EMTP Simulations and Theoretical Formulation of Induced Voltages to Pipelines from Power Lines

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Abstract

This paper has investigated induced voltage characteristics on a pipeline system from an overhead line based on EMTP simulation results and theoretical formulation developed by the authors. The induced voltages are significantly dependent on the configuration of the power line. A horizontal line induces the largest voltage to the pipeline, and an induced voltage by a vertical twin-circuit line is smaller by about 20% than that by a vertical single-circuit line. The simulation result shows a reasonable agreement with a field test result. The basic characteristic of the induced voltages and the effect of the power line currents are explained by applying the theoretical formulation, which is very useful to explain simulation results from the physical viewpoint.

Keywords: induced voltage, pipeline, power line, EMTP, theoretical formulation

1. Introduction

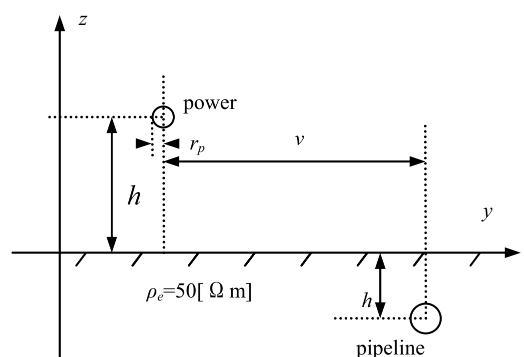
A pipeline is widely used to supply gas and oil to customers. A defect such as pinhole on a coating layer of a steel pipeline causes a damage on the steel pipe by electro-chemical corrosion and may result in a fault of the pipeline [1, 2]. The corrosion is caused either by leakage currents from a railway system or by induced voltages from a power transmission line. The former has been studied in detail and countermeasure such as voltage application have been adopted. On the contrary, the latter has not been well investigated though low resistance grounding has been adopted in Japan. Thus, it is essential to predict the induced voltages and to investigate the characteristics. There are a number of softwares to simulate the induced voltages [3-7]. Among them, a numerical electromagnetic analysis such as an FDTD method [8] seems to give the most accurate solution because it is able to consider any parameters if necessary and if available, while a conventional circuit-theory based approach such as EMTP can not deal with some parameters. The numerical electromagnetic analysis, however, has a disadvantage to handle a complex system composed of various circuit elements. On the contrary, the EMTP is very advantageous to deal with the complex system [9].

This paper shows EMTP simulations of induced voltages and currents to an underground pipeline [9-11]. The accuracy of the EMTP simulation is investigated in comparison with a field test result. The effect of line configuration is discussed. Also, a basic characteristic of induced voltages is explained by applying a theoretical formulation of a cascaded pipeline system developed by the authors [12].

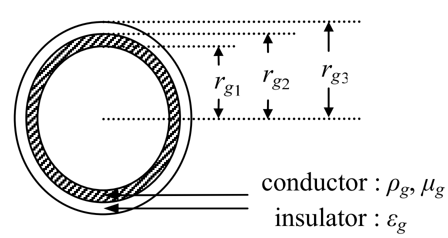
2. EMTP Analysis

Fig. 1(a) illustrates a power line and pipeline system, and (b) the cross-section of the pipeline which is coated by an insulating layer. The pipeline is represented as an underground cable. The parameters required for representing the pipe as a PI-equivalence or as a distributed line are evaluated by the EMTP Cable Parameters [11].

It should be noted that the distributed-parameter line model can not give an accurate steady-state solution because of the real part expression of the characteristic impedance and the transformation matrix. The conductance G of the pipeline is calculated using the conductivity of a coating layer as explained in Reference [10].



(a) System configuration



(b) Cross-section of a pipeline

Fig. 1 A power line and pipeline system

r_{g1} = 191.3 [mm], r_{g2} = 203.2 [mm], r_{g3} = 206.4 [mm]

$\rho_g = 1.5\times10^{-7}$ [Ωm], μ_g = 280, ε_g = 2.30

The conductance being far smaller than the conductance of the pipe grounding resistance, it is neglected in general.

A mutual impedance is calculated by numerical integration of Pollaczek's formula [13] reminding that the infinite integral is numerically very unstable. If necessary, it is calculated approximately by the CP[14].

2. 1 Single Section of a Pipeline

(1) Single-phase power line

Fig.2 illustrates a model circuit of a simulation. The pipeline (h_g=−1.8m) is parallel with the separation distance y to a 500kV power transmission line (h_p=16m) between nodes G1 and G2 with the length of x_1. There is no parallel power line to the gas pipeline form node G2 to G3 with the length of x_2. An ac current source I_0 with the amplitude of 1kA and the frequency of 50 Hz is applied to node P1 of the power line. The pipeline is grounded through a resistance R_g at the both ends. Under the condition, node voltage V_{Gi} of the pipeline and induced voltage $V_m = V_{G1} - V_{G2}$ are calculated by the EMTP. Table 1 shows simulation conditions, the mutual impedance Z_m and analytical results of $V_m = Z_m I_0$. Table 2 is EMTP simulation results by a lumped-parameter model. A distributed-line model gives nearly the same results as those in Table 2.

It is reasonable in Table 2 that the induced voltages are determined by the separation distance and the parallel length of the power line and the pipeline, and by the inducing current I_0. Simulation results in Table 2 agree with the analytical results by $V_m = Z_m I_0$ in Table 1. Also, the node voltages V_{G1} and V_{G2} on the pipeline in Table 2 satisfy the relation $V_{G1} \cong V_{G2} = Z_m I_0 / 2$. Thus, it is confirmed that the proposed simulation method is appropriate.

It is interesting to know that the voltage V_{G3} at node G3 is nearly equal to V_{G1} and V_{G2}, and also V_{G3} is rather independent of the pipeline length x_2 .In a transient, voltage distribution is determined by a traveling wave and its reflected wave, and thus the voltage is a function of the line length. On the contrary in a steady state, there exists no induced voltage between the nodes G2 and G3 where there is no power line, and thus the voltage at the node G3 is the same as that at the node G2 following an electro-static theory.

The above results are for a single-phase power line which corresponds to an induced voltage during a single-line-to-ground fault as is well-known in the field of telephone line induction interference [15,16].

2. 2 Effect of power line configuration

(1) Three-phase horizontal line (case1i)

Induced voltages from a 500kV three-phase horizontal line in Fig. 3(a) is investigated when the following ac current is applied to the three phases at nodeP1.

$$I_a = I_0 \cos(\omega t), I_b = I_0 \cos(\omega t - 2\pi/3), I_c = I_0 \cos(\omega t + 2\pi/3)$$
$$I_0 = 1\text{k}A, \quad f = 50 \text{ Hz}$$

The pipeline is the same as Fig. 1 (b). The self surge impedance of the horizontal line is 380Ω by which the line is terminated. The grounding resistance R_g of the pipeline is taken to be 10Ω. The line length x_1 is fixed to 1 km, and x_2=0. In the figure, the distance y is the horizontal separation of the pipe from the center phase. Table 3(a) shows simulation results of induced voltages in the horizontal line.

It is observed in the table that induced voltage is the largest in case 12 and 16 where the horizontal separation y is ±28. When y is 0 (beneath the center phase) and ±100m, the induced voltage is the smallest among the investigated cases. The reason for this is readily explained as a total flux density due to three-phase symmetrical ac currents. When the separation y is infinity, the induced voltage becomes zero. The simulation results in Table 3(a) are also analytically explained by using the analytical formula $V_m = Z_m I_0$.

Table 1 Simulation conditions and analytical results on a single-phase line

x_1/x_2 [km]			y [km]	I_0 [kA]	Z_m [Ω/km]	θ °	V_m [V/km]	θ °
0.5	/	0.0	0.5	1.0	0.0431	41.4	21.5	41.1
0.5	/	0.0	1.0	1.0	0.0174	18.4	8.7	18.4
1.0	/	0.0	0.5	1.0	0.0431	41.4	21.5	41.1
1.0	/	0.0	1.0	1.0	0.0174	18.4	17.4	18.4
0.5	/	2.0	1.0	1.0	0.0174	18.4	8.7	18.4
0.5	/	10.0	1.0	1.0	0.0174	18.4	8.7	18.4
1.0	/	2.0	1.0	1.0	0.0174	18.4	17.4	18.4
1.0	/	10.0	1.0	1.0	0.0174	18.4	17.4	18.4
0.5	/	0.0	0.5	0.5	0.0431	41.4	21.5	41.1
0.5	/	0.0	1.0	0.5	0.0174	18.4	4.4	18.4
1.0	/	0.0	0.5	0.5	0.0431	41.4	21.6	41.1
1.0	/	0.0	1.0	0.5	0.0174	18.4	8.7	18.4

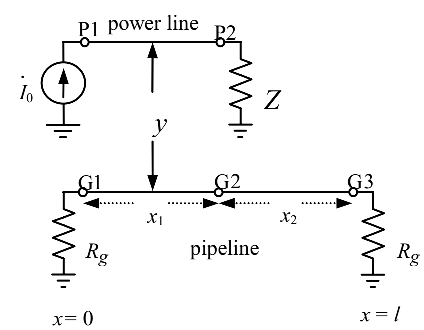


Fig. 2 A model circuit of an EMTP simulation

$$\dot{I}_0 = I_0 \cos(\omega t), f = 50 \text{ Hz}$$

Table 2 Simulation results on a single-phase power line

case	V_{G1} [V]	θ_1 °	V_{G2} [V]	θ_2 °	V_{G3} [V]	θ_3°	V_m [V]	θ_m °
11	10.7	40.6	10.7	-139.4	—		21.4	40.6
12	4.33	17.6	4.33	-162.4	—		8.7	17.6
13	21.4	39.7	21.4	-140.3	—		42.8	39.7
14	8.64	16.7	8.64	-163.3	—		17.3	16.7
21	4.27	15.8	4.40	-160.7	4.28	-167.2	8.7	17.6
22	3.89	10.5	4.82	-156.5	4.05	174.3	8.7	17.7
23	8.51	15.0	8.77	-161.5	8.53	168.0	17.3	16.6
24	7.73	9.77	9.61	-157.2	8.06	173.60	17.2	17.0
31	5.37	40.6	5.37	-139.4	—		10.7	40.6
32	2.17	17.6	2.17	-162.4	—		4.3	17.6
33	10.7	39.7	10.7	-140.3			21.4	39.7
34	4.32	16.7	4.32	-163.3			8.6	16.7

For example, the mutual impedances in case 11 are given by:

$Z_{ma} = 0.137\angle 69.82°, \quad Z_{mb} = 0.128\angle 658.56°$
$Z_{mc} = 0.121\angle 67.35°\,[\Omega/\mathrm{km}]$

Then, the following analytical result is obtained.

$V_{ma} = 136.5\angle 69.8°, \quad V_{mb} = 128.0\angle -51.4°$
$V_{mc} = 120.5\angle 129.4°$ [V/m]

The total induced voltage to the pipeline is given as a vector sum of the above.

$$V_m = V_{ma} + V_{mb} + V_{mc} = 14.6\angle -5.65°\,[\mathrm{V/km}]$$

The above result agrees well with the simulation results of case 11 in Table 3(a). Also, a comparison of V_{mi} with V_m explains that the induced voltage from a three-phase power line is far smaller than that from a single-phase line because of a vector sum of the magnetic fluxes due to the three-phase line.

(2) Three-phase vertical line (case2i)

Table 3(b) shows simulation results in cases 21 to 27. It should be clear that the induced voltage is smaller by about a half than that in the horizontal line case, and it is the largest beneath the power line(y=0). The observations are readily understood by the vertical configuration of the three phase line, and also by the following mutual impedance between the lines and the gas pipe in the vertical line case with y=−100m. (case 21)

$Z_{ma} = 0.128\angle 69.61°, \quad Z_{mb} = 0.128\angle 68.55°$
$Z_{mc} = 0.128\angle 68.48°\,[\Omega/\mathrm{km}]$

The analytical result for case 21 is given as $V_m = 0.38\angle 111.3°$, and agrees with the simulation results in case 21 in Table 3(b), and also explains the observations made for the table.

(3) Vertical twin-circuit line (case3i)

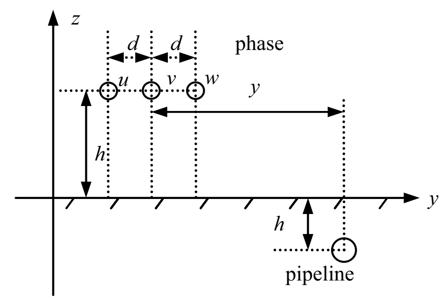
Table 3(c) gives simulation results for the line in Fig. 3(b). Because of the vertical symmetry of the two circuits and of the vertical configuration of the three phases in each circuit, the induced voltage is the smallest when y=0 and is smaller than those in cases 1i and 2i, the single-circuit case.

The analytical result of the induced voltage in case of 32 is calculated as $8.51\angle 0.074°$ [V/km] which agrees well with the EMTP simulation result.

(4) Three-cascaded sections of a pipeline

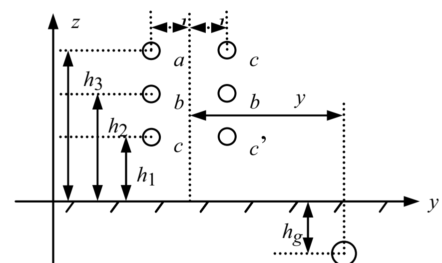
Fig. 4 illustrates three-cascaded sections of a pipeline in which each section is paralleled to a power line different from the other lines with the inducing current I_{pi}. EMTP simulation results are given in Fig.5 together with analytical results which will be explained in Sec. 3. 2. The simulation results show a reasonable agreement with the analytical results.

Various observations of induced voltage characteristics can be made from the simulation results. For example, the maximum induced voltage always appears at the pipeline end. The both ends of the pipeline being grounded through the same resistance R_1=R_4=10Ω, the both ends show the maximum voltage in Table 4, but it should be noted that the phase angle at the sending end, node 1, is opposite to that at the other end. This is the basic characteristic of the induced voltage and has indicated that there exists a node in the pipeline where the voltage to the earth becomes zero.



d = 14, h = 16, y = -100, -28, -14, 0, 14, 28, 100 [m]

(a) 3-phases horizontal line



h_1 = 16, h_2 = 20, h_3 = 24 [m]

(b) Vertical twin-circuit line

r_p = 16.77 [cm], ρ_p = 3.18×10^{-8}, ρ_e = 50 [Ωm]

Fig. 3 Line configuration

Table 3 Simulation results on a multiphase line

(a) Three-phases horizontal line (case 1)

case	y [m]	V_{G1} [V]	θ_1 °	V_{G2} [V]	θ_2 °	V_m [V]	θ_m °
11	-100.0	7.29	-5.65	7.29	174.4	14.6	-5.65
12	-28.0	18.5	-4.79	18.5	175.2	37.0	-4.79
13	-14.0	16.3	5.95	16.3	-174.1	32.6	5.95
14	0.0	7.1	88.2	7.1	-91.8	14.2	88.2
15	14.0	16.3	170.2	16.3	-9.77	32.6	170.2
16	28.0	18.4	-179.3	18.4	0.70	36.8	-179.3
17	100.0	7.25	178.2	7.25	-1.77	14.5	178.2

(b) Three-phases vertical line (case 2)

case	y [m]	V_{G1} [V]	θ_1 °	V_{G2} [V]	θ_2 °	V_m [V]	θ_m °
21	-100.0	0.17	108.4	0.16	-53.7	0.33	117.1
22	-28.0	2.37	-179.5	2.40	1.2	4.77	-179.1
23	-14.0	5.05	179.0	5.74	3.6	10.7	178.6
24	0.0	8.59	174.4	9.47	5.3	17.9	179.9
25	14.0	5.05	179.0	5.74	3.59	10.7	178.6
26	28.0	2.37	-179.5	2.40	1.21	4.77	-179.1
27	100.0	0.16	108.4	0.16	-53.7	0.32	117.3

(c) Vertical twin-circuit line (case 3)

case	y [m]	V_{G1} [V]	θ_1 °	V_{G2} [V]	θ_2 °	V_m [V]	θ_m °
31	-100.0	1.52	-158.1	1.29	-155.8	0.24	-170.7
32	-28.0	4.18	-176.2	4.22	3.95	8.40	-176.1
33	-14.0	5.90	-175.4	7.30	-2.55	13.1	-179.4
34	0.0	3.16	116.1	3.07	118.6	0.16	60.9
35	14.0	6.67	6.37	6.55	-171.4	13.2	7.5
36	28.0	4.28	3.59	4.18	-175.3	8.46	4.1
37	100.0	1.41	13.8	1.17	21.2	0.29	17.3

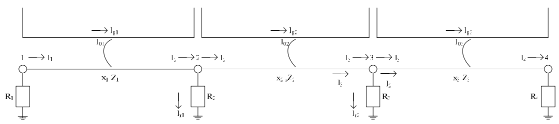
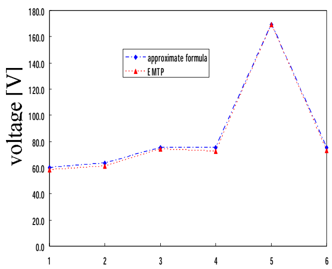
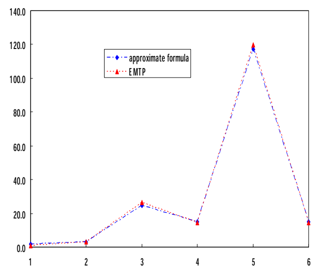


Fig. 4 Three-cascaded sections of a pipeline

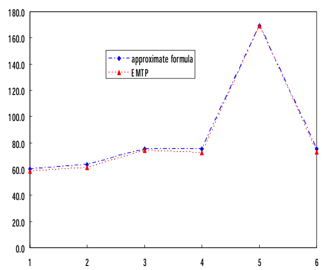
$Z_1 = z \cdot x_1 = Z'$, $Z_2 = z \cdot x_2$, $Z_3 = z \cdot x_3$



(a) Node 1 voltage



(b) Node 2



(c) Node 4

case No.	$I_{P1}/I_{P2}/I_{P3}$ [A]	$x_1/x_2/x_3$ [km]	$R_1/R_2/R_3/R_4$ [Ω]
1	1000/0/1000	1/1/1	10
2	1000/100/1000	1/1/1	10
3	1000/100/1000	1/10/1	10
4	1000/500/1000	1/1/1	10
5	1000/500/1000	1/10/1	10
6	1000/500/1000	1/1/1	10/ ∞ / ∞ /10

Fig.5 A comparison of EMTP simulation and analytical results

This fact should be reminded by engineers and researchers in this field. The phase angle of the induced voltage has been neglected as in the CIGRE Guide [17], it might be better to consider the phase angle as far as possible so that the zero potential at the middle of a pipeline is physically understood.

(5) Simulation of a field test result

Fig. 6 illustrates system configuration of a real pipeline in which a field measurement was carried out. The configuration of the gas pipeline is the same as Fig. 1. The pipeline is composed of 13 sections from node GP00 to GP13 and some parts of the pipeline are nearly parallel to power lines which are shown as A (66kV line) and B(500kV line) in the figure. The pipeline is assumed to be parallel to the 500kV line from node GP02 to GP10 and to the 66kV line from GP11 to GP12. The power line is of three-phase twin-circuit as in Fig. 3(c). An angled (not parallel) part of the pipeline and the power line is assumed to be parallel with the following separation distance y [18].

$$y \cong \sqrt{y_i \cdot y_j}\ ,\ y \cong 4.68\sqrt{y_i} \quad \text{for} \quad y_j = 0 \qquad (9)$$

where

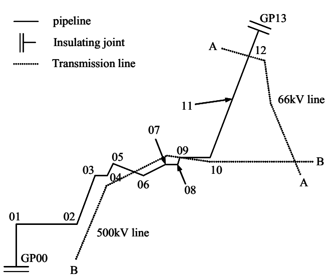
y_i : separation distance at the sending end

y_j : separation distance at the receiving end

The current source on the power line is assumed to be $I_0 = 1000$[A] for the 500kV line and $I_0 = 120$[A] for the 66kV line. The ground wires of the power line are grounded at the both ends.

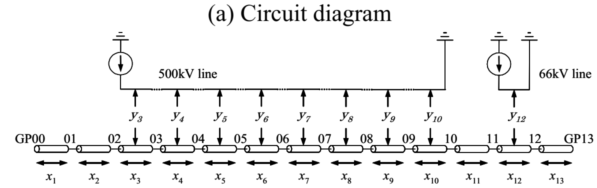
A simulation result is shown in Fig. 7. It is clear in the figure that the voltages at far ends are greater than those in the center nodes. The field test result in the pipeline in Fig. 6 was 1.17 to 2.48[V].

The simulation results in Fig.7 are said to agree reasonably with the field test result considering unknown factors such as the power line configuration and the earth resistivity.



A : 66kV transmission line, B : 500kV transmission line

(a) Circuit diagram



x_i : section length [km]

y_i : distance between apipeline and transmission lines [m]

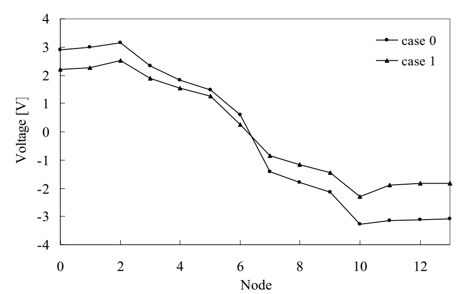
$x_1 = 3.3$[km], $x_2 = 3.2$, $x_3 = 2.1$, $x_4 = 0.8$, $x_5 = 0.5$, $x_6 = 1.1$, $x_7 = 0.8$, $x_8 = 0.4$, $x_9 = 0.3$,$x_{10} = 1.1$, $x_{11} = 3.0$, $x_{12} = 1.5$

$x_{13} = 1.3$, $y_3 = 800$[m], $y_4 = 566$, $y_5 = 490$, $y_6 = 105$

$y_7 = 387$, $y_8 = 424$, $y_9 = 346$, $y_{10} = 66$, $y_{12} = 954$

(b) Circuit configuration

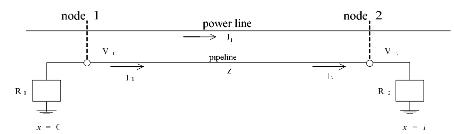
Fig. 6 System configuration



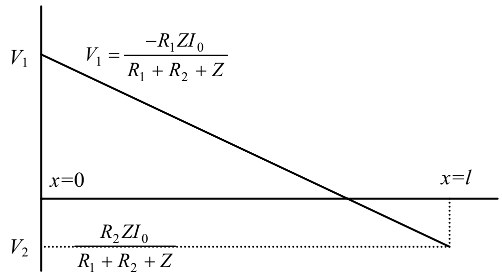
case 0: both ends grounded by R=10Ω

case 1: all the nodes grounded by R

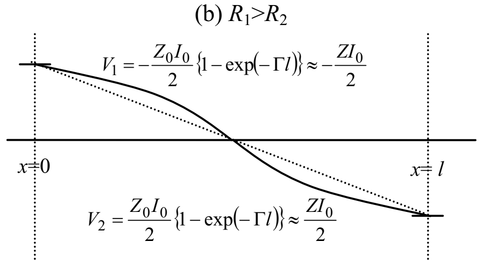
Fig. 7 Simulation results



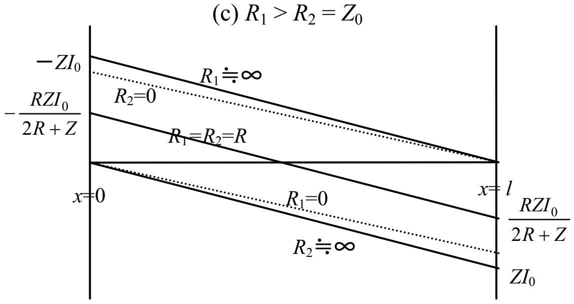
(a) A circuit configuration



(b) $R_1 > R_2$



(c) $R_1 > R_2 = Z_0$



(d) Effect of grounding resistances R_1 and R_2

Fig. 8 Voltage profile along a pipeline

3. Theoretical Analysis

3. 1 F-parameter formulation of induced voltages

(1) F-parameter formulation

The four-terminal parameter (F-parameter) equation for induced voltages and currents on a distributed-parameter line illustrated is given in the following form[9].

$$\begin{pmatrix} V_1 \\ I_1 - I_0 \end{pmatrix} = \begin{bmatrix} A & B \\ C & A \end{bmatrix} \begin{pmatrix} V_2 \\ I_2 - I_0 \end{pmatrix}$$

where

$A = \cosh(\Gamma \cdot l), B = Z_0 \sinh(\Gamma \cdot l), C = Y_0 \sinh(\Gamma \cdot l)$

$I_0 = -z_m I_p / z$: artificial induced current

and

z : series impedance of pipeline [Ω/m]

z_m : mutual impedance [Ω /m]

y : shunt admittance of pipeline [S/m]

Z_0 :characteristic impedance, Γ : propagation constant

(2) Cascaded connection of pipeline sections

Cascaded pipeline sections are handled by multiplication of F-parameter matrices corresponding to every section of the pipeline in the same manner as a conventional F-parameter theory. Remind that an artificial induced current I_{0i} different from each other[9].

3. 2 Application Examples

(1)Single section terminated by R_1 and R_2

In a circuit illustrated in Fig.8 (a), by applying the boundary conditions, the following solution is obtained.

$$V_x = -Z_0 \sinh(\Gamma \cdot x) \cdot (I_1 - I_0) - R_1 \cosh(\Gamma \cdot x) \cdot I_1$$
$$I_x = \{\cosh(\Gamma \cdot x) + (R_1 / Z_0) \sinh(\Gamma \cdot x)\} I_1 - \{\cosh(\Gamma \cdot x) - 1\} I_0$$
$$I_1 = [Z_0 \sinh(\Gamma \cdot l) + R_2 \{\cosh(\Gamma \cdot l) - 1\}] \cdot I_0 / K$$
$$I_2 = [Z_0 \sinh(\Gamma \cdot l) + R_1 \{\cosh(\Gamma \cdot l) - 1\}] \cdot I_0 / K$$

where

$K = (Z_0 + R_1 R_2 / Z_0) \sinh(\Gamma \cdot l) + (R_1 + R_2) \cosh(\Gamma \cdot l)$

It is hard to observe the characteristic of V_x and I_x based on the above equation. By applying the approximation $\Gamma \cdot l \ll 1$, the following approximate solution is obtained.

$$V_x = \{(R_1 + R_2) \cdot z \cdot x - R_1 Z\} I_0 / (R_1 + R_2 + Z)$$
$$I_x = I_1 = I_2 = Z I_0 / (R_1 + R_2 + Z)$$

for $R_1 \neq 0$, $R_2 \neq 0$

where $z \cdot l = Z$ [Ω], z [Ω /m], l [m]

The voltage along the pipeline in Fig. 8(a) is drawn as in Fig. 8(b) where

$$V_1 = -R_1 Z I_0 / (R_1 + R_2 + Z)$$
$$V_2 = R_2 Z I_0 / (R_1 + R_2 + Z)$$
$$V_{\max} = |V_1| \text{ for } R_1 > R_2 ,\ V_{\max} = V_2 \text{ for } R_2 > R_1$$

The voltage profile along the pipeline appears linear because of the approximation. If we adopt the accurate solution, the profile becomes not linear as in Fig. 8(c) due to the characteristic of hyperbolic functions but it is continuous in the region of $0 \leq x \leq l$. Thus, there exists a position x where the voltage of the pipeline becomes zero. It might be better to consider the phase angle, or the polarity at the both ends, of the pipeline voltage from the viewpoint of realizing the physical nature of the induced voltage corresponding to the theoretical analysis, although it is conventionally neglected.

(a) $R_1 = R_2 = Z_0$

This is identical to a semi-infinite pipeline connected at nodes 1 and 2 , and the power line is parallel to the pipeline only for the section between the nodes. The voltage profile along the pipeline is shown in Fig. 8(c).

(b)Effect of grounding resistances of a pipeline

The profiles are shown in Fig. 8(d). The basic characteristics of the induced voltages can be observed from the figure.

(2) Three-cascaded sections

Fig. 4 illustrates three-cascaded sections of a pipeline where each section is parallel to a power line different from the other power lines and has an induced current I_{0i} (i =1 to 3).

Some examples are demonstrated in Fig.5 in comparison with EMTP simulation results.

4. Conclusions

This paper has carried out EMTP simulations of induced voltages and currents on various configurations of power lines and pipelines. The induced voltages are significantly dependent on the power line configuration. The induced voltages on a vertical twin-circuit line is less than a half of that on a horizontal signal-circuit line which is about 1/10 of that of a single-phase line. The EMTP simulation result shows a reasonable agreement with a field test result and thus accuracy of an EMTP simulation has been confirmed to be reasonable.

Also, this paper has explained a theoretical formulation of induced voltages and currents developed by the authors based on F-parameter theory. An analytical formula of the induced voltages and currents is easily obtained by the theoretical formulation taking into account various grounding conditions and inducing currents. The accuracy of the theoretical formulation is comparable to an EMTP simulation. This theoretical approach is very useful to explain a simulation result from the physical viewpoint.

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