Study on induction voltage of multi loop cable with laying area

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Abstract. In order to reduce the induced voltage of the metal sheath of high voltage single core cable and reduce the excavation area, so as to increase the transmission efficiency and reduce the cost of the project, this paper studies the induced voltage of the cable line under the condition of the laying area. By calculating the influence of any adjacent three phase in double loop and multi loop cable, the influence of the multi loop cable is explored, and a double loop model is established according to the law. Then, the simulation results of electromagnetic transient simulation software ATP-EMTP are compared with the existing double circuit arrangement method, and the accuracy and feasibility of this method is verified. Therefore, it is suggested that the increase of the land use rate and the two aspects of the induction voltage of the cable metal sheath should be considered when the laying of the multi loop cable.

1. Introduction

With the rapid development of cities and rapid increase in demand for electricity, at present, most of the city cable lines use multi circuit laying method, so that the induced voltage on the cable mental is also increased. The conductor current is not only distribute heat in course of the cable line, but also because the electromagnetic coupling effect on the adjacent conductor result induced voltage[1,3]. When high voltage single core cable working current is large and the cable line is long, but there is no limiting voltage measures on metal sheath , the induced voltage on it may reach tens to hundreds of volts, even more[4,6].

In the paper[7] have numerical simulation analysis it by using finite element simulation, then the influence of the metal sheath volume conductivity and relative magnetic permeability on the induced voltage is obtained. A method to balance the voltage of the protective layer by add compensation device on cable termination (in fact is compensation inductor) is presented in the paper[8] , theoretical analysis can achieve the effect of reducing the induced voltage. But paper[7,8], none of them have research on optimized cable layout. In paper[9] ,use formula calculation method and vector method, analyzing the multi circuit high voltage cable line change layout method have influence on cable metal sheath induced voltage, so that sequence of different combinations has significant effect on the induced voltage, however, it is only for the horizontal layout of the research, the layout scheme and the cross section area of cable laying channel are not put forward.

Theoretical analysis shows that reasonable optimization of the arrangement of multi circuit cable line can reduce the induced voltage of the metal sheath of high voltage cable. The article analyze the influence factors of electromagnetic induction, at the same time, take into account the land occupation area of cable laying, it aims to both reduce the induced voltage and increase the land use efficiency of multi circuit cable arrangement, reduce the number of high voltage power cable and cable trench excavation earthwork, so as to reduce the project cost effectively.

2. Calculation principle of the induced voltage

when the single core cable through the alternating current, it will be bound to produce an alternating magnetic field and the flux of cable loop, which bound to the metal sheath of the cable with the strand, Because the cable length is far greater than the cable spacing(L>>S),therefore, it is

considered that the induced voltage on the cable metal sheath is uniform. By this assumption, the induced voltage on the metal sheath of the unit length can be calculated.

Fig.1 shows arbitrary three phase single core cable laying position in multi loop cable line selected for induced voltage of cable metal sheath. Where O are required to calculate the cable position of the metal sheath induced voltage; A、B、C are expressed in the arrangement of any three-phase cable, which are parallel to each other, and cable specification are the same. Assuming OA=S1，OB=S2，OC =S3；AB=D1、BC=D2、AC =D3，the linear current in A、B、C phase cable is respectively IA、IB、IC , the O metal sheath and the A phase of the magnetic flux of the cable:

$$\Psi_{OA} = 2 \times 10^{-7} I_A \ln \frac{S_1}{R_S} \tag{1}$$

R_S——Average radius of metal sheath

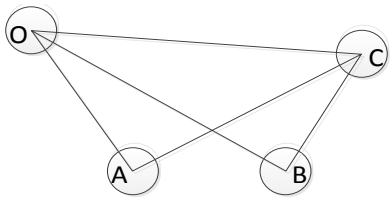

Fig.1 Any Arrangement of Three-phase Cable Laying

In the same way, the magnetic flux of the metal sheath of O and the B、C phase is respectively:

$$\begin{cases} \Psi_{OB} = 2 \times 10^{-7} I_B \ln \frac{S_2}{R_S} \\ \Psi_{OC} = 2 \times 10^{-7} I_C \ln \frac{S_3}{R_S} \end{cases} \tag{2}$$

The total magnetic flux of the O metal sheath and the A、B、C phase cable delivery chain is:

$$\Psi_O = 2 \times 10^{-7} (I_A \ln \frac{S_1}{R_S} + I_B \ln \frac{S_2}{R_S} + I_C \ln \frac{S_3}{R_S}) \tag{3}$$

If O and A coincide, then OB=S2，OC =S3，because OA=RS,(3)can be simplified as:

$$\Psi_O = 2 \times 10^{-7} (I_B \ln \frac{S_2}{R_S} + I_C \ln \frac{S_3}{R_S}) \tag{4}$$

Cable Ⅰ per kilometer of induced voltage is :

$$E_{\mathrm{I}} = -j\omega 2 \times 10^{-4} (I_{\mathrm{II}} \ln \frac{S_2}{R_S} + I_{\mathrm{III}} \ln \frac{S_3}{R_S}) \tag{5}$$

Cable Ⅱ and cable Ⅲ per kilometer of induced voltage :

$$\begin{cases} E_{\mathrm{II}} = -j\omega 2 \times 10^{-4} (I_{\mathrm{I}} \ln \frac{S_1}{R_S} + I_{\mathrm{III}} \ln \frac{S_3}{R_S}) \\ E_{\mathrm{III}} = -j\omega 2 \times 10^{-4} (I_{\mathrm{I}} \ln \frac{S_1}{R_S} + I_{\mathrm{II}} \ln \frac{S_2}{R_S}) \end{cases} \tag{6}$$

3. Multi Circuit Cable Line Induced Voltage

3.1 Induced Voltage Calculation and Analysis method

As can be seen from formula (5) and (6) about induced voltage: the greater the current, the greater the induced voltage .But when the cable is laid in the loop to reach double or more ,as the formula of calculating induced voltage involves many parameters ,it is difficult to analyze the regularity for the effect current phase between phase distance to induced voltage. Therefore, this paper through the analysis of induction voltage of double loop and multi loop cable in any adjacent cable, so as to explore the impact of the universal law of current phase angle and the phase distance of cable loop induction voltage.

The paper establishes a physical model of the induction voltage of the metal sheath of the Multi loop cable line, as shown in Figure 2 to 6.By changing the relative location of three cables and the

phase of current to simulate any three- phase cable of adjacent double loop and multi loop cable .For example ,in the current phase of the model one cable Ⅰ assumed to be 0°, and the current phase of cable Ⅱ is assumed to be 120° or -120° ,cableⅢ is to be 0° ,120° , or -120° , any combination of the phase angle can be simulated the distribution of double loop and multi loop cable lines of any adjacent three-phase cable arrangement, then it get the influence of the current phase to cable metal sheath induction voltage，the same as model two to five.

Meanwhile, we can know the distance of cable Ⅰ to cable Ⅱ and cable Ⅱ and cableⅢ is same in modle2, but the distance between cable Ⅰ and cableⅢ is changed. Therefore, by comparison the change of similar cable distance in models one to five, the influence of cable and phase distance on the induction voltage of cable metal sheath is also analyzed. Therefore, based on the analysis results of current phase angle and phase distance of the induction voltage, it can be concluded that the arrangement of the multi circuit cable that the section is minor.

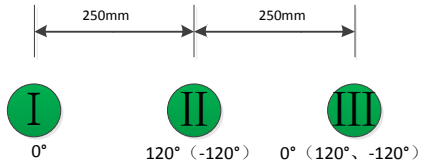

Fig.2 Model 1

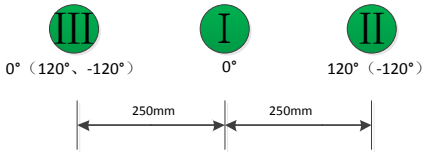

Fig.3 Model 2

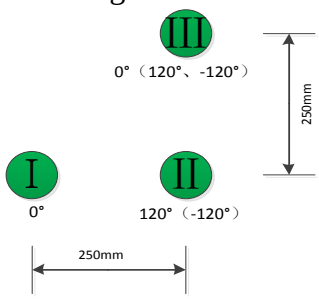

Fig.4 Model 3

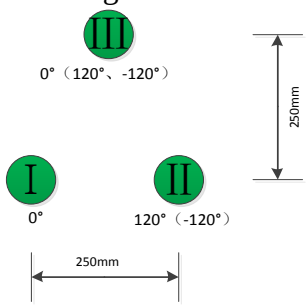

Fig.5 Model 4

Assuming the length of cable line is infinite, load current is 1000A,and current phase, phase distance and loop space as shown in Figure 2 to 6.RS=45mm is used formula(5)and (6) the model of every kilometer induced voltage calculation results in the following table 1 shows.

Table 1 Research Model Calculation Data

Model 1	E_I	E_{II}	E_{III}
0°-120°-0°	134.829∠-46.237°	215.379∠-90°	134.829∠-46.237°
0°-120°-120°	134.830∠-73.764°	107.689∠-150°	134.829∠-46.237°
0°-120°-（-120°）	258.908∠30°	107.689∠-30°	134.829∠-46.237°
0°-（-120°）-0°	134.829∠-133.763°	215.379∠-90°	134.829∠-133.763°
0°-（-120°）-120°	134.830∠	107.689∠-30°	134.829∠-133.763°
0°-（-120°）-（-120°）	258.906∠-150°	107.689∠-150°	134.829∠-133.763°
Model 2	**E_I**	**E_{II}**	**E_{III}**
0°-120°-0°	107.689∠-30°	258.908∠-90°	134.829∠-13.764°
0°-120°-120°	215.379∠30°	134.829∠-13.764°	134.829∠-13.764°
0°-120°-（-120°）	107.689∠90	134.829∠-166.236°	134.829∠-13.764°
0°-（-120°）-0°	107.689∠-150°	258.908∠-90°	134.829∠-166.236°
0°-（-120°）-120°	107.689∠90	134.829∠-13.764°	134.829∠-166.236°
0°-（-120°）-（-120°）	215.379∠150°	134.829∠-166.236°	134.829∠-166.236°
Model 3	**E_I**	**E_{II}**	**E_{III}**
0°-120°-0°	120.057∠-39.033°	215.379∠-90°	120.057∠-39.033°
0°-120°-120°	237.143∠-30°	107.689∠-30°	120.057∠-39.033°
0°-120°-（-120°）	120.054∠-99.028°	107.689∠-150°	120.057∠-39.033°
0°-（-120°）-0°	120.057∠-140.967°	215.379∠-90°	120.057∠-140.967°

0°-（-120°）-120°	120.054∠-80.771°	107.689∠-30°	120.057∠-140.967°
0°-（-120°）-（-120°）	237.143∠150°	107.689∠-150°	120.057∠-140.967°
Model 4	E_I	E_{II}	E_{III}
0°-120°-0°	107.689∠-30°	215.379∠-90°	107.689∠-30°
0°-120°-120°	215.379∠30°	107.689∠-30°	107.689∠-30°
0°-120°-（-120°）	107.689∠90°	107.689∠-150°	107.689∠-30°
0°-（-120°）-0°	107.689∠-150°	215.379∠-90°	107.689∠-150°
0°-（-120°）-120°	107.689∠90°	107.689∠-30°	107.689∠-150°
0°-（-120°）-（-120°）	215.379∠150°	107.689∠-150°	107.689∠-150°

Annotation: In the first column of Table 1 angle from left to right are the phase of cable Ⅰ、cable Ⅱ and cable Ⅲ.

Analysis table 1 shows:1) The metal sheath of high voltage single core cable will increase along with the increase of phase distance ,and the same with the current value. 2) The current sequence of three adjacent cable layout is not at the same time, the induced voltage is smaller at the situation of same phase current.3)The voltage that three cables are arranged in a triangular arrangement is smaller than the horizontal arrangement.4)When phase current is same in three adjacent roots, the induced voltage that is combined with a triangle is less than the horizontal arrangement. From the above conclusion can be concluded, that adjust the cable sequence can change induction voltage value; and a right angled triangle arrangement in a horizontal row ripe has many advantages, in the engineering design of cable lines it is worth considering.

2.2 The influence of Phase sequence change and alternate with Distance

When the distance between the three cables and current amplitude is fixed, as shown in Fig6:the induced voltage cable Ⅱ and cableⅢ in different phase in the case of the cable Ⅰ were respectively E_{PII} and E_{PIII}, their vector sum is E_{P1};when the current phase is same on cable Ⅱ and cable Ⅲ,they produce the inductive voltage is E_{PII} and E'_{PIII} ,their vector sum is E'_{P1}.From formula (5)and(6) can be known, three the induced voltage of any one cable in the cable is the vector sum of the induction voltage of the remaining two cables. it is can be obtained that $E'_{PI} > E_{PI}$. Therefore, the induction voltage of three adjacent sheath cable arrangement in the current phase three cables with different minimum value.

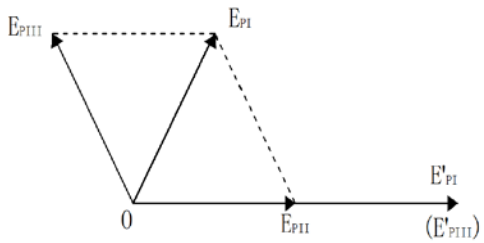

Fig. 6 Vector analysis of Influence of Current Phase on the Induction Voltage

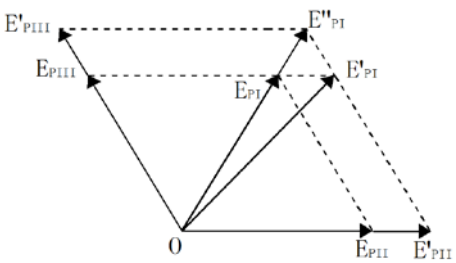

Fig.7 Distance of Vector Analysis Phase of the Induced Voltage

Fig.7 shows cable Ⅱ and cable Ⅲ generated the induced voltage on the cable Ⅰ which were E_{PII} and E_{PIII}, Their vector sum is E_{PI}. From the formula (5) and (6) shows that, when the current amplitude and current phase angle is determined, the mutual inductance of voltage magnitude between the two cables only associated with the phase distance, With the increase of the distance of the interphase; And determines that magnitude of the current and phase angle, Its mutual induction voltage of phase angle is constant. Therefore, the relative distance between cable Ⅱ,cable Ⅲ and cable Ⅰ increases, the corresponding of the induced voltage will increase accordingly to E'_{PII}, E'_{PIII}, the induced voltage of the Metal Sheath of cable Ⅰ accordingly increase E'_{PI} and E''_{PI}. When current value and phase angle which are from model one to model five is the same, the induced voltage of right triangle arrangement is less than the horizontal arrangement, and the maximum occurred at a greater distance from its opposite phase.

In summary, in this paper, in a comprehensive view of the above conclusions and reducing the

arrangement of land occupied area, Phase sequence permutation scheme of double circuit cable line shown in Fig. 8 were recommend.

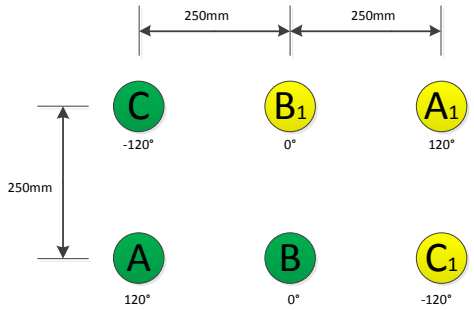

Fig.8 Double Triangle Arrangement

4. Simulation verification

In order to verify the validity and accuracy of the proposed method ,this paper selects double-circuit cable line model were compared to verify, Current amplitude is 1000A, Voltage rating of 110kV, phase distance of 250mm, Grounding both ends of the base mode is the way to ground at both ends, Grounding resistance of 3Ω, Cable Type adopt YJLW03-64/110-630mm2 XLPE insulated corrugated aluminum sheath PE sheathed power cable, Interconnected computing unit is segmented into a cross of 630m ×3. Its ATP-EMTP simulation model as shown in Fig 9;

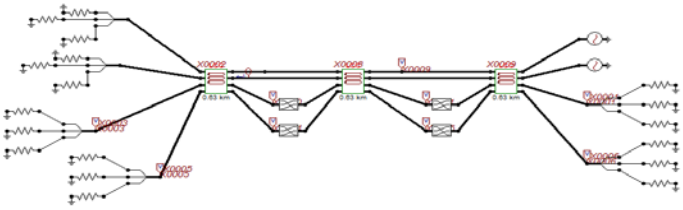

Fig.9 Double Loop Cable ATP-EMTP Simulation Model

The arrangement of double-loop cable is derived from the existing solution of literature [9],[8],[10]. These programs will be proposed that is arrangement of shown in Figure 9 were analyzed.

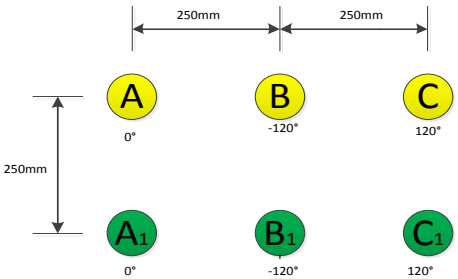

Fig. 10 Double Back Horizontally Aligned

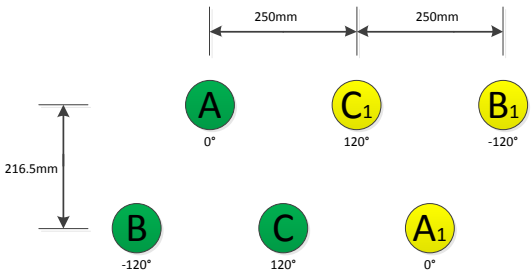

Fig.11 Double Back of Equilateral Triangle Arrangement

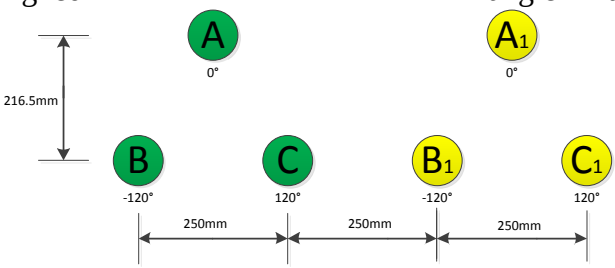

Fig. 12 Double Back Parallel of Equilateral Triangle

Figure 8, figure 10, figure 11 and figure 12 four arrangement corresponding to the number 1 in table 2, 2, 3 and 4. The simulation to calculate the metal sheath maximum induced voltage as shown in table 2.

Table 2 The Maximum Induced Voltage Value of The four Kinds of Arrangement

No	Double phase sequence	The largest induction Voltage (V)	No	Double phase sequence	The largest induction Voltage (V)
1	C-B_1-A_1 A-B-C_1	79.094	3	A-C_1-B_1 B-C-A_1	90.036
2	A-B-C A-B-C	131.95	4	A A_1 B-C B_1-C_1	82.13

Table 2 shows 4 kinds of pattern induced voltage corresponding to the maximum amplitude were 79.094V, 131.95 V, 90.036 V, 82.483V; Sectional area of its arrangement of were 125000mm^2, 125000mm^2, 135312.5mm^2, 162375mm^2; The arrangement shown in Fig.8 ways to reduce the 39.30%, 12.153%, 4.11% compared with the other three were induced voltage arrangement, cross-sectional area were reduced to 0%, 7.62%, 23.03%.

Fig.8 shows arrangement under the induced voltage is smaller than the other three, cross-sectional area is also the smallest. Considering the induced voltage and cross-section shows, the arrangement shown in Figure 8 satisfies this article search for a metal sheath induced voltage value is smaller and less land area occupied by the cable laying program. The accuracy and validity of the general rule to the special law of arbitrary adjacent three phase method are verified.

5.Conclusion

1) High voltage single-core cable with metal sheath induced voltage phase distance increases, with the increase of the current value increases.

2) The same horizontal line of adjacent phase cable of current phase sequence is not the same, the induced voltage value is less than the presence of the same current phase angle cable on the same level.

3) The same two-phase current phase angle of cable is of adjacent the three phases, its combined into a right triangle, or the like when the induced voltage maximum equilateral triangle are smaller than their horizontal arrangement.

4) Fig.9 double loop cable arrangement shown in Figure text induced voltage reaches the lower and decreasing laying occupied land area, the economy is higher in multi-loop cable design results of this study can be a reference.

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