Non-fault Identification Based on External Injection before Interphase Fault Reclosing in Distribution Network with Shunt Capacitors

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Abstract. The existing interphase fault auto-reclosure of distribution network has the risk of reclosing in permanent faults, it is necessary to identify the fault nature before three-phase reclosing. By using the more abundant electrical information after the injection of external voltage source, the varied characteristics of phase differences between voltage and current of interphase faults under different fault natures are analyzed for the 10kV distribution lines with shunt capacitors. The analysis shows that the circuit structure changes after the transient fault disappeared, and the phase difference between voltage and current becomes 90°, while the permanent fault circuit is stable with a phase difference of 120°. Therefore, using the phase differences between voltage and current before and after the fault disappearance, build a fault nature identification scheme. The results of simulation show that the proposed method can accurately identify the fault nature and is basically not affected by fault location and transition resistance which has good adaptability.

1. Introduction

Most of distribution networks in China adopt neutral non-effective grounding mode [1~3], when a single phase grounding fault occurs in a distribution line, it can continue running for 1~2 hours, but in the event of interphase fault, three-phase circuit breakers require to trip to reduce the non-full-phase running time of the system. If the reclosing operation recloses in the interphase fault blindly, it may reclose in a permanent fault which will have a great impact on power system and electrical equipment. Therefore, it is of great practical significance to study an adaptive reclosure method for interphase faults in distribution networks that can identify fault natures before reclosing.

Research on fault identification for EHV/UHV transmission lines has made some progress [4~9], but compared with the transmission line, the distribution line has a lower voltage level, a more complicated structure, and a more rapid voltage damping after the trip, the adaptive reclosure schemes proposed for the transmission line are not suitable to the distribution line. [10] uses the voltage and current of shunt capacitors at the head of distribution line to identify whether the fault has disappeared or not. This method is simple and easy to implement, but different fault locations and transition resistances will affect the reliability of the identification. [11, 12] use thyristors to control the inverter power supply and connect it to the low voltage side of distribution transformer, detecting the fault nature by applying a transient high voltage. This method does not consider the effect of shunt capacitors in the line. [13] uses parameter identification to study the difference between actual value and recognition value of the line capacitance after the fault of photovoltaic power distribution system, according to the actual value of transient fault is close to the recognition value while the difference between the two values of permanent fault is large to judge the fault nature.

In this paper, an active identification method using the phase difference between voltage and current of a distribution line to judge the fault nature is studied in domestic 10kV distribution network. This method is simple and has high accuracy, it basically not affected by fault location and transition resistance, which can reliably avoid blind reclosing of distribution lines and has good applicability.
2. Analysis of distinguish principle based on phase difference

Take the simple 10kV distribution system shown in Fig. 1 as an example. When the three-phase circuit breakers trip in interphase fault, the shunt capacitors and the energy storage components begin to discharge in the line, affected by different fault locations and transition resistances the continuous discharge time is extremely short. In some severe conditions, the electrical signals decay to zero in a few milliseconds, it difficult to make accurate fault discrimination by the limited feature quantities. Using an external voltage source to inject signals into the system can provide richer electrical information for the tripped line and effectively avoid misjudgment caused by the weak signals.

![Figure 1. Simple 10kV distribution system.](image1)

Fig. 2 is the structure of an external voltage source in distribution line, its control strategy for interphase fault is shown in Table 1.

| Fault phase | Control strategy                        |
|-------------|-----------------------------------------|
| AC-phase    | Close S₁ and S₄; Open the other switches |
| AB-phase    | Close S₂ and S₆; Open the other switches |
| BC-phase    | Close S₃ and S₅; Open the other switches |

According to the control strategy in Table 1, taking the fault between B-phase and C-phase as an example, the equivalent circuit of applying a switchable external voltage source to the fault line after three-phase circuit breakers tripping is shown in Fig. 3.

![Figure 3. Equivalent circuit diagram of fault between B-phase and C-phase for distribution lines with shunt capacitors.](image2)

In Fig. 3, $C_n$ is the capacitance of shunt capacitors, $C_p$ is the grounding capacitance of lines, $C_m$ is the interphase capacitance of lines, $U_{EX}$ is the external switchable voltage source, $R_l$ and $L_l$ are the resistance and the inductance of lines respectively, $p$ is the ratio of the length from fault point to the head of the line to the whole line, $R_f$ is the fault transition resistance, $L_f$ is the equivalent inductance of distribution transformers.

For a convenient analysis, ignoring the influence of line capacitances, the equivalent circuit in Fig. 3 is simplified as shown in Fig. 4.

![Figure 4. Simplified circuit of fault between B-phase and C-phase.](image3)
In Fig. 4, there is an obvious difference in circuit structures of the fault state and the non-fault state. Using the variation of the phase difference between voltage and current caused by this difference feature can realize the non-fault identification before three-phase reclosure.

The expression of the phase difference between voltage and current is
\[ \theta = \arctan \frac{U_{ex}}{I}. \] (1)

When the fault occurs, analyzing the fault loop in Fig. 4(a). Considering the fault phase short-circuit current, the current flowing through the line is
\[ i = (1 + j\sqrt{3}) \frac{U_{ex}}{4pR + 4pjwL + 2R_f}. \] (2)

Substitute Eq. 2 into Eq. 1, the phase difference between voltage and current in fault state is
\[ \theta_f = \arctan \frac{4pR_f + 4pjwL + 2R_f}{1 + j\sqrt{3}}. \] (3)

Reduce Eq. 3 as
\[ \theta_f = \arctan \frac{2pwL}{2pR_f + R_f} + 120^\circ. \] (4)

Eq. 4 is the expression of the phase difference between voltage and current when a permanent fault occurs in the line or the transient fault has not disappeared. In actual operation, affected by the line capacitances the phase difference between voltage and current in continuous fault state is about 120°.

When the fault disappears, the voltage and current in Fig. 4(b) have the following relationship as
\[ i = \frac{U_{ex}}{2R_f + 2jwL_f + jwL_f}. \] (5)

where \( L_f = \frac{4}{3}L_f \). Then substitute Eq. 5 into Eq. 1, the phase difference between voltage and current in non-fault state is
\[ \theta_n = \arctan \frac{3wL_f + 2wL_f}{3R_f}. \] (6)

Because the inductive reactance of distribution transformer is much larger than the line impedance, according to Eq. 6 the phase difference between voltage and current is close to 90° when the system is in a non-fault state.

3. Construction of non-fault identification criterion before three-phase reclosure

For the distribution line with shunt capacitors, the short-time discharge of shunt capacitors after three-phase trip can extend the continuous discharge time, but it is still necessary to consider transition resistance to inject external voltage source for fault detection. If a transient interphase fault occurs in the line and the fault has not disappeared, the phase difference between the detected voltage and current is consistent with the phase difference of permanent interphase fault, which is about 120°. If the transient interphase fault has disappeared, the phase difference is close to 90° due to the great inductive reactance of transformer. According to above characteristics, using the difference of phase differences before and after the disappearance of fault establish a non-fault identification criterion as
\[ \lambda_n < \frac{\theta(h)}{\theta_{set}} < \lambda_n \quad (h = 1, 2, 3, \ldots, n). \] (7)
In Eq. 7, $\theta(h)$ is the angle of phase difference between voltage and current at the $h$-th sampling point after the injection of external voltage source. $\theta_{set}$ is the angle setting threshold, takes $90^\circ ~ 120^\circ$. $\lambda_1$, $\lambda_2$ are the identification deviation thresholds, $\lambda_1 \in (0.7, 0.95)$, $\lambda_2 \in (0.8, 1.05)$. When the calculated values of 10 consecutive sampling points in Eq. 7 meet the condition at the same time, it can be judged as a transient fault and the fault has disappeared, reclosing act. When any one of the calculated values in Eq. 7 is not satisfied the condition, continuously judge to the maximum discriminant time, if the calculated values are still not meet the condition, judge it as a permanent fault, not reclosing.

The flow chart of fault nature judgment is shown in Fig. 5.

![Flow Chart of Fault Nature Judgment](image)

**Figure 5.** Flow chart of fault nature judgment.

4. Simulation and verification

Using PSCAD simulation software to build a 10kV distribution system with 6 feeders for simulation and verification, the simulation system is shown in Fig. 6.

![10kV Distribution System with 6 Feeders](image)

**Figure 6.** 10kV distribution system with 6 feeders.

In Fig. 6, the shunt capacitors are located at the head of distribution lines, it line decentralized compensation capacity is 200kVar [14]. $L_1$ and $L_4$ are overhead lines, $L_2$ and $L_5$ are cable lines, $L_3$ and $L_6$ are cable-overhead hybrid lines. Overhead line parameters are $R_1=0.125\Omega/km$, $R_0=0.275\Omega/km$, $L_1=1.299mH/km$, $L_0=4.586mH/km$, $C_1=0.04\mu F/km$, $C_0=0.012\mu F/km$. Cable line parameters are $R_1=0.27\Omega/km$, $R_0=2.7\Omega/km$, $L_1=0.254mH/km$, $L_0=1.019mH/km$, $C_1=0.339\mu F/km$, $C_0=0.28\mu F/km$.

Setting the BC interphase metallic fault occurs on $L_6$ at 0.4s, the three-phase circuit breakers trip at 0.5s, and injecting external voltage source into the fault phase at 0.6s. The amplitude of source is 3kV and the frequency is 50Hz. Calculate the phase differences in fault loop by using the data of 10 consecutive sampling points after the injection of signals. For the convenience of analysis, $\theta_{set}$ in Eq. 7 takes $100^\circ$, and the two identification deviation thresholds take $\lambda_1 = 0.85$, $\lambda_2 = 0.95$ respectively.
Fig. 7 shows the phase differences between voltage and current of BC interphase fault in different fault natures when $p = 0.25$, where the duration of transient fault is 0.3s. From Fig. 7, it can be seen that the larger the transition resistance is, the faster the phase differences decay. When injecting an external voltage source, the phase differences between voltage and current keep increasing to nearly 120°. If the fault is transient, the phase differences will return to 90° after the fault disappears, it changes are shown in Fig. 7(a). If the fault is permanent, the phase differences will not change after it nearly reaches to 120°, the changes of phase differences at this time are shown in Fig. 7(b).

![Figure 7. Phase difference between voltage and current of BC interphase fault when $p=0.25$.](image)

(a) Phase difference of BC interphase transient fault.  
(b) Phase difference of BC interphase permanent fault.

In order to verify the correctness of the proposed criterion, a large number of simulations and calculations in different fault cases for BC interphase fault are conducted on $L_0$. The specific data are shown in Table 2 and Table 3.

| Transition resistance [Ω] | Fault location | $\theta(h)/\theta_{	ext{set}}$ |
|--------------------------|---------------|-------------------------------|
|                          |               | Transient fault | Permanent fault |
| 1                        | 0.25          | 0.9009           | 1.241           |
| 5                        | 0.25          | 0.9036           | 1.207           |
| 10                       | 0.25          | 0.9027           | 1.162           |
| 20                       | 0.25          | 0.8969           | 1.106           |
| 30                       | 0.25          | 0.8964           | 1.037           |
| 40                       | 0.25          | 0.8955           | 0.9843          |

| Fault location | Transition resistance [Ω] | $\theta(h)/\theta_{	ext{set}}$ |
|---------------|--------------------------|-------------------------------|
| Transient fault |                           | Permanent fault |
| 0.125         | 5                         | 0.9045           | 1.216           |
| 0.375         | 5                         | 0.8982           | 1.200           |
| 0.500         | 5                         | 0.8955           | 1.192           |
| 0.625         | 5                         | 0.8937           | 1.183           |
| 0.750         | 5                         | 0.8928           | 1.171           |
| 0.875         | 5                         | 0.8947           | 1.170           |

The results of Table 2 and table 3 show that there is an obvious difference in identification values of phase differences between voltage and current before and after the metallic fault disappears. According to the constructed non-fault identification criterion before three-phase reclosure calculate the fault identification values in different fault cases to realize the fault nature discrimination. This method is basically not affected by fault location and transition resistance. It should be pointed out that when the fault transition resistance exceeds 40Ω, the identification value of permanent fault of the distribution line is close to the setting identification deviation threshold, which will affect the performance of criterion. To ensure the reliability of reclosing process, the fault discrimination time can be appropriately extended to improve the success rate of reclosing.

5. Conclusion

By analyzing the changes of phase differences of transient fault and permanent fault after the injection of external voltage source, a new method of non-fault identification before three-phase reclosure based on the phase difference between voltage and current is proposed in this paper. This method only uses voltage and current of distribution lines to calculate the phase difference, it is simple with high recognition accuracy. The established fault nature identification criterion can accurately judge fault nature, it is basically not affected by fault location and transition resistance. What’s more, it is suitable for the distribution line with shunt capacitors, which has good adaptability.
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