A Study of Phase-Wire Voltage Variations due to Corona Wave-Deformation

A. Ametani K. Yoshida
Doshisha University
Kyotanabe, 610-0321, Japan
aametani@mail.doshisha.ac.jp

S. Sekioka
Kansai Tech Corp.
Osaka, 552-0013, Japan
kantech@asahi-net.or.jp

T. Higuchi Y. Kato
Kansai Electric Power Co.
Amagasaki, 661-0974, Japan
K509590@kepco.co.jp

Abstract

The paper presents measured results of corona wave-deformation on a 6.6 kV test line with various boundary conditions corresponding to substation and switching station termination. The measured results have shown an increase of the phase-wire voltage at the receiving-end under a certain boundary condition, while the ground-wire voltage is always decreased by the corona wave-deformation. The phenomenon is theoretically investigated, and it has been made clear that the increase is, in principle, caused by heavier attenuation of a traveling-wave on a ground wire than that on a phase wire, and negative reflection of the traveling-wave from the ground wire to the phase wire. The condition of the voltage increase has been theoretically derived.

Keywords : Traveling-wave, Corona wave-deformation, Transmission line, Substation entrance.

1. Introduction

It has been well known that a corona discharge causes attenuation and deformation of a traveling-wave on a transmission line. The corona wave-deformation leads to traveling-wave voltage reduction as observed from various measured results /1-3/. The measured results in previous publications concerned only of the traveling-wave voltage which was simply decreased by the corona wave-deformation. It has been reported by one of the authors that a phase-wire voltage at a substation entrance could be increased by the corona wave-deformation /4/.

The present paper carries an experiment of corona wave-deformation on a 6.6 kV test line with various boundary conditions corresponding to substation / switching station termination. A weatherproof impulse current generator with the maximum amplitude of 60 kA is used as a source representing a lightning current /5/. An applied current on a ground-wire and phase-wire voltages at the both ends of the test line are measured for various applied voltage from −300 kV to −900 kV. The measured result shows an increase of the receiving-end voltage on the phase wire under a certain boundary condition, while the ground-wire voltage is always decreased by the corona wave-deformation.

To investigate the phenomenon, a theoretical formula of the receiving-end voltage is derived applying a traveling-wave theory /6/. A possibility of the increase of the phase-wire voltage due to the corona wave-deformation is discussed based on the formula. The theoretical results of the phase-wire voltages are compared with the measured results.

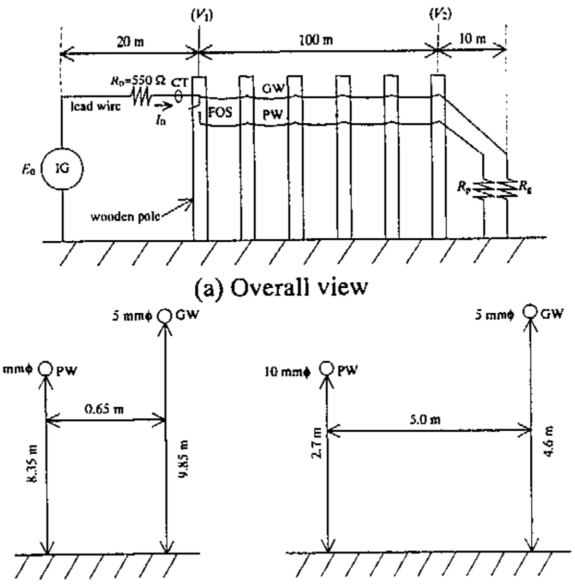
2. Experiment

2. 1 Experimental setup

A test line used in the experiment is of 1/3.5 reduced configuration of a 77 kV line, and is composed of a phase wire (PW) and a ground wire (GW) as illustrated in Fig. 1 because of a limit of available facilities. In the figures, R_0 = 550 Ω connected to an impulse generator (IG) represents a lightning path impedance, which is recommended to be 400 Ω in Japan. CT is a current transformer. A resistance R_g at the GW end is taken to be (1) 7 Ω representing a grounding resistance of a guntry, (2) 170 Ω representing a tower surge impedance, and (3) infinite (open circuit). A resistance R_p at the PW end is (1) 70 Ω representing a surge impedance of a gas-insulated bus, (2) 500 Ω to represent a matching condition (an infinite length) of a phase wire, and (3) infinite corresponding to an open-circuited line. It should be pointed out that a 30 Ω resistance is to be added to the above terminating resistances R_g and R_p as a grounding resistance including the grounding wire impedance. FOS at the sending end in Fig. 1 is a switch to represent a back flashover from the GW to the PW. Table 1 summarizes the experimented condition and the corresponding results.

2. 2 Experimental result

Fig. 2 and Fig. 3 show measured results of transient waveforms of (a) output current I_0 from the IG, (b) PW sending-end voltage V_{1p} and (c) PW receiving-end voltage



(b) Transmission Line (c) Substation entrance

Fig. 1 Experimental setup

V_{2p}. Cases measured are as explained in Sec. 2. 1 and as in Table 1. A parameter in each figure is an applied voltage E_0 from the IG changed from –300 kV to –900 kV.

It is hard to estimate corona attenuation constants quantitatively from the measured voltage waveforms, because a discharge voltage of the IG corresponding to applied voltage E_0 is probabilistic and non-reproducible, and also the origin (arrival time) of the receiving-end voltage is not clear in the measured waveform. Considering the above, the following ratio between normalized voltages is used to estimate the corona attenuation.

$$K = V_n / E_n \quad \text{[pu]} \tag{1}$$

where $E_n = E/E_0$: normalized applied voltage from IG

$V_n = V/V_0$: normalized line voltage

E_0 : lowest applied voltage = –300 kV

V_0 : line voltage when E_0 is applied

V : line voltage when E is applied

Although E_0 and V_0 in eq. (1) are desired to be lower than the critical voltage of corona discharge, the lowest one among the measured voltage is taken to be E_0. If there is no corona discharge on a line, K should almost equal to 1. On a single-phase line, corona discharge results in $K < 1$. The corona discharge on a multiphase line results in $K > 1$ or $K < 1$.

Fig. 4 shows K as a function of an applied voltage. (a) is the case of no flashover, and (b) the case of a flashover. It is observed in Fig. 4 (a) that the induced-phase (PW) voltage increases as the applied voltage increases, i.e. by corona wave-deformation. The phenomenon will be theoretically discussed later. In the case of a flashover, no increase of a voltage is observed, but no significant decrease due to corona is also observed. The effect of a terminating condition of the GW and the PW is not clear in the measured results.

Table 1 Test conditions and results

(a) Without flashover

Case	R_g^* [Ω]	R_p^* [Ω]	E_0 [kV]	$I_0(0)$ [kA]	$I_0(2\tau)$ [kA]	$V_{1p}(0)$ [kV]	$V_{1p}(2\tau)$ [kV]	$V_{2p}(\tau)$ [kV]	$V_{2p}(3\tau)$ [kV]
1-1 Fig. 2.1	7	70	-300	-0.242	-0.604	-40.0		-5.0	
			-375	-0.333	-0.721	-44.0		-6.6	
			-450	-0.396	-0.883	-57.0		-8.2	
			-600	-0.625	-1.167	-80.0		-11.3	
			-750	-0.750	-1.542	-98.0	-40.0	-14.8	-12.0
			-900	-0.875	-1.842	-123.0	-50.0	-17.6	-14.0
1-2 Fig. 2.2	7	500	-300	-0.242	-0.604	-34.8		-3.7	
			-375	-0.333	-0.721	-48.4		-5.7	
			-450	-0.396	-0.883	-58.1		-9.4	-7.0
			-600	-0.625	-1.167	-80.0		-17.1	-9.0
			-750	-0.750	-1.542	-103.0	-29.0	-23.7	-12.0
			-900	-0.875	-1.842	-126.0	-33.0	-30.0	-14.0
1-3 Fig. 2.3	7	∞	-300	-0.242	-0.604	-38.0		-4.0	
			-375	-0.333	-0.721	-49.0		-7.0	
			-450	-0.396	-0.883	-60.0		-9.0	-4.0
			-600	-0.625	-1.167	-80.0	-20.0	-18.0	-6.0
			-750	-0.750	-1.542	-105.0	-25.0	-27.0	-9.0
			-900	-0.875	-1.842	-129.0	-32.0	-38.0	-12.0
1-4 Fig. 2.4	170	70	-300		-0.417	-40.0		-7.0	
			-375		-0.500	-43.0		-8.0	
			-450		-0.625	-52.0	-18.0	-10.0	
			-600	-0.625	-0.875	-78.0	-23.0	-16.0	-7.0
			-750	-0.792	-1.083	-100.0	-30.0	-21.0	-9.0
			-900	-0.958	-1.375	-120.0	-38.0	-27.0	-11.0
1-5 Fig. 2.5	∞	∞	-300	-0.250		-35.0	-56.25	-68.8	
			-375	-0.313		-43.0	-75.00	-87.5	
			-450	-0.375		-62.5	-93.75	-106.3	
			-600	-0.583		-81.3	-143.8	-156.3	
			-750	-0.708		-106.3	-181.3	-200.0	
			-900	-0.917		-131.3	-237.5	-250.0	

* : grounding resistance 30 Ω to be added.

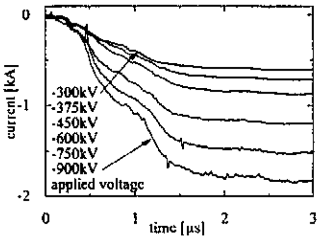
(b) With flashover

Case	R_g^* [Ω]	R_p^* [Ω]	E_0 [kV]	$I_0(0)$ [kA]	$I_0(2\tau)$ [kA]	$V_{1p}(0)$ [kV]	$V_{1p}(2\tau)$ [kV]	$V_{2p}(\tau)$ [kV]	$V_{2p}(3\tau)$ [kV]
2-3 Fig. 3	7	∞	-300	-0.375	-0.583	-110.0		-146.9	
			-375	-0.438	-0.750	-135.0		-176.2	
			-450	-0.542	-0.917	-170.0		-214.1	
			-600	-0.750	-1.208	-230.0		-292.3	
			-750	-0.958	-1.542	-290.0		-379.2	
			-900	-1.167	-1.917	-350.0		-458.2	

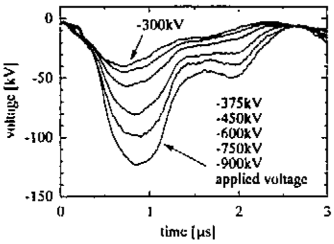
3. Theoretical investigation

3. 1 Derivation of analytical formula

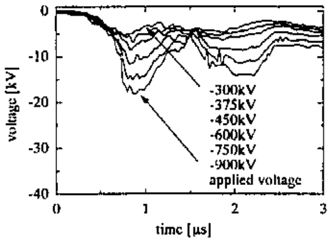
A transient voltage in the experimental circuit illustrated in Fig. 1 is analytically derived for the time period $0 \le t < 3\tau$ based on a traveling-wave theory. Fig. 5 shows a model circuit to derive an analytical formula of the transient voltage. In the figure, the surge impedance matrices are given by :



(a) I_0

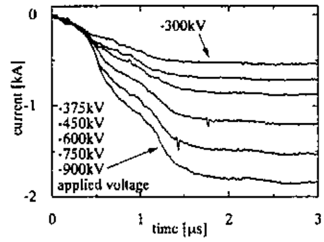


(b) V_{1p}

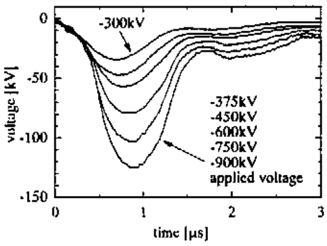


(c) V_{2p}

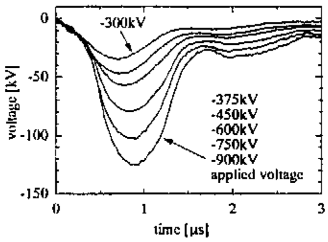
Fig. 2.1 Case 1-1



(a) I_0

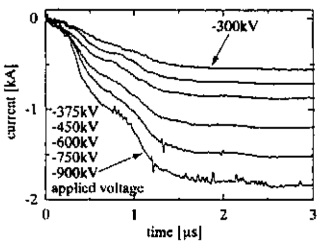


(b) V_{1p}

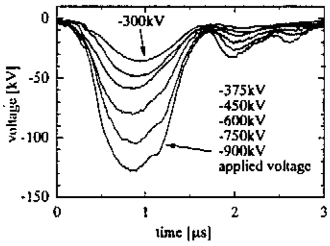


(c) V_{2p}

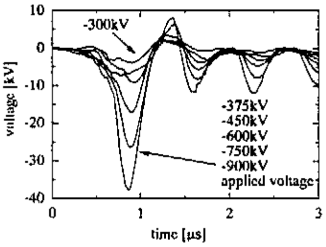
Fig. 2.2 Case 1-2



(a) I_0

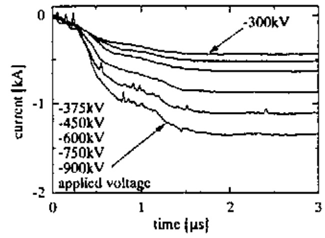


(b) V_{1p}

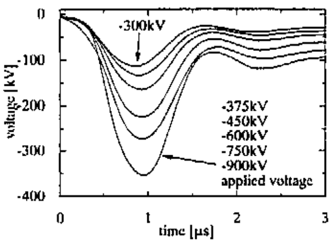


(c) V_{2p}

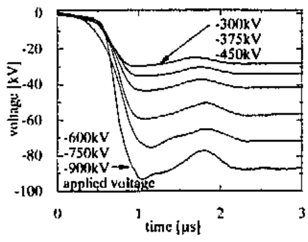
Fig. 2.3 Case 1-3



(a) I_0

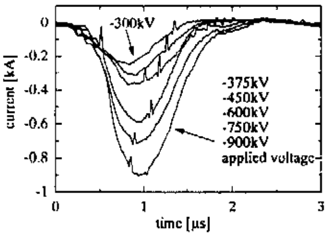


(b) V_{1p}

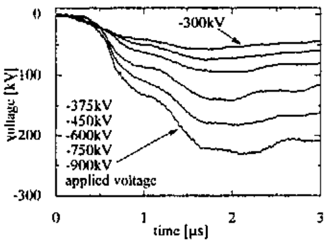


(c) V_{2p}

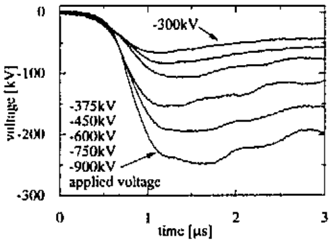
Fig. 2.4 Case 1-4



(a) I_0

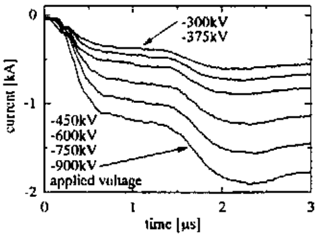


(b) V_{1p}

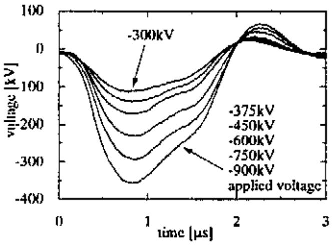


(c) V_{2p}

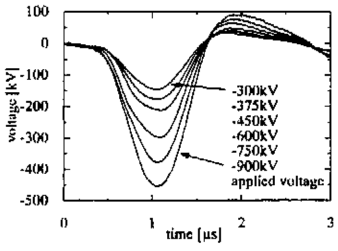
Fig. 2.5 Case 1-5



(a) I_0

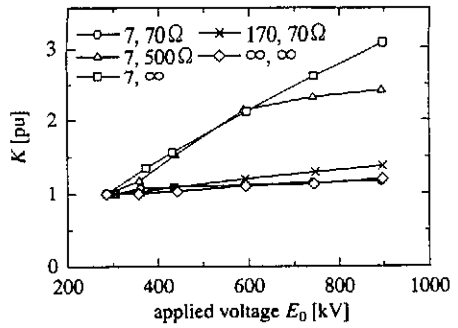


(b) V_{1p}

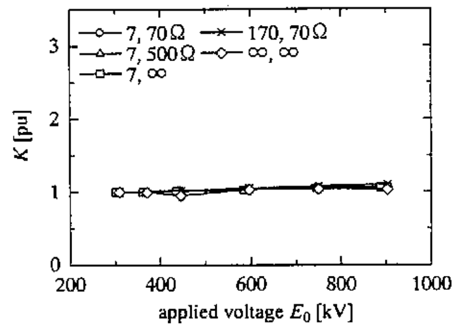


(c) V_{2p}

Fig. 3 Case 2-3 (With FO)



(a) Without flashover



(b) With flashover

Fig. 4 Experimental K-curve of PW receiving-end voltage

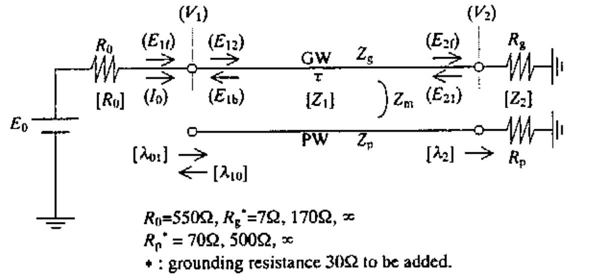


Fig. 5 Analytical model circuit

$$[R_0]=\begin{bmatrix} R_0 & 0 \\ 0 & M \end{bmatrix},\ [Z_1]=\begin{bmatrix} Z_g & Z_m \\ Z_m & Z_p \end{bmatrix},\ [Z_2]=\begin{bmatrix} R_g & 0 \\ 0 & R_p \end{bmatrix} \quad (2)$$

where M : an infinitely large value

The refraction coefficients are given in the following equation /6/.

$$[\lambda_{01}]=\frac{2}{R_0+Z_g}\begin{bmatrix} Z_g & 0 \\ Z_m & 0 \end{bmatrix} \quad (3)$$

$$[\lambda_2]=\frac{2}{\Delta}\begin{bmatrix} R_g(Z_p+R_p) & -R_gZ_m \\ -R_pZ_m & R_p(Z_g+R_g) \end{bmatrix}$$

where $\Delta=(Z_g+R_g)\cdot(Z_p+R_p)-Z_m^2$

The transient voltage and current with no flashover ($E_{1fg}=E_0/2$, $E_{1fp}=0$) is obtained using the above refraction coefficients.

(i) $0 \le t < 2\tau$

$$V_{1g}(t)=\{Z_g/(R_0+Z_g)\}\cdot E_0(t)=Z_gI_0(t) \quad (4)$$
$$V_{1p}(t)=\{Z_m/(R_0+Z_g)\}\cdot E_0(t)=Z_mI_0(t)$$
$$I_{1g}(t)=E_0(t)/(R_0+Z_g)=I_0(t),\ I_{1p}(t)=0$$

(ii) $\tau \le t < 3\tau$

$$V_{2g}(t)=2R_g\{Z_g(R_p+Z_p)-Z_m^2\}\cdot I_0(t-\tau)/\Delta \quad (5)$$
$$V_{2p}(t)=2R_gR_pZ_mI_0(t-\tau)/\Delta$$

3. 2 Investigation of corona wave-deformation

To simplify an analysis, source voltage $E_0(t)$ is assumed to be a unit step function, i.e. $E_0(t)=E_0$. Then,

$$E_{12g}(t)=e_0=\{Z_g/(R_0+Z_g)\}\cdot E_0 \quad (6)$$
$$E_{12p}(t)=\{Z_m/(R_0+Z_g)\}\cdot E_0=(Z_m/Z_g)\cdot e_0=me_0$$

It is assumed that the above traveling-waves are attenuated in the following form when those arrive at the receiving end.

$$E_{2fg}=e_{fg}=k_gE_{12g}=k_ge_0 \quad (7)$$
$$E_{2fp}=e_{fp}=k_pE_{12p}=k_pme_0$$

where $k=E_{2f}/E_{12}$: ratio of corona attenuation ($0<k\le 1$)

The receiving-end voltages are then given by :

$$V_{2g}=A_g\{k_g(R_p+Z_p)-k_pmZ_m\} \quad (8)$$
$$V_{2p}=A_p\{k_pm(R_g+Z_g)-k_gZ_m\}$$

where $A_g=2R_ge_0/\Delta$, $A_p=2R_pe_0/\Delta$

(1) No corona wave-deformation : $k_g=k_p=1$

The voltages V_{g0} and V_{p0} with no corona wave-deformation are given by taking $k_g=k_p=1$ in eq. (8).

$$V_{g0}=A_g(R_p+Z_p-mZ_m) \quad (9)$$
$$V_{p0}=A_p\{m(R_g+Z_g)-Z_m\}$$

(2) With corona wave-deformation : $0<k_g<k_p\le 1$

The voltages V_g and V_p with corona wave-deformation are given by :

$$V_g=A_g\{k_g(R_p+Z_p)-k_pmZ_m\} \quad (10)$$
$$V_p=A_p\{k_pm(R_g+Z_g)-k_gZ_m\}$$

The second term of V_p in eq. (10) is a component induced from a traveling-wave on the ground wire at the time when traveling-waves arrive at the receiving end. The component has the opposite polarity to that of the traveling-wave on the phase wire, and thus it decreases the node voltage V_p. When there is a corona discharge on the ground wire which attenuates the traveling-wave on the ground wire, i.e. $k_g<1$, the component becomes smaller as per k_gZ_m in eq. (10). This results in an increase of the phase-wire voltage V_p.

The above is a qualitative explanation of an increase of the phase-wire voltage due to a corona wave-deformation of a traveling-wave on the ground wire. A condition that the receiving-end voltage with corona wave-deformation becomes greater than that with no corona can be found from a comparison of eqs. (9) and (10). When a difference of eq. (10) from eq. (9)

becomes negative, a node voltage is increased by the corona wave-deformation.

Thus, the following condition is obtained.

$$\mathrm{GW}: r_p > \{(R_p + Z_p)/mZ_m\} \cdot r_g \qquad (11)$$

$$\mathrm{PW}: r_g > \{m(R_g + Z_g)/Z_m\} \cdot r_p = (1 + R_g/Z_g) \cdot r_p \qquad (12)$$

where $r = 1 - k$: normalized amount of corona attenuation $(0 < r < 1)$ (13)

In general, the following relations exist in a physical reality.

$$r_g > r_p, \quad m = Z_m/Z_g < 1, \quad R_p + Z_p > Z_m$$

$$\therefore (R_p + Z_p)/mZ_m > 1 \qquad (14)$$

Considering the above relation, the following equation is always satisfied.

$$\{(R_p + Z_p)/mZ_m\} \cdot r_g > r_p \qquad (15)$$

Thus, eq. (11) for a ground wire is not satisfied in a reality.

On the contrary, eq. (12) for a phase wire can be satisfied under a certain condition, which is given approximately using the following analytical formula of a surge impedance /6/.

$$Z_{ij} = 60\ln(D_{ij}/d_{ij}) \quad [\Omega] \qquad (16)$$

where

$$D_{ij} = \sqrt{(h_i + h_j)^2 + y_{ij}^2}, \quad d_{ij} = \sqrt{(h_i - h_j)^2 + y_{ij}^2} \ ; \ i \neq j$$

$$D_{ii} = 2h_i, \quad d_{ii} = r_i$$

Adopting the above formula, the surge impedance of a test line is given by :

$Z_g = 538.3\ \Omega$, $Z_p = 486.8\ \Omega$, $Z_m = 144.6\ \Omega$ (17)

Substituting the above values into eq. (12), the following condition for $V_{po} > V_p$ is obtained.

$$r_g/r_p > 1 + R_g/538.3 \qquad (18)$$

For examples,

i) $R_g = 37\ \Omega$: $r_g/r_p > 1.07$ or $k_g < 1.07k_p - 0.07$ (19)

ii) $R_g = 200\ \Omega$: $r_g/r_p > 1.37$ or $k_g < 1.37k_p - 0.37$

It should be noted that a grounding resistance of 30 Ω is added to the terminating resistances given in Table 1.

3. 3 Analytical evaluation of line voltages

(1) No corona wave-deformation : $k_g = k_p = 1$

As for the line configuration in Fig. 1 (b), the line surge impedance is given in eq. (17). In the case of the circuit parameters ; $R_0 = 550\ \Omega$, $R_g = 37\ \Omega$ and $R_p = \infty$, the node voltage are given in the following form.

(i) $0 \le t < \tau = 110/300 = 0.367\ \mu s$

$$(V_1) = \begin{pmatrix} 0.4946E_0 \\ 0.1329E_0 \end{pmatrix} = (E_{12}), \quad I_0 = 0.9189 \times 10^{-3} E_0$$

(ii) $\tau \le t < 2\tau = 0.734\ \mu s$

$$(V_2) = \begin{pmatrix} 0.0636E_0 \\ 0.0172E_0 \end{pmatrix}$$

(iii) $2\tau \le t < 3\tau = 1.100\ \mu s$

$$(V_1) = \begin{pmatrix} 0.0589E_0 \\ 0.0160E_0 \end{pmatrix}, \quad I_0 = 1.7111 \times 10^{-3} E_0$$

(2) Corona wave-deformation : $k_g = 0.9$, $k_p = 1$ (no corona deformation on PW)

Assume that the ratio of corona wave-deformation on GW is 0.9 and that on PW is 1, i.e. no corona wave-deformation. Then, the following result is obtained.

(i) $0 \le t < \tau$

$$(V_1) = \begin{pmatrix} 0.4946E_0 \\ 0.1329E_0 \end{pmatrix} = (E_{12}), \quad I_0 = 0.9189 \times 10^{-3} E_0$$

(ii) $\tau \le t < 2\tau$

$$E_{2fg}' = k_g \times E_{12g} = 0.4451E_0, \quad E_{2fp}' = k_p \times E_{12p} = 0.1329E_0$$

$$(V_2) = \begin{pmatrix} 0.05724E_0 \\ 0.04205E_0 \end{pmatrix}$$

(iii) $2\tau \le t < 3\tau$

$$(V_1) = \begin{pmatrix} 0.1417E_0 \\ 0.04386E_0 \end{pmatrix}, \quad I_0 = 1.567 \times 10^{-3} E_0$$

For examples, taking the source voltage $E_0 = -900$ kV, the analyzed waveform is given in Fig. 6. The waveform clearly shows the phenomenon that the PW voltage is increased by the corona wave-deformation on the GW. In the case of $k_g = k_p = 1$, i.e. no corona wave-deformation, the PW voltage is about 15 kV, while the voltage with $k_g = 0.9$ and $k_p = 1$ increases to 38 kV which agrees quite well with the measured result of case 1-3 for $E_0 = -900$ kV in Table 1 (a). Table 2 shows a comparison of the analytical and the measured results of case 1-3 for E_0 from −300 kV to −900 kV. It is observed that the analytical results agree well with the measured results. Thus, the theoretical analysis given in the above has been confirmed to be appropriate physically and qualitatively.

(3) Corona wave-deformation

In the same manner as the above, the case of $k_g = k_p = 0.9$ is calculated and the result is shown in Fig. 6. In this case, it should be clear that the PW voltage is not increased, because the condition of eq. (19) is not satisfied. The PW voltage is decreased to about 14 kV which is proportional to the ratio of corona attenuation.

Table 2 Analytical conditions and results of case 1-3

			Measured results			Analytical results		
E_0 [kV]	k_g	k_p	I_0 [kA]	V_{1n}[kV]	V_{2n}[kV]	I_0 [kA]	V_{1p}[kV]	V_{2n}[kV]
-300	1.0	1.0	-0.242	-38.0	-4.0	-0.276	-39.9	-5.15
-375	1.0	1.0	-0.333	-49.0	-7.0	-0.345	-49.8	-6.44
-450	0.95	1.0	-0.396	-60.0	-9.0	-0.414	-59.8	-13.3
-600	0.95	1.0	-0.625	-80.0	-18.0	-0.551	-79.7	-17.8
-750	0.9	1.0	-0.750	-105.0	-27.0	-0.689	-99.7	-31.5
-900	0.9	1.0	-0.875	-129.0	-38.0	-0.827	-119.6	-37.9

(4) Corona deformation with flashover

The above analyses concern the case of no flashover. When there is a back-flashover from a GW to a PW, the PW voltage becomes far greater than that with no flashover as observed from a comparison of Fig. 3 with Fig. 2.3. Thus, corona wave-deformation inherently appears on a PW. An analytical calculation corresponding to Fig. 3 with k_g = 0.9 and k_p = 1.0 ~ 0.9 is shown in Fig. 7. It is observed that the PW voltage is increased by the corona deformation with k_g = 0.9 and k_p = 1. Thus, it should be clear that the PW voltage increase occurs even in the flashover case.

(5) Ratio of node voltage

Corresponding to Fig. 4 (a), the ratio K defined in eq. (1) is obtained from the analytical result, and a comparison with the experimental results is given in Fig. 8. A satisfactory agreement is observed in the figure, and thus it has been confirmed experimentally and theoretically that a phase-wire voltage at a substation entrance can be increased by corona wave-deformation on a ground wire.

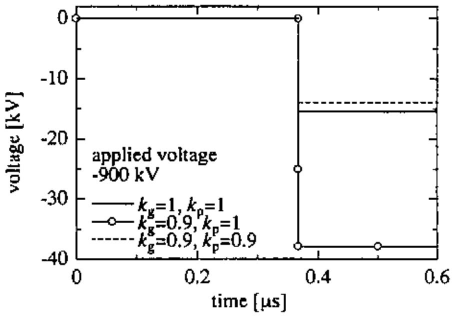


Fig. 6 Theoretical waveform without flashover

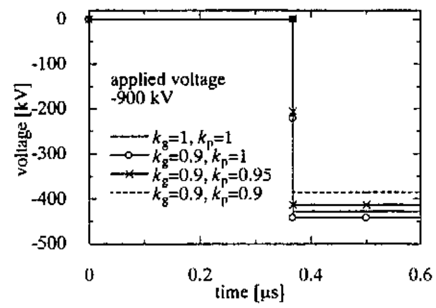


Fig. 7 Theoretical waveform with flashover

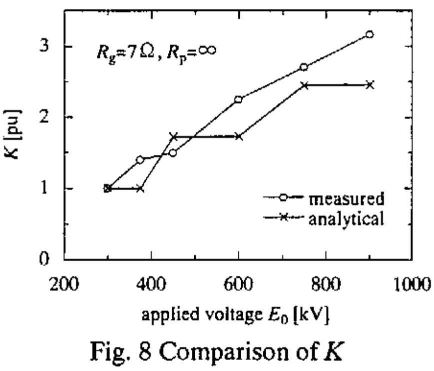


Fig. 8 Comparison of K

4. Conclusions

The present paper has carried an experiment of corona wave-deformation on a 6.6 kV test line with various boundary conditions. The measured result has shown an increase of the phase-wire voltage at the receiving end under a certain boundary condition, while the ground-wire voltage is always decreased by the corona wave-deformation.

A theoretical formula has been derived to investigate the phenomenon in the case of no flashover. The theoretical result clearly shows an increase of the phase-wire voltage, which agrees satisfactorily with the measured result. The increase is caused by heavier attenuation of a traveling-wave on the ground wire than that on the phase wire, and negative reflection of the traveling-wave from the ground wire to the phase wire. The condition of the voltage increase has been theoretically derived. The voltage increase is observed in an analytical calculation even in the case of back-flashover, although it was not clear in the measured result. This needs a further investigation.

The voltage increase seems to be very important in an insulation design of a transmission line and a substation. It is expected that the present paper makes a significant contribution to an overvoltage study due to the corona wave-deformation.

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