Estimation Program of Lightning Outage Rate in Power Distribution Line with Reference to Japanese Grounding System

T. Yamada, M. Ota, T. Ootaki, and S. Sekioka

Abstract: Considering that a number of lightning protection methods in power distribution lines such as a shielding wire and surge arresters should be investigated for rational coordination design, it is necessary to estimate lightning outage rate of the protection method associated with its cost. This paper describes an estimation method, which uses the EMTP to calculate lightning overvoltages and absorption energies in the distribution lines, to obtain the lightning outage rate.

Keywords: Distribution line, EMTP, Lightning outage rate, Lightning protection.

I. Introduction

THE Japanese electric power companies have constructed power distribution lines with surge arresters (ARs) and a shielding wire (SW). The SW is very effective to protect the distribution lines from lightning-induced voltages [1], and the number of lightning outages has been decreased. However, the lightning is still a main cause of the outages in the distribution lines [2]. The direct lightning stroke to the distribution lines is the main factor to cause the lightning outages [3, 4]. Japanese electric power companies adopt a non-effective grounding system in 6.6kV lines (HV lines). One-phase sparkover is not a cause of over-current faults in this system, but two-phase sparkover causes line outage. Chubu Electric Power Co. applies some countermeasures such as the SW, lightning-protection arcing horn (LPH), which causes no sparkover on an insulator, and lightning-protection primary cutout switch (LPC), which reduces the lightning overvoltage on a transformer (TR), to the distribution lines [5]. These countermeasures greatly contribute the reduction of the lightning outages in the distribution lines. However, these countermeasures are mainly targeted for the HV lines, and lightning protection methods of 100/200V lines (LV lines) should be studied.

Grounding lead conductors (GLCs) are laid along and insulated from a reinforced concrete pole (RCP), which is usually used in Japanese distribution lines to sustain the lines and power apparatuses. Fig.1 illustrates a configuration of grounding system of the Japanese distribution line. A-type grounding corresponds to the grounding for the ARs and often for the SW, and B-type for the TR. The RCP should be treated as a grounding electrode (GE) and a GLC for lightning overvoltages [6]. The TR and the ARs are often installed on the same RCP, and these groundings are closely located. Consequently, the overvoltage on the LV line is induced from the A-type GE to the B-type one. Sparkover between the RCP and the GLCs frequently occur due to the lightning overvltages. Thus, the grounding system is one of the most important and complicated factors to determine the lightning overvoltages on the distribution lines.

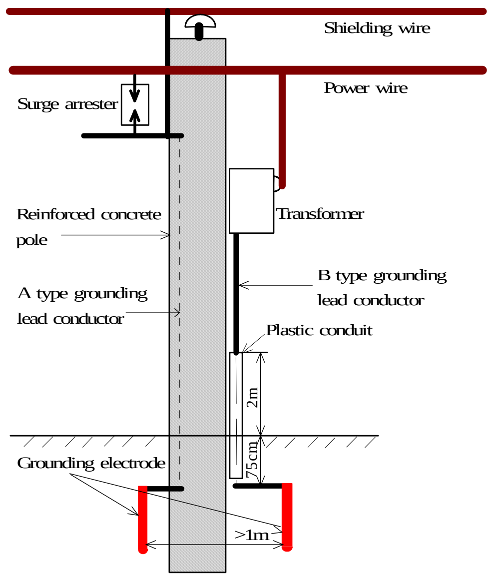

Fig. 1. A grounding system in Japanese distribution line.

The electric power companies are required to make cost as low as possible, while maintaining conventional reliability of the electric power systems. Lightning outage rate is a useful and reasonable guide to evaluate the countermeasure in association with making cost low. The computer program developed by CRIEPI to estimate the lightning sparkover rate in the distribution line is a useful tool [7, 8]. This program is targeted for the sparkover in the HV lines, but does not treat the damage of the ARs due to large energy and the outages in the LV lines. The authors, therefore, developed a new computer program to estimate the lightning outage rate in the LV lines as well as the HV lines.

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This paper describes the estimation method of the lightning outage rate in the distribution line. Then, the paper shows examples of the damage of a watt-hour meter in the LV line and an influence of lightning protection method on the lightning outage rate in the HV lines by the use of the proposed method.

II. Computer Program to Estimate Lightning Outage Rate of Power Distribution Line

A. Outline of the Program

Fig. 2 illustrates a flowchart of a computer program to estimate a lightning outage rate of a power distribution line.

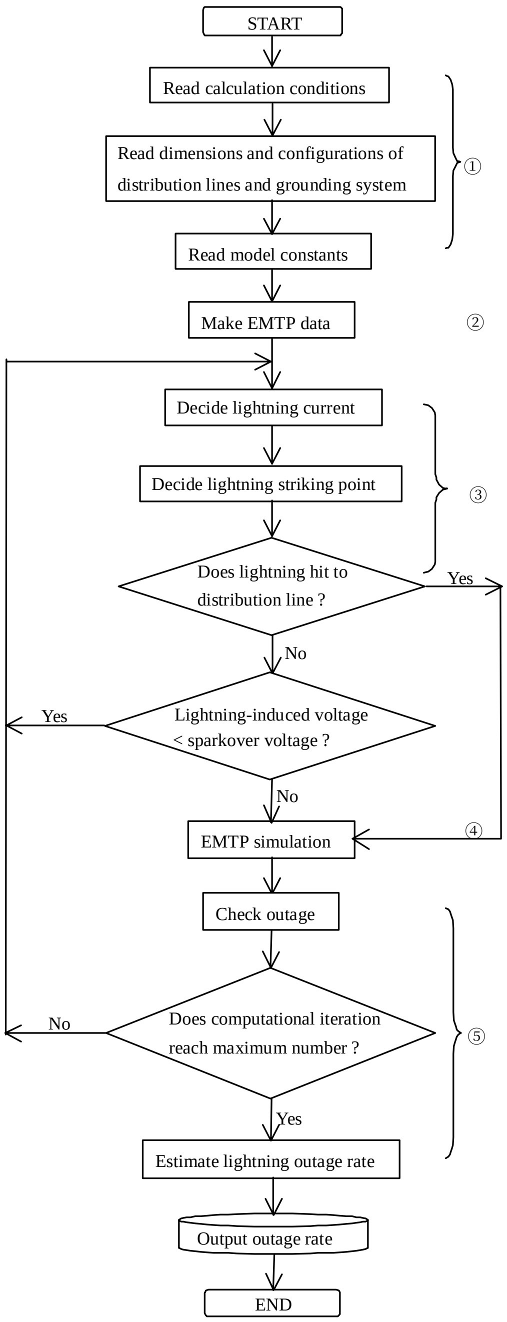

Fig. 2. Flowchart of the program.

The program consists of five parts as follows:

(1) Input of calculation conditions and model constants

Calculation conditions, constants of simulation models, and lightning parameters are read from data files.

(2) Making EMTP data cards

The EMTP [9] is used to calculate lightning overvoltages, energies and sparkovers in the distribution lines. Constants of EMTP simulation models for distribution line, grounding system, TR, AR, customer, sparkover, lightning current and output requests are made in this procedure.

(3) Decision of lightning striking point

A lightning striking point is decided using an estimation method of shielding failure of overhead line such as the electrogeometric model [10]. When the peak value of lightning-induced voltage due to nearby lightning stroke is less than sparkover voltage of the line, EMTP simulation is not carried out in this case because no sparkover occurs. The peak voltage is roughly estimated using an approximate formula, which can consider the wavefront duration of the lightning current [11] in this part.

(4) EMTP simulation

EMTP simulation is carried out to estimate lightning over-voltages, absorption energies through lightning protection devices, and sparkovers. Simulation results of instantaneous values of the voltages, the currents and the energies, and the operation of the switches are written in a list file from the EMTP. The constants of the lightning current and the lightning striking point are varied in each EMTP simulation.

(5) Estimation of simulation results

The judgment whether a lightning outage occurs in the distribution line is determined from the simulation results by the EMTP. The outages in the distribution lines are assumed to occur when the two/three-phase sparkover occurs or the absorption energy of an apparatus exceeds a critical value.

B. Output from the Program

The program can deal with the following estimation.

(i) Estimation of the sparkovers (breakdown) on insulators and apparatuses in the distribution lines

(ii) Estimation of the damage of the AR due to large absorption energy

(iii) Estimation of an influence of both the arrangement of the ARs and the configuration of the grounding system on the lightning outage rate

(iv) Estimation of an influence of the structures near the distribution lines and the lightning characteristics, which depend on local area.

III. Models Prepared in the Program

The program prepares the following simulation models.

(a) Distribution line: Dommel’s line model [9], which takes the frequency dependence into no account, is adopted in the program because short computation time and numerical stability are needed. Moreover, it is not necessary to obtain the line constants for each simulation when the lightning strikes a conductor between the poles because the constants of the Dommel model are independent of the conductor length. The distribution line is relatively short, and the frequency dependence is little effect for lightning surge analysis. The line model for lightning-induced voltage analysis is different from the one for direct lightning stroke. External sources generated by electromagnetic fields radiated from lightning stroke must be considered. One of the authors proposed an equivalent circuit of the line for indirect lightning strokes. The proposed circuit consists of the Dommel model and current sources to consider the external sources, and shows high accuracy and short computation time [12].

(b) Grounding: RCP should be treated as a GLC and a GE for lightning surge analysis. Fig. 3 illustrates a lightning surge analysis model of a grounding system in the distribution line [13]. The constants of the grounding system model used in the EMTP are calculated from the soil resistivity, the configuration and dimension of the grounding system. Reduction of the grounding resistance due to soil ionization is important in case of high grounding resistance [14].

(c) Transformer: TR is frequently represented by capacitances for lightning surge analysis when the analysis is targeted only for the HV line. However, this simplest model cannot deal with secondary transition voltages. Therefore, this program adopts an accurate transformer model, which considers the secondary voltage and high frequency characteristics [14].

(d) Customer: An equivalent circuit of a customer can be modeled precisely using concentrated constant circuits, distributed-parameter lines and nonlinear resistances. Customer’s impedance is sufficiently high, and the customer should be modeled as simply as possible because the program estimates the lightning outage of the power distribution line. A simple customer model is represented by input impedance seen from the drop line as illustrated in Fig. 4 [15]. The simple model enables the simulation circuit to consider many customers. However, this simple model does not give the voltages on the home appliances.

(e) Surge arrester: AR is represented by a series circuit of a voltage-controlled switch and a nonlinear resistance,

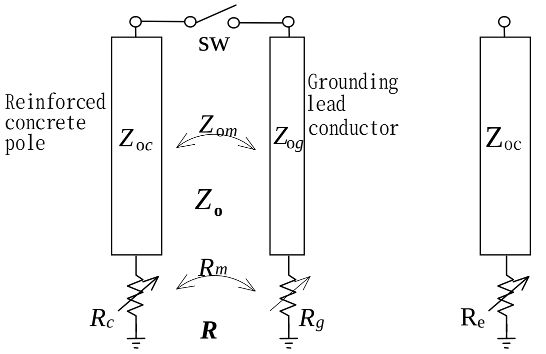

Fig. 3. Grounding system model.

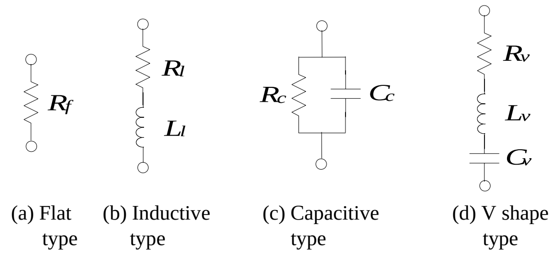

Fig. 4 Customer model for lightning surge analysis

which is given by current-voltage characteristics. Surge protective device (SPD) for communication line is often modeled by the voltage-controlled switch.

(f) Sparkover: The voltage-controlled switch is used to judge sparkover and breakdown. The switch is closed when the switch voltage exceeds a critical value. This model is very convenient, but can not deal with an influence of the voltage waveform. An integration method [16] should be used if more accurate simulation results are needed.

(g) Lightning striking point: The location of the leader of the lightning discharge is randomly decided according to the Monte Carlo method. The electrogeometric model [10] is applied to a distribution line and the leader to decide the lightning striking point. A rectangular shape structure near the distribution lines can be considered. The lightning-induced voltage calculation is carried out when the lightning stroke does not hit to the distribution line.

(h) Lightning current: The lightning current waveform is represented by a ramp shape, which is the most simple model. The amplitude, wavefront and wavetail durations are decided from cumulative probability distribution [7, 8] given by:

$$P(x) = \frac{1}{1 + (x / x_0)^a} \tag{1}$$

where x: variable such as peak value and waveform, x_0: 50% value of x, a: constant.

Characteristics of the lightning current in summer season are quite different from those in winter season, and damages of power apparatuses are also different [17, 18].

IV. EXAMPLE

A. *The lightning outage in LV line*

The first example is the estimation of the lightning outage rate of a watt-hour meter. The watt-hour meter is set at the entrance of a residence, and is appropriate for a demonstration of the worth usefulness of the program.

(1) Calculation Conditions

Fig. 5 illustrates a calculation circuit including SW, lightning-protection equipments of lightning-protection horn (Lh) and lightning-protection PC (LPC).

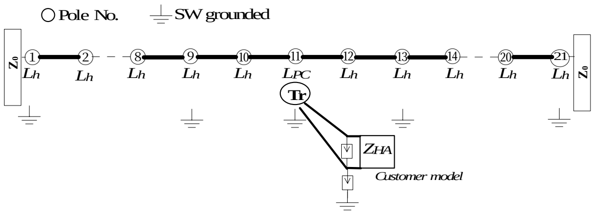

Fig. 5. Calculation circuit of lightning overvoltage.

TABLE I CALCULATION CONDITION.

Conditions	Values, method
Line length	1 km
Span length	50 m
Distance between poles where SWs are grounded	100 m
Condition at line ends	Matching circuit
Power-frequency angle to cause continuing current	90 degrees
Soil resistivity	200 Ωm
Surge protective apparatus	LPC: TR mounted pole LPH: other poles
Characteristics of MOAr device	LPC: 14.9kV(1mA), 32kV(10kA) LPH: 7.5kV(1mA), 16kV(10kA) SPD: 270V(1mA), 800V(10kA)
Location of transformers	Middle of the line
Distance between watt-hour meter and SPD of home appliance	Parameter from 1 to 8 m
IKL	30 days/year
Amplitude and waveform of lightning current	Amplitude: x_o=26kA, a=2.6 Wavefront: x_o= 3.5μs, a=3.6 Wavetail: x_o= 42μs, a=4.4
Sparkover voltage of watt-hour meter	6 kV, 8 kV
Structure	Distance from line: 50m Height: 10m
Ns	1000 times

Two TRs of 6.6kV/100V are mounted on a pole to supply electric power to the customer. In this example, one customer is considered for simplicity. Table I shows calculation conditions used in the analysis. A watt-hour meter in Japanese residence has no SPD. Lightning impulse withstanding voltage of the meter is improved to raise the insulation level. Most of home appliances have the SPDs, and reduce the overvoltage on the meter.

Fig. 6 illustrates configuration and dimension of a distribution line and a grounding system including an RCP. Those of the GE and the RCP in the ground are illustrated in Fig. 7.

The main GE is a single rod with radius r of 5 mm and length l of 3m. A grounding plate of 0.25m x 0.2m to reduce the grounding resistance is replaced with an equivalent rod electrode (l=0.08m, r=0.127m). The radius and length are determined so that the grounding resistance and the surface area of the equivalent rod electrode are same as those of the grounding plate. A metal arm to sustain the insulators and the power conductors is assumed to be connected to the RCP for lightning surge analysis.

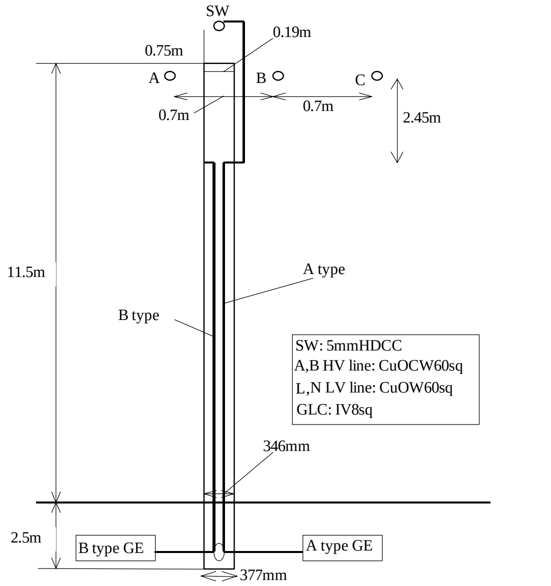

Fig. 6. Configuration and dimension of a distribution line and a grounding system.

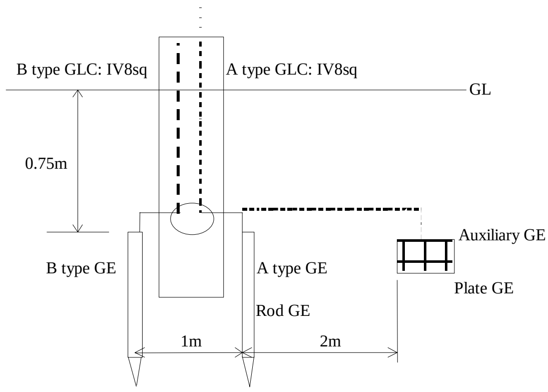

Fig. 7. A grounding system.

(2) Estimation Results

The estimation of the lightning outage rate of the watt-hour meter is carried out for a parameter of the distance between the watt-hour meter and a SPD of a homeappliance in the residence. Sparkover voltage of the watt-hour meter is 6kV as standard lightning withstanding voltage and 8kV, which is assumed to be improved about 30%. The authors investigated the lightning overvoltages on the almost same distribution line as in this circuit [19]. Lightning-induced voltages on the line are much lower than the overvoltages due to the direct lightning hit to the distribution line, and are sufficiently less than the sparkover voltages. Therefore, the indirect lightning stroke does not contribute the outage in this example. The lightning outage rate of the watt-hour meter is calculated using the following equation.

$$P_w = \frac{\theta}{360} \cdot \frac{N_d}{N_s} \cdot \frac{IKL}{10} \quad \text{[Number/km.year]} \qquad (2)$$

where θ: range of power-frequency angle to cause continuing current [degree], N_d: number of outages, N_s: number of iterative estimation, IKL: iso-keraunic level, which is the average number of thunderstorm per year, and is dependent on area [days/year]

Fig. 8 shows estimation results of the outage rate of the watt-hour meter. As is clear from the figure, the outage rate of the watt-hour meter is increased, as the distance between the meter and the SPD is longer. Furthermore, when the sparkover voltage of the watt-hour meter becomes higher from 6kV to 8kV, the lightning outage rate is remarkably reduced.

B. The lightning outage in HV line

ARs and SW are often used simultaneously in the same Japanese distribution line to protect the line from the lightning strokes, and span length of the line is about 40m. Many combinations of lightning protection methods, therefore, must be considered for rational insulation design. The second example of the proposed program is the estimation of the lightning outage rate of a HV distribution line associated with lightning protection methods.

(1) Calculation Conditions

Table II shows calculation conditions in the analysis. In this example, the lightning-induced incident is not considered for simplicity.

(2) Estimation Results

The estimation of the lightning outage rate in the HV is carried out as a parameter of the relation between various lightning protection design and lightning outage rate.

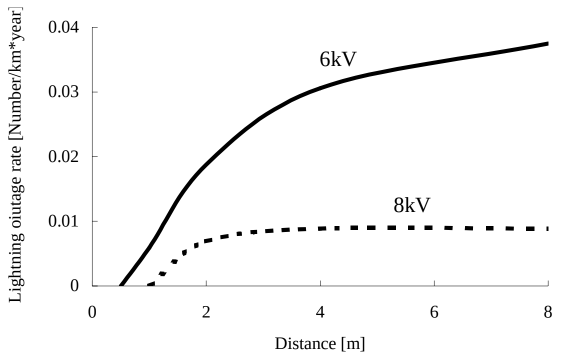

Fig. 8. Estimation results of lightning outage rate in watt-hour meter.

TABLE II CALCULATION CONDITION.

Conditions	Values, method
SW	5mmHDC
HV lines	60sqCuOCW
Span length	45.5 m
The sparkover voltage of insulator	80,100,120,150,200kV
Characteristics of AR	11.2kV(1mA), 23kV(10kA)
Grounding resistance	30,100Ω
Amplitude and waveform of lightning current	Amplitude: x_o=26kA, a=2.6 Wavefront: x_o= 3.5μs, a=3.6 Wavetail: x_o= 42μs, a=4.4
IKL	30 days/year
Grounding condition	Grounding of SW is connected to that of ARs

Figs. 9 and 10 show estimation results in case of grounding resistance of 30Ω and 100Ω, respectively. The following is clear from these figures,

(i) The lightning outage rate is decreased, as installing interval of grounding of SW is shorter and as installing interval of ARs is shorter approximately.

(ii) The difference between 30 and 100Ω of the grounding resistance is little.

V. CONCLUSIONS

This paper has described a development of a computer program to estimate the lightning outage rate in customers, and in low-voltage distribution line as well as high-voltage one. The program can estimate the efficiency of countermeasures of lightning protection. This program has an advantage in dealing with damage due to large absorption energy and enables engineers to use high accuracy lightning surge analysis models. This paper has presented estimation results of lightning outage rate of a watt-hour meter at an entrance of a residence in a low voltage line and the relation between various lightning protection design and lightning outage rate in a high voltage line.

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VII. BIOGRAPHIES

Takukan Yamada was born in Shizuoka, Japan on May 9,1973. He received the M.Sc. from Tohoku University in 1999. He joined Chubu Electric Power Co. in 1999, and has been engaged in the planning of the lightning protection design in distribution lines.

Shozo Sekioka was born in Osaka, Japan on December 30, 1963. He received the B.Sc., and D. Eng degrees from Doshisha University in 1986 and 1997, respectively. He joined Kansai Tech Corp. in 1987, and Shonan Institute of Technology from 2005. He has been engaged in the lightning surge analysis in electric power system.

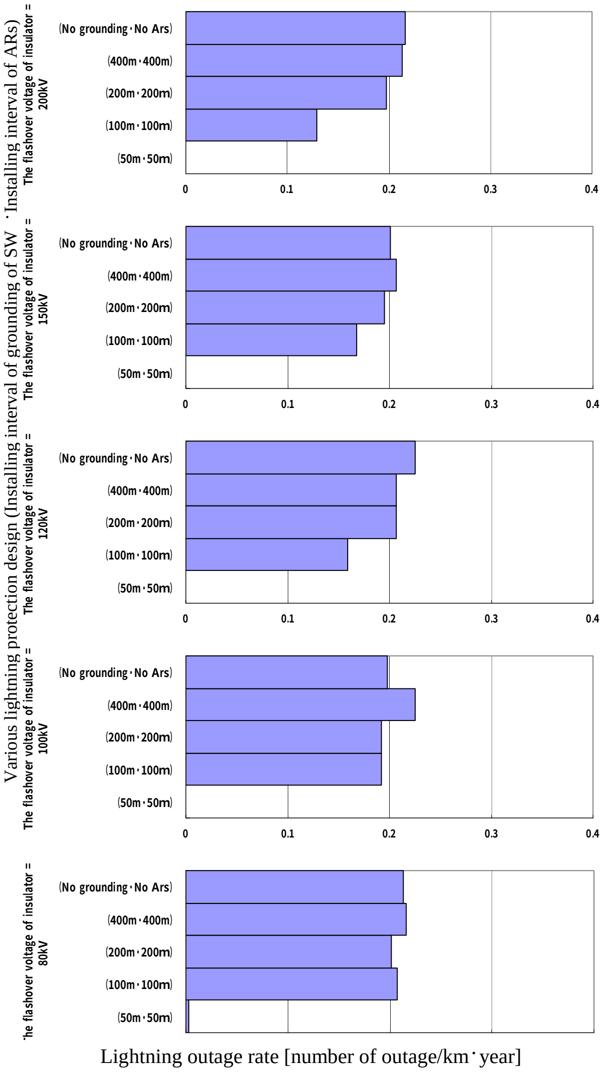

Fig. 9. Relation between lightning protection design and lightning outage rate. (Grounding resistance = 30Ω)

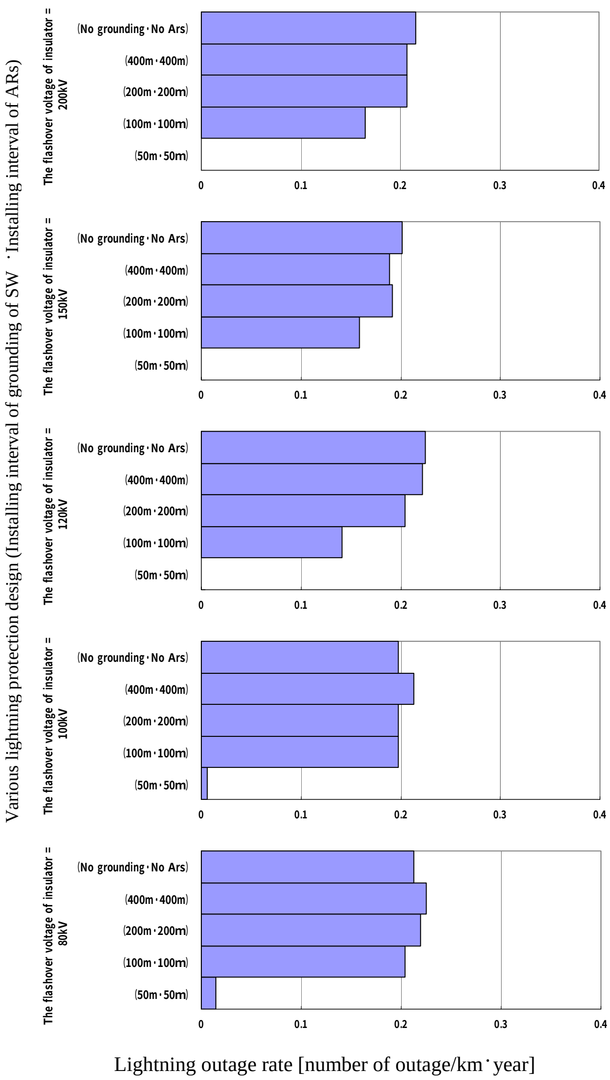

Fig. 10. Relation between lightning protection design and lightning outage rate. (Grounding resistance = 100Ω)