Tower Structure Effect on a Back-Flashover Phase

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Abstract-- The paper has investigated a difference of flashover phases between extra-high voltage (EHV) and high-voltage transmission lines based on EMTP simulations. The number of ground wires and a tower footing resistance cause a significant effect on the three-phase archorn voltages. A higher probability of a back-flashover across the upper-phase archorn is very noticeable in the case of a tower with two ground wires and a lower footing resistance, i. e. transmission lines of 275kV and above. A uniform probability of flashovers on each phase is characteristic to a transmission line with one ground wire and a high footing resistance corresponding to low-voltage transmission.

Keywords: lightning surge, archorn, back-flashover, ground wire, transmission line

I. INTRODUCTION

It is essential to investigate a lightning surge for a reliable operation of a power system, because the lightning surge overvoltage is a dominant factor for the insulation design of the power system and the protection of equipments in power stations and substations. When lightning strikes the top of a transmission tower, a lightning current flows down to the bottom of the tower and causes a tower voltage rise which results in a back-flashover across an archorn.

A multistory tower model [1, 2] is well-known and is widely used for a lightning surge analysis in Japan [3]. The tower model shows in general high probability of upper-phase flashovers [4], while a measured result of flashover phases on a 77kV transmission line shows a nearly the same probability of flashovers on each phase [5]. The discrepancy seems to be caused by a difference of the tower configuration.

This paper investigates the effect of the tower configuration on the archorn voltages including the effect of the conductor type and the number of phase and ground wires based on EMTP simulations [6] of a lightning surge by using the multistory tower model.

II. DESCRIPTION OF THE PROBLEM

A. Field test result

Fig. 1 shows field test results of back-flashover phases as a function of the phase voltages (the phase angle of the lower phase) on a 77kV transmission line in a high IKL (about 30 thunderstorm days per year) area during a summer in Japan [5]. The ac source voltage is given by :

$$e_i(t) = E_0 \sin(\omega t - 2i\pi/3) \qquad (1)$$

$i = 0, 1, 2$ for lower, middle, upper phase

The gap length of the archorn is 650mm.

It is observed in the figure that 1LG occurs at a nearly positive peak of a phase voltage. This is quite reasonable for summer lightning is of negative polarity in most cases in Japan. 2LG indicated by the corresponding two phases occurs also in the positive voltage region except for one data observed at around 220 deg. on the upper phase. Only one 3LG is observed at the positive peak (90 deg.) of the lower phase. This is estimated due to an excessive lightning current which is quite rare.

The following important remarks are made from the field test results.

(1) Back-flashover probability is uniform on the three phases independently from the geometrical position of the three phases : lower phase / 10 flashovers, middle phase / 10, upper phase / 9, total 29.

(2) Most back-flashovers (25 cases) occur in the positive voltage region on each phase (total 26 cases except 3LG) .

B. Simulation result by multistory tower model

Fig. 2 shows an example of a simulation result by using the multistory tower model [7] . It should be clear in the figure that most flashovers occur on the upper phase (18 cases) and 8 flashovers occur on the middle phase, but no flashover on the lower phase. For the accuracy of the multistory tower model has been confirmed in comparison with measured results of lightning surge waveforms on 500kV and 1100kV transmission lines [1, 2, 8, 9] and the field test of Fig. 1 was on a 77kV line, the discrepancy seems to be attributed by a difference of the tower configuration including the number of ground wires and the type of a phase and the ground wires.

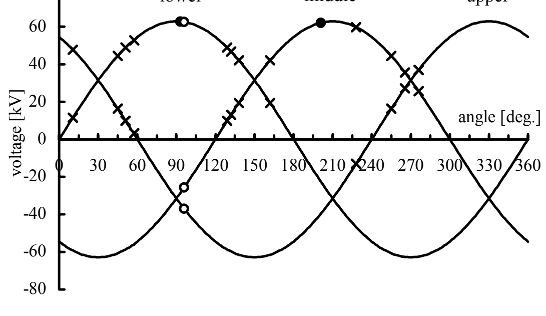

Fig. 1 Field test results of back-flashover phases and the corresponding voltage phase-angle

● one line to ground fault (1LG), × 2LG, ○ 3LG

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Also, the input data based on reference data for a 500 kV line [2] attributes the difference. The problem of the multistory tower model is explained in reference [4].

III. SIMULATION MODEL

Fig. 3 illustrates a model system of a lightning surge simulation by the EMTP. No substation model is included in Fig. 3 (a) because the target of the simulation is archorn voltages rather than lightning overvoltages in the substation. The transmission line in the figure is an untransposed vertical double-circuit line of which the tower configuration is shown in Fig. 3 (b) and the parameters are given in Table 1. The span length between towers is fixed to be 300m so as to avoid its effect on the archorn voltages, although it is dependent on the transmission voltage. A tower footing resistance R_f in Fig. 3(c) is varied from 10 to 50Ω.. The earth resistivity is taken to be 100Ωm which is the average value in Japan. A direct lightning strike to the tower No. 0 is assumed. The lightning current is a lumped wave with the wavefront and tail duration of 1μs and 70μs respectively, and its amplitude is normalized to be 1000pu. An ac steady-state voltage is not included in a simulation by the same reason as the span length. The transmission line is represented by a distributed line model with constant parameters [10].

IV. SIMULATION RESULTS AND DISCUSSIONS

A. Primary investigation

Fig. 4 shows EMTP simulation results of voltage waveforms of archorns and tower arms on transmission lines given in Table 1. Table 2 summarizes the maximum voltage and the time of appearance. It is obvious in the figure and

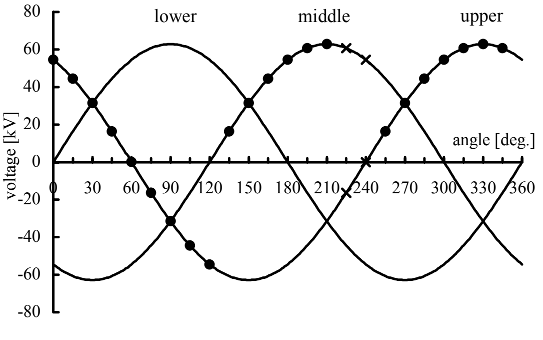
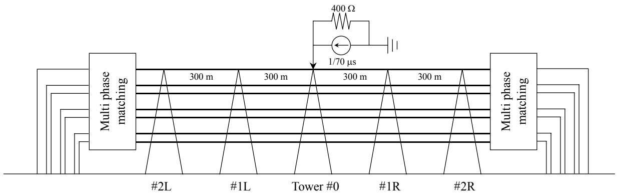


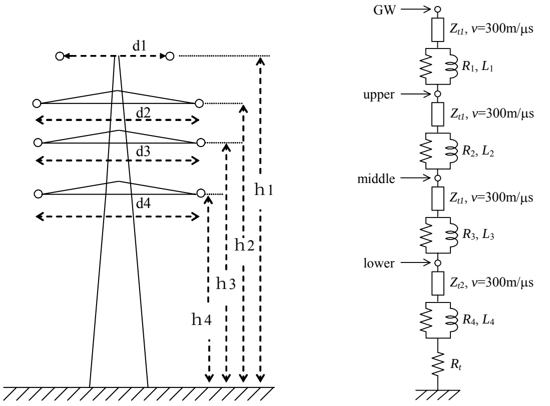
Fig. 2 Simulation results by the multistory tower model

TABLE 1 PARAMETERS OF VARIOUS TOWERS AND LINES

voltage [kV]		66	77	154	275	500
tower	h1 [m]	28.0	37.7	45.8	52.0	79.5
	h2	24.5	34.2	39.6	43.0	72.0
	h3	20.5	30.4	35.3	35.4	57.5
	h4	17.0	27.0	31.0	27.8	43.0
	d1 [m]	0	0	0	13.4	29.0
	d2	4.5	4.8	7.0	12.6	22.4
	d3	9.4	7.8	7.0	13.4	23.2
	d4	6.0	5.4	7.0	14.2	24.0
line	PW [mm^2]	ACSR 610	TACSR 610	TACSR 810	TACSR 410	TACSR 410
	banbles	1	1	2	4	6
	separation	—	—	0.5	0.5	0.5
	GW [mm^2]	AW 70 / 1	AC 70 / 1	AW 90 / 1	IACSR 120 / 2	IACSR 150 / 2



(a) A model system



(b) Tower configuration (c) A multistory tower model

Fig. 3 A model system

TABLE 2 MAXIMUM VOLTAGES AND THE TIME OF APPEARANCE ON AN ACTUAL TOWER

transmission voltage		maximum voltage [kpu] / time of appearance [μs]				
		66kV	77kV	154kV	275kV	500kV
archorn voltage	upper	26.04 / 1.012	29.10 / 1.012	32.33 / 1.021	25.63 / 1.030	31.55 / 1.025
	middle	24.70 / 1.025	27.34 / 1.024	29.56 / 1.035	23.51 / 1.055	28.89 / 1.073
	lower	21.65 / 1.037	24.00 / 1.035	25.97 / 1.049	19.92 / 1.081	22.82 / 1.122
tower voltage	upper	37.88 / 1.011	43.80 / 1.011	46.37 / 1.020	44.61 / 1.030	56.65 / 1.025
	middle	32.71 / 1.024	38.13 / 1.024	40.73 / 1.035	37.56 / 1.055	46.01 / 1.073
	lower	28.17 / 1.036	33.03 / 1.035	35.05 / 1.049	30.38 / 1.080	34.71/1.121

the table that the archorn and tower voltage are the highest on the upper phase and the lowest on the lower phase independently from the transmission voltage. This indicates that the archorn on the upper phase has the highest probability of a flashover.

It is interesting to observe that the archorn voltage on the 154kV line is the highest followed by the 500kV line, and the tower voltage is the highest on the 500kV line followed by the 154kV line. This means that each tower has its own characteristic from the lightning surge viewpoint. It, however, is difficult to discuss a relation between a flashover phase and the tower of each transmission voltage from the results. Table 3 shows a lightning current for each transmission voltage recommended by the Japanese standard of the high voltage testing [9], corresponding gap length of an archorn, 50% flashover voltage of the archorn [10] and the maximum voltage of each phase archorn. It is clear that all the phases can flashover across the archorns if the 50% flashover voltage for a 1/5μs impulse wave is applied to the archorn gap length.

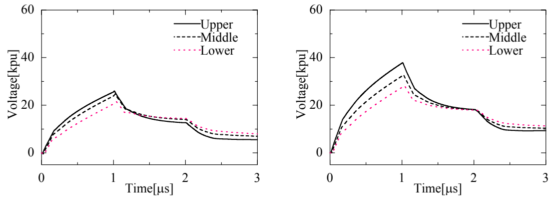
B. *Simulation with normalized tower height*

To observe a relation between a flashover phase and the tower of each transmission voltage, an EMTP simulation is carried out for towers whose height is normalized to the lowest one (28m/66kV) and the highest one (79.5m/500kV). Table 4 shows the configuration of the normalized tower to the lowest one, and Table 5 is simulation results. Fig. 5 shows calculated results of archorn voltages.

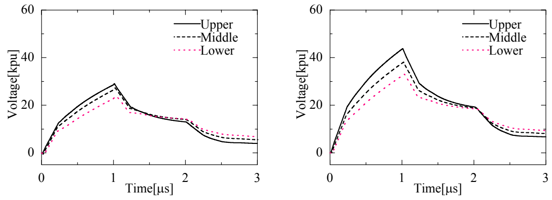
It is clear in Fig. 5 and Table 5 that the lower the transmission voltage, the higher the archorn and tower voltages. Especially the archorn voltages on the 66kV to 154kV towers are far greater than those on the 275kV and 500kV towers. A difference between those two groups is that the former has one ground wire (GW) but the latter has two ground wires. The reason for this is readily attributed that a current flowing into the tower is greater and induced voltage to phase wire is smaller in the former case. Furthermore it is observed that the archorn voltage on each phase is the highest on the 66kV tower whose heights of the middle and lower phases are the smallest and the distances of the phases from the tower center are the largest among the

TABLE 3 RECOMMENDED LIGHTNING CURRENT AND ARCHORN GAP LENGTH

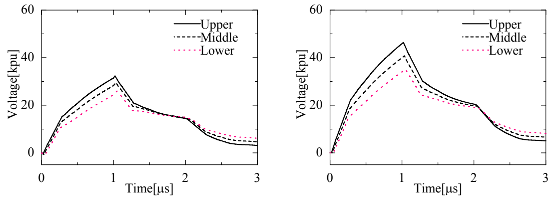
trans. volt. [kV]	lightning current [kA]	archorn volt. [kV] upper / middle / lower	gap length [m]	50%flashover voltage 1/5μs [kV]
66	30	781/ 882/ 650	0.59	525
77	30	873/ 820/ 722	0.59-0.70	591
154	80	2586/2365/2079	1.17	925
275	100	2563/2351/1992	1.87-1.91	1555
500	150	4733/4334/3423	3.40-3.44	2749



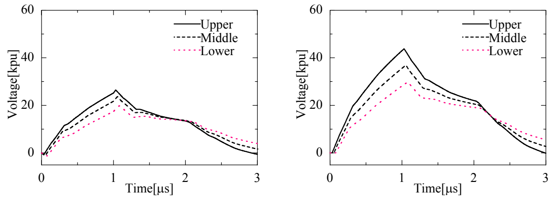
(a) 66kV tower



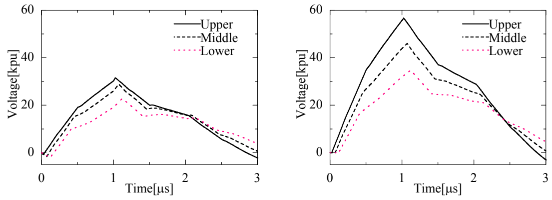
(b) 77kV tower



(c) 154kV tower



(d) 275kV tower



(e) 500kV tower

(1) Across archorn (2) Tower arm

Fig. 4 Archorn and tower voltages on an actual tower

TABLE 4 TOWER PARAMETERS WITH THE NORMALIZED HEIGHT OF 28M

transmission volatge[kV]		66	77	154	275	500
tower configuration	h1 [m]	28.0	28.0	28.0	28.0	28.0
	h2	24.5	25.40	24.21	23.15	25.36
	h3	20.5	22.58	21.58	19.06	20.25
	h4	17.0	20.05	18.95	14.97	15.14
	d1 [m]	0	0	0	7.22	10.21
	d2	4.5	3.56	4.28	6.78	7.89
	d3	9.4	5.79	4.28	7.22	8.17
	d4	6.0	4.01	4.28	7.65	8.45

towers with the one GW. That is, the archorn voltage on each phase becomes higher as the distance from GW becomes greater. The same observations are made in the case of the tower height being normalized to the highest one.

C. *Effect of the number of ground wires*

Having found that the number and the position (distance to a phase wire) of ground wires cause a significant effect on an archorn voltage, the effect of the GW is investigated on the 77kV tower in the following 5 cases.

Case 0 : no GW
Case 1 : one GW at the tower top (centre)
Case 2 : one GW above the 1L upper phase
Case 3 : one GW above the 2L upper phase
Case 4 : two GWs above the upper phases

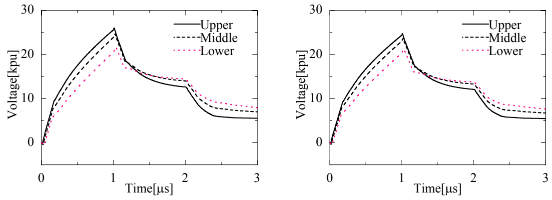
Table 6 gives the mutual inductance, capacitance and surge impedance between the ground wire and a phase wire. Those values are observed to be the largest in Case 2 followed by Case 1. Thus, it is estimated that an induced voltage to a phase wire is the highest in Case 2 and the smallest in Case 3 in the one GW case. Fig. 6 shows voltage waveforms of the tower top, the archorns and the upper phase wire of the 1st circuit. Fig. 6 (e) agrees with the above explained estimation. Case 4 shows the largest induced voltage which is given as a sum of the voltages in Cases 2 and 3. Case 0 shows no induced voltage because of no GW. On the contrary in Fig. 6 (a), the tower top voltage in Case 0 is the largest for all the lightning current flows into the tower because of no GW. Cases 1 to 3 show the same voltage at the tower top, and the voltage in Case 4 is the smallest because a large amount of the lightning current flows into the two ground wires. As a result, the archorn voltage, which is given as a difference of the tower and the phase wire voltages, is the largest in Case 0 : no GW, and is the smallest in Case 4 : two GWs as observed in Fig. 6 (b) to (d).

The above observation leads to a conclusion that the relatively small archorn voltages in the two GWs case result in a high probability of the upper phase of which the archorn voltage is the highest among the three phases, while the relatively high archorn voltages results in multiphase flashovers in the one GW case.

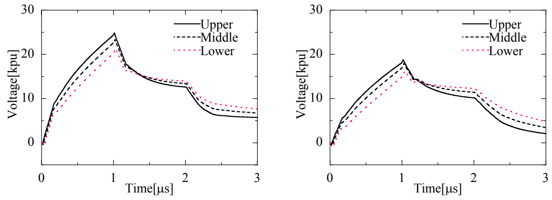
D. *Effect of conductor type*

The effect of ground wires on an induced voltage to a phase wire is quite similar to that on a telephone line. Similarly, the conductor type of the ground and phase wires is attributed to affect the induced voltage, although the initial part of the induced voltage (at t≅0) is determined by the mutual surge impedance between the ground and phase wires which depends mostly on the geometrical configuration.

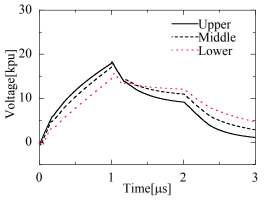
Fig. 7 shows modal attenuation constants for various types of a ground wire on the 77kV line in Table 1. There exist 7 propagation modes because the 77kV line is composed of six phase wires and one ground wire. Among the 7 modes, the mode 5 is the same as the mode 3 (1st aerial mode) and the modes 6 and 7 are the same as the mode 4 (2nd aerial mode). It is clear in the figure that the aerial modes are not dependent



(a) 66kV tower (b) 77kV tower



(c) 154kV tower (d) 275kV tower



(e) 500kV tower

Fig. 5 Archorn voltages with the normalized height of 28m

TABLE 5 MAXIMUM VOLTAGES AND THE TIME OF APPEARANCE ON TOWERS WITH THE NORMALIZED HEIGHT OF 28M

transmission voltage		maximum voltage [kpu] / time of appearance [μs]				
		66kV	77kV	154kV	275kV	500kV
archorn voltage	upper	26.04 / 1.012	24.74 / 1.009	24.86 / 1.013	18.79 / 1.016	18.30 / 1.009
	middle	24.70 / 1.025	23.68 / 1.018	23.35 / 1.021	19.98 / 1.030	17.96 / 1.026
	lower	21.65 / 1.037	21.21 / 1.027	21.26 / 1.030	16.23 / 1.044	15.77 / 1.043
tower voltage	upper	37.88 / 1.011	37.78 / 1.008	36.50 / 1.012	34.05 / 1.016	36.06 / 1.009
	middle	32.71 / 1.024	33.36 / 1.018	32.70 / 1.021	29.53 / 1.029	30.45 / 1.026
	lower	28.17 / 1.036	29.38 / 1.026	28.89 / 1.030	25.00 / 1.043	24.81 / 1.043

on the conductor type. The earth-return mode shows a difference between IACSR (regarded as tubular conductor) and the others (solid conductor) in a frequency range less than 10kHz. The difference does not affect a lightning surge for its frequency component is much higher than 10kHz. The inter-circuit mode is dependent on the conductor type. In a high frequency range corresponding to the lightning surge, the IACSRs show less attenuation. Thus, it is expected that a phase wire voltage is greater and an archorn voltage is smaller in the IACSR case than in the other (AW and AC) case.

It is observed that the archorn voltage in the case of a ground wire being AW or AC is greater by about 5% than that in the case of IACSRs as estimated from Fig. 7, although the calculated result is not shown. The conductor type of a phase wire is also investigated, but no significant effect on the phase wire voltage has been found.

E. Effect of tower surge impedance

The surge impedance of a tower was fixed to be 220Ω for the upper part and 150Ω for the lower part of the tower in the investigations in Sec. IV-A to D. The surge impedance is dependent on the tower configuration, especially on the height "h" and the equivalent radius "r" as is approximated in the following formula obtained analytically and empirically [13-15].

$$Z_0 = 60\ln\left(h/e\,r\right) \qquad (2)$$

where e=2.7... : natural number

It is observed in the calculated result that the greater the surge impedance, the higher the tower and archorn voltages. It should be noted that a relative difference between the archorn voltages on the three phases becomes smaller as the surge impedance becomes smaller. Considering the fact that the tower surge impedance in a low voltage transmission line is relatively small, the smaller difference results in a uniform flashover probability on each phase.

F. Effect of tower footing resistance

For a tower footing resistance affects a lightning surge voltage significantly, its effect on an archorn voltage is to be investigated. Calculated results with the footing resistance 10Ω to 50W show that the greater the footing resistance, the higher the tower and archorn voltages. It should be noted that a difference between the archorn voltages on the three phases becomes smaller as the resistance becomes higher. In the 50Ω case, no difference is observed. The observation has clearly indicated that any of the three-phase archorns can flashover probably depending on the ac source voltage on the phase in the high footing resistance case, i. e. the low-voltage line case, while the upper phase flashover is most probable in the high voltage line case where the footing resistance is low.

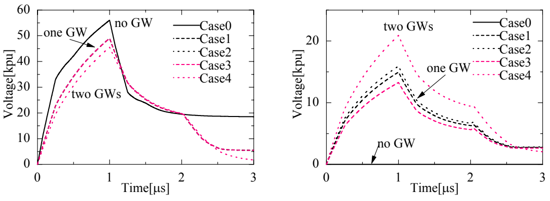
V. CONCLUSIONS

Based on the investigations of an archorn voltage, it becomes clear that the parameters of a multistory tower model has to be determined corresponding to its voltage class. Also, the following remarks have been obtained.

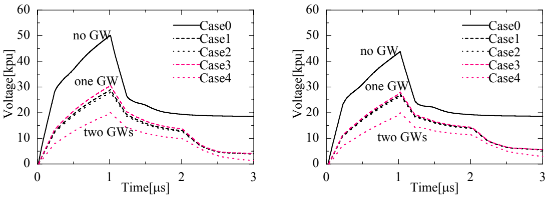
TABLE 6 GW PARAMETER IN EACH CASE

	Case1	Case2	Case3
L_{ga}[mH/km]	0.5938	0.6322	0.5268
L_{gb}[mH/km]	0.4510	0.4718	0.4208
L_{gc}[mH/km]	0.3846	0.3906	0.3706
C_{ga}[μF/km]	0.001415	0.001673	0.001043
C_{gb}[μF/km]	0.000595	0.000710	0.000488
C_{gc}[μF/km]	0.000369	0.000406	0.000335
Z_{ga}[Ω]	175.12	186.66	154.98
Z_{gb}[Ω]	130.22	136.33	121.23
Z_{gc}[Ω]	110.23	112.09	106.10

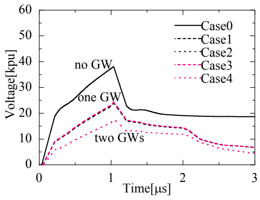
Case4 : GW1 (1st circuit) =Case2, GW2 (2nd circuit) =Case3



(a) Tower top (b) Upper phase wire



(c) Upper phase archorn (d) Middle phase archorn



(e) Lower phase archorn

Fig. 6 Effect of GW on tower top, phase wire and archorn voltages of the 1st circuit

(1) Multiple GWs, common to a transmission line of 275kV and above, result in a relatively small archorn voltage, and the upper phase flashover is most probable. On the contrary, any phases can flashover in the single GW case for the three-phase archorn voltages are relatively high.

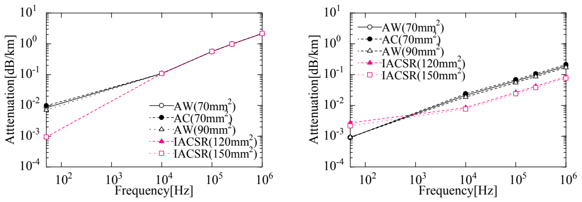
(2) A high footing resistance in a low-voltage transmission line results in nearly the same voltage of the three-phase archorn which makes a flashover probability on each phase uniform.

(3) In the case of a GW being AW or AC, common to a low-voltage line, an archorn voltage becomes greater by about 5% than in the IACSR case.

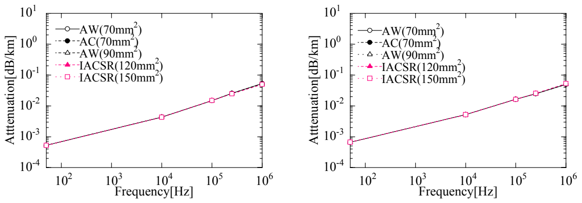
(4) A lower surge impedance of a tower results in a relatively small difference of three-phase archorn voltages.

(5) The above remarks lead to a conclusion that the upper-phase flashover is most probable in a transmission line of 275kV and above, while the flashover probability of each phase is rather uniform in a low-voltage transmission line. The conclusion agrees with field test results.

(6) The observations in the paper suggest a possibility of controlling a flashover probability of each phase by means of the number of ground wires, a conductor type of the ground wire, distance from the ground wire to a phase wire and the footing resistance of a tower.



(a) Mode1 (earth-return) (b) Mode2 (inter-circuit)



(c) Mode3 (aerial 1) (d) Mode4 (aerial 2)

Fig. 7 Effect of GW conductors on modal attenuation constants

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VII. BIOGRAPHIES

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