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

Kirill Zimin¹, Nina Rubtsova², Vladimir Ryabchenko³, Andrey Tokarskii⁴

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 of 200 kV double circuit (SC) calculation are considered.

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.

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_A=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 Om, and from S2 side is Z_S2=0.841+j5.796 Om.

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: \( r_{slw} \) (mm) - nominal radius; \( R_{LW} \) (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 \( r_{slw}, R_{LW} \) and \( I_{SCLW}/t \) values

| FOLW brand           | \( r_{slw}, \) mm | \( R_{LW}, \) 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
ground specific resistance are calculated by full
Carson’ expressions [1, 2]:

\[
Z_{\text{WS}} = \frac{j\omega\mu_0}{2\pi \times 10^{-7}} \left[ \ln \frac{\sqrt{E_\delta}}{r_{\text{w1w}}} - j \frac{\pi}{4} \cdot \frac{4}{\frac{h_{\text{w1w}}}{\delta_0}} \cdot (1+j) - 0.0772 \right], \quad \text{Ohm/km},
\]

\[
Z_{\text{w0}} = \frac{j\omega\mu_0}{2\pi \times 10^{-7}} \times \left[ \ln \frac{\sqrt{E_\delta}}{\sqrt{(h - h_{\text{w1w}})}} - j \frac{\pi}{4} \cdot \frac{2}{\frac{h_{\text{w1w}}}{\delta_0}} + \frac{h_{\text{w1w}}}{\delta_0} \cdot (1+j) - 0.0772 \right], \quad \text{Ohm/km},
\]

where \( \omega = 2\pi f \) – angular frequency, \( f = 50 \text{ Hz}; \ \mu_0 = 4\pi \times 10^{-7} \text{ H/m} \) – permeability of vacuum; \( r_{\text{w1w}} \) – LW wire radius, m; \( a = |x_{\text{w}} - x_{\text{w0}}| \) – distance along the x axis between k phase wire and LW wire, m; \( h_{\text{w}} \) and \( h_{\text{w1w}} \) – k phase wire and LW wire equivalent heights, m; \( \delta_0 = \sqrt{2\rho_0/\omega \mu_0} \) – penetration depth, m; \( \rho_1 \) – earth resistivity, Ohm-m.

Electromotive force \( E_{\text{w1}} \) induced in LW wire to the span length \( h_{\text{w}} \) (km) by 220 kV OTL k phase \( I_1 \) current magnetic field is calculated by expression [2]:

\[
E_{\text{w1}} = Z_{\text{wp}} I_{\text{w1}} = \frac{j\omega \mu_0}{2\pi \times 10^{-7}} \times \left[ \ln \frac{\sqrt{E_\delta}}{\sqrt{(h - h_{\text{w1w}})}} - j \frac{\pi}{4} \cdot \frac{2}{\frac{h_{\text{w1w}}}{\delta_0}} + \frac{h_{\text{w1w}}}{\delta_0} \cdot (1+j) - 0.0772 \right], \quad \text{V}.
\]

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 \( R_\text{A} \) arc resistance. \( R_x \) value for 220 kV OTL under 15 kA SC current is determined by lines in [3] and is: \( R_\text{A} = 0.42 \text{ Ohm} \).

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 \( Z_{\text{S1}} \) and S2 with \( Z_{\text{S2}} \) the modules of the SPhSC current values powered by S2 are higher than modules powered by S1 because \( Z_{\text{S1}} > Z_{\text{S2}} \). 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.

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 \( r_{\text{w1w}}=0.00935 \text{ m} \) and \( R_{\text{w0}}=0.20 \text{ Ohm/km} \) under SPhSC \( l_{\text{SC2}}=0.5 \text{ km} \) distance from S2.

For \( \rho_1 = 100 \text{ Ohm-m} \) from (1) we obtain \( Z_{\text{WS}} = 0.04571 + j0.7268 \text{ Ohm/km} \). Then the specific active-inductive resistance of wire [5], located above the ground, \( Z_{\text{w0}} = R_\text{T0} + j\text{Im}[Z_{\text{WS}}] = 0.20 + j0.7268 \text{ Ohm/km} \) and the specific active resistance of the wire from losses in the ground \( Z_{\text{w2}} = \text{Re}[Z_{\text{WS2}}] = 0.04571 \text{ Ohm/km} \). Wire resistance and losses in the ground (earth) at span length \( l_{\text{wp}} = 0.32675 \text{ km} \) are:

\[
Z_{\text{w}} = Z_{\text{w0}} l_{\text{wp}} = 0.0654 + j0.2375 \text{ Ohm};
\]

\[
Z_{\text{e}} = Z_{\text{w2}} l_{\text{wp}} = 0.0149 \text{ Ohm}.
\]

For \( I_{\text{SC2}} = 0.20,75 \angle 41.8^\circ \text{ kA} \) C2 phase SPhSC current electromotive force \( E_{\text{wC2}} \), this current induced in LW calculate by expression (3): \( E_{\text{wC2}} = 2.085.6 \angle -56.8^\circ \text{ V} \). Figure 3 shows the scheme of induced current calculation in LW under SPhSC at \( l_{\text{SC2}} = 0.5 \text{ km} \) distance from S2.
We write a system of equations by the method of contour currents for scheme shown in Fig. 3:

\[
\begin{align*}
J_1 (Z_w + Z_e + R_{GD1} + R_{GD2}) - J_2 R_{GD2} &= E_{w2c} ;
\end{align*}
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + R_{GD2} + Z_{NE}) &= E_{w2c} .
\]

(4)

Resistance \( Z_{NE} \) value calculate. At fig. 4 there is shown the sequence of LW contours without electromotive force \( E_{w2c} \).

\[ Z_N = \frac{(Z_{NN} R_{GD1})}{(Z_{NN} + R_{GD1})} \]  

The second packaging of input resistance \( Z_{NN} = Z_w + Z_e + Z_N \) and resistance \( R_{GD1} \) is carried out by equation: 
\[ Z_{w1} = \frac{(Z_{NN} R_{GD1})}{(Z_{NN} + R_{GD1})} \]  

etc. until the end of 2nd span.

Figure 4 scheme: \( R_{GD1} = 10 \text{ Ohm} \); \( R_{GD2} = 0.5 \text{ Ohm} \) in case of LW is grounded by GD last time in S, and \( R_{GD2} = 10 \text{ Ohm} \) in case of LW grounding by GD OTL tower. 

After 50 packaging (16.34 km from S1 and 30.32 km from S2) resistance \( Z_{SN} \) ceases to change in thousands of the real and imaginary parts, as both for \( R_{GD2} = 0.5 \text{ Ohm} \), and for \( R_{GD2} = 10 \text{ Ohm} \, \text{ and } Z_{NE} = 0.1245 + j0.809 \text{ Ohm} \).

\[ Z_{NE} = (2R_{GD0} + Z_{NE}) \]  

Fig. 4. The sequence of LW contours without electromotive force \( E_{w2c} \).

Initial data for the equations of system (4):
\[ Z_w + Z_e + R_{GD1} + R_{GD2} = 10.580 + j0.2375 \text{ Ohm} ; \]
\[ Z_w + Z_e + R_{GD2} + Z_{NE} = 11.334 + j1.0465 \text{ Ohm} ; \]
\[ R_{GD2} = 10 \text{ Ohm} ; \]
\[ E_{w2c} = 2.0856.59.68^\circ \text{ V} \]  

Current values in LW calculate by system of equations (4) solving:
\[ I_w = J_1 = 1.8555.3\angle-89^\circ \text{ A} ; \]
\[ I_w = J_2 = 1.7876.3\angle-91^\circ \text{ A} . \]

Electromotive forces \( E_{w2c} \) is \( E_{w2c} \), induced by B2 and A2 phases SPhSC currents \( I_{GD1} = 20.75.\angle162.3^\circ \text{ kA} \) and \( I_{SCA2} = 20.75.\angle77.5^\circ \text{ kA} \), calculated by equation (3) are \( E_{w2c} = 1.876.3\angle59^\circ \text{ V} \) and \( E_{w2c} = 1.734.2\angle178^\circ \text{ V} \), that is lower than \( E_{w2c} = 2.085.6.59.68^\circ \text{ V} \). Therefore the currents in LW under phases B2 and A2 SPhSC are low 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 \( I_{SC2} = 0.5, 5 \text{ and } 10 \text{ km distance from S2. For example, consider phase C2 220 kV OTL SPhSC with FOLW-sh-1-24(G.652)-18.7/93 following at } I_{SC2} = 5 \text{ km distance (see Figure 5).} \)

Fig. 5. The scheme of current in LW calculation under SPhSC at \( I_{SC2} = 5 \text{ km distance from S2.} \)

\[ I_{SC2} = 15.74 \angle 39.1^\circ \text{ kA current applies to } 15 \text{ LW spans from S2 side, and in the each span induces electromotive force } E_{w2c} = 1.582.1 + 59.5^\circ \text{ V according to equation (3). A system of equations write by the method of contour currents:} \]

\[
\begin{align*}
J_1 (Z_w + Z_e + R_{GD1} + R_{GD2}) - J_2 R_{GD2} &= E_{w2c} ;
\end{align*}
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

\[
- J_1 R_{GD2} + J_2 (Z_w + Z_e + 2R_{GD2}) - J_1 R_{GD2} &= E_{w2c} ;
\]

The data for system of equations (5):
\[ Z_w + Z_e + R_{GD1} + R_{GD2} = 10.580 + j0.2375 \text{ Ohm} ; \]
\[ Z_w + Z_e + 2R_{GD2} = 20.080 + j0.2375 \text{ Ohm} ; \]
\[ Z_{NE} = 1.245 + j0.809 \text{ Ohm} ; \]
\[ Z_w + Z_e + R_{GD2} + Z_{NE} = 11.334 + j1.0465 \text{ Ohm} ; \]
\[ R_{GD1} = 0.5 \text{ Ohm} ; \]
\[ R_{GD2} = 10 \text{ Ohm} . \]

Solving the system (5), we obtain the values of induced in LW currents:
\[ I_{w1} = 4.981\angle-114.0^\circ \text{ A} ; \]
\[ I_{w2} = 5.178\angle-114.1^\circ \text{ A} ; \]
\[ I_{w3} = 5.325\angle-114.3^\circ \text{ A} ; \]
\[ I_{w4} = 5.424\angle-114.5^\circ \text{ A} ; \]
\[ I_{w5} = 5.475\angle-114.7^\circ \text{ A} ; \]
\[ I_{w6} = 5.480\angle-114.9^\circ \text{ A} ; \]
\[ I_{w7} = 5.440\angle-115.1^\circ \text{ A} ; \]
\[ I_{w8} = 5.353\angle-115.3^\circ \text{ A} ; \]
\[ I_{w9} = 5.221\angle-115.6^\circ \text{ A} ; \]
\[ I_{w10} = 5.042\angle-115.9^\circ \text{ A} ; \]
\[ I_{w11} = 4.817\angle-116.6^\circ \text{ A} ; \]
\[ I_{w12} = 4.544\angle-117.3^\circ \text{ A} ; \]
\[ I_{w13} = 4.226\angle-118.7^\circ \text{ A} ; \]
\[ I_{w14} = 3.863\angle-120.6^\circ \text{ A} ; \]
\[ I_{w15} = 3.463\angle-123.9^\circ \text{ A} . \]

The greatest value of induced in LW current modulus falls in the sixth span, where \( I_{wmax} = I_{w6} = 5.480 \text{ kA} \), 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 \( I_{wmax} \) under C2 phase SPhSC at \( I_{SC2} = 0.5, 1, 2, 3, 4, 5, 7.842 \text{ and } 10 \text{ km distances from S2 for FOLW-sh-1-24(G.652)-18.7/93 and FOLW-c-1-24(G.652)-12/94 (with the greatest differences in nominal radii } r_{wLW} \text{ and resistivities } R_{LW}). \)
Table 2 given distances $I_{SC2}$ of SC points, number of spans $P_{SC}$, exposed by SC current magnetic field (MF), the values of C2 phase SC current $I_{SC2}$ as well as electromotive force $E_{WC2}$, induced in FOLW span by current $I_{SC2}$ MF. Current module histograms $I_{wmax}$ shown in Figure 6.

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

| $I_{SC2}$, km | $P_{SC}$ | $I_{SC2}$, kA | $E_{WC2}$, V |
|---------------|---------|--------------|-------------|
| 0.5           | 2       | 20.75 ≈ 41.8° | 2.085.6 ≈ 56.8° |
| 1             | 3       | 19.96 ≈ 41.6° | 2.006.2 ≈ 57.0° |
| 2             | 6       | 18.69 ≈ 41.0° | 1.878.6 ≈ 57.6° |
| 3             | 9       | 17.56 ≈ 40.4° | 1.765.0 ≈ 58.2° |
| 4             | 12      | 16.57 ≈ 39.9° | 1.665.5 ≈ 57.8° |
| 5             | 15      | 15.47 ≈ 39.1° | 1.582.1 ≈ 59.5° |
| 7.842         | 24      | 13.60 ≈ 38.5° | 1.367.0 ≈ 60.1° |
| 10            | 31      | 12.42 ≈ 37.7° | 1.248.4 ≈ 60.9° |

Fig. 6. Current module $I_{wmax}$ change dependence on $I_{SC2}$ 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 $I_{SC2}$ increase the number of LW span exposed to $I_{SC2}$ 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 $I_{SC2}$ distance increase leads to SC current module $I_{SC2}$ 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 $I_{SC2} < 5$ km, and for distances $I_{SC2} > 5$ km process of $I_{SC2}$ current value decrease as well as current decrease prevail. Thus when $I_{SC2} = 5$ km $I_{wmax}$ current reaches its greatest value $I_{wmax} = 5480$ A for FOLW -sh-1-24(G.652)-18.7/93 and $I_{wmax} = 3100$ 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 $I_{SC2} = 5$ km from S2 there are simultaneous SC self-title phases C1 and C2 on the earth (see Figure 7).

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 $E_{CS2} = 127,017 ≈ 120°$ V.

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

- $I_1 = 18,194.5 ≈ 38.6°$ A; $I_1 = 9,097.2 ≈ 38.6°$ A;
- $I_2 = 9,097.2 ≈ 38.6°$ A.

Phase C1 and C2 SC currents are equal: $I_{SC1} = I_{SC2} = 9,097.2 ≈ 38.6°$ 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: $a_{WC1} = 3.680$ m, and between LW and 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): $E_{WC1} = 902.1 = 60.1°$ V, $E_{WC2} = 914.4 ≈ 60.0°$ V.

Resulting voltage induced in LW by C1 and C2 phases SPhSC currents is: $E_{WC} = E_{WC1} + E_{WC2} = 1816.5 ≈ 60.0°$ V, and it substitute electromotive force (voltage) $E_{WC}$ 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 $E_{WC}$ and solving it, we obtain the values of induced in LW currents:

- $I_{w1} = 5,722 ≈ 114.5°$ A; $I_{w2} = 5,948 ≈ 114.7°$ A;
- $I_{w3} = 6,117 ≈ 114.8°$ A; $I_{w4} = 6,231 ≈ 115.0°$ A;
- $I_{w5} = 6,290 ≈ 115.2°$ A; $I_{w6} = 6,296 ≈ 115.4°$ A;
- $I_{w7} = 6,249 ≈ 114.6°$ A; $I_{w8} = 6,150 ≈ 115.8°$ A;
- $I_{w9} = 5,997 ≈ 116.1°$ A; $I_{w10} = 5,792 ≈ 116.4°$ A;
- $I_{w11} = 5,533 ≈ 117.0°$ A; $I_{w12} = 5,220 ≈ 117.8°$ A;
- $I_{w13} = 4,854 ≈ 119.1°$ A; $I_{w14} = 4,437 ≈ 121.1°$ A;
- $I_{w15} = 3,978 ≈ 124.4°$ A.
The greatest value of induced in LW current module is at the 6th span, where $I_{w6} = 6.296$ kA, and according to Table 1, FOLW-sh-1-24(652)-18.7/93 1 s withstand the 18.7 kA short-circuit current, i.e can operate with more than a double margin for thermal resistance.

6 Currents induced in LW by magnetic field of 220 kV OTL, operating in the connected mode, but without power transfer SPhSC

Figure 8 shows the scheme of calculation the currents in case of 220 kV double-circuit OTL, operating in the connected mode, but without power transfer, C2 phase SPhSC. SC point is located at 5 km distance from S2.

![Diagram of C2 phase SPhSC](image1)

**Fig. 8.** The scheme of calculation the currents in case of 220 kV double-circuit OTL, operating in the connected mode, but without power transfer, C2 phase SPhSC.

C2 phase $l = 46.956$ km length consists of 142 spans and is divided into two parts: $l_1 = 5$ km from S2 to SC point contains 15 spans, and $l_2 = 41.956$ km from SC point to S1 contains 127 spans. Since the capacitive resistances between phase and SC arc earth of C2 phase both parts are shunted by resistance $R_p = 0.42$ Ohm, currents in capacitive resistances (tens of kOhm) are neglected. C1 phase is represented by T-shaped replacement circuit. $I_3$ and $I_4$ currents are oppositely directed, $I_1$ and $I_5$ currents are in the same direction, but opposite $I_3$ current.

Figure 8 scheme parameters: $R_{Phb} = 0.073$ Ohm/km, $L_{GC1} = L_{GC2} = 0.141-10$ H/km, $C_{GC1} = 0.8379-10^{-8}$ F/km, $R_{C21} = R_{Phb}l_1 = 0.365$ Ohm, $R_{C22} = R_{Phb}l_2 = 3.063$ Ohm, $X_{GC21} = oL_{GC2}l_1 = 2.213$ Ohm, $X_{GC22} = oL_{GC2}l_2 = 18.751$ Ohm, $0.5X_{GC1} = 10.392$ Ohm, $0.5R_{C1} = 1.714$ Ohm, $X_{GC1} = 8.0904$ Ohm, $E_{C31} = 127.017\angle120^\circ$ V.

On the subroutine "Stationary electric circuit" of the program "WMRUS" we get the values of currents in the branches for C2 phase SPhSC:

$I_1 = 14.983\angle42.5^\circ$ A; $I_2 = 5.815\angle42.0^\circ$ A;

$I_3 = 18.608\angle42.6^\circ$ A; $I_4 = 1.822\angle41.8^\circ$ A;

$I_5 = 20.806\angle42.4^\circ$ A; $I_6 = 7.29\angle155.6^\circ$ A;

$I_7 = 4.000\angle42.0^\circ$ A; $I_8 = 1.815\angle41.8^\circ$ A.

Figure 9 shows the diagram of the phases C1 and C2 with SC currents, combined with the circuit grounded at the ends of wire W spans.

![Diagram of C1 and C2 phases with SC currents](image2)

**Fig. 9.** The diagram of C1 and C2 phases with SC currents, combined with the circuit grounded at the ends of LW spans.

$E_{WC21} = $ voltage in LW from $I_1$ current C2 phase part $l_1$, $E_{WC21} = $ voltage in LW from $I_4$ current C1 phase part $l_1$, $E_{WC22} = $ voltage in LW from $I_7$ current C2 phase part $l_2$, $E_{WC22} = $ voltage in LW from $I_8$ current C2 phase part $l_2$.

For scheme shown in Figure 9, by the method of contour currents we obtain:

$$J_1 (Z_W + Z_r + R_{GDS} + R_{GD}) - J_2 R_{GD} = E_{WC1};$$

$$-J_2 R_{GD} + J_1 (Z_W + Z_r + 2R_{GD}) - J_1 R_{GD} = E_{WC1};$$

$$-J_1 R_{GD} + J_2 (Z_W + Z_r + 2R_{GD}) - J_1 R_{GD} = E_{WC2};$$

$$-J_1 R_{GD} + J_2 (Z_W + Z_r + 2R_{GD}) - J_1 R_{GD} = E_{WC2}.$$  

(6)

Voltage (electromotive force) values:

$E_{WC21} = 1.689\angle56.2^\circ$ V; $E_{WC21} = 180.9\angle56.9^\circ$ V; $E_{WC22} = 402.0\angle56.6^\circ$ V; $E_{WC22} = 180.2\angle56.9^\circ$ V; $E_{WC21} = 1.508\angle56^\circ$ V; $E_{WC22} = 582\angle57^\circ$ V.

Resistance values:

$Z_W + Z_r + R_{GDS} + R_{GD} = 10.580 + j0.2375$ Ohm; $Z_W + Z_r + 2R_{GD} = 20.080 + j0.2375$ Ohm; $Z_W + Z_r + R_{GD} + Z_{NE} = 11.334 + j1.0465$ Ohm; $Z_{NE} = 1.245 + j0.809$ Ohm; $R_{GDS} = 0.5$ Ohm; $R_{GD} = 10$ Ohm.

Solving the system of equations (6), we obtain the currents in LW $I_{w1} = J_1$. Current $I_{w1}$ modules distribution along OTL is shown in Figure 10.

220 kV OTL operating in the connected mode at both ends, but without power transfer SPhSC at 5 km distance from S2 leads to induce in LW current with maximal module value $I_{wmax} = 5,152$ A in 5th span, but it is less than $I_{wmax} = 5,480$ A under SPhSC in the same OTL in no-load mode.

![Diagram of current modules $I_{w1}$ distribution along 220 kV OTL](image3)

**Fig. 10.** Current modules $I_{w1}$ distribution along 220 kV OTL.
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 line 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: \( R_{C2} + jX_{LW} \) – 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; \( Z_{res} \) – mutual inductive reactance C2 phase and LW in span, obtained by equation (2); \( R_{SW} + jX_{SW} \) – network resistance for S2; \( Z_{NE} \) – resulting resistance after wire passive two-terminal network folding withresulting extreme opposition parallel current pasing to the line of two-phase wire reversion contacts. Further, 

\[
\begin{align*}
I_{SC} &= \frac{1}{R_{GD} + jX_{GD}} \\
I_{LW} &= \frac{1}{R_{GD} + jX_{GD}} \\
I_{P} &= \frac{1}{R_{GD} + jX_{GD}} \\
I_{P2} &= \frac{1}{R_{GD} + jX_{GD}}
\end{align*}
\]

Let us formulate a system of equations by the method of simultaneous method of current modules:

\[
\begin{align*}
J_1 &+ J_{C}(I_{C1} + \frac{15(I_{C2} + I_{C1})}{15} + I_{C2}) + J_{LW}(I_{LW1} + \frac{15(I_{LW2} + I_{LW1})}{15} + I_{LW2}) = 0.1053 \frac{A}{km} \\
J_2 &+ J_{C}(I_{C1} + \frac{15(I_{C2} + I_{C1})}{15} + I_{C2}) + J_{LW}(I_{LW1} + \frac{15(I_{LW2} + I_{LW1})}{15} + I_{LW2}) = 0.1053 \frac{A}{km} \\
J_3 &+ J_{C}(I_{C1} + \frac{15(I_{C2} + I_{C1})}{15} + I_{C2}) + J_{LW}(I_{LW1} + \frac{15(I_{LW2} + I_{LW1})}{15} + I_{LW2}) = 0.1053 \frac{A}{km}
\end{align*}
\]

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

\[
\begin{align*}
I_{F1} &= 14.098 \angle 43.5^\circ \frac{A}{km} \\
I_{W1} &= 6.876 \angle 133.6^\circ \frac{A}{km} \\
I_{W2} &= 5.650 \angle 131.0^\circ \frac{A}{km} \\
I_{W3} &= 5.679 \angle 130.3^\circ \frac{A}{km} \\
I_{W4} &= 5.421 \angle 129.2^\circ \frac{A}{km} \\
I_{W5} &= 5.169 \angle 128.0^\circ \frac{A}{km} \\
I_{W6} &= 4.920 \angle 126.9^\circ \frac{A}{km} \\
I_{W7} &= 4.668 \angle 125.8^\circ \frac{A}{km} \\
I_{W8} &= 4.400 \angle 124.9^\circ \frac{A}{km}
\end{align*}
\]

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 - \( I_{SC2} \), maximal currents in LW - \( I_{Wmax} \), allowable currents of heat resistance - \( I_{SCLW} \), and margin \( \Delta I \) by heat resistance current for all chosen FOLW types.

| FOLW brand | \( I_{SC2} \), kA | \( I_{Wmax} \), kA | \( I_{SCLW} \), kA | \( \Delta I \), 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-e-1-48(G.652)-12/94 | 13.669 | 3.993 | 5.6 | 1.61 |

Reference

1. M.V. Kostenko, L.S. Perelman, Yu.P. Shkarin Wave processes and electrical disturbances in multi-wire high-voltage lines. Energy. M., 272, (1973).
2. G.N. Tsitsikian Electromagnetic compatibility in power industry. ELMOR. St.-Petersburg, 184, (2007).
3. Guidelines for the calculation of short-circuit currents and the selection of electrical equipment. GI53-34.0-20.527-98. Energia. M., 83, (1998).
4. M.Sh. Misirlikhanov, Yu.A. lostson, N.B. Ribtsova, Computer program “Electromagnetic parameters of overhead transmission lines № 2006613744, 27.10.2006.
5. A.Yu. Torkarskiy, N.B.Rubtsova Distribution of voltage induced by parallel transmission line along dead and grounded line. Safety in the Technosphere, 4 (June-July), 32-38, (2015).