Currents in the overhead transmission line lighting wire in case of single-phase short circuit

Kirill Zimin¹, Nina Rubtsova², Vladimir Ryabchenko^{1*}, Andrey Tokarskiy¹

¹ Joint-Stock Company "Research and Development Center of the Federal Grid Company of Unified Energy System", Kashirskoe shosse, 22, bld.3, Moscow, Russia

² Federal State Budgetary Scientific Institution "Izmerov Research Institute of Occupational Health", prospect Budennogo,31, Moscow, Russia

Abstract. The algorithms for currents induced in a grounded lightning wire (LW) with single-phase short circuit (SC) calculation are considered. It is shown that the method of short-circuit current and current in LW simultaneous determination gives more correct results for the assessment of LW thermal resistance.

1 Introduction

At the present time overhead transmission lines (OTL) are equipped with lighting wires (LW) containing fiber-optic communication channels (FOLW). FOLW technologically are grounded through even OTL tower by grounding device. In case of single phase short circuit (SPhSC) the damaged OTL phase current magnetic field induces the current in FOLW. This current magnitude should not be more than permissible thermal resistance.

2 OTL and FOLW parameters

Current induced in FOLW value determine on example of 200 kV double-circuit OTL placed on intermediate tower of Itph220-2+5 brand as shown in Figure 1.

Fig. 1. 220 kV double-circuit OTL on intermediate tower.

OTL phases made by one wire of AC-400/51 brand with 0.01375 m radius, lighting wire – by FOLW wire.

Phases wires and LW suspension heights are: $h_A=20.1$ m, $h_B=25.2$ m, $h_C=30.3$ m and $h_{LW}=36.8$ m. Phases wires and LW SAG arrows are: $f_{ph}=10.1$ m, $f_{LW}=8.786$ m. Phases wires and LW equivalent heights are: $h_{AE}=13.37$ m, $h_{BE}=18.47$ m, $h_{CE}=23.57$ m and $h_{LWE}=30.94$ m.

220 kV OTL with 46.956 km length and 326.75 m span length is made without transpositions. Network resistance from substation 1 (S1) side is $Z_{S1}=0.932+j8.455$ Ohm, and from S2 side is $Z_{S2}=0.841+j5.796$ Ohm.

There were chosen the following brands of wires for currents induced in FOLW in case of SPhSC: FOLW-sh-1-24(G.652)-18.7/93, FOLW-sh-1-16(G.652)-14.7/61, FOLW-sh-1-24(G.652)-13.1/54 and FOLW(G.652)-12/94. Table 1 shows the values: r_{wLW} (mm) -nominal radius; R_{LW0} (Ohm/km) - resistivity, and I_{SCLW} (kA) - SC permissible current by thermal resistance for t (sec) - permissible duration – I_{SCLW}/t (kA/s) for each of FOLW chosen types.

Table 1. Chosen FOLW types r_{wLW} , R_{LW0} and I_{SCLW}/t values

FOLW brand	r_{wLW} , mm	R_{LW0} , Ohm/km	I_{SCLW}/t , kA/s
FOLW-sh-1-24(G.652)-18.7/93	9.35	0.200	18.7/1.0
FOLW-sh-1-16(G.652)-14.7/61	7.35	0.329	11.5/1.0; 15.0/0.59
FOLW-sh-1-24(G.652)-13.1/54	6.55	0.443	8.9/1.0
FOLW-c-1-24(G.652)-12/94	6.00	1.116	5.6/1.0

Wire intrinsic specific inductive resistance (Z_{LW0}) as well as mutual specific inductance resistance between LW and k phase (Z_{Wk0}) taking into account

* Corresponding author: ryabchenko.vn@yandex.ru

ground specific resistance are calculated by full Carson' expressions [1, 2]:

$$Z_{LW0} = \frac{j\omega\mu_0}{2\pi \cdot 10^{-3}} \left(\ln \frac{\sqrt{2}\delta_e}{r_{WLW}} - j\frac{\pi}{4} + \frac{4}{3} \frac{h_{LWE}}{\delta_e} (1+j) - 0,0772 \right) \quad (1)$$

, Ohm/km,

$$Z_{Wk0} = \frac{j\omega\mu_0}{2\pi \cdot 10^{-3}} \times \left[\ln \frac{\sqrt{2}\delta_e}{\sqrt{a^2 + (h_{kE} - h_{LWE})^2}} - j\frac{\pi}{4} + \frac{2}{3} \frac{h_{kE} + h_{LWE}}{\delta_e} (1+j) - 0,0772 \right], \quad (2)$$

Ohm/km.

where $\omega = 2\pi f$ – angular frequency, $f = 50$ Hz; $\mu_0 = 4\pi \cdot 10^{-7}$ H/m – permeability of vacuum; r_{WLW} – LW wire radius, m; $a = |x_{kE} - x_{LWE}|$ – distance along the x axis between k phase wire and LW wire, m; h_{kE} и h_{LWE} – k phase wire and LW wire equivalent heights, m; $\delta_e = \sqrt{2\rho_e/\omega\mu_0}$ – penetration depth, m; ρ_e – earth resistivity, Ohm·m.

Electromotive force E_{Wk} , induced in LW wire to the span length l_{sp} (km) by 220 kV OTL k phase I_k current magnetic field is calculated by expression [2]:

$$E_{Wk} = -Z_{Wk} I_k l_{sp} = -\frac{j\omega\mu_0 I_k l_{sp}}{2\pi \cdot 10^{-3}} \times \left[\ln \frac{\sqrt{2}\delta_e}{\sqrt{a^2 + (h_{kE} - h_{LWE})^2}} - j\frac{\pi}{4} + \frac{2}{3} \frac{h_{kE} + h_{LWE}}{\delta_e} (1+j) - 0,0772 \right], \quad (3)$$

V.

3 220 kV OTL operating in the no-load operation mode SPhSC currents

SC lead to the arc emission between OTL damaged phase and the earth (grounded object), with R_A arc resistance. R_A value for 220 kV OTL under 15 kA SC current is determined by lines in [3] and is: $R_A = 0.42$ Ohm.

Consider the option when OTL operation mode is no-load operation (NLO) with the connection of one side to the busbar source, and on the other – with the disconnection of all phases from the busbar. There were calculated SPhSC currents at different distances from S1 and S2 by use computer program «EMPVL», «OTL EMF»[4] computer program later modification. In case of equal distances from S1 with Z_{S1} and S2 with Z_{S2} the modules of the SPhSC current values powered by S2 are higher than modules powered by S1 because $Z_{S1} > Z_{S2}$. When calculating the currents induced in LW should focus on high SPhSC currents, i.e. the currents powered by S2.

Figure 2 shows the lines of phase C2 (nearest to LW phase) SPhSC current module distribution along to 220 kV OTL for SPhSC distances 0.5, 5, 10 and 30 km from S2. SPhSC current module decrease with SC place distance from S2.

Fig. 2. Distribution along 220 kV OTL phase C2 SPhSC current module for SPhSC 0.5, 5, 10 and 30 km distances from S2.

4 Currents induced in LW for case of 220 kV OTL SPhSC in the no-load mode

Currents induced in double-circuit 220 kV OTL LW calculate for FOLW-sh-1-24(G.652)-18.7/93 wire with $r_{WLW}=0.00935$ m and $R_{W0}=0.20$ Ohm/km under SPhSC $I_{K32}=0.5$ km distance from S2.

For $\rho_e=100$ Ohm·m from (1) we obtain $Z_{LW0} = 0.04571 + j0.7268$ Ohm/km. Then the specific active-inductive resistance of wire [5], located above the ground, $Z_{W0} = R_{T0} + j\text{Im}[Z_{LW0}] = 0.20 + j0.7268$ Ohm/km, and the specific active resistance of the wire from losses in the ground $Z_{e0} = \text{Re}[Z_{LW0}] = 0.04571$ Ohm/km. Wire resistance and losses in the ground (earth) at span length $l_{sp} = 0.32675$ km are:

$$Z_W = Z_{W0} l_{sp} = 0.0654 + j0.2375 \text{ Ohm};$$

$$Z_e = Z_{e0} l_{sp} = 0.0149 \text{ Ohm}.$$

For $I_{SCC2}=20.75\angle 41.8^\circ$ kA C2 phase SPhSC current electromotive force E_{WC2} , this current induced in LW calculate by expression (3): $E_{WC2}=2,085.6\angle -56.8^\circ$ V.

Figure3 shows the scheme of induced current calculation in LW under SPhSC at $l_{SC2} = 0.5$ km distance from S2.

Fig. 3. Scheme of the current calculation in LW under SPhSC at $l_{SC2} = 0.5$ km distance from S2.

In case of SPhSC distance $l_{SC2} = 0.5$ km from S2 SPhSC current I_{SCC2} affect to the first two spans of LW, grounded on each tower i by means of grounding device (GD) resistance R_{GDi} . The rest spans are a sequence of passive double-poles, rolling the input resistance of which from the end of the OTL to the end of its second span, we obtain the resulting resistance Z_{NE} .

by current module than current in LW under closer to LW phase C2 SPhSC.

Currents induced for chosen FOLW types are carried out under phase C2 SPhSC at $l_{SC2} = 0.5, 5$ and 10 km distance from S2. For example, consider phase C2 220 kV OTL SPhSC with FOLW-sh-1-24(G.652)-18.7/93 following at $l_{SC2} = 5$ km distance (see Figure 5).

[illegible]

Fig. 5. The scheme of current in LW calculation under SPhSC at $l_{SC2} = 5$ km distance from S2.

$\mathbf{I}_{\text{SCC2}} = 15.74 \angle 39.1^\circ$ kA current applies to 15 LW spans from S2 side, and in the each span induces electromotive force $\mathbf{E}_{\text{WC2}} = 1,582.1 \angle -59.5^\circ$ V according to equation (3). A system of equations write by the method of contour currents:

$$\left. \begin{aligned} & \mathbf{J}_1(\underline{Z}_W + Z_e + R_{\text{GDIC}} + R_{\text{GD}}) - \mathbf{J}_2 R_{\text{GD}} = \mathbf{E}_{\text{WC2}}; \\ & -\mathbf{J}_1 R_{\text{GD}} + \mathbf{J}_2(\underline{Z}_W + Z_e + 2R_{\text{GD}}) - \mathbf{J}_3 R_{\text{GD}} = \mathbf{E}_{\text{WC2}}; \\ & \dots\dots\dots \\ & -\mathbf{J}_{13} R_{\text{GD}} + \mathbf{J}_{14}(\underline{Z}_W + Z_e + 2R_{\text{GD}}) - \mathbf{J}_{15} R_{\text{GD}} = \mathbf{E}_{\text{WC2}}; \\ & -\mathbf{J}_{14} R_{\text{GD}} + \mathbf{J}_{15}(\underline{Z}_W + Z_e + R_{\text{GD}} + \underline{Z}_{\text{NE}}) = \mathbf{E}_{\text{WC2}}. \end{aligned} \right\} \quad (5)$$

The data for system of equations (5):
 $\underline{Z}_W + \underline{Z}_e + R_{GDIC} + R_{GD} = 10.580 + j0.2375 \text{ Ohm};$
 $\underline{Z}_W + \underline{Z}_e + 2R_{GD} = 20.080 + j0.2375 \text{ Ohm}; \underline{Z}_{NE} = 1.245 +$
 $j0.809 \text{ Ohm}; \underline{Z}_W + \underline{Z}_e + R_{GD} + \underline{Z}_{NE} = 11.334 + j1.0465$
 $\text{Ohm}; R_{GDS} = 0.5 \text{ Ohm}; R_{GD} = 10 \text{ Ohm}.$

Solving the system (5), we obtain the values of induced in LW currents:

The greatest value of induced in LW current modulus falls in the sixth span, where $I_{W_{\max}} = I_{w_6} = 5.480$ kA, and according to table 1 FOLW-sh-1-24(G.652)-18.7/93 1 s withstand 18.7 kA SC current, ie, it can operate with a large margin for thermal stability.

There were carried out the calculations of the highest currents $I_{w\max}$ under C2 phase SPhSC at $l_{SC2} = 0.5, 1, 2, 3, 4, 5, 7.842$ and 10 km distances from S2 for FOLW-sh-1-24(G.652)-18.7/93 and FOLW-c-1-24(G.652)-12/94 (with the greatest differences in nominal radii r_{wLW} and resistivities R_{LW0}).

Table 2 given distances l_{SC2} of SC points, number of spans P_{K3} , exposed by SC current magnetic field (MF), the values of C2 phase SC current I_{SCC2} as well as electromotive force E_{WC2} , induced in FOLW span by current I_{SCC2} MF. Current module histograms I_{Wmax} shown in Figure 6.

Table 2. Distances l_{SC2} , span number P_{SC} , current value I_{SCC2} and electromotive force E_{WC2} in FOLW span

l_{SC2} , km	P_{SC}	I_{SCC2} , kA	E_{WC2} , V
0.5	2	20.75 $\angle$ 41.8°	2,085.6 $\angle$ -56.8°
1	3	19.96 $\angle$ 41.6°	2,006.2 $\angle$ -57.0°
2	6	18.69 $\angle$ 41.0°	1,878.6 $\angle$ -57.6°
3	9	17.56 $\angle$ 40.4°	1,765.0 $\angle$ -58.2°
4	12	16.57 $\angle$ 39.9°	1,665.5 $\angle$ -58.7°
5	15	15.47 $\angle$ 39.1°	1,582.1 $\angle$ -59.5°
7.842	24	13.60 $\angle$ 38.5°	1,367.0 $\angle$ -60.1°
10	31	12.42 $\angle$ 37.7°	1,248.4 $\angle$ -60.9°

Fig. 6. Current module I_{Wmax} change dependence on l_{SC2} histogram for FOLW-sh-1-24(G.652)-18.7/93 and FOLW-c-1-48(G.652)-12/94.

On one side, as the distance l_{SC2} increase the number of LW span exposed to I_{SCC2} SC current rise, each of which adds FOLW longitudinal resistance, GD cross-resistance and longitudinal electromotive force E_{WC2} , which leads to current module I_{Wmax} elevation.

But on another side l_{SC2} distance increase leads to SC current module I_{SCC2} decrease, induced by current electromotive force E_{WC2} reduce as well as I_{Wmax} current value decrease. For considered 220 kV OTL the process of I_{Wmax} current value increase prevails for distances from SC point $l_{SC2} < 5$ km, and for distances $l_{SC2} > 5$ km process of I_{SCC2} , current value decrease as well as current decrease prevails. Thus when $l_{SC2} = 5$ km I_{Wmax} current reaches its greatest value $I_{Wmax} = 5480$ A for FOLW -sh-1-24(G.652)-18.7/93 and $I_{Tmax} = 3100$ A for FOLW -c-1-24(G.652)-12/94.

5 Currents in LW under no-loaded mode OTL two self-titled phases SPhSC

Consider the rare but possible case when in 220 kV OTL at $l_{SC2} = 5$ km from S2 there are simultaneous SC self-title phases C1 and C2 on the earth (see Figure 7).

Fig. 7. The scheme of phases C1 and C2 simultaneous SC on the earth currents values calculation

Figure 7: $R_{C1} = R_{C2} = 0.356$ Ohm, $X_{LC1} = X_{LC2} = 2.213$ Ohm, $R_{S2} = 0.841$ Ohm, $X_{LS2} = 5.796$ Ohm, $R_D = 0.42$ Ohm and $E_{CS2} = 127,017\angle 120^\circ$ V.

The scheme contains three branches and two nodes. Entering data of the scheme Fig. 7 in sub "Stationary electric circuit" program «WMRUS», get the current values in the branches:

$$I_0 = 18,194.5\angle 38.6^\circ \text{ A}; \quad I_1 = 9,097.2\angle 38.6^\circ \text{ A}; \\ I_2 = 9,097.2\angle 38.6^\circ \text{ A}.$$

Phase C1 and C2 SC currents are equal: $I_{SCC1} = I_{SCC2} = 9,097.2\angle 38.6^\circ$ A.

Phase C1 and C2 equivalent height $h_{C1} = h_{C2} = 23.57$ m. LW equivalent height: $h_W = 30.94$ m. The distance between LW and C1 phase by x-axis x: $a_{WC1} = 3.680$ m, and between LW C2 phase: $a_{WC2} = 2.400$ m.

Electromotive forces (voltages) E_{WC1} and E_{WC2} , induced in LW by C1 and C2 phases SPhSC currents determine by equation (3): $E_{WC1} = 902.1\angle -60.1^\circ$ V, $E_{WC2} = 914.4\angle -60.0^\circ$ V.

Resulting voltage induced in LW by C1 and C2 phases SPhSC currents is: $E_{WC\Sigma} = E_{WC1} + E_{WC2} = 1816.5\angle -60.0^\circ$ V, and it substitute electromotive force (voltage) E_{WC2} in equations (5).

Current values in LW calculations are carried out for all of chosen FOLW types. Let us consider, as an example, the case of 220 kV OTL equipped with FOLW -sh-1-24(G.652)-18.7/93. The initial data for the resistances of the system of equations (5) are given earlier and do not change. Substituting in the system of equations (5) the resistance and $E_{WC\Sigma}$ and solving it, we obtain the values of induced in LW currents:

$$\begin{aligned} I_{W1} &= 5,722 \angle -114.5^\circ \text{ A}; & I_{W2} &= 5,948 \angle -114.7^\circ \text{ A}; \\ I_{W3} &= 6,117 \angle -114.8^\circ \text{ A}; & I_{W4} &= 6,231 \angle -115.0^\circ \text{ A}; \\ I_{W5} &= 6,290 \angle -115.2^\circ \text{ A}; & I_{W6} &= 6,296 \angle -115.4^\circ \text{ A}; \\ I_{W7} &= 6,249 \angle -114.6^\circ \text{ A}; & I_{W8} &= 6,150 \angle -115.8^\circ \text{ A}; \\ I_{W9} &= 5,997 \angle -116.1^\circ \text{ A}; & I_{W10} &= 5,792 \angle -116.4^\circ \text{ A}; \\ I_{W11} &= 5,533 \angle -117.0^\circ \text{ A}; & I_{W12} &= 5,220 \angle -117.8^\circ \text{ A}; \\ I_{W13} &= 4,854 \angle -119.1^\circ \text{ A}; & I_{W14} &= 4,437 \angle -121.1^\circ \text{ A}; \\ I_{W15} &= 3,978 \angle -124.4^\circ \text{ A}. \end{aligned}$$

7 Simultaneous determination of SC currents and induced in LW currents

The considered methods for calculating the currents induced in LW by SPhSC current MF do not take into account SC current itself passage in LW from SC point to the phase electromotive force (voltage) in the line beginning, for example E_{C2} . Figure 11 shows the scheme of simultaneous SC current at 5 km from S2 distance and currents in LW determination for 220 kV OTL in no-loaded mode. Figure 11: $R_{C2} + jX_{LC2}$ – phase C2 wire in single span resistance-inductive reactance; $R_W + jX_{LW}$ – wire LW in single span resistance-inductive reactance; Z_e – resistance to reverse current in the ground for a single span; Z_{WC2} – mutual inductive reactance C2 phase and LW in span, obtained by equation (2); $R_{S2} + jX_{LS2}$ – network resistance for S2; Z_{NE} – resulting resistance after wire passive two-terminal network folding with результирующее сопротивление после сворачивания пассивных двухполюсников троса with step $l_{sp} = 0.33$ km; $R_{GDS} = 0.5$ Ohm – S GD resistance; $R_{GD} = 10$ Ohm – OTL tower GD resistance; $R_D = 0.42$ Ohm – SC arc resistance; $E_{C2} = 127,017 \angle 120^\circ$ V – C2 phase electromotive force.

Fig. 11. The scheme of C2 phase SC current and induced in LW current determination

According Figure 11 scheme for single span of OTL and LW FOLW-sh-1-24(G.652)-18.7/93: $R_{C2} + jX_{LC2} = 0.02433 + j0.23388$ Ohm; $R_W + jX_{LW} = 0.0667 + j0.2422$ Ohm; $Z_e = 0.01533$ Ohm; $Z_{WC2} = 0.015 + j0.101$ Ohm; $R_{S2} + jX_{LS2} = 0.841 + j5.796$ Ohm; $Z_{NE} = 1.257 + j0.816$ Ohm; $R_{GDS} = 0.5$ Ohm; $R_{GD} = 10$ Ohm; $R_D = 0.42$ Ohm.

Let us formulate a system of equations by the method of contour currents:

$$\left. \begin{aligned} & J_0[R_S + jX_{LS} + 15(R_{C2} + jX_{LC2} + Z_e) + R_D + R_{GDS}] + \\ & + J_1(R_{GDS} + Z_e + Z_{WC2}) + J_2(Z_e + Z_{WC2}) + \dots + J_{15}(Z_e + Z_{WC2}) = E_{C2}; \\ & J_0(R_{GDS} + Z_e + Z_{WC2}) + J_1(R_W + jX_{LW} + R_{GD} + Z_e + R_{GDS}) - J_2R_{GD} = 0; \\ & J_0(Z_e + Z_{WC2}) - J_1R_{GD} + J_2(R_W + jX_{LW} + 2R_{GD} + Z_e) - J_3R_{GD} = 0; \\ & \dots \\ & J_0(Z_e + Z_{WC2}) + 0 + \dots + 0 - J_{13}R_{GD} + J_{14}(R_W + jX_{LW} + 2R_{GD} + Z_e) - J_{15}R_{GD} = 0; \\ & J_0(Z_e + Z_{WC2}) + 0 + \dots + 0 - J_{14}R_{GD} + J_{15}(R_W + jX_{LW} + R_{GD} + Z_e + Z_{NE}) = 0. \end{aligned} \right\} \quad (7)$$

Solving the system of equations (7), we obtain the values of SPhSC currents as well as currents in LW spans:

$$\begin{aligned} I_1 = I_{K3} &= 14,098 \angle 43.5^\circ \text{ A}; & I_{W1} &= 6,876 \angle -133.6^\circ \text{ A}; \\ I_{W2} &= 6,544 \angle -133.1^\circ \text{ A}; & I_{W3} &= 6,237 \angle -132.1^\circ \text{ A}; \\ I_{W4} &= 5,950 \angle -131.4^\circ \text{ A}; & I_{W5} &= 5,679 \angle -130.3^\circ \text{ A}; \\ I_{W6} &= 5,421 \angle -129.2^\circ \text{ A}; & I_{W7} &= 5,169 \angle -128.0^\circ \text{ A}; \\ I_{W8} &= 4,920 \angle -126.9^\circ \text{ A}; & I_{W9} &= 4,668 \angle -125.8^\circ \text{ A}; \\ I_{W10} &= 4,40 \angle -124.9^\circ \text{ A}; & I_{W11} &= 4,135 \angle -124.3^\circ \text{ A}; \end{aligned}$$

$I_{W12} = 3,845 \angle -124.1^\circ \text{ A};$ $I_{W13} = 3,535 \angle -124.6^\circ \text{ A};$
 $I_{W14} = 3,204 \angle -126.0^\circ \text{ A};$ $I_{W15} = 2,858 \angle -128.9^\circ \text{ A}.$
Maximin value of current in LW module is in the 1st span, where $I_{W1} = 6.876$ kA. SPhSC current passes in LW trough even R_{GD} from SC point to electromotive force E_{C2} and by summation become maximal in 1st OTL span. According table 1 data, FOLW-sh-1-24(G.652)-18.7/93 within 1 s withstand 18.7 kA SC current, i.e can be operated with margin $\Delta I = 11.8$ kA for heat resistance. SPhSC currents and currents induced in LW are calculated by the method of simultaneous determination for all of chosen FOLW types.

8 Conclusion

The currents induced by SPhSC currents in LW are maximal and most accurate in case of its simultaneous determination. Table 3 gives the results of the calculation by simultaneous method of current modules: SPhSC currents - I_{SCC2} , maximal currents in LW - I_{Wmax} , allowable currents of heat resistance - I_{SCLW} and margin ΔI by heat resistance current for all chosen FOLW types.

Table 3. The values of calculated by simutanious calculation method I_{SCC2} , I_{Wmax} , I_{SCLW} and ΔI

FOLW brand	I_{SCC2} , kA	I_{Wmax} , kA	I_{SCLW} , kA	ΔI , kA
FOLW-sh-1-24(G.652)-18.7/93	14.098	6.876	18.7	11.8
FOLW - sh -1-16(G.652)-14.7/61	14.023	6.301	11.5	5.18
FOLW - sh -1-24(G.652)-13.1/54	13.957	5.846	8.9	3.05
FOLW -c-1-48(G.652)-12/94	13.669	3.993	5.6	1.61

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