Computation of Corona Radio Interference Levels in HVDC Transmission Lines

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Abstract

This article presents an analysis of radio interference (RI) lateral profiles produced in different design options for a bipolar HVDC transmission line proposed for the Turkish Power Transmission System. The method used to compute the radio interference levels considers a transmission line model that takes in consideration the skin effect in conductors, and in the ground plane. Also, the attenuation constants are calculated from the line parameters and the bipolar system is decoupled by using modal decomposition. The results show how some proposed designs can exceed the recommended RI limits while others can produce RI with values considered acceptable.

1. Introduction

High voltage direct current (HVDC) systems have shown to be the best option to transmit electrical energy over long distances. Nowadays, several countries, as part of their electric power system modernization programs, are considering the installation of HVDC lines in the cases where this technology can present advantages over the installation of new HVAC lines. In Mexico HVDC lines are planned to be constructed in the next few years, while in Turkey the installation of these systems is under analysis.

As in HVAC systems, during the design process of HVDC transmission lines, the effects of the corona discharge are important factors to be considered. The corona effect is a partial and localized discharge that occurs at the surface of high voltage conductors when the local electric field is high enough to produce the ionization of the air. Some of the main consequences of the presence of corona discharges in transmission lines are: power loss, audible noise, wave distortion and electromagnetic interference [1], [2]. The electromagnetic interference produced by corona discharges is present in a wide frequency range in which this phenomenon can affect the normal operation of electromagnetic devices located in the vicinity of the line. Due to the frequency range in which corona discharge produces interference (below 3 MHz), the problem is usually defined as Radio Interference (RI) [1].

In this paper, the RI lateral profiles produced by corona discharges in HVDC transmission lines are calculated using a method presented in previous works for HVAC transmission lines [2]. The method is based on the method proposed by Gary [3] [4], with modifications in the calculation of the electric parameters, since it includes the skin effect by using the concept of complex penetration depth, both in the pole conductors, and in the ground plane. The multiconductor system is decoupled by using modal decomposition theory. The method is applied to determine the RI levels of different designs proposed for an HVDC transmission line considered for Turkey.

2. Corona Radio Interference and Excitation Function for HVDC Lines

In high voltage transmission lines, the corona discharge appears at the surface of the conductors when a certain critical value of electric field is reached. In positive polarity the corona discharge can adopt different modes, being the inception streamer mode, a pulsed form of the corona, the first form that is adopted by the discharge. In negative polarity the first form that adopts the discharge is in form of pulses called Trichel pulses, these are more regular, of higher frequency and of less amplitude than the streamers in positive polarity. Due to the higher amplitude of the positive streamers, up to one order of magnitude, than the Trichel pulses, the streamer pulses from positive corona are considered as the main source of RI in transmission lines. For this reason, in bipolar HVDC lines only the positive conductor is considered as the source of RI, neglecting the contribution of the negative conductor [1]. The injection of corona current pulses can be considered as current sources randomly distributed along the conductors surface. The current pulses travel in both directions from the injection point becoming distorted and attenuated as these propagate along the line [1].

In order to analyze the radio interference produced by corona in transmission lines, either in AC or DC, the random and pulsed nature of the corona current has led to the necessity of defining the concept of excitation function (Γ) [5]. Empirical formulas for Γ have been derived by different research groups, based on experimental work done on corona cages or test lines [6]. In the case of AC these formulas have been developed considering the dense rain as the condition in which the line produces the maximum RI level [5]. For DC, the formulas reported for the excitation functions are few, one of these formulas can be found in [7], for different seasons of the year in fair and foul weather conditions, and it is given as:

$$\Gamma = \Gamma_0 + k_1(g_{\max} - g_0) + k_2 \log_{10}\left(\frac{n_c}{n_0}\right) + 40\log_{10}\left(\frac{d}{d_0}\right) \text{ [dB]} \quad (1)$$

the magnitude in dB considering $1\mu A/\sqrt{m}$ as the base reference value, and:

g_{max}: is the maximum bundle electric field in kV/cm
n_c: is the number of sub-conductors in the bundle
d: is the sub-conductor diameter in cm.

The reference value Γ_0 and the empirical constants k_1 and k_2 are given for all seasons in different weather conditions in Table 1.

Table 1. Parameters defining the empirical formula for RI excitation function [7]

Season	Weather condition	Γ_0 (dB)	k_1	k_2
Summer	Fair	27.0	1.83	45.8
	Foul	20.4	1.39	48.0
Fall/Spring	Fair	23.4	1.68	29.9
	Foul	19.8	1.68	63.5
Winter	Fair	18.7	1.63	19.7
	Foul	19.5	1.47	10.0

g_0 and d_0 are reference values given by n_0=6, d_0=4.064 cm and g_0=25 kV/cm.

The average maximum bundle gradient is obtained as:

$$g_{\max} = g_a \left[1 + (n_c - 1)\frac{r}{R} \right] \quad (2)$$

where r is the sub-conductor radius and R is the equivalent bundle radius given by:

$$R = \sqrt[n]{rnA^{n-1}} \quad (3)$$

A is the bundle spacing:

$$A = \frac{s}{2\sin\left(\frac{\pi}{n_c}\right)} \quad (4)$$

where s is the distance between two pieces of bundle conductor. Also, g_a in equation (2) is the average sub-conductor gradient calculated as:

$$g_a = \frac{1}{n_c}\frac{q}{2\pi\varepsilon_0 r} \quad (5)$$

The charge q is calculated with:

$$q = CV \quad (6)$$

where C is the capacitance and V is the voltage of the line. The empirical formula (1) is used in this work with the model presented in the next section to determine the RI lateral profiles in HVDC transmission lines.

3. Model for Corona Propagation Analysis

In this section the transmission line model used to simulate the propagation of the corona current along multiconductor transmission lines is presented. The propagation analysis allows computing the corona current on the conductors which is then used to calculate the resulting magnetic, and electric fields in the vicinity of the line.

The transmission line model is derived from the per unit length equivalent circuit for a Δz section, presented in Fig. 1. The transmission line is considered of infinite length, and with uniform corona current density injections (J), per unit length.

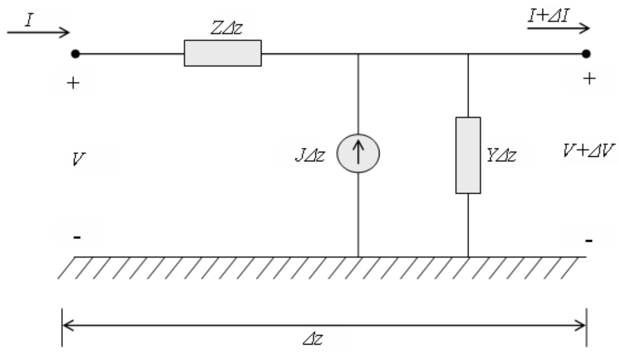

Fig. 1. Per unit length equivalent transmission line circuit with corona

By applying circuit analysis, the telegrapher equations for multiconductor lines, including the corona current density source, are obtained as:

$$\frac{d\mathbf{V}}{dz} = -\mathbf{ZI} \quad (7)$$

$$\frac{d\mathbf{I}}{dz} = -\mathbf{YV} + \mathbf{J} \quad (8)$$

where **V** and **I** are the voltage and current at any point on the line, and **J** is the column vector of corona current densities injected into the conductors. The parameters **Z** and **Y** are square matrices that represent the series impedance and shunt admittance per unit length of the line. As mentioned before, the parameters are determined considering the skin effect by using the concept of complex penetration depth, in the conductors and in the ground return [2], [8].

The series impedance, and shunt admittance matrices are comprised of self as well as mutual terms. Thus equations (7) and (8) represent n sets of equations for the voltage and current on the n-conductor line. Because of the inductive and capacitive coupling between the conductors, the n sets of equations are also coupled. Direct solution of these equations is therefore an extremely difficult task.

The modal analysis is used to simplify equations (7) and (8) into a number of uncoupled sets of equations which can each be solved as in the case of a single conductor line. The modal transformation matrices **M** and **N** are defined by:

$$\boldsymbol{\lambda}_V = \mathbf{M}^{-1}\mathbf{ZYM} \quad (9)$$

$$\boldsymbol{\lambda}_I = \mathbf{N}^{-1}\mathbf{YZN} \quad (10)$$

where $\boldsymbol{\lambda}_V$ and **M** are the eigenvalues (diagonal) and eigenvectors matrices of **ZY**. Also, $\boldsymbol{\lambda}_I$ and **N** are the eigenvalues (diagonal) and eigenvectors matrices of **YZ**. Moreover, $\boldsymbol{\lambda}_V = \boldsymbol{\lambda}_I = \boldsymbol{\lambda}$. The modal propagation constants $\boldsymbol{\Psi}$ and the modal attenuation constants $\boldsymbol{\alpha}_m$ matrices are given as:

$$\boldsymbol{\Psi} = \sqrt{\boldsymbol{\lambda}} \quad (11)$$

$$\boldsymbol{\alpha}_m = \mathrm{Re}\{\boldsymbol{\Psi}\} \quad (12)$$

The corona currents density vector is obtained as:

$$\mathbf{J} = \frac{\mathbf{C}}{2\pi\varepsilon_0}\mathbf{\Gamma} \tag{13}$$

where **C** is the capacitance matrix of the line and **Γ** is the function excitation vector. Since the positive conductor of the bipolar line is the only source of RI, the vector **Γ** may be expressed as:

$$\mathbf{\Gamma} = \begin{bmatrix} \Gamma_+ \\ 0 \end{bmatrix} \tag{14}$$

The modal corona current density vector is given by:

$$\mathbf{J}_m = \mathbf{N}^{-1}\mathbf{J} \tag{15}$$

Using equations (12) and (15), the modal components of current on the conductors are obtained as:

$$\mathbf{I}_m = \begin{bmatrix} \dfrac{J_{m1}}{2\sqrt{\alpha_{m1}}} \\ \dfrac{J_{m2}}{2\sqrt{\alpha_{m2}}} \end{bmatrix} \tag{16}$$

where J_{m1} and J_{m2} are elements of the vector $\mathbf{J}_m$, while α_{m1} and α_{m2} are the modal attenuation constants.

Then, conductor currents are obtained as:

$$\mathbf{I} = \mathbf{N}\mathbf{I}_\mathbf{m} \tag{17}$$

The current in each conductor is the sum of two modal components.

By knowing the currents flowing in all the conductors of the line, the corresponding horizontal component of the magnetic field at ground level at any point (x, 0), is calculated as:

$$H_x = \sum_{i=1}^{n} \frac{I_i}{2\pi}\left[\frac{h_i}{h_i^2 + (x_i - x)^2} + \frac{h_i + 2P}{(h_i + 2P)^2 + (x_i - x)^2}\right] \tag{18}$$

where:
I_i = current in the i^th^ conductor
h_i = i^th^ conductor height
x_i = i^th^ conductor distance
x = measurement point
P = complex depth of penetration for the ground return defined as:

$$P = \sqrt{\frac{\rho_e}{j\omega\mu_e}} \tag{19}$$

where ρ_e y μ_e are the resistivity and permeability of the ground, respectively.

The corresponding vertical component of the electric field is calculated, assuming a quasi–TEM propagation, as:

$$E_y = Z_0 H_x \tag{20}$$

where the wave impedance of free space Z_0 is:

$$Z_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}} \approx 120\pi \tag{21}$$

After determining the electric field component, the resultant field is determined by an rms addition:

$$E_{y,total} = \sqrt{\sum_{k=1}^{n} \left|E_{y,k}\right|^2} \tag{22}$$

Electric field due to corona $E_{y,total}$, is usually expressed in dB above 1μV/m using the next equation:

$$E_{y,total}(dB) = 20\log_{10}\frac{E_{y,total}(\mu V/m)}{1\mu V/m} \tag{23}$$

4. Computation of RI lateral profiles of an HVDC line for Turkey

The determination of RI levels has become an important requirement during the design stage of a transmission line, usually as a part of the electromagnetic compatibility studies (EMC) which can be required to know the magnitude of the impact on the environment in the vicinity of the transmission line. The RI is usually determined until certain distance from the center of the line, giving the RI lateral profile.

Experimental measurements of RI lateral profiles are usually performed at a certain distance from the ground (typically one or two meters), when these lateral profiles are computed, the RI levels can be reported at the ground level and extended up to 100 m to each side of the center of the line [2], [9]. The frequency at which this interference is usually measured is 0.5 MHz [10].

In this section the RI lateral profiles are computed in order to compare different design options of an HVDC transmission line that is being considered to be installed in Turkey. This HVDC line would go from Keban in the south-east part of Turkey, where a high hydro generation capacity is installed, to Adapazari, close the area of Marmara Region (Istanbul, Kocaeli, Adapazari, Bursa), a high energy consuming area in Turkey. The power capacity of the HVDC transmission system is considered of 3000 MW, bipolar, and with a length of around 1000 km.

In Fig. 2, the tower geometry and the dimensions considered for this study are shown. The design options analyzed are for two voltage levels, 500 kV and 600 kV, two conductor types and three different bundle conductor configurations. In the Table 2, the three configurations are presented, and in Table 3 the data considered in the simulation.

The RI levels are given in dB with 1μV/m as base magnitude. The profiles are plotted 40 m from each side of the center of the tower at ground level. The ground resistivity was assumed to be 100 Ω-m. The frequency in the simulations was 500 kHz. The parameters used for the excitation formula were those corresponding to fair weather condition in summer; see Table 1, which is assumed the more critical condition for the RI level in HVDC lines.

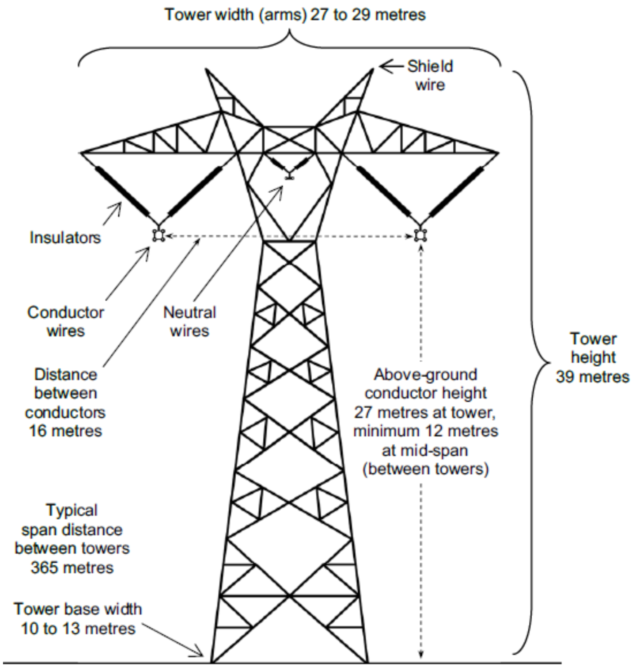

Fig. 2. HVDC tower geometry and dimensions [11]

Table 2. Bundle conductor configurations

Configuration	Number of sub-conductors	Conductor Type
3x954 mcm	3	954 mcm
3x1272 mcm	3	1272 mcm
4x1272 mcm	4	1272 mcm

Table 3. Data of the HVDC line considered in the simulations

Number of Poles	2	
Conductor Height	27 m	
Distance between Poles	16 m	
Distance between Bundle Sub-conductors	0.45 m	
Number of Bundle Sub-conductors	3 or 4	
Voltage	500 or 600 kV	
Conductor Radius	1272 mcm	954 mcm
	1.71 cm	1.48 cm

In Fig. 3 the RI lateral profiles for the 4x1272 mcm bundle configuration are shown for 500 kV and 600 kV voltages. As can be expected, the magnitude of the RI levels in the 600 kV line are superior for more than 6 dB than the values with 500 kV.

The RI lateral profiles for the three different bundle configuration are presented in Fig. 4 and Fig. 5, for 500 kV and 600 kV respectively. In Table 4, the maximum values of RI for all the cases are listed.

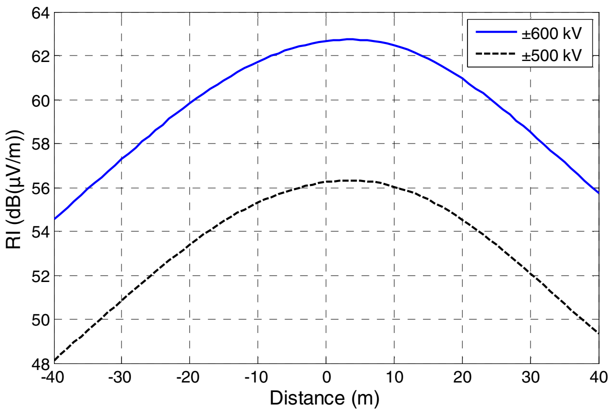

Fig. 3. RI lateral profiles for 4x1272 mcm bundle configuration for 500kV and 600kV

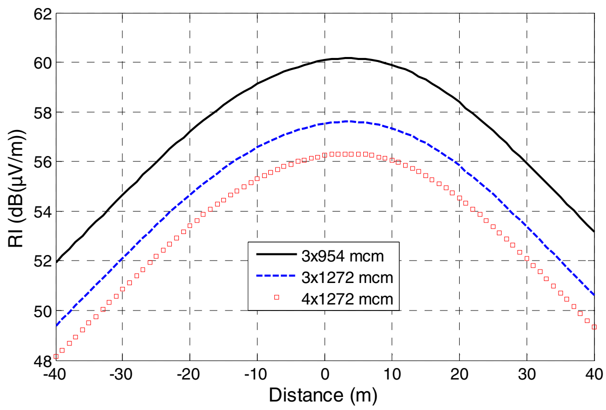

Fig. 4. RI lateral profiles from the tower center for the three bundle configuration at 500kV

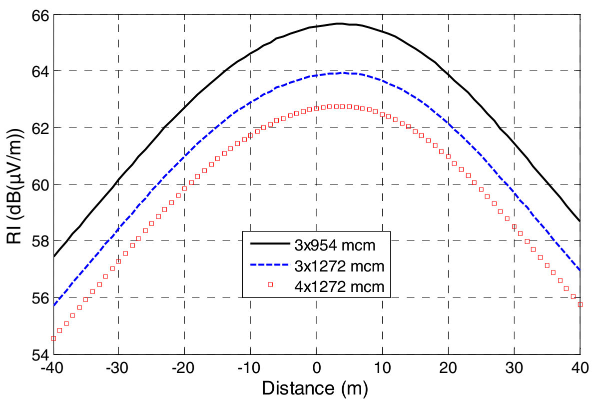

Fig. 5. RI lateral profiles from the tower center for the three bundle configuration at 600kV

Table 4. Maximum RI level for the different configuration

Boundle Configuration		Maximum RI level dB
500 kV	4x1272 MCM	56.3
	3x1272MCM	57.6
	3x954 MCM	60.2
600 kV	4x1272 MCM	62.7
	3x1272MCM	63.9
	3x954 MCM	65.7

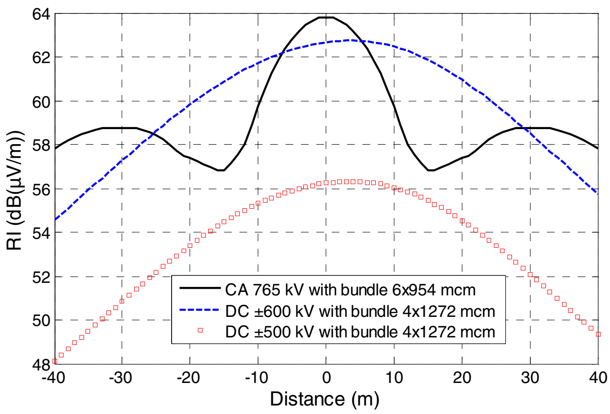

Fig. 6. RI lateral profiles for two HVDC design options compared with an equivalent HVAC line option

If the limit of 60 dB above 1µV/m is considered as the value of RI that lines between 400 kV and 600 kV should not exceed [1], only the designs for 500 kV with 4x1272 MCM and with the 3x1272 MCM bundle configuration, are acceptable. The option with the bundle configuration 4x1272 MCM is the one with less RI levels.

In order to compare the RI performance of the HVDC line options with an equivalent option in an HVAC line, the RI lateral profile was calculated for a 765 kV AC transmission line. The HVAC 765 kV line has a horizontal configuration, with six conductors per phase. The sub-conductor radius is 1.48 cm, the distance between bundle conductors is 0.43 m. The distance between phases is 18 m and the vertical position is 27.7 m. The ground resistivity was the same as in the DC examples, 100 Ω-m. The formula used for the excitation function is given by the Bonneville Power Administration [2]. In Fig. 6, the RI lateral profile for the HVAC line is presented and compared to the profiles with lower RI levels for the 500 kV and 600 kV HVDC designs. The 765 kV AC line reaches higher values than the DC lines, around 6 dB higher than the 500 kV DC case, and a little more than one dB for the 600 kV DC case.

5. Conclusions

In this work, the RI performance of different designs for a bipolar HVDC transmission line was analyzed. The used method computes the attenuation constants from the line parameters, and decouples the bipolar system by using modal decomposition.

The RI lateral profiles for different design examples of a 3000 MW HVDC transmission line are compared. This HVDC line is a possible option to transmit electrical energy from the south-east part of Turkey, with a large hydro generation capacity, to the area of Marmara, a high energy consumption area.

Models as the one used in this work allow to estimate, during the design process, the radio interference levels that will be produced by the line. This information can be used as a part of the electromagnetic compatibility studies (EMC), which can be required to know the magnitude of the impact on the environment in the vicinity of the transmission line.

In this case, it is shown how the bipolar HVDC transmission line with a voltage of 600 kV exceeds the maximum recommended levels of RI. The bundle configurations for 500 kV, that use 1272 MCM conductors present RI magnitudes below the recommend maximum level.

6. Acknowledgements

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