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Induced Pipeline Voltage Near-by Hybrid Transmission Lines

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Abstract

The aim of this paper is to calculate the induced voltage, nearby hybrid transmission lines. Two hybrid transmission lines are simulated and modeled. The first line is double-circuit operating with ac voltage of 220 kV and bipolar circuit with a dc voltage of ±500 kV, while the second line is with flat configuration operating at 500 kV ac and of ±500 kV. The induced voltage on the pipeline is calculated due the mutual effect of the electric field of these lines. The charge simulation technique and COMSOL computer package are used for calculating the electric field underneath the hybrid lines with and without pipelines and are used to determine the induced voltage on the pipelines.

The maximum induced voltage is 9.5 kV for the first line at spacing (S) of 10 m and DC circuit height of 15.7 m against 4.3 kV for height of 24.9 m. The corresponding values for the second line at the same spacing S of 10 m are 7.08 and 3.1 kV for DC circuit heights of 19.1 m and 30 m respectively. The maximum induced voltage on the pipeline is slightly changed due to changing the phase sequence of the AC circuit and the spacing between AC and DC circuits.

Keywords: Induced Voltage, – Electric Fields, HVDC Transmission, Finite Element Method, Hybrid Transmission Lines.

1. Introduction

In recent years, the possibility for direct current (DC) and alternating current (AC) transmission lines operating parallel to each other, having the same Right Of Way (ROW) or even the same tower has been maximized to push more power and improve the stability of the AC power transmission system [1 – 6]. Designing of such hybrid dc-ac transmission lines requires accurate calculation of the electric field underneath these lines, and then the corona, audible noise and field effects on human, will be taking into consideration and calculated [7].

As a result of the possible effects of magnetic and electric fields on human being and objects underneath and adjacent these lines, the research work and studies have been received an increasing interest in these area [8–10].

A detailed illustration of the electrostatic field underneath these lines has been introduced and presented in many researches and papers. The effect of the electric fields on transmission lines' maintenance workers is an important task that electric utilities are most often need to reply to the potential health hazards. The long term effect of the electric fields was reported and studied in several organizations and countries before [7-9].

Quantitative descriptions and illustrations of the electric field effect on the pipelines underneath and near-by ac overhead transmission lines have been introduced in many papers and works [13–15]. But rarely papers introduce the effect of hybrid transmission line on pipelines.

In this paper COMSOL computer package is used for calculating the induced pipeline voltage underneath hybrid transmission lines with different spacings, heights of ac, dc circuits and different phase sequence of ac circuit. The calculated induced voltage values are checked and compared with those estimated and calculated before for AC transmission lines.

2. Calculation method

A) Charge Simulation Technique

The charge simulation technique (CST) for field calculation underneath overhead lines was reported before in previous papers [22–25]. In this technique, the distributed charge on the surface of a voltage stressed conductor is changed by number N of imaginary simulation charges positioned in the conductor at a radius R_f as shown in Fig. 1, R_f.is a fraction of a conductor radius r_c. To find the magnitudes of the simulation charges, boundary points are chosen on the surface of the conductor to satisfy dirichlet the boundary conditions. The number of boundary points is chosen equal to the number of simulation charges. At each boundary point, the voltage due to all the simulation charges is equal to the well-known conductor voltage. Let, $\boldsymbol{Q_j}$ is the jth imaginary charge and $\boldsymbol{V}$ is the known voltage of the conductor. Thus, dirichlet condition at the jth boundary points is expressed as follows:

$$V = \sum_{j=1}^{n} P_{ij}\, Q_j \qquad (1)$$

Where P_{ij} is called potential coefficient, which can be determined analytically depending on the type of simulation charges. Application of equation (1) is applied to the N boundary points results in the formulation of N linear equations in N unknown simulation charges, expressed as:

$$[P]_{NxN}\,[Q]_N = [V]_N \qquad (2)$$

Where [P] is the potential coefficient matrix, [Q] is the column vector of unknown simulation charges, and [V] is the voltage applied to the conductor. Solution of equation (2) determines the unknown simulation charges. Once the undetermined charges are known, the field intensity and potential at any point around the line conductors and the pipeline can be calculated. While the voltage is found by equation number one, the two dimension components of electric field are estimated by superposition principle of all field vector components.

For a system of Cartesian coordinate, the x, y components E_x and E_y are expressed as:

$$E_x = \sum_{j=1}^{N} \frac{\partial p_{ij}}{\partial x} Q_j \quad = \sum_{j=1}^{N} \left(f_x\right)_{ij} Q_j \qquad (3)$$

$$E_y = \sum_{j=1}^{N} \frac{\partial p_{ij}}{\partial y} Q_j \quad = \sum_{j=1}^{N} \left(f_y\right)_{ij} Q_j \qquad (4)$$

Where $(f_x)_{ij}$, $(f_y)_{ij}$ are the electric field intensity coefficients" in the x and y direction.

Application to Hybrid Transmission Line with and Without Pipeline

In the present work, the CST is combined with the method of imaging to increase the efficiency of simulation for induced voltage calculation on the pipeline adjacent hybrid transmission lines with and without the pipeline. The number and positions of simulation charges in each sub-conductor and pipeline is no longer spotted but dependent on the number of sub-conductors, geometry of pipeline and how they are arranged in space.

For the pipeline, the distributed surface charges on the surface of the pipeline are simulated by $\mathbf{n_p}$ unknown infinite line charges uniformly represented around imaginary cylinder of radius R_F in the pipeline and coaxial with it, while the distributed surface charges on the surface of each sub-conductor of the hybrid transmission line are simulated by line charges existing at the center of the sub-conductor The hybrid transmission line has **m** sub-conductors per phase, the number of sub-conductors is (5m). To achieve zero voltage at the ground plane, (5m) images are depended and then the total number of sub-conductors of the system is 2(5m) as shown in Fig. 2.

Each sub-conductor is simulated by the images of the remaining sub-conductors and images in it i.e. by [2*(3*m)-l] line charges. The image of the jth sub-conductor in the ith sub-conductor is positioned along the line connecting the two sub-conductors at a distance R_i^2/l_{ij} from the center of the ith sub-conductors where, R_i is the radius of the sub-conductor i and l_{ij} is the length of the line joining them, as illustrated sin Fig. 3.

To find the undetermined charges, recalling the set of equations 2 and 3 here to be subedited at a number of boundary points selected on the sub-conductors' surface where the potentials' array [V] is equal to the sub-conductor's voltage and initially the charges on the pipeline voltage is to be assumed zero [22-23].

B) COMSOL Computer Package

The finite element (FE) analysis and solver software package COMSOL Multi-physics (COMSOL Inc., Burlington, USA) was used for calculating the induced pipeline voltage. A two dimensional (2D) simulation was completed for the induced pipeline voltage calculations due to the electrostatic field. Modeling was performed for the sub-conductors of the hybrid transmission line and the pipeline. The controlling equations for the model are adjusted from COMSOL (2006) as the following:-

The equations to settle the electrical voltage are established on charge preservation:

$$-\nabla.(\sigma\nabla V - J^e) = 0 \qquad (5)$$

Where σ is the electrical conductivity (S/m), V is the electrical voltage (V) and J^e (A/m^2) is an outwardly created current density. The relation between the electric field and the electrical voltage is given by Eq. (2):

$$E = -\nabla V \qquad (6)$$

Where E is the strength of electric field (V/m)

The simulation model with COMSOL software is used the following boundary conditions:
1- The sub-conductors is stressed by ac and dc voltages
2- Zero voltage for ground wire
3- Zero charge for the pipeline (floating potential) [22-23].

3. Results and Discussions

Case study 1: A hybrid transmission line with 220 kV AC and ±500kV DC

The configuration of the hybrid transmission line is shown in Fig. 4. For 220 kV AC line, the number of sub-conductors per phase is two, the radius of a single sub-conductor, r_c is 0.0135 m, the sub-conductor spacing, D is 0.3 m, the heights H_1, H_2 and H_3 are 15.7, 24.9 and 35.1 m respectively, where H_1 is the height from ground level to the lower conductor, H_2 is the height from ground surface to the middle conductor and H_3 is the height from ground level to the upper conductor. The tower arm lengths B_1, B_2 and B_3 are 8.55, 8.55, 8.55 m respectively. For 500 kV DC line, the number of sub-conductors per phase is four, Sub-conductor cross sectional area = 775 mm^2, sub-conductor to sub-conductor spacing = 35 cm, pole-to-pole spacing B_{dc} is equal to 25 meters. The height H_{dc} from the ground level to the conductor is considered variable.

The spacing S is the distance between the AC and DC lines, while S_1 is the distance between the pipeline and the center of AC transmission line.

Figure 5 shows the induced voltage of the pipeline for the configuration shown in Fig. 4 at variable horizontal distances with spacing S=10 m and equal heights H_{dc}, H_1 of 15.7 m. The maximum induced voltage is to be 9.5 kV at 40 m from the center of 220kV line. It is clear the induced voltage is reduced when the pipeline is to be far from the hybrid lines. Faring the pipeline from the transmission line is an effective method to reduce and mitigate the induced voltage of the pipeline if possible.

Figure 6 shows plot of the induced voltage on the pipeline with fixed spacing S of 10 m between AC and DC lines and variable height H_{dc} of H_1, H_2 and H_3. It is clear that the maximum induced voltage on the pipeline is 9.5, 4.3 and 2.7 kV respectively for the mentioned heights respectively. The percentage reduction of the induced voltage on the pipeline is 71%, 54% for the used heights

Figure 7 shows plot of the induced voltage on the pipeline with fixed height H_{dc} =H_1 and different Spacing S between AC and DC lines of 10, 30, 50, and 100 m. From Fig. 7, the induced voltage on the pipeline is 9.5, 9.3, 9.27 and 9.8 kV respectively for the mentioned spacings. It is clear that, there is a slightly change on pipeline induced voltage when changing the spacing between AC and DC line.

Effect of phase sequence on induced voltage of pipeline

By applying the COMSOL computer program to the transmission line shown in Fig. 4 with the same dimensions mentioned above. But with changing the phase sequence of the AC double circuit line conductors to (ABC-ABC, ABC-ACB, and ABC-BCA).

Figure 8 shows plot of the induced voltage on the pipeline field at the surface of pipeline when changing the phase sequence of the sub-circuit of AC line closed to DC line.

From Fig. 8, it is noted that when changing the phase sequence, there is no change on the pipeline induced voltage but the induced voltage at the surface of ground on the right side of AC line is slightly changed.

Case Study 2: A hybrid transmission line with 500 kV AC and ±500kV DC

Figure 9 shows the configuration of the hybrid transmission line. For 500 kV AC line, The sub-conductor numbers per phase is three, the radius of sub-conductor r_c is 0.0153 m, the spacings between sub-conductor, D_1, D_2 and D_3 are 0.47, 0.45, 0.45 m respectively. The height from ground surface H_{ac} is19.1 m and the length B of the arm of the tower is 12 m.

But for 500 kV DC line, the sub-conductor numbers per phase is four, the single sub-conductor radius, r_c is 0.00886 m, the sub-conductor spacings are equal, D is 0.35 m, the height from the ground level to the conductor is equal to H_{dc}, the clearance between the two poles B_{dc} and equal to 25 m. The spacing S is the distance between the AC and DC lines while the spacing S_1 is the distance between the pipeline and the center of AC line.

Figure 10 shows plots of the pipeline induced voltage for the configuration shown in Fig. 9 at S=10 m with different DC line heights and variable distance from pipeline to the center of AC line.

From Fig. 10, the induced voltage is 10.2, 7, 4.47 and 3.15 kV for DC line heights of 15, 19.1, 25 and 30 m respectively. Figure 10 show that the maximum induced voltage on the surface of the pipeline field decreases with the increase of the DC line height and when the pipeline is faring from the hybrid line.

Figure 11 shows a graph plot of the induced voltage on the pipeline for the configuration shown in Fig. 9 at H_{dc} =19.1 m with different spacing S between AC and DC lines with variable distance from pipeline to the center of AC line.

From Fig. 11, the induced voltage is 7.08, 6.9, and 6.97 kV for spacings S of 10, 30, and 50 m respectively. It is clear that the induce voltage is slightly changed when the spacing S is changed; also the induced voltage is reduced when the pipeline is go away from the hybrid line.
=19.1 m and different Spacing S between AC and DC circuits with variable distance $S_1$from pipeline to the center of AC line.

Figure 11 clears the induced voltage on the pipeline of Fig. 9 at H_{dc} =30 in ground wire position.

Figure 12 show that the induced pipeline voltage for different DC circuit polarity. From the shown figure, it is clear the maximum induced pipeline voltage is the same for the two polarities but with changing the position.

Figure 13 shows a plot of the induced voltage distribution on pipeline of Fig. 6 at S=10 m and DC line Hdc=19.1 m with changing the phase sequence of the AC line.

The maximum induced voltage values are 7.39, 7.08, and 7 kV for phase sequences ABC, CBA and BCA respectively. It is noted that, there is no remarkable modification in the maximum induced voltage due to changing the phase sequence.

C) Conclusions

The maximum values of the induced voltage on the surface of pipeline are reduced when the pipeline is faring from the center of hybrid line.
The maximum induced voltage on the surface of pipeline is reduced when the height of DC line is increased.
The maximum values of the induced voltage on the surface of pipeline are slightly reduced when the spacing between the DC and AC line is changed.
No noticeable change in the maximum induced voltage level on the surface of pipeline when changing the phase sequence of the AC line.

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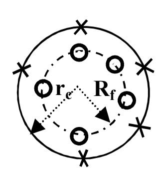

●●● Line charges
××× Boundary points

Fig. 1: Charge representation for the line conductors and pipeline [23].

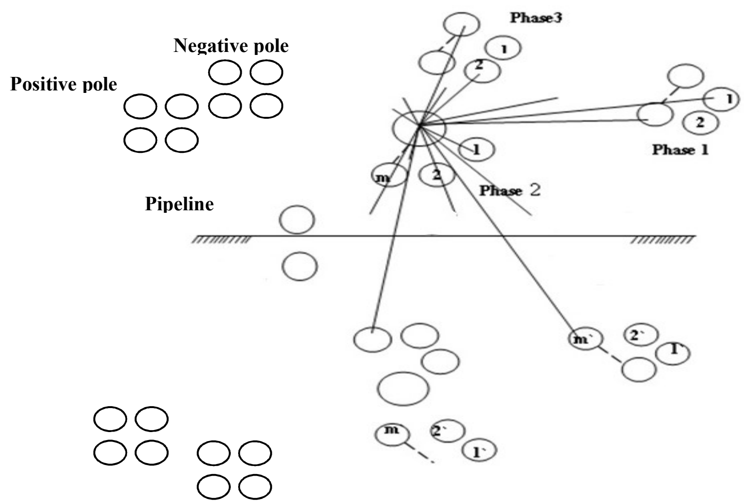

Fig. 2: The pipeline adjacent the hybrid transmission line with m sub-conductors

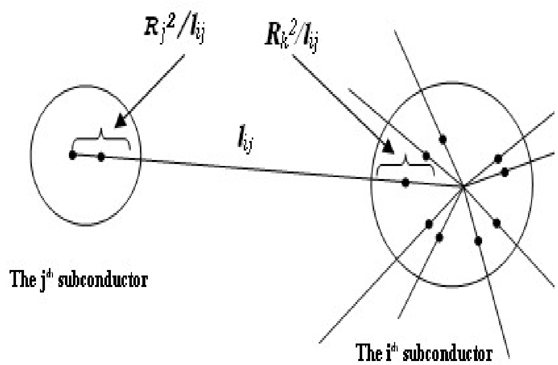

Fig. 3 The simulation charges locations on hybrid transmission line.

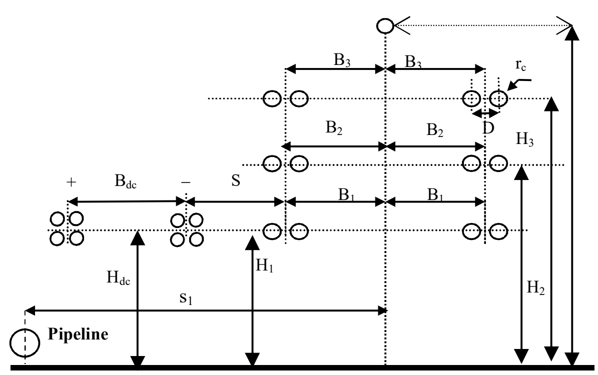

Fig. 4: The Hybrid Transmission Line of 220 kV AC and ± 500 kV DC

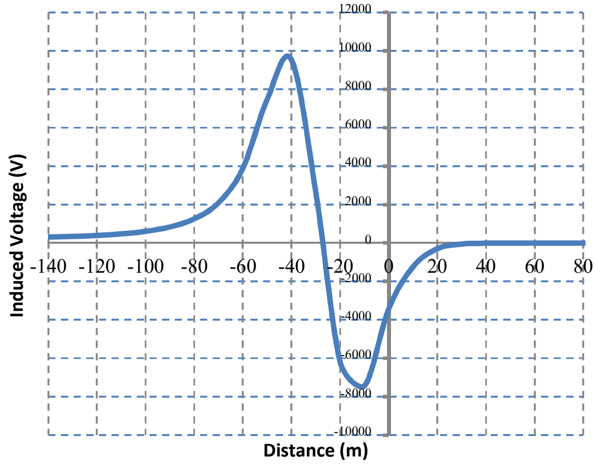

Fig. 5: Induced pipeline voltage with variable horizontal distance of pipeline of Fig. 1 at S=10 m and $H_{dc} = H_1$.

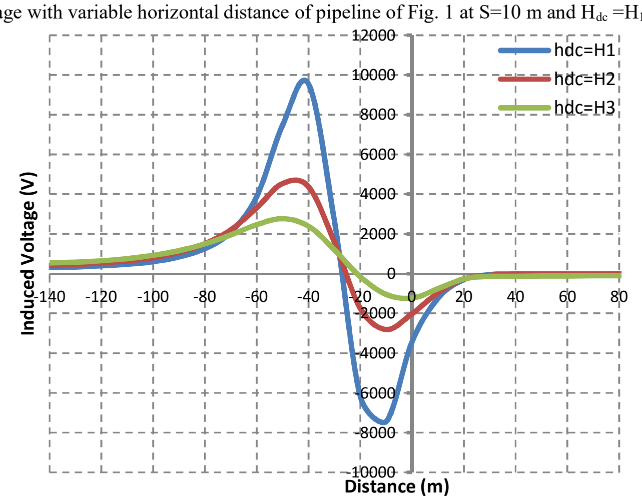

Fig. 6: Induced pipeline voltage of Fig. 1 at S=10 m and variable heights of DC line H_{dc}

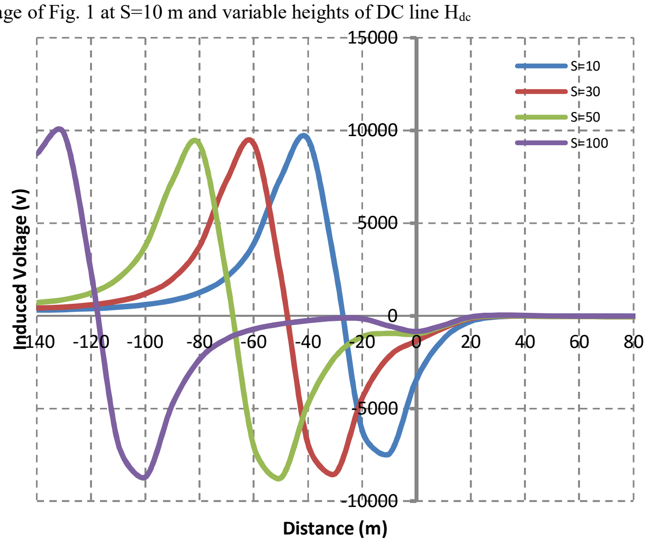

Fig. 7: Induced pipeline voltage of Fig. 1 at $H_{dc} = H_1$ and variable spacing S between AC and DC circuits.

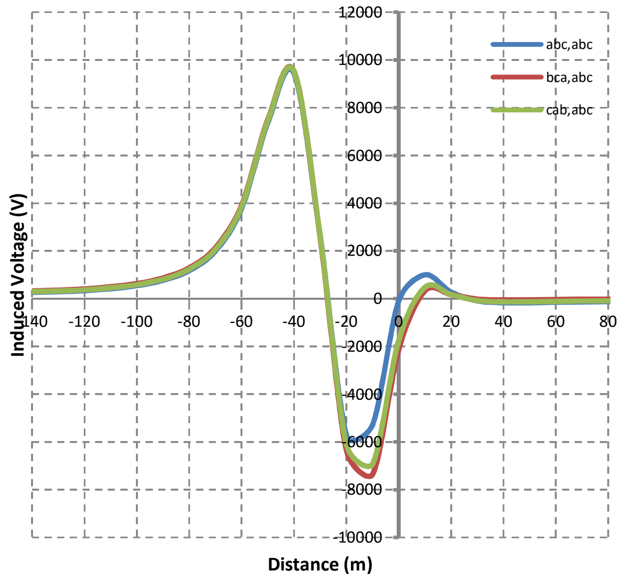

Fig. 8: Induced pipeline voltage of Fig. 1 at different phase sequence of ac line with fixed height $H_{dc}=H_1$, and spacing S=10 m.

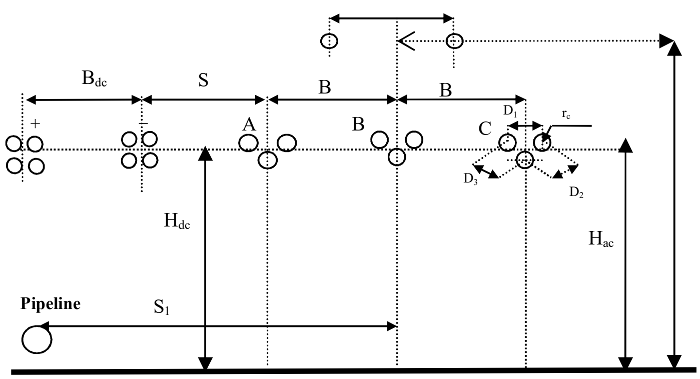

Fig. 9: The Hybrid Transmission Line of 500 kV AC and ± 500 kV DC

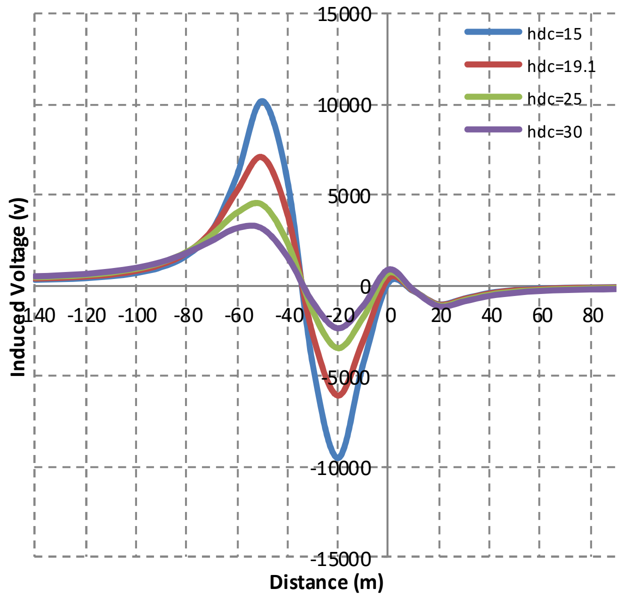

Fig. 10: Induced pipeline voltage of Fig. 9 at S=10 m and variable heights H_{dc} of DC line

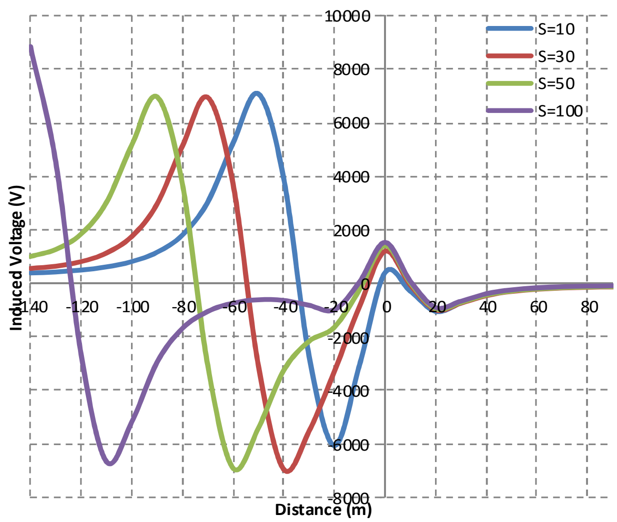

Fig. 11: Induced pipeline voltage of Fig. 6 at H_{dc} =19.1 m and different Spacing S between AC and DC circuits with variable distance S_1 from pipeline to the center of AC line.

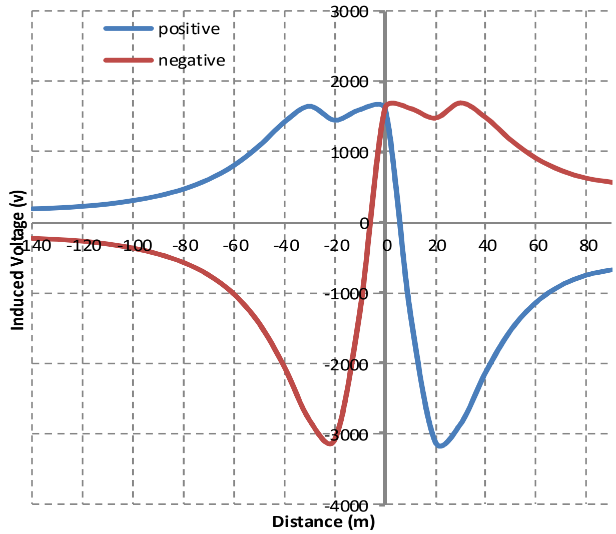

Fig. 12: Induced voltage distribution on pipeline of Fig. 6 at H_{dc} =30 in ground wire position

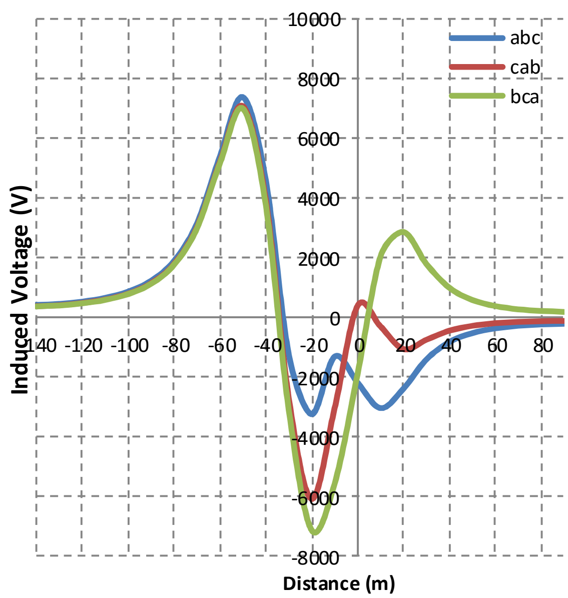

Fig. 13: Induced pipeline voltage of Fig. 6 at S=10 m and DC line height H_{dc}=19.1 m with changing the phase sequence of the AC line