Overvoltages in a transformer caused by lightning surge from a small wind turbine generation system

Kazuo Yamamoto

Abstract: Small wind turbine generation systems are connected to distribution systems via pole-mounted transformers as well as solar energy generation systems, lightning surge propagated from small wind turbine generation systems causes damage to pole-mounted transformers. This paper presents the result of a study of lightning overvoltages in a pole-mounted transformer connected to small wind turbine generation systems using experimental results when a lightning strokes to the small wind turbine generation systems.

1. Introduction

Wind turbine generation systems are often struck by lightning, because they are often built at a location which is at risk for lightning strokes so as to obtain good wind condition. Effective lightning protection methods for wind turbine generation systems are needed [1]. Small wind turbine generation systems are connected to distribution systems via pole-mounted transformers as well as solar energy generation systems, lightning surge propagated from small wind turbine generation systems causes damage to pole-mounted transformers. It is difficult to say that lightning protection of the pole-mounted transformer is enough. There is concern that damages caused by such lightning surges increase in number [2].

This paper presents the results of a study of lightning overvoltages in a pole-mounted transformer connected to small wind turbine generation systems using experimental results when a lightning strokes to the small wind turbine generation systems. It has been investigated how the following points have an effect on the overvoltages in the pole-mounted transformer: (i) Connections between low voltage terminals of a pole-mounted transformer and small wind turbine generation systems. (ii) Routes of incoming lightning surge from the low voltage terminals of the transformer. (iii) Value of the load connected to the high voltage terminals of the transformer. (iv) Grounding resistance of the transformer.

2. Pole-Mounted Transformer

The case of the pole-mounted transformer used in this paper is cylinder type and is made from metal. A single phase transformer is contained in it. The inside of it is filled by insulation oil. The capacity is 10 kVA, the primary voltage is 6600 V and secondary voltage is 210 or 105 V. The interconnections of windings are shown in Fig. 1.

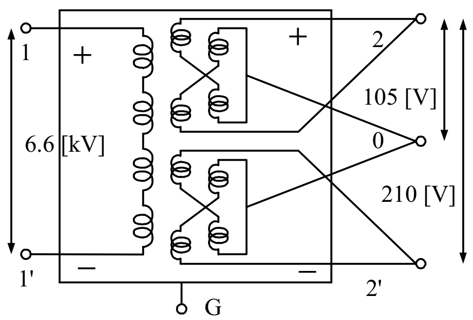


Fig. 1 Structure of the pole-mounted transformer

3. Experimental Conditions

3.1 Pulse generator

The self-produced pulse generator (P.G.) is used for the following experiment. A commercial P.G. usually has complicated internal circuitries for multipurpose. To simulate the experimental results for researches in other situations, the detail circuitries of P.G. should be known. The wave front and tail of the output of P.G. is

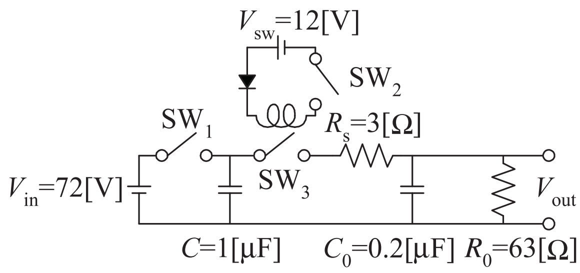


Fig. 2 Electrical circuit of P.G.

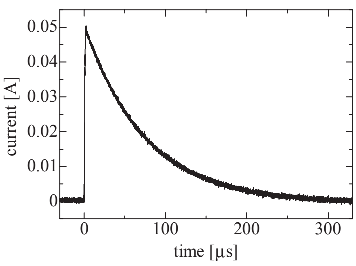


Fig. 3 Output current

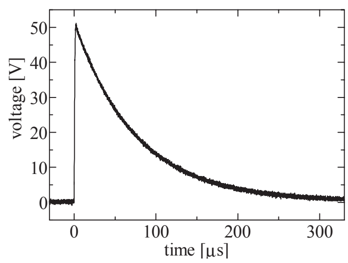


Fig. 4 Out put voltage

1.2 μs and 50 μs respectively. When responses to other input waveforms are required, EMTP simulations are executed using the pole-mounted transformer model after confirmation of accuracy about lightning surge incoming from the low voltage side of the pole-mounted transformer.

The electrical circuit of P.G. is shown in Fig. 2. Electrostatic energy in a capacitor is discharged as a lightning waveform. Mercury relay of SW$_3$ realizes a high speed switching. The resistance of 1 kΩ connected to the output terminal is inserted to regard P.G. as an equivalent current source. The output current and voltage waveforms on condition that 1 kΩ resistance is connected to the output terminals are shown in Fig. 3 and 4 respectively.

3.2 Measuring equipments and points of measurements

The pole-mounted transformer is set up on an aluminous board, the metal case and the earth terminal of the transformer are connected to the aluminum board via a resistance representing a ground resistance. The points of measurements are shown in Fig. 5. The current probe used in these measurements is Pearson Current Monitor 2877 whose useable rise time is 2 ns. The voltage probe is Tektronix P6139A whose useable frequency is 500 MHz. The oscilloscope is Tektronix TDS3054 whose useable frequency is 500 MHz. Those measuring instruments have enough facilities for a few microsecond rise time of the input signal.

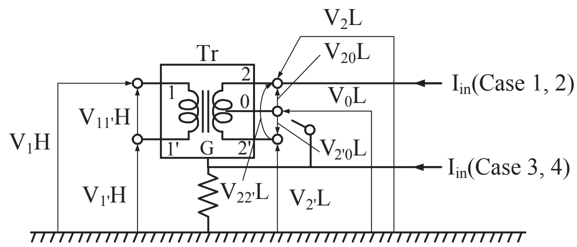


Fig. 5 Points of measurements

3.3 Connections between a pole-mounted transformer and small wind turbine generation systems

There are two types of connections between small wind turbine generation systems and a pole-mounted transformer as shown in Fig. 6 and 7. Three of the low voltage terminals of the pole mounted transformer are connected to power conditioners in small wind turbine generation systems in Fig. 6, the neutral point is grounded. Two of the low voltage terminals except neutral point are connected to power conditioners in Fig. 7.

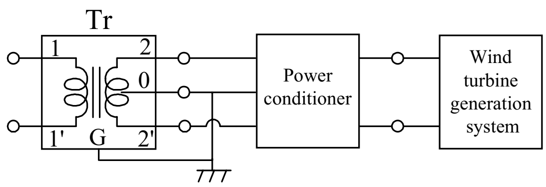


Fig. 6 Three terminals connections

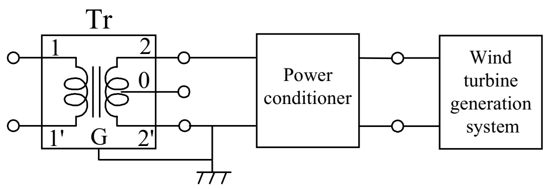


Fig. 7 Two terminals connections

3.4 Routes of incoming lightning surge

When lightning strokes small wind turbine generation systems or its neighborhood, the routes of incoming lightning surge fall into two types. One of routes is the grounding wire in low voltage terminals of the pole-mounted transformer, and another route becomes one of power lines when dielectric breakdowns occur in the small wind turbine generation system.

3.5 Value of the load as a resistance

Load conditions in a high voltage side of pole-mounted transformer are depend on the place where the transformer is set up and others. It is not easy to describe such detail conditions as a load model in indoor experiments. Therefore, in the following three cases, the measurements are carried out. (A) The high voltage terminals of the pole-mounted transformer are opened, this case represents no load in the high voltage terminals. (B) A resistance exists as an equivalent load depends on the power factor, the detail of the relations between the value of the equivalent resistance road and the power factor is explained in the following paragraph. (C) There are few loads around the small wind turbine generation system and it can be assumed that long distance distribution lines are connected to the high voltage terminals of the pole-mounted transformer.

The relations between the value of the equivalent resistance road and the power factor can be represented as follows, where the electric power of the transformer is P_a (= 10 kW), the power factor is $\cos\theta$, the rated voltage at the high voltage terminals is V_e (= 6600 V), and the current at the high voltage terminals is I_e. In this paper, the value of power factor is changed from 0.94 to 0.11 correspond to the value of the equivalent resistance road from 510Ω to 4080Ω

$$P_a = V_e I_e \cos\theta \tag{1}$$

$$I_e = \frac{P_a}{V_e \cos\theta} \tag{2}$$

$$R = \frac{V_e}{I_e} = \frac{V_e}{P_a / V_e \cos\theta} = \frac{V_e^2 \cos\theta}{P_a} \tag{3}$$

The height h and the radius r of the distribution line in case (C) are 12.5 m and 5.0 mm respectively. Those values are standard in Japan. The inductance L_x and the capacitance C_x of such distribution line are represented as following equations (4) and (5), and the surge impedance Z_0 can be calculated as (6) from (4) and (5). Therefore the 511Ω resistance is connected between the high voltage terminals and ground as shown in Fig. 8 – 11 [3].

$$L_x = \frac{\mu_0}{2\pi} \ln\left(\frac{2h}{a}\right) = 1.7[\mu\text{H/m}] \tag{4}$$

$$C_x = 2\pi\varepsilon_0 \Big/ \ln\left(\frac{2h}{a}\right) = 6.5[\text{pF/m}] \tag{5}$$

$$Z_0 = \sqrt{L_x / C_x} = \sqrt{\frac{\mu_0 / 2\pi}{2\pi\varepsilon_0}} \ln\frac{2h}{a} = 60 \ln\frac{2h}{a} = 511[\Omega] \tag{6}$$

$(\mu_0 = 4\pi \times 10^{-7},\ \varepsilon_0 = 8.854 \times 10^{-12})$

3.6 Grounding resistance

The value of grounding resistance is usually 150Ω and below. In Japan, the decision of the value depends on the value of earth capacitance of distribution lines around the pole-mounted transformer and others. In this paper, 0 - 150Ω resistance has been used for measurements.

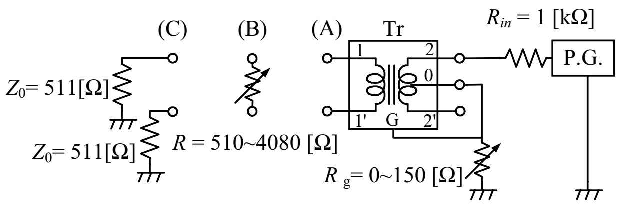


Fig. 8 Test circuit of Case 1

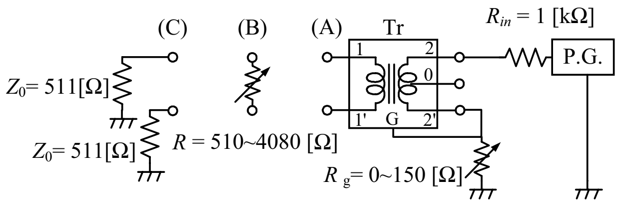


Fig. 9 Test circuit of Case 2

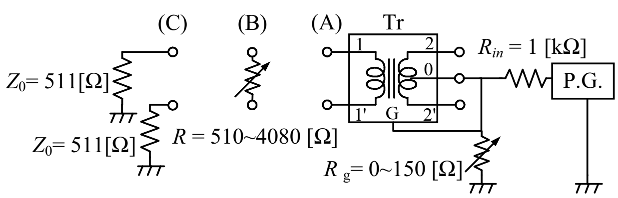


Fig. 10 Test circuit of Case 3

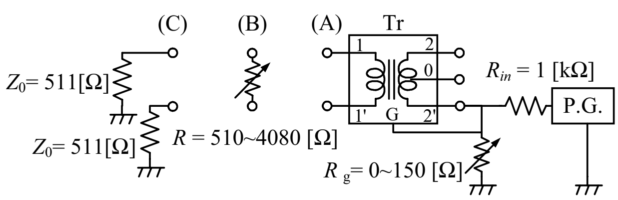


Fig. 11 Test circuit of Case 4

Table 1 Experimental cases

	Three of low voltage terminals in the pole-mounted transformer is used	Two of low voltage terminals in the pole-mounted transformer is used
Surge injected from one of power lines	Case 1-(A) No road Case 1-(B) Resistance road in association with power factor Case 1-(C) Distribution line model	Case 2-(A) No road Case 2-(B) Resistance road in association with power factor Case 2-(C) Distribution line model
Surge injected from the grounding wire	Case 3-(A) No road Case 3-(B) Resistance road in association with power factor Case 3-(C) Distribution line model	Case 4-(A) No road Case 4-(B) Resistance road in association with power factor Case 4-(C) Distribution line model

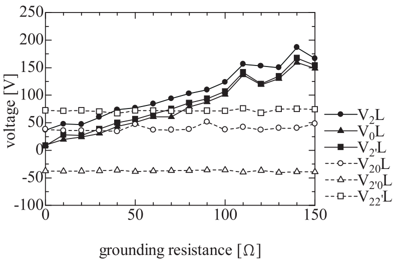
4. Experimental Cases

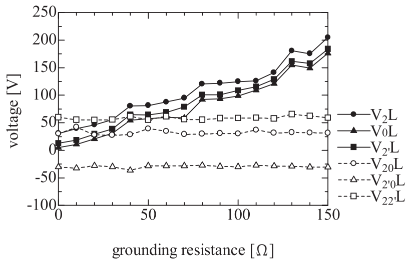
The experimental cases are put together in Table 1. In Case 1 and 2, the surge current is injected from one of power lines, in Case 3 and 4, the surge current is injected from the grounding wire. In Case 1 and 3, three of low voltage terminals in the pole-mounted transformer is used for connections between the transformer and small wind turbine generation systems, in Case 2 and 4, two of low voltage terminals except the neutral point is used for connections. The details of (A), (B) and (C) are explained in section 3.5. The test circuits of Case 1 to 4 are shown in Fig. 8 - 11. In each case, the value of grounding resistance is 0 - 150 Ω the value of the equivalent resistance road at the high voltage terminals is 510 - 4080 Ω (the grounding resistance is 150 Ω).

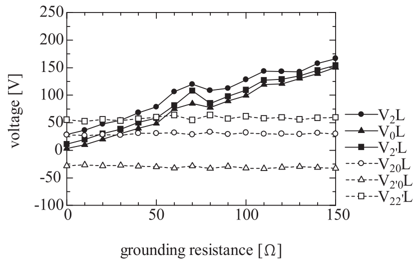
5. Experimental Results

The measured overvoltages in all cases are standardized by the input lightning current of 1 A. The maximum values of overvoltage waveforms at the low voltage terminals measured against the grounding resistance (0 - 150 Ω) in Case 1 are shown in Fig. 12 - 14 (a), and the maximum values at the high voltage terminals are shown in Fig. 12 - 14 (b). The measured results in Case 2 - 4 are shown in Fig. 15 - 23 correspondingly. However, in Case 3 and 4, the terminal voltages $V_{20}L$, $V_{2'0}L$, $V_{22'}L$ and $V_{11'}H$ are far smaller than others, and then those values are eliminated from those figures.

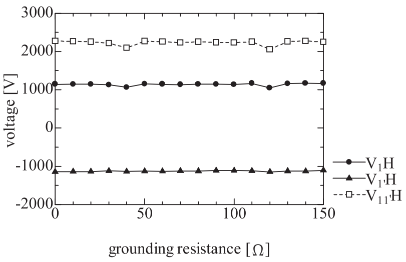
The maximum values of overvoltage waveforms measured against the load resistance (410 - 4080 Ω) shown in Fig. 24 - 27. The terminal voltages $V_{20}L$, $V_{2'0}L$, $V_{22'}L$ and $V_{11'}H$ are far smaller than others similarly, and

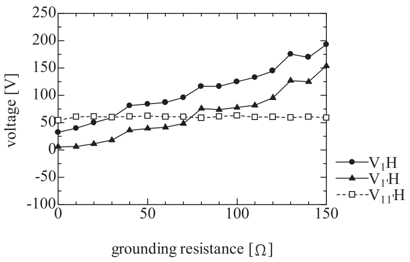


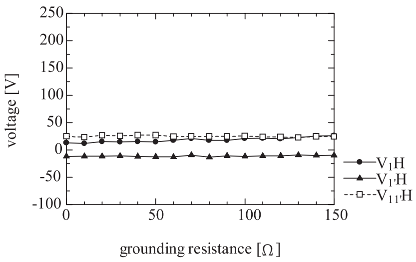




(a) Low voltage terminals

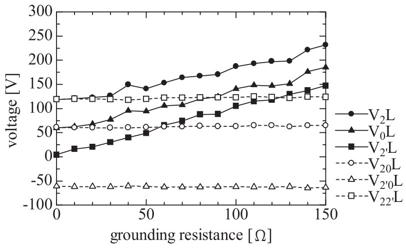


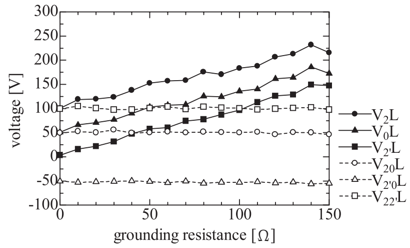


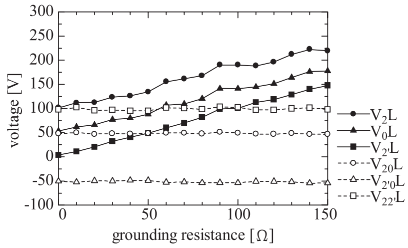


(b) High voltage terminals

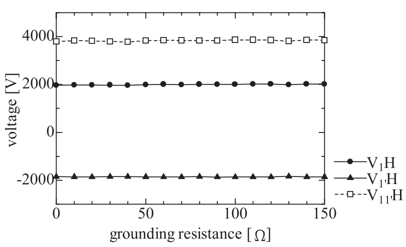
Fig. 12 Case 1-(A)　　Fig. 13 Case 1-(B)　　Fig. 14 Case 1-(C)

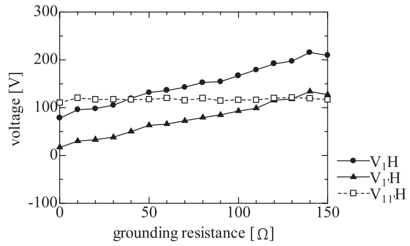


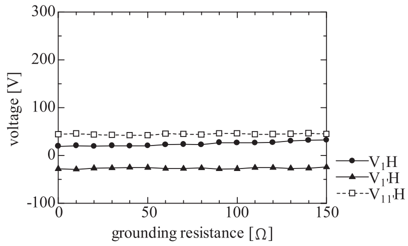




(a) Low voltage terminals

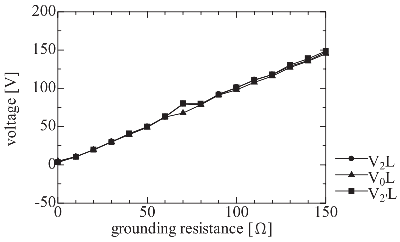


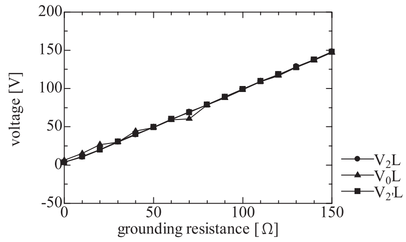


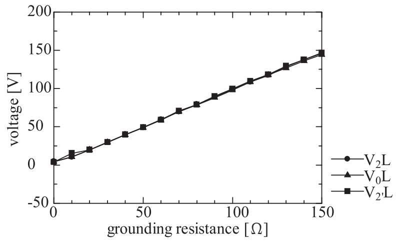


(b) High voltage terminals

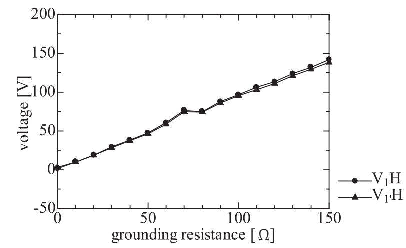
Fig. 15 Case 2-(A) Fig. 16 Case 2-(B) Fig. 17 Case 2-(C)

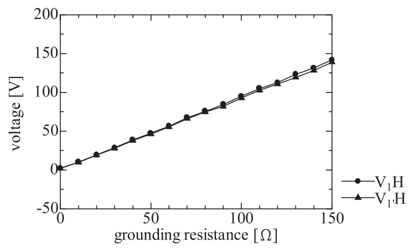


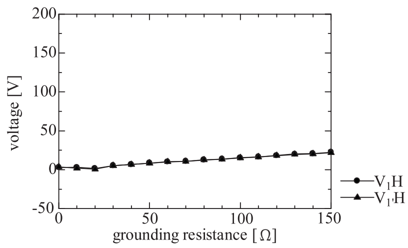




(a) Low voltage terminals







(b) High voltage terminals

Fig. 18 Case 3-(A) Fig. 19 Case 3-(B) Fig. 20 Case 3-(C)

then those values are eliminated from those figures.

6. Consideration based on the experiments

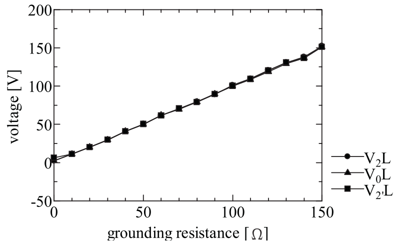
From the relations between grounding resistance and overvoltages from Fig. 12 - 23, the following matters becomes obvious. 1) The value of grounding resistance influences the node voltages at the low voltage terminals when the lightning current is injected from a power line as in Case 1 and 2. 2) The influences on the node voltages at the high voltage terminals depend on the style of loads connected to the high voltage terminals, the value of grounding resistance influences the node voltage in Case 1 and 2 when the load at the high voltage terminals is represented as a resistance. 3) Comparatively large overvoltages appear at the high voltage terminals in Case 1 and 2 when there is no load at the high voltage terminals. 4) The value of grounding resistance influences all node voltages when the lightning current is injected from the grounding wire as shown in Case 3 and

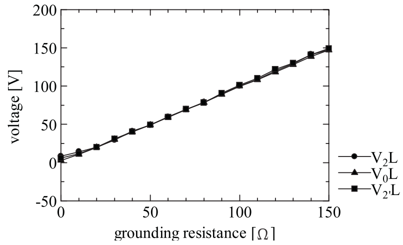
4, increase of the node voltages at the high voltage terminal is smaller than others when distribution line models are connected to the high voltage terminals. 5) When Case 1 where three of low voltage terminals is used are compared with Case 2 where two of low voltage terminals except the neutral point is used, the overvoltages in Case 2 become larger than those in Case 1, however same patterns can not be observed in Case 3 and 4.

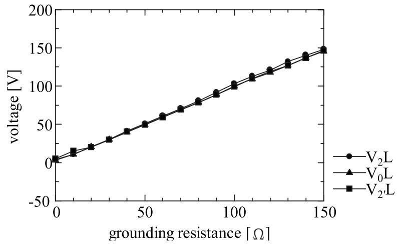
From the relations between the load resistance based on the phase factor and overvoltages from Fig. 24 - 27, the following matters becomes obvious. 1) In Case 1 and 2, the load resistance influences the terminal voltages at the high voltage terminals, but do not influence the terminal voltages at the low voltage terminals so much. 2) In Case 3 and 4, the load resistance do not influence the terminal voltages so much.

7. Conclusions

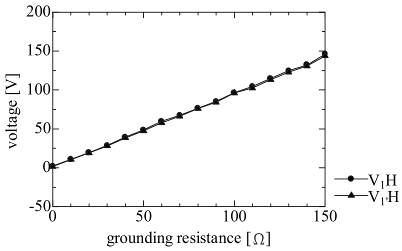
In this paper, we present the result of an experimental study for lightning protection of a pole-mounted transformer connected to small wind turbine generation systems. The overvoltages shown in this paper can be

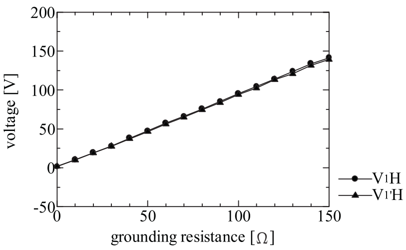


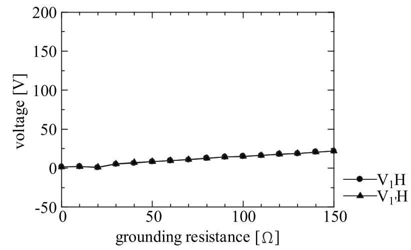




(a) Low voltage terminals

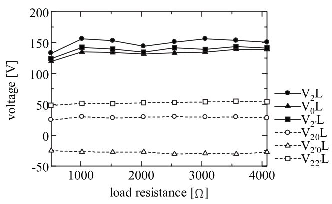


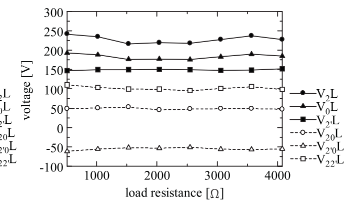


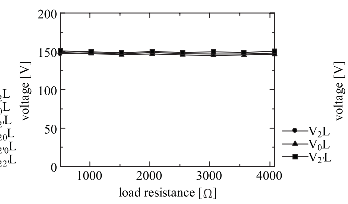


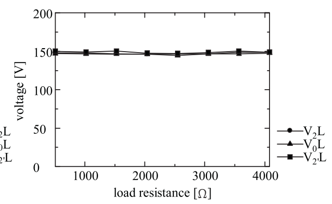
(b) High voltage terminals

Fig. 21 Case 4-(A)　　Fig. 22 Case 4-(B)　　Fig. 23 Case 4-(C)

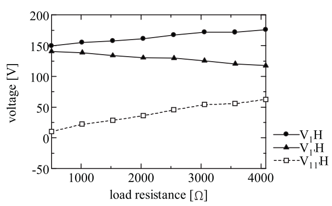


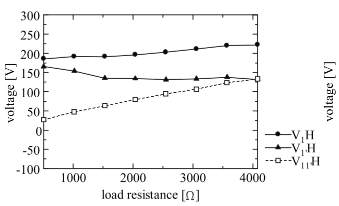


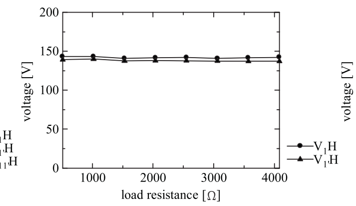


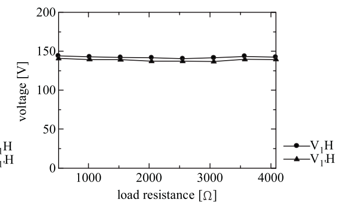


(a) Low voltage terminals









(b) High voltage terminals

Fig. 24 Case 1-(B)　　Fig. 25 Case 2-(B)　　Fig. 26 Case 3-(B)　　Fig. 27 Case 4-(B) fundamentals of further lightning protection studies.

The measured result of overvoltages will be simulated using EMTP [4], and effects of arresters set up around the pole-mounted transformer and length of grounding wire should be researched in future.

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