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Lightning Induced Voltage on Control Cable in Traction Substation

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***Abstract*—An electronic circuit in a control panel installed in a substation for Japanese bullet train (Shinkansen) was damaged due to a lightning. A field test is carried out to clarify the cause of the failure. The results show that a voltage is induced on a control cable for a earthing system and its amplitude exceeds the lightning withstand voltage of the control circuit. The effect of an earthing of an unused core in the control cable is investigated at a traction substation. To reduce the induced voltage, the unused core has to be earthed at the end of the control panel. If the core is earthed at the other side, a high voltage appears at the control panel. The effect of the lightning surge waveform on the induced voltage is also discussed. These results are effective for a proposal of a countermeasure to the fault and insulation design of traction substations.**

Keywords-induced voltage; control cable; traction substation; lightning surge; surge analysis; Shinkansen

I. INTRODUCTION

A control panel in a traction substation for Sanyo-Shinkansen (bullet train) was damaged due to a lightning in September 2013. The authors have been carried out a field test using a model circuit simulating the failure [1]. A current was injected from an earthing wire for an arrester or a ground wire (GW) of a transmission line into the earthing mesh of the fault substation by an impulse generator. The measured induced voltage on a control cable was higher than the lightning withstand voltage of a control circuit. To reduce the failure, further investigations are required.

The Sanyo-Shinkansen began its operation between Shin-Osaka and Okayama on March 1972, and has been extended from Okayama to Hakata on March 1975. PVC insulated and sheathed control cable with tape (CVVS) is used as a control cable in the traction substations for the Shinkansen between Hakata and Okayama (the second segment) for shealding the electrostatic induction and switching surge induced from apparatuses such as circuit breakers. Although the first segment (between Okayama and Shin-Osaka) has been received many lightning strikes, PVC insulated and sheathed control cable (CVV), i.e., a control cable without a metallic sheath has been employed. Any countermeasure has to be introduced into the old-fashioned substations immediately.

In this paper, the number of lightning strikes over the past five years are investigated, at first. From the results, a substation, which is the highest possibility of the lightning damage, is selected. A field test is carried out at the substation to simulate the induced voltage on the control cable. Three impulse generator are used to clarify the effect of the waveforms on the induced voltage.

II. MEASURMENTS OF POTENTIAL DISTRIBUTION

A. *Mesurement Conditions*

Fig. 1 illustrates the experimental circuit for the measurement of the induced voltage on the control cable. The cable is used to control apparatus in the substation from a circuit in a control panel installed in a building. An impulse current is injected into the earthing mesh via one of earthing wires for the arresters (Point A or B) for the first and second circuit of the AC transmission line or the anchor steel of the second circuit (Point C). A ground wire is tied to the anchor.

The injected current and each voltage waveform at the injecting point are measured with a wide-band current transformer, a voltage probe and a digital oscilloscope as illustrated in Fig. 2. In order to suppress the influence of the impedance mismatching between the impulse generator and the current injecting wire, two resistors of 450 Ω are inserted as shown in Fig. 2(a).

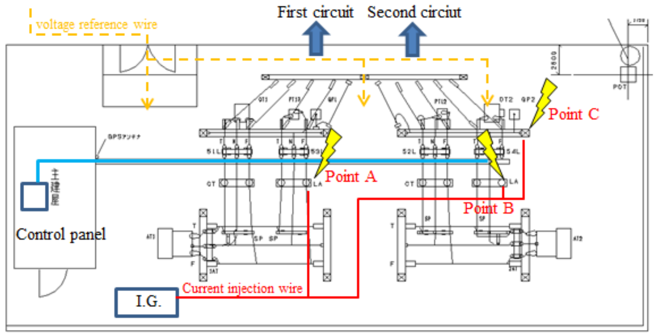
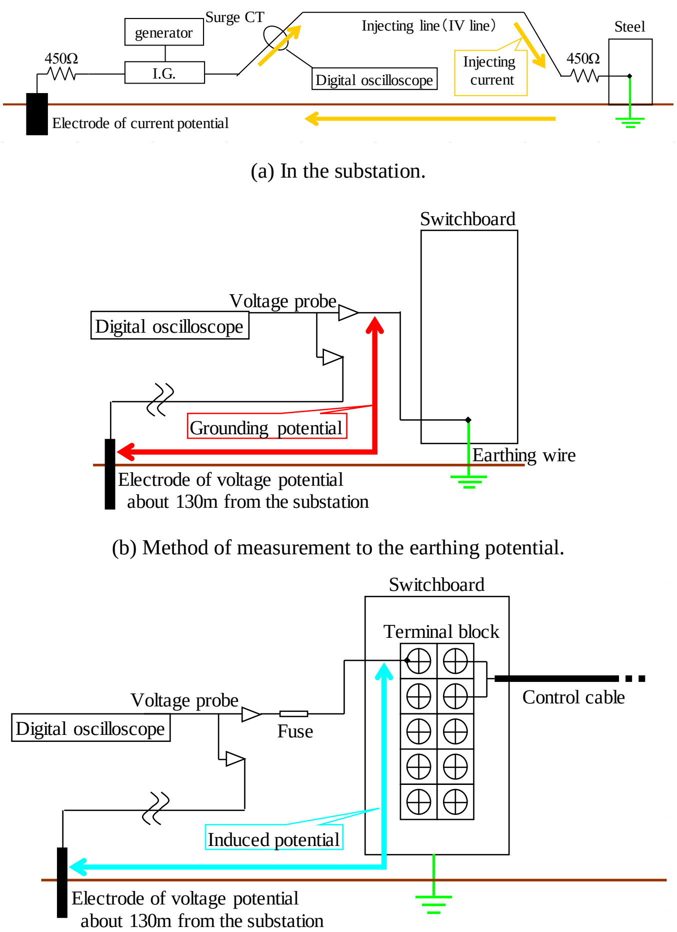


Figure 1. Measurement circuit in the substation.



(a) In the substation.

(b) Method of measurement to the earthing potential.

(c) Method of measurement to the induced potential.

Figure 2. Measurement circuit.

The potentials of the earthing mesh and a control cable at the control panel are measured as shown in Figs. 2 (b) and (c). The potential is defined as a difference between the voltage on the measuring object and that on the voltage reference wire, which is earthed by an electrode buried about 130 m apart from the substation. When a lightning impulse current is injected into the earthing mesh, a voltage is induced on the control cable. The substation has four main control circuits, 51L, 52L, 53L and 54L, and uses CVV control cables with five cores. The longest control cables for "54L control circuit" is selected as a measuring object as shown in Fig. 1. TABLE I shows measurement cases. Case 1 is the voltage on an earthing wire of the control panel (Fig. 2 (b)). A voltage on a core, which is currently used for a control, is measured in the other cases (Fig. 2 (c)). Case 2 denotes the induced voltage on a core of the CVV cable when unused cores are open-circuited. This is a current configuration of the substation. In [3], it is recommended that unused wires in the control cable are earthed at their both ends as a countermeasure for a lightning damage. In Cases 3 and 4, an unused core in the control cable is earthed at one of its ends. In Case 3, the core is earthed at the control panel. In Case 4, an unused core is earthed at the disconnector 54L, i.e., the other end of the control panel. The both ends of the core are earthed in Case 5.

B. *Measured Results*

Fig. 3 shows the injected current waveform used in the investigation. A current is generated by an impulse generator whose maximum current and its wavefront time is 50 A and 3.6 μs, respectively. Fig. 4 shows the maximum measured results of the induced potential on the control cable at the control panel. When an unused wires is earthed at the other side of the control panel, i.e., at the disconnector 54L (Case 4), the potential becomes the maximum among the cases. The differences in the induced potentials between Cases 2, 3 and 5 are small. The induced potentials are defined as the difference between voltages on the terminal and that on the voltage reference wire as shown in Figs. 2 (b) and (c).

The lightning damage has to be discussed based on a voltage difference within the control panel. The maximum difference between each induced potential on the core of the control cable for 54L disconnector and the potential on the earthing terminal of the control panel (Case 1) is shown in Fig. 5 and TABLE II. From a comparison between the results in Figs. 4 and 5, the voltage falls by 13.8 to 71.3 % in Cases 2, 3 and 5. The most effective countermeasure for reducing the induced voltage is Case 5, i.e., the unused core is earthed at the both side. The results show in Figs. 4 and 5 are for a current of 50 A amplitude. If the amplitude of the lightning current is assumed to be 30 kA, the voltage in Case 2 will be reduced from 2.28 kV (3.8 V/50 A) to 1.38 kV (2.3 V/50 A).

TABLE I. MEASUREMENT CASES

Case 1	Earthing wire
Case 2	None earthing
Case 3	Single side earthing at the control panel
Case 4	Single side earthing at the control circuit 54L
Case 5	Both ends earthing

On the other hand, the induced voltage between the core and the earthing terminal in Case 4 (single earthing at the apparatus) at Point C is greater by 36.3 % than the potential from the voltage reference wire. The single end earthing at the apparatus is not recommended from the view point both from the potential and the voltage in the control panel.

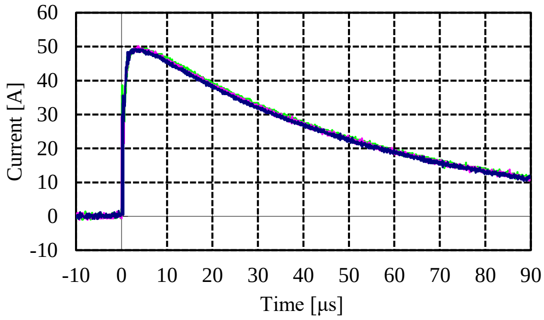


Figure 3. Injected current waveform (IG).

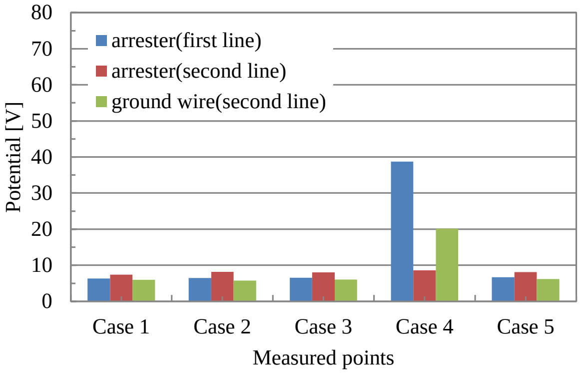


Figure 4. Measured induced voltage of 54L control cable.

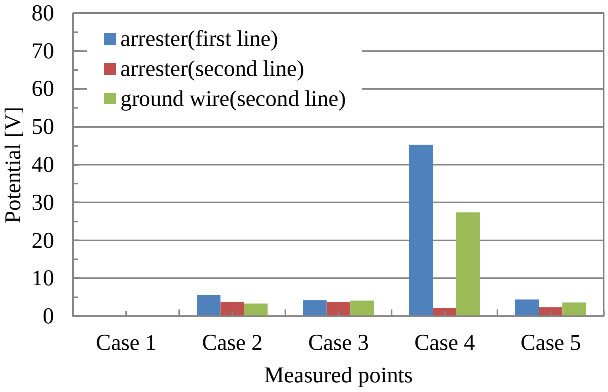


Figure 5. Voltage diffenence between the induced voltage of 54L control cable and the earthing terminal in the swtchboard.

TABLE II. MAXIMUM INDUCED VOLTAGES

	Point A			**Point B**			**Point C**		
	Fig. 4 [V]	***Fig. 5*** [V]	***diff.*** [%]	***Fig. 4*** [V]	***Fig. 5*** [V]	***diff.*** [%]	***Fig. 4*** [V]	***Fig. 5*** [V]	***diff.*** [%]
Case 2	6.44	5.55	-13.8	8.2	3.8	-53.9	5.7	3.4	-41.3
Case 3	6.51	4.21	-35.3	8.1	3.7	-54.7	6.0	4.1	-32.3
Case 4	38.7	45.3	17.1	8.6	2.2	-74.4	20.1	27.4	36.3
Case 5	6.69	4.41	-34.1	8.1	2.3	-71.3	6.2	3.6	-42.1

III. EFFECT OF LIGHTNING SURGE WAVEFORM ON POTENTIAL RISE

A. Current Sources

In this chapter, the effects of the rise time of the injected current on the potential rise of the earthing mesh and the control cable are evaluated. Three current sources listed in TABLE III are used. IG has the maximum current among the sources. The wave-front and -tail time of PG is the shortest and those of ICG is the longest. Figs. 3 and 6 show the waveforms of the currents.

B. Mesurement Conditions

Fig. 7 shows the arrangement of the current sources. The surge impedances, which is defined by the ratio between the maximum voltage and the maximum current, are measured by a current injection to Point A, B or C. The wire for the current injection is assembled by an insulated wire putting on the ground. To measure the potential of the measuring point, an insulated cable, which is earthed by an electrode at a distance of 130 m apart from the earthing mesh for the substation, is used. This electrode is the reference for the potential measurement. A current return electrode is driven into soil at a side of the substation.

C. Measured Results

Fig. 8 shows the measured surge impedances of the earthing mesh obtained by the field measurements. From Fig. 8, the maximum surge impedance of 24 Ω is observed when the current source PG having the shortest wavefront time is used. However, this impedance is low compared with a measured surge impedance for an earthing wire of the arrester in the other substation [4]. It is considered that this earthing wire connected with the earthing mesh is shorter than that of the substation. In addition, the voltages at the bottom of the arresters for the first circuit is smaller by 24.9 % than that for the second circuit. This difference is assumed due to the arrangement of the surge arresters. The arrester for the second circuit is located at the end of the earthing mesh.

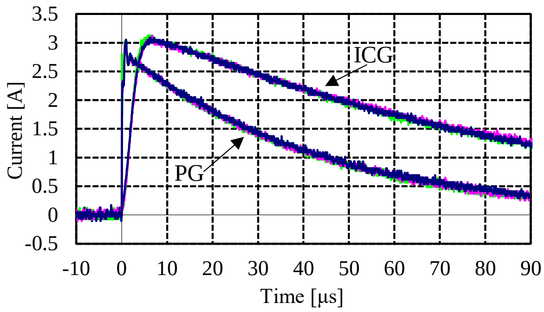


Figure 6. Injected current waveform (PG and ICG).

TABLE III. CURRENT SOURCES

Source	**Maximum Current**	**Wavefront**	**Wavetail**
IG	49.7A	3.6µs	44.3µs
PG	3.04A	0.72µs	27.1µs
ICG	3.11A	6.48µs	70.0µs

Fig. 8 clearly shows the higher impedance is observed with a decrease of the wavefront time. It indicates an overvoltage will appears when a fast current is injected as well as a large current injection. Even if the wavefront time of the lightning current is long, the potential of the earthing mesh is raised by the operation of the arrester because the arrester suddenly discharges the lightning current when the voltage across the arrester exceeds its impulse sparkover voltage.

From Fig. 8, the surge impedance of the earthing mesh when a current is injected by PG is twice of that by IG whose wavefront time is longer by five times than that of PG. The surge impedance obtained by IG is 10 times higher than that by ICG whose wavefront time is longer by 1.8 times than that of IG. The results shows that the impedance of the earthing mesh is inductive and the characteristic is saturated in a high frequency region.

Fig. 9 shows the induced potentials on an open-circuited core of the control cable (CVV) measured at the terminal in the control panel. The current is injected by PG or ICG whose maximum current is about 3 A. Although the voltage on the mesh heavily depends on the wavefront time of the injected current (Fig. 8), the effect of the induced voltage on the control wire is small. The results shows that the maximum induced potential can be estimated as at least 7 kV (=0.7V×30 kA/3 A) if a 30 kA current is discharged from an arrester. The results indicate that the cause of the failure of the traction substation occurred in 2013. Even if the arrester connected with the AC bus protects the apparatus in the substation, there is a possibility of a failure due to the sparkover current flowing into the earthing mesh. The current generates an induced voltage on a control cable, and the voltage may damage an electronic circuit whose lightning withstand voltage is low.

IV. SUMMARY

This paper investigates the transient response of a traction substation to a lightning surge focusing on the induced voltage on a control cable. The voltage is high enough to damage an electronic circuit. The sparkover current of the arrester is one of causes of the induced voltage. Although the arrester is effective for protecting the power apparatuses from the lightning surge, the arrester current has to be taken into account to the design of the control system of a traction substation.

Earthing unused cores in the control cable is effective in reducing the voltage induced on the control cable. The unused core can be earthed at the control panel or at both ends. Since a high voltage is induced on the control cable, the core should not be earthed at an equipment side. In addition, the effect of lightning surge waveform on the induced voltage on the control cable is quantitatively clarified. Although the effect of the current waveform is strong on the voltage rise of the earthing mesh, it is small on the induced voltage on the control cable, in the case of the investigated substation.

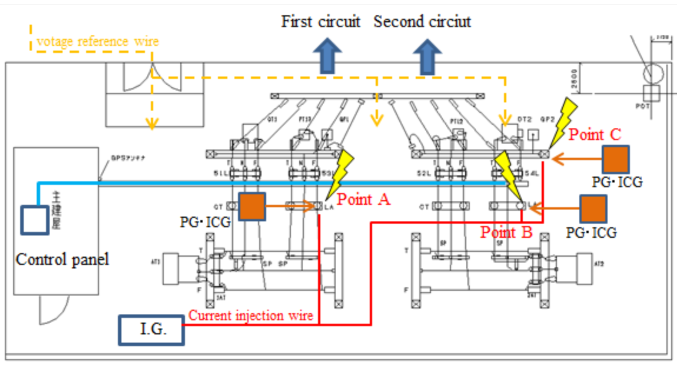


Figure 7. Measurement circuit by comparison of the power supply device.

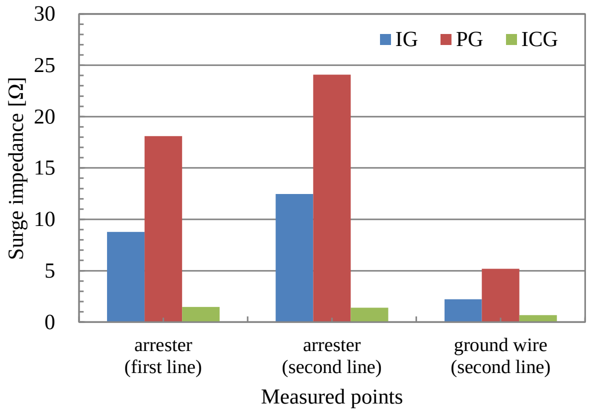


Figure 8. Surge impedance by the difference of the power supply devices.

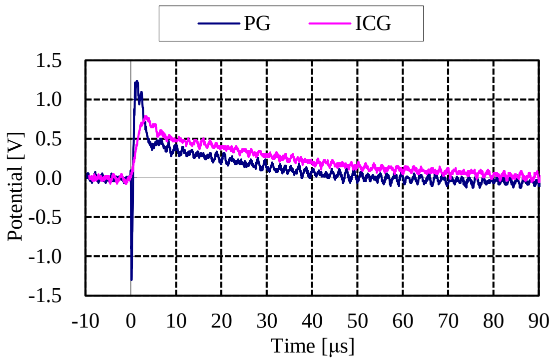


Figure 9. The potential of the earthing wire of 54L..

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