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Experimental Study on New Type Earth Mesh in Railway Substations Aimed at Lightning Protection

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***Abstract*— In Japanese electrical railways, earth meshes are normally utilized as earthing electrodes in the traction substations. The earthing meshes are designed and optimized for low-frequency phenomena, such as earth-fault whose frequency is about between zero (dc) and few kilo hertz (power frequency and its low-order harmonics). Because the earthing impedance of the earthing mesh has positive frequency dependence, it is difficult to design or construct an earthing mesh so as to be also suitable for high-frequency phenomena, such as lightning. This paper proposes a new design of earthing meshes for railway substations aimed at lightning protection and also at fault protection. Experimental validations are carried out through the comparison between the conventional design and the proposed one.**

Keywords-component; railway substation, earthing electrode, earth mesh, earth mat, high-frequency impedance, surge, equipotential bonding, earth bonding wire, connecting wire

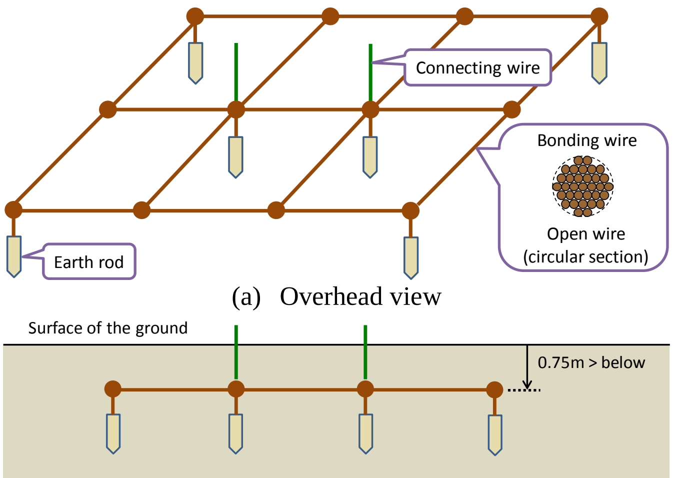
I. Introduction

In Japanese electrical railways (particularly in JR group), earth meshes (earth mats) are normally utilized as earthing electrodes in the traction substations [1]. The earthing meshes are designed and optimized for low-frequency phenomena, such as earth-fault whose frequency is about between zero (dc) and few kilo hertz (power frequency and its low-order harmonics) [2][3][4]. For protection against higher frequency phenomena like lightning strike, lightning arresters and ground wires (GW) are utilized additionally. However, it is difficult to design or construct an earthing mesh so as to be also suitable for high-frequency phenomena, because the earthing impedance of the earthing mesh has large positive frequency dependence [5][6][7]. This paper proposes a new design of earthing meshes for railway substations aimed at lightning protection and also at fault protection.

II. Conventional Earthing Mesh

A. Structure of Earthing Mesh

Figure 1 shows a typical, but simplified earthing mesh for Japanese railway substations. The earth mesh consists of earth rods (earth electrodes) and earth wires (bonding wires and connecting wires), and is buried underground at the position equal or more than 0.75m in depth. The bonding wires are used to equalize the potential of the earth mesh. Electrical equipment such as switch-gears, transformers and control boards are connected to the earth mesh through connecting wires. Lightning arresters and ground wires are also connected to it in the same way.



(a) Overhead view

(b) Cross-section view

Figure 1. Structure of the conventional earth mesh for a railway substation

B. Earth Wires

Open metal wires, for which copper stranded wires are typically used, are utilized for earth wires to equalize the potential (voltage difference from the earth) of the earthing mesh or/and to make electric connection between the mesh and the electric equipment or buildings as shown in Figure 1. The earth wires are basis of protection of human and electric equipment, since the fault currents or the surge currents run through the wires under earth fault conditions or lightning striking conditions. The characteristics, such as kind of material and cross-section area of conductor, mechanical strength of the wires are regulated by the technical standards of the government or railway companies in Japan. Typically, the earth wires have circular sections.

C. *Earth Rods*

Earth rods (earth electrodes) are used to make electric connection between the earth mesh and the ground at the edge or at the node of the earth mesh as shown in Figure 1. Copper rods which are spiked vertically into the ground, or structural steels including rebar of a building are used as the earth rods. Copper rods with a length of 1.5m are typically used in railway substations in Japan.

III. FREQUENCY DEPENDENCE OF EARTHING MESH

A. *Frequency Dependence of Earth Rod*

The earthing impedance of an earth rod with a length of a few meter, such as 1.5m, 3.0m and 4.5m, has negative dependency on the frequency [7]. Figure 2 shows the measurement results of the impedance versus frequency characteristics which were obtained by using frequency response analyzer. As it can be seen in the figure, earth rods function like a set of a resister and a capacitor parallel to each other (RC parallel circuit) below 1MHz. The parameters of circuit components have non-linear properties (not constants) on the frequency.

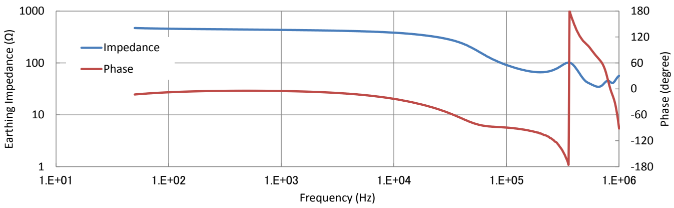


Figure 2. Earthing impedance of a 1.5m long earth rod against the frequency (resistivity of the soil is about 500Ωm)

B. *Frequency Dependence of Earth Wire*

The earthing impedance of an earth wire has positive frequency dependency in contrast to that of the earth rod. Figure 3 shows the measured data of an open earth wire buried underground with no termination (open terminal condition). The experiment was carried out under the same condition as that of Figure 2. As shown in the figure, earth wires function like a series of a register and a inductor (RL series circuit) with a few resonance frequencies. In addition, more precise analysis of the earth wires can be done based on the distributed constant circuit theory.

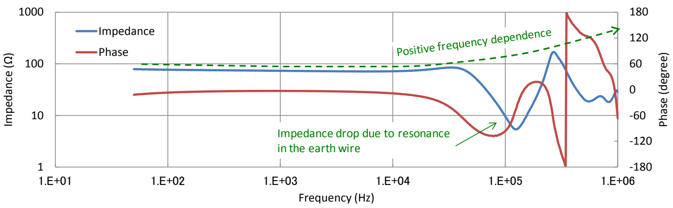


Figure 3. Earthing impedance of an open earth wire (cross-section area is $22mm^2$, buried at the depth of 0.8m) without termination against the frequency

C. *Overall Frequency Dependence*

Overall frequency dependency of an earth mesh can be modeled qualitatively as shown in Figure 4 according to the above-mentioned discussion. The components in series with the positive frequency dependency represent the impedance of the earth wires, and the components in parallel with the negative frequency dependency represent that of the earth rods. The earth mark in the figure expresses the true ground (complete zero potential point). All circuit components except for the earth in the figure have non-linear characteristics to the frequency.

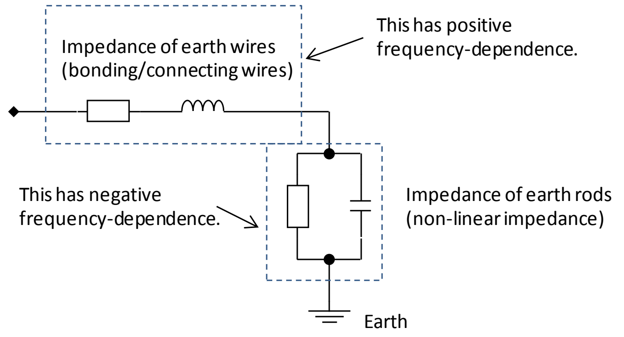


Figure 4. Qualitative schematic diagram of earthing mesh

Figure 5 shows the experimental results of measurement of the earthing impedance of an earth wire terminated with the earth rod. As it can be seen in this figure, the impedance reduces in the range between 1kHz and 100kHz with the help of the earth rod. On the other hand, the impedance increases over 100kHz due to the effect of the earth wire.

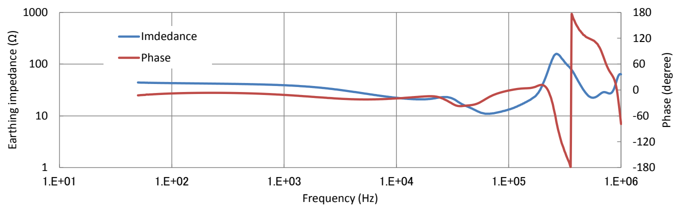


Figure 5. Earthing impedance of an earth wire (cross-section area is $22mm^2$, buried at the depth of 0.8m) terminated with an 1.5m long earth rod against the frequency

IV. REDUCTION TECHNIQUE OF EARTH IMPEDANCE

A. *Redesign of Earth wires*

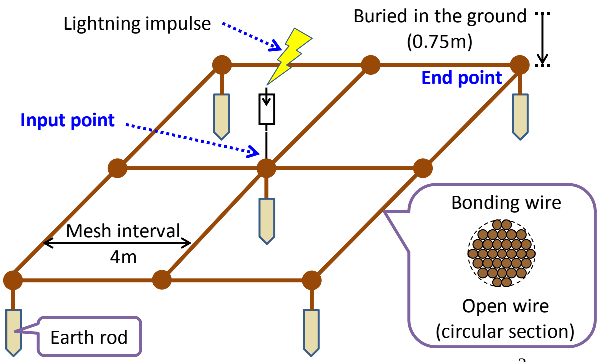
For the protection against high-frequency phenomena, such as lightning strike, it is quite important to reduce the earthing impedance of the earth mesh at high-frequencies such as a few hundred kilo hertz. According to the above-mentioned discussion (see Figure 4), the most effective measure is to reduce the impedance of the earth wire.

An impedance of a wire increases due to the skin effect in the conductor and in the ground in the range of high-frequencies. If the skin effect can be abated, the impedance of a wire can be reduced correspondingly. For this purpose, the author proposed the use of flat stranded wires as the earth wires.

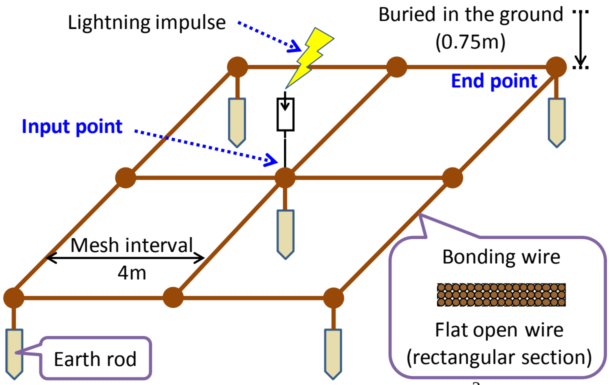
In case of a flat wire, the skin effect is smaller than the case of a conventional wire because of the flat cross-section.

B. *Conditions of Experiment for Validation*

Experimental validation of the redesign of the earth wire was carried out by comparing an earth mesh using the conventional earth wire and that using the flat earth wire. Figure 6 shows the structure and conditions of the experiment. The testing earth mesh is a square of 8m times 8m buried at the position 0.75m in depth from the surface of the ground. The earth wire of one mesh is the open circular wire (the conventional wire) and that of the other is the open flat wire. The conductor of each wire has the same cross-section area of 22mm^2 for the fair comparison.



(a) Using conventional earth wire (22mm^2)



(b) Using flat earth wire (22mm^2)

Figure 6. Structures and conditions of testing earth meshes (earth resistivity was about 50Ωm and section areas of bonding wires are 22mm^2)

Figure 7 shows the measurement circuit for the experiment. There are two circuits: the circuit for current supply and the circuit for voltage measurement, and two additional earth rods for the experiment. An impulse generator is utilized for the current supply.

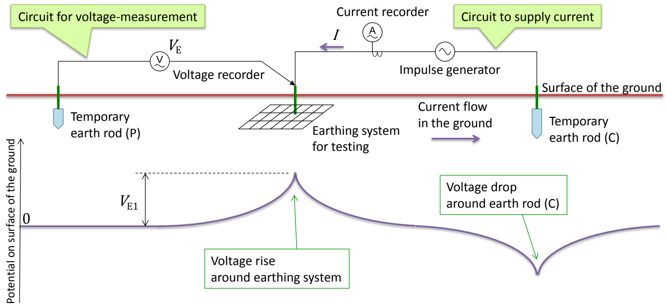
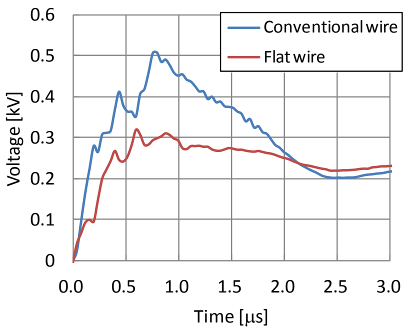


Figure 7. Structure of the measurement circuit

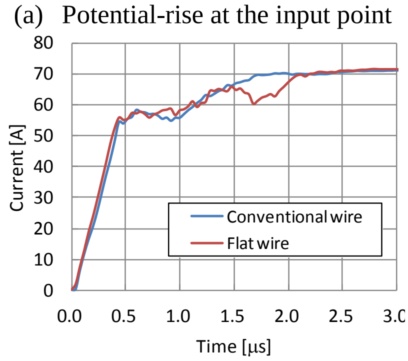
C. *Experimental Result*

Figure 8 shows the experimental results of potential-rise and current at the input point of the testing earth mesh (Figure 6). The crest length of the impulse of the voltage is about 0.5μs to 1.0μs as shown in Figure 8 (a). The current shapes against time of the two testing earth meshes were almost the same as shown in Figure 8 (b), and the peak currents were about 73A for both the meshes.

The peak voltage during the transient period was 507V in the conventional earth wires and 319V in the flat earth wires. That is, surge impedance, which means earthing impedance during the transient period in this paper, was reduced to about 60% by using the flat wires as the earthing wires.



(a) Potential-rise at the input point



(b) Current of the input impulse

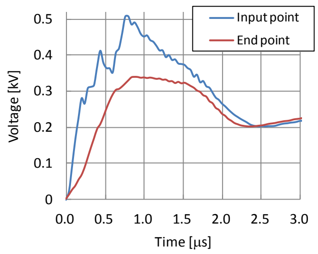
Figure 8. Comparison between the potential-rise and the current wave of the conventional bonding wires and those of the flat ones (experimental result)

V. Equipotential Bonding at High-Frequencies

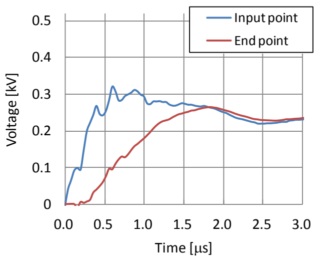
A. Difficulty of Equipotential Bonding

For the protection against lightning strikes, potential equalization of the earth mesh is important in addition to reduction of the earthing impedance, because a large voltage difference in the earthing mesh may damage humans or/and electric equipment by the surge voltage or current generated and running through main cables (high voltage line) or control cables (low voltage line).

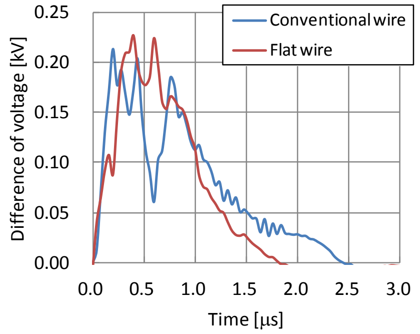
The potential equalization can be evaluated by voltage transfer characteristics obtained by measuring a voltage difference in the earth mesh. Figure 9 shows the characteristics obtained as result of the experiment explained in Figure 6 and 7. As mentioned in the previous section, the potential-rise was reduced by using the flat earth wire as the substitute for the conventional earth wire; however, the voltage transfer characteristics were almost the same. That is, another technique is required to improve the voltage equalization.



(a) Potential in earth mesh using conventional wires



(b) Potential in earth mesh using flat wires



(c) Voltage differences in earth meshes

Figure 9. Comparison between the voltage transfer characteristics of earth meshes of the conventional bonding wires and those of the flat ones (experimental result)

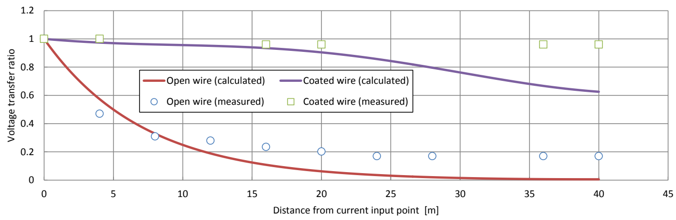
B. Open Wires and Coated Wires

In general, two types of earth wires are used in railway substations: one is the open wire discussed above, and the other is the coated wire (wire covered with an insulation coat). The open wires are used as bonding wires in the ground outside the building, but the coated wires are used as connecting wires outside/inside the building or earth wires inside the building. The authors clarified the difference in electric property between the two types of the earth wires as follows.

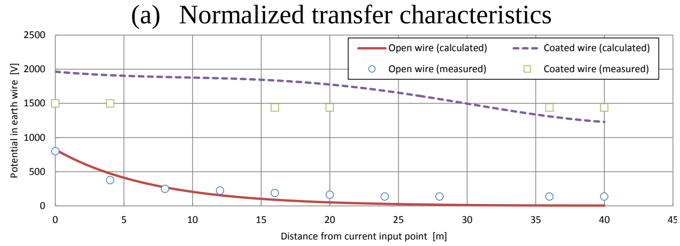
Figure 10 shows the voltage transfer characteristics of an earth wire of 40m length with an earth rod termination which are obtained as both the experimental and theoretical results. Theoretical analysis are carried out based on the distributed constant circuit theory with the frequency dependency of parameters taken into account. Figure 10 (a) shows the normalized property in which the voltage curves are drawn as the relative values to the supply voltage. Figure 10 (b) shows the actual voltage in volts.

From the point of view of potential equalization, the coated wires are better, since the curve of potential-rise versus distance of the coated wire is flat in the range less than 20m in distance, but that of the open wire shows the tendency of rapidly decrease like the exponential function in the same range of distance. The rapid decreasing property of the open wires pushes up the voltage difference in the earth mesh (see also Figure 9).

However, from the point of view of earthing impedance, the open wires are better as obviously shown in Figure 10 (b). As discussed above, the open wires and the coated ones have complementary (trade-off) aspect in their use for an earth mesh.



(a) Normalized transfer characteristics



(b) Real voltage

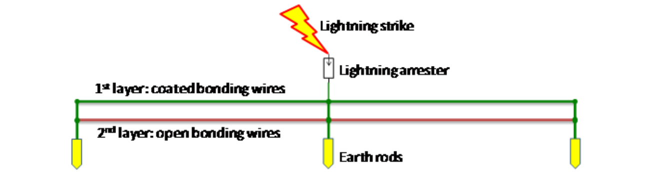
Figure 10. Voltage transfer characteristics on an earth wire with an earth rod termination subject to about 73A peak impulse (earth resistivity was about 50Ωm and the earth wire is a flat one with section area of 22mm^2)

VI. New Type Earthing Mesh

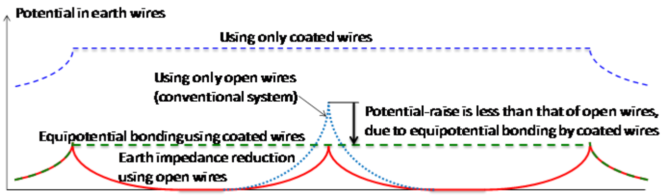
A. Basic Concept

The authors proposed a new type earth mesh for lightning protection as shown in Figure 11 (a) based on the above discussions. The new system has double layered parallel bonding wires: the 1st layer is the coated flat wires and the 2nd layer is the open flat wires. Figure 12 shows an overhead view of the new type earth mesh in contrast to Figure 1.

Since the open wires and the coated ones have properties complementary to each other with respect to equipotential bonding and reduction of impedance, both of them are utilized together to make their advantages work harmoniously with each other. That is, as shown in Figure 11 (b), the coated wires for equipotential bonding equalize the potential of the earth mesh by their strong voltage transfer characteristics, and the open wires which are connected to the soil reduce the earthing impedance by their low surge impedances.



(a) Cross-section structure



(b) Potential-rise

Figure 11. Basic concept of the new type earth mesh

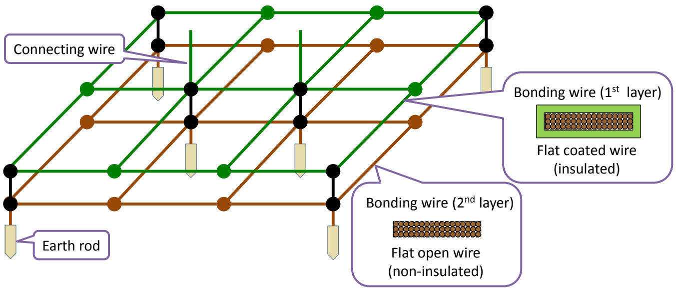


Figure 12. Structure of the proposed earth mesh

Because more than one earth rods can function together by potential equalizing of the coated wires when lightning strikes, the overall earthing impedance of the earth mesh is expected to be smaller than that of a mesh as shown in Figure 6 (b) which has only open wires (see Figure 11 (b)).

B. Validation of Reduction of High-Frequency Earthing Impedance

Validation of a reduction of the earthing impedance in the proposed earth mesh was carried out experimentally. Figure 13 shows the structure and the conditions of the testing earth meshes in the experiment. The place, the date and other conditions are the same as those of the experiment shown in Figure 6. The cross-section areas of the conductors of the earthing wires are also 22mm^2 to ensure the fairness of evaluation. The vertical distance between the 1st layer and the 2nd layer of the bonding wires is 0.25m.

Figure 14 shows the experimental results of the potential-rise and the current at the input point in contrast to those shown in Figure 8. The shape and the peak of the current wave of the proposed earth mesh are almost the same as those of the conventional one, and the peak voltage during transient period reduced from 507V to 252V. Also as it can be seen in Figure (a), the local maximum point of the potential curve during the transient period, which is clearly seen in the conventional earth mesh, seems to vanish in the proposed earth mesh. In other words, the earthing impedance of the proposed earth mesh has no transient (surge) impedance but only static one.

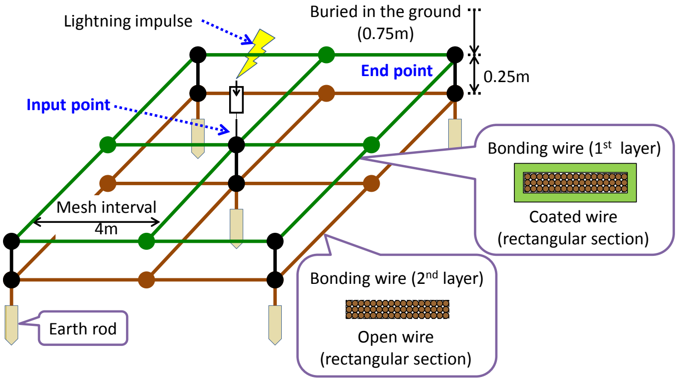
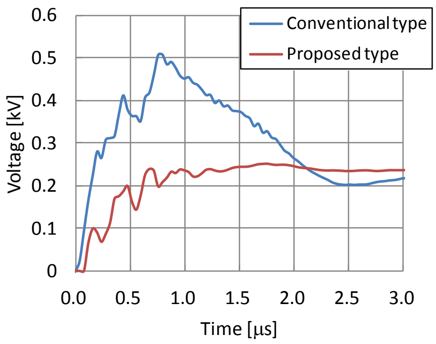
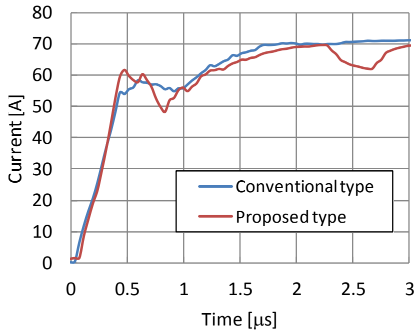


Figure 13. Structures and conditions of testing earth meshes (the earth resistivity was about 50Ωm and the section ereas of bonding wires are 22mm^2)



(a) Potential-rise at the input point

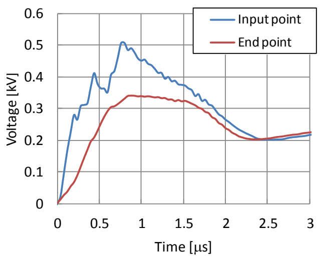


(b) Current of the input impulse

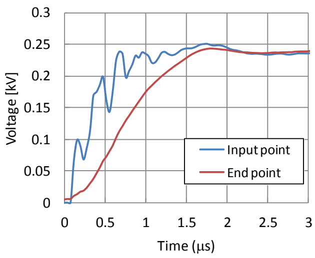
Figure 14. Comparison between the potential-rise and current wave of the conventional earth meshes and those of the proposed ones (experimental result)

C. Validation of Effectiveness of High-Frequency Equipotential Bonding

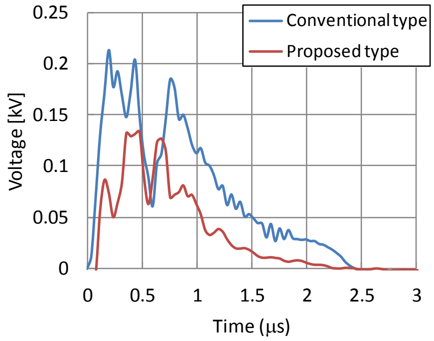
Figure 15 shows the voltage transfer characteristics of the conventional earth mesh and the proposed earth one measured respectively in the experiment. The potential curve at the input point and that at the output point in the case of the proposed earth mesh (see (b)) are more similar to each other than in the case of the conventional earth mesh (see (a)). The peak voltage difference between the input point and the output point of the earth mesh of the proposed type is reduced by 40% (from 213V to 134V) compared with that of the conventional type.



(a) Potential of the conventional earth mesh



(b) Potential of the proposed earth mesh



(c) Peak voltage differences of earth meshes

Figure 15. Comparison of voltage transfer characteristics between the conventional earth meshes and the proposed ones (experimental result)

VII. Conclusion

This paper describes high frequency electric phenomena of the earth mesh in railway substations and the proposed new type earth mesh with validation by an experiment. The conclusion is as follows:

- The earth mesh consists of earth wires, whose frequency dependency of impedance is positive, and earth rods, whose frequency dependency of impedance is negative.
- Two important measures should be considered for the protection against the lightning strike, which contains high-frequency components. One is reduction of the high-frequency impedance of the earth mesh, and the other is equipotential bonding at high-frequencies of it.
- An experimental result clarified that the earthing impedance of an earth mesh at high-frequencies can be reduced by using the flat wires instead of the wires with circular cross-section used commonly for the earth wires.
- Experimental and theoretical study clarified the difference in electric characteristics between the open wires and the coated ones. That is, the open wires have lower earthing impedances and the coated wires have stronger voltage transfer characteristics according to the comparison between them. In other words, they have advantages complementary each other .
- The authors proposed a new type earth mesh for lighting protection. The proposed earth mesh has double layered earth wires: the one is the open bonding wires and the other is the coated ones, complementing their respective strong points.
- An experimental validation for the proposed earth meshes shown as follows. The high-frequency earthing impedance of the proposed earth mesh was reduced by 50% compared with that of the conventional one, and the transient impedance rise in the proposed one seems to vanish. The voltage difference of the earth mesh of the proposed one was reduced by 40% compared with that of the conventional one.

The author is going to revise the technical standards of the West Japan Railway Company in order to introduce the new type earth meshes into their railway substations.

Acknowledgment

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