Mechanism and solution of zero-sequence directional protection maloperation caused by broken line faults in multi-circuit transmission lines on the same tower

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Abstract. When one loop line of the multi-circuit transmission lines on the same tower is in states of non-full-phase operation or asymmetric line-breaking faults, the zero-sequence direction of functioning loop lines is likely to maloperation due to zero-sequence voltage compensation. The multi-circuit transmission lines on the same tower with different voltage classes will induce the same zero-sequence voltage distribution trend as the fault line due to the mutual inductance between loop lines, and thus may conduct improper operation as well. This paper analyses the causes of maloperation of zero-sequence directional protection caused by non-full phase operation or line-breaking fault of multi-circuit lines on the same tower, and puts forward a method to prevent maloperation by extracting line status from station domain information. In the case of multi-circuit lines on the same tower with same voltage class, the crossing point of zero-sequence voltage of the line can be calculated and the zero-sequence voltage can be compensated in reverse to prevent maloperation. In the case of multi-circuit lines on the same tower with different voltage class, fault characteristics can be identified according to substation information and the zero-sequence direction protection can be automatically blocked. RTDS is used to simulate and verify the electrical characteristics, malfunction process and the effectiveness of prevention methods of multi-circuit lines on the same tower when a non-full-phase operation or abnormal line breakage occurs.

1. Introduction

Multi-circuit transmission lines on the same tower can multiplies the transmission capacity with only one transmission corridor is used. At the same time, when fault occurs, it is easier to maintain both ends of the power grid synchronized through a sound circuit[1-2]. Its remarkable economic benefits, safety performance and stability are self-evident, and has been popularized and enlarged application recently. The zero-sequence directional protection, which has the characteristics of high sensitivity, fast and reliable, free from system oscillation[3] and normal load variation, is widely deployed on various transmission lines[4].

The Zero-sequence voltage introduced into the protection might be too small to trigger an action because of high resistance grounding or distant fault point from protective installation point and other reasons. For this reason, zero-sequence voltage compensation is adopted in practice to improve the sensitivity of zero-sequence directional protection[5-6]. However, this action may cause malfunction when the asymmetric line-breaking fault occurs on the multi-circuit lines on the same tower[7]. At
present, while the research on Maloperation of zero-sequence directional protection for multi-circuit transmission lines on the same tower is mainly focused on short-circuit fault \cite{8-13}, there is little research on line-breaking problem, but in fact, abnormal disconnection, switch trip and reclosing may cause the protection to maloperation as well. Additionally, causation for maloperation of multi-circuit line on the same tower with same voltage class and with different voltage classes is entirely different under line-breaking fault.

In this paper, a zero-sequence directional protection maloperation prevention method based on substation information is proposed. For multi-circuit lines with the same voltage class, the zero-sequence voltage crossing point can be detected and the direction of zero-sequence voltage compensation can be adjusted. For multi-circuit lines with different voltage classes, the substation information can be used to determine whether the line is faulty or not, and to select whether to lock the zero-sequence direction protection. The simulation model is established, and the correctness of the method is verified.

2. Electrical characteristics analysis of asymmetrical line-breaking fault for multi-circuit lines on the same tower with same voltage class

For N-loop transmission line on the same tower, the system topology is shown in Fig. 1 when a single-phase abnormal line-breaking fault occurs.

![Diagram](image.png)

**Figure 1.** System topology under asymmetric line-breaking fault on multi-circuit transmission lines on same tower

Because there is only magnetic connection between two lines in the multi-voltage classes circuit of the same tower, the electrical characteristics for the lines of the sound voltage class is basically the same as those of the faulted voltage classes. In this paper, only the electrical characteristics of multi-circuit lines on the same tower with same voltage classes under occurrence of non-full-phase operation or asymmetric line-breaking faults are analyzed. Define $\bar{Z}_1$, $\bar{Z}_0$ and $\bar{Z}_m$ are positive-sequence impedance, zero-sequence impedance and zero-sequence mutual inductance; $\bar{Z}_M$, $\bar{Z}_N$ the system impedance for both sides of the system; $E_M$, $E_N$ the electrodynamic potential for both sides; $U_M$, $U_N$ the bus voltage of both sides; $i_{\phi}^{(N)}$, $U_{\phi}^{(N)}$ the phase current and phase voltage of loop N, with $\phi \in \{A,B,C\}$; $i_0^{(N)}$, $U_0^{(N)}$ the zero-sequence current and zero-sequence voltage of loop N; $l$ the length of lines.

When a non-full-phase operation or abnormal line-breaking fault occurs on the C1 line of a multi-circuit lines on the same tower with same voltage class, it can be equivalent to a three phase voltage source $\Delta U_\phi^{(1)}$ in series at the fault point, its effect on the zero-sequence network is equivalent to the
synthesis of an equivalent zero-sequence voltage source from this three-phase voltage source \( \hat{U}_{0(F-F')} \) in series. According to the boundary conditions and the sequence network, it is known that:

\[
\begin{align*}
\hat{I}_A^{(1)} &= \Delta U_B^{(1)} = \Delta U_C^{(1)} = 0 \\
\hat{I}_A^{(1)} + j\hat{I}_A^{(1)} + \hat{I}_{A0}^{(1)} &= 0 \\
\Delta U_A^{(1)} &= \Delta U_A^{(1)} = \Delta U_A^{(1)}
\end{align*}
\]  

Where \( \Delta U_A^{(1)} \) and \( \hat{I}_A^{(1)} \) are the equivalent series voltage source and the sequence component of phase current based on phase A, \( n \in \{0,1,2\} \). Because the electric potential of both sides of the fault point is equal to the potential of buses on both sides after breaking, According to the third line of formula (1), the zero-sequence potential difference between the two sides of the fault point is:

\[
3\hat{U}_{0(F-F')} + \frac{1}{3} = \hat{U}_{MA} - \hat{U}_{NA} \quad (2)
\]

The zero-sequence topology of multi-circuit transmission lines on the same tower after fault is shown as follows:

![Zero-sequence topology of multi-circuits transmission line after fault](image)

Where \( \hat{i}_{M0} \) and \( \hat{i}_{N0} \) are the zero-sequence current that flow through the two buses; \( \alpha \) the percentage of length of bus M from point F to full length of the line. The diagram above shows that the zero-sequence potential difference between the two buses is:

\[
\hat{U}_{0(M-N)} = \hat{i}_0^{(1)} [(\hat{Z}_m + \hat{Z}_M + \hat{Z}_N)/(n-1)\hat{Z}_m] \quad (3)
\]

It is uniquely determined by the line parameters and the impedance of both sides of the bus, and is independent of the location of the broken line fault. In addition, under the condition of constant impedance of system M and N, the zero-sequence voltages of both buses are determined by the following formula:

\[
\begin{align*}
\hat{U}_{M0} &= I_{M0}(\alpha \hat{Z}_m + \hat{Z}_M) \\
\hat{U}_{N0} &= 0 - I_{N0}(1-\alpha)\hat{Z}_m + \hat{Z}_M
\end{align*}
\]  

(4)

Moreover, it is known from the structure of transmission lines with the same voltage class that 6the load current flowing through the lines is as follows:

\[
\hat{i}_{(N)}^{(1)} = \frac{E_\phi - E_\omega}{\hat{Z}_m + \hat{Z}_N + \frac{1}{n} \hat{Z}_l} \times \frac{1}{n}
\]

(5)

If M circuits occurred single-phase abnormal disconnection or incomplete-phase operation, the current flowing through a sound line of the same name and phase is:
From the analysis above, the following conclusions can be reached:

1) After a single-phase abnormal line-breaking fault occurs, the influence of the break on the zero-sequence network is equivalent to that of a series of zero-sequence voltage sources connected at the fault point, whose magnitude is 1/3 of the potential difference between the two buses.

2) The phase angle difference of zero-sequence potential between two buses is about 180 degrees, and the difference of zero-sequence potential between two buses is independent with the fault location, so the zero-sequence current flowing through each branch does not change with the fault location.

3) There are zero-sequence voltage crossing points on sound circuits. When the system impedance and line parameters remain unchanged, the zero-sequence voltage crossing position is fixed.

4) In the case of non-full-phase operation or abnormal line-breaking fault, the load of the corresponding phase of the line-breaking should be transmitted to the opposite side through other sound lines, thus increasing the load current of the line-breaking.

3. Maloperation mechanism of zero-sequence directional protection for non-fault lines

For multi-circuit lines with the same voltage class on the same tower, the double-circuit lines can be taken as an example to form a zero-sequence voltage distribution diagram of the system as follows:

\[ j_{(N)}^{(N)} = \frac{E_{g} - E_{p}}{Z_{M} + \frac{1}{n-m}Z_{1}} + \frac{1}{n-m} \]  \hspace{1cm} (6)

\[ \theta = 0^\circ + \theta_{1} < \arg \frac{U_{0}}{I_{0}} < 180^\circ + \theta_{2} \]  \hspace{1cm} (8)
Where $\theta_1$ and $\theta_2$ are the margin of avoiding interference. Apparently, the zero-sequence directional protection on both sides of C2 is judged to be a forward direction fault, thus causing maloperation. The schematic diagram of the zero-sequence voltage distribution after compensation is shown in Figure 4.

![Diagram](image)

**Figure 4.** A schematic of zero-sequence voltage distribution after compensation

For multi-circuit transmission lines with different voltage classes on the same tower, the cause of maloperation is quite different. The schematic diagram of the mixed four-circuit transmission lines on the same tower is shown in Figure 5.

![Diagram](image)

**Figure 5.** A schematic of zero-sequence voltage distribution after compensation on mixed four-circuit transmission lines on the same tower

When the abnormal A-phase disconnection fault occurs in S1C1 circuit, due to the mutual inductance between lines, the S2C1 circuit will induce the zero-sequence voltage with the same distribution trend as line S1C1. The zero-sequence voltage of buses on both sides of S2C1 circuit will cause zero-sequence voltage crossing point to be existing in S2C2 circuit, which will cause maloperation on S1C2, S2C1 and S2C2 lines. After fault, the zero-sequence voltage distribution of loop S1C1 and S2C1 is shown in Figure 6.

![Diagram](image)

**Figure 6.** Zero-sequence voltage distribution of loop S1C1 and S2C1
4. Maloperation preventing methods for zero-sequence directional protection in non-fault lines

4.1. Zero-sequence voltage reverse-compensation method

Obviously, the fundamental cause of maloperation of zero-sequence directional protection caused by non-full-phase operation or line-breaking fault is zero-sequence voltage overcompensation. To this end, we judge whether the following formula is established for each loop in the transmission lines:

\[ \frac{|U_0^{(n)}|}{(Z_0 - Z_n)I_0^{(n)}} < 1 \]  \hspace{2cm} (9)

If not, the zero-sequence voltage will be compensated according to the conventional method; else it will reverse the zero-sequence voltage compensation direction as followed:

\[ U_0 = U_0 + Z_0 I_0 \]  \hspace{2cm} (10)

For multi-circuit lines with same voltage class on the same tower, since the position of the zero-voltage crossing point can be calculated, a rather simple idea is that, Adaptively adjusting the compensation coefficient \( k \) and makes the zero-sequence voltage of sound lines to not over-compensate, but under-compensate to be less than the action threshold, thus preventing maloperation. But the problem is that such methods will weaken the sensitivity of zero-sequence directional protection, it makes the result of zero-sequence directional protection criterion fuzzier, and has no advantage compared with the zero-sequence voltage reverse compensation method.

4.2. Fault detection and protection locking method based on substation information

For multi-circuit lines on the same tower with different voltage classes, the fundamental reason for the maloperation of zero-sequence protection in non-fault voltage class is that the zero-sequence voltage induced by mutual inductance between lines. Based on this, a fault detection and protection locking method can be constructed. The steps are as follows:

(A) Detect the breakage of lines. When any loop line satisfies all 4 listed conditions, it is determined that the line is not running in full phase: (1) \( I_{\text{load}} > k_i I_{L,N} \), where \( I_{\text{load}} \) is the instantaneous value of load current, \( I_{L,N} \) is rated load current, \( k_i \) is the load gain coefficient. If the line is still loaded, then the three-phase disconnection fault is excluded. (2) \( I_0^{(n)} > I_{\text{seq}} \), where \( I_0^{(n)} \) is the zero-sequence current, \( I_{\text{seq}} \) is the zero-sequence current threshold. The existence of zero-sequence current means that an asymmetric fault may have occurred. (3) \( \Delta U_{\phi} < k U_{\phi} \), where \( \Delta U_{\phi} \) is the phase voltage variation measured. One of the main characteristics of line-breaking cases is that there should be no marked change of measured value of three-phase voltage. (4) \( I_{\phi} < k_2 I_{N,\phi} \), where \( I_{N,\phi} \) is the rated phase current, \( k_2 \) is the current gain coefficient. Broken lines must have no current flowed through them.

(B) When a non-full-phase operation or abnormal line-breaking fault occurs in a certain voltage class, use the method described in step (A) to determine whether a disconnection occurs on the same-name circuit of a sound voltage class. If no non-full-phase operation or abnormal line-breaking fault occurs in the corresponding circuit, step (C) is entered and the zero-sequence direction protection on all sound lines with zero-sequence voltage zero-crossing points is blocked according to equation (7).

(C) Determine whether a zero-sequence voltage crossing point exists in any line of sound voltage classes. If there is, all zero-sequence directional protection on the same name loop is locked. This step is mainly used to prevent zero-sequence directional protection from rejection when transverse fault occurs.

5. Simulation analysis

RTDS software is used to model and simulate a multi-circuit transmission lines on the same tower with same / Different voltage classes shown in Figures 1 and 5. For multi-circuit lines with the same voltage class, let \( N = 2 \), \( l = 100 \text{km} \), and 500 kV Bergeron model is adopted. The impedance parameters of lines and two sides are shown in Table 1.
In the case of a disconnected of phase A in the C1 loop occurs at the location \( l_p \) km from the protection installation site of M side, the A-phase electrical measurements at the fault point are shown in Table 2.

**Table 2. Measuring value of Phase A electrical fault at fault point**

| \( l_p \)  | \( U_{MA} \)          | \( U_{NA} \)          | \( I_{A}^{(1)} \)        | \( I_{A}^{(2)} \)        |
|-----------|----------------------|----------------------|------------------------|------------------------|
| 30 km     | 292.586 V / 0.000°   | 291.039kV / -3.796°  | 35.349A / 88.932°      | 1188.3A / -1.401°      |
| 50 km     | 293.808kV / 0.000°   | 290.563kV / -6.934°  | 59.019A / 88.917°      | 1187.4A / -2.265°      |
| 70 km     | 294.105kV / 0.000°   | 290.300kV / -6.923°  | 82.798A / 88.937°      | 1186.8A / -3.139°      |

At this time, the average phase current of sound lines is about 630A. It can be seen that the Phase A current of the C1 loop is almost transferred to the Phase A of the C2 line when the fault occurs. In addition, the bus voltage does not change much with the fault location because the two systems are still synchronized.

The zero-sequence electrical value of transmission lines are shown in the following table when line breakage occurs, where \( I_{0}^{(i)} \) is the zero-sequence current of line C1, \( U_{0F} \) and \( U_{0F'} \) are zero-sequence voltage of Bus M and N.

**Table 3. Zero-sequence electrical values of transmission lines**

| \( l_p \)  | \( I_{0F}^{(i)} \)   | \( U_{0F} \)          | \( U_{0F'} \)          | \( U_{MS} \)          |
|-----------|----------------------|----------------------|----------------------|----------------------|
| 30 km     | 488.434A / -178.102° | 24.885kV / -98.729°  | 6.863kV / 82.501°    | 6.960kV / -97.658°   |
| 50 km     | 489.263A / -179.877° | 19.693kV / -100.601°| 6.911kV / 80.405°    | 6.911kV / -99.595°   |
| 70 km     | 490.708A / -177.856° | 14.532kV / -102.348°| 6.656kV / 78.343°    | 6.868kV / -101.498°  |

It can be seen that although \( U_{0F} \) and \( U_{0F'} \) do change with the fault location, \( U_{0F+F'} \) doesn’t, and the zero-sequence current flowing through two buses is basically unchanged so that the zero-sequence voltage on Bus M and N is also unchanged. The angle difference of zero-sequence voltage between two sides is about 180 degrees, and there is a zero-crossing point on transmission lines. The relationship between zero-sequence voltage and bus potential difference at fault point is shown in Table 4.

**Table 4. Relationship between zero-sequence voltage and bus potential difference at fault point**

| \( l_p \)  | \( U_{AMS} / kV \) | \( U_{DF,F'} / kV \) | \( U_{1(M,N)} / kV \) |
|-----------|---------------------|----------------------|----------------------|
| 10 km     | 39.493 / 83.411°    | 35.504 / 82.233°     | 13.837 / 84.433°     |
| 30 km     | 39.406 / 81.411°    | 35.491 / 81.317°     | 13.824 / 82.421°     |
| 50 km     | 39.387 / 79.399°    | 35.485 / 80.393°     | 13.823 / 80.405°     |
| 70 km     | 39.434 / 77.412°    | 35.486 / 79.497°     | 13.833 / 78.422°     |
| 90 km     | 39.555 / 75.417°    | 35.496 / 78.592°     | 13.857 / 76.44°      |

It can be seen that the zero-sequence voltage on both sides of point F basically does not change with the fault location, and is very close to the electric potential difference between Phase A of the two buses.

In the case of abnormal disconnection occurs at the location where 50km away from bus M in the loop C1, the electrical values of C1 line before and after breakdown is shown in Table 5.
It can be seen that loop C1 satisfies the 4 judging conditions mentioned in step(A). It is judged that phase A of the circuit is not in full-phase operation or breaking fault, so that no adjustment or locking measures are taken to protect the pilot zero-sequence direction of the C1 circuit to make it operate normally. As for C2, obviously \(\frac{U_{M0}}{Z_0 - Z_m}I_{0}^{(n)} = 0.54 < 1\), means that zero-sequence voltage crossing point exists in the loop C2. On the meantime, the zero-sequence voltage is 46.4006∠76.196° after reverse compensation. Therefore, a forward direction fault is is judged by the zero-sequence directional protection on side M, while side N is judged as backward direction fault, thus prevent maloperation and ensure the sensitivity of zero-sequence direction protection.

For different voltage class multi-circuit transmission lines on the same tower, take N=4 and build a 100km four circuit transmission model as shown in Fig. 5. Among them, S1 is a 500kV double-circuit transmission lines on the same tower, while the voltage class of S2 is 220 kV. The positive-sequence, zero-sequence impedance and mutual inductance between all lines are the same as those shown in Table 1. When an abnormal line breakage occurs in the S1C1 line where 50km away from side M, the fault or non-full-phase state in any line of the same voltage class by analyzing the substation protection maloperation preventing methods can be used to determine whether there is a zero-sequence operation or line-breaking fault. At this time, there is a zero-sequence voltage zero-crossing point in S2C2 circuit, which means that there is no fault in this circuit, thus blocking the logic criterion mentioned in the disconnection criterion method (step A), and it is determined that there is no non-full-phase operation or line-breaking fault. At this time, there is a zero-sequence voltage zero-crossing point in S2C2 circuit, which means that there is no fault in this circuit, thus blocking the pilot zero-sequence direction protection of S2C1 and S2C2 circuit, the protection does not malfunction.

### 6. Conclusion

In this paper, the electrical characteristics of multi-circuit transmission lines on the same tower under occurrence of non-full-phase operation or asymmetrical line-breaking faults are analyzed, and the fundamental causes of asymmetrical line-breaking faults or maloperation in non-full-phase operation of zero-sequence directional protection on other circuits are discussed. The zero-sequence directional protection maloperation preventing methods can be used to determine whether there is a zero-sequence voltage zero-crossing point in the sound lines and whether there is asymmetric line-breaking fault or non-full-phase state in any line of the same voltage class by analyzing the substation information of terminals. The zero-sequence directional protection can be blocked pertinently and can be used to prevent multiple-circuit lines with the same or different voltage classes to mal-operate.
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