EMTP Simulations of Induced Voltages to an Underground Gas Pipeline and Its Contermeasures

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Abstract - This paper has proposed a modeling method to simulate steady-state and transient induced voltages to an underground gas pipeline from an overhead transmission line. The simulation results of the steady-state ac induced voltages agree well with analytical results obtained from a well-known formula. The induced voltages are significantly dependent on the configuration of an overhead line. A horizontal line induces the largest voltage to a gas 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 method is applied to investigate the effect of shielding wires and plates on reduction of the induced voltage, and the simulation results agree well with analytical results. It has been found that the induced voltage can be reduced by about 10% by one shielding wire and by about 25% by five shielding wires, and an iron plate can reduce the induced voltage by about 50% assuming the shielding wires and the plate are ideally grounded.

Keywords - induced voltage, gas pipeline, overhead line, shielding, EMTP

1 INTRODUCTION

Induced voltages to an underground gas pipeline from an overhead transmission line are a cause of corrosion of the pipeline, and countermeasures against the induced voltages are quite significant[1],[2]. It, however, is hard to measure the induced voltages in a real pipeline, and thus it has been desired to establish a method for simulating the induced voltages. The authors have developed an EMTP simulation method of the induced voltages to the gas pipeline[3] based on an approximate formula of the mutual impedance proposed by one of the authors[4]. There exists an accurate formula of the mutual impedance between an overhead line and an underground cable derived by Pollaczek[5], but the formula is of a complex integral form and its numerical evaluation is very hard because the integral has a hardly converging nature. By applying the proposed method, EMTP simulations of the induced voltages is carried out, and the basic characteristic of the induced voltages to a buried gas pipeline is investigated together with an analytical evaluation. Also, the effect of shielding wires and plate (Fig. 3) on reduction of the induced voltages are investigated.

2 MODELING METHOD AND MODEL SYSTEM

2.1 Modeling method

Fig. 1 illustrates a system composed of an underground gas pipeline (GP), an overhead power transmission line (PW) and a shielding wire (SW).

In the figure, both the power line and the gas pipeline are represented as a distributed parameter line in the EMTP[6]. If it concerns a steady state, a PI equivalent circuit is accurate enough. When a transient is concerned, either Marti's frequency-dependent or Dommel's fixed frequency line model is adopted[3]. The parameters of the line models are evaluated by the EMTP Cable Parameters (CP) program[7]. First, the model system is evaluated as an overhead line system, i.e. ISYST=1, by the CP with a negative sign of the depth of the gas pipe. By the input date, the CP calculates self impedance/admittance of the overhead power line and the mutual impedance between the overhead line and the underground gas pipeline. Secondly, the self impedance/admittance of the underground pipeline is calculated as an underground SC cable, i.e. ISYST=-1 by the CP. Finally, the self impedance/admittance of the gas pipe in the first calculation is replaced by those in the second calculation, and also the mutual admittance is modified to be zero because there exists no mutual admittance between an overhead line and an underground cable.

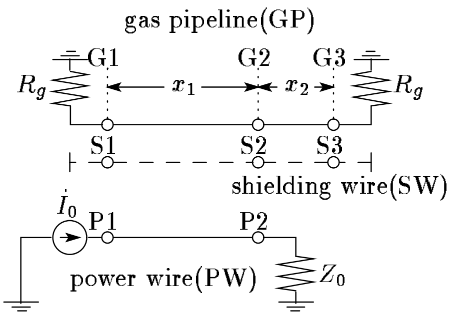
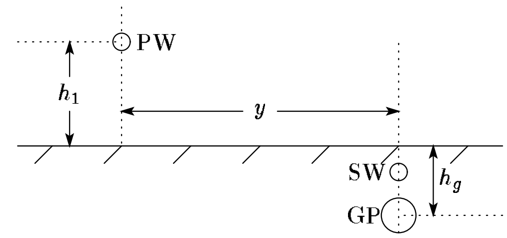


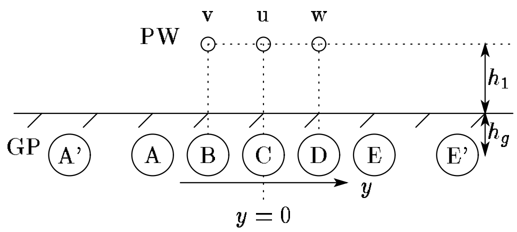
Figure 1: A system composed of an overhead line and a buried gas pipeline

2.2 Model system

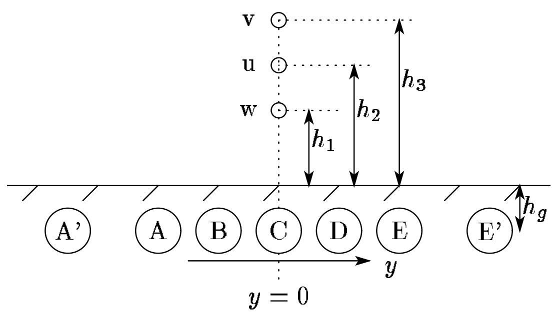
Fig. 2 illustrates the cross-section of a model system. (a) is the cross-section in the case of a single-phase power line and SW in the figure shows a shielding wire. (b) is the case of a three-phase horizontal line, (c) a three-phase vertical line, and (d) a three-phase vertical twin-circuit line which is most widely adopted in Japan. Circled A to E in Fig. 2 (b) to (d) show the position of the gas pipeline in the y-direction.



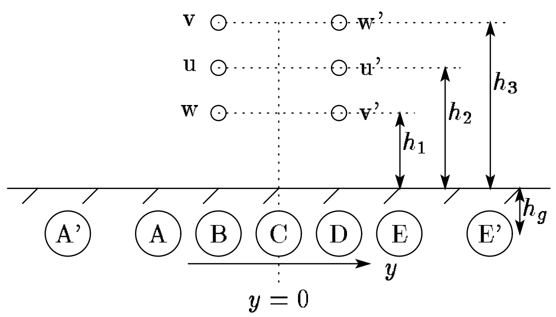
(a) Single-phase power line



(b) 3-phase horizontal line



(c) 3-phase vertical line



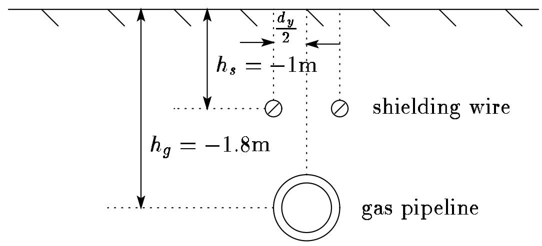
(d) Vertical twin-circuit line

Figure 2: A model system

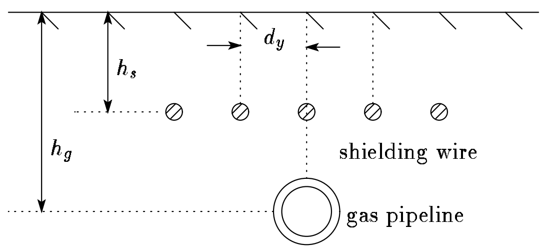
In Fig. 2 (a), the gas pipeline is parallel with the separation distance of y to the power transmission line between nodes G1/P1 and G2/P2 in Fig. 1 with the length of x_1. There is no parallel power line to the gas pipeline from node G2 to G3 with the length of x_2. An ac current source I_0 with the amplitude of 1kA and the frequency of 50Hz is applied to node P1 of the power line of which the other end, node P2, is terminated by a matching resistance Z_0. The gas pipeline is grounded through a resistance R_g at both ends, nodes G1 and G3.

2.3 Shielding

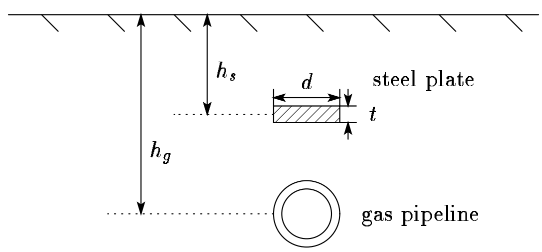
Fig. 3 illustrates the cross-section of a gas pipeline and shielding wires and plate. A single-phase overhead power line as in Fig. 2(a) is considered, although it is not illustrated in Fig. 3. In the case of shielding wires, one wire in Fig. 2(a), two wires in Fig. 3(a) and five wires in Fig. 3(b) are investigated. Fig. 3(c) is the case of a shielding plate made of steel. The plate is represented as equivalent circular conductor[8] in an EMTP simulation so that the impedance and the admittance are evaluated by existing impedance and admittance formulas.



(a) Two shielding wires



(b) Five shielding wires



(c) Shielding plate

Figure 3: A gas pipeline and its shielding

A shielding conductor, which is not insulated from surrounded soils, is modeled in the same manner as a grounding electrode as illustrated in Fig. 4[9], [10].

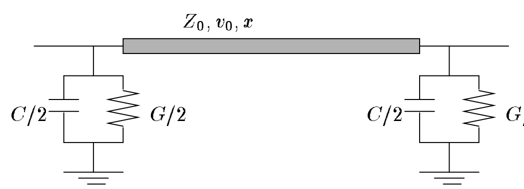


Figure 4: A model circuit of a shielding conductor

3 Steady-State Induced Voltages

3.1 *Single-phase power line, Fig. 2(a)*

Table 1 gives simulation conditions and results when an ac current of $I_0 \cos \omega t$ is applied, and the separation y and the length x_1 and x_2 are changed.

It is clear in the table that the voltages V_{G1} and V_{G2} at nodes G1 and G2 of the gas pipe induced from the power line are nearly proportional to the mutual impedance Z_m between the power line and the gas pipe in cases 11 and 12 where the separation distance y is 500m and 1000m respectively with $x_1 = 1$km and $x_2 = 0$. In fact, the induced voltage V_m along the gas pipe, which is the voltage difference between nodes G1 and G2, i.e. $V_m = V_{G2} - V_{G1}$, is almost the same as that evaluated by the well-known analytical formula:

$$V_m = -Z_m I \tag{1}$$

This is also true in cases 21 and 22 where x_2 is not zero.

It is interesting to know that the voltage V_{G3} at node G3 is nearly equal to V_{G2}, although there is no power line from node G2 to G3. Therefore, the induced voltage to a gas pipe from a power line is only dependent on the length of the power line parallel to the gas pipe, i.e. not dependent on the length of the gas pipe.

The induced voltage to the gas pipe in the case of a single-phase power line is, in general, far greater than that in the multiphase line case[11], and corresponds to that in the case of a single-phase to earth fault as is well-known in an induced voltage to a telecommunication line[12].

3.2 *Three-phase horizontal line, Fig. 2(b)*

Table 2 summarizes simulation results of induced voltages to a gas pipe from a 500kV three-phase horizontal line of which one phase is composed of 4 bundles in Fig. 2(b) when the following ac current is applied to the three phases at node P1.

$$\left.\begin{array}{rl} & I_u = I_0 \cos(\omega t) \\ & I_v = I_0 \cos(\omega t - 120^\circ) \\ & I_w = I_0 \cos(\omega t + 120^\circ) \\ \text{where} & I_0 = 1\text{kA}, \quad f = 50\text{Hz} \end{array}\right\} \tag{2}$$

In the table, case 1A' corresponds to the case where the gas pipe is buried at position A' in Fig. 2 (b). The distance ($y = -100$m) in case 1A' is the horizontal separation of the gas pipe from the center phase of the power line as illustrated in Fig. 2 (b).

It is observed in the table that the induced voltage is the largest in case 1A where the horizontal separation y is 28m. 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.

case	x_1/x_2[km]	y[m]	$Z_m\angle\theta_0$[Ω/km]	$V_{G1}\angle\theta_1$[V]	$V_{G2}\angle\theta_2$[V]	$V_{G3}\angle\theta_3$[V]	$V_m\angle\theta_m$[V]
11	1/0	500	$0.0431\angle 41.4^\circ$	$21.4\angle 39.7^\circ$	$21.4\angle -140.3^\circ$	–	$42.8\angle -140.3^\circ$
12	1/0	1000	$0.0174\angle 18.4^\circ$	$8.64\angle 16.7^\circ$	$8.64\angle -163.3^\circ$	–	$17.3\angle -163.3^\circ$
21	1/2	1000	$0.0174\angle 18.4^\circ$	$8.51\angle 15.0^\circ$	$8.77\angle -161.5^\circ$	$8.53\angle -168.0^\circ$	$17.3\angle -163.2^\circ$
22	1/10	1000	$0.0174\angle 18.4^\circ$	$7.73\angle 9.77^\circ$	$9.61\angle -157.2^\circ$	$8.06\angle 173.6^\circ$	$17.2\angle -163.0^\circ$

$h_1 = 16$m, $r_p = 0.1677$m, $h_g = -1.8$m, $r_g = 0.2032$m, $R_g = 10\Omega$, $Z_0 = 400\Omega$

Table 1: Simulation conditions and results for a single-phase power line, Fig. 2(a)

case	y[m]	$V_{G1}\angle\theta_1$[V]	$V_{G2}\angle\theta_2$[V]	$V_m\angle\theta_m$[V]
1A'	-100.0	$7.29\angle -5.65^\circ$	$7.29\angle 174.4^\circ$	$14.6\angle 174.3^\circ$
1A	-28.0	$18.5\angle -4.79^\circ$	$18.5\angle 175.2^\circ$	$37.0\angle 175.2^\circ$
1B	-14.0	$16.3\angle 5.95^\circ$	$16.3\angle -174.1^\circ$	$32.6\angle -174.1^\circ$
1C	0.0	$7.09\angle 88.2^\circ$	$7.09\angle -91.8^\circ$	$14.2\angle -91.8^\circ$
2A'	-100.0	$0.17\angle 108.4^\circ$	$0.16\angle -53.7^\circ$	$0.33\angle -62.9^\circ$
2A	-28.0	$2.37\angle -179.5^\circ$	$2.40\angle 1.21^\circ$	$4.77\angle 0.9^\circ$
2B	-14.0	$5.05\angle 179.0^\circ$	$5.74\angle 3.59^\circ$	$10.7\angle 1.4^\circ$
2C	0.0	$8.59\angle 174.4^\circ$	$9.47\angle 5.32^\circ$	$17.9\angle 0.1^\circ$
3A'	-100.0	$1.52\angle -158.1^\circ$	$1.29\angle -155.8^\circ$	$0.24\angle 9.3^\circ$
3A	-28.0	$4.18\angle -176.2^\circ$	$4.22\angle 3.95^\circ$	$8.40\angle 3.9^\circ$
3B	-14.0	$5.90\angle -175.4^\circ$	$7.30\angle -2.55^\circ$	$13.1\angle 0.6^\circ$
3C	0.0	$3.16\angle 116.1^\circ$	$3.07\angle 118.6^\circ$	$0.16\angle -119.1^\circ$

case 1: horizontal line, Fig. 2(b): $h_1 = 16$m, $R_g = 15\Omega$
case 2: vertical line, Fig. 2(c): $h_1 = 16$m, $h_2 = 20$m, $h_3 = 24$m
case 3: vertical twin-circuit line, Fig. 2(d): $h_1 = 16$m, $h_2 = 20$m, $h_3 = 24$m

Table 2: Simulation results for a multiphase line, Fig. 2(b) to (d)

3.3 Three-phase vertical line, Fig. 2 (c)

Table 2 shows simulation results in case 2. It should be clear that the induced voltage is far 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.

3.4 Vertical twin-circuit line, Fig. 2 (d)

Table 2 gives simulation results in case 3. 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 that in case 2, the single-circuit case.

4 Countermeasures-Shielding Wires and Plate

4.1 Shielding effect

The effect of shielding wires and a shielding plate on induced voltages is investigated for a single-phase power line in Fig. 1 and Fig. 2(a), where the length $x_1 = 1$km, $x_2 = 0$, and the separation $y = 500$m, and the shielding wire length $x_s = 1$km, depth $h_s = -1.0$m, and radius $r_s = 1.0$cm. The earth resistivity and relative permittivity are taken to be $\rho_e = 50\Omega$m and $\varepsilon_e = 40$.

Table 3 summarizes simulation results of the shielding effect of wires and a plate. The reduction of the induced voltage by the shielding wires and by the plate is clearly observed in the table. The induced voltage to a gas pipeline is reduced by about 12% by one shielding wire, by about 30% by five wires and by 22% by the plate. In the above simulations, the both ends of the shielding conductor are open-circuited, i.e. the grounding resistances R_s at the both ends of a shielding conductor are infinite. When R_s is taken to be 10 Ω, the reducing ratio in Table 3 for two shielding wires(case 2) becomes 0.831.

Table 4 shows simulation results when the length x_s and the position of the two shielding wires (case 2 in Table 3) changed. It is observed in the table that the ratio of induced voltage reduction is somehow proportional to the length of the shielding wire, and the position of the shielding wire installation does not affect the ratio. The observation leads to a conclusion that the length of a shielding wire is preferred to be longer, but the position along a gas pipeline is not significant.

4.2 Analytical Investigation

In the case of one shielding wire, voltages and currents are expressed by the following equation.

$$\begin{pmatrix} -V_p \\ -V_g \\ -V_s \end{pmatrix} = \begin{bmatrix} Z_{pp} Z_{pg} Z_{ps} \\ Z_{pg} Z_{gg} Z_{gs} \\ Z_{ps} Z_{gs} Z_{ss} \end{bmatrix} \begin{pmatrix} I_0 \\ I_g \\ I_s \end{pmatrix} \quad (3)$$

Assuming the terminating resistance of the shielding conductor is zero, the above equation is rewritten by:

$$I_s = -(Z_{ps}/Z_{ss})I_0 - (Z_{gs}/Z_{ss})I_g \quad (4)$$

$$V_g = Z_{pg}(1 - Z_{ps}Z_{gs}/Z_{ss}Z_{pg})I_0 + Z_{gg}(1 - {Z_{gs}}^2/Z_{gg}Z_{ss})I_g \quad (5)$$

$$= Z_{pg}\lambda_1 I_0 + Z_{gg}\lambda_2 I_g \quad (6)$$

For I_g is far smaller than I_0, the equation is further simplified, and the following formula is obtained.

$$V_g = -Z_{pg}\lambda_1 I_0 \quad (7)$$

where $\lambda_1 = 1 - Z_{ps}Z_{gs}/Z_{ss}Z_{pg}$: shielding factor

Furthermore, the shielding wire being installed nearby the gas pipeline, Z_{pg} nearly equals Z_{ps}. Thus,

$$\lambda_1 \simeq 1 - Z_{gs}/Z_{ss} \quad (8)$$

For case 1 in Table 3, λ_1 in the above equation is evaluated as:

$$\lambda_1 = 0.9214 - j0.0522 \quad (9)$$

case	condition	$V_{G1}\angle\theta_1$[V]	$V_{G2}\angle\theta_2$[V]	$V_m\angle\theta_m$[V]	ratio
0	no shield	$21.4\angle 39.7°$	$21.4\angle -140.3°$	$42.8\angle -140.3°$	1.000
1	1 wire	$18.8\angle 25.7°$	$18.9\angle -154.3°$	$37.7\angle -154.3°$	0.880
2	2 wire	$18.1\angle 28.5°$	$17.6\angle -159.0°$	$35.6\angle -155.2°$	0.832
3	5 wire	$14.9\angle 19.1°$	$14.9\angle -160.9°$	$29.8\angle -160.9°$	0.697
4	plate	$16.6\angle 20.6°$	$16.7\angle -159.5°$	$33.3\angle -159.4°$	0.778

Table 3: Simulation results of shielding effect

case	x_sm	position	$V_{G1}\angle\theta_1$[V]	$V_{G2}\angle\theta_2$[V]	$V_m\angle\theta_m$[V]	ratio*
20	1000	all	$18.1\angle 28.5°$	$17.6\angle -159.0°$	$35.6\angle -155.2°$	0.832
21	800	sending	$18.3\angle 28.6°$	$18.6\angle -157.1°$	$36.8\angle -154.3°$	0.860
22	600	sending	$18.7\angle 29.2°$	$19.3\angle -155.5°$	$38.0\angle -153.2°$	0.888
23	400	sending	$19.4\angle 30.3°$	$19.8\angle -154.3°$	$39.2\angle -152.0°$	0.915
24	400	recieving	$20.3\angle 33.5°$	$18.8\angle -156.6°$	$38.9\angle -151.4°$	0.908
25	200	sending	$20.2\angle 32.2°$	$20.0\angle -153.5°$	$40.2\angle -150.6°$	0.938

* ratio to case 0 in Table 3

Table 4: Effect of shielding wire length and position

Thus, the induced voltage V_m is given analytically by:

$$V_m = 39.75\angle - 141.8^\circ \qquad (10)$$

The above analytical result agrees reasonably with the EMTP simulation result in Table 3. The same approach is applicable to a shielding plate by adopting an equivalent circular conductor method[8].

5 Conclusions

This paper has investigated an induced voltage to an underground gas pipeline from a neighboring power transmission line and the effect of shielding conductors based on EMTP simulations and analytical calculations. The following remarks have been obtained.
(1) EMTP simulation results agree with analytical results obtained from the well-known formula of the induced voltage $V_m = -Z_m \cdot I$.
(2) The induced voltages assuming a single phase power line is far greater than that from a real three-phase line and a twin-circuit line.
(3) The induced voltage is significantly dependent on the configuration of a power line. A horizontal line induces the largest voltage to a gas pipeline. An induced voltage by a vertical twin-circuit line is smaller by about 30% than that by a vertical single-circuit line.
(4) The induced voltage depends on the separation distance between the gas pipe and the power line as is well-known, but its characteristic is quite dependent on the power line configuration.
(5) Shielding conductors installed nearby a gas pipe are effective to reduce the induced voltage to the gas pipe. Two shielding wires can reduce the voltage by about 19%, and an iron shielding plate by 20%.

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