Research on Extinction of Secondary Arc in UHV Double-circuit Transmission Lines

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Abstract

The UHV transmission lines will produce recovery voltage and arc current when single-phase ground fault occurs, and the high arc current and the recovery voltage will impact the reliability of single-phase reclosing. The EHV and UHV lines often adopt the method of a shunt reactor with the neutral reactor to limit the arc current and the recovery voltage in our country. This article analyzes from the circuit of double lines, and the expressions of neutral reactors are derived , which provide a basis for an engineering calculation. Then we use the ATP-EMTP to establish a double-circuit line model, so we can find that the value of a neutral reactor impacts on the arc current and the recovery voltage; and we can also get the transposition modes impacting on it, and then a right reactor value is recommended.

Keywords: UHV, arc current, neutral reactor, double- circuit

1. Introduction

In order to improve the stability and reliability of a power supply system, single-phase reclosing is widely used in 220kV and the above power system in our country. Research shows that whether it will success depends on the value of arc current and amplitude of recovery voltage and the size of the rising speed[1-2]. The coupling phenomenon of double-circuit lines on the same tower are more serious, then the value of arc current and recovery voltage will increase, and also it is difficult to extinguish a secondary arc. Its principle is to assign a high voltage neutral reactor to inter-phase through a neutral reactor to compensate a capacitive component of arc current by the inter-phase capacitance flowing to the fault phase. The capacitive component of arc current will greatly be reduced by a reasonable neutral reactor , and at the same time it can be limited to a very low level of recovery voltage[3-5].

The measures to limit an arc current are a shunt reactor with a neutral reactor and high speed grounding switch(HSGS). The EHV and UHV lines often adopt the method of a shunt reactor with a neutral reactor to limit the arc current and the recovery voltage in our country[6]. The shunt reactor with neutral reactors can be divided into single and double circuit compensations in two ways. The single-circuit compensation can effectively reduce the arc current and the recovery voltage in single-phase ground fault, but it can not reduce the arc current and recovery voltage among the lines fault. Double-circuit compensation can effectively reduce the arc current and recovery voltage in single-phase ground fault and inter-lines fault. However, since the double-circuit lines maintain electrical contacts, a single-circuit line during a normal operation is not conducive to the return line for another overhaul. For the way of a shunt reactor with a neutral reactor, it only applies to fully transposed lines. For the short line of no transposition, this method is not applicable. HSGS is still applied at short line maintenance and line transposition, but its function decreases in different locations that limit the arc current and the recovery voltage [7-10].

Reference[11]gives the expression of a neutral reactor in single-circuit line. According to the circuit transformation in reference [12], the calculation formula of a neutral reactor is derived in double-circuit lines. Reference [13] adopts six sequence component methods in double-circuit lines, which calculate the expressions of a neutral reactor in different compensation modes. This paper are based on reference [14], which obtain the sequence component by decoupling the admittance matrix value, then calculate the expression of a neutral reactor, and provide the basis for the selection of a neutral reactor on double-circuit lines.

In this article, we calculate the expressions of neutral reactor at first, and then we use the simulation software ATP-EMTP to establish a double-circuit line model, we can find that neutral reactor values impact on the arc current and the recovery voltage, and a right reactor value is recommended. So far, there are less research on UHV double-circuit lines.

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2. The Principle of the Secondary Arc

Secondary arc is a long arc moving downstream in atmospheric conditions; it usually produces in the long line of single-phase arc ground fault. When a single-phase ground fault occurs among the three-phase lines, after the breaker in fault phase ends jump, the other two phases continue to operate normally, and maintain fault voltage to the normal phases. At this time, the non-fault phase and disconnect exist by static action (via capacitance) and electromagnetic (through mutual inductance), although the short-circuit current has been cut off, and some constant current is still flowing in the fault arc, which is called arc current. Because of the arc current, arc sustain combustion, which produce a secondary arc [15]. The mechanism is shown in Figure 1 (C phase fault):

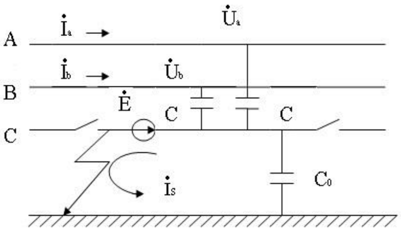


Figure 1: The mechanism of secondary arc

The dynamic physical process of a secondary arc is closely related to many factors, epitomizing two categories, which are uncertainty and non-deterministic factors: certainties include line length, voltage level, shunt reactors, location and degree of compensation (or fast grounding switch), and the tower structure; Uncertainties factors include fault locations, sizes of short-circuit current and duration, wind speed and direction, and the arc recovery voltage. Its presence leads to a single-phase auto-reclosing coincidence in ground fault conditions, which bring a disturbance to the system three times, exacerbate the oscillation, and affect system security and stability, which is seriously harmful to power transmission equipment[16].

3. The Calculation of Neutral Reactor in Single-Circuit Line

Secondary arc current includes capacitive component and inductive component, and the capacitive component dominates. We often adopt the method of a shunt reactor with a neutral reactor to limit the arc current in our country, as shown in Figure2 (a), where X_{lp} express high voltage neutral reactor, $X_{\ln}$ express neutral reactor. High voltage neutral reactor was assigned to the phase and phase to ground, as shown in Figure 2(b), where X_{lm} is equal to inter-phase reactor, X_{ld} is equal to relatively ground reactance. The value of a neutral reactor meets a full compensation between phases, through a simple circuit transformation, and you can get.

$$X_{\mathrm{lm}} = 3X_{\ln} + X_{lp} \tag{1}$$

$$X_{ld} = \frac{X_{lp}^{2}}{X_{\ln}} + 3X_{lp} \tag{2}$$

$$X_{\ln} = \frac{X_{lp}^{2}}{X_{ld} - 3X_{lp}} \tag{3}$$

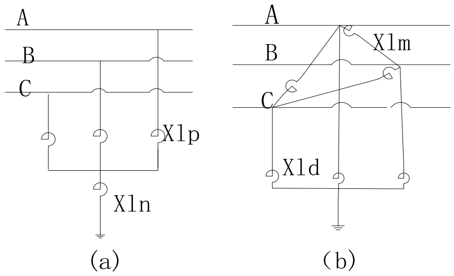


Figure 2: The schematic of shunt reactor with neutral reactor

4. The Calculation of Neutral Reactor in Double-Circuit Lines

For the double-circuit UHV transmission line in the same tower, the traditional wiring mode is shown in Figure 3 (a), due to the existence of serious electromagnetism coupling, you cannot well compensate a capacitor component. Some scholars put forward the wiring mode of [17] Figure 3(b). In this paper, a neutral reactor is calculated under the mode of connection in Figure 3(b):

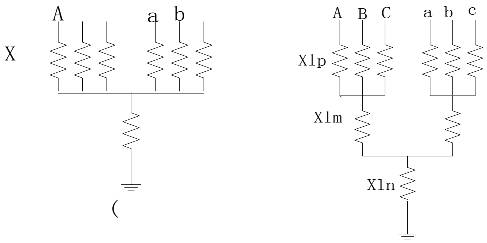


Figure 3: The schematic of shunt reactor with neutral reactor in double-circuit line

The capacitance of inter phase, circuits and the ground in double-circuit lines on the same tower are shown as Figure 4. Compared with the single-circuit operation mode, the circuit coupling capacitor will also provide a secondary arc current to the point of fault phase in the double-circuit line.

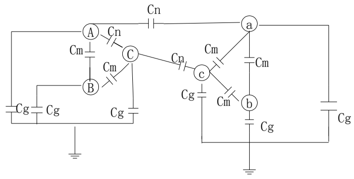


Figure 4: Running of double-circuit

In Figure 4, the ground capacitance is C_g, the inter-phase capacitance is C_m, and the capacitance between the circuit is Cn; We set up self-admittance Ys, inter-phase mutual admittance Ym, and mutual admittance between the circuits Y_m', so self-admittance is $Y_s=\omega C_g-2Y_m-3Y_m'$. We can get from the admittance matrix:

$$\begin{bmatrix} I_{IA} \\ I_{IB} \\ I_{IC} \\ I_{IIA} \\ I_{IIB} \\ I_{IIC} \end{bmatrix} = \begin{bmatrix} Y_s & Y_m & Y_m & Y_m' & Y_m' & Y_m' \\ Y_m & Y_s & Y_m & Y_m' & Y_m' & Y_m' \\ Y_m & Y_m & Y_s & Y_m' & Y_m' & Y_m' \\ Y_m' & Y_m' & Y_m' & Y_s & Y_m & Y_m \\ Y_m' & Y_m' & Y_m' & Y_m & Y_s & Y_m \\ Y_m' & Y_m' & Y_m' & Y_m & Y_m & Y_s \end{bmatrix} \begin{bmatrix} U_{IA} \\ U_{IB} \\ U_{IC} \\ U_{IIA} \\ U_{IIB} \\ U_{IIC} \end{bmatrix} \tag{4}$$

We can see that the admittance matrix is a diagonal matrix. Decoupling between lines at first [14], then decoupling between circuits, we suppose that the transformation matrix is [P] as follows:.

$$\left[P\right]=\begin{bmatrix} 1 & 0 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & -1 & 0 & 0 \\ 0 & 1 & 0 & 0 & -1 & 0 \\ 0 & 0 & 1 & 0 & 0 & -1 \end{bmatrix} \tag{5}$$

We can see from the Equation (4) that the top right and bottom left of admittance matrix are all the same, so we decouple it into six-phase voltage and current; after decoupling between the lines Equation (4) becomes

$$\begin{bmatrix} I_{TA} \\ I_{TB} \\ I_{TC} \\ I_{FA} \\ I_{FB} \\ I_{FC} \end{bmatrix} = \begin{bmatrix} Y_s+Y_m' & Y_m+Y_m' & Y_m+Y_m' & 0 & 0 & 0 \\ Y_m+Y_m' & Y_s+Y_m' & Y_m+Y_m' & 0 & 0 & 0 \\ Y_m+Y_m' & Y_m+Y_m' & Y_s+Y_m' & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_s-Y_m' & Y_m-Y_m' & Y_m-Y_m' \\ 0 & 0 & 0 & Y_m-Y_m' & Y_s-Y_m' & Y_m-Y_m' \\ 0 & 0 & 0 & Y_m-Y_m' & Y_m-Y_m' & Y_s-Y_m' \end{bmatrix} \begin{bmatrix} U_{TA} \\ U_{TB} \\ U_{TC} \\ U_{FA} \\ U_{FB} \\ U_{FC} \end{bmatrix} \tag{6}$$

And then we decompose the circuits with the traditional sense of symmetrical components:

$$\begin{bmatrix} I_{I0} \\ I_{II0} \\ I_{I1} \\ I_{II1} \\ I_{I2} \\ I_{II2} \end{bmatrix} = \begin{bmatrix} Y_{I0} & 0 & 0 & 0 & 0 & 0 \\ 0 & Y_{I1} & 0 & 0 & 0 & 0 \\ 0 & 0 & Y_{I2} & 0 & 0 & 0 \\ 0 & 0 & 0 & Y_{II0} & 0 & 0 \\ 0 & 0 & 0 & 0 & Y_{II1} & 0 \\ 0 & 0 & 0 & 0 & 0 & Y_{II2} \end{bmatrix} \begin{bmatrix} U_{I0} \\ U_{II0} \\ U_{I1} \\ U_{II1} \\ U_{I2} \\ U_{II2} \end{bmatrix} \tag{7}$$

$$\left[M\right]=\begin{bmatrix} 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & a^2 & a^2 & a & a \\ 1 & 1 & a & a & a^2 & a^2 \\ 1 & -1 & 1 & -1 & 1 & -1 \\ 1 & -1 & a^2 & -a^2 & a & -a \\ 1 & -1 & a & -a & a^2 & -a^2 \end{bmatrix} \tag{8}$$

The sequence component value of admittance matrix in Equation (7) is eigen-values of admittance matrix in (6), we suppose the admittance matrix in (6) is A, Ys=a, Ym'=b,Ym=c ; we let $|A-\lambda E|=$

$$\begin{vmatrix} a+b-\lambda & b+c & b+c & 0 & 0 & 0 \\ b+c & a+b-\lambda & b+c & 0 & 0 & 0 \\ b+c & b+c & a+b-\lambda & 0 & 0 & 0 \\ 0 & 0 & 0 & a-b-\lambda & c-b & c-b \\ 0 & 0 & 0 & c-b & a-b-\lambda & c-b \\ 0 & 0 & 0 & c-b & c-b & a-b-\lambda \end{vmatrix}$$

$$= (a+3b+2c-\lambda)(a-3b+2c-\lambda)(a-c-\lambda)^4$$
=0

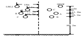
We can get: $\lambda 1 = a+3b+2c$，

$$\lambda 2 = a-3b+2c$$

$$\lambda 3 = \lambda 4 = \lambda 5 = \lambda 6 = a-c \text{；}$$

That is: $\lambda_1 = \lambda_3 + 3(b+c)$，

$\lambda_2 = \lambda_3 + 3(c-b)$；

Ignoring the conductance of wire, then  ; We suppose the positive sequence of compensation: $k = {B_{l1}}/{B_{c1}}$，Positive sequence susceptance

$$B_{l1} = kB_{c1} = k\lambda_3 = k[B_{cg} + 3(B_{cm} + B_{cn})]$$

Zero-sequence of circuit I：

$$B_{l1} = kB_{c1} = k\lambda_3 = k[B_{cg} + 3(B_{cm} + B_{cn})]$$

Zero-sequence of circuit II ：

$$B_{l3} = \lambda_3 + 3(\mathrm{c}-\mathrm{b}) = B_{l1} + 3(B_{cm} - B_{cn})$$

According to the method of six sequence components [18],zero-sequence of circuit I and circuit II susceptance can be shown as：

$$X_{lo} = X_{lp} + 3X_{lm} + 6X_{\mathrm{ln}}, X_{l1} = X_{lp}, X_{l3} = X_{lp} + 3X_{lm}.$$

Because

$$X_{l0} = \frac{1}{B_{l0}}，X_{l1} = \frac{1}{B_{l1}}，X_{l3} = \frac{1}{B_{l3}}，$$

we can draw the expressions of a high voltage neutral reactor and a neutral reactor：

$$X_{lp} = \frac{1}{k(B_{Cg} + 3B_{Cm} + 3B_{Cn})} \tag{9}$$

$$X_{lm} = \frac{Xlp}{{1}/{[X_{lp}(B_{cm} - B_{cn}})] - 3} \tag{10}$$

$$X_{\mathrm{ln}} = \frac{Bcn}{\left[{1}/{X_{lp}} - 3(B_{cm} + B_{cn})\right]\left[{1}/{X_{lp}} - 3(B_{cm} - B_{cn})\right]} \tag{11}$$

5. Impact on the Arc Current and the Recovery Voltage to Reactor Values

Taking a double-circuit on the same tower UHV lines as an example. The voltage of the line is 1000kV, the maximum operating voltage is 1100kV, and the total length of line is 320km. The first and last lines install a group of 720MVA of shunt reactors. The simplified system diagram is shown in Figure 5. Equivalent parameters are as following.

At the sending end, $Z_{k1} = Z_{k2} = 0.38 + j30.04\Omega$, $Z_{k0} = 0.17 + j10.07\Omega$; at the receiving end $Z_{s1} = Z_{s2} = 1.89 + j150.18\Omega, Z_{s0} = 0.84 + j50.35\Omega$. The compensation of the high resistance is 80%, and the three sections of transposition method are adopted. The ground and wire arrangement are shown in Figure 6.

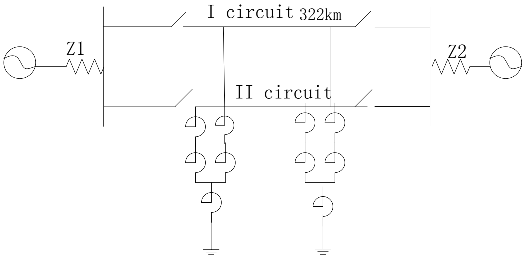


Figure 5: Simplified diagram of the system

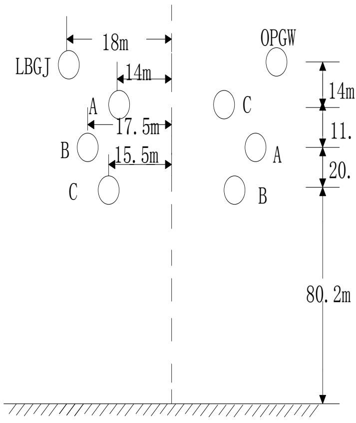
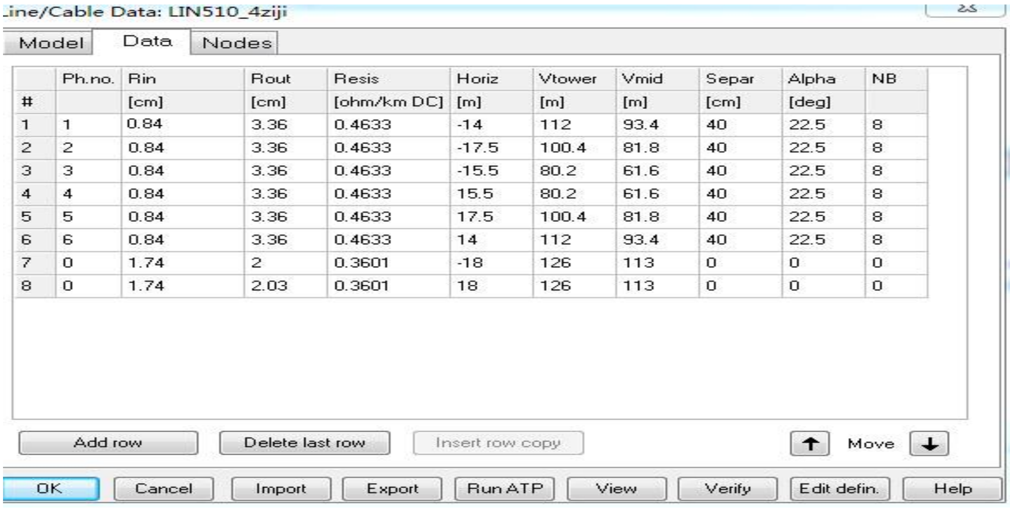


Figure 6: Ground and wire arrangement

There are many line models in ATP-EMTP, such as lumped, distributed, and LCC model. In this paper, the length of line is 320km. Therefore, we use the LCC model. Taking the line transposition into account, Jmarti model is more accurate, so we use Jmarti model. In this model, data are given by filling cards, and data cards are shown as Figure 7. The ATP-EMTP model are shown as Figure 8.

After importing the data cards, we click the line check (which is very useful for calculation) , and then we can get the parameters of the line. The ground capacitance is 0.0065μF/km and the interphase capacitance is 0.00171μF/km, The capacitance between the circuit is 0.001258μF/km. And then you put it in Eqs (9), (10), (11), you can calculate the values of X_{lp} , X_{lm} , X_{ln} ,which are 1615Ω,160Ω,920Ω respectively.



	Ph.no.	Rin	Rout	Resis	Horiz	Vtower	Vmid	Separ	Alpha	NB
#		[cm]	[cm]	[ohm/km DC]	[m]	[m]	[m]	[cm]	[deg]	
1	1	0.84	3.36	0.4633	-14	112	93.4	40	22.5	8
2	2	0.84	3.36	0.4633	-17.5	100.4	81.8	40	22.5	8
3	3	0.84	3.36	0.4633	-15.5	80.2	61.6	40	22.5	8
4	4	0.84	3.36	0.4633	15.5	80.2	61.6	40	22.5	8
5	5	0.84	3.36	0.4633	17.5	100.4	81.8	40	22.5	8
6	6	0.84	3.36	0.4633	14	112	93.4	40	22.5	8
7	0	1.74	2	0.3601	-18	126	113	0	0	0
8	0	1.74	2.03	0.3601	18	126	113	0	0	0

Figure 7: data cards

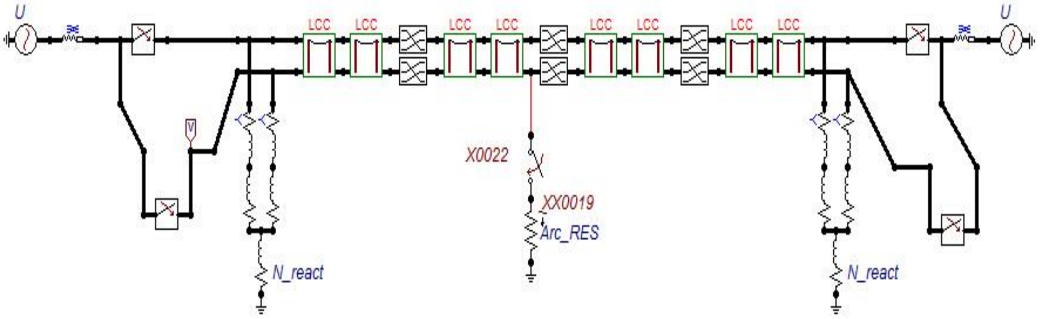


Figure 8: ATP-EMTP model

In this model, we can import the line parameter in the data cards, and the shunt reactor and neutral reactor are what we calculate above; and then we suppose that a single-phase ground fault occurs at 0.0178s, both sides of the circuit breaker trip at 0.13s, and simulations end at 0.5s. And we assumed that the fault occurs in the middle of the line, and the wave of arc current and recovery voltage in different reactor are shown in Figure 9.

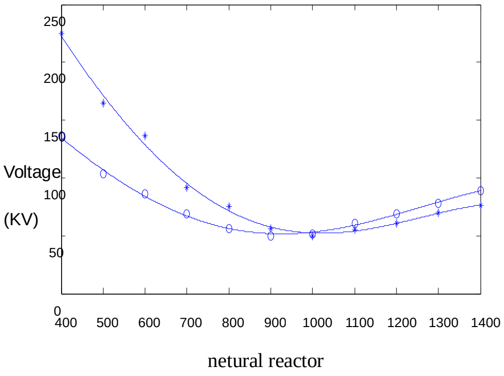


Figure 9:(a) Relationship of neutral reactor recovery voltage

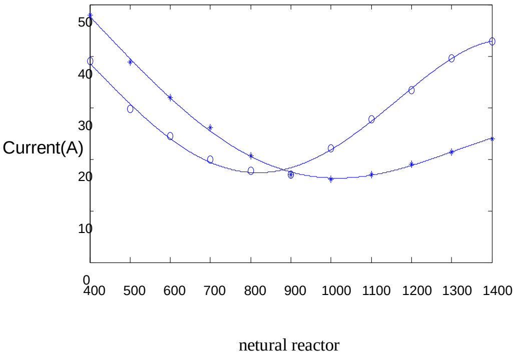


Figure 9 (b): Relationship of neutral reactor and arc current

Figure 9 is the relationship of neutral reactors with arc current and recovery voltage; we take the operating modes into account, and the operating modes of the line are single-circuit line and double-circuit line. In this figure * stands for a double-circuit operating mode, o stands for a single -circuit operating mode. Seen from Figure 9, the recovery voltage and arc current are limited within the required range (we can use the expression of arc current and the time of reclosing). Arc Current should be limited to less than 20A, and neutral reactor values can be chosen within 880Ω-950Ω, so the calculated 920Ω is more reasonable.

The transposition modes of double-circuit lines have greater impact on arc current. The line of complete transposition and the length of each phase are equal in each position; a complete transposition of the line is called a complete cycle. According to the literature [19], the arc current of reverse transposition is relatively small; therefore, this paper considers only the reverse transposition. Figure 10 (a) is the round robin transposition (three-stage transposition); Figure 10 (b) is the transposition of the double loop; Figure 10 (c) is three cycles transposition.

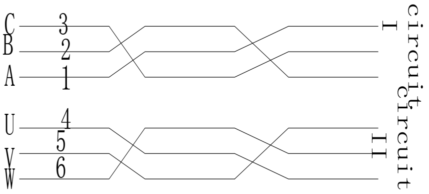


Figure 10(a): Reverse-cycle transposition

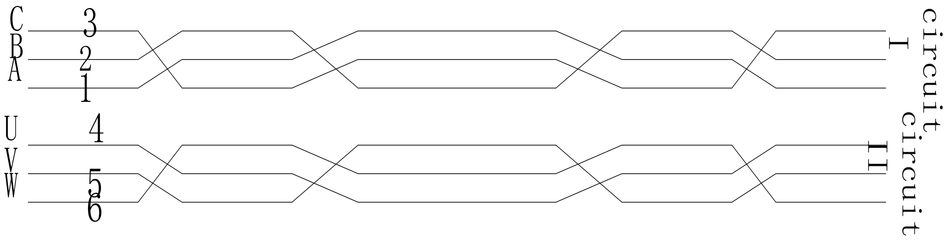


Figure 10(b): Double-loop and reverse transposition

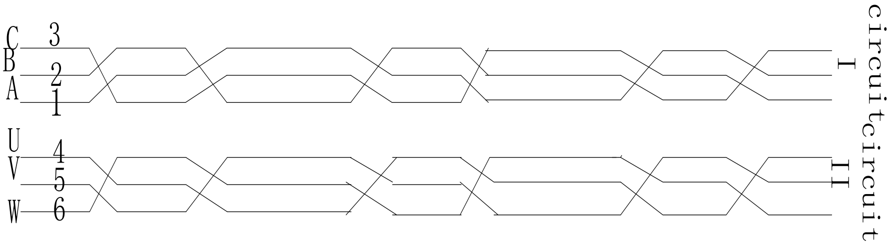


Figure 10(c): Tribal circulation and reverse transposition

Neutral reactor is adopted 920Ω, the three cycles were simulated and calculated, the arc current and recovery voltage are shown as in Table 1:

Table 1: The Arc Current and Recovery Voltage in different transpositions

Transposition modes	arc current	recovery voltage
Reverse-cycle transposition	25.4(A)	118.3(A)
Double-loop transposition	15.8(A)	73.1(A)
Trible transposition	12.1(A)	52.8(A)

We can see from Table 1, when using single-cycle mode transposition, arc current is 25.4A, and it can be slowly reclosed, which increases the outage time; When using double-loop transposition, arc current is 15.8(A), and it can be quickly reclosed; When using triple transposition, arc current is 12.1(A), and it can be quickly reclosed, but it needs six towers, which greatly increase the investment[20]. From the above, a double-loop transposition is more reasonable.

6. Conclusions

This paper calculates the expression of a neutral reactor in different ways on double-circuit lines, and verifies rationality by simulation calculations. The results shows that arc current and recovery voltage values are quite different in different operation modes, which then produce a great effect on the value of the neutral reactor; the reactor value needs to be considered when selecting an operating mode. And the transposition modes are also important for limiting the arc current.

References

[1]. Wang Hao, Li Yongli, Li Bin. Secondary arc extinction methods for 750kV and UHV Transmission lines[J]. Electric Power,2005, 38(12): 29-32.

[2]. Moustafa Mohammed Eissa, Malik O P.A Novel Approach for Auto Reclosing EHV/UHV Transmission Lines[J]. IEEE Trans on Power Delivery, 2000, 15(3)

[3]. Yi Qiang, Zhou Hao, Ji Rongrong, etc. The limit of arc current and recovery voltage in the same Tower and double circuit UHV[J]. Automation of Electric Power System, 2011, 35(10): 83-88.

[4]. Liu Hongshun, Li Qingmin, ZouLiang, et al.Secondary arc characteristics and single-phase auto-reclosure scheme of EHV transmission line with fault current limiter [J]. Proceedings of the CSEE, 2008, 28(31): 62-67 (in Chinese).

[5]. Wang Xiaotong, Lin Jiming, Ban Liangeng, et al. Analysis on unbalance factor and transposing modes for 1000kV double-circuit transmission lines on the same tower[J]. Power System Technology, 2009, 33(5):1-5(in Chinese).

[6]. Niu Tao, Xie Jianzhen, Qian Kang, et al. Analysis on Factors Impacting Secondary Arc Current in 1000kV Transmission Line From Xuzhou to Nanjing and Optimized Calculation of Grounding Reactor. Electric Power 908-912.

[7]. Zhang Xu. Extinguishing measures in UHV parallel lines [D]. Bei Jing: North China Electric Power University, 2012.

[8]. Yi Qiang, Zhou Hao, JiRongrong, etc. Upper Limit of Compensation Degree Of High Voltage Shunt Reactor for UHV AC Transmission Lines[J]. (Power System Technology, 2011, 35（7）:6-18 ·

[9]. Li Zhenqiang, Dai Min, Lou Ying, et al. Effect of UHV ground wire disposition on its electric energy loss and secondary arc current [J]. Power System Technology, 2010, 34(2):24-28 (in Chinese).

[10]. Mei Zhongshu. Secondary arc current and single-phase reclosing on UHV transmission lines[J].Yunnan Electric Power, 1999, 27(3):15-18(in Chinese)．

[11]. Li Zhaoxiong, Wen Jun, Miao Wenjing, et al. Calculation analysis of secondary arc current on UHV transmission lines[J]. Modern Electric Power, 2010, 27(1): 6-11(in Chinese)．

[12]. Shang Liqun, SHI Wei. Study of the secondary arc extinction at EHV double circuit transmission lines [J]. Automation of Electric Power System, 2005, 2（10）:60-63.

[13]. Liu Haijun, Han Minxiao, Wen Jun. The Optimal design of Shunt reactors and neutral reactor in UHV double-circuit line[J]. Electric Power Automation Equipment, 2009, 29(11）:87-91.

[14]. Fan Chunju, Shu Qiaojun. Application of Sequence Component Method in Power System[J]. Journal of EEE, 2010, 32(5):32-36．

[15]. Danyek M, Danyek P. Improving the reliability of experimental data about secondary arc duration [C]//Proceeding of the 17th Hungarian-Korean Seminar, EHV Technology-II. Keszthely-Lake Balaton, Hungary: Budapest University of Technology and Economics, 2001:32-40．

[16]. Salehi V, Jeffery M, Lesani H, et al. Single Phase Tripping and Auto Re-closing of Transmission Lines [C]// Industrial Technology, ICIT 2009. IEEE International Conference on 10-13 Feb. 2009:1-7.

[17]. Edward W Kimbark. Selective-Pole Switching of Long Double-Circle EHV Line[J]. IEEE Trans,1976,1(95): 219-230.

[18]. Wang Xiaotong, Lin Jiming, Ban factor and transposing modes for 1000kV doublecircuit transmission lines on the same tower [J].Power System Technology, 2009, 33(5):1-5.

[19]. KIMBARKEW. Selective-pole switching of long double－circle EHV line[J].IEEE Transactions on Power Apparatus and Liangeng, et al. Analysis on unbalanceSystems, 1976, 95（1）:219-230.

[20]. Shi Wei. Over-voltage power systemcalculation[M]. Higher Education Press,2006:45-46.

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