

Analysis of Lightning Overvoltages in Low-Voltage Power Distribution Lines with Service Drop Lines

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Lightning outages on high-voltage power distribution lines have been decreased steadily for lightning protection with surge arresters and overhead ground wires for high-voltage power distribution lines in Japan. However the number of lightning outages on low-voltage distribution lines is on the increase for the information-oriented and computerized society. We have examined lightning overvoltages in low-voltage distribution lines with service drop lines for customers. The peak value of the line conductor voltage in a low-voltage line is reduced and the waveform of it resembles that of the neutral conductor voltage due to installing a DV wire and a grounding at the neutral conductor. The service drop line should be taken into account when lightning overvoltages in low-voltage distribution lines is examined. We have studied protection of low-voltage distribution lines against lightning induced overvoltages with the model of low-voltage distribution line using the Electro-Magnetic Transients Program (EMTP) on the basis of the experimental results. Nevertheless the grounding resistance value is higher, separate groundings on the closest pole to a pole transformer and the termination of low-voltage line is as effective as a single low grounding on the middle of low-voltage line.

Keywords: distribution lines, lightning, low-voltage distribution lines, lightning overvoltages, service drop lines

1. Introduction

Lightning outages on high-voltage power distribution lines have been decreased steadily for 6.6kV, 22kV and 33kV overhead power distribution lines in Japan because of lightning protection measures with surge arresters and overhead ground wires. However the number of lightning outages on low-voltage power distribution lines is on the increase for the information-oriented and computerized society in addition to usual watt-hours meters and so on. Therefore we have investigated the lightning protection for low-voltage power distribution lines. Previous studies [1], [2] treated the low-voltage distribution lines only. In this study we have examined lightning overvoltages in low-voltage distribution lines with the service drop lines for customers. This paper presents the experimental result of the influence of installing service drop lines upon lightning overvoltages in low-voltage distribution lines. We have revealed how lightning surge propagates from a high-voltage distribution line to a low-voltage customer entrance through a pole transformer. Moreover, lightning performance of low-voltage power distribution lines against lightning induced overvoltages is examined using the Electro-Magnetic Transients Program (EMTP) on the basis of the experimental results.

2. Influence of installing service drop lines upon lightning overvoltages in low-voltage distribution lines

2.1 Experimental methods Experiments were performed using actual-size distribution lines at the UHV Shiobara Testing Yard of CRIEPI. Schematic diagrams of the experimental distribution lines are shown in Figure 1. The experimental high-voltage distribution line consists of three-phase conductors and concrete poles. All conductors are connected to a shunt resistance (400 Ω) at the No.1 pole to prevent current reflection. Three-phase surge arresters consisting of ZnO components and an air gap are installed on poles No.2, No.6 and No.7. The grounding resistance values of them are about 30 Ω. A pole transformer is installed on

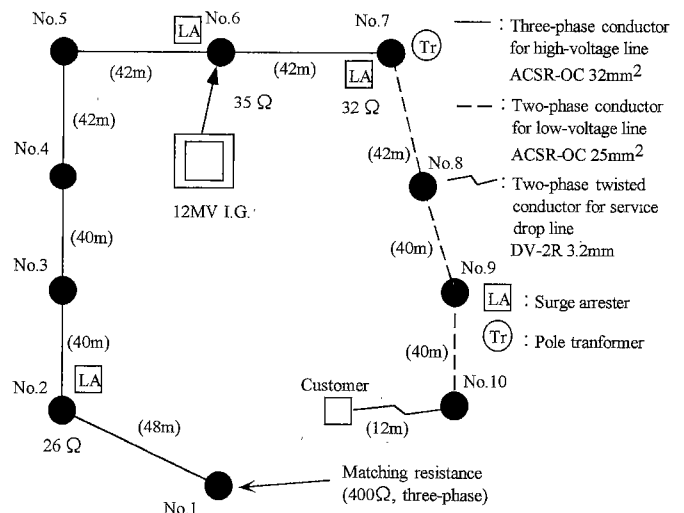


Fig. 1. Layout of experimental distribution lines.

Table 1. Experimental condition of low-voltage line.

Case No.	Condition of low-voltage line		
	No.7 pole	No.10 pole	
	Grounding resistance for pole transformer	Grounding resistance for neutral conductor	Number of service drop lines
1	32 Ω	Not grounded	Without line
2	32 Ω	61 Ω	Without line
3	32 Ω	61 Ω	One line
4	32 Ω	61 Ω	Two lines
5	32 Ω	61 Ω	Three lines
Injected current	Peak of current : -7kA Time to crest : 2μs, Time to half : 11μs		

No.7 pole. There are five types for a low-voltage distribution line (a single-phase two-wire system, a single-phase three-wire system, a three-phase four-wire system, and so on) in Japan. There are a two-phase wire and a three-phase wire for a service drop line. Therefore there are various low-voltage distribution systems. For a basic investigation, the experimental low-voltage distribution line consists of two-phase horizontal conductors of which height is about 8m. The distance between two conductors is 1.4m. The total length of three spans of the low-voltage line is about 120m with no termination at the end. Polyvinyl chloride insulated twisted conductors (DV wire) is used for a two-phase service drop line, which is connected to the low-voltage distribution line at No.10 pole. The length of the DV wire is 12m. The termination of the DV wire is open-ended. The experimental condition of service drop lines and groundings on the low-voltage line are summarized in Table 1. We used the 12MV impulse generator at the Shiobara Testing Yard of CRIEPI. A lightning impulse current with a peak value of 7 kA and a waveform of 2/11μs was injected into the top of No.6 pole. A current waveform and three voltage waveforms were measured, namely the injected current at No.6 pole, the voltage between the line conductor and the grounding (Vl) at No.10 pole, the voltage between the neutral conductor and the grounding (Vn) at No.10 pole and the voltage between the line conductor and the neutral conductor (Vb) at No.10 pole.

2.2 Experimental results Figure 2 shows the peak value of each voltage at No.10 pole in five experimental cases. In the case of No.10 pole without grounding (Case No.1), the neutral conductor voltage at No.10 pole is the same peak value as the line conductor voltage at No.10 pole. In the case that the neutral conductor at No.10 pole is grounded (Case No.2), the neutral conductor voltage at No.10 pole has attenuated considerably. On the other hand, the attenuation of the line conductor voltage at No.10 pole is small, therefore the voltage between the line conductor and the neutral conductor at No.10 pole is large. In addition, a single DV wire is installed on No.10 pole (Case No.3), the line conductor voltage at No.10 pole has attenuated considerably. The peak value of the voltage between the line conductor and the neutral conductor

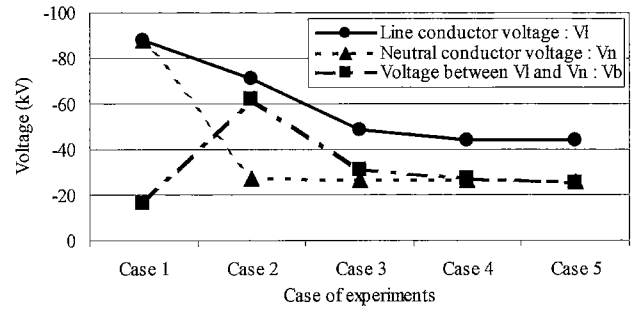
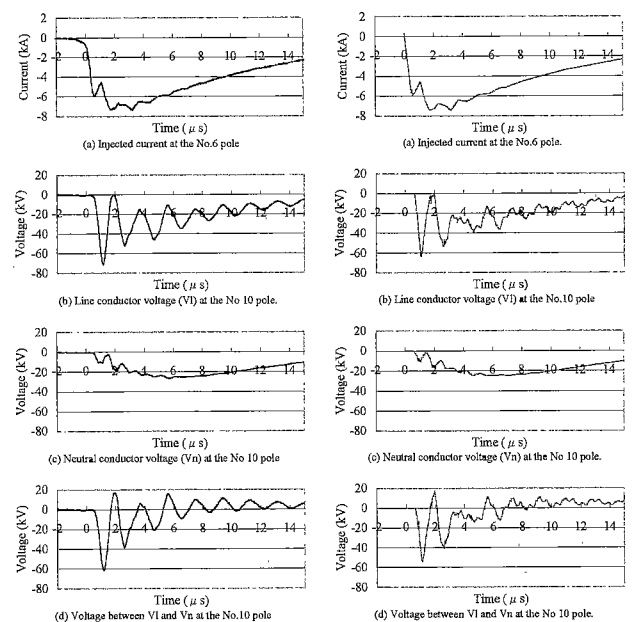


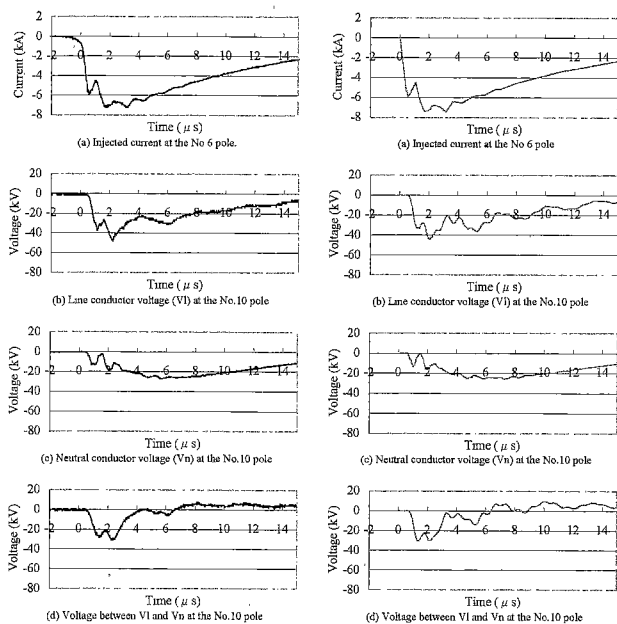
Fig. 2. Peak value of voltages at No.10 pole. (measured results)

at No.10 decreases with reduction of the line conductor voltage at No.10 pole. The neutral conductor voltage at No.10 pole is not different from that without the DV wire. These results are attributed to electromagnetic coupling of the DV wire. The difference between the line conductor voltage and the neutral conductor voltage is reduced owing to the grounding at No.10 pole.

The measured waveforms of a current and voltages are shown in Figure 3 in the case of a low-voltage line without a service drop line (Case No.2). The measured waveforms in the case of a low-voltage line with a service drop line (Case No.3) are shown in Figure 4. Although the neutral conductor voltage at No.10 pole is greatly influenced by the grounding at No.10 pole, it is not affected by installing a single DV wire at No.10 pole. The peak value of the line conductor voltage at No.10 pole is reduced and the waveform of it resembles that of the neutral conductor voltage at No.10 pole due to a DV wire on No.10 pole. The oscillatory wave is attenuated after three microseconds. The relationship between the number of DV wires and measured voltages is shown in Figure 2. The line



(1) Measured waveforms (2) Calculated waveforms
Fig. 3. Measured and calculated waveforms (case 2).



(1) Measured waveforms (2) Calculated waveforms
 Fig. 4. Measured and calculated waveforms (case 3).

conductor voltage at No.10 pole is reduced with increase of the number of DV wires. The overvoltages at No.10 pole are slightly reduced even by the two DV wires or more.

The distance between conductors of a service drop line becomes short generally by the reason that the available voltage of service drop line is low and it is matched with its surroundings. Lightning overvoltages in low-voltage distribution lines are greatly influenced by the electromagnetic coupling in service drop lines. The service drop line should be carefully studied when lightning overvoltages in low-voltage distribution lines is considered.

3. Study of reducing lightning overvoltages in low-voltage distribution lines

Simulation of the experimental distribution line is performed by the EMTP. The calculated waveforms of a current and voltages in the case of a low-voltage line without a service drop line (Case No.2) and with a service drop line (Case No.3) are shown in Figure 3 and 4, respectively. The measured and calculated waveforms are in good agreement with regard to peak value and overall shape. Thus we have studied the effect of the grounding position, the grounding resistance and the number of grounding in low-voltage distribution lines using the EMTP.

3.1 Calculation conditions

(1) **High-voltage distribution line** The high-voltage distribution line model consists of three-phase horizontal conductors and an overhead ground wire (OGW). The total length of high-voltage line (10 spans) is 400m. Three-phase surge arresters

consisting of ZnO components and an air gap are installed on poles No.2, No.6, No.10 and No.11. The grounding resistances of them values are 30Ω. We assume that the discharge voltage of surge arresters is 29kV, and the residual voltage of these is 19kV when discharge current of surge arresters reaches 2.5kA. An OGW is grounded at each pole using the same grounding as that used for surge arresters. The frequency-dependent line model of phase conductors and an OGW is used in this analysis by the EMTP. We assume that the surge impedance of a concrete pole with an earth wire installed along this pole is 200Ω and its propagation velocity is 300m/μs, based on experimental results [3]. A pole transformer is installed on No.11 pole. The pole transformer is simulated by a capacitance.

(2) **Low-voltage distribution line** The low-voltage line is simulated as two-phase horizontal conductors, of which total length (4 spans) is 160m. The height of low-voltage conductors is 7.9m, and the distance between these conductors is 1.4m.

(3) **Service drop line** A two-phase DV wire composed of twisted conductors is used for a service drop line. The length of the DV wire is 15 m. In the case of Figure 5 (1), a single DV wire is connected to low-voltage distribution line at the termination of the line, namely No.15 pole. In the case of Figure 5 (2), a single DV wire is connected to each pole of the low-voltage distribution line. The distribution line models used in this analysis are shown in Figure 5.

(4) **Lightning stroke current** The time to crest and the time to half value of lightning currents are fixed at 1μs and 70μs, respectively [4]. The peak value of lightning current is -10kA. The reason for this is that the peak value of surge arresters on No.11 pole becomes approximately 1kA on the basis of the data of "Lightning protection design standard for distribution lines"[5] for the purpose of studying lightning protection against lightning induced overvoltages.

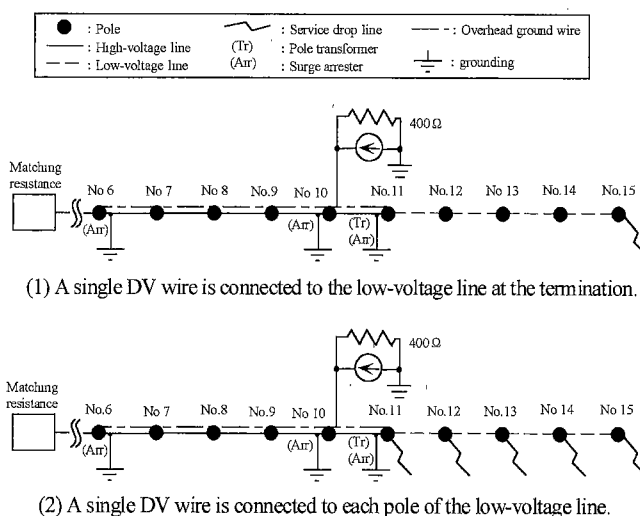


Fig. 5. Configuration of analytical distribution lines.

3.2 Effect of distance between low-voltage line conductors

The distance between two conductors of the experimental low-voltage line is 1.4m, the distance between conductors of a low-voltage line is shortened for matching with its surroundings. The short distance between conductors of the low-voltage line reduces lightning overvoltages in low-voltage distribution lines for the electromagnetic coupling in addition to the effect of the DV wire. We have determined the effect of reducing the lightning overvoltages at the termination of low-voltage line, namely No.15 pole due to shortening the distance between conductors of the low-voltage line in the case of Figure 5 (1). Figure 6 shows the relationship between the distances of low-voltage conductors with value ranging from 0.15m to 1.4m and each voltage at No.15 pole. The voltages at No.15 pole of a distance between low-voltage conductors of 1.4m are replaced as 100%. This figure indicates that the line conductor voltage and the voltage between the line conductor and the neutral conductor at No.15 pole drop inversely proportional to logarithmic values of the distances of low-voltage conductors. The arrangement of low-voltage distribution lines should be carefully studied as well when lightning overvoltages in low-voltage distribution lines is considered.

3.3 Effect of grounding position in low-voltage lines

We have studied the effect of grounding position in low-voltage lines in the case of being a distance between low-voltage conductors of 0.15m and installed a DV wire on each pole (Figure 5 (2)). Figure 7 shows the relationship between the grounding position from No.12 pole to No.15 pole and the line conductor voltage and the neutral conductor voltage at each pole. The grounding resistance value in low-voltage line is 60Ω. In the case of low-voltage line without grounding, the line conductor and the neutral conductor voltages rise as the pole is close to the termination of low-voltage line. Installing a grounding in low-voltage line, the line conductor and the neutral conductor voltages from No.11 pole to the grounded

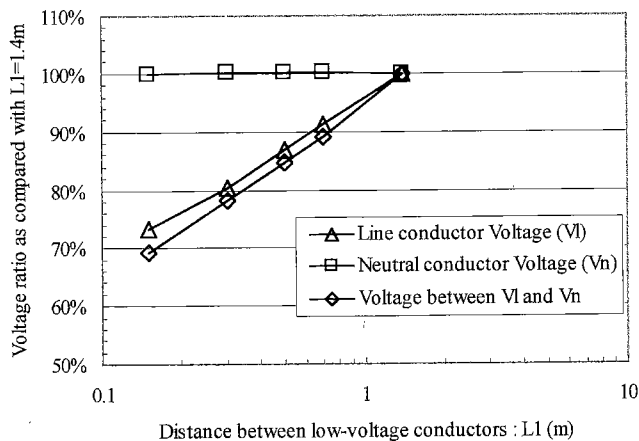
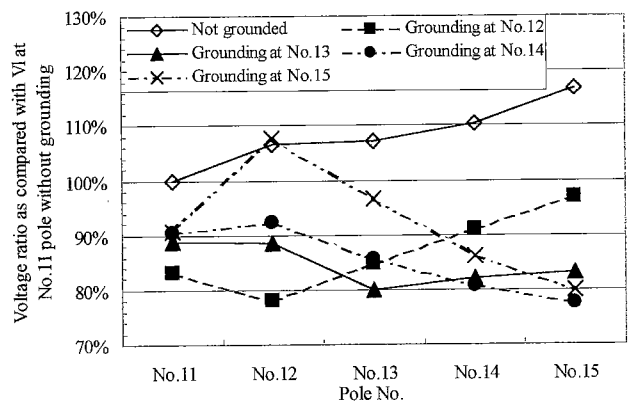


Fig. 6. Relationship between the distances between low-voltage conductors and the voltages at No.15 pole (case of Fig. 5. (1)).

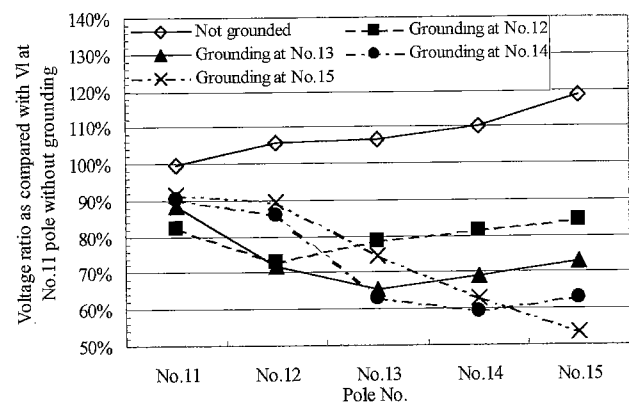
pole lower, however, the line conductor and the neutral conductor voltages from the grounded pole to No.15 pole rise as the pole is close to the termination of low-voltage line. This figure indicates that the grounding on No.13 pole, namely the middle of low-voltage line is effective for reducing lightning overvoltages in the overall low-voltage line.

3.4 Effect of number of grounding in low-voltage lines

We have studied the effect of two separate groundings in low-voltage lines in the case of being a distance between low-voltage conductors of 0.15m and installing a DV wire on each pole (Figure 5 (2)). Figure 8 shows the relationship between six combinations of two groundings from No.12 pole to No.15 pole and the line conductor voltage and the neutral conductor voltage at each pole. Each grounding resistance value in low-voltage line is 60Ω. Figure 8 indicates that two groundings on No.12 pole and No.15 pole, namely the closet pole to a pole transformer and the termination of low-voltage line are effective for reducing lightning overvoltages in the overall low-voltage line. Then we have compared the effect of two separate groundings on the closet pole to a pole transformer and the termination of low-voltage line and that of a single grounding on the middle of low-voltage line. For the grounding



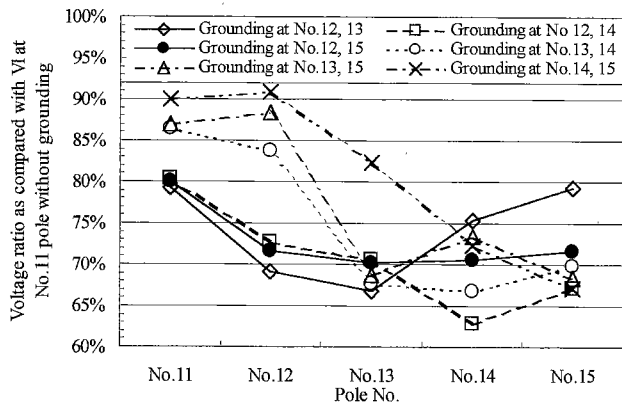
(1) Line conductor voltage (VI)



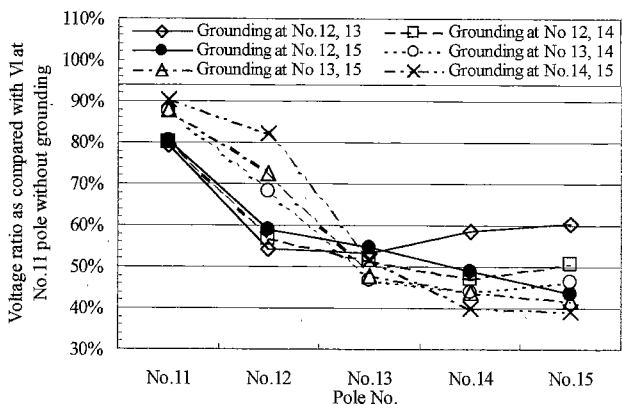
(2) Neutral conductor voltage (Vn)

Fig. 7. Relationship between the grounding position and the voltages at each pole.

(Grounding resistance in low-voltage line is 60 Ω)



(1) Line conductor voltage (VI)



(2) Neutral conductor voltage (Vn)

Fig. 8. Relationship between two separate groundings and the voltages at each pole.

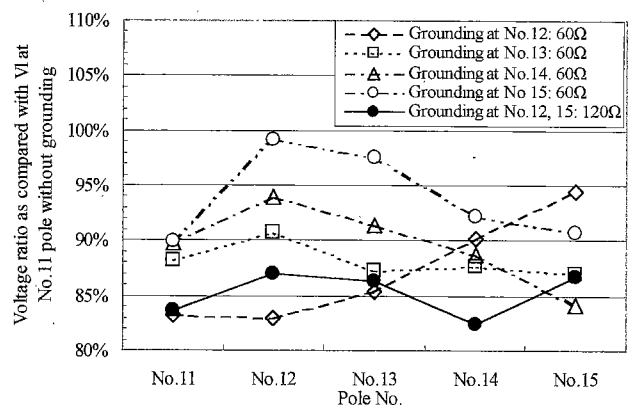
(Grounding resistance in low-voltage line is 60Ω)

conditions are equal, the resistance value of two groundings and a single grounding are 120Ω and 60Ω , respectively. These results are shown in Figure 9. Nevertheless the grounding resistance value is higher, two separate groundings on the closest pole to a pole transformer and the termination of low-voltage line is as effective as a single low grounding on the middle of low-voltage line.

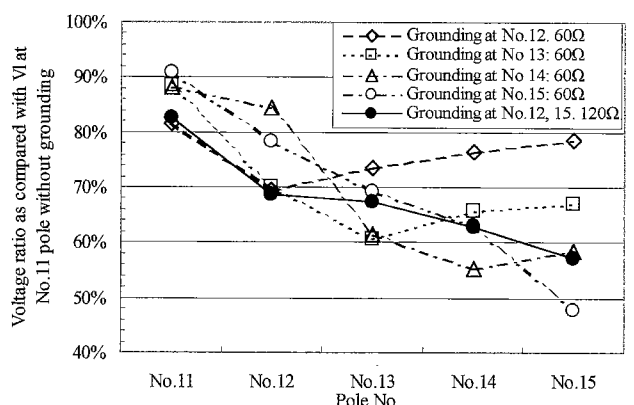
4. Conclusions

We have examined lightning overvoltages in low-voltage distribution lines with service drop lines for customers. We have clarified the influence of installing service drop lines upon lightning overvoltages in low-voltage distribution lines experimentally. We have also studied protection of low-voltage distribution lines against lightning induced overvoltages with the model of low-voltage distribution line on the basis of the experimental results using the EMTP. The main conclusions are summarized as follows;

- (1) The peak value of the line conductor voltage in a low-voltage line is reduced and the waveform of it resembles that of the neutral conductor voltage due to installing a DV wire and a grounding at the neutral conductor. The service drop line should be carefully studied when lightning overvoltages in low-voltage distribution lines is considered.



(1) Line conductor voltage (VI)



(2) Neutral conductor voltage (Vn)

Fig. 9. Comparison between two separate groundings and a single grounding in low-voltage line.

(Grounding resistance of two groundings and a single grounding are 120Ω and 60Ω)

- (2) The grounding of the neutral conductor on the middle of low-voltage line is effective for reducing lightning overvoltages in the overall low-voltage line.
- (3) Two separate groundings on the closest pole to a pole transformer and the termination of low-voltage line are effective for reducing lightning overvoltages in the overall low-voltage line.
- (4) Nevertheless the grounding resistance value is higher, two separate groundings on the closest pole to a pole transformer and the termination of low-voltage line is as effective as a single low grounding on the middle of low-voltage line.

Acknowledgment

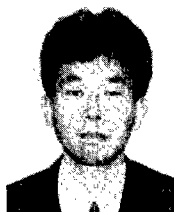
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References

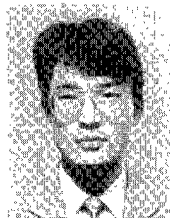
- [1] H. Ohnishi, Y. Imai, S. Yokoyama and A. Asakawa, "Analysis lightning Induced Overvoltages on Low Voltage Power Distribution Lines due to Overvoltages on High Voltage Power Distribution Lines", IEE of Japan, ED-87-91, HV-87-38, 1987.
- [2] Y. Imai, N. Fujiwara, H. Yokoyama, T. Shimomura, K. Yamaoka and S. Ishibe, "Analysis lightning Overvoltages on Low Voltage Power Distribution Lines due to Direct Lightning Hits to Overhead Ground Wire", IEE of Japan Trans., Vol.113-B, No.8, 1993.
- [3] S. Sekioka, K. Yamamoto, and S. Yokoyama, "Measurements of a Concrete Pole Impedance with an Impulse Current Source", Pro. of International Conference on Power Systems Transients, pp.457-462, 1995.
- [4] Subcommittee for Power Stations and Substations, Lightning Protection Design Committee, "Guide to Lightning Protection Design of Power Stations, Substations and Underground Transmission Lines", Technical Report in CRIEPI, No.T40, 1995.
- [5] Sectional Committee for Distribution Lines, Lightning Protection Design Standard Study Committee, "Lightning Protection Design Standard for Distribution Lines", Technical Report in CRIEPI, No.13, Vol.4, 1963.

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