB→G       | 0.261         | -25.861       | 0.985         |
| AC→G       | -0.061        | -0.035        | 0.985         |
| BC→G       | 0.649         | 26.285        | 0.985         |
| ABC→G      | 0             | 0             | 0             |
| A→B        | 0.144         | 0.469         | 0.995         |
| A→C        | 0.001         | 0.023         | 0.995         |
| B→C        | 0.273         | 0.497         | 0.995         |

When there is an asymmetric short-circuit fault, the power of phase \( a \) winding increases greatly due to the sharply increased short-circuit current. At the same time, the negative sequence component of the secondary side increases greatly. Especially in the case of a two-phase short circuit, the negative sequence voltage is close to the positive sequence voltage. When a symmetrical three-phase-to-ground
short circuit occurs, the three electrical characteristics in Table 2 are the same as the electrical characteristics of the single open phase condition, but the phase voltage on both sides of the transformer drops to zero, which is inconsistent with characteristic (I).

3.2. Proposal of new open-phase detection scheme

(a) When the transformer is lightly loaded, power and voltage can be combined to form an integrated criterion to detect single OPC. The action logic is shown in Fig. 8.

![Figure 8. Action logic for OPC detection under lightly loaded condition.](image)

Among them, $U_{\varphi,S}$ and $U_{\varphi,T}$ represent the RMS phase voltage of primary side and secondary side. $U_{\varphi,N}$ represents the RMS phase voltage during the normal operation. The criterion (1) is used to prevent the malfunction under the condition of unbalanced state of the power system during normal operation and three-phase-to-ground short-circuit fault. Criterion (2) is set to prevent the protection device from malfunction when there is asymmetric short-circuit faults. $V_1$ and $V_2$ represent the magnitude of positive sequence and negative sequence voltage on secondary side. The reference value of $\eta$ can be set according to the maximum ratio of negative sequence voltage to positive sequence voltage during normal operation, generally 0.1. $P_a$ and $Q_a$ are the active power and reactive power of phase $a$ winding on the low-voltage side. $P_{set}$ and $Q_{set}$ are set according to the copper and iron losses of the winding during normal operation. $t_0$ is set according to the time to avoid single-phase automatic reclosing, which is generally 1.5s.

(b) When the transformer is under no-load condition, such as the standby transformer or the main transformer during the startup and shutdown process of units, even if no fault occurs, the electrical quantities still meet the criterion discussed above, so in order to prevent the relay protection device from malfunction under no-load conditions, the current criterion should be added.

Therefore, the comprehensive criterion of single OPC on primary side under lightly loaded conditions is shown in Fig. 9

![Figure 9. Open phase detection action logic.](image)
Adding criterion (3), where $I_1$ represents the line current on secondary side. And $I_{set}$ is set according to the capacitor-to-ground current on the secondary side of the transformer, which can be measured by experiment.

To verify the feasibility of the above method, PSCAD is used to simulate the open phase fault test. The iron loss and copper loss are set at 5% and 0.5% respectively, and the low-voltage side capacitance to ground is 0.26μF. Other parameters are the same as above. Single phase open fault occurs on phase A, the fault time of which is set at 0.5s. The simulation results are shown in Fig. 10.

![Logical Output](image)

**Figure 10.** Simulation results.

Fig. 10(1) shows that with fault occurring at 0.5s, the output of OPC detection logic is 1 after a short transient process. The protection device will clear the fault after the time delay of 1.5s. Fig. 10(2) shows the current of the primary side. The current of phase A drops to zero after the fault, and the currents of phase B and C increase by nearly 50%, which is consistent with the previous analysis results. Although there is a transient process, the system can be switched to the standby power supply within 2s to resume normal operation which proves that the open phase detection scheme is feasible and effective.

In conclusion, the scheme of open phase detection proposed in this paper is sensitive and effective to single open phase condition. Besides, it will not malfunction when other types of faults occur, and the performance is reliable.

4. Conclusion
Open phase condition can occur in all types of power plants and substations, but there is no unified and mature detection scheme. The traditional detection method based on negative sequence voltage or zero sequence current cannot deal with all working conditions, which may cause overstepping action of the relay protection device and expand fault scope. This paper comprehensively analyzes the electrical characteristics of both sides of the transformer after a single open phase fault occurs. The paper also deeply studies the power characteristics of the winding after the fault, which is different from the previous research, and combines with voltage and current to obtain a comprehensive scheme for OPC detection. The detection scheme presents a good protective effect under lightly loaded conditions. The new protection scheme can be applied not only to nuclear power plants, but also to other types of power plants.

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