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Open-phase temporary overvoltage before and after an intermediate substation accessing a long distance transmission line

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Abstract
In transmission lines, shunt-reactors are commonly applied to counteract the “Ferranti effect.” However, in highly compensated lines, hazardous overvoltage may occur during unbalanced open-phase conditions. In addition, when a new substation is put into operation, π circuit can be selected by accessing an existing transmission line and the original shunt-reactor configuration is maintained. Severe overvoltage may occur on the shunt-reactor side of the newly installed transmission line. In this study, we analysed the effects of compensation, neutral-reactor, and system frequency on open-phase overvoltage. The maximum deviation of system frequency is $\pm 0.5$ Hz, therefore, we suggested maximum critical compensation of the shunt-reactor under different proportional coefficients of neutral-reactor. We analysed the impact of line division, when an intermediate substation is accessed, and a risk range in which the substation located may cause severe overvoltage was proposed. Finally, according to an actual line division project, we optimised the original configuration scheme of the shunt and neutral-reactors. We used electromagnetic transient simulation to verify whether severe overvoltage occurred before and after the power station is accessed. The study results may provide guidance for selection of the π circuit accessing point and for optimising the configuration of the shunt and neutral-reactors.

1 INTRODUCTION

SHUNT reactors are commonly applied to long-distance transmission lines to limit power frequency overvoltage and high-amplitude operation overvoltage [1]. However, during the dead time of single-pole trip-and-reclose (SPTR) or non-synchronous operation of circuit breakers (CBs), the system may be in unbalanced open-phase conditions. The connected phase and shunt reactors on the disconnected phase form a series resonant circuit through interphase and phase-to-ground capacitances [2,3]. Therefore, severe overvoltage may occur under open-phase conditions, which may jeopardise equipment safety. An overvoltage incident that occurred on a 500-V 72% shunt-compensated line in the BC Hydro system led to surge arrester failures at both terminals [4]. In addition, a transformer in the sub-network with delta-connected secondary or tertiary windings can also cause excessive overvoltage [5].

Open-phase overvoltage is primarily caused by unbalanced compensation of the shunt reactor for interphase and phase-to-ground capacitances [6]. A neutral reactor can be adopted to counteract the secondary arc current and transient recovery voltage [7,8] and effectively limit open-phase overvoltage [9]. If the neutral reactor is selected in accordance with the principle of complete compensation between interphase capacitance, theoretically, no high-amplitude open-phase overvoltage occurs. However, there is a certain difference between the actual and design value of shunt reactor, neutral reactor and transmission line electrical parameters. The actual frequency of the system may also deviate from the nominal frequency, which may cause open-phase overvoltage. When the compensation of a shunt reactor is $<100\%$, the smaller value of neutral reactor or the lower system frequency may cause interphase under-compensation and phase-to-ground over-compensation, which may result in severe open-phase overvoltage [10]. When a new...
power station is put into operation, the solution of the π circuit accesses a long-distance transmission line can be selected. The compensation of the shunt reactor changes according to the length of the transmission line, and severe overvoltage may occur. Therefore, the necessity and safety of a shunt reactor before a new station is installed are of special interest in engineering. Analysing the risk range of an accessing point causing severe open-phase overvoltage is necessary to realise the optimal shunt reactor configuration on a long-distance transmission line in the design stage and to obtain a guide for selecting the accessing point.

In this study, we analysed the effects of shunt reactor compensation, proportional coefficient of the neutral reactor, and system frequency on open-phase overvoltage. We analyse the impact of line division, when an intermediate substation is accessed and the original shunt compensation is maintained in the system, proposed the risk range of an accessing point causing severe open-phase overvoltage for the shunt reactor configuration at one end or both ends. According to an actual project, we optimised the configuration schemes of shunt and neutral reactors and used electromagnetic transient simulation to verify the open-phase overvoltage of the project. No severe open-phase overvoltage was observed before and after the new power substation accessing the transmission line.

2 MECHANISM OF OPEN-PHASE OVERVOLTAGE

An extra-high-voltage transmission line can experience uneven phase operations during SPTR operations or in case of failure of a CB pole. The voltage is coupled to the disconnected phase from the connected phase through interphase capacitance. When the shunt reactor capacity is improperly configured, a series resonant circuit is formed, and severe open-phase overvoltage may occur.

2.1 Single-phase tripping overvoltage

The source side impedance is much smaller than that of transmission line, when it is connected to two power systems of large capacity. On the other hand, the resistance is about one-tenth of inductance for multi-conductor bundles adopted in high-voltage overhead lines. To simplify the derivation in the theoretical analysis, the source side impedance is not taken into account, and the Overhead line is treated as ideal. The schematic of the system during a single-phase trip-out is presented in Figure 1. $C_M$ is the interphase capacitance, $C_D$ is the phase-to-ground capacitance, $L_P$ is the shunt reactor, and $L_N$ is the neutral reactor.

Equivalent analysis on the connection modes of the shunt and neutral reactors is presented in Figure 2.

The shunt and neutral reactors can be divided into interphase inductance ($L_M$) and phase-to-ground inductance ($L_D$), which can be calculated using Equation (1):

$$\begin{cases} L_D = 3L_N + L_P \\ L_M = \frac{L_P^2}{L_N} + 3L_P \end{cases} \quad (1)$$

Therefore, the equivalent circuit diagram of the circuit in Figure 1 is displayed in Figure 3. For circuit ① in Figure 3(a), the voltage at point A can be calculated using Equation (2):

$$U_A = \frac{X_D}{X_D + 0.5X_M} \times \frac{U_B + U_C}{2}. \quad (2)$$

where, $U_B$ and $U_C$ are the RMS of B and C phase-to-ground voltages, respectively, $X_D$ and $X_M$ are phase-to-ground and
interphase reactance, respectively:

\[
X_D = \frac{1}{\omega L_D - \omega C_D}
\]  
(3)

\[
X_M = \frac{1}{\omega L_M - \omega C_M}
\]  
(4)

When the parameters match properly, the denominator in Equation (2) approaches zero, and \(U_A\) approaches infinity:

\[
X_D + 0.5X_M = 0.
\]  
(5)

When \(X_D > 0\), it is inductive; when \(X_D < 0\), it is capacitive. Similarly, when \(X_M > 0\), it is inductive; when \(X_M < 0\), it is capacitive.

### 2.2 Two-phase tripping overvoltage

The equivalent circuit diagram of the two-phase trip-out of a transmission line is presented in Figure 3(b). The voltage of phases A and B can be calculated as follows:

\[
U_A = U_B = \frac{X_D}{X_D + X_M} \times U_C.
\]  
(6)

Similarly, if the denominator in Equation (6) approaches zero, we obtain Equation (7):

\[
X_D + X_M = 0.
\]  
(7)

### 3 ANALYTICAL AND EVALUATION STUDIES

#### 3.1 Selection of a neutral reactor

Assuming that the shunt reactor compensation capacity of a high-voltage long-distance transmission line is \(Q_{LP}\), we obtain Equation (8):

\[
Q_{LP} = \frac{3U_N^2}{\omega L_P} = \frac{\left(\sqrt{3}U_N\right)^2}{\omega L_M} + \frac{U_N^2}{\omega L_D} = Q_{L_D} + Q_{L_M}.
\]  
(8)

The compensation capacity of a shunt reactor can be divided into phase-to-ground compensation capacity (\(Q_{L_D}\)) and interphase compensation capacity (\(Q_{L_M}\)). The compensation degree \(k_1\) can be expressed using Equation (9):

\[
k_1 = \frac{Q_{L_D}}{Q_C} = -\frac{X_G}{X_{LP}} = \frac{1}{\omega^2 L_P C_1}.
\]  
(9)

where \(C_1\) is the positive-sequence capacitance of the transmission line. The relationship between positive-sequence, zero-

The interphase reactance can be calculated using Equation (10):

\[
\begin{aligned}
C_1 & = C_D + 3C_M \\
C_0 & = C_D
\end{aligned}
\]  
(10)

When the interphase capacitance is completely compensated, the interphase impedance is infinite, which is equivalent to an open circuit, and open-phase overvoltage does not occur. Therefore, after determining the shunt reactor compensation degree \(k_1\), positive-sequence capacitance \(C_1\), and zero-sequence capacitance \(C_0\) of the transmission line, the neutral reactor when the interphase capacitance is completely compensated can be calculated using Equation (11):

\[
L_N = \frac{1}{3\omega^2 C_1 k_1} \times \frac{C_1 - C_0}{C_1 k_1 - C_1 + C_0}.
\]  
(11)

However, the actual value and the demand value of the neutral reactor may differ because of design and manufacturing error. If the actual value of the neutral reactor is represented by \(L_N'\), the deviation from the demand value can be expressed using the proportional coefficient \(k_2\), as follows:

\[
L_N' = k_2 L_N.
\]  
(12)

In practical engineering applications, the equivalent interphase inductance \(L_{D}'\) and phase-to-ground inductance \(L_{M}'\) are expressed using Equation (13):

\[
\begin{aligned}
L_{D}' & = \frac{k_2}{\omega^2 C_1 k_1} \times \frac{C_1 - C_0}{C_1 k_1 - C_1 + C_0} + \frac{1}{\omega^2 C_1 k_1} \\
L_{M}' & = \frac{3}{\omega^2 C_1 k_1} \left[ \frac{k_2 k_1 - C_1 + C_0}{k_2 (C_1 - C_0) + 1} \right].
\end{aligned}
\]  
(13)

In addition, according to Equation (11), the demand value of the neutral reactor inductance is related to the system angular frequency \(\omega\). When the system frequency fluctuates during the switching process, open-phase overvoltage may occur. It is advisable to consider the design and manufacturing error of the shunt reactor and neutral reactor during the calculation of open-phase overvoltage. In addition, the influence of frequency variation of the power system on the overvoltage in case of a fault must be considered [11].

#### 3.2 Open-phase overvoltage on long-distance transmission lines

When open-phase overvoltage occurs on a transmission line, whether it is a single-phase or two-phase trip-out, the two series parts of the circuit in Figure 3(a)(b) are divided into two parts: Inductive and capacitive. According to Equations (2) and (6), we can obtain the relationship between the open-phase overvoltage
amplitude and \( n = X_{D}/X_{M} \) during single-phase and two-phase trip-outs, as indicated in Figure 4.

According to Figure 4, to avoid high-amplitude open-phase overvoltage in case of single-phase and two-phase trip-outs (in this case, the open-phase overvoltage amplitude is < 1.0 p.u.), the following conditions should be satisfied:

\[
n > -\frac{1}{3}.
\]  

(14)

In actual engineering, generally, under-compensation is the compensation strategy of shunt reactors for high-voltage transmission lines. When \( k_1 < 100\% \), \( 1/X_{D} + 3/X_{M} < 0 \), which may lead to several scenarios:

1. When \( X_{D} < 0 \) and \( X_{M} < 0 \), \( n \) is located in the OB curve (OB'), and the open-phase overvoltage amplitude is < 1 p.u.;
2. When \( X_{D} < 0 \) and \( X_{M} > 0 \), \( n \) is located in the OC curve (OC'), and the open-phase overvoltage amplitude is < 1 p.u.;
3. When \( X_{D} > 0 \) and \( X_{M} < 0 \), \( n \) is located in the CDE curve (C'E'), and the open-phase overvoltage amplitude is > 1 p.u.;

Therefore, when \( k_2 > 1 \); that is, the neutral reactor is large and the interphase is over-compensated (which corresponds to situation ②), high-amplitude open-phase overvoltage does not occur on the line. When \( k_2 < 1 \); that is, the neutral reactor is small and the interphase is under-compensated, \( X_{D} < 0 \). If the compensation degree \( k_1 \) is small and \( X_{D} < 0 \), which corresponds to situation ③, high-amplitude open-phase overvoltage may occur.

Combining Equations (4), (5) and (13), we obtain Equation (15):

\[
n = \frac{C_x}{3} \times \frac{C_1 k_1 k_2 - k_2 C_x - C_y}{C_1 k_1 C_y - C_0 k_2 C_x - C_0 C_y}.
\]  

(15)

**TABLE 1** Typical 500-, 750-, and 1000-kV single-circuit transmission line capacitance parameters

| Voltage level | \( C_x \) (nF km\(^{-1}\)) | \( C_y \) (nF km\(^{-1}\)) |
|--------------|----------------|----------------|
| 500 kV       | 13.237         | 8.816          |
| 750 kV       | 14.397         | 9.120          |
| 1000 kV      | 15.201         | 9.281          |

where

\[
\begin{aligned}
C_x &= C_1 - C_0, \\
C_y &= C_1 k_1 - C_1 + C_0.
\end{aligned}
\]  

(16)

For typical 500-, 750-, and 1000-kV single-circuit transmission lines, the positive-sequence and zero-sequence capacitance parameters are listed in Table 1. Equations (15) and (16) can be used to obtain the relationship between the open-phase voltage amplitude, shunt reactor compensation degrees \( (k_1) \) and neutral reactor proportional coefficient \( (k_2) \) as indicated in Figure 5.

Partial conclusions can be obtained from Figure 5, as follows:

1. When the shunt reactor compensation is low, even if the neutral reactor is not installed, high-amplitude open-phase overvoltage does not occur on the line. However, when the shunt reactor compensation degree \( k_1 > 60\% \), the open-phase overvoltage amplitude may exceed 1.0 p.u.
2. When the shunt reactor compensation is high, whether high-amplitude open-phase overvoltage occurs depends on the difference between the actual value and the demand value of the neutral reactor. When the neutral reactor proportional coefficient \( k_2 \geq 1 \), high-amplitude open-phase overvoltage does not occur; when \( k_2 < 1 \), high-amplitude open-phase overvoltage occurs easily when the value of \( k_2 \) is small. When \( k_2 > 0.8 \), the shunt reactor compensation degree \( k_1 < 95\% \) can ensure that high-amplitude open-phase overvoltage does not occur.

In addition to the shunt reactor compensation and neutral reactor deviations, the system frequency deviation affects open-phase overvoltage. When the system frequency is higher than 50 Hz, the design value of the neutral reactor calculated according to Equation (10) is larger, and open-phase overvoltage does not occur. Open-phase overvoltage occurs only when the system frequency is lower and the design value of the neutral reactor is smaller. Considering that the maximum limit of the frequency deviation under normal operating conditions is ±0.5 Hz [12], the critical value of the shunt reactor compensation degree \( k_1 \) is calculated when the open-phase overvoltage amplitude of a 500-kV single-circuit transmission line does not exceed 1.0 p.u. for different neutral reactor proportional coefficients. The results are presented in Figure 6.

According to the aforementioned analysis, for a typical single-circuit high-voltage transmission line without a neutral reactor, when the compensation degree of shunt reactor \( k_1 < 67\% \), or
3.3 | Open-phase overvoltage after a new power station accessing an existing long-distance transmission line

When a new power station accesses an existing transmission line, the compensation degree of the shunt reactor changes as the length of the line changes. If parameters are configured improperly, severe open-phase overvoltage may occur.

3.3.1 | Shunt reactor at both ends of the original transmission line

Firstly, we analysed the case in which the shunt reactor is equally distributed at both ends of the original transmission line. Assuming that the length of the original transmission line is $l$, the relationship between the lengths of the transmission lines after the new power station is accessed is expressed in terms of the introducing coefficient $k_0$ as follows:

$$ l' = k_0 l. \quad (17) $$

According to the analysis in Section III Part B, in addition to the completely interphase compensation, in actual engineering, open-phase overvoltage do not occur in original transmission lines in the following cases:

$X_D < 0$ and $X_M < 0$ of the original transmission line

When $k_0$ decreases from 0.5 to 0, both $C_M$ and $C_D$ decrease, and both $X_M$ and $X_D$ change from negative to positive. Both interphase and phase-to-ground compensations transition from under-compensated to over-compensated, and open-phase overvoltage may occur. When $k_0$ increases from 0.5 to 1, both $C_M$ and $C_D$ increase, and $X_M$ and $X_D$ remain negative, interphase and phase-to-ground compensations are always under-compensated, then open-phase overvoltage does not occur.

$X_D < 0$ and $X_M > 0$ of the original transmission line

When $k_0$ decreases from 0.5 to 0, $X_D$ first decreases from negative to $-\infty$ and then from $+\infty$ to $\omega L_D/2$, $X_M$ is positive and gradually decreases, and $n'$ decreases from negative first and then becomes positive, which may cause open-phase overvoltage. When $k_0$ increases from 0.5 to 1, $X_D$ is still negative and increases gradually, $X_M$ increases from positive to $+\infty$ and then becomes negative, and $n'$ increases from negative to positive. Before the new station is accessed, $n > -1/3$; thus, $n' > -1/3$, and open-phase overvoltage does not occur.

In summary, after a new power station accessing an existing long-distance transmission line, severe open-phase overvoltage may occur only when $k_0 < 0.5$, that is, in case of a short transmission line.
After a new station accessing a transmission line, the phase-to-ground and interphase reactance of the transmission line can be expressed using Equation (18):

\[
\begin{align*}
X_D' &= 1 / \left( \frac{1}{2 \omega L_D} - k_0 \omega C_D \right) \\
X_M' &= 1 / \left( \frac{1}{2 \omega L_M} - k_0 \omega C_M \right)
\end{align*}
\] (18)

Equation (19) can be derived from Equation (18):

\[
n' = \frac{C_x}{3} \times \frac{k_1 k_2 C_1 - 2 k_0 C_1 - 2 k_0 k_2 C_x}{k_1 C_x - 2 k_0 C_0 C_x - 2 k_0 k_2 C_0 C_x}.
\] (19)

Figure 7 presents the relationship curve between the introducing coefficient \(k_0\) and the open-phase overvoltage amplitude when the shunt reactor compensation factor \(k_1 = 80\%\) and the neutral reactor proportional coefficient \(k_2 = 1\).

3.3.2 | Shunt reactor at one end of the original transmission line

In actual engineering, a shunt reactor may be installed only on one end of a long-distance transmission line, generally on the longer line side after the new station accessing the transmission line.

The neutral reactor of the original transmission line assumed to be fully compensated interphase capacitance. After a new station accessing the transmission line, the interphase capacitance decreases, and interphase is over-compensated, that is, \(X'_M > 0\).

1. When \(X'_D > 0\) and \(n' > 0\), high-amplitude open-phase over-voltage does not occur. Interphase and phase-to-ground are both over-compensated; that is, the line length is short after the new station is accessed and \(k_0\) is small.

2. When \(X'_D < 0\), if \(-1/3 < n' < 0\), high-amplitude open-phase overvoltage does not occur, and if \(n' < -1/3\), high-amplitude open-phase overvoltage occurs.

According to the analysis of situation ②, after the new station accessing the transmission line, it can be obtained as follows:

\[
n' = \frac{X'_M}{X'_D} = \frac{1}{3} \frac{Q_{L,M} + Q_{C,M} - 2 Q_{C,D}}{Q_{L,D} - Q_{C,D}}.
\] (20)

where \(X'_D\) and \(X'_M\) are the phase-to-ground and interphase reactance after the new station accessing the transmission line. Because the shunt reactor is installed only at one end of the line, after the new station accessing the transmission line, the phase-to-ground and interphase compensation capacities, \(Q_{L,D}\) and \(Q_{L,M}\), respectively, remain unchanged. \(Q_{C,D}\) and \(Q_{C,M}\) are the phase-to-ground and interphase charging powers before the new station accessing the transmission line. \(Q'_{C,D}\) and \(Q'_{C,M}\) are the phase-to-ground and interphase charging powers after the new station is accessed, which can be obtained using Equation (21):

\[
\begin{align*}
Q_{L,D} + Q_{L,M} &= k_1 (Q_{C,D} + Q_{C,M}) \\
Q'_{C,D} &= k_0 Q_{C,D} \\
Q'_{C,M} &= k_0 Q_{C,M}
\end{align*}
\] (21)
The risk range of $k_0$ when the open-phase overvoltage $>1.0$ p.u. at different compensation degrees of the shunt reactor (shunt reactors of the original transmission line are installed on one end)

We obtain Equation (22) by substituting Equation (21) into Equation (20):

$$n' = \frac{X''_D}{X''_M} = -\frac{1}{\frac{Q_{CM}}{Q_{CD}}(K_0 - 1) + \frac{Q_{CM}}{Q_{CD}}(K_1 - 1)}.$$ (22)

When $n' = -1/3$ and $k_0 = k_1$, after the new station accessing the transmission line, the open-phase overvoltage of the transmission line with a shunt reactor is 1.0 p.u. If $k_0$ is slightly larger than $k_1$, then $C''_D$ increases, $X''_D < 0$ and $X''_D$ also increases, then $n' > -1/3$; a severe open-phase overvoltage will not occur. If $k_0$ is slightly smaller than $k_1$, then $C''_D$ decreases, $X''_D < 0$ and $X''_D$ also decreases, then $n' < -1/3$; high-amplitude open-phase overvoltage may occur.

The shaded part in Figure 9 represents the value range of $k_0$ when the amplitude of open phase overvoltage is $>1.0$ p.u. in the context of an original 500-kV single-circuit transmission line with a shunt reactor installed on one end of the line; the compensation degrees are 50%, 60%, 70%, 80%, 90% and 95%. In summary, risk ranges in which the accessing point may cause open-phase overvoltage amplitude $>1.0$ p.u. under different shunt reactor configuration schemes are presented in Table 2.

### 4 Simulation Study of Engineering Case

#### 4.1 Case study for a new power station accesses a long-distance transmission line

The length of the 500 kV transmission line was 300 km, which was evenly divided into three sections, and a complete cycle transposition was implemented every 100 km. The source side positive sequence impedance is about 10 Ω, and the zero sequence impedance is about 12 Ω. The positive-sequence and zero-sequence capacitance parameters of the transmission line are consistent with those in Table 1. The schematic of the transmission line is displayed in Figure 10.

After the transmission line has been in operation for a specific period, an intermediate substation is planned to be accessed as a π circuit. The schematic of line division is displayed in Figure 11. The lengths of the lines after the power station studied in this paper was accessed are 186 and 114 km.

#### 4.2 Analysis and simulation verification of open-phase overvoltage of the original transmission line

According to the results of the aforementioned case study, the neutral reactor value of interphase full compensation under different compensation degrees of shunt reactor can be calculated.
by substituting the transmission line parameters in Equation (11). According to Figure 5, the demanded proportional coefficient $k_2$ of neutral reactor can be obtained when the open-phase overvoltage amplitude is $< 1.0 \text{ p.u.}$, as shown in Table 3.

The aforementioned analysis was verified using the electromagnetic transient program EMTP/ATP. The 500 kV overhead line 4xJL/LB1A-500/45 was used, and the transmission tower was a typical cup type tower with a height of 40 m. Considering the example of single-phase and two-phase trip-out when the CB was closed to calculate open-phase overvoltage, the switching action time at both ends of the transmission line was $t = 0.2 \text{ s}$, the loss of transmission line is considered in the calculation.

Generally, in engineering, the value of neutral reactor is an integer (a multiple of 50 $\Omega$). The value of neutral reactor adopted in simulation and the results are presented in Table 4.

According to the simulation results, when the neutral reactor is selected according to Table 3, the open-phase overvoltage amplitudes are $< 1.0 \text{ p.u.}$ When the neutral reactor value is nearly that of interphase complete compensation, the open-phase overvoltage amplitude reduces further.

### 4.3 Analysis and simulation verification of open-phase overvoltage after a new power station accessing the transmission line

According to the project plan, the $k_0$ after a new power station accessing the long-distance transmission line are 0.62 and 0.38, respectively. Analysis of Table 2 reveals that when the shunt reactor is single-ended and the compensation is 70%, or when the reactor is double-ended and the compensation is 80%, the amplitude of open-phase overvoltage after the new power station accessing the transmission line may be $> 1.0 \text{ p.u.}$ In addition, when the reactor is single-ended and the degree of compensation is 60%, or when the reactor is double-ended and the degree of compensation is 70%, $k_0$ is approximately in the risk range. Considering the change in line parameters after the new power station accessing the transmission line and the error after assuming the integer value of the neutral reactor, high-amplitude open-phase overvoltage may also occur in these two shunt reactor configuration schemes.

The accuracy of the aforementioned analysis was verified using simulation calculations with the same input parameters as Chapter A. Table 5 shows the results of the open-phase overvoltage amplitude of the transmission line under different shunt configuration schemes.

The results indicate that in case of double-ended and the compensation degree is 80% or 70%, single-ended and the compensation degree is 70%, the open-phase overvoltage is $> 1.0 \text{ p.u.}$; in case of single-ended and the compensation degree is 60%, the overvoltage is less than but approximately equal to 1.0 p.u. The simulation results agree well with those of the previous analysis.

To limit power frequency overvoltage, the compensation degree of the shunt reactor should not be too low. However, considering the errors of line parameters, neutral reactor and shunt reactor design parameters and actual parameters, the shunt reactor compensation degree should not be too high. Therefore, considering the current operation and the access of the long-term power station, we recommend that a single-ended configuration be used with a shunt reactor compensation of 80% and a neutral reactor of neutral reactor 500 $\Omega$. 

| TABLE 3 | Demanded neutral reactor when open-phase overvoltage amplitude is $< 1.0 \text{ p.u.}$ |
|---------------------------------|---------------------------------|
| **Compensation of shunt reactor** | 60% | 70% | 80% | 90% |
| Neutral reactor at full compensation ($\Omega$) | 560 | 349 | 240 | 175 |
| Demanded neutral reactor proportional coefficient | $\geq 0$ | $\geq 0.056$ | $\geq 0.281$ | $\geq 0.595$ |
| Demanded neutral reactor when shunt reactor installed at single end ($\Omega$) | $\geq 0$ | $\geq 20$ | $\geq 68$ | $\geq 104$ |
| Demanded neutral reactor when shunt reactor installed at both ends ($\Omega$) | $\geq 0$ | $\geq 40$ | $\geq 136$ | $\geq 208$ |

| TABLE 4 | Open-phase overvoltage with different neutral reactors |
|---------------------------------|---------------------------------|
| **Overvoltage (p.u.)** | Shunt reactor configuration | Neutral reactor ($\Omega$) | Single-phase trip | Two-phase trip |
|---------------------------------|---------------------------------|
| $k_1$ | One end | Both ends | One end | Both ends | One end | Both ends | One end | Both ends | One end | Both ends |
| 60% | 0 | 0 | 0.357 | 0.030 | 0.385 | 0.018 | 0.358 | 0.046 | 0.486 | 0.025 | 0.577 | 0.036 | 0.999 | 0.023 |
| 70% | 50 | 1100 | 0.358 | 0.064 | 0.486 | 0.031 | 0.358 | 0.043 | 0.957 | 0.063 | 0.056 |
| 80% | 100 | 250 | 0.281 | 0.034 | 0.478 | 0.024 | 0.281 | 0.043 | 0.937 | 0.063 | 0.056 |
| 90% | 150 | 200 | 0.313 | 0.031 | 0.478 | 0.024 | 0.313 | 0.043 | 0.917 | 0.063 | 0.056 | 0.056 | 0.058 |
| $k_1$ | Configuration scheme | Neutral reactor (Ω) | $k_0 = 0.38$ | $k_0 = 0.62$ |
|-------|----------------------|---------------------|-------------|-------------|
|       |                      |                     | Single-phase | Two-phase   | Single-phase | Two-phase   |
| 60%   | One end              | 550                 | -           | -           | 0.83        | 0.77        |
|       | Both ends            | 1100                | 0.42        | 0.08        | 0.11        | 0.01        |
| 70%   | One end              | 350                 | -           | -           | 1.01        | 1.35        |
|       | Both ends            | 700                 | 1.09        | 0.38        | 0.13        | 0.01        |
| 80%   | One end              | 250                 | -           | -           | 0.33        | 0.49        |
|       | Both ends            | 500                 | 1.38        | 0.27        | 0.16        | 0.02        |
| 90%   | One end              | 200                 | -           | -           | 0.22        | 0.31        |
|       | Both ends            | 350                 | 0.48        | 0.13        | 0.21        | 0.02        |

5 | CONCLUSION

In this paper, the effects of the compensation degree of the shunt reactor, neutral reactor, and system frequency on open-phase overvoltage were analysed. Parameters of a typical 500 kV single-circuit transmission line were considered, and a risk range was determined in which the amplitude of open-phase overvoltage after the new power station accessing the transmission line was $> 1.0$ p.u. The conclusions of this paper can guide the optimal configuration of the shunt reactor of the original line. In addition, the paper can provide guidance for the selection of the accessing point of the solution of a $\pi$ circuit when a new power station is put into operation. The main conclusions are as follows:

1. The difference between the actual value and design value of the shunt reactor and neutral reactor may cause severe open-phase overvoltage. For a transmission line that is under-compensated by a shunt reactor, when the neutral reactor is large, high-amplitude open-phase overvoltage does not occur.

2. Considering that the maximum frequency deviation limit is $\pm 0.5$ Hz under normal operating conditions of the system, the shunt reactor compensation $k_1$ should be $< 66.65\%$ when the neutral reactor is not installed. Considering the difference between the actual and design values of neutral reactor, when the neutral reactor proportionality coefficient $k_2 > 0.7$, the shunt reactor compensation degree $k_0$ should be $< 92.45\%$.

3. In case of the single-ended configuration of the original line shunt reactor, the shunt reactor is generally installed on the longer line side after the new power station accessing the transmission line, and open-phase overvoltage may occur. As the compensation degree of the shunt reactor increases, the risk range of $k_0$ becomes smaller.

4. When the shunt reactor of the original line is equally divided and configured at both ends, open-phase overvoltage may only occur on the short line after the new power station accessing the transmission line. Similar to the single-ended configuration, as the shunt reactor compensation degree increases, the risk range of $k_0$ becomes smaller.

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Appendix A. Derivation of Equation (1)

Equivalent analysis on the connection modes of the shunt and neutral reactors is presented in Figure 12.

For circuit in Figure 12(a), the voltage on the nodes can be calculated using Equations (23) to (25):

\[ U_A = j\omega i_{11} L_D. \]  
(23)
\[ U_B = j\omega i_{22} L_D. \]  
(24)
\[ U_C = j\omega i_{33} L_D. \]  
(25)

For circuit in Figure 12(b), the voltage on the nodes can be calculated using Equations (26) to (28):

\[ U_A = j\omega [(i_{11} + i_{12} - i_{31}) L_P + (i_{11} + i_{22} + i_{33}) L_N]. \]  
(26)
\[ U_B = j\omega [(i_{22} + i_{33} - i_{12}) L_P + (i_{11} + i_{22} + i_{33}) L_N]. \]  
(27)
\[ U_C = j\omega [(i_{33} + i_{31} - i_{23}) L_P + (i_{11} + i_{22} + i_{33}) L_N]. \]  
(28)

Obviously (A1) + (A2) + (A3) = (A4) + (A5) + (A6), we can obtain Equations (29) and (30):

\[ (i_{11} + i_{22} + i_{33}) L_D = (i_{11} + i_{22}) L_P + 3(i_{11} + i_{22} + i_{33}) L_N. \]  
(29)
\[ L_D = L_P + 3L_N. \]  
(30)

The voltage between phase A and phase B in Figure 12(b) can be expressed by Equation (31):

\[ U_{AB} = j\omega [(i_{11} + i_{12} - i_{31}) L_P - (i_{22} + i_{33} - i_{12}) L_P]. \]  
(31)
\[ = j\omega (i_{11} + i_{22} + 2i_{12} - i_{31} - i_{23}) L_P. \]

The line voltage in Figure 12(a) can be expressed by Equations (32) to (34):

\[ U_{AB} = j\omega i_{12} L_M. \]  
(32)
\[ U_{BC} = j\omega i_{23} L_M. \]  
(33)
\[ U_{CA} = j\omega i_{31} L_M. \]  
(34)

\[ (a) \text{ Equivalent analysis} \hspace{1cm} (b) \text{Engineering connection} \]

Figure 13 is further simplified to Figure 3.

Taking the equivalent model in Figure 2 into Figure 1, the schematic of the system during a single-phase trip-out can be equivalent to Figure 13(a). As the concern is the voltage of open phase A, it is mainly related to the voltage of phases B and C, which is fixed and determined by the system. Therefore, the connection between B and C phases can be ignored, the simplified circuit is shown in Figure 13(b).