Study on Reactive Power Imbalance and Its solution of Parallel Coupled Transmission Lines

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Abstract. In view of the imbalance and even the abnormal phenomenon of reactive circulation of parallel high voltage transmission lines with similar measured parameters in actual operation, combined with field investigation and test, theoretical analysis and simulation demonstration, it is clear that this phenomenon is caused by the use of unconventional phase sequence and unreasonable transposition of the two-circuit lines when erecting the same tower. Based on the PSCAD simulation, the corresponding improvement measures are put forward from two aspects of optimizing the arrangement of phases and transposition. The results show that in order to solve the power imbalance problem of parallel coupled transmission lines, it is recommended to optimize the phase sequence of conductors in consideration of economy and operability.

1. Introduction

With the continuous improvement of power grid intelligence, the dependence of dispatchers on real-time on-line monitoring systems, such as supervisory control and data acquisition (SCADA) system and on-line security and stability analysis systems, is also increasing. At present, the real-time on-line monitoring of power grid is mainly based on grid model and algorithm, and the accuracy of grid parameters determines the accuracy of grid model, and then determines the accuracy and reliability of the real-time on-line monitoring system in state estimation, power flow calculation, fault analysis, stability analysis and other application functions [1]. Therefore, improving the accuracy of power grid parameters is of great significance to ensure the safe and stable operation of the power grid.

In order to alleviate the tension of transmission corridors, high-voltage transmission lines usually use double-circuit or multi-circuit parallel transmission lines on the same tower. In principle, high voltage transmission lines usually adopt transposition measures to reduce the asymmetry of current and voltage in normal operation of power system [2]. When the parallel transmission lines erected on the same tower are reasonably arranged and transposed, it is often considered that the electrical quantities of each sequence are independent and symmetrical, and the electromagnetic coupling effects among loops, phases and phases are often neglected in the actual measurement of parameters. However, in actual operation, some parallel high voltage transmission lines of the same type still have unbalanced power, even abnormal power circulation phenomena, which seriously affect the normal
operation of state estimation, online safety analysis and other links, and cause misjudgments to power grid operators [3]. In the first ten days of December 2017, through D5000 platform, regulator automation personnel of a power grid company found that the reactive power of two return lines (L1 and L2) of a 500 kV power plant (A power plant) was unbalanced, even the phenomenon of reactive power circulation, which seriously affected the results of state estimation. Through on-site investigation, theoretical analysis and simulation demonstration, it is clear that the reactive power imbalance of the transmission lines of the power plant is caused by the non-conventional arrangement of the two-circuit lines in the same tower but not reasonable transposition, which results in the asymmetry of the parameters, and the corresponding countermeasures are put forward.

2. Phenomenon Description

A power plant is connected to 500 KV B substation through double-circuit 500 KV lines L1 and L2. Its 500 KV system structure is shown in Figure 1.

![Figure 1. Primary connection diagram of outgoing lines of plant A](image)

By inquiring D5000, the historical power records of L1 and L2 on the power plants side at several times since A power plant was connected to the grid are shown in Table 1. Historical records show that the active power of L1 and L2 is basically balanced, but the reactive power varies greatly, and even the phenomenon of different reactive power flows has existed since the grid-connected generation of A power plant.

| Time            | L1 P(MW) | L1 Q(MVar) | L2 P(MW) | L2 Q(MVar) |
|-----------------|----------|------------|----------|------------|
| 2nd Feb., 2017  | 281.98   | -11.86     | 279.67   | -35.11     |
| 3rd Feb., 2017  | 308.99   | -0.07      | 306.16   | -25.74     |
| 29th Jun, 2017  | 160.86   | 16.88      | 161.37   | 3.31       |
| 30th Jun, 2017  | 172.09   | 5.87       | 171.22   | -7.47      |
| 15th Nov., 2017 | 636.89   | 6.80       | 632.32   | -46.47     |
| 16th Nov., 2017 | 546.94   | -36.11     | 538.98   | -80.28     |
| 20th Dec., 2017 | 463.41   | 6.41       | 459.01   | -31.31     |
| 5th Jan., 2018  | 513.48   | 33.98      | 513.09   | -7.87      |
3. Cause Analysis

3.1. Analysis of Accuracy of Acquisition Data

Because the above phenomenon is based on D5000 system data records, in order to check whether this phenomenon is caused by D5000 data anomalies, it is necessary to verify the accuracy of D5000 system data records.

Firstly, it is necessary to verify the acquisition accuracy of voltage transformer (PT) and current transformer (CT) in L1 and L2 power plants. The values of three-phase current, three-phase voltage and PMU (phasor measurement unit, synchronous phasor measurement unit) measured at 8:40:13 on January 5, 2018 are shown in Table 2. The results of Table 2 show that the maximum error rates of the three-phase voltage and current test values of line L1 and L2 meet the technical requirements of the relevant regulations in reference [4].

| A phase voltage (kV) | B phase voltage (kV) | C phase voltage (kV) | Maximum error rate |
|----------------------|----------------------|----------------------|--------------------|
| Test result          | PMU                  | Test result          | PMU                | Test result          | PMU                |                      |
| L1 301.82            | 301.596              | 302.95               | 303.224            | 303.86               | 303.474            | 0.13%               |
| L2 301.66            | 301.495              | 302.58               | 302.808            | 303.98               | 303.428            | 0.18%               |

Next, we need to verify the correctness of D5000 system data display. The D5000 values of active power, reactive power and voltage of L1 and L2 at 8:45 and 8:50 on January 5, 2018 are randomly selected and compared with those of PMU. The results are shown in Table 3. From Table 3, it can be seen that the maximum error rate between the active, reactive and voltage values of L1 and L2 in D5000 and the corresponding values in PMU is only 2.02%. At the same time, PMU data also show that there is reactive circulation phenomenon in L1 and L2.

Based on the above analysis, it can be determined that the acquisition and display of D5000 system are normal, and the L1 and L2 reactive circulation phenomenon does exist.

| A phase current (A) | B phase current (A) | C phase current (A) | Maximum error rate |
|---------------------|---------------------|---------------------|--------------------|
| Test result         | PMU                 | Test result         | PMU                | Test result         | PMU                |                      |
| L1 536.66           | 535.896             | 560.12              | 559.089            | 585.22              | 584.724            | 0.18%               |
| L2 581.02           | 580.452             | 561.09              | 561.531            | 531.63              | 531.013            | 0.12%               |

| Active power (MW)   | L1                  | Reactive power (MVar) | L2                  | Power plant side voltage (kV) |
|---------------------|---------------------|-----------------------|---------------------|-------------------------------|
| D5000               | PMU                 | Error(%)              | D5000               | PMU                          | Error(%) |
| 513.48              | 514.12              | 0.12                  | 33.98               | 34.04                         | 0.17     |
| 518.98              | 518.87              | 0.02                  | 33.39               | 33.2                          | 0.58     |
| 524                 | 524.35              | 0.07                  | 524.21              | 524.19                        | 0.01     |
| 524.21              | 524.51              | 0.06                  | 524                 | 524.03                        | 0.01     |
3.2. Theoretical analysis

Under normal operation mode, L1 and L2 operate in parallel, so the two lines have the same voltage drop. Combining with power flow calculation equation of power system, the expression of reactive power on the two lines can be deduced as follows:

\[ Q_1 = \frac{1}{X_1 + X_2} \left[ QX_1 + P_1 R_1 - P_2 R_1 + \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1) \right] \quad (1) \]

\[ Q_2 = \frac{1}{X_1 + X_2} \left[ QX_2 - P_2 R_2 + P_1 R_1 - \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1) \right] \quad (2) \]

In the formula, \( P_1, P_2, Q_1 \) and \( Q_2 \) are respectively the active and reactive power injected into the first end of L1 and L2 circuits (power plant side); \( Q \) is the total reactive power injected into the boost transformer outlet of A power plant; \( U_1 \) is the 500 kV bus voltage of A power plant; \( R_1, X_1, B_1, R_2, X_2 \) and \( B_2 \) are the positive sequence equivalent impedance and admittance parameters of L1 and L2 circuits (including switch strings and transmission lines).

Formulas (1), (2) show that:

①When \( X_1 = X_2 \), the reactive power of L1 and L2 is equalized, i.e. \( Q_1 = Q_2 \), if:

\[ P_2 R_2 - P_1 R_1 + \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1) = 0 \quad (3) \]

②When \( X_1 \neq X_2 \), the reactive power of L1 and L2 is equalized, i.e. \( Q_1 = Q_2 \), if:

\[ Q = \frac{(P_2 R_2 - P_1 R_1) + U_1^2 (B_1 X_2 - B_1 X_1)}{X_2 - X_1} \quad (4) \]

③Assuming \( P_2 R_2 - P_1 R_1 + \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1) < 0 \), the reactive circulation occurs in line L1 and L2, i.e. the condition of \( Q_1 = Q_2 < 0 \) is

\[ -\frac{(P_2 R_2 - P_1 R_1) + \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1)}{X_2} < Q \left< \frac{(P_2 R_2 - P_1 R_1) + \frac{U_1^2}{2} (B_1 X_2 - B_1 X_1)}{X_1} \right] \quad (5) \]

By inquiring the intelligent dispatching management system, it can be seen that the measured positive sequence impedance and admittance parameters of L1 and L2 circuits are very close to each other (see table 4), which basically satisfies the first case, ignoring the influence of switching circuit. Therefore, the reactive power of the two circuits should be basically balanced, but this is not consistent with the actual situation.

Table 4. Positive sequence measured parameters for line L1 and L2

| Line | \( R(\Omega) \) | \( X(\Omega) \) | \( B(10^{-4}S) \) |
|------|--------------|--------------|----------------|
| L1   | 1.6727       | 16.1985      | 2.5202         |
| L2   | 1.6553       | 16.2276      | 2.5208         |

By inquiring D5000 and PMU data, it can be seen that the three-phase voltages of L1 and L2 are symmetrical. According to electrical theory, under the premise of symmetrical three-phase voltages of the first and the end of parallel transmission lines, the cause of power imbalance is caused by the asymmetry of parameters between parallel lines [5].

3.3. Asymmetric Analysis of Line L1 and L2 Parameters

Considering that line L1 and L2 are parallel lines on the same pole, with a length of 58.08km, the possible reasons for the asymmetric of their parameters are analyzed as follows:

① In the steady-state analysis of power system, when measuring power frequency parameters of parallel lines erected on the same tower, the traditional measurement methods are usually based on the
The premise of symmetry of three-phase parameters of lines, usually using the lumped parameter model, ignoring the influence of mutual inductance flux between lines and between circuits [6]. Especially for short and medium-length parallel lines with the same tower (less than 100 km), affected by the specific erection methods (phase sequence arrangement and conductor transposition, etc.), there are often asymmetrical line parameters caused by the different magnitudes of mutual inductance flux between lines and between circuits [7]. In this case, the distributed parameter model is needed to calculate in order to obtain more accurate results.

(2) Ideally, the impedance of the series of switches connected to the line is usually neglected. In some special cases, the asymmetric impedance of switches, knife gates, CT and lead wires in the switching string where the two loops are located may also lead to the asymmetric impedance parameters of the two loops, such as the asymmetric arrangement of the primary wiring in the station, the different types of connected devices in the two loops such as circuit breakers or disconnecting switches, and the incomplete contact between the static and dynamic contacts of the switches due to the defects of the devices [8]-[9].

In order to find out the specific reasons for the asymmetry of L1 and L2 parameters, the operation and maintenance personnel of the power plant inspected and infrared detected the contacts between dynamic and static contacts of all circuit breakers and disconnecting switches in L1 and L2 circuits. The results showed that there was no abnormality.

By inquiring the voltage, current amplitude and phase angle curves of L1 and L2 in PMU, it is found that there are serious unbalances in the amplitude and phase angle of the three-phase current of the two lines: (1) the amplitude of line L1 increases gradually according to a-b-c phase sequence current, while the amplitude of line L2 decreases gradually according to a-b-c phase sequence current; (2) the B phase current of the two lines is basically equal; The amplitude of the A phase current of line L1 is basically equal to that of the C phase current of line L2; The C phase current of line L1 and the A phase current of line L2 are basically equal in amplitude; (3)The voltage of the two lines is three-phase symmetry. Based on the above analysis, it can be inferred that when two lines are erected, A and C phases are arranged in reverse order, which results in the asymmetry of the parameters of the two lines, while the measured parameters adopted in D5000 neglect the asymmetry caused by the influence of magnetic flux coupling between the loops and obtain approximate symmetry parameters.

4. Simulation Demonstration

In order to further demonstrate the correctness of the above inference, a detailed modeling and power flow simulation of L1 and L2 based on PSCAD software is carried out to realize the simulation reappearance of the reactive power unbalance between the two lines.

4.1. System Simulation Wiring Diagram

Figure 2 shows a simplified simulation model for the delivery system of A power plant. The equivalent parameters are set as follows:

- Equivalent power supply: Rated voltage $U_N=525kV$. Positive sequence impedance $Z_{r1}=Z_{r2}=72.56 \angle 89.9^\circ$; zero sequence impedance $Z_{o0}=31.158 \angle 89.99^\circ$; Load: $P_L=1090MW$; $Q_L=152Mvar$.

4.2. Transmission Line Model

L1 and L2 are double-circuit transmission lines on the same tower. In order to take into account the influence of mutual inductance between phases and loops on the degree of parameter asymmetry, it is
necessary to establish a distributed parameter model of transmission lines. So Frequency Dependent (Phase) model in PSCAD software is chosen to simulate.

The design data show that the L1 and L2 double-circuit lines are erected on the same tower with a total length of 58.08 km, the conductor type is 4*JL/G1A-400/35, and the conductors are arranged in different phases (BAC/bca) without transposition. The main towers used in the line erection are double-circuit straight towers, and the relevant parameters are shown in Figure 3. The corresponding lengths of pole towers (a) and (b) account for half of the total length of the line.

Taking the power flow of the outgoing system of A power plant at 08:53 on January 10, 2018 as an example (as shown in Figure 4), the accuracy of the simulation results is verified. The specific simulation model and results are shown in Figure 5. From Figure 5, it can be seen that under the BCA/bac phase sequence arrangement of L1 and L2 conductors and the non-transposition mode of the whole line, the active power of the two lines is basically balanced, and the reactive power unbalance is relatively high. The simulation results are basically consistent with the actual results of Figure 4 (see Table 5 for details).

Figure 3. Tower model of transmission line for L1 and L2
Figure 4. Power flow diagram of output system of A power plant

Figure 5. Reactive power simulation of Line L1 and L2

| Line  | P(MW)  | Q(Mvar) | U(kV)  |
|-------|--------|---------|--------|
| L1    | 595    | 57.2    | 525.2  |
|       | Actual value | 595 | 57 | 525.2 |
| L2    | 597.1  | 8.2     | 525.2  |
|       | Actual value | 594 | 8  | 525.2 |
5. Measurement Research

Based on the analysis of the above reasons, it can be seen that in order to improve the reactive power unbalance between parallel coupled transmission lines, it is necessary to improve the asymmetry of transmission line parameters. Although there are many factors affecting the parametric asymmetry of parallel coupled transmission lines, previous studies have shown that conductor arrangement and transposition have the most significant impact on the parametric asymmetry [10].

5.1. Impact Analysis of Phase Sequence Arrangement

Because of the complex electromagnetic and electrostatic coupling effect between conductors, there exists not only a traversing unbalanced current under different phase sequence arrangement, but also a larger circulating unbalanced current under other arrangement modes besides in-phase sequence arrangement [10] - [12].

The simulation results of L1 and L2 double-circuit power flow under seven different phase sequence arrangement without conductor transposition are shown in the table below.

Table 6 Power flow simulation of L1 and L2 double circuit lines with different phase sequence arrangements

| Phase sequence    | P(MW)     | Q(Mvar)   | Reactive power unbalance |
|-------------------|-----------|-----------|--------------------------|
| ABC/abc (same)    | 596/596   | 34.2/34.2 | 0.0%                     |
| ABC/cba (inverse) | 600.5/599.6 | 29.6/28.3 | 2.2%                     |
| ABC/acb (different 1) | 593.5/602.4 | 56.4/8.8 | 73.0%                    |
| ABC/cab (different 2) | 596.5/602.6 | 51.4/8.5 | 71.6%                    |
| ABC/bac (different 3) | 595.7/598.6 | 7.0/58.1 | 78.5%                    |
| ABC/bca (different 4) | 593.5/602.4 | 56.4/8.8 | 73.0%                    |
| BAC/bca (practical) | 597.1/595 | 57.2/8.2 | 74.9%                    |

Note: “/” represents L1 and L2 before and after respectively; “Reactive power unbalance” refers to the ratio of absolute value of D-value between reactive power of one loop and half of the sum of reactive power of two lines to half of the sum of reactive power of two lines, expressed in percentage.

From the results of Table 6, it can be seen that the order of reactive power unbalance of L1 and L2 double-circuit lines from small to large is: in-phase sequence < reverse sequence < different phase sequence 2 = different phase sequence 1 = different phase sequence 4 < practical phase sequence < different phase sequence 3. The reactive power unbalance of L1 and L2 is as high as 74.9% in the practical phase sequence. If the same or reverse phase sequence is used, the reactive power unbalance of L1 and L2 double-circuit lines will be significantly improved.

5.2. Impact Analysis of Conductor Transposition

For high-voltage parallel AC transmission lines on the same tower, if the length is long, conductor transposition is often used in engineering to reduce the unbalance between lines and circuits. It is stipulated in our country that all the lines with the length of EHV transmission lines exceeding 100 km should be transposed[13]. Incomplete transposition or even non-transposition lines may aggravate the unbalanced current problem of high-voltage double-circuit transmission lines [14]. For short distance (less than 100 km) lines on the same tower, unbalanced phenomena caused by no transposition during erection are common.

In order to analyze the influence of conductor transposition on the reactive power balance of L1 and L2, based on BAC/bac phase sequence, four modes of conductor transposition are adopted as shown in Figure 6(a)–(d):

Case 1: The whole line is transposed only once, and it is still in different phase sequence after transposition.

Case 2: The whole line is transposed only once, and it is still in-phase sequence after transposition.
Case 3: The whole line is transposed only once, and it is still reverse phase sequence after transposition.

Case 4: The whole line is transposed twice, and the transposition is in-phase sequence.

The simulation results of the four modes are shown in Table 7. From the results of Table 7, it can be seen that the reactive power unbalance of L1 and L2 can be significantly improved by transposition of mode 2 and mode 4.

![Diagram showing transposition modes for L1 and L2](image)

**Figure 6.** Transposition mode of conductors for L1 and L2

| Transposition mode | L1-Q (Mvar) | L2-Q (Mvar) | Reactive power unbalance |
|--------------------|-------------|-------------|-------------------------|
| Non transposition  | 57.2        | 8.2         | 74.9%                   |
| Case 1             | 4.9         | 58.2        | 84.5%                   |
| Case 2             | 35.6        | 33.1        | 3.6%                    |
| Case 3             | 30.4        | 22.7        | 14.5%                   |
| Case 4             | 36.8        | 36.8        | 0.0%                    |

6. Conclusions and Suggestions

6.1. CONCLUSIONS

Through on-site investigation, mechanism analysis and simulation, the following conclusions are drawn:

1) The fundamental reason for the unbalanced reactive power of L1 and L2 transmission lines in A power plant is that the two transmission lines are arranged in unconventional phase sequence while erecting on the same tower, but the parameters are not symmetrical due to the unreasonable transposition.
2) The phase sequence arrangement has a great influence on the reactive power balance of parallel coupled lines. The reactive power imbalance of L1 and L2 double-circuit lines can be reduced from 74.9% to 2.2% and 0% respectively by using in-phase or reverse-phase sequence arrangement of conductors.

3) Reasonable transposition of conductors can also effectively improve the parametric asymmetry of parallel coupling lines. If mode 3 and mode 4 in Table 6 are used to transpose L1 and L2 lines, the reactive power imbalance of the two lines can be reduced from 74.9% to 3.6% and 0%.

4) Considering the economy and feasibility, it is recommended to adopt the measures of optimizing the phase sequence of conductors to solve the problem of reactive power imbalance in L1 and L2 double-circuit.

6.2. SUGGESTIONS
For new or reconstructed parallel transmission lines on the same tower in the future, especially for medium and short distance lines, it is suggested that the unbalance degree of transmission lines should be studied from the aspects of phase sequence arrangement, transposition and transposition mode at the design stage in order to avoid later transformation.

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