Corona model

Jean Mahseredjian, 2016-04-06 08:12:00

1 Introduction

Corona modeling is used for an accurate knowledge of the magnitudes of lightning and switching overvoltages in an optimized design of transmission lines. Corona has a significant effect on overvoltage and on wave propagation. The currently available methodology for corona modeling relies heavily on experimental testing of transmission lines for extracting the charge-voltage characteristic.

The physical phenomenon of corona is very complex (see [1] and [4]). It includes ionization, effects of mobility, diffusion, deionization and the mutual effect of space charges and electric field. Sophisticated transmission line models are currently available in the EMTP (see [10]).These models can accurately represent the distributed nature and the frequency dependence of transmission line parameters. The representation of corona, however, involves a distributed nonlinear hysteresis behavior and is difficult to combine with the EMTP transmission line mathematics.

Most EMTP type corona models are based on the representation of the macroscopic effects of the corona phenomenon (see [5]). The charge-voltage (q-v) response of a conductor can be used to characterize the corona phenomenon. Extensive experimental studies on the corona characteristics of single and bundled conductors under impulse voltage conditions in a large cage are available in [6]. Four line conductors were examined: 2 single 1.2" and 1.823" diameter conductors, a bundle of 4x1.2" diameter conductors and a bundle of 6x1.1823" diameter conductors. The applied impulse waveforms of both polarities were covering the range of switching and lightning surges: 260x2500μs, 75x2500μs, 15x1000μs and 2.5x60μs. A typical q-v curve is shown in Figure 1.

In Figure 1 the corona onset voltage is given by V_0, E_0 is the corona onset voltage gradient and V_{cr} is the applied impulse crest voltage. Corona occurs when the strength of the electric field on the surface of a conductor becomes sufficient to ionize the surrounding air. The electric field intensity at the onset of corona can be predicted from the Peek's formula:

$$E_0 = 31m\delta\left(1+\frac{0.308}{\sqrt{\delta r}}\right)\ (\mathrm{kV/cm}) \qquad (1)$$

where m is the irregularity factor (0.7 for fair weather and 0.5 for rain, see [6]), δ d is the relative air density factor (3.92 x atmospheric pressure (in cmHg) over temperature in Kelvin) and r is the conductor's radius in cm.

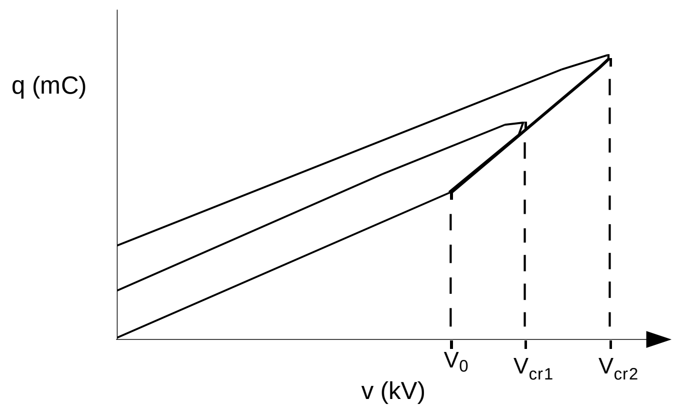


Figure 1 A typical q-v characteristic of a conductor

If the geometrical capacitance of a conductor (or bundle) is given by C_0 and C is the apparent capacitance after corona onset, then the following experimental observations are found in [6]:

- rain conditions lower the dissipated energy (the area of the q-v curve)
- E_0 is lower under rain conditions
- the slope after corona onset is less steep and the area enclosed by the q-v curve is smaller for a negative polarity impulse compared to a positive polarity impulse
- E_0 is lower for impulses of positive polarity
- E_0 decreases as the conductor diameter increases
- E_0 is lower for a single conductor compared to a bundle of conductors
- the corona onset level increases for impulses with steeper fronts
- C/C_0 is a voltage independent ratio and it is found to be higher for shorter impulses, for conductors of larger diameter, fair weather conditions and for a decreasing number of conductors in a bundle
- the q-v characteristic for fast impulses (or high frequency ac) is narrower than for slow impulses
- Peek's formula is in good agreement for switching impulse measurements, but for faster impulses the measured corona onset gradient is 10 to 15% higher.

2 The Suliciu model

The nonlinear q-v characteristic can be simulated directly using RC circuits and diodes or can be described by analytical expressions. Such models are static models where a fixed q-v characteristic is assumed. But, as indicated earlier, experimental data shows that q-v curves are significantly affected by the rate of rise of the applied surge. The only model that has been so far able to account for this dynamic behavior is called the Suliciu model (see [7]).

This report presents the implementation of the Suliciu corona model in the EMTP line models. The major difficulty for corona modeling is the availability of field tests for practical transmission line cases. The parameters needed for the Suliciu model are particularly difficult to establish. The fitting method remains a trial and error method based on q-v characteristics measured in cages. The module proposed in [8] can be used for simulating the q-v characteristic of a line with the Suliciu model and comparing with q-v data from field tests. It requires an initially known set of Suliciu model parameters and can simulate only a single line section connected to a voltage source and an external resistance to account for losses.

2.1 Basic Assumptions

To approximately account for the distributed nature of corona, EMTP multiphase transmission line models must be subdivided into a large number of sections to insert corona branches connected from node to ground. The choice of a section length must be such that its travel time is a fraction of the surge rise-time. It is assumed that at any given simulation time-point, the voltage along each line section is uniform.

The basic corona branch model equations are presented in [8], they are conveniently recalled and modified according to the proposed solution context.

If x is the radius of a cylinder on which space charge is concentrated when conductor voltage falls to zero, then for a multiphase system (vectors and matrices at time t):

$$V = V_x + C_r^{-1} Q \tag{2}$$

$$Q = C_x V_x + Q_c \tag{3}$$

$$C_r^{-1} = C_0^{-1} - C_x^{-1} \tag{4}$$

where V is the line end (or section end) voltage, V_x is the voltage inside the cylinder, Q is the total line charge, C_r is the capacitance of the cylinder to ground, C_x is the capacitance of the line conductor to cylinder boundary, Q_c is the corona charge inside the cylinder and C_o is the geometric capacitance of the line. If $P_r = C_r^{-1}, P_x = C_x^{-1}$ and $P_0 = C_0^{-1}$ then the phase voltage of phase *a* in a 3-phase system can be found from equation (4):

$$v_a = v_{x_a} + \left(p_{0_{11}} - p_{x_{11}}\right) q_a + p_{0_{12}} q_b + p_{0_{13}} q_c \tag{5}$$

Where

$$V = \begin{bmatrix} V_a & V_b & V_c \end{bmatrix}^t$$

$$V_x = \begin{bmatrix} V_{xa} & V_{xb} & V_{xc} \end{bmatrix}^t$$

$$Q = \begin{bmatrix} q_a & q_b & q_c \end{bmatrix}^t$$

$$p_0 \in P_0 \text{ and } p_x \in P_x$$

he first two terms of this equation, represent voltage induced on phase *a* by its own charge and the last two terms represent mutual capacitive coupling from other phases. Equations (2) and (3) can be rewritten using equation (4) :

$$V = P_0 C_x V_x + P_r Q_c \tag{6}$$

$$Q = C_0 V + C_0 P_x Q_c \tag{7}$$

It follows that the corona charge is given by:

$$Q_{cor} = C_0 P_x Q_c \tag{8}$$

and the corona current (the corona branch current) is found from:

$$I_{cor} = C_0 P_x I_c \tag{9}$$

I_c is the corona current vector Inside the cylinder and its members can be found from the Suliciu equation:

$$I_c = \frac{d}{dt} q_c = \begin{cases} \left.\begin{matrix} 0 & \text{if } g_2 \le 0 & \text{state 6} \\ g_2 & \text{if } g_1 \le 0 < g_2 & \text{state 2} \\ g_1 + g_2 & \text{if } g_1 > 0 & \text{state 1} \end{matrix}\right\} V_x > 0 \\ \left.\begin{matrix} 0 & \text{if } g_4 \ge 0 & \text{state 5} \\ g_4 & \text{if } g_4 < 0 \le g_3 & \text{state 4} \\ g_3 + g_4 & \text{if } g_3 < 0 & \text{state 3} \end{matrix}\right\} V_x \le 0 \end{cases} \tag{10}$$

$$g_j = k_j \left[\left(c_j - c_x\right)\left(v_x - v_j\right) - q_c \right] \quad j = 1 \ldots 4$$

where k_j, c_j and v_j are model parameters, $c_x \in C_x, v_x \in V_x$ and $q_c \in Q_c$.

2.2 Solution method

The corona branch appears as a nonlinear function connected at intermediate line section nodes. The solution method uses an iterative setup with the entire system of linear equations. The solution for each time step is found iteratively through the following steps:

1. Find the linear network solution.
2. Find the corona state from the voltage solution and determine the equivalent corona charge.
3. Use the charge solution to determine the equivalent current from the trapezoidal representation of equation (10).
4. Place the Current equivalent into the linear sub network.
5. If the solution did not converge go back to step 1.

The trapezoidal rule of integration relates charge to current at each solution time-point:

$$Q_c = \frac{\Delta t}{2} I_c + Q_{hist} \tag{11}$$

$$Q_{hist} = \frac{\Delta t}{2} I_{c,t-\Delta t} + Q_{c,t-\Delta t} \tag{12}$$

Equation (6) now becomes

$$V_x + \left(C_0 P_x P_r \frac{\Delta t}{2} \right) I_c = C_0 P_x V - C_0 P_x P_r Q_{hist} \tag{13}$$

Equation (13) is used in the above step 3 to determine the current solution.

2.3 Validation

This section provides a single case of field test comparison for the previously described EMTP corona model.

The field tests reported in [2] and [3] (Gary's line) are measurements of surge propagation in an actual 12.5 km 220 kV 3-phase line and laboratory measurements of the conductor q-v curves. Only phase *a* is energized with a surge function:

$$u(t) = U_m \left[0.988 e^{-0.123t} - 1.064 e^{-4.1t} \sin\left(12.3t + 70^\circ\right) \right] \tag{14}$$

Waveforms were originally measured for $U_m = 850\text{kV}$ and $U_m = 995\text{kV}$ (see [5]), but only data for 850kV case is available in this document.

The Suliciu model parameters (for equation (10)) are:

$c_x = 8.41 \text{ pF/m},$

$c_1 = c_3 = 16.8 \text{ pF/m},$

$c_2 = c_4 = 35 \text{ pF/m},$

$k_1 = k_3 = 4\text{MHz},$

$k_2 = k_4 = 0.8\text{MHz},$

$v_1 = v_3 = 320\text{kV}$ and

$v_2 = v_4 = 220\text{kV}$

2.3.1 Validation with the constant parameter (CP) line model

The original line is subdivided into 500 sections of 25 meters. Model parameters are evaluated at 100 kHz. The simulation results with corona are shown in Figure 3. It is concluded that the model can reproduce the field test with a reasonable accuracy. The simulation results without corona modeling are shown in Figure 2. This illustrates that corona modeling provides a much more realistic estimate of the attained maximum voltages and the rate of voltage rise.

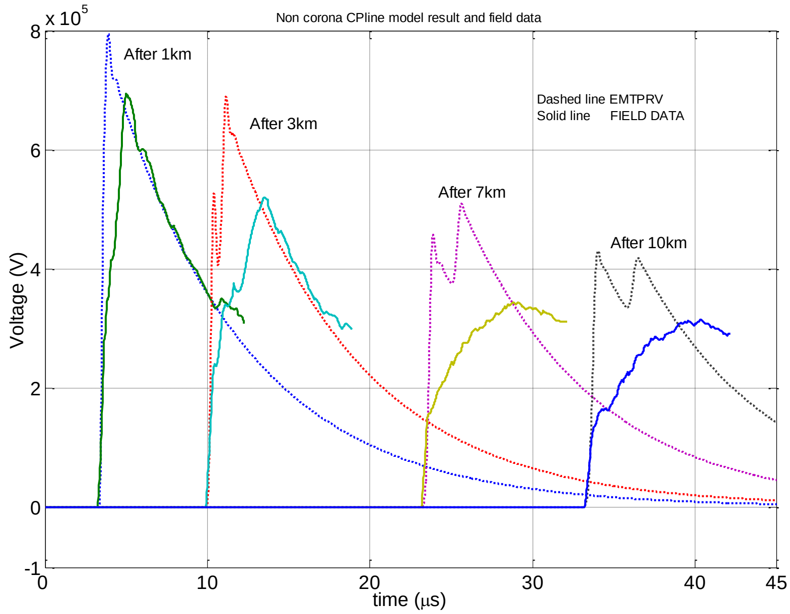


Figure 2 Gary's field test, simulation with CP-line (100 kHz data), no corona model

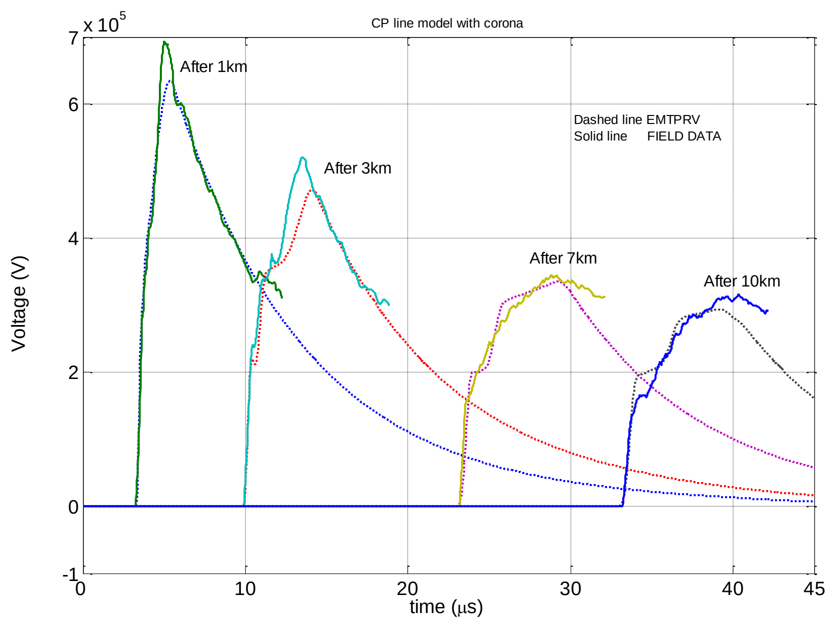


Figure 3 Gary's field test, simulation with CP-line (100 kHz data) and the Suliciu corona model

2.3.2 Validation with the frequency dependent (FD) line model

The original line is again subdivided into 500 sections of 25 meters. The T_i transformation matrix is evaluated at 100 kHz. The simulation results with corona are shown in Figure 5. The simulation results without corona modeling are shown in Figure 4.

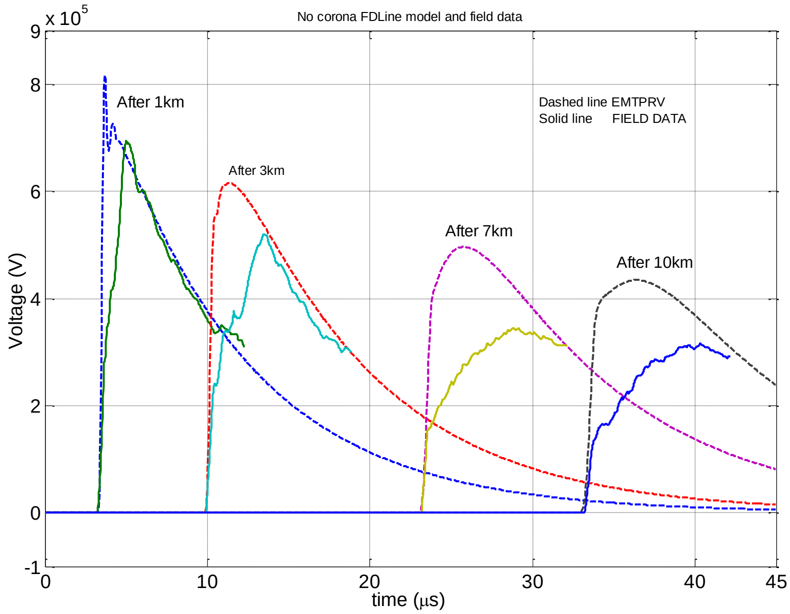


Figure 4 Gary's field test, simulation with FD-line (100 kHz data), no corona model

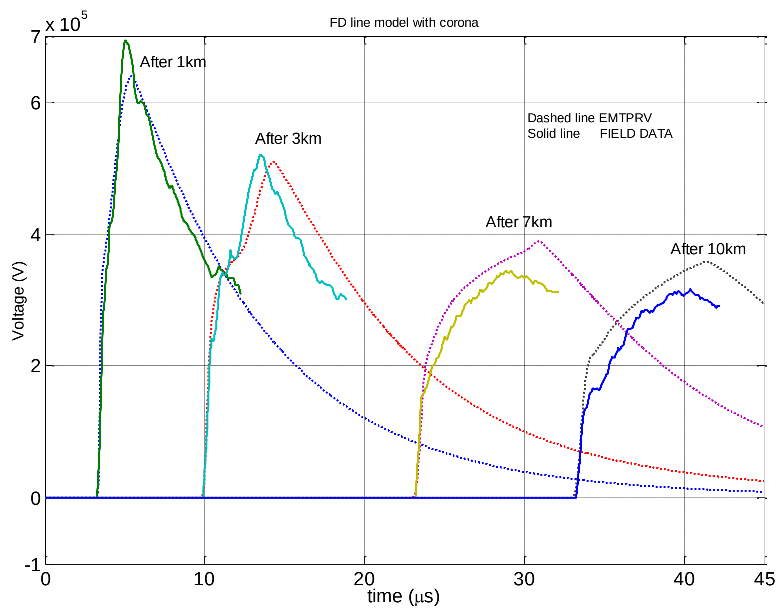
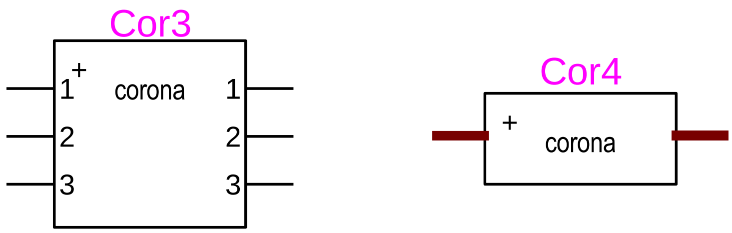


Figure 5 Gary's field test, simulation with FD-line (100 kHz data) and the Suliciu corona model

The overall effect of frequency dependence is less important when corona is modeled. When corona is not modeled, then the parameters of the CP-line model are only correct at one frequency, but as the surge propagates along the line its frequency content changes and thus a frequency dependent model becomes more appropriate.

3 Corona device parameters

The graphical representation of the Corona device is given in Figure 6. Single-phase pin and three-phase pin versions are available.



a) Single-phase pin symbol b) Three-phase pin symbol

Figure 6 Corona device symbol

The corona tab of this device allows entering all the required parameters:

- **Device data are** defined as reference or shared from another device. This allows diminishing the number of data printed in the netlist file.
- **Section length** of the associated transmission line.
- **Number of phases.**
- **C per unit length** is the line capacitance matrix C_0 defined in equation (4).
- **Suliciu** model parameters.

4 Netlist format

```
_Cor;Cor4;6;6;s19,s20,s21,s22,s23,s24,
3,,25,8.41,1,1pF,1e-4,
7.6633105098748 -1.215991511705 -0.4936031405052
-1.215991511705 7.8243753122838 -1.215991511705
-0.4936031405052 -1.215991511705 7.6633105098748
4e6 800 4e6 800
16.8 35 16.8 35
320000 220000 -320000 –220000
```

Cor	part name
Cor4	part instance name
6	pin count of this element
6	pin names on this line
s19,s20,s21	signal name of the input (k side)
s22,s23,s24	signal name of the output (m side)
3	number of phases.
ref	reference name of the corona device. If the device is his own reference the name is not shown as in this example.
25	section length
8.41	C_x capacitance value
1	section length unit. Default is m
1pF	Line capacitance C_0 unit.
C_0	Line capacitance matrix C_0 values. The number of lines needed for the matrix is equal to the number of phases.
k_j	K parameters of the Suliciu model
c_j	C parameters of the Suliciu model
v_j	V parameters of the Suliciu model

An example of three-phase version is shown below

```
_Cor;Cor2a;6;2;s13a,s14a,
3,,25,8.431,1,1nF,1e-8,
_Cor;Cor2b;6;2;s13b,s14b,
_Cor;Cor2c;6;2;s13c,s14c,
7.41 0 0
0 7.41 0
0 0 7.41
4e6 .8e-3 4e6 .8e3
16.8e3 35e3 16.8e3 35e3
320000 220000 -320000 -220000
```

5 References

[1] C. Gary et M. Moreau, "L'effet Couronne en Tension Alternative. Pertes et Perturbations Radioélectriques Engendrées par les Lignes de Transport d'Énergie Électrique". Collection de la Direction des Etudes et Recherches d'Electricité de France. EYROLLES 1976.

[2] C. Gary, G. Dragan and D. Critescu, "Attenuation of Travelling Waves Caused By Corona". CIGRE Report 33-13, 1978.

[3] C. Gary, A. Timotin and D. Critescu, "Prediction of Surge Propagation Influenced By Corona and Skin Effect". Proc. IEE, 130-A, pp. 264-272, July 1983.

[4] A. Semlyen and H. Wei-Gang, "Corona Modeling For Calculation Of Transients On Transmission Lines", IEEE Trans. on Power Delivery, Vol. 1, No. 3, July 1986, pp. 228-239.

[5] S. Carneiro and J. Marti, "Evaluation of Corona and Line Models in Electromagnetic Transients Simulations". IEEE Trans. on Power Delivery, Vol. 6, No.1, January 1991.

[6] P. S. Maruvada, H. Menemenlis and R. Malewski, "Corona Characteristics of Conductor Bundles Under Impulse Voltages". IEEE Trans. on Power Apparatus and Systems, Vol. 96, No. 1, January 1977, pp. 102-115.

[7] M.M. Suliciu and I. Suliciu, "A Rate Type Constitutive Equation for the Description of the Corona Effect", IEEE Trans., Vol. PAS-100, No. 8, pp. 3681-3685, August 1981.

[8] J. Mahseredjian, Support Routine for the EMTP Dynamic Corona Model. Rapport (IREQ-4534, décembre 1989.

[9] P. Lacasse and J. Mahseredjian, "Implementation of a Multiphase Corona Line Model in the EMTP User's Manual". IREQ Report 94-326, October 94.

[10] H.W. Dommel, Editor, "Electromagnetic Transients Program Reference Manual (EMTP Theory Book)", Bonneville Press Administration, August 1986.