Lightning Surges on a Control Cable Incoming through a Grounding Lead

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Keywords: lightning surge, low-voltage control cable, grounding mesh, sheath grounding, induced voltage

The present paper investigates induced voltages to a control cable based on EMTP simulations. A simulation neglecting mutual coupling between a control cable and a grounding mesh gives voltages on the cable core produced by a circulating current between the cable sheath and the mesh due to sheath grounding. An induced voltage from the lightning current along the grounding mesh is also investigated considering the current flowing into the soil. The effect of cable sheath grounding and a grounding lead is also discussed.

Figure 1 illustrates a model circuit for investigating transient voltages and currents on a control cable.

Figure 2 shows simulation results with mutual coupling between a control cable and a counterpoise. It is clear in Fig. 2(a) that only an induced voltage, about 2.5 V, due to a counterpoise current appears on the core and the sheath, because the sheath is not grounded. It is observed that the current on the sheath is nearly the same as that with no mutual coupling, and the cable voltages at the both ends are given as the sum of those with no mutual coupling and the induced voltages in Fig. 2(a). (a) and (b) shows no difference of a core voltage and thus, the core voltage is an induced voltage from the counterpoise. Figure 2 (c) shows a twice greater core voltage compared with (a) and (b), and thus a half the core voltage in (c) is a result of a sheath circulating current because of sheath both ends grounding. No significant difference is observed for the counterpoise voltages and currents with and without mutual coupling as is clear from (b) and (c) in comparison with (a).

Based on investigations of lightning surges on a control cable incoming through a grounding mesh, the following remarks have been obtained.

(1) So-called induced voltages on a control cable is a sum of an induced voltage due to a current on a counterpoise and of a voltage transferred from the counterpoise. When the both ends of the cable are grounded, a circulating current in a closed loop composed of the

cable sheath and the counterpoise affects significantly the core voltage at the receiving end which becomes the largest among various sheath grounding.

(2) When the parallel length of the control cable and the counterpoise is long, current decrease along the counterpoise should be taken into account to evaluate an induced voltage to the cable core due to mutual coupling between the cable and the counterpoise.

(3) The inductance of a grounding lead reduces a current flowing into the sheath because of its high impedance for a high frequency transient. At the same time, a current flowing into the counterpoise parallel to the cable increases and the current results in a higher induced voltage to the cable core due to mutual coupling between the cable and the counterpoise.

Fig. 1. A model circuit

(a) Sheath not grounded to counterpoise

(b) Receiving-end sheath grounded to counterpoise

(c) Sheath both-end grounded to counterpoise

Fig. 2. Simulation results of voltages considering mutual coupling ($x = 2$ m)

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The present paper has investigated the effect of sheath grounding on a control cable based on EMTP simulations, when a lightning current flows into counterpoises representing a part of a grounding mesh. Voltages and currents observed on the control cable are given as a superposition of an well-known induced voltage due to the lightning current on the counterpoise, of a voltage transferred from the counterpoise to which the cable metallic sheath is grounded, and of a lightning current circulating in a closed loop composed of the metallic sheath and the counterpoise when the cable both ends are grounded. The induced voltage from the counterpoise is not necessarily dominant even in a long cable because the current along the counterpoise decreases rapidly as the distance from the sending end increases. Although the sheath grounding decreases the node voltage due to the induced voltage, but at the same time increases a voltage transferred from the counterpoise. The inductance of a grounding lead reduces a current flowing into the cable sheath during a high frequency transient, and thus a more current flows through the counterpoise. This results in a higher induced voltage to the control cable from the counterpoise.

Keywords: lightning surge, low-voltage control cable, grounding mesh, sheath grounding, induced voltage

1. Introduction

Electromagnetic interference becomes more and more significant in control circuits of generator stations and substations as the number of digital control equipments increases. A survey of failures and malfunctions of low voltage control equipments in generator stations and substations shows that nearly 70 percents of the failures are caused by lightning surges⁽¹⁾⁽²⁾. The lightning current flows into a grounding mesh in a station and it has been understood that the current causes an induced transient voltage on a control cable. Because the metallic sheath of the control cable is grounded to the mesh as recommended by a standard and a guideline for the electromagnetic interference⁽²⁾⁻⁽⁵⁾, the cable sheath voltage becomes the same as that of the grounding mesh. If the both ends of the metallic sheath are grounded following the IEC/CIGRE recommendation, a current is circulating in a closed loop composed of the cable sheath and the grounding mesh. The circulating current induces a voltage to the cable core, and the core voltage is given as a vector sum of the induced voltages from the lightning current along the grounding mesh and the circulating current. Also, the lightning current along conductors of the mesh flows into the soil and becomes a function of the length of the conductor⁽⁶⁾. Thus, the induced voltage to the cable is a function of the conductor length.

The above fact seems not well understood, and a detailed analysis of the components, i.e. (1) the induced voltage due to mutual coupling from the lightning current along the grounding mesh, (2) the counterpoise voltage transferred to the cable sheath because of the sheath grounding, and (3) the circulating current due to sheath both-end grounding, has not been made. The reason for this is that all the measured results have involved the above components⁽²⁾⁽⁷⁾⁻⁽⁹⁾.

The present paper investigates induced voltages to a control cable based on EMTP simulations. It is easy to evaluate the above mentioned components separately in the EMTP simulations. That is, a simulation neglecting mutual coupling between a control cable and a grounding mesh gives voltages on the cable by grounding the cable sheath to the mesh. An induced voltage from the lightning current along the grounding mesh is also investigated considering the current flowing into the soil. The effect of cable sheath grounding and a grounding lead is also discussed.

2. Model Circuit

Figure 1 illustrates a model circuit for investigating transient voltages and currents on a control cable. A counterpoise representing a part of a grounding mesh is buried at the depth of $h_g = 0.3$ m from the earth surface. The counterpoise is a copper cylinder with the outer radius of $r_g = 2.5$ cm, and the earth resistivity is $100 \Omega\text{m}$. As a control cable, a 3D2 V cable, of which the cross-section and the physical parameters are given in Fig. 2, is suspended at the height of $h_c = 0.1$ m above the earth surface. A step-function current with the amplitude

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Fig. 1. A model circuit

Fig. 2. A control cable (3D2V)

Fig. 3. A model circuit of a counterpoise

of 1 A is applied to the sending end of the counterpoise as in Fig. 1. Transient voltages and currents on the control cable and the counterpoise are calculated by EMTP.

A counterpoise is represented by a model circuit illustrated in Fig. 3 which is composed of a distributed line with the surge impedance Z_0 and the propagation velocity v_0 and a shunt admittance $Y_g^{(10)}$. In this paper, m and n are set to be 1 and 5 respectively. Fig. 4 shows a comparison of experimental results and EMTP simulation results by the model circuit of Fig. 3 for transient voltages and currents along the counterpoise with the total length of 6 m in Fig. 1. The figure shows that the accuracy of the counterpoise model in Fig. 3 is satisfactory in comparison with the measured results.

In a simulation of an induced voltage to an overhead control cable from a counterpoise, the control cable and the counterpoise are represented as a distributed parameter line in the EMTP [11]. The parameters of the line models are evaluated by the EMTP Cable Parameters (CP) [12]. First, the model system is evaluated as an overhead line system by the CP with a negative sign of the depth of the counterpoise. By the input date, the CP gives self impedance/admittance of the overhead cable and the mutual impedance to the counterpoise. Then the self impedance/admittance of the counterpoise is calculated as an underground cable. Finally, the self impedance/admittance of the counterpoise in the first calculation is replaced by those in the second one.

Table 1 gives simulation conditions such as grounding of the metallic sheath of a control cable, and results of maximum voltages and currents. In the table, case $Xi-Lj$ represents:

$X = A$: $x = 2$ [m], B : $x = 10$ [m], C : $x = 20$ [m]

D : $x = 2$ [m] and two more counterpoises connected to

Fig. 4. Comparison of measured and simulation results of counterpoise voltages and currents

Table 1. Simulation conditions and results

(a) No mutual coupling (Case X0-Lj)														
case	x [m]	L [μH]	connection	maximum voltage [V]								maximum current [A]		
			S1	S2	C1	C2	S1	S2	G1	G2	G0	S1	S2	
A0-01	-	-	-	-	0.00	0.00	0.00	0.00	19.40	16.68	0.729	-	-	
02	-	-	on	-	4.46	1.38	19.26	20.70	19.26	16.64	0.728	0.116	-	
03	-	-	on	on	0.633	1.30	16.76	16.64	19.26	16.64	0.735	-	0.039	
04	-	-	on	on	4.93	-3.61	17.00	16.48	17.00	16.48	0.743	0.263	-0.262	
12	-	-	on	-	2.74	1.51	27.25	29.07	18.5	16.8	0.723	0.087	-	
13	-	-	on	on	0.822	1.32	19.10	18.32	19.34	16.80	0.741	-	0.044	
14	-	-	on	on	2.701	-1.28	19.08	17.27	18.05	16.71	0.735	0.104	-0.105	
B0-01	-	-	-	-	0.00	0.00	0.00	0.00	19.40	6.17	0.826	-	-	
02	-	-	on	-	8.13	2.28	17.32	19.38	17.32	6.21	0.828	0.211	-	
03	-	-	on	on	0.340	0.723	6.348	6.210	19.40	6.21	0.827	-	0.021	
04	-	-	on	on	8.13	-6.00	15.74	6.70	15.74	6.70	0.840	0.229	-0.230	
C0-01	-	-	-	-	0.00	0.00	0.00	0.00	19.40	1.42	0.839	-	-	
02	-	-	on	-	8.15	2.13	15.78	17.85	15.78	1.32	0.838	0.207	-	
03	-	-	on	on	0.104	0.289	1.176	1.319	19.40	1.32	0.839	-	0.008	
04	-	-	on	on	8.15	-6.07	15.78	3.321	15.78	3.32	0.871	0.209	-0.204	
12	-	-	on	-	6.87	1.82	17.47	19.73	17.16	1.29	0.841	0.174	-	
13	-	-	on	on	0.100	0.321	1.079	1.280	19.39	1.296	0.838	-	0.009	
14	-	-	on	on	6.87	-4.84	14.46	7.02	17.16	2.83	0.867	0.179	-0.185	
D0-04	2	0	on	on	2.73	-1.99	9.98	9.91	9.98	9.91	0.934	0.154	-0.151	

(b) With mutual coupling (Case X1-Lj)														
case	x [m]	L [μH]	connection	maximum voltage [V]								maximum current [A]		
			S1	S2	C1	C2	S1	S2	G1	G2	G0	S1	S2	
A1-01	-	-	-	-	2.34	-2.53	2.82	-2.70	19.31	16.54	0.711	-	-	
02	-	-	on	-	4.52	-1.96	19.29	16.61	19.29	16.49	0.709	0.111	-	
03	-	-	on	on	3.10	-2.10	16.81	16.49	18.93	16.49	0.716	-	0.042	
04	-	-	on	on	5.47	-4.36	18.04	16.47	18.04	16.47	0.711	0.243	-0.239	
12	-	-	on	-	4.46	-1.66	26.15	24.29	18.63	16.51	0.707	0.077	-	
13	-	-	on	on	3.18	-1.46	21.93	19.03	19.10	16.51	0.722	-	0.052	
14	-	-	on	on	4.42	-2.67	20.97	17.30	18.66	16.55	0.712	0.075	-0.075	
B1-01	-	-	-	-	2.53	-2.57	2.96	-2.89	19.38	6.019	0.821	-	-	
02	-	-	on	-	8.41	-2.52	17.69	16.46	17.69	6.025	0.822	0.199	-	
03	-	-	on	on	2.88	-2.28	8.280	6.025	19.38	6.025	0.822	-	0.030	
04	-	-	on	on	8.41	-6.56	16.29	6.371	16.29	6.371	0.830	0.236	-0.233	
C1-01	-	-	-	-	2.23	-2.25	2.60	-2.551	19.37	1.495	0.837	-	-	
02	-	-	on	-	8.45	-2.32	16.35	15.85	16.35	1.459	0.839	0.198	-	
03	-	-	on	on	2.48	-2.21	5.071	1.459	19.37	1.459	0.837	-	0.028	
04	-	-	on	on	8.45	-6.63	16.35	2.783	16.35	2.783	0.853	0.200	-0.200	
12	-	-	on	-	7.50	-2.60	17.85	16.24	17.49	1.509	0.843	0.163	-	
13	-	-	on	on	2.59	-2.17	5.511	1.725	19.37	1.509	0.837	-	0.023	
14	-	-	on	on	7.47	-5.60	15.53	6.595	17.49	2.148	0.850	0.163	-0.162	
D1-04	2	0	on	on	2.94	-2.33	10.00	9.914	10.00	9.914	0.924	0.148	-0.147	

node GC1

$i = 0$: no mutual coupling between control cable and counterpoise

$i = 1$: mutual coupling between control cable and counterpoise

$L = 0$: no inductance considered for a grounding lead

$L = 5$: $5 \mu\text{H}$ for a lead wire

j for grounding of metallic sheath to counterpoise

$j = 1$: no grounding, $j = 2$: sending end grounded

$j = 3$: receiving end, $j = 4$: both ends

3. Simulation Results and Discussions

Figures 5 to 12 show simulation results of transient voltages and currents. The peak values are summarized in Table 1.

3.1 No Mutual Coupling (Case X0-Lj)

3.1.1 Case A0-0j: $x = 2$ m, $L = 0$ Figure 5 is the case of neglecting mutual coupling between a control cable and a counterpoise with the parallel length $x = 2$ m. Thus,

Fig. 5. Simulation results neglecting mutual coupling between the control cable and the counterpoise ($x = 2$ m)

the voltages and currents on the control cable in the figure are caused only by connecting (grounding) the metallic sheath of the cable to the counterpoise.

No voltage and no current appear on the control cable in Fig. 5(a) for there is no connection nor mutual coupling between the cable and the counterpoise. When one end of the sheath is grounded to the counterpoise, a voltage and a current appear on the grounded node. In case A0-02 (sending-end sheath to counterpoise), the sheath voltage at the sending end S1 becomes nearly the same as the counterpoise voltage of about 20 V at the grounded node G1, and the core voltage at the sending end C1 reaches 4 V as observed in Fig. 5(b)-(2). Also, a small voltage of about 1 V is observed at the core receiving-end. The core voltages are produced by electro-static and magnetic coupling between the cable core and the sheath during an initial transient period up to about 300 ns as a small current, about 0.1 A, on the cable sheath at the sending end is observed in Fig. 5(b)-(1) during

the time period. A similar trend is observed for the receiving-end sheath grounded to the counterpoise (Case A0-03), that is, the sheath voltage becomes nearly the same as the counterpoise voltage at the receiving end. Small voltages appear on the both ends of the core and a very small current is observed on the sheath in Fig. 5(c). It should be noted that the core voltages and the sheath current are much smaller than those in Case A0-02.

When the both ends of the cable sheath are grounded to the counterpoise, a large current, nearly 0.25 A which is about 30% of the current I_{G0} flowing into node GC1 of the counterpoise, flows into the sheath as in Fig. 5(d)-(1), and results in nearly 5 V at the core sending end and -3.5 V at the receiving end as observed in Fig. 5(d)-(2). The core voltages are generated by electromagnetic coupling between the sheath and the core. It should be noted that the counterpoise voltages and currents are not much affected by the sheath grounding.

In summary, grounding the metallic sheath of a control

Fig. 6. Effect of parallel length x with no mutual coupling

cable to a counterpoise results in a current flowing into the sheath and generating core voltages due to electromagnetic and static coupling between the cable core and the sheath. Especially the grounding of the sheath both ends to the counterpoise produces a sheath current of about 30% of the counterpoise current and the voltage proportional to the current appears on the core during the initial time period of a transient. Grounding the sending-end sheath to the counterpoise also produces a rather high voltage to the core at the sending end.

3.1.2 Effect of length x Figure 6 shows the case of no mutual coupling with the parallel length $x = 20$ m between a control cable and a counterpoise. It is clear that currents at the sending end of the counterpoise are greater and the voltages are smaller than those in Fig. 5 for $x = 2$ m, because the longer counterpoise length decreases its impedance seen from the sending end. Also, the currents along the counterpoise show a smooth increasing characteristic while the voltage at the sending end takes the peak at around $t = 250$ ns and then converges to a certain value. The above explained characteristics of the counterpoise agree with those for measured results⁽⁶⁾⁻⁽⁹⁾.

The sheath currents in Fig. 6 for $x = 20$ m show a remarkable difference from those in Fig. 5 for $x = 2$ m. The current in Fig. 6(a)-(1) for the sending-end sheath grounded to the counterpoise is nearly a twice of that in Fig. 5(b)-(1), and is sustained up to 160 ns corresponding a twice the propagation time of a traveling wave on the sheath from the sending end to the receiving end. Corresponding to this fact, the sending-end core voltage reaches 8 V which is about 2 times of that in Fig. 5(b). A similar trend is observed in Fig. 6(c) for $x = 20$ m

in comparison with Fig. 5(d) for $x = 2$ m. It is quite clear in Fig. 6(c)-(1) that there exists a circulating current between the control cable sheath and the counterpoise, i.e. current S1 at the sheath sending end and current S2 at the receiving end. The sheath current produces the core voltages about 8 V at the sending end and -6 V at the receiving end which are much greater than those in Fig. 5(d)-(2). On the contrary, the cable voltages and current in Fig. 6(b), the receiving-end sheath connected to the counterpoise, are much lower than those in Fig. 5(c), because the counterpoise current at the receiving end becomes much smaller due to current penetration into the earth. It should be noted that the voltage difference between the cable core and the counterpoise is large at the sending end as in Table 1(a), but that at the receiving end becomes much smaller in comparison with the case of $x = 2$ m.

3.2 With Mutual Coupling (Case X1 - L_j)

3.2.1 Case A1-0j : $x = 2$ m, $L = 0$ Figure 7 shows simulation results with mutual coupling between a control cable and a counterpoise corresponding to Fig. 5 with no mutual coupling. It is clear in Fig. 7(a) that only an induced voltage, about 2.5 V, due to a counterpoise current appears on the core and the sheath, because the sheath is not grounded to the counterpoise. The polarity at the receiving end is opposite to that at the sending end as in Ref. (13). It is observed in Fig. 7(b) that the current on the sheath is nearly the same as that in Fig. 5(b) and the core voltages at the both ends are given as the sum of those in Fig. 5(b) and the induced voltages in Fig. 7(a). The same observation is made for Fig. 7(c) in comparison with Fig. 5(c). It should be noted that Fig. 7(d) is nearly the same as Fig. 5(d). This means that the

Fig. 7. Simulation results considering mutual coupling between the control cable and the counterpoise ($x = 2$ m)

core voltage in Fig. 7(d) is generated by a circulating current between the sheath and the counterpoise, although the induced voltage, 2.5 V, by the current on the counterpoise is decreased by the both-end grounding. If the sheath is grounded to another counterpoise on which no lightning current flows, the sheath both-end grounding results in the smallest voltage on the cable core as recommended by standards and guides⁽²⁾⁻⁽⁵⁾. The recommendation is correct only in the case of no lightning current on a counterpoise to which the sheath is grounded. No significant difference is observed for the counterpoise voltages and currents between Figs. 5 and 7.

In summary, the sending-end voltage is the largest in the sending-end and the both-end grounded cases. The receiving-end voltage becomes the largest in the both-end grounded case because of a circulating current in a closed loop composed of the cable metallic sheath and the counterpoise. Thus, the receiving-end grounding is preferable than the sending and the both-end grounding. The observations agree qualitatively with measured results in references⁽²⁾⁻⁽⁷⁾⁻⁽⁹⁾, especially in Ref. (9) for the same 3D2 V cable.

3.2.2 Effect of length x Figure 8 shows simulation results of voltages for $x = 20$ m. Current waveforms are not shown because those are nearly the same as Fig. 6-(1). It is clear in Fig. 8(a) for sheath not grounded to counterpoise that the induced voltages to the core and the sheath from the counterpoise are far greater than those in Fig. 7(a) for $x = 2$ m. This is reasonable because an induced voltage is proportional to the parallel length of the inducing circuit, as is well-known⁽¹³⁾. The length for Fig. 8 being 20 m, a 10 times greater induced voltage than that in Fig. 7 is expected if it is in a steady state, but the induced voltage at node C1 is about 2 V in Fig. 8(a) which is smaller than that in Fig. 7. The reason for the smaller induced voltage than that expected from the theory of steady-state induction is that the inducing current on the counterpoise decreases as the distance from the sending end increases as shown in Fig. 9. It is clear in Fig. 9 that the current along the counterpoise is decreasing exponentially as the distance increases. Furthermore, the rise time of the current, i.e. di/dt decreases rapidly. The transient induced voltage is given as:

(a) Sheath not grounded to counterpoise (Case C1-01)

(b) Sending-end sheath grounded to counterpoise (Case C1-02)

(c) Receiving-end sheath grounded to counterpoise (Case C1-03)

(d) Sheath both-end grounded to counterpoise (Case C1-04)

Fig. 8. Effect of parallel length

Fig. 9. Currents along the counterpoise at the distance x from the sending end

$$v_m(t) = M di/dt \dots \dots \dots (1)$$

where M : mutual inductance

It should be clear from the above equation that the transient induced voltage decreases rapidly in proportion to the rise time decrease of the inducing current.

The core voltages in Fig. 8(b) to (d) are given as the sum of the induced voltage in Fig. 8(a) and the voltage in Fig. 6 due to the sheath grounding to the counterpoise. Thus, the sending-end core voltage reaches nearly 8 V in Fig. 8(b) and (d), and the receiving-end core voltage is about -7 V in

(a) A single counterpoise

(b) Counterpoises connected at node G1

Fig. 10. Crossing counterpoises at node G1

Fig. 8(d), and -6 V in Fig. 8(c).

3.2.3 Effect of crossing counterpoises (part of a mesh)

In practice, the metallic sheath of a control cable may be grounded to a node of a grounding mesh where mesh branches, i.e. counterpoises, are connected each other as illustrated in Fig. 10. The impedance at node G1 seen from the left in Fig. 10(b) becomes about 1/3 of that in Fig. 10(a) on which all the previous investigations are based. The impedance variation in Fig. 10(b) results in current distribution different from that in Fig. 10(a), and thus, a current flowing into the cable sheath connected to node G1 differs. An example is presented in the figure. It is observed in Fig. 10 that the current flowing into the sheath is about 30% of the original current I_{G0} on the counterpoise when the sheath is grounded to an intermediate node of a single counterpoise as in (a), while it is less than 20% when the sheath is grounded to the mesh node as in (b). This difference certainly results in different transient voltages and currents on a control cable as shown in Table 1.

A comparison of case D1-04 with case A1-04 and D0-04 with A0-04 in Table 1 makes clear that the cable voltages are reduced to less than a half by grounding the sheath to the node of a grounding mesh where counterpoises are connected to each other. The result is reasonable because of smaller current flowing into the sheath (I_{S1}) and that on the counterpoise to the right of node G1 (I_{G1}) which is the inducing current to produce the cable voltage when the sheath is not grounded to the counterpoise.

The above result has indicated that an analysis of the induced voltage to the control cable can be carried out assuming a single counterpoise as the severest case. Also, it should be mentioned that counterpoises which are a part of grounding mesh parallel to a control cable induces voltages on the cable. The voltage induced by the counterpoise nearest to the cable is the largest, and those due to the other counterpoises are much smaller because of the distance to the cable, and are somehow cancelled out because of the symmetrical configuration of the counterpoises to the cable. Therefore, it is expected that only the induced voltage from the nearest one is enough to be considered in the transient analysis of the induced voltage.

3.2.4 Effect of lead wire inductance

It is well-known that a transient response in a circuit is significantly affected by the impedance of a lead wire used for grounding, connecting circuits and measurements ⁽²⁾⁽³⁾. In Ref. (2),

(1) No mutual coupling (Case C0-12)

 (2) Mutual coupling (Case C1-12)
(a) Sending-end grounding

(1) No mutual coupling (Case C0-13)

 (2) Mutual coupling (Case C1-13)
(b) Receiving-end grounding

(1) No mutual coupling (Case C0-14)

 (2) Mutual coupling (Case C1-14)
(c) Both-end grounding

(1) No lead wire inductance (Case C1-02)

 (2) Lead wire inductance considered (Case C1-12)
(a) Sending-end grounding

(1) No lead wire inductance (Case C1-03)

 (2) Lead wire inductance considered (Case C1-13)
(b) Receiving-end grounding

(1) No lead wire inductance (Case C1-04)

 (2) Lead wire inductance considered (Case C1-14)
(c) Both-end grounding

Fig. 12. Core voltages to sheath and counterpoise

Fig. 11. Effect of lead wire inductance on cable voltages

it is said that the grounding of the metallic sheath of a control cable may not be effective at all during a high frequency transient because of the grounding lead inductance.

Figure 11 shows the effect of the grounding lead inductance assuming $1 \mu\text{H}/\text{m}$ on voltages and currents of a control cable. It is observed in Table 1 that the inductance of $5 \mu\text{H}$, corresponding to the 5m grounding lead, reduces a current flowing into the sheath and the core voltages nearly a half for the case of no mutual coupling. However Fig. 11 with mutual coupling shows that the cable voltages are not much different from those in Fig. 8. The reason for this is readily explained that the high impedance of the grounding lead due to the inductance decreases the current flowing into the sheath and thus the current on the counterpoise increases which induces more voltages on the cable core. Similarly to Sect. 3.2.1. the largest core voltage at the receiving end is observed when the sheath both ends are grounded. Thus, it is concluded that the receiving end grounding is preferred even when a lead wire inductance is considered.

The above observations agree with those explained in Ref. (2) that sheath grounding becomes not effective for a transient due to the inductance of a lead wire.

3.2.5 Core voltages to sheath and counterpoise The previous sections concern voltages to the zero potential surface to investigate the effect of sheath grounding. In practice, a voltage difference from the core of a control cable to the sheath or to a counterpoise is used as the core voltage. Fig. 12 show the voltage difference. It is clear that the voltage difference from the core to the sheath is nearly the same as that to the counterpoise independently from the lead wire inductance. However, the voltage difference to the sheath is entirely dependent on the sheath grounding, and is greater than that to the counterpoise. The voltage difference is the greatest in the case of the sheath sending-end grounding. The receiving-end grounding shows the smallest difference. The results again suggest that the receiving-end grounding is better than the both-end grounding.

4. Conclusions

Based on investigations of lightning surges on a control cable incoming through a grounding mesh, the following remarks have been obtained.

(1) So-called induced voltages on a control cable is a sum of an induced voltage due to a current on a counterpoise and of a voltage transferred from the counterpoise. When the both ends of the cable are grounded, a circulating current in a closed loop composed of the cable sheath and the counterpoise affects significantly the core voltage at the receiving end which becomes the largest among various sheath grounding.

(2) When the parallel length of the control cable and the counterpoise is long, current decrease along the counterpoise should be taken into account to evaluate an induced voltage to the cable core due to mutual coupling between the cable and the counterpoise. Otherwise, an excessive induced voltage due to the mutual coupling is expected.

(3) A lightning current incoming into a node of a grounding mesh distributes to every branches (counterpoises) connected at the node, and thus currents flowing into the cable sheath and the counterpoise parallel to the cable become

smaller. This results in smaller voltages on the cable. Thus, an analysis assuming a single counterpoise gives the severest voltage on the cable, that is on a safer side

(4) The inductance of a grounding lead reduces a current flowing into the sheath because of its high impedance for a high frequency transient. At the same time, a current flowing into the counterpoise parallel to the cable increases and the current results in a higher induced voltage to the cable core due to mutual coupling between the cable and the counterpoise.

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