Electromagnetic Transient Analysis of 750kV Four-circuit Transmission Line on the Same Tower

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Abstract. The ATP-EMTP program is used to calculate the power frequency overvoltage, open-phase power frequency resonant overvoltage, induced voltage and current, secondary arc current and recovery voltage, and switching overvoltage of 750kV four-circuit transmission line on the same tower. The study reveals that the configuration of four circuits on the same tower has little influence on the power frequency and switching overvoltage, but greatly influences the secondary arc current and recovery voltage, and induced voltage and current. Therefore, measures like installing high-voltage shunt reactor and neutral grounding reactor and line transposition are required. Also, the induced voltage and current ratings of earthing switch are proposed.

1. Introduction
The configuration of four circuits on the same tower of a 750kV AC transmission line can increase the transmission capacity per unit area of line corridor and cut the project cost, making it an ideal solution to the limited line corridor, especially for areas where line corridor resources are scarce.

Arranging multiple circuits on the same tower of an extra-high voltage (EHV) transmission line will create significant economic and social benefits, but will inevitably bring some technical challenges. Typical problems include overvoltage, secondary arc current, induced voltage and induced current. With more circuits and smaller spacing of conductors, a four-circuit transmission line suffers severer electromagnetic induction and electrostatic induction as compared with a double-circuit transmission line. This may result in higher overvoltage, secondary arc current and recovery voltage, and pose higher requirements on the induced current and voltage ratings of earthing switches in type selection [1-3].

2. System simulation model
Three schemes are considered. In Scheme 1, Circuits I and II are 100km long, and III and IV are 50km long. The length of four circuits carried on the same tower is 20km, and the remaining line section adopts the configuration of two circuits on same tower. In Scheme 2, Circuits I and II are 100km long, and III and IV are 50km long. The length of four circuits carried on the same tower is 50km, and the remaining line section adopts the configuration of two circuits on same tower. In Scheme 3, the length of each circuit line is 100km long and the length of four circuits carried on the same tower is also 100km long. The conductors used are LGJK-400/45 type six-conductor bundles, and the shield wires used are of JLB20A-150 and OPGW145 types. Two types of transmission towers are considered, whose conductor arrangements are respectively shown in figure 1 and figure 2[4].
The calculation results of line sequence parameters are given in Table 1.

Table 1. Line sequence parameters

| Tower Type               | Positive Sequence Parameters | Zreo Sequence Parameters |
|--------------------------|------------------------------|--------------------------|
|                          | Resistance (Ω/km)           | Inductive Reactance (Ω/km) | Capacitance (μF/km) | Resistance (Ω/km) | Inductive Reactance (Ω/km) | Capacitance (μF/km) |
| Four-cross-arm tower     | 0.01032                      | 0.26372                   | 0.01368              | 0.21177           | 0.81272                   | 0.00833               |
| Six-cross-arm tower      | 0.01092                      | 0.26342                   | 0.01388              | 0.21283           | 0.80297                   | 0.00783               |

Circuit I has 1×360Mvar high-voltage shunt reactor at one end, circuit IV has 1×300Mvar high-voltage shunt reactor at one end, and circuits II and III have no high-voltage shunt reactors.

3. Secondary arc current and recovery voltage

Three operating modes of the line are considered in the calculation, i.e. normal operation, N-1 and N-2. The maximum values of secondary arc current and recovery voltage of the four circuits are listed in Table 2 and Table 3.[5]

(1) In Scheme 1, circuits compensated with high-voltage shunt reactors are capable of quick single-phase reclosing within 0.5s, while for non-compensated circuits, the shortest reclosing time is 0.9s–1.4s. So high-voltage shunt reactors are recommended. In terms of the secondary arc current and recovery voltage, the calculation results show that the four-cross-arm tower outperforms the six-cross-arm tower.

(2) In Scheme 2, the length of four circuits carried on the same tower accounts for 52% of circuits I and II and 100% of circuits III and IV, both higher than the percentage values as used in Scheme 1 (i.e. 21% and 40%). For the four-cross-arm tower, the secondary arc current and recovery voltage of compensated circuits increase by 75%–126%, while for non-compensated circuits, the values increase by 9%–13%. For the six-cross-arm tower, the secondary arc current and recovery of compensated circuits increase by 30%–69%, while for non-compensated circuits, the values increase by 4%–8%. It
follows that increasing the length percentage of four circuits carried on the same tower has significant impact on compensated circuits, but little impact on non-compensated circuits.

(3) In Scheme 3, the secondary arc current and recovery voltage are larger where there is no transposition. When the line conductors are transposed once, the compensated circuits are capable of quick single-phase reclosing.

**Table 2.** Secondary arc current and recovery voltage of transmission line carried on four-cross-arm tower

| Tower Type | Line Scheme       | Circuit | Recovery Voltage (kV) | Secondary Arc Current (A) |
|------------|-------------------|---------|-----------------------|----------------------------|
|            | Scheme 1          | Circuit I   | 78.50                | 10.96                      |
|            |                   | Circuit II  | 85.98                | 30.92                      |
|            |                   | Circuit III | 94.09                | 17.73                      |
|            |                   | Circuit IV  | 33.92                | 8.16                       |
|            | Scheme 2          | Circuit I   | 84.36                | 13.50                      |
|            |                   | Circuit II  | 93.89                | 33.65                      |
|            |                   | Circuit III | 102.38               | 20.04                      |
| Four-cross-arm |               | Circuit IV  | 53.10                | 13.66                      |
|            | Scheme 3 (no transposition) | Circuit I | 165.92 | 27.98 |
|            |                   | Circuit II  | 111.38               | 40.65                      |
|            |                   | Circuit III | 102.84               | 40.41                      |
|            |                   | Circuit IV  | 199.78               | 28.05                      |
|            | Scheme 3 (transposed once) | Circuit I | 85.17 | 12.41 |
|            |                   | Circuit II  | 81.66                | 30.87                      |
|            |                   | Circuit III | 87.99                | 35.03                      |
|            |                   | Circuit IV  | 109.97               | 11.00                      |

**Table 3.** Secondary arc current and recovery voltage of transmission line carried on six-cross-arm tower

| Line Scheme   | Tower Type       | Circuit | Recovery Voltage (kV) | Secondary Arc Current (A) |
|---------------|------------------|---------|-----------------------|----------------------------|
| Scheme 1      | Six-cross-arm    | Circuit I | 105.02               | 14.76                      |
|               |                  | Circuit II | 90.05                | 32.30                      |
|               |                  | Circuit III | 93.84                | 17.47                      |
|               |                  | Circuit IV  | 33.80                | 8.16                       |
| Scheme 2      |                  | Circuit I   | 98.16                | 14.47                      |
|               |                  | Circuit II  | 93.69                | 33.60                      |
|               |                  | Circuit III | 99.48                | 18.93                      |
|               |                  | Circuit IV  | 48.02                | 12.43                      |
| Scheme 3 (no transposition) | Six-cross-arm | Circuit I | 166.25 | 25.94 |
|               |                  | Circuit II  | 104.27               | 38.29                      |
|               |                  | Circuit III | 100.09               | 38.23                      |
|               |                  | Circuit IV  | 170.24               | 25.75                      |
| Scheme 2 (transposed once) | Six-cross-arm | Circuit I | 103.49 | 13.00 |
|               |                  | Circuit II  | 102.71               | 38.26                      |
|               |                  | Circuit III | 91.81                | 35.14                      |
|               |                  | Circuit IV  | 112.87               | 12.97                      |
4. Type selection of earthing switch

Table 4 lists the ratings of 800kV earthing switch specified in company, industrial, Chinese national and IEC standards. The requirements for earthing switch ratings set forth in DL/T 486-2010 High-voltage Alternating-Current Disconnectors and Earthing Switches are representative [6-8].

| Table 4. Requirements for ratings of 800 kV earthing switch in different standards |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| Ratings of 800 kV Earthing Switch | Class | Electrostatic Induced Voltage (kV) | Electrostatic Induced Current (A) | Electromagnetic Induced Voltage (kV) | Electromagnetic Induced Current (A) |
|---------------------------------|-----------------|-----------------|-----------------|-----------------|
| DL/T 486-2010 High-voltage Alternating-Current Disconnectors and Earthing Switches | A | 12 | 3 | 2 | 80 |
| Q/GDW 106—2003 Specification for High-voltage Alternating-current Disconnecting Switch of 750 kV Power System | B | 32 | 25/50 | 25 | 200 |
| GB 1985—2014 High-voltage Alternating-current Disconnectors and Earthing Switches | A | 12 | 3 | 2 | 80 |
| IEC 62271—102: High-voltage Switchgear and Controlgear- Part 102: High-voltage Alternating Current Disconnectors and Earthing Switches | B | 32 | 25 | 20 | 160 |

In Scheme 1, the calculation results of inductive and capacitive voltage and current, with N-1 and N-2 operation taken into account, are given in table 5. As to the calculation of induced voltage and current, the operating voltage is conservatively taken as 800 kV at the starting end, and the power flow of one circuit is 3000MW+j600Mvar[9-10].

For the four-cross-arm tower, the maximum capacitive voltage of the four circuits is 45.84kV, the maximum capacitive current is 9.44A, the maximum inductive voltage is 4.92kV and the maximum inductive current is 166.08A. Obviously, the required ratings of earthing switch will exceed the values specified for a Class B earthing switch in the relevant standards. The ratings of earthing switch are required to be 25A/50kV (capacitive) and 200A/25kV (inductive).

For the six-cross-arm tower, the maximum capacitive voltage of the four circuits is 64.25kV, the maximum capacitive current is 8.57A, the maximum inductive voltage is 4.31kV, and the maximum inductive current is 148.51A. Obviously, the required ratings of earthing switch will exceed the values specified for a Class B earthing switch in the relevant standards. The ratings of earthing switch are required to be 25A/70kV (capacitive) and 200A/25kV (inductive).

The calculation results for the four-cross-arm tower are higher than the six-cross-arm tower, except for the maximum capacitive voltage.

Table 5. Induced voltages and currents of Scheme 1

| Tower Type | Circuit Outage | Capacitive Outage (kV) | Capacitive Current (A) | Inductive Voltage (kV) | Inductive Current (A) |
|------------|---------------|-----------------------|-----------------------|-----------------------|-----------------------|
| Four-cross-arm | Circuit I | 45.84 | 6.41 | 4.05 | 106.12 |
|             | Circuit II | 29.37 | 9.44 | 4.92 | 141.67 |
|             | Circuit III | 41.88 | 6.27 | 3.44 | 166.08 |
The induced voltages and currents of Schemes 2 and 3 under four-cross-arm tower and six-cross-arm tower configurations are given in table 6 and table 7. For Scheme 2, the maximum capacitive voltage is 121.61kV with the four-cross-arm tower, much larger than that under the six-cross-arm tower configuration (i.e. 77.75kV). For Scheme 3 (no transposition), the maximum capacitive voltage is 251.33kV with the four-cross-arm tower, much larger than that under the six-cross-arm tower configuration (i.e. 164.53kV). For Scheme 3 (transposed once), the induced voltages and currents are comparable under the four-cross-arm and the six-cross-arm tower configurations. Where four-cross-arm tower is used, the ratings of earthing switch should be 25A/150kV (capacitive) and 350A/25kV (inductive); where six-cross-arm tower is used, the ratings of earthing switch should be 25A/100kV (capacitive) and 230A/25kV (inductive). In Scheme 3, one transposition is recommended, and the ratings of earthing switch should be 25A/100kV (capacitive) and 200A/25kV (inductive) for both four-cross-arm tower and six-cross-arm tower.

**Table 6.** Induced voltages and currents of Scheme 2 and Scheme 3 under four-cross-arm tower configuration

| Tower Type          | Circuit | Capacitive Outage (kV) | Capacitive Current (A) | Inductive Voltage (kV) | Inductive Current (A) |
|---------------------|---------|------------------------|------------------------|------------------------|------------------------|
| Scheme 2            | Circuit I | 121.61                 | 17.96                  | 7.47                   | 187.56                 |
|                     | Circuit II | 56.80                  | 17.55                  | 8.25                   | 200.46                 |
|                     | Circuit III | 93.73                  | 14.78                  | 7.16                   | 320.0                  |
|                     | Circuit IV | 56.52                  | 14.54                  | 7.61                   | 320.0                  |
| Scheme 3 (no transposition) | Circuit I | 251.33                  | 35.59                  | 12.01                  | 360.0                  |
|                     | Circuit II | 106.15                 | 34.84                  | 13.51                  | 380.0                  |
|                     | Circuit III | 94.09                  | 29.63                  | 13.06                  | 320.0                  |
|                     | Circuit IV | 239.54                 | 29.09                  | 13.68                  | 340.0                  |
| Scheme 3 (transposed once) | Circuit I | 85.91                  | 11.13                  | 4.12                   | 144.51                 |
|                     | Circuit II | 36.99                  | 12.63                  | 5.63                   | 161.64                 |
|                     | Circuit III | 34.08                  | 11.30                  | 6.94                   | 187.30                 |
|                     | Circuit IV | 96.91                  | 10.09                  | 3.94                   | 122.99                 |

**Table 7.** Induced voltages and currents of Scheme 2 and Scheme 3 under six-cross-arm tower configuration

| Tower Type          | Circuit | Capacitive Outage (kV) | Capacitive Current (A) | Inductive Voltage (kV) | Inductive Current (A) |
|---------------------|---------|------------------------|------------------------|------------------------|------------------------|
| Scheme 2            | Circuit I | 77.75                  | 11.76                  | 5.55                   | 129.91                 |
|                     | Circuit II | 34.78                  | 9.50                   | 5.17                   | 117.64                 |
|                     | Circuit III | 63.46                  | 10.45                  | 4.01                   | 173.89                 |
|                     | Circuit IV | 42.15                  | 10.87                  | 4.78                   | 211.05                 |
| Scheme 3 (no transposition) | Circuit I | 164.53                 | 23.28                  | 9.92                   | 260.0                  |
|                     | Circuit II | 75.38                  | 23.20                  | 9.71                   | 260.0                  |
|                     | Circuit III | 63.64                  | 20.99                  | 10.02                  | 260.0                  |
5. Transient power frequency overvoltage

According to 4.1.3 of GB/T 50064—2014 Code for Design of Overvoltage Protection and Insulation Coordination for AC Electrical Installations, for systems whose maximum voltage is higher than 252kV but does not exceed 800kV, the power frequency overvoltage should not exceed 1.3p.u. on the substation side of line breaker, and it should not exceed 1.4p.u. and last for more than 0.5s on the line side of line breaker.

Transient power frequency overvoltage on the line side and the substation side is mainly caused by sudden load shedding, Ferranti effect of long transmission line, and system asymmetry. The calculation of transient power frequency overvoltage takes into account two operating conditions:

1. Three-phase load shedding of one circuit at the receiving end (or three-phase tripping without fault);
2. Single-phase grounding of one circuit at the receiving end, and three-phase tripping at the receiving end.

Table 8 shows the calculation results of power frequency overvoltage of line. The maximum power frequency overvoltage does not vary greatly among the four circuits, and the calculation result with six-cross-arm tower is only 0.01p.u. lower than the value calculated with four-cross-arm tower. So, the effects of tower type on the power frequency overvoltage are negligible. The maximum power frequency overvoltage is insignificantly affected by the length (percentage) of the four circuits carried on the same tower and the tower type.

| Scheme 3 (transposed once) | Circuit IV | 149.75 | 21.12 | 9.87 | 260.0 |
|---------------------------|------------|--------|-------|------|------|
| Circuit I                 | 96.45      | 11.36  | 4.74  | 109.28 |
| Circuit II                | 36.67      | 11.03  | 4.96  | 119.12 |
| Circuit III               | 28.85      | 9.18   | 4.89  | 106.79 |
| Circuit IV                | 77.00      | 8.86   | 4.92  | 108.19 |

Table 8. Power frequency overvoltage of line

| Scheme 1 | Tower Type | Busbar Side (p.u.) | Line Side (p.u.) |
|----------|------------|--------------------|------------------|
| Scheme 1 | Four-cross-arm | 0.99               | 1.11             |
|          | Six-cross-arm | 0.99               | 1.10             |
| Scheme 2 | Four-cross-arm | 0.99               | 1.11             |
|          | Six-cross-arm | 0.99               | 1.10             |
| Scheme 3 | Four-cross-arm | 1.00               | 1.11             |
|          | Six-cross-arm | 1.00               | 1.12             |

During open-phase operation, voltage may be present on the open phase as a result of inter-phase coupling with the normal phases. When shunt reactors are installed, the open phase-to-ground impedance may be inductive and the inter-phase impedance may be capacitive. Under certain parameter values, high power frequency resonant overvoltage may take place on the open phase.

To suppress the power frequency resonant overvoltage and secondary arc current, neutral grounding reactor provides an efficient and economical solution. Table 9 shows the calculation results of open-phase power frequency resonant overvoltage of circuits I and IV in Scheme 1 with different tower types.

As circuits I and IV are overcompensated by high-voltage shunt reactors, switching the neutral grounding reactor in or out of service (neutral point of high-voltage shunt reactor directly grounded) will not result in high power frequency resonant overvoltage on the open phase.
### Table 9. Calculation results of power frequency resonant overvoltage during open phase operation of Scheme 1 (p.u.)

| Tower Type | Line | Open Phase | Operation Status of Neutral Grounding Reactor | Power Frequency Resonant Overvoltage |
|------------|------|------------|---------------------------------------------|-------------------------------------|
|            |      |            |                                             | Open Phase | Neutral Grounding Reactor |
| Four-cross-arm |      | One open phase | In service. | 0.09 | 0.12 |
| Circuit I  |      | One open phase | Out of service. | 0.25 | / |
|            |      | Two open phases | In service. | 0.10 | 0.11 |
|            |      | Two open phases | Out of service. | 0.30 | / |
| Circuit IV |      | One open phase | In service. | 0.02 | 0.07 |
|            |      | Two open phases | Out of service. | 0.14 | / |
| Six-cross-arm |      | One open phase | In service. | 0.05 | 0.07 |
| Circuit I  |      | One open phase | Out of service. | 0.12 | / |
|            |      | Two open phases | In service. | 0.07 | 0.11 |
|            |      | Two open phases | Out of service. | 0.32 | / |
| Circuit IV |      | One open phase | In service. | 0.14 | 0.11 |
|            |      | Two open phases | Out of service. | 0.33 | / |
|            |      | One open phase | In service. | 0.06 | 0.07 |
|            |      | Two open phases | Out of service. | 0.08 | / |
| Max.       |      | One open phase | In service. | 0.06 | 0.08 |
|            |      | Two open phases | Out of service. | 0.08 | / |

In China, the grid frequency varies within 49–51Hz in the worst case. Figure 3 shows the resonant frequency vs. the open phase voltage (obtained through frequency sweeping method) of circuit I (with 300Ω neutral grounding reactor) under open phase operation when the length of four circuits carried on the same tower is 20km long and four-cross-arm tower is selected. It can be seen from the figure that the recovery voltage is 38.46 kV (RMS) at 49Hz and is 59.96kV (RMS) at 51 Hz. No hazardous resonant overvoltage is present, and the maximum power frequency resonant overvoltage occurs at 59Hz which however goes far beyond the allowable frequency range.

![Figure 3](image_url)

**Figure 3.** Frequency sweeping of open phase voltage of circuit I (with 300 Ω neutral grounding reactor) in Scheme 1 with four-cross-arm tower
6. Switching overvoltage
Under same system conditions, the switching overvoltage depends on the line length. Table 10 lists the switching overvoltage levels of transmission line in Scheme 3. According to this table, under 2% phase-to-ground overvoltage, the maximum closing overvoltage of the four circuits is 1.22 p.u., and the maximum switching overvoltage caused by three-phase opening operation following a single-phase grounding fault is 1.67 p.u., both lower than the limit, i.e. 1.8 p.u., as specified in the Chinese national standard.

| Type of Switching Overvoltage | Line | 2% Phase-to-ground Overvoltage (p.u.) | Maximum Phase-to-phase Overvoltage (p.u.) |
|------------------------------|------|--------------------------------------|------------------------------------------|
|                              |      | Sending End                  | Receiving End                  | Maximum along the Line | Sending End | Receiving End |
| Closing of no-load line       |      | 1.07 | 1.22 | 1.22 | 1.91 | 2.10 |
| Circuit I                     |      | 1.07 | 1.19 | 1.19 | 1.91 | 2.04 |
| Circuit II                    |      | 1.08 | 1.19 | 1.19 | 1.99 | 2.00 |
| Circuit III                   |      | 1.07 | 1.19 | 1.19 | 1.89 | 1.99 |
| Circuit IV                    |      | 1.05 | 1.12 | 1.12 | 1.87 | 1.88 |
| Single-phase reclosing        |      | 1.07 | 1.16 | 1.16 | 1.83 | 1.93 |
| Circuit I                     |      | 1.06 | 1.12 | 1.12 | 1.82 | 1.90 |
| Circuit II                    |      | 1.01 | 1.08 | 1.08 | 1.76 | 1.85 |
| Circuit III                   |      | 1.61 | 1.62 | 1.63 | 2.54 | 2.56 |
| Circuit IV                    |      | 1.45 | 1.47 | 1.49 | 2.22 | 2.22 |
| Three-phase opening following single-phase grounding fault | | 1.57 | 1.61 | 1.61 | 2.29 | 2.29 |
| Circuit III                   |      | 1.65 | 1.65 | 1.67 | 2.61 | 2.63 |
| Max.                          |      | 1.65 | 1.65 | 1.67 | 2.61 | 2.63 |

7. Conclusions
(1) The secondary arc current and recovery voltage increase as the length percentage of four circuits carried on the same tower becomes greater. When the length of four circuits carried on the same tower is selected to be 100km, it is recommended to install high-voltage shunt reactors and transpose the line conductors once so as to facilitate quick single-phase reclosing.

(2) As the length percentage of four circuits carried on the same tower becomes greater, the ratings of earthing switch are required to be 25A/100kV (capacitive) and 200A/25kV (inductive). Where the length is longer than 100km, it is recommended to transpose the line conductors once.

(3) The maximum power frequency overvoltage does not vary greatly among the four circuits, and the calculation result with six-cross-arm tower is only 0.01 p.u. lower than the value calculated with four-cross-arm tower. Therefore, the effects of length percentage of four circuits carried on the same tower and tower type on the maximum power frequency overvoltage are negligible.

(4) The switching overvoltage of transmission line can be effectively suppressed below the limit specified in the Chinese national standards by installing line surge arresters and closing resistor for line breaker.

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