Distortion Phenomena on Transmission Lines Using Corona Modeling ATP/EMTP

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ABSTRACT

The influence of corona on the propagation of transient voltages on transmission lines can be studied by modeling the impulse corona discharge, taking into account its physical properties. The technique of corona characteristics (charge-voltage) is more favorable than the propagation delay characteristic which is known to be less accurate and leads to results that are far from reality. In this paper, a mathematical model of corona discharge is integrated into the Alternative Transients Program of the Electro-Magnetic Transients Program software (ATP/EMTP), using the MODELS interface. The attenuation and distortion phenomena on the overhead transmission line caused by corona is modeled and simulated by the implementation of a corona model with the user-defined multi-branch type-94circuit in ATP. Comparison between the computed results and literature experimental investigations gives a good agreement between them.

Index Terms — **Corona, Q-V curves, ATP/EMTP, Type94, attenuation and distortion**

1 INTRODUCTION

LIGHTNING protection and insulation coordination of transmission lines and substations require an accurate knowledge of the magnitudes and waveforms of lightning overvoltages. For power transmission lines, high voltage can cause a strong electric field near the surface of conductors, where, when its intensity exceeds the critical value, corona discharges will occur [1- 2], and it is responsible for: radio interference (RI), audible noise (AN), and corona loss (CL) [3]. This phenomenon is related to an electromagnetic environmental problem in the vicinity of transmission lines.

The corona phenomenon has a beneficial effect in the sense that it reduces the transient overvoltage's magnitude. This distortion is due to the dissipation of energy by the injection of space charge around the conductors [4-8].

To solve the nonlinearity of corona discharge, some investigators turned to circuit representations, in which corona were considered by nonlinear branch consisted of a diode and capacitor [5-8]. In other works, they consisted of a diode, resistor, and capacitor [9-11]. Meanwhile, some authors used experimental charge-voltage (Q-V) curves to evaluate the parameters of the equivalent circuit [6, 12-15]. The numerical model adopted in the previous papers intended to evaluate the Q-V curves and to predict the corona energy losses. As corona discharge is a highly nonlinear phenomenon and, consequently, modeling of corona for the computation of attenuation and distortion is very complex. In the most studies of the attenuation and distortion of overvoltage are made by using simple circuit elements as Kudyan and Shih models [7, 8, 10, 16-18], so more accurate model is needed.

In this study, the ATP/EMTP is used, because it is widely used in the transient simulation of power systems. The implemented corona model consists of two sections: the MODELS section and its network (ATP-Draw) section. Algebraic, differential and Boolean equations can be introduced and solved in the MODELS section, and in the ATP-Draw part the additional circuit elements can be used.

Manuscript received on 30 November 2016, in final form 16 July 2017, accepted 21 September 2017. Corresponding author: Z. Anane.

DOI: 10.1109/TDEI.2017.006484

2 CORONA MODEL

In this study, the used corona model is based on the following assumptions:

- It depends on the waveform, voltage polarities, and values of the superficial electric field and the geometric characteristics of the conductor.

- The space charge is emitted from the corona conductor in the form of a shell of unipolar charge, where the field takes with its external limit of the streamer propagation field E_c, which is equal to 5 kV/cm for positive polarity and 18 kV/cm for negative polarity.

- The electric field at the corona conductor is restricted to the value E_0 of the corona inception field determined by the empirical formula of Waters [6].

$$E_0 = 23.8\, m \left[1 + \frac{0.67}{r_0^{0.4}}\right] \quad (1)$$

where m is the roughness factor (surface state of conductor) [19], r_0 is the radius of the corona conductor. The effect of the air density is taken into account by

$$E_0(\delta) = E_0 \delta^b \quad (2)$$

where b is an empirical constant restricted between 0.5 and 0.67 and depended with the relative density of air δ given by

$$\delta = \frac{P_r(T_0 + 273)}{P_0(T + 273)} \quad (3)$$

where T is the environment temperature in °C, and $T_0 = 20$ °C, P_r is the environment pressure in kPa, and $P_0 = 101$ kPa is the standard atmospheric pressure.

During corona process, the charge q bound on the conductor takes the critical value q_0, when the instantaneous charge q exceeds this critical value a new shell of charge will emerge from the conductor. At each time step, this shell moves away from the corona conductor under the influence of the local electric field [20], and this movement was computed iteratively by the Dichotomy numerical method.

The present model is used to predict the variations of the corona characteristics Q-V curves which depend on the line configuration: coaxial cylinder configuration and wire above the ground.

2.1 COAXIAL CYLINDER

The first configuration adopted in this study is coaxial cylinder system with the parameters of: r_0 inner radii and r_b extern radii, where corona appears when the critical charge corresponding to the corona onset voltage.

$$q_0 = C_g V_0 \quad (4)$$

where C_g is the geometric capacitance and calculated by

$$C_g = \frac{2\pi\varepsilon_0}{ln\left[\frac{r_b}{r_0}\right]} \quad (5)$$

And the corona onset voltage V_0 (in kV) is calculated by [21]:

$$V_0 = 31\left(1 + \frac{0.308}{\sqrt{r_0}}\right) r_0\, ln\frac{r_b}{r_0} \quad (6)$$

When this value is reached a new quantity q_{sc} of space charge is created around the conductor, and the total charge increases with increasing of voltage from V_0 to V and it gives by [6, 22].

$$Q = C_g V + q_{sc} \quad (7)$$

Then the corona Q-V curves are obtained by the resolution of the two following equations [6, 22].

$$Q = 2\pi\varepsilon_0 r_c E_c \quad (8)$$

$$V = E_0 r_0 ln\left[\frac{r_c}{r_0}\right] + E_c r_c ln\left[\frac{r_b}{r_c}\right] \quad (9)$$

where r_c is the radius of the corona shell (in cm), so it is the position of a new created charge.

For this geometry, the dynamic corona capacitance is calculated as [23]:

$$C_c = C_g \frac{ln(r_c/r_0)}{ln(r_b/r_c)} \quad (10)$$

We use the Dichotomy method to provide the space charge positions which is the radius r_c for any voltage $V > V_0$ in resolving equations (8) and (9).

For the purpose of comparing the results of our corona model with those adopted by other authors, we used coaxial system with $r_0 = 0.475$ cm and $r_b = 29.05$ cm, for the slow impulse voltage of 120/2200 µs.

Figures 1 and 2 show the variations of the corona shell positions r_c and the total charge q respectively, A good agreement can be seen between the simulated results and those obtained experimentally [6, 24].

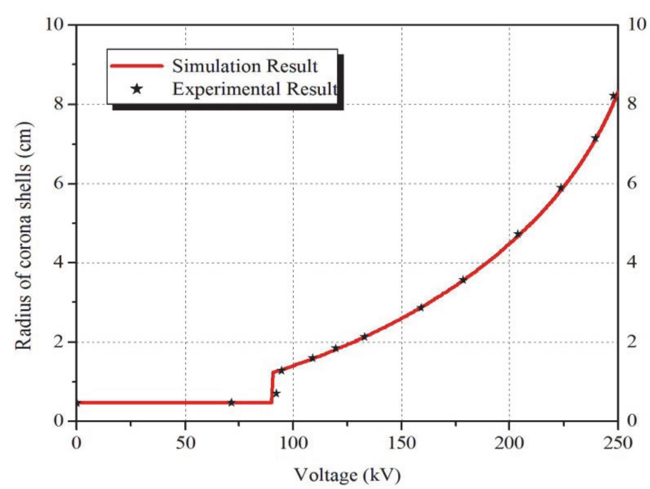

Figure 1. Corona shells position around the conductor.

In Figure 2, when the applied voltage is less than the corona threshold, it means that no space charge is generated around the conductor surface, and the total charge is equal to the geometric one, calculated by the using of equation (4), and the slope of the Q-V curve is equal to the geometrical capacitance C_g. For the applied voltage greater than the critical threshold and less than the peak value, corona discharge grows and the space charge is generated and increases nonlinearly with a slope equal to the corona capacitance which is larger than C_g. For the voltage decreasing part, the total charge decreases with the voltage and the slope of the Q-V curve is close to the natural capacitance Cg. The slopes of these three sections produce the variation of the capacitance as shown in Figure 3, where it can be seen that the curve deviates from the natural capacitance and increases rapidly.

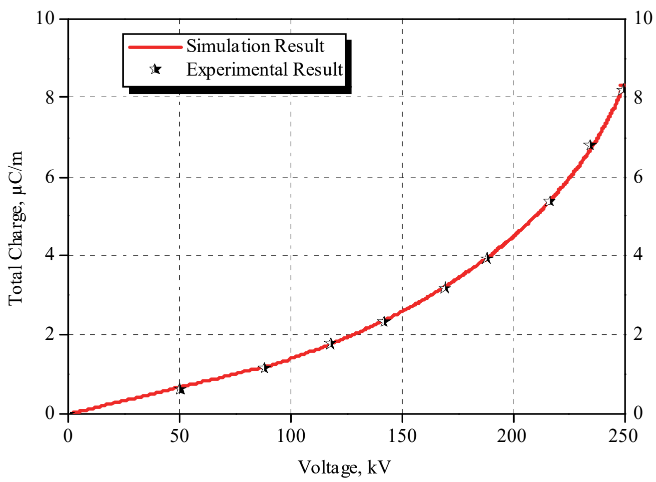

Figure 2. Total charge on the conductor surface.

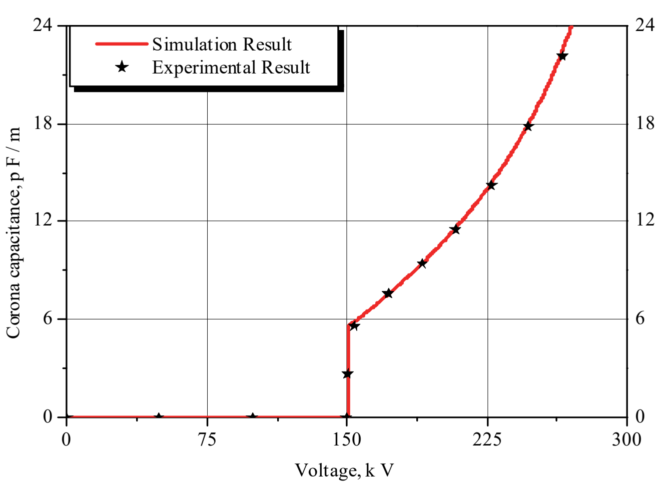

Figure 3. Nonlinear variation of the corona capacitance for the coaxial system.

2.2 CONDUCTOR ABOVE THE GROUND

For a wire with a radius of r_0 and average height of h above the ground, corona characteristics are calculated by [1, 6]

$$Q = 2\pi\varepsilon_0 r_c E_c \left[\frac{2h - r_c}{2h}\right] \tag{11}$$

$$V = E_0 r_0 \, ln\left[\frac{r_c(2h-r_0)}{r_0(2h-r_c)}\right] + \frac{E_c r_c\,(2h-r_c)}{2h} \, ln\left[\frac{2h-r_c}{r_c}\right] \tag{12}$$

The resolution of the two equations above by the iterative methods gives the positions of the corona shells, and here again the Dichotomy numerical method is used.

The dynamic capacitance due to corona space charge becomes equal to [1]

$$C_c = C_g \frac{ln\left[\frac{(2h-r_0)r_c}{(2h-r_c)r_0}\right]}{ln\left[\frac{2h-r_c}{r_c}\right]} \tag{13}$$

The calculation of the change in the line corona capacitance can be obtained from the slope of the Q-V curves. Numerical examples are given in Figures 4 and 5 for a wire of 1.32 cm radius situated at 7.5 m of height.

A quite accurate agreement of computed Q-V curves with the experimental results available in the literature has been found to [25].

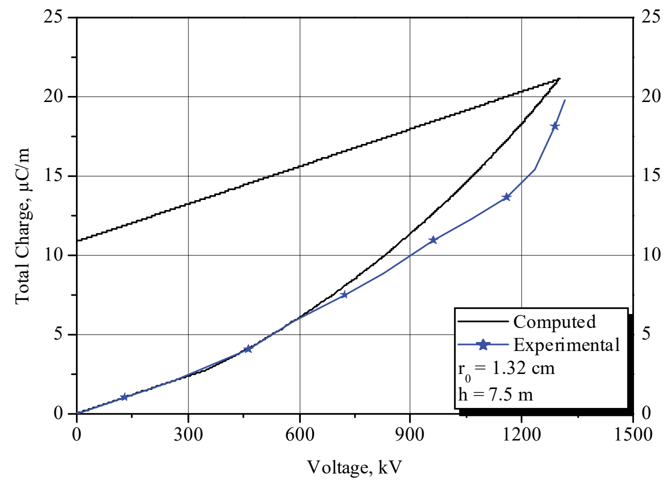

Figure 4. Q-V curve for a 1300 kV, 1.2/50 µs wave.

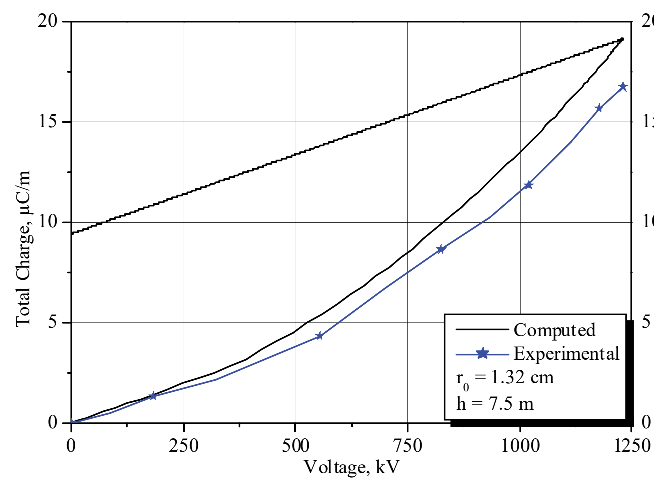

Figure 5. Q-V curve for a 1230 kV, 10/75 µs wave.

3 SIMULATION OF CORONA ON TRANSMISSION LINES

This section shows the simulation of overvoltage wave propagation along the overhead line by digital computers and results are discussed for lightning overvoltage studies.

3.1 TRANSMISSION LINE MODELING

The overhead transmission line is simulated by J. Marti's multi-conductor model. Input data consists of conductors' geometric configuration, diameters, and geometry of the bundles. The line parameters are calculated by the LINE CONSTANTS routine built in the ATP/EMTP, and the line characteristics of Marti's transmission line are shown in Figure 6.

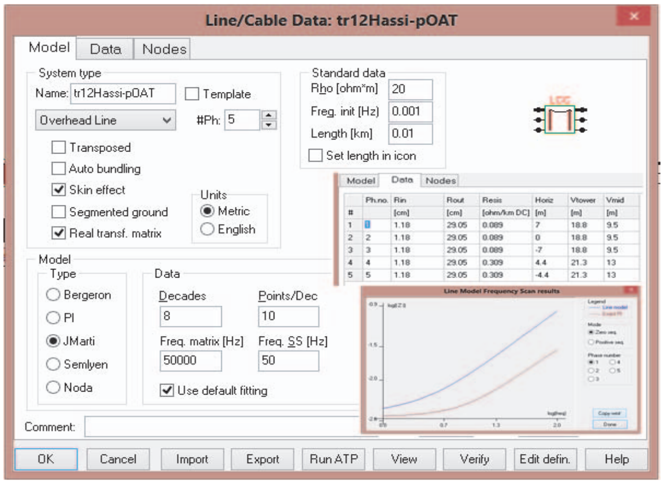

Figure 6. Characteristics of J. Marti's transmission line model.

3.2 TYPE-94 NORTON FOR NONLINEAR CORONA MODEL

In surge propagation computation, the difficulty of considering corona was its nonlinear characteristics, so, to solve the problem, the Q-V curves are proposed as input data. A new methodology to develop the dynamic simulations of distortion phenomena along transmission lines is proposed by using of modeling corona itself.

As the present corona model on the transmission line will be modeled as an additional capacitance, so each section of the line is connected in cascades with the nonlinear element to represents the corona capacitance (Figure 7). For a transient study, this nonlinear capacitance is introduced by the type-94 element of ATP/EMTP, and it has been inserted along the transmission line to compute the attenuation and distortion of the lightning surges as they propagate along the line.

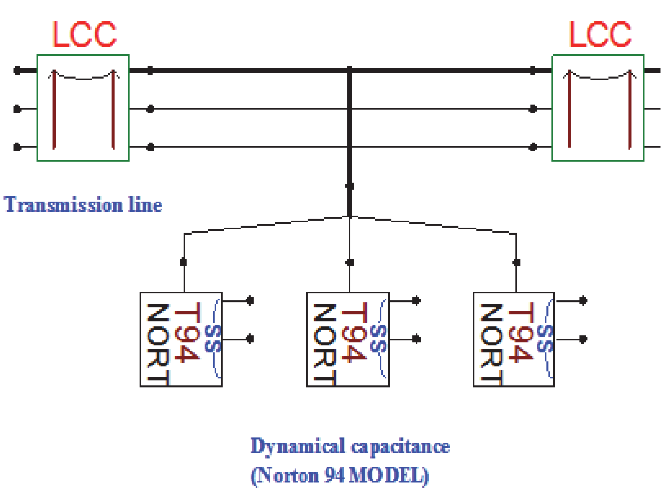

Figure 7. The nonlinear type 94 component of corona.

The type-94 component is a special ATP interface of MODELS that partly avoids the time step delay and gives direct access to the system description and nodal admittance matrix. So as to avoid the problem of errors and instability in the solution of the electric circuit, corona is introduced by a non-delayed interface to MODELS in ATP/EMTP. And the Norton type-94 nonlinear component used to represent the corona as a nonlinear capacitance is shown in the fragment in Figure 8, which is implemented on the overhead transmission lines. So it is a MODELS component that connects directly into the circuit description.

```
BEGIN NEW DATA CASE
$DUMMY, XYZ000
MODELS
MODEL Capa
DATA   n   ng  {dflt: n*(n+1)/2}
INPUT v[1..n]     v0[1..n]    ...
VAR    i[1..n]     g[1..ng]    ...
OUTPUT i[1..n],is[1..n],g[1..ng],flag
DATA   R0,RB,Rx,H1
        ...
constNmax   {VAL:1000}  ...
VAR     at       ...
HISTORY Cg     {dflt: 0}
EXEC
IF ((sign(v)=1  and ... Then   X:=Rc   Cc:=0.0
 ■    Dichotomy Method
...
ELSIF   (sign(v)=1  and  ... THEN
     Cc:=0
endif
...
   IF t=0  THEN   ...
   ELSE
i   := g0*v  -is...
   ENDIF
   g0  := g
 ENDEXEC
ENDMODEL
RECORD
NDMODELS
$INCLUDE, C:\ATP\work\tr12Hassi-pOAT.lib,
X0003A,...
BEGIN NEW DATA CASE
BLANK
```

Figure 8. Fragment of corona model in type-94 Norton MODELS components.

3.3 SIMULATION RESULTS AND DISCUSSION

In this section we studied three cases of lines: single phase, three phase and tree phase with ground wires, and the simulation results are discussed.

As the line section length might be an effect influencing simulation results of propagation wave. We use the single phase line for the first case, in which the section lengths of 5, 10, and 15 m are chosen and the voltage waveforms are observed at a distance of 450 m from the sending-end. The surge of 1/5 µs and 1800 kV is applied at the sending-end, the conductor radius is 1.18 cm and the average height is 20 m. The propagated voltage waveforms have been obtained for different section length as illustrated in Figure 9. It can be noticed that substantial differences can be found between different section lengths. As the longer sections have larger corona capacitance, significant errors in numerical integration can be caused. To overcome this adverse we will choose the section length as short as possible in the following simulations.

For the purpose of confirming the credibility of the corona model we used the applied voltage with a crest value of 1280 kV which is similar to the voltage used by Wagner [5].

The deformation of wave surges due to corona has been found to be satisfactorily reproduced by the corona model as shown in Figure 10 when it is shown that the typical distortion of the wavefront and reduction in the peak value is associated with corona losses.

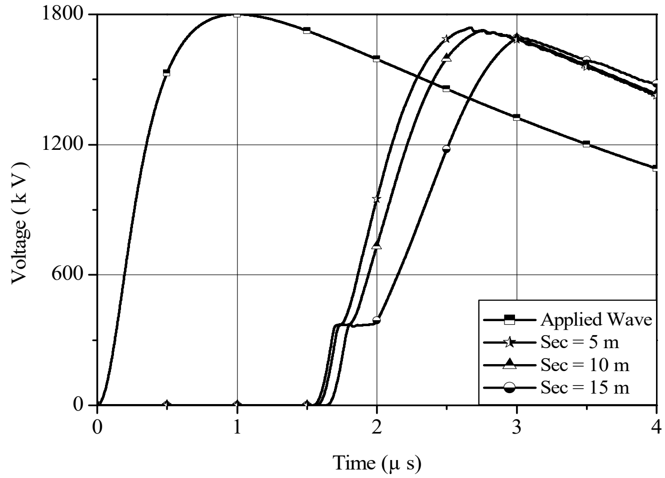

Figure 9. Effect of the section length on the simulation results.

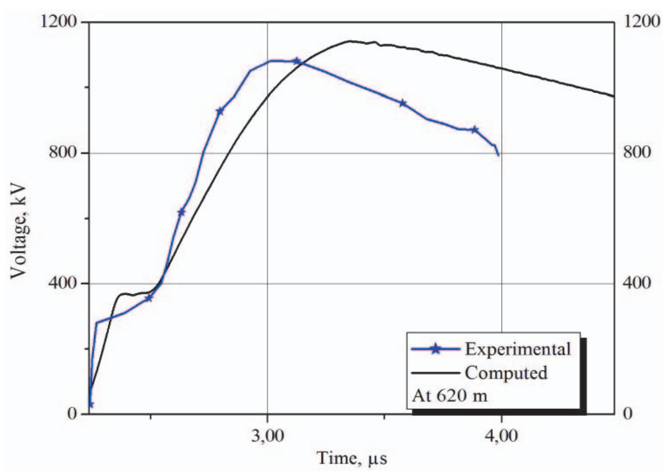

Figure 10. Simulated and experimental voltage waveforms at 620 m.

In order to figure out the behavior of the overvoltage surge on the wave tail part, two surges are applied, 1.2/50 and 1/7.5 µs, where the attenuation and distortion occurred to corona are shown in Figures 11 and 12. The attenuation of the surge is appreciably higher in the case of short wave (1/7.5 µs) surge, which confirm the attenuation of peak due to corona effect is

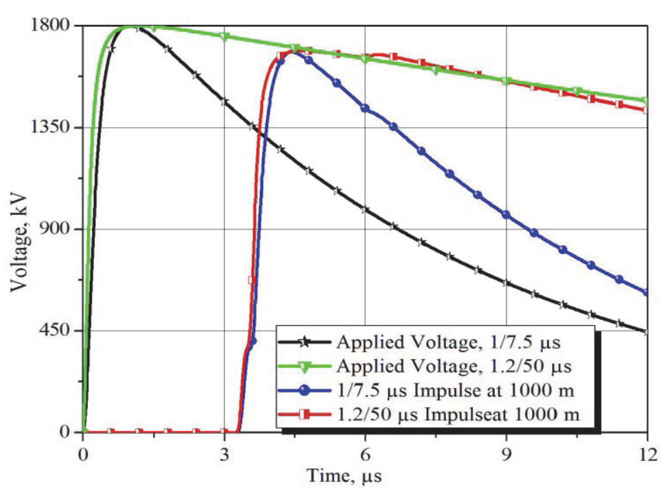

Figure 11. Voltage waveforms at 1000 m for a peak value of 1800 kV.

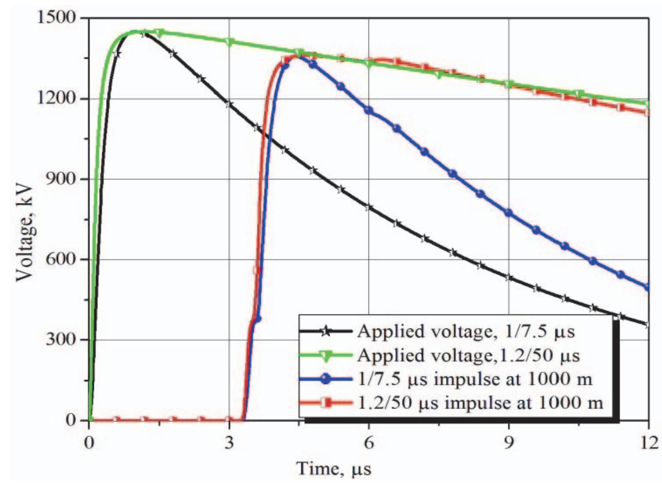

Figure 12. Voltage waveforms at 1000 m for a peak value of 1450 kV.

more obvious for the surges of shorter tail duration as compared with the surges has longer tail, and this phenomenon is also obtained in [6] and [25].

For the second case, corona model is introduced in each phase of transmission line, where it's divided into 45 sections, and each section with a length of 25 m.

Figure 13 shows the simulated waveforms including corona effect at different distances from the sending-end, where the attenuation and distortion increases with the distance it has travelled.

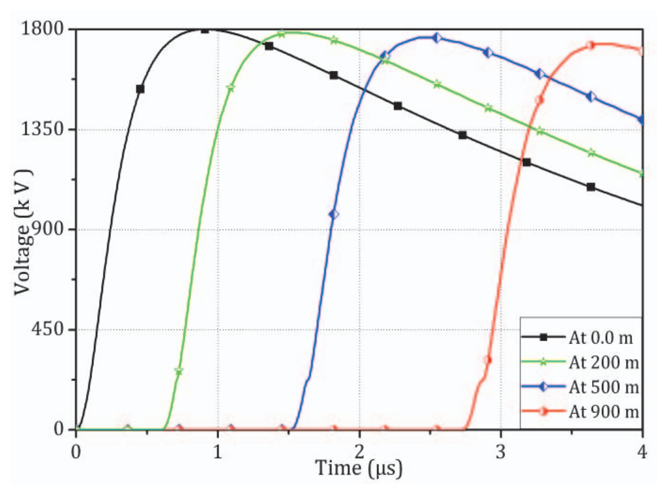

Figure 13. Attenuation and distortion of the surge at different distances.

For the third case, on the base of the second case two earth wires are added. The simulation result of this investigation is shown in Figure 14. It shows that the grounding wires cause weaker delay of the waveform, and attenuation is noticed in case without earth wires (see Figure 13).

4 CONCLUSION

A mathematical corona model has been developed in the present paper, and implemented in the ATP/EMTP software, using the MODELS simulation language, to predict the charge-voltage characteristics based on the empirical formulas of the Q-V curves.

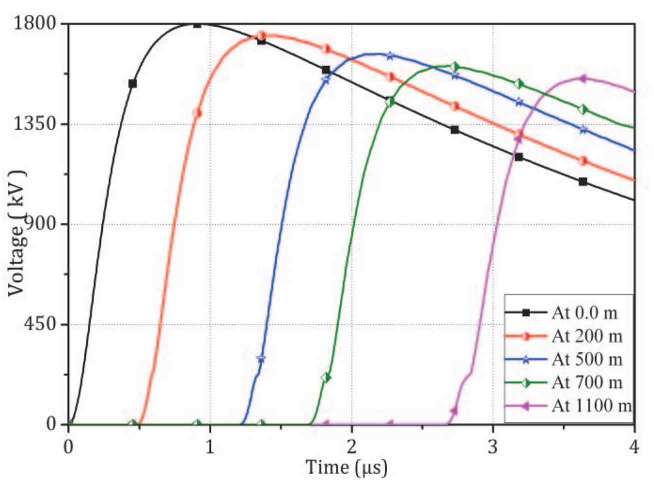

Figure 14. Computed voltage waveforms with earth wires at different distances.

The impulse corona could lead the great attenuation and distortion to the overvoltage waveshape due to lightning surge propagated along the overhead transmission line. The corona model with the aid of the non-linear NORTON type94 circuit component in the ATP/EMTP software environment is connected to nodes among transmission line model sections, for analyzing, by simulation, the phenomenon of attenuation and distortion, which obtained more obvious for surge with shorter wave tail and this phenomenon is also increased by the presence of the grounding wires.

The simulation results show a good agreement with measurements results available in the literature.

ACKNOWLEDGMENT

The authors thank Professor. Dr. Saad Mekhilef at the Department of Electrical Engineering, University of Malaya for providing encouragements and important suggestions and all efforts.

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