Currents and Voltages Induced by Electric Field in Two Converging Single-wire Overhead Transmission Lines

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Abstract. The calculations of induced by electric field voltage and current for i line grounded and ungrounded ends depending on p - line convergence part length, a0 minimal distance between convergence lines, and Θ - the angle of lines convergence. Limit values of ρ, a0 and Θ are determined, one of which disturbance allows to neglect the electric effect of converging transmission lines.

Introduction

Personnel working on overhead transmission lines (OTL) under induced voltage health maintenance requires these voltages limit values compliance. These requirements compliance ensure is possible by use the developed algorithms for calculation the current and voltage distribution along the disconnected grounded single-wire (single-phase) i line, induced by electric field (EF) of operating single-wire (single-phase) k line, converging with the i line under Θ angle.

1 Partial capacitance between convergent single-wire i and k lines

Consider first two parallel single-wire i and k OTLs located from each other at a distance and at h_i = h and h_k = H height above the ground (Figure 1, 1a). Figure 1b shows the scheme of i and k single-wire OTLs connection between lines and with the ground by partial capacitances.

C_{i0}, C_{i0 i} and C_{k0} specific partial capacitances are determined by Maxwell’s formulas first group potential factors use (1).

\[
\alpha_{i1} = \alpha_{i2} = \frac{1}{2\pi\varepsilon_0} \ln \frac{2H}{R}, \quad \alpha_{22} = \alpha_i = \frac{1}{2\pi\varepsilon_0} \ln \frac{2R}{r} \quad \left\{ \begin{array}{l}
\alpha_{12} = \alpha_{21} = \alpha_{i2} = \alpha_a = \frac{1}{2\pi\varepsilon_0} \ln \frac{\sqrt{a^2 + (H + h)^2}}{\sqrt{a^2 + (H - h)^2}}.
\end{array} \right.
\]

(1)

where: H and h are the heights above the ground; R and r are k and i line wires radiuses, respectively.

Potential factors α matrix has the form (2):

\[
\alpha = \begin{bmatrix} \alpha_{i1} & \alpha_{i2} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}.
\]

(2)

Matrix α inversion leads to obtain the Maxwell’s formulas second group potential factors β matrix (3):

\[
\beta = \begin{bmatrix} \beta_{i1} & \beta_{i2} \\ \beta_{21} & \beta_{22} \end{bmatrix} = \begin{bmatrix} \alpha_{i1} & \alpha_{i2} \\ \alpha_{21} & \alpha_{22} \end{bmatrix}^{-1} = \alpha^{-1}.
\]

(3)

Potential factors have dimension is meter per farad [m/F], and capacity factors dimension is farad per meter [F/m].

Consider lines k and i, converging at Θ angle (Figure 2).

Potential factors α matrix has the form (2):

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(3)

Potential factors have dimension is meter per farad [m/F], and capacity factors dimension is farad per meter [F/m].

Consider lines k and i, converging at Θ angle (Figure 2).
line, and so at the and α(p) of line we know k u i Θ converging angle, because:

\[ \Theta = \arctg \left( \frac{a(p) - a_{0}}{p} \right) = \arctg \frac{\Delta a(p)}{p}. \]

Let’s count, that \( a_{0} = 5 \text{ m} \) and \( a(p) = 100 \text{ m} \). Limes \( k \) and \( i \) parameters are: \( H = 19 \text{ m}, h = 17.5 \text{ m}, R = r = 0.014 \text{ m} \). Partial capacity values between \( k \) and \( i \) lines are determined by the expression \([1, 2] C_{ki} = -\beta_{k1} = -\beta_{i2} = -\beta_{1}\), then on expressions (1) \((1) \) we obtain \( C_{ki}(a) \) values with \( a \) change from 5 m to 100 m in 5 m increments, as it is shown in table 1.

It should be noted that to obtain the values of partial capacities between phases and lighting wires of converging working and disconnected three- or more-phase power lines, \( C_{ki}(a) \) value calculation must be carried out taking into account all of these OTL phases and lighting wires. \( C_{ki}(a) \) values can be calculated for case from one to six three-phase OTL by computer program “OTL EMF” [3].

Table 1. Capacity \( C_{ki}(a) \) values depending on the distance \( a \), obtained by the expressions (1) \((1) \) \((1) \). (3)

| \( a \), m | \( C_{ki}(a) \), \( \times 10^{-12} \) F/m | \( a \), m | \( C_{ki}(a) \), \( \times 10^{-12} \) F/m | \( a \), m | \( C_{ki}(a) \), \( \times 10^{-12} \) F/m | \( a \), m | \( C_{ki}(a) \), \( \times 10^{-12} \) F/m |
|---|---|---|---|---|---|---|---|
| 5 | 1.8704 | 30 | 0.4081 | 55 | 0.1863 | 80 | 0.08477 |
| 10 | 1.2197 | 35 | 0.3304 | 60 | 0.1412 | 85 | 0.07386 |
| 15 | 0.8774 | 40 | 0.2718 | 65 | 0.1229 | 90 | 0.06826 |
| 20 | 0.6614 | 45 | 0.2258 | 70 | 0.1078 | 95 | 0.06172 |
| 25 | 0.5137 | 50 | 0.1916 | 75 | 0.09529 | 100 | 0.05606 |

To represent \( C_{ki}(a) \) capacity value changes from \( a \) distance in the graphical form, fill in the MathCAD the matrix named \( Z \), containing one row and \( c = 20 \) columns, \( C_{ki} \) values from the table. 1. Next, we transform it into column matrix and, choosing the boundaries and the step of \( y \) argument changing we obtain \( Z_{j} \) curve with \( C_{ki} \) values linear interpolation. To smooth \( Z_{j} \) curve, create \( ZZ(y) \) function and set the limits and the step of argument \( a \) changing (4):

\[
\begin{align*}
\text{ORIGIN} & : = 1 \\
Z & : = (1.8704 \ \ 1.2197 \ \ \ldots \ \ 0.06172 \ \ 0.05606) \\
Z & : = Z' \cdot 10^{-12} \ \ c := 20 \ \ y' := y \cdot 5 \ \ ZZ(\alpha) := \text{interp}(\text{cspline}(y,Z),y,a) \ \ a = 5.5 \ldots 1.100
\end{align*}
\]

\( ZZ(\alpha) \) function allows carrying out numerical mathematical operations with it, but it is not analytically determined. Define an analytical expression for \( C_{ki}(a) \) capacity value.

For this purpose, in MathCAD, using the expressions (1) and (2) at \( \varepsilon_{0} = \varepsilon \), we carry out the operation of matrix \( \alpha \) analytical inversion analytical equal sign \((\rightarrow)\) using:

\[
\alpha^{-1} \rightarrow \ln \left[ \frac{\sqrt{a^{2} + H^{2} + 2Hh + h^{2}}}{\sqrt{a^{2} + H^{2} - 2Hh + h^{2}}} \right] - \ln \frac{2H}{R} \ln \frac{2h}{r}
\]

\[
\times \ln \frac{2h}{r} - \ln \left[ \frac{\sqrt{a^{2} + H^{2} + 2Hh + h^{2}}}{\sqrt{a^{2} + H^{2} - 2Hh + h^{2}}} \right] - \ln \frac{2H}{R} \ln \frac{2h}{r}
\]

Then analytically obtained \( C_{ki}^{an}(a) \) capacity value can be written (5):

\[
C_{ki}^{an}(a) = \frac{2\pi \ln \left[ \frac{\sqrt{a^{2} + H^{2} + 2Hh + h^{2}}}{\sqrt{a^{2} + H^{2} - 2Hh + h^{2}}} \right] - \ln \frac{2H}{R} \ln \frac{2h}{r}}{\ln \frac{2h}{r} - \ln \left[ \frac{\sqrt{a^{2} + H^{2} + 2Hh + h^{2}}}{\sqrt{a^{2} + H^{2} - 2Hh + h^{2}}} \right] - \ln \frac{2H}{R} \ln \frac{2h}{r}}
\]

\( C_{ki}^{an}(a) \) function disadvantage is complexity, and complexity degree increases dramatically with increasing number of converging lines.

Will hold a rough interpolation (approximation) \( ZZ(\alpha) \) curve function (6) using:

\[
C_{ki}^{an}(a) = d \cdot e^{b(\alpha - 5)} + \frac{d}{1 - v \cdot (\alpha - 5)}
\]

Let us take follows values of \( d, b \) and \( v \) indexes:
\( d = ZZ(\alpha) = 0.935 \cdot 10^{-12} \), \( b = -0.6 \) \( v = -0.15 \). Figure 3a shows \( ZZ(\alpha) \) and \( C_{ki}^{an}(a) \) functions distribution curves, and Figure 3b shows \( ZZ(\alpha) \) and \( C_{ki}^{an}(a) \) distribution under \( a \) change from \( 5 \text{ m} \) to \( 100 \text{ m} \) with 5 m.

![Fig. 3. ZZ(\alpha) and C_{ki}^{an}(a) functions change curves (a), as well as ZZ(\alpha) and C_{ki}^{an}(a) (b)](image-url)
Thus, when calculating transverse voltage induced on the disconnected and grounded single-wire \( i \) line by converging single-wire \( k \) line electric field, partial capacity between these lines, depending on the distance between them, can be described by \( C_{iwk}(a) = ZZ(a) \), \( C_{iwk}(a) \) and \( C_{wki}(a) \) functions.

## 2 Currents and voltages distribution along grounded at one end \( i \) line converging to \( k \) line

OTL \( k \) \( l_k \) length is in idle mode under voltage \( \bar{U}_k = \bar{E}_k = 127 \) kV, and \( i \) line \( l_i < l_k \) length is disconnected and grounded at one end remote from \( k \) line substation (in this case, the left end) (Figure 4).

Fig. 4. OTLs converging at \( \Theta \) angle: operating \( k \) line and \( i \) line disconnected and grounded at one end remote from substation

Descriptions in Figure 4:
\[ Z_{w0} = R_{w0} + j \omega L_{w0} \] - is \( i \) line specific active-inductive resistance (Ohm/km); \[ Z_{0e} = \text{Re} \left[ \omega Z_{w0} \right] \] - is earth resistivity (Ohm/km); \( R_{GD} \) - is grounding device (GD) resistance (Ohm); \[ Z_{a0} \] - is own \( i \) line wire specific inductive resistance by Carson (Ohm/km) [4-6]:
\[ Z_{a0}^{(\text{Car})} = \frac{j \omega \mu_0 10^6}{2 \pi} \ln \left[ \sqrt{2} \frac{\delta_i}{r_{wi}} - j \frac{\pi}{4} + \frac{4 h_{wi}}{3} \delta_i (1 + j) \right] - 0.0772 \]

Where: \( \omega = 2 \pi f \) - angular frequency, \( f = 50 \) Hz; \( \mu_0 = 4 \pi 10^{-7} \) H/m - permeability of vacuum; \( r_{wi} \) - \( i \) line wire radius, \( m \); \( \delta_i = \sqrt{2} p_i / \omega \mu_0 \) - penetration depth, \( m \); \( \rho_3 \) - earth resistivity, Ohm\( \cdot \)m; \( h_{wi} \) - \( i \) wire height above the earth. For case \( \rho_3 = 100 \) Ohm\( \cdot \)m \[ Z_{a0}^{(\text{Car})} = 0.0473 + j0.716 \text{ Ohm/km}, \] wire resistivity \( R_{w0} = 0.074 \text{ Ohm/km}, R_{GD} = 10 \text{ Ohm}. \]

The distance \( a(l) \) between \( k \) and \( i \) OTLs change (Figures 2 and 5) is described by the expression (7):
\[ a(l) = a_0 + \Delta a(l) = a_0 + l \cdot \tan \Theta. \]
Fig. 6. Current module \( I(l) \) distribution of \( ZZ(a(l)) \), \( C(l)_{k0}^{ext} \) and \( C(l)_{l0}^{ext} \) at \( p = 100 \) km; \( a_0 = 5 \) m, \( \Delta a(p) = 100 \) m: (a) converging \( k \) and \( l \) lines; (b) at \( p = 100 \) km, \( a_0 = 5 \) m, \( \Delta a(p) = 0 \) m 0

Figure 7 shows the distribution of voltages \( U_{A}(l) \) and \( U_{ab}(l) \) modules (a) and arguments (b) of \( ZZ(a(l)) \), \( C(l)_{k0}^{ext} \) and \( C(l)_{l0}^{ext} \) at \( a_0 = 5 \) m, \( \Delta a(p) = 100 \) m, \( p = 100 \) km.

Consider the case of \( i \) line grounded at near to \( k \) line right end (Figure 8).

![Fig. 8](image)

Fig. 8. The scheme of converging at \( \Theta \) angle \( k \) and \( i \) OTLs with \( i \) line grounded at right end

\[ I(l) \] current in graphic, analytical and interpolation forms are presented in (8):

\[
\begin{align*}
I(l) &= \int_0^l dI(l) = j\omega E_k \int_0^l ZZ(a(l))dl = \\
&= j\omega E_i \int_0^l C(l)_{k0}^{ext} dl = j\omega E_i \int_0^l C(l)_{l0}^{ext} dl.
\end{align*}
\] (8)

Since there is no current in \( Z_{e0} \) resistance, the voltage is \( U_{ab}(l) = U_{A}(l) \):

\[
U_{ab}(l) = U_{A}(l) = Z_{e0} \int_0^l I(l)dl + \hat{I}(p)R_{cd}.
\] (9)

Figure 9 shows \( I(l) \) current module distribution along grounded at left end \( i \) line \( l_i = p = 100 \) km length, calculated for \( ZZ(a(l)) \), \( C(l)_{k0}^{ext} \) and \( C(l)_{l0}^{ext} \) capacities: at \( a_0 = 5 \) m, \( \Delta a(p) = 100 \) m and \( \Theta = 0.0573^\circ \) angle (a); as well as for parallel \( i \) and \( k \) lines at \( a_0 = 5 \) m, \( \Delta a(p) = 0 \) m and \( \Theta = 0^\circ \) angle (b).

![Fig. 9](image)

Fig. 9. Current module \( I(l) \) distribution for \( ZZ(a(l)) \), \( C(l)_{k0}^{ext} \) and \( C(l)_{l0}^{ext} \): (a) converging \( i \) and \( k \) lines at \( p = 100 \) km, \( a_0 = 5 \) m, \( \Delta a(p) = 100 \) m; (b) parallel lines at \( p = 100 \) km, \( a_0 = 5 \) m, \( \Delta a(p) = 0 \) m.
Figure 10 shows voltages $\hat{U}_A(l) = \hat{U}_{ab}(l)$ modules (a) and arguments (b) distribution for $\hat{Z}(a(l))$, $C(l)_{\text{e}}^{\text{m}}$ and $C(l)_{\text{m}}^{\text{m}}$ at $a_0 = 5$ m, $\Delta a(p) = 100$ m, $p = 100$ km.

Voltage module $\hat{U}_{ab}(l) = \hat{U}_{ab}(0)$ at the ungrounded $i$ line end, when it is grounded at far from $k$ line end (Figure 8), exceed 2.4 times voltage module $\hat{U}_{ab}(l) = \hat{U}_{ab}(p)$ value at ungrounded $i$ line end (Figure 7a) when it is grounded at near to with $k$ line end (Figure 5). This is mathematically explained by larger area under the curve $\hat{I}(l)$ in Figure 9a, than in Figure 7a, calculated by the integral $\hat{I}(l)dl$, included in the expression of voltage $\hat{U}_A(l) \& \hat{U}_{ab}(l)$. The physical explanation is that in case of $i$ line grounded at far from $k$ end induced current $\hat{I}(l)$ module from the beginning to the end of $l$ line is higher than in case of $i$ line grounded at near $k$ line end.

3 Currents and voltages of grounded at one end $i$ line depending on length $l=p$, angle of convergence $\Theta$ and minimal distance $a_0$ between $k$ and $i$ lines

Consider the case of $i$ line grounding at far from $k$ line end (Figure 8), when induced voltage in ungrounded end of $i$ line is most significant.

In expression (7) a function variables will be $a_0$, $l$ and $\Theta$: $a(a_0,l,\Theta)$. Partial capacity between lines we present in analytical form: $C_{\text{e}}^{\text{m}}(a) = C_{\text{m}}^{\text{m}}(a)$. Substituting $a(a_0,l,\Theta)$ function in expression (5) instead of variable $a$ get $C_{\text{e}}^{\text{m}}(a_0,l,\Theta)$. Similarly, by introducing additional variables into formulas (7) and (8), we obtain equations for current and voltage: $\hat{I}(a_0,l,\Theta)$ and $\hat{U}_{ab}(a_0,l,\Theta)$.

Take the angle $\Theta = 0.0573^\circ$. Figure 11 shows the distribution of current modules $\hat{I}(a_0,l=p,\Theta)$ (a) and voltage modules $\hat{U}_A(a_0,l=p,\Theta) = \hat{U}_{ab}(a_0,l=p,\Theta)$ (b), for case of grounded $(l=p)$ $i$ line, as well as Figure 12 shows voltage $\hat{U}_A(a_0,l=0,\Theta) = \hat{U}_{ab}(a_0,l=0,\Theta)$ module values for case of ungrounded $(l=0)$ $i$ line end $l_i = p = 100, 50 \text{ and } 10 \text{ km}$ length with minimum distance $a_0$ between $k$ and $i$ lines change from 5 to 100 km.

Current module values in ungrounded end as well as voltage module values at both $i$ line end decreases rapidly for all line $p$ length values with $a_0$ increase.

Take the minimal distance $a_0 = 50$ m. Figure 13 shows current module values $\hat{I}(a_0=5,l=p,\Theta)$ (a), and voltage module values $\hat{U}_A(a_0=50,l=p,\Theta) = \hat{U}_{ab}(a_0=50,l=p,\Theta)$ (b) for all $l_i$ distribution for $i$ line $(l=p)$ $l_i = p = 100, 50$ and 10 km.
length grounded case with $\Theta$ angle change from $0^\circ$ to $1^\circ$. Figure 14 shows voltage module $U_A^i(a_0 = 50, l = 0, \Theta) = U_{ab}^i(a_0 = 50, l = 0, \Theta)$ values distribution for the same $i$ line ($l = 0$) ungrounded at the end.

![Figure 14: Voltage module values](image)

Fig. 13. Current module $I(50, p, \Theta)$ value (a); voltage module $U_A^i(50, p, \Theta) = U_{ab}^i(50, p, \Theta)$ (b), distribution for $i$ line ($l = p$) $l = p = 100, 50$ and 10 km length grounded case with $\Theta$ angle change from $0^\circ$ to $1^\circ$

![Figure 13](image)

Fig. 14. Voltage module values $U_A^i(50, 0, \Theta) = U_{ab}^i(50, 0, \Theta)$ distribution at ungrounded end of $i$ line ($l = 0$) with $l = p = 100, 50$ and 10 km length under $a_0 = 50$ m and $\Theta$ angle change from $0^\circ$ to $1^\circ$

![Figure 14](image)

Angle $\Theta$ increase from $0^\circ$ to $1^\circ$ at $a_0 = 50$ m leads to the same sharp decrease in current module values $I(50, p, \Theta)$, and in voltage module values $U_A^i(50, p, \Theta) = U_{ab}^i(50, p, \Theta)$ in grounded $i$ line end: for $p = 100$ km by 31 times, for $p = 50$ km by 16 times, and for $p = 10$ km by 4 times. Voltage module values $U_A^i(50, 0, \Theta) = U_{ab}^i(50, 0, \Theta)$ at $i$ line ungrounded left end reduced by less: for $p = 100$ km by 17.6 times, for $p = 50$ km by 10.2 times and for $p = 10$ km by 3.7 times.

Current and value changes curve have are similar but more expressed for the same conditions and minimal distance $a_0 = 5$ m (Figures 15 and 16).

![Figure 15](image)

Fig. 15. Current module $I(5, p, \Theta)$ distribution in grounded end ($l = p$) of $i$ line with $l = p = 100, 50$ and 10 km under $a_0 = 5$ m and $\Theta$ angle change from $0^\circ$ to $1^\circ$

![Figure 16](image)

Fig. 16. Voltage module values $U_A^i(5, p, \Theta) = U_{ab}^i(5, p, \Theta)$ distribution at the ends of $i$ line with length $l = p = 100, 50$ and 10 km under $a_0 = 5$ m and $\Theta$ angle change from $0^\circ$ to $1^\circ$: (a) grounded ($l = p$) and $U_A^i(5, 0, \Theta) = U_{ab}^i(5, 0, \Theta)$ line end; (b) ungrounded ($l = 0$) $\Theta$ angle increase from $0^\circ$ to $1^\circ$ under $a_0 = 5$ m leads to the same sharp decrease the values of current module $I(5, p, \Theta)$ and voltage module $U_A^i(50, p, \Theta) = U_{ab}^i(5, p, \Theta)$ of $i$ line grounded end: for $p = 100$ km by 85.8 times, for $p = 50$ km by 43.3 times and for $p = 10$ km by 9.3 times.

Herewith voltage module $U_A^i(5, 0, \Theta) = U_{ab}^i(5, 0, \Theta)$ values at ungrounded left end of $i$ line reduce by less: for $p = 100$ km by 46.3 times, for $p = 50$ km by 25.6 times and for $p = 10$ km by 8.4 times.

**Conclusion**

Calculation results synthesis shows that for partial capacity values between phases and cables of converging under voltage and unconnected three-phase lines determination $C_{\text{calc}}(a)$ calculation must be carrying out taking into account the phases and cables of all, both converging and parallel lines of the considered part.
Transfer from single-phase to three-phase designs, both under voltage and unconnected OTL leads to \( C_{\text{OTL}}(a) \) capacity value decrease from \( 1.87 \times 10^{-12} \) F/m (Table 1) to \( 1.43 \times 10^{-12} \) F/m under \( H = 19 \) m, \( h = 17.5 \) m and \( a = 5 \) m, that in result leads to induced current and voltage values in disconnected line decrease.

Given algorithms with superposition method use allow to determine the values of converging three-phase OTL induced voltage that lead to personnel' work reliability and safety elevation.

\( U_{\text{ab}} \) transverse voltage induced in \( i \) unconnected line by electric field of converging with it \( k \) line under voltage can be neglected in case of violation from the values of any tested parameters presented in table 2 as well as in [7]: the length of \( i \) line converging part \( l_i = p \), minimal distance \( a_0 \) between converging lines, convergence angle \( \Theta \).

### Table 2. Tested parameters values

| Parameter value for \( U_{\text{ab}} \) voltage possibility of neglect | \( U_{\text{ab}} \) voltage as well as another parameters |
|---|---|
| - The length of \( i \) line converging part \( l_i = p < 1 \) km | \( \hat{U}_k = 2 \) V at ungrounded end, even under \( a_0 = 5 \) m and converging angle \( \Theta = 0.0573^\circ \) (Figure 12) |
| - Minimal distance between converging lines \( a_0 \geq 100 \) m | Highest voltage value \( \hat{U}_k = 5.3 \) V at ungrounded end, even under \( l_i = p = 100 \) km and converging angle \( \Theta = 0.0573^\circ \) (Figure 12) |
| - Converging angle \( \Theta \geq 5^\circ \) (with reserve) | Highest voltage value \( \hat{U}_k = 6.2 \) V at ungrounded end, even under \( a_0 = 5 \) m, \( l_i = p = 100 \) km and \( \Theta = 1^\circ \) (Figure 16b) |

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