International Journal on
"Technical and Physical Problems of Engineering"
(IJTPE)
Published by International Organization of IOTPE

ISSN 2077-3528
IJTPE Journal
www.iotpe.com
ijtpe@iotpe.com

June 2022	Issue 51	Volume 14	Number 2	Pages 7-14

EFFECT OF LINE CORONATION ON OVERVOLTAGE IN TRANSFORMERS OF RATED VOLTAGE 330 KV

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Abstract- When over voltage waves arrive at substations from power lines, in their different points the value of the overvoltage magnitude becomes different. The value of these voltages at substation is determined by the parameters of the line wave, the structure of the substation, the protection scheme and the type of its equipment. The parameters of the waves in the lines change due to parameters of the line and the discharge that may occur in it. Crown discharge is one of these discharges in lines with an operating voltage of 330 kV and above, and when lightning strikes the line, the pulse generated in it due to over voltages. The occurrence of crown discharge changes the form of the voltage waves on the lines, and this change affects the over voltages on the lines and substations.

Keywords: Over Voltage, Crown Discharge, Transformer, High Voltage Lines, Higher Harmonics, Wave Impedance, Transients.

1. INTRODUCTION

Overvoltage waves arrive at substations from power lines, the magnitude of the overvoltage changes at different points. The magnitude of these voltages at the substation is determined by the parameters of the line wave, the structure of the substation, the protection circuit and the type of its equipment. The parameters of waves traveling along the lines, change depending on the parameters of the line and the events that can occur in it. Crown discharge is one of such case in lines with an operating voltage of 330 kV and above, and when lightning strikes the line, the pulse generated in then it is caused by extreme voltages. The occurrence of crown discharge changes the shape of the voltage waves exiting the lines, and this change affects the extreme voltages in the lines and substations. Therefore, the identification and assessment of such an impact on extreme voltages in lines and substations, especially in transformer windings became more interesting.

The article is devoted to the study of the crown discharge on extreme voltages in power lines and transformer windings. Research is carried out by mathematical modeling; the model of the crown discharge is determined first. When a crown discharge occurs around a line wire, the capacitance and conductance of the line increases, it means that the geometric capacitance and conductance values of the line are added to the instantaneous line voltage values and environmental parameters.

2. DETERMINATION OF THE CROWN EFFECT MODEL

The modeling of the crown effect is the replacement of variable capacitance and conductivity of sections of the line length with a corresponding crown discharge with parallel branches consisting of a series-connected capacitance and resistance of a fixed value. In this case, an increase in the number of parallel branches expands the frequency range, which makes it possible to use the considered model. In other words, the real line ensures that the frequency response of the model overlaps even at higher frequencies. Ensuring that the frequency characteristics of the real line and the model match is a very important requirement for the model to be usable.

The determination of the crown effect model is based on the improvement of the model proposed by the St. Petersburg Polytechnic University. When developing the proposed model, it was determined that if the model consists of 4 parallel branches, the overlap of the frequency characteristics of the line and the model is possible up to 1000 Hz, but up to 5000 Hz if it consists of 5 branches. In this study, since the impulse voltage is a 1.2/50 µS impulse voltage wave, we divide this impulse voltage by the Fourier series to determine that 5000 Hz covers this impulse for 90 µS days, until its amplitude will not decrease by 98%. So, to adopt a 5-branch model in the modeling of the crown discharge, to be considered sufficient to study the transition processes caused by the propagation of the pulse voltage wave in the resulting line where crown discharge occurs.

Considering the above, in the work under consideration, a model is used that contains parallel branches, one of which has only a capacitance, and the other three have a series-connected capacitance and resistance (Figure 1) [1]. A branch with one resistance takes into account the removal of electric charges from the line wire at the end of the crown discharge. The parameters of this model are determined from the condition of equality of the total conductivities of the line and the model.

The condition of coincidence of the frequency characteristics of the line and model is considered in the following form [1], [2].

$$j\omega_k C_1 + \sum_{s=2}\left(R_s + \frac{1}{j\omega_k C_s}\right)^{-1} + g_0 = G(\omega_k) + j\omega_k C(\omega_k) \quad (1)$$

where, k = 1, 2, 3, …, n; C_1, C_s, R_s, g_0 are model parameters.

The $G(\omega_k)$ and $C(\omega_k)$ are the line parameters corresponding ω_k frequency.

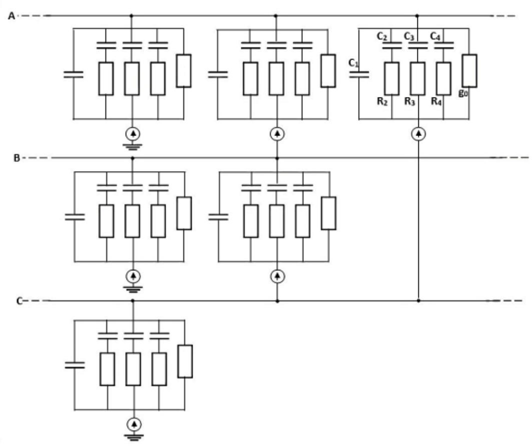

Figure 1. The scheme arrangement of the crown

The minimum number of branches of the model and its elements, overlap of frequency characteristics in a certain interval of frequency change at any instantaneous value of voltage on the line, parameters that provided at certain accuracy and is determined by form the n- Equation below for a given number of branches. These Equations are [1-3]:

$$\begin{cases} j\omega_1 C_1 + \sum_{s=2}^{n}\left(R_s + \frac{1}{j\omega_1 C_s}\right)^{-1} + g_0 = G(\omega_1) + j\omega_1 C(\omega_1) \\ j\omega_2 C_1 + \sum_{s=2}^{n}\left(R_s + \frac{1}{j\omega_2 C_s}\right)^{-1} + g_0 = G(\omega_2) + j\omega_2 C(\omega_2) \\ \ldots \\ j\omega_n C_1 + \sum_{s=2}^{n}\left(R_s + \frac{1}{j\omega_n C_s}\right)^{-1} + g_0 = G(\omega_n) + j\omega_n C(\omega_n) \end{cases} \quad (2)$$

The solution of the system (2) determines the parameters of the model's frequency characteristics at ω_1, ω_2 and ω_n frequency values when the frequency characteristics of the model and real line are the same [1], [2], [11] and [12].

2.1. Model Parameters Calculation

The analytical method is a more effective method for calculation of model parameters. However, increasing the number of parallel branches to provide required accuracy within a wide range of frequencies makes this calculation much more difficult. In this case, the use of the iteration method can be considered expedient.

Let's determine the model parameters for scheme shown in Figure 1. We need to find C_1, C_2, C_3, C_4, R_2, R_3, R_4 and g_0 parameters [1], [2].

$$\begin{aligned} & j\omega_k C_1 + \sum_{s=2}\left(R_s + \frac{1}{j\omega_k C_s}\right)^{-1} + g_0 = \\ & = G(\omega_k) + j\omega_k C(\omega_k) \\ & j\omega_k C_1 + \frac{j\omega_k C_2}{j\omega_k X_2 + 1} + \frac{j\omega_k C_3}{j\omega_k X_3 + 1} + \frac{j\omega_k C_4}{j\omega_k X_4 + 1} + g_0 = \\ & = G(\omega_k) + j\omega_k C(\omega_k) \end{aligned} \quad (3)$$

where, $X_2 = C_2R_2$, $X_3 = C_3R_3$ and $X_4 = C_4R_4$.

Let us assume that $Y_1 = X_2 + X_3 + X_4$, $Y_2 = X_2X_3 + X_2X_4 + X_3X_4$, $Y_3 = X_2X_3X_4$ [1], [2]. Therefore, Equation (3) can be represented as [12]

$$\begin{aligned} & -\omega_k^2\left[C_2(X_3+X_4)+C_3(X_2+X_4)+C_4(X_2+X_3)\right]+ \\ & +j\omega_k\left[C_2+C_3+C_4-\omega_k^2(C_2X_3X_4+C_3X_2X_4+C_4X_2X_3)\right]= \\ & =\left(G(\omega_k)-g_{\grave{a}}\right)\left(1-\omega_k^2 y_2\right)-\omega_k^2\left(C(\omega_k)-C_1\right)\left(y_1-\omega_k^2 y_3\right)+ \\ & +j\omega_k\left[\left(G(\omega_K)-g_{\grave{a}}\right)\left(y_1-\omega_k^2 y_3\right)+\left(C(\omega_k)-C_1\right)\left(1-\omega_k^2 y_2\right)\right] \end{aligned} \quad (4)$$

If we make such a substitution [15]

$$\begin{cases} \alpha = C_2(X_3+X_4)+C_3(X_2+X_4)+C_4(X_2+X_3) \\ \beta = C_2+C_3+C_4 \\ \gamma = C_2X_3X_4+C_3X_2X_4+C_4X_2X_3 \end{cases} \quad (5)$$

If we use substitution of Equation (5) in Equation (4), then we can write down as [2]

$$\begin{aligned} & -\omega_k^2\alpha + j\omega_k\left(\beta-\omega_k^2\gamma\right) = -\omega_k^2 C(\omega_k)y_1 + \\ & +C_1y_1\omega_k^2 - \omega_k^2 G(\omega_k)y_2 + g_0\omega_k^2 y_2 + \\ & +\omega_k^4 C(\omega)y_3 - \omega^4 C_1 y_3 + G(\omega_k) - g_0 + \\ & +j\omega_k\begin{bmatrix} G(\omega_k)y_1 - g_0y_1 - \omega_k^2 C(\omega_k)y_2 + \omega_k^2 C_1 y_2 \\ -\omega_k^2 G(\omega_k)y_3 + g_0\omega_k^2 y_3 + C(\omega_k) - C_1 \end{bmatrix} \end{aligned} \quad (6)$$

Let us write the true and imaginary parts in the expression (6) [1-3]

$$\begin{cases} -\omega_k^2\alpha = -\omega_k^2\left[C(\omega_k)y_1 + G(\omega_k)y_2 - \omega_k^2 C(\omega_k)y_3 - \right. \\ \left. -\omega_k^{-2}G(\omega_k)\right] + \omega_k^2\left[C_1y_1 + g_0y_2 - \omega_k^2 C_1 y_3 - \omega_k^{-2} g_0\right] \\ \beta - \omega_k^2\gamma = G(\omega_k)y_1 - \omega_k^2 C(\omega_k)y_2 - \omega_k^2 G(\omega_k)y_3 + \\ +\left[-g_0y_1 - \omega_k^2 C_1 y_2 + g_0\omega_k^2 y_3 + C(\omega_k) - C_1\right] \end{cases} \quad (7)$$

Let us do the substitution again as follows [1-3]

$$\begin{cases} N_1 = C_1Y_3 \\ N_2 = \alpha + C_1Y_1 + g_0Y_2 \\ N_3 = \beta + g_0 + C_1 \\ N_4 = \gamma + C_1Y_2 + g_0Y_3 \\ Y_4 = g_0 \end{cases}$$

then, we can write down the Equation (7) [6], [7]

$$\begin{cases} \omega_k^2 N_1 - N_2 = -C(\omega_k)Y_1 - G(\omega_k)Y_2 + \omega_k^2 C(\omega_k)Y_3 + \\ +\omega_k^{-2} G(\omega_k) - \omega_k^{-2} Y_4 \\ N_3 - \omega_k^2 N_4 = G(\omega_k)Y_1 - \omega_k^2 C(\omega_k)Y_2 + \\ +\omega_k^2 G(\omega_k)Y_3 + C(\omega_k) \end{cases} \quad (8)$$

From first part [1-3] of the Equation (8), we can get k = 1, 2, 3, 4, 5.

$$\omega_1^2 N_1 - N_2 = \omega_1^{-2} G(\omega_1) - C(\omega_1)Y_1 - G(\omega_1)Y_2 + \omega_1^2 C(\omega_1)Y_3 - \omega_1^{-2} Y_4$$
$$\omega_2^2 N_1 - N_2 = \omega_2^{-2} G(\omega_2) - C(\omega_2)Y_1 - G(\omega_2)Y_2 + \omega_2^2 C(\omega_2)Y_3 - \omega_2^{-2} Y_4$$
$$\omega_3^2 N_1 - N_2 = \omega_3^{-2} G(\omega_3) - C(\omega_3)Y_1 - G(\omega_3)Y_2 + \omega_3^2 C(\omega_3)Y_3 - \omega_3^{-2} Y_4$$
$$\omega_4^2 N_1 - N_2 = \omega_4^{-2} G(\omega_4) - C(\omega_4)Y_1 - G(\omega_4)Y_2 + \omega_4^2 C(\omega_4)Y_3 - \omega_4^{-2} Y_4$$
$$\omega_5^2 N_1 - N_2 = \omega_5^{-2} G(\omega_5) - C(\omega_5)Y_1 - G(\omega_5)Y_2 + \omega_5^2 C(\omega_5)Y_3 - \omega_5^{-2} Y_4$$

From the second Equation of (8), we can get [13]

$$-\omega_1^2 N_4 - N_3 = C(\omega_1) + G(\omega_1)Y_1 - \omega_1^2 C(\omega_1)Y_2 - \omega_1^2 G(\omega_1)Y_3$$
$$-\omega_2^2 N_4 - N_3 = C(\omega_2) + G(\omega_2)Y_1 - \omega_2^2 C(\omega_2)Y_2 - \omega_2^2 G(\omega_2)Y_3$$
$$-\omega_3^2 N_4 - N_3 = C(\omega_3) + G(\omega_3)Y_1 - \omega_3^2 C(\omega_3)Y_2 - \omega_3^2 G(\omega_3)Y_3$$
$$-\omega_4^2 N_4 - N_3 = C(\omega_4) + G(\omega_4)Y_1 - \omega_4^2 C(\omega_4)Y_2 - \omega_4^2 G(\omega_4)Y_3$$
$$-\omega_5^2 N_4 - N_3 = C(\omega_5) - G(\omega_5)Y_1 - \omega_5^2 C(\omega_5)Y_2 + \omega_5^2 G(\omega_5)Y_3$$

The solution of these Equations allows to determine parameters of the crown effect model [3]. The results of the calculations are given below

C_1 = 496, 5234 pF/km; R_2 = 0.6976 MΩ/km
C_2 = 1943, 1008 pF/km; R_3 = 0.11414 MΩ/km
C_3 = 917, 4673 pF/km; R_4 = 0.2223 MΩ/km
C_4 = 331, 7460 pF/km; g_0 = 0.5697 1/MΩ.km

2.2. The Calculation of Overhead Line Parameters

Parameters of the line can be calculated as below expressions [1]:

$$\begin{cases} G(\omega_k) = 0.83\left(\dfrac{f}{50}\right)^{0.62}\left[1 - e^{-3.05\left(\frac{V_m}{V_n}-1\right)}\right] \quad \left(\dfrac{1}{\text{M}\Omega.\text{Km}}\right) \\ C(\omega_k) = 1.9\left(\dfrac{50}{f}\right)^{0.42}\left(\dfrac{V_m}{V_n}-1\right)10^3 \quad \left(\dfrac{\text{pF}}{\text{Km}}\right) \end{cases} \quad (9)$$

The $\left(\dfrac{V_m}{V_n}\right)$ is a coefficient of overvoltage, and f is a frequency, Hz.

Frequency values are 50, 200, 700, 1000, 1200, 2000, 5000, 7500 and 10000 Hz. The coefficients of over voltage are 1.1, 1.2, 1.5, 1.8, 2, 2.2, 2.5 and 2.7 (The coefficient of overvoltage for 330 kV line is 2.7) [5-7].

Figures 2 and 3 show the frequency dependence of the geometric conductivity and the geometric capacitance of the transmission line for different overvoltage values. As it seen the geometric conductivity of the line increases with both the increase in frequency and the increase in overvoltage value. The geometric capacity of the line increases with increasing voltage but decreases with increasing frequency [9].

To verify the adequacy between model and real line, model's frequency characteristics must be compared with frequency characteristics of the line.

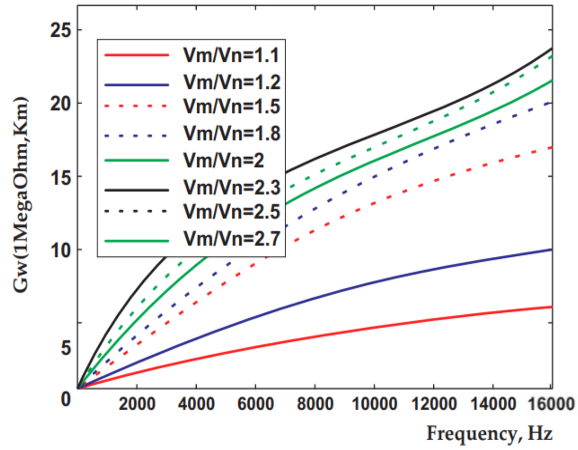

Figure 2. Frequency dependence of conductivity for various overvoltage values

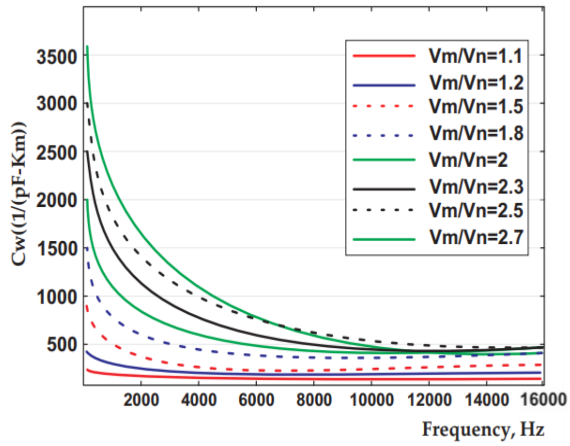

Figure 3. Frequency dependence of capacity for various overvoltage value

Calculation errors are calculated as follows [8]

$$\begin{cases} \Delta G(\%) = \dfrac{G(\omega_k) - G_M}{G(\omega_k)} \times 100 \\ \Delta C(\%) = \dfrac{C(\omega_k) - C_M}{C(\omega_k)} \times 100 \end{cases} \quad (10)$$

2.3. Analysis of the Values of Model Parameters

Analysis of certain values of model parameters. Figures 4 and 6 show the dependences of the conductivity and capacitance, respectively, of the line and model on frequency, and in Figures 5 and 7 are the relative error of these dependencies. As can be seen from Figures 4 and 5, at frequencies up to 5000 Hz, the line and model conductivities are very close and the relative error does not exceed 13%, while at frequencies exceeding 5000 Hz, the model conductivities and the corresponding relative error increase sharply. For frequencies up to 5000 Hz, the capacitance values of the line and the model are also close, but the relative error is somewhat larger, up to 17% (Figures 6 and 7).

At frequency values exceeding 5000 Hz, the conductivity of the model, the capacitance of the model, the capacitance of the model and, accordingly, the relative error increase sharply.

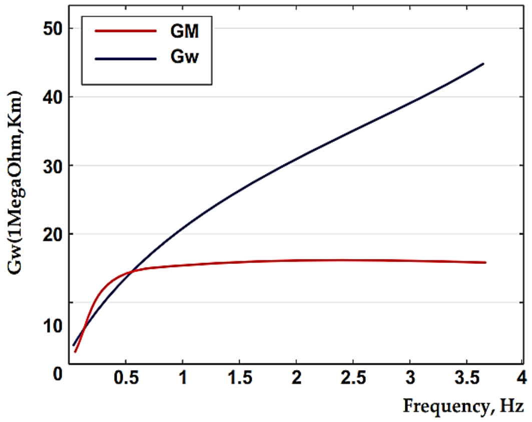

Figure 4. Frequency dependence of the line and model conductivities

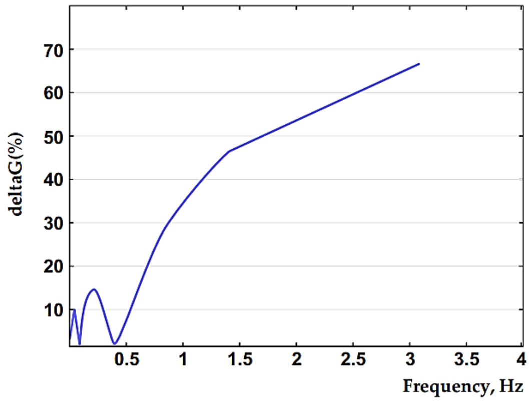

Figure 5. The ratio error of conductivity dependence from frequency

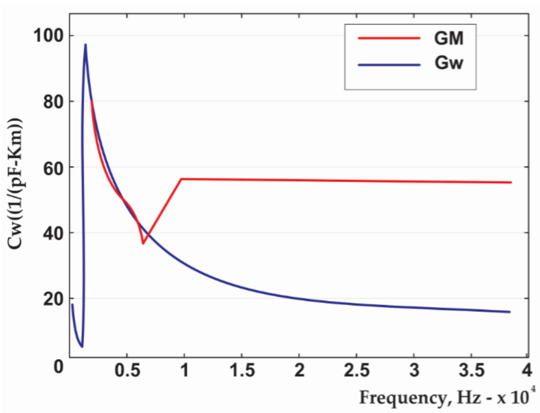

Figure 6. Frequency dependence of line and model capacities

Thus, the proposed model shows that during transient processes caused by atmospheric overvoltage in the 330 kV power grid, the found values of the line parameters can be used for the frequency range 50-5000 Hz.

2.4. Modeling Lines and Transformers

Type of the wire is accepting as AC-500. The parameters of this wire are R_0 = 0.06 Ω/km, X_0 = 0.32 Ω/km, Q_0 = 0.42 MVAR/km (B_0 = 3.5 10-6 1/Ω.km).

The crown losses are ΔP_0 = 2.7 kW/km. This value of crown losses also corresponds to G_0 = 1.46924×10^{-8} 1/Wkm [3]. It is assumed that the lightning struck 30 km from the substation. The substation is single-line and installed transformer type is TDC - 250000/330.

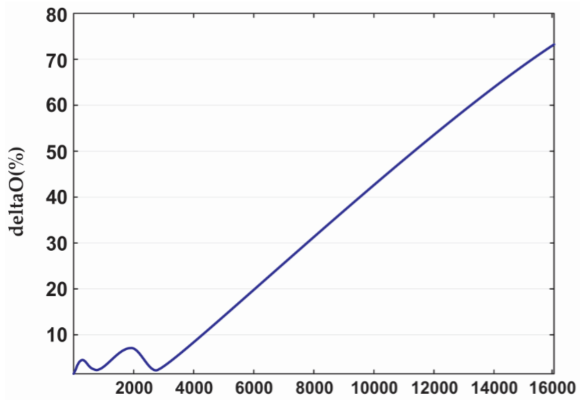

Figure 7. The ratio error of the frequency dependence of the line and model capacities

Each of the line and transformer equivalent circuits is divided into 10 elements [5, 6]. The overvoltage limiter is located at a distance of 120 m from the transformer, which corresponds to 330 kV substations [4]. To assess the impact of the crown effect, calculation is carried out in presence and absence of the crown discharge in the line. In the second case it is used equivalent substitution scheme with the scheme in which line crown discharge considered.

A full test voltage of 725 kV, 1.2/50 µS, is used as the impact voltage surge. This value of the amplitude is the maximum impulse voltage value that can be generated in a line with a rated voltage of 330 kV [3]. The purpose of such high voltage value is to ensure that the results obtained can be used for the transition process in more severe conditions. The calculation results are given in Figures 8-12.

The over voltages in the line and in the transformer windings in the absence of crown discharge are shown in Figures 8 and 9, respectively.

2.5. Analysis of Over Voltages Calculation Results

It can be seen from the curves given in figure 8 that in the absence of crown discharge, the overvoltage along the line first decreases, in the middle of the line it exceeds its minimum value, then it begins to increase and reaches its maximum value at the end of the line.

This is because at the end of the line, there is a transformer where wave resistance is much larger than its wave resistance. Therefore, at the transformer inputs, for example, in the absence of a crown, the overvoltage reaches 1450 kV, while at the beginning of the line the voltage value is 725 kV.

In its winding, the over voltage along the winding is gradually reduced and become zero at the neutral point. So, this point is connected to the ground (330 kV network neutral works as neutral connected to earth) as shown in Figure 9.

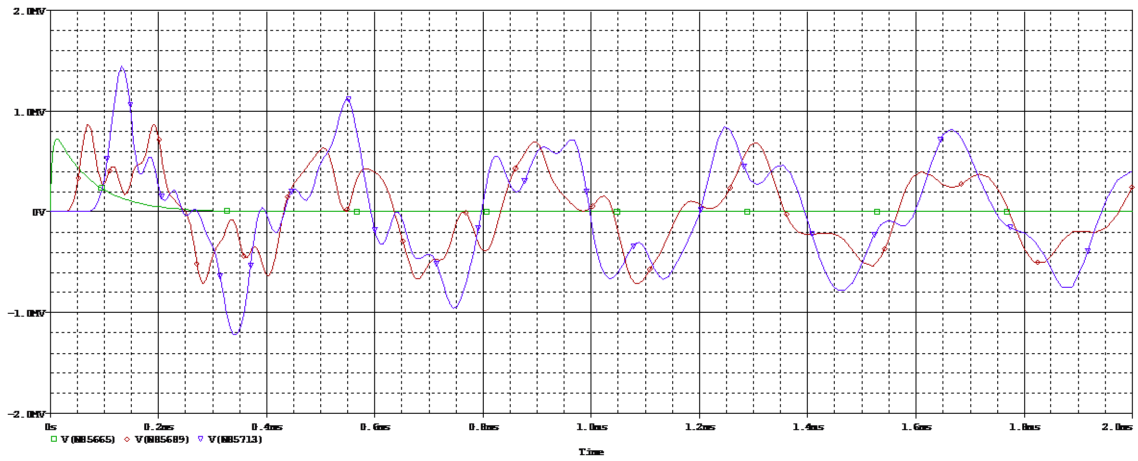

Figure 8. Over voltages in the transmission line without crown discharge,
Green - initial voltage of the line, red and blue, voltage at intermediate points (Points 4 and 7 on the scheme) of the line, yellow, voltage at the end of the line

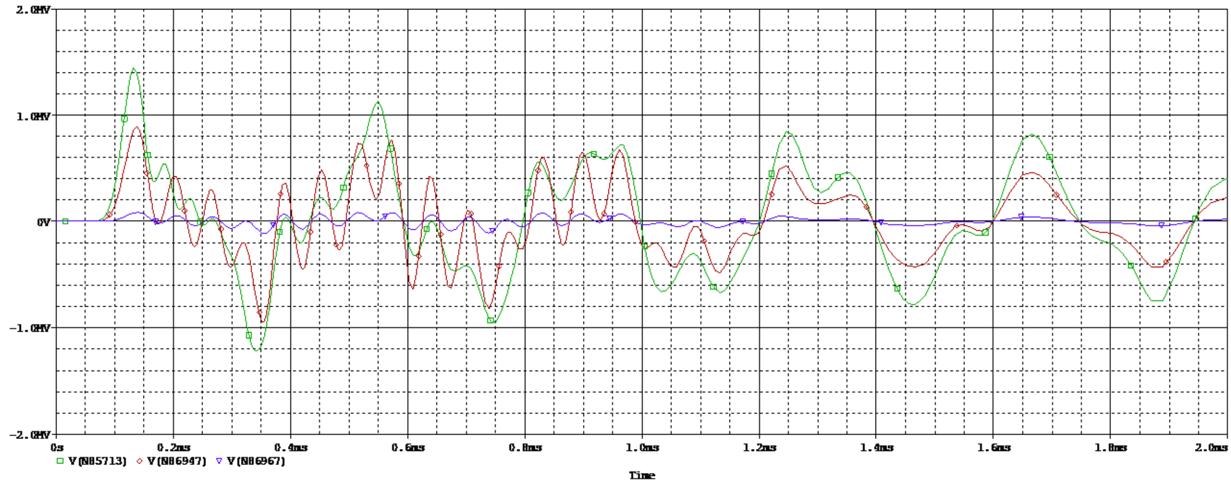

Figure 9. Over voltages in the transformer without crown discharge,
Green, red, blue and yellow, accordingly, the voltages at the transformer terminals and the points 4, 7 and 10

Green curve is an applied voltage, red and blue curves are the over voltages at points 4 and 7, yellow curve is the overvoltage at the end of the line, respectively.

Green, red, blue and yellow curves are the over voltages at the input terminal of the transformer winding and at points 4, 7 and 10, respectively.

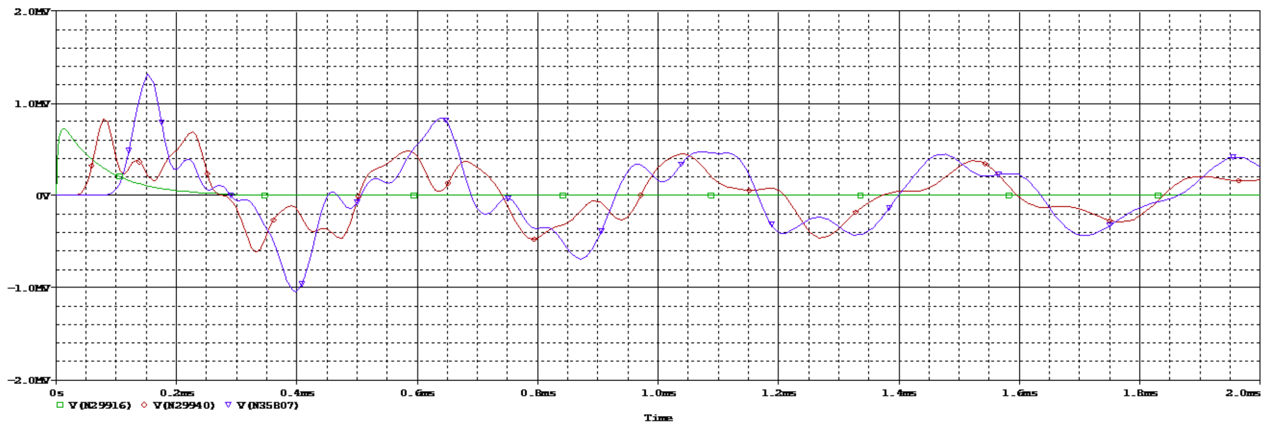

Figure 10. Over voltages in the transmission line with crown discharge,
Green - initial voltage of the line, red, blue and pink, voltage at intermediate points (points 4 and 7 on the scheme) of the line

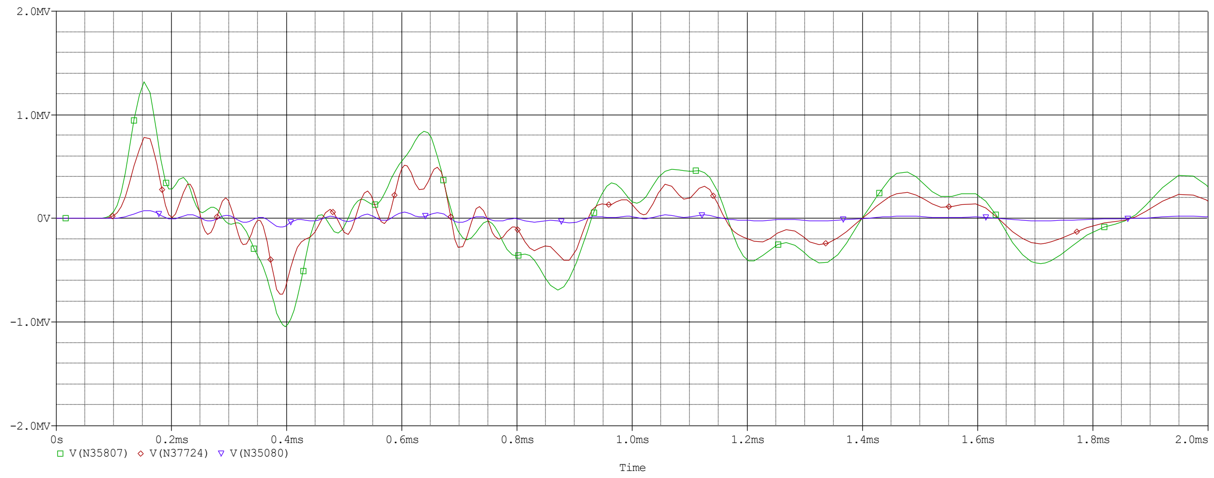

Figure 11. Transformer in case of crown discharge. green, red, blue and Yellow, accordingly, the voltages at the transformer terminals and the points 4,7 and 10

The presence of a crown reduces overvoltage in power lines and, consequently, in the windings of transformers Figures 10 and 11. In the case under consideration, in the presence of a crown, the overvoltage at the transformer inputs is 1317 kV, while in the absence of 1450 kV. The overvoltage reduction is about 9%. An increase in line capacitance reduces its capacitance, which leads to a decrease in overvoltage in these lines. On the other hand, an increase in line capacitance reduces its wave impedance. In this case, the reflected wave and the overvoltage in the line increases. Usually, the influence of the above first factor is stronger.

In the case of crown discharge presence, the curves of the extreme voltages in the line and in the transformer, winding are given in Figures 10 and 11, respectively. In the case of crown discharge presence in the lines, a slight decrease of the overvoltage is observed in them and transformer windings. This decrease is obviously seen in the curves shown in Figures 10 and 11. For example, at the end of the line (this point is also the input of the transformer winding) the value of the overvoltage is equal to 1254 kV.

A comparison of this value with the corresponding value in the absence of crown discharge shows that in the case of crown discharge, the overvoltage at the input of the transformer winding is reduced by 6%. As a result of the operation of the OVL, the value of this over voltage drops to 528 kV (Figure 12).

Thus, in power lines, overvoltage waves not only experience deformation of the front, but also attenuation under the action of the crown. According to the results of the calculations, the steepness of the overvoltage wave at the end of the line decreases from 36250 kV/ms to 29260 kV/ms, i.e. The reduction for each km of the line is 233 kV/ms·km. The presence of crown discharge on the lines also affects the speed of wave propagation on them. As can be seen from Figures 8 and 10, in the presence of a crown, the time to overcome a distance equal to 30 km by an overvoltage wave is longer than this time in the absence of a crown. With the appearance of a crown discharge, higher harmonics are created on the lines, which distort the overvoltage curves (Figures 8 and 10). It should be noted that these harmonics decay rapidly (within almost four periods of natural oscillation of the transformer winding).

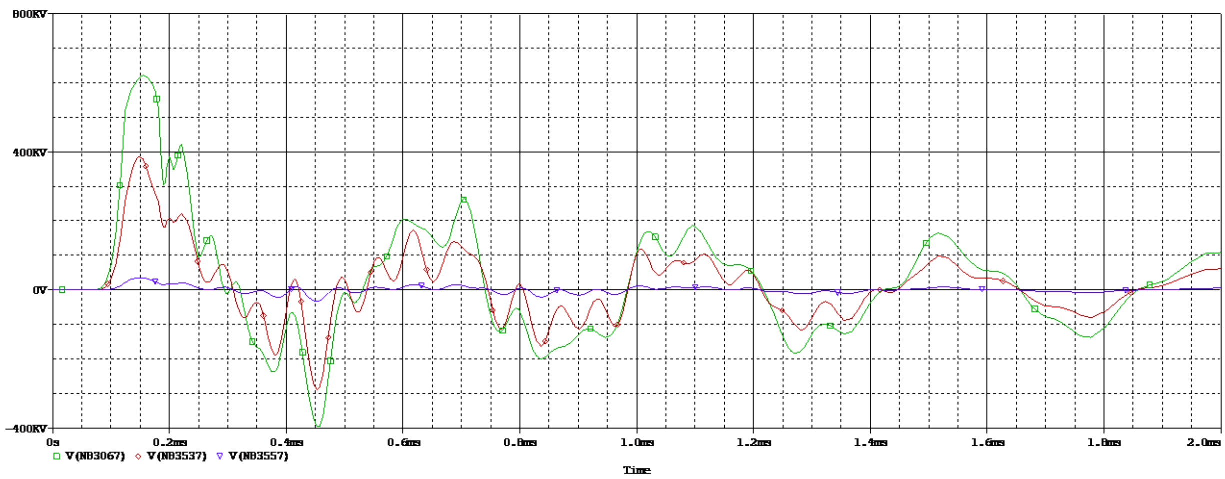

Figure 12. Over voltages in transformer windings with crown discharge with OVL, Green, red, blue and yellow - accordingly, the voltages at the transformer terminals and the points 4, 7 and 10

Inside the transformer winding, the overvoltage is distributed as in a winding with a grounded neutral - Figures 9 and 11 [8-12].

The operation of the surge arrester significantly reduces overvoltage in the final sections of the line and in the transformer winding. At the transformer inputs, the overvoltage decreases to a value of 621 kV, Figure 12. At the same time, the current in the arrester does not exceed 3 kA, and such a small current does not require the installation of a second set of arresters to ensure normal protection of the substation. As noted above, an increase in capacitive current reduces the longitudinal current in the line and, at the same time, the currents reaching the arrester may be less than the maximum current of the arrester. In calculations in which the line is represented by wave impedance, the surge currents in the line completely reach the arrester and their values can exceed the maximum current of the arrester. In this case, it is considered that the installation of a second set of surge arresters is mandatory.

3. CONCLUSIONS

The model is assigned to determine the influence of the crown effect on the over voltage lines and transformers. The model with 5 branches provides the good accordance with real line for frequency characteristics up to 5000 Hz and allows to study the impact of the crown effect on the transient processes caused by the motion of pulsed overvoltage waves in the transmission lines.

The study of the effect of the crown effect on the extreme voltages generated in the lines and transformers was carried out by combining the equivalent circuits of the line and the transformer winding with the model reflecting this effect. The results of the study show that the occurrence of crown discharge in the line under consideration reduces the overvoltage in this line and in the transformer winding by about 6%. The occurrence of crown discharge also reduces the steep and velocity of the overvoltage front in lines and transformer windings and increases the period of oscillations. Decrease in depth is equal to 163 kV/ms for each km of the line's length. The period and time duration required for overvoltage wave to overcome the full length of the line are 1 ms/km and 0.4 ms/km, respectively. Besides, the crown effect also causes high-frequency harmonics of over voltages.

The application of OVL sufficiently limits the over voltage magnitude.

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