Development of New Earthing System Inspection Method for the Evaluation of Lightning Protection

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This paper describes new inspection equipment and a new circuit structure used for evaluating the lightning protection performance of earthing systems in railway substations. The new inspection equipment consists of an impulse generator and a measurement unit, and allows the inspector to measure the earth resistance, the high frequency earth impedance and the voltage difference of an earthing system without specialist knowledge. The new measurement circuit for the inspection of the earthing system only makes use of existing infrastructure components, i.e. independent earthing for a remote terminal unit, the earthing system of an adjacent substation and an overhead contact line. Therefore, the proposed circuit requires no temporary test earth electrodes for measurement.

Keywords: earthing system, lightning protection, earth resistance, earth impedance, voltage difference, inspection equipment

1. Introduction

The aim of earthing systems installed in fixed power supply installations, such as substations, is to prevent human damage, and to protect electric and electronic devices inside or near the installation from overvoltage caused by an earth fault or a lightning strike. The Japanese government (the Ministry of Economy, Trade and Industry and the Ministry of Land, Infrastructure, Transport and Tourism) has implemented a maximum limit value for earth resistance and set earthing construction procedures based on technical criteria. Therefore inspection techniques are important to be able to validate a new or replaced earthing system and to maintain the performance of the earthing system. However, there are problems with conventional earthing system inspection methods, which are described below:

(1) The main target frequency of the conventional earthing system inspection (earth resistance measurement) based on technical criteria is DC and power frequencies such as 50 Hz and 60 Hz. Therefore, lightning strikes containing higher frequency components of between 10 kHz to 1 MHz are not covered in the inspection scope.

(2) Earthing system inspections for lightning protection have until now been carried out by inspection companies (not railway operators) [1]. However, the inspections require two types of independent measurement (measurement of earth impedance and voltage difference), specialist skills and special equipment.

(3) Two test electrodes connected to the conventional inspection equipment are required to inspect the earthing system. However, this requirement is difficult to fulfil, particularly in inner-city substations, due to the many buildings and public roads surrounding substations.

Accordingly, new inspection equipment and a new circuit structure were developed for the evaluation of lightning protection performance of earthing systems.

2. Conventional earthing system inspection

The inspection of earthing systems includes measurement of earth resistance (low frequency characteristics) based on the technical criteria, measurement of earth impedance for evaluation of lightning protection (high frequency characteristics), and measurement of voltage difference (high frequency characteristics).

2.1 Measurement of earth resistance

Measurement of earth resistance is a test to confirm that the earthing system meets the earth resistance reference value (such as 10 Ω) specified by the technical criteria. There are typically two types of inspection method to perform the test [2]; they are the fall-of-potential method and measurement with an earth resistance ohmmeter.

The fall-of-potential method shown in Fig. 1 is specified as an inspection method for a large-scale earthing system such as an earth grid, which is used as an earthing system for fixed power supply installations in the Japan Railway (JR) companies. The test circuit consists of two independent circuits: a current injection circuit which supplies a test current (approximately 20 A or more) into the earthing system, and a potential measurement circuit which measures the ground potential rise (GPR) of the earthing system. Two test earth electrodes are required as the terminals of the two test circuits: one is a current probe (C) as the terminal of the current injection circuit, and another is a potential probe (P) as the reference point of the potential measurement circuit. In addition to preparing these probes, three time measurements and post-processing are...
required to remove the effect of electromagnetic induction from surrounding transmission and distribution lines.

An earth resistance ohmmeter is used for measuring earth resistance of a small-scale earthing system composed of several earth electrodes. The circuit configuration of the earth resistance ohmmeter is almost the same as that of the fall-of-potential method. The ohmmeter can evaluate the earth resistance in one operation by supplying a small test current of several milliamperes to several amperes without specialist data processing skills. By using the ohmmeter, measurement and data processing are made simpler than in the fall-of-potential method.

The earth impedance corresponds to the GPR of the earthing system, particularly during a lightning strike, which is measured by simulated lightning (lightning impulse) injection. In general, when a lightning current flows into an earthing system, the earthing system acts as a nonlinear distributed constant circuit [1, 2]. Therefore, earthing impedance has a characteristic which varies with time and converges with the earth resistance in several tens of microseconds as shown in Fig. 2.

The impulse impedance, which is the peak earth impedance value, is an important value in lightning resistance evaluation. In a large-scale earthing system such as in a substation, the impulse impedance usually has a higher value than low-frequency earth resistance as shown in Fig. 2.

The test circuit for the earth impedance measurement is almost the same as the fall-of-potential method except for the inspection equipment. The earth impedance is obtained by dividing the instantaneous value of GPR by the instantaneous value of the current. In the measurement, simulated lightning is injected by an impulse voltage generator (PG) owned by an inspection company. The front time of the current of PG, which is the most effective parameter to the transient characteristics of the earth impedance, is set to a very short time of about 0.05 μs. The value is sufficiently shorter than the front time of 0.22 μs, which covers 95% of the subsequent negative short-time lightning strike. The value also represents the most severe past lightning conditions based on current statistics, shown in Table 1. However, it is difficult to manufacture an impulse generator which has both a short front time and a large current. Therefore, the current peak of PG is about 1 A, which is not suitable for the measurement of voltage differences described later.

2.3 Measurement of voltage difference

If a large voltage difference occurs in the earthing system caused by a lightning strike, surge voltage or current propagates through power or low-voltage lines. The surge increases the risk of equipment damage. In particular, equipotential-bonding has been the basis of recent lightning protection technology [3], and it can be evaluated by measuring the voltage difference between two points in the earthing system. Similar to the relationship between the earth impedance and the earth resistance, the voltage difference at a high frequency such when there is a lightning strike has a higher value than the voltage difference at low frequency.

The voltage difference is evaluated by the difference between the potential measurement data at two or more points on the earthing system. However, in order to accurately perform this measurement, the testing current should be propagated through the entire earthing system. Therefore, an impulse current generator (IG) owned by an inspection company, which is capable of outputting current with a peak value of several tens of amperes or more, is used as a power supply. Since the IG is installed and operated from a medium-sized car, the IG has a less portability than that of the earth resistance ohmmeter and the PG. Since the peak value and the front time of the output current from an impulse generator are traded off, the front time of the output current of an IG is several microseconds, which is about one digit longer than that of a PG. Compared to the past lightning current statistics, an evaluation covering approximately 50% of the first negative short-time lightning strike is possible using an IG (see Table 1).

3. Development of inspection equipment

3.1 Basic concept

In order to overcome the issues faced with the conventional inspection equipment for earthing systems, new inspection equipment was developed based on the following premises:

### Table 1 Lightning current statistics [3]

| Parameter | Cumulative frequency (%) | Type of stroke |
|-----------|--------------------------|----------------|
| Peak      | 98% 40% 20% 10% 5%       | First negative short |
| Front time| 4.9 kA 20 kA 40 kA 60 kA | First positive short |
| Stroke duration | 1.8 μs 5.5 μs 18 μs | First negative short |
| AC        | 22 μs 1.1 μs 4.5 μs   | Subsequent negative short |
| DC        | 3.5 μs 22 μs 200 μs  | First positive short |
| Supply    | 30 μs 75 μs 200 μs  | First negative short |
| Other     | 6.5 μs 32 μs 140 μs  | Subsequent negative short |

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(1) Earth resistance, earth impedance, and voltage difference can all be measured with one piece of inspection equipment.
(2) Evaluation using a current with a front time of 0.2 \( \mu s \) is possible, to cover approximately 95\% of all lightning strikes.
(3) A current with a stable waveform (low oscillation, and reproducible rise form and front time) can be supplied regardless of the surge impedance of the current injection circuit.
(4) The calculation process from the measurement data to the evaluation values is automated, to allow inspections to be carried out even without specialist skills.
(5) The inspection equipment can be carried on a maintenance car commonly used by the railway operators.

3.2 Specifications

The developed inspection equipment consists of a power supply unit and a measurement unit. By applying the test circuit configuration shown in Fig. 3, earth resistance, earth impedance, and voltage difference can be encompassed in one measurement. Figure 4 is an image of the developed inspection equipment.

Figure 5 shows the schematic diagram and specification of the inspection equipment. By insulating the frame ground (Ef) of the power supply unit from the negative output terminal (C) and positive output terminal (E-c) with a withstand voltage of 40 kV, no additional protective measures are required to protect against electric shocks.

![Fig. 4 Developed inspection equipment](image)

The following two measures were introduced into the measurement unit to reduce noise and protect the unit: first, equipotential-bonding was performed between the frame ground (Ef) and internal components. Second, the input terminal (P) connected to the potential probe (P) was insulated from the frame ground with a withstand voltage of 40 kV.

3.3 Features

3.3.1 Power supply unit

A lightning impulse generator was used as the simulated lightning current generator in the power supply unit. A new circuit configuration was designed to exploit the advantages of both the PG and the IG, despite the trade-off between the front time and peak value of current.

The output resistance is adjustable between 1 k\() and 4 \text{k} \(). Since the output resistance is sufficiently larger than the surge impedance of the earthing system (several tens to several hundreds of ohms), the power supply unit acts as a current source to avoid the output current problems encountered with conventional power supplies, such as waveform oscillation and instability. Since natural lightning can be considered to be a current source [3], this power supply behavior is reasonable from a physical phenomenon point of view. The peak value of the output current is approximately 10 A to 40 A, which is approximately the same as that of the conventional IG, and is both necessary and sufficient for measuring both the earth impedance and the voltage difference.

The front time of the output current is adjustable from 0.2 \( \mu s \) to 5.0 \( \mu s \). The lower limit of the front time of 0.2 \( \mu s \) is larger than the PG (0.05 \( \mu s \)). The reason for this is that it was deemed that a front time of 0.05 \( \mu s \) for the simulated...
waveform of the natural lightning current was too severe (See Table 1). The tail time of the output current was designed to be over 100 μs, to measure the earth resistance at a steady state.

3.3.2 Measurement unit

The measurement unit consists of an oscilloscope, a control laptop computer (control PC), and other attached devices. In order to reduce noise propagating from the low-voltage power supply line, the low-voltage power supply is disconnected from the power supply unit before the current injection work. The uninterruptible power supply (UPS) supplies the operation power to all the components of the measurement unit during the current injection. The measurement unit has two potential measurement terminals for measuring the earth impedance and the voltage difference and one potential terminal for measuring the voltage difference between the potential probe (P) and the frame ground of the measurement unit (EG). The measurement unit also has a high-frequency current sensor (through-type) to measure the injected current.

In addition, a newly developed algorithm to calculate the evaluation value was implemented in the measurement unit as an automatic evaluation function. The algorithm is as follows:

(1) Since the measurement data, which is a waveform in the time domain, generally contains noise, the measured data is processed through a digital second-order low-pass filter.

(2) The time region to be analyzed, where the current value is large enough to negate the noise, is calculated by the waveform particularly around the front of the impulse current.

(3) The offsets of the measurement unit to be subtracted from the evaluation results are calculated by the measured data.

(4) The earth impedance \( z_E(t) \) is calculated dividing the GPR at the injection point \( v_1(t) \) by the injection current \( i(t) \) (time). The impulse impedance is calculated as the peak value of \( z_E(t) \). The earth resistance is calculated as the convergence value of \( z_E(t) \).

(5) The voltage difference \( v_2(t) \) is calculated from the difference between \( v_1(t) \) and the GPR at the terminal point \( v_2(t) \).

3.4 Verification of measurement accuracy

The measurement accuracy of the developed inspection equipment was verified in field tests. The verification was performed at three substations (A, B and C as shown in Table 2) on a DC electrified line (single track), which had suffered severe winter lightning damage. As shown in the table, the surrounding soil properties of each substation were dry, general and wetland respectively. In order to improve lightning protection by reducing earth impedance, conductive concrete was used to fill the ground under each substation around the down conductor of the surge arrester for receiving line. The verification was carried out by comparing measurements taken using the developed inspection equipment with the results of an inspection carried out on completion of work, by a railway constructor or an inspection company.

The test circuit was configured as shown in Fig. 1. The testing impulse current was injected through the down conductor of phase S of the surge arrester for the receiving line. The distance between the testing earthing system and the potential probe P was about 50 m to 100 m, and that between the earthing system and the current probe C was about 10 m to 50 m, respectively. The terminal point for the voltage difference measurement was the point near the rectifier approximately 10 m away from the injection point.

3.4.1 Current waveform

The stability (reproducibility and oscillation) verification of the waveform of the output impulse current of the inspection equipment was carried out by comparing the current waveforms injected at the testing substations (A, B and C). Figure 6 shows the waveforms of the output current under the strictest condition where the front time (expected) is set to 0.2 μs. When the output resistance was 1 kΩ, the waveforms from 0 μs (the beginning of discharge) to about 3 μs were different for each substation, and the actual front times were from approximately 0.2 μs to 1.0 μs.

| Substation | Line | Main power converter(s) | Earth resistivity |
|------------|------|-------------------------|------------------|
| A          | Single track with DC electric traction | A rectifier (3600 kW) and a distribution transformer (500 kV, A) | 820 Ω・m (dry soil) |
| B          | Single track with DC electric traction | A rectifier (4000 kW) | 805 Ω・m (general) |
| C          | Single track with DC electric traction | A rectifier (4000 kW) | 8.2 Ω・m (wetland soil) |

Table 2 Substations for testing

Fig. 6 Output current waveform of inspection equipment (expected front time: 0.2μs)
When the output resistance was 2 kΩ, the front time stabilized around the expected value of 0.2 μs, and the instability of waveforms was lower in comparison to the previous condition although there were some vibration components. By increasing the output resistance to 4 kΩ, the stability of the waveforms was improved compared to that of 2 kΩ.

### 3.4.2 Earth resistance

The accuracy of the earth resistance evaluated with the inspection equipment (the evaluation values) was verified by comparing the obtained values with the results of inspections carried out when constructions of the substations were originally completed using the fall-of-potential method (the reference values), as shown in Table 3.

The evaluation and reference values agreed well regardless of the output resistance value at substation A, where the earth resistance was the highest among the three substations. On the other hand, the error between the two values seemed to be larger in substations B and C, where the earth resistances were lower than substation A, because of the limit of the resolution of the oscilloscope (8 bits) in the inspection equipment. In substations B and C, because the order of impulse impedance and earth resistance differed in seconds in the order of magnitude, the vertical resolution insufficient for the earth resistance.

However, the accuracy described above for earth resistance is enough for a confirmation, such as in the case of a maintenance inspection, to the limit set by technical criteria (such as 10 Ω). Accordingly, it was confirmed that the inspection equipment was sufficiently applicable for measuring the earth resistance in substation maintenance inspections.

| Output resistance | Developed inspection equipment | Completion inspection (reference) |
|-------------------|-------------------------------|-----------------------------------|
| 1 kΩ              | 4.2 Ω                         | 4.1 Ω                             |
| 2 kΩ              | 4.4 Ω                         | 4.1 Ω                             |
| 3 kΩ              | 3.9 Ω                         | 3.7 Ω                             |
| 4 kΩ              | 3.6 Ω                         | 3.3 Ω                             |

### 3.4.3 Impulse impedance

The accuracy of impulse impedance evaluations using the inspection equipment, which is the peak value of earth impedance, was verified through comparison with the measurement results using PG by an inspection company (the reference values) as shown in Table 4.

As a result, when the output resistance was about 1 kΩ to 2 kΩ, the evaluation and reference values agreed well with a maximum error of approximately 20%.

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 43.7 Ω                        | 50.1 Ω                         |
| 2 kΩ              | 40.0 Ω                        | 39.6 Ω                         |
| 3 kΩ              | 39.2 Ω                        | 39.7 Ω                         |
| 4 kΩ              | 40.4 Ω                        | 40.9 Ω                         |

### 3.4.4 Voltage difference

Table 5 compares voltage differences measured using the inspection equipment and by the inspection company using IG. The current front time of the inspection device was set to 2.0 μs, the same value as IG. The relative values obtained by dividing the peak value of the voltage difference by the peak value of the injection current were used for the comparison, since the peak values of current were not the same. The evaluation and reference values agreed with a maximum error of approximately 20% to 50% in substation B and C.

Examining the relationship between the output resistances and the evaluation values, the evaluation values tended to increase as the output resistance increased in substations A and B, while this tendency was not found in substation C. The reason for the difference is considered to be that the power supply unit with an output resistance of 3 kΩ or more (peak current is less than 10 A) cannot inject the impulse current into the whole earthing systems of substation A and B, which have larger earth resistivities and lower slopes of GPR than substation C.

In addition, the inspection equipment can supply an impulse current with a front time of 0.2 μs at minimum, which is one tenth of that of the IG. While the IG can cover approximately 50% of all lightning strikes, the developed inspection equipment is expected to cover approximately 95%. In other words, the inspection equipment is expected to perform tests in more sever conditions than with the IG. Table 6 shows the evaluated voltage differences obtained using a current with the minimum front time (0.2 μs). The evaluation values shown in Table 6 were 2 to 3 times of those of Table 5 with a front time of 2.0 μs. Accordingly, it was confirmed that the inspection equipment can be used to make evaluations under more severe conditions than with the IG.

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 11.5 V/A                      | 13.9 V/A                       |
| 2 kΩ              | 12.8 V/A                      | 13.8 V/A                       |
| 3 kΩ              | 8.8 V/A                       | 11.3 V/A                       |
| 4 kΩ              | 34.7 V/A                      | 40.2 V/A                       |

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 34.7 V/A                      | 40.2 V/A                       |
| 2 kΩ              | 32.1 V/A                      | 35.9 V/A                       |
| 3 kΩ              | 18.6 V/A                      | 20.9 V/A                       |

### 4. Proposal of new measurement circuit

#### 4.1 Circuit structure

A new measurement circuit structure for earthing system inspections was proposed without temporary test electrodes and temporary measurement lines. Figure 7 shows the proposed circuit structure, whose equivalent circuit is

Table 3 Earth resistances evaluation results

| Output resistance | Developed inspection equipment | Completion inspection (reference) |
|-------------------|-------------------------------|-----------------------------------|
| 1 kΩ              | 43.7 Ω                        | 50.1 Ω                           |
| 2 kΩ              | 40.0 Ω                        | 39.6 Ω                           |
| 3 kΩ              | 39.2 Ω                        | 39.7 Ω                           |
| 4 kΩ              | 40.4 Ω                        | 40.9 Ω                           |

Table 4 Earth impedances evaluation results

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 43.7 Ω                        | 50.1 Ω                           |
| 2 kΩ              | 40.0 Ω                        | 39.6 Ω                           |
| 3 kΩ              | 39.2 Ω                        | 39.7 Ω                           |
| 4 kΩ              | 40.4 Ω                        | 40.9 Ω                           |

Table 5 Voltage differences evaluation results with current front time of 2.0 μs

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 11.5 V/A                      | 13.9 V/A                       |
| 2 kΩ              | 12.8 V/A                      | 13.8 V/A                       |
| 3 kΩ              | 8.8 V/A                       | 11.3 V/A                       |
| 4 kΩ              | 34.7 V/A                      | 40.2 V/A                       |

Table 6 Voltage differences evaluation results with current front time of 0.2 μs

| Output resistance | Developed inspection equipment | Inspection company (reference) |
|-------------------|-------------------------------|--------------------------------|
| 1 kΩ              | 34.7 V/A                      | 40.2 V/A                       |
| 2 kΩ              | 32.1 V/A                      | 35.9 V/A                       |
| 3 kΩ              | 18.6 V/A                      | 20.9 V/A                       |

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the same as the conventional circuit shown in Fig. 1. The differences with the conventional circuit are as follows: the earth pole for remote terminal unit (RTU) of the tested substation is used as the potential probe (P), the earthing system of the next substation is used as the current probe (C), and the overhead contact line system is used as an earth return path in the current injection circuit. Therefore, no temporary devices are required for the proposed circuit.

Yamashita H. et al. previously reported on experimental examination results using a similar circuit structure for an earthing system in a Shinkansen traction substation [4]. In this previous study two adjacent fixed power supply installations were used as the test electrodes (P and C). However, they reported that it was difficult to use the earthing system of the adjacent installation as the potential probe (P), due to large interference (mutual resistance) in the potential measurement circuit [4].

The improvement in this proposal in relation to the previous study is that the earth pole for RTU is used as the potential probe (P), and the target frequency range is extended from power frequencies to 1 MHz of lightning current using the same circuit structure.

4.2 Verification of measurement accuracy

The measurement accuracy of the proposed measurement circuit was verified in field tests in the above-mentioned substations A, B, and C. The verification was carried out by comparing the evaluation results of the proposed circuit with those of the conventional circuit shown in Fig. 1. The earth resistance, impulse impedance and voltage difference were measured using the developed test equipment in each circuit structure. The front time of the injection current was set to 0.2 μs.

4.2.1 Earth resistance

Table 7 compares the evaluated earth resistance values obtained with the conventional and proposed (new) circuit structures. As shown in Table 7, the values obtained with the inspection equipment using the conventional and proposed circuits agreed approximately. This demonstrates that the interference between the potential measurement circuit and the earth pole for RTU, which was a concern in the previous study [4], was sufficiently small in the low frequency range. Accordingly, the proposed circuit structure could be applied for measuring earth resistance.

4.2.2 Impulse impedance

Table 8 compares the evaluated impulse impedance values obtained with the conventional and proposed circuits, where the current front time was set to 0.2 μs. The evaluation values using the conventional and proposed circuits were almost the same. This demonstrates that the interference reported in the previous study [4] is sufficiently small even in the high frequency range concomitant with a lightning strike. Therefore, the proposed circuit structure can also be applied to the measurement of earth impedance.

Since the proposed circuit structure uses an overhead contact line system, which is much longer than the conventional measurement circuit, as the earth return path, the attenuation of the traveling wave is expected to be higher than that of the conventional circuit. There were some cases using the conventional circuit structure where the peak value of reflected wave of the earth impedance was higher than that of the first traveling wave (the impulse impedance to be evaluated). The inspection equipment incorrectly evaluated the values of the impulse impedances in these cases as shown as the blue curve in Fig. 8(a). However, by using the proposed circuit structure, this problem was abated, as shown with the red curve in the figure, due to a reduction in the reflected wave.

4.2.3 Voltage difference

Table 9 shows the comparative results of the peak value of voltage difference using the conventional and proposed circuits, where the current front time was set to 0.2 μs. As with the earth impedance, the evaluation values of the conventional and proposed circuits were almost the same under all conditions. Therefore, it was confirmed that the proposed circuit structure is applicable to the measurement of voltage difference. Figure 8(b) shows an example of the waveform of the potential difference measured in substation A.

Table 7  Earth resistance evaluation results

| Output resistance | 1 kΩ | 2 kΩ | 3 kΩ | 4 kΩ |
|-------------------|-----|-----|-----|-----|
| Circuit           | Conv. | New | Conv. | New | Conv. | New | Conv. | New |
| Substation A      | 43.7 Ω | 41.4 Ω | 50.1 Ω | 44.8 Ω | 60.5 Ω | 48.1 Ω | 53.3 Ω | 51.7 Ω |
| Substation B      | 40.4 Ω | 36.5 Ω | 40.9 Ω | 36.9 Ω | 39.0 Ω | 38.3 Ω | 39.7 Ω | 40.1 Ω |
| Substation C      | 37.2 Ω | 33.2 Ω | 41.0 Ω | 35.5 Ω | 40.6 Ω | 35.2 Ω | 55.5 Ω | 57.8 Ω |

※ Current front time of inspection equipment was set to 0.2s.

Table 8  Earth impedance evaluation results

| Output resistance | 1 kΩ | 2 kΩ | 3 kΩ | 4 kΩ |
|-------------------|-----|-----|-----|-----|
| Circuit           | Conv. | New | Conv. | New | Conv. | New | Conv. | New |
| Substation A      | 34.7 V/A | 34.5 V/A | 40.2 V/A | 32.1 V/A | 30.3 V/A | 29.3 V/A | 34.5 V/A | 30.9 V/A |
| Substation B      | 32.5 V/A | 30.1 V/A | 38.0 V/A | 35.1 V/A | 35.9 V/A | 32.2 V/A | 34.5 V/A | 32.7 V/A |
| Substation C      | 18.8 V/A | 16.0 V/A | 20.9 V/A | 19.2 V/A | 33.3 V/A | 19.9 V/A | 33.3 V/A | 17.3 V/A |

※ Current front time of inspection equipment was set to 0.2s.
5. Conclusions

New inspection equipment and a new circuit structure for earthing systems for fixed power supply installations were developed. The developed inspection equipment can evaluate conformity of earth resistance of an earthing system with given technical criteria and lightning resistance of the earthing system. Results of tests to verify the method in field tests confirmed that the inspection equipment can be used to measure and evaluate both the low-frequency parameter (earth resistance) and high-frequency parameters (earth impedance and voltage difference) with sufficient accuracy.

The proposed test circuit structure employs the earthing system of adjacent substations and earth poles for RTUs instead of test electrodes, and does not require any temporary devices to be used. Field test results confirmed that the earth resistance, earth impedance and voltage difference could be measured and evaluated with sufficient accuracy.

The results of this paper can be applied for maintenance inspections of earthing systems, verifying the effectiveness of lightning protection countermeasures, and prioritizing protection countermeasures.

Acknowledgements

The authors would like to express their sincere thanks to Mr. Y. Koga of the Otowa Electric Co. for his cooperation.

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