Flashover Risk-Based Probabilistic Design of Transmission Line Insulators under Contamination Conditions

Yukio Mizuno, *Member, IEEE*, Motohiro Maeda, and Kuniaki Kondo, *Member, IEEE*

***Abstract*—In the traditional designs against contamination of transmission line insulators, the maximum insulator contamination severity and insulator surface wetting are assumed as the most severe conditions. Then, the required number of insulator units per string is determined, where a safety margin of insulator unit(s) is usually allowed based on knowledge obtained at sites and in laboratory tests. Other insulator designs may be created by considering the probabilistic distributions of factors affecting insulator flashover, such as contamination severity, surface wetting, and flashover voltage. Based on this concept, flashover risk, which indicates flashover probability in a certain period, is used in this study as an evaluation function of reliability. The characteristics of flashover risk are discussed, and the proposed probabilistic method is applied to the insulation design of a 500 kV ac transmission line. Assuming a certain acceptable flashover risk, the number of cap-and-pin insulator units per string is calculated and compared with that obtained using the conventional deterministic method. When the number of insulator units per string is fixed, flashover risk can determine the number of flashover events in a certain period, such as a year. Findings suggest that the probabilistic approach is a potential insulation design method under contamination conditions.**

***Index Terms*—Contamination, flashover risk, insulator, probability, transmission lines, wetting.**

I. INTRODUCTION

TRASMISSION line insulators are traditionally designed using the deterministic method. The worst contamination and wetting conditions are assumed, and a certain margin is set between the withstand and target operating voltages. This approach is persuasive because the said margin depends on long-term performance of insulators at sites and/or results of artificial contamination tests conducted in laboratories. Most insulation designs developed using this method are safe as the probability of the worst contamination and wetting conditions is extremely low.

However, a probabilistic approach based on flashover may result in more rational and therefore more economical designs. In such a method, a proper evaluation function of flashover probability is derived using the probability distribution functions of factors affecting flashover. Flashover voltage is a probabilistic variable affected by insulator contamination severity and insulator surface wetting, which have distinct statistical distributions depending on the environmental conditions at the installation sites of insulators.

Probabilistic approaches can be classified into two categories: static and dynamic methods. In a static method, the probability functions of flashover voltage and factors affecting flashover are considered, and insulation reliability in a certain period is evaluated. In a dynamic method, real-time reliability is calculated using time-varying instantaneous values of factors affecting flashover. The flashover performance of contaminated ceramic insulators was analyzed via both static [1], [2], [3], [4], [5] and dynamic [6], [7], [8] methods from the 1970s to the 1990s.

Probabilistic approaches have been attracting attention again since the statistical approach for flashover of contaminated insulators was provided in an appendix of an IEC standard [9]. Application cases of these probabilistic methods have been reported for ac [10] and dc [11]. These papers proposed statistical approaches considering log-normal statistical distributions of the equivalent salt deposit density (ESDD; mg/cm^2) and non soluble deposit density (NSDD; mg/cm^2) based on many measurements. The unified specific creepage distance (USCD) is defined as a function of the salt deposit density (SDD; mg/cm^2). The relation between the number of flashover events per year and required insulator length is calculated under a given condition. Statistical approaches permit a more rational design in general, but the evaluation function of flashover probability has not been clarified.

A statistical method of flashover probability assessment was proposed to develop a unified model applicable to various insulators with different shapes [12]. Based on fog test results of insulators with different specifications, flashover voltage is regressed as functions of leakage distance, ESDD, hydrophobicity, form factor, and form factor ratio. Then, flashover probability is calculated by standardizing the flashover voltage distribution.

A more comprehensive and practical discussion is needed to apply the probabilistic approach to actual insulator design

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Yukio Mizuno is with the Department of Electrical and Mechanical Engineering, Nagoya Institute of Technology, Nagoya 466-8555, Japan (e-mail: mizuno.yukio@nitech.ac.jp).

Motohiro Maeda is with the Engineering Section, Energy & Industry Business Group, NGK Insulators, Ltd., Nagoya 467-8530, Japan (e-mail: moto–mae@ngk.co.jp).

Kuniaki Kondo is with the NGK High Voltage Laboratory, Energy & Industry Business Group, NGK Insulators, Ltd., Nagoya 467-8530, Japan (e-mail: kondok@ngk.co.jp).

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TABLE I
COMPARISON OF DETERMINISTIC AND PROPOSED PROBABILISTIC DESIGNS

	Deterministic design	Proposed probabilistic design
Input	-voltage -insulator contamination severity	-voltage -insulator contamination severity -number of strings -acceptable flashover risk*

Design process	-determination of withstand voltage (kV/unit) based on laboratory tests and field experience
	-consideration of a certain margin
		-derivation of evaluation function (flashover risk)
		-determination of statistical distribution of
		  -insulator contamination severity (ESDD, NSDD)
		  -insulator surface wetting (relative humidity)
		  -flashover voltage (standard deviation of 50% FOV and truncation rate on low-voltage side)
		-calculation of flashover risk for each number of insulator units

Output	-required number of insulator units per string	-required number of insulator units per string to achieve the acceptable flashover risk*

*When the number of insulator units per string is inputted, the number of flashover events of insulator strings in a certain period (number of flashovers/certain period) or a period in which one flashover occurs can be outputted.

against contamination. One of the authors has proposed a probabilistic flashover assessment of transmission line insulators in [4], where the evaluation function of flashover risk was derived. Basic studies of risk of failure were performed as the first step of the probabilistic approach [4], [5]. The present study is intended to progress the proposed approach to the next stage and to discuss a possibility of its application to a practical insulation design of transmission line insulators under contamination conditions through a case study.

Table I outlines the deterministic design and the proposed probabilistic design. The effect of the statistical distributions of flashover voltage, insulator contamination severity, and insulator surface wetting on flashover risk is discussed first. Then, assuming five levels of flashover risk, the number of cap-and-pin insulator units required per string of a 500 kV ac transmission line is calculated probabilistically to compare the proposed probabilistic method and the conventional method.

II. PROBABILISTIC EVALUATION FUNCTION OF FLASHOVER

The probabilistic evaluation function of flashover (denoted as flashover risk) derived in our previous paper [4] is explained briefly.

Flashover voltage follows a normal distribution [4]. Thus, the flashover probability of a single insulator string is expressed by (1).

$$P_1(U_x,\ w,\ h) = \frac{1}{\sqrt{2\pi}\sigma(w)} \int_0^{U_x} exp\left\{-\frac{1}{2}\left(\frac{t-V_{50}(w,\ h)}{\sigma(w)}\right)\right\}^2 dt, \quad (1)$$

where

$P_1(U_x, w, h)$: flashover probability of a single string under U_x, w, and h;
U_x : applied voltage;
w : insulator contamination severity;
h : degree of insulator surface wetting;
$V_{50}(w,h)$: 50% flashover voltage under w and h;
$\sigma(w)$: standard deviation of flashover voltage under the condition of w; and
t : dummy variable for integration.

Equation (2) gives the flashover risk of a single insulator string considering the statistical distributions of insulator contamination severity and insulator surface wetting. For simplicity, insulator contamination severity and insulator surface wetting are assumed to be independent of each other in this study.

$$R_1(U_x,\ w,\ h) = \iint P_1(U_x,\ w,\ h)\ f(w)\, g(h)\, dwdh, \quad (2)$$

where

$R_1(U_x, w, h)$: flashover risk of a single insulator string under U_x, w, and h;
$f(w)$: probability density function of insulator contamination severity; and
$g(h)$: probability density function of the degree of insulator surface wetting.

This concept is expanded to the case of N parallel insulator strings subjected to the same contamination and wetting conditions in a limited area. The flashover probability P_N and flashover risk R_N are given by (3) and (4), respectively.

$$P_N(U_x,\ w,\ h) = 1 - \{1 - P_1(U_x,\ w,\ h)\}^N, \quad (3)$$

$$R_N(U_x,\ w,\ h) = \iint P_N(U_x,\ w,\ h)\ f(w)\, g(h)\, dwdh, \quad (4)$$

where

$P_N(U_x, w, h)$: flashover probability of N parallel insulator strings under U_x, w, and h and
$R_N(U_x, w, h)$: flashover risk of N parallel insulator strings under U_x, w, and h.

When one-year statistical distributions are used for $f(w)$ and $g(h)$, (4) gives flashover risk in one year. Flashover is assumed to occur after the insulator surface is contaminated rapidly, dried, and wetted. Because this process consumes at least one day, flashover is considered to occur once a day at most. When flashover occurs every day (365 days), the flashover risk is regarded as 1. So, the product of 365 and flashover risk means the number of flashover days in a year. Considered from different angle, the flashover rate, which is the period during which one flashover event occurs, can also be calculated from flashover risk.

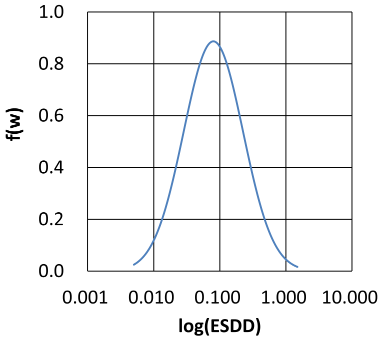


Fig. 1. Assumed statistical distribution of $f(w)$ based on measured ESDD obtained at exposure stand at Takeyama, Japan.

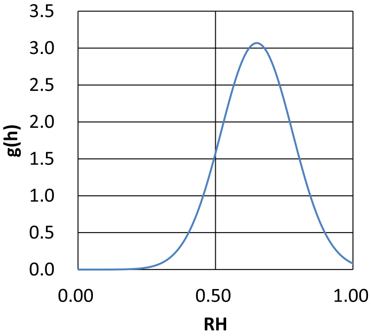


Fig. 2. Assumed statistical distribution of $g(h)$ based on RH recorded at Yokohama weather observatory station in Japan.

III. Factors Affecting Flashover Risk

Equation (4) indicates that the probabilistic distributions of insulator contamination severity $f(w)$, insulator surface wetting $g(h)$, and flashover voltage $P_N(U_x,\ w,\ h)$ affect the evaluation of flashover risk $R_N(U_x,\ w,\ h)$. In this section, statistical distribution functions of factors affecting flashover risk are formulated as examples, referring to available data.

A. Insulator Contamination Severity

Insulator contamination severity is reasonably represented by the ESDD. Few studies have been published about the statistical distributions of ESDDs recorded at fixed locations for long durations. One of available data are results of exposure tests of 250 mm cap-and-pin insulator strings performed for four years at Takeyama, Japan [13]. The upper and lower surfaces of three insulator units were washed separately with water and ESDD was measured every 3 months. Since the test site locates near the coast, quick salt accumulation by wind and self-cleaning by rain may result in large variation of ESDD (0.005–1.50 mg/cm^2).

In the present study, ESDD of the upper surface is used because of its higher value, and its statistical distribution is assumed by (5) for simplicity. The mean and standard deviation values are calculated according to their definitions from raw data. Fig. 1 shows the statistical distribution of *f*(*w*). The actual distribution does not satisfy (5) strictly.

$$f\ (w) = \frac{1}{0.45\sqrt{2\pi}}\, exp\left\{-\frac{1}{2}\left(\frac{log_{10}w - log_{10}0.08}{0.45}\right)^2\right\}. \tag{5}$$

f(*w*) is formulated based on four-year observation data, but flashover risk in a year is discussed in the present study. So, the *f*(*w*) is regarded as a one-year distribution function for convenience because ESDD data of one year is not available.

Although NSDD is also an important factor affecting flashover risk, it is not considered here due to the unavailability of its appropriate distribution. Nonetheless, the effect of NSDD on flashover risk is discussed in Section V.

B. Insulator Surface Wetting

Long-term measurement data of insulator surface wetting are unavailable, so relative humidity (RH) is used as an index of insulator surface wetting. Utilized RH data are hourly observation data recorded for a year at Yokohama weather observatory station near the place where the ESDD distribution is obtained. The actual distribution does not follow a normal distribution, but the probability density function of $g(h)$ is assumed by (6) and shown in Fig. 2. The mean and standard deviation values are calculated according to their definitions from raw data.

$$g\ (h) = \frac{1}{0.13\sqrt{2\pi}}\, exp\left\{-\frac{1}{2}\left(\frac{h - 0.65}{0.13}\right)^2\right\} \tag{6}$$

Actual wetting is affected not only by RH but also by other factors, such as the temperature difference between the insulator and the surrounding atmosphere. Such effects are not considered in this study for simplicity.

C. 50% Flashover Voltage

A series of experiments are conducted on the influence of the ESDD and RH on the flashover voltage of a small glass plate contaminated with NaCl (0.001, 0.005, 0.1, and 0.2 mg/cm^2) and kaolin (0.2 mg/cm^2) [14]. Dimension of the glass plate is 80 mm (length) x 50 mm (width) x 2 mm (thickness). The electrode distance is 60 mm. The glass plate is fixed horizontally, and flashover voltage is measured by the up-and-down method under the controlled RH (65–95%) and temperature (20 degrees C). The contamination layer suddenly shows a high conductivity at an RH of 75%, and the resultant flashover voltage drops drastically.

Since suitable experimental data are not available for transmission line insulators, it is assumed the results of glass plates in [14] can be applicable to insulator strings. An extrapolation gives the following equation:

$$\begin{aligned} V_{50}\,(w,h) \ &= K_h\left\{1 - \frac{1}{1 + exp\left\{-100\,(h - 0.75)\right\}}\right\} \\ &\quad + K_w w^{-0.2}\frac{1}{1 + exp\left\{-100\,(h - 0.75)\right\}}. \end{aligned} \tag{7}$$

K_h and K_w are constants related to the dry and contamination flashover voltages, respectively. K_h is determined based on the relation between flashover voltage and the length of insulator

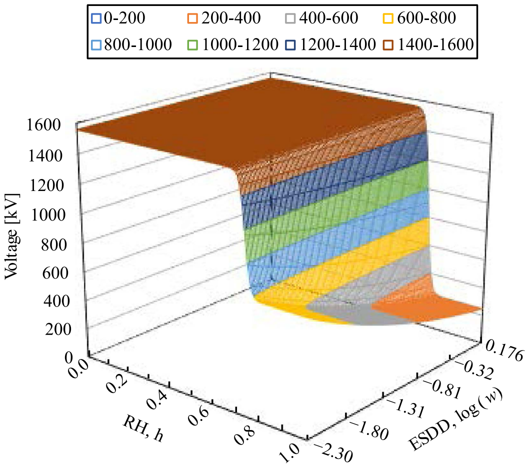


Fig. 3. $V_{50}(w,h)$ in case with 46 insulator units.

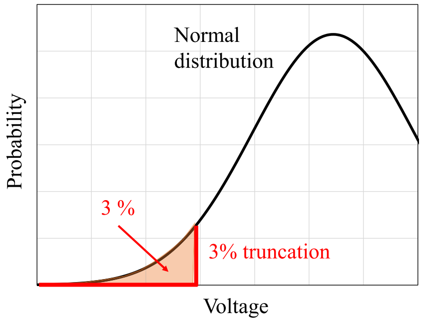


Fig. 4. Schematic illustration of 3% cut distribution.

string at RH = 0%. K_w is calculated based on ESDD dependence of withstand voltage of unit insulator at RH = 100%.

As an example, the ESDD and RH dependence of $V_{50}(w,h)$ in the case with 46 insulator units is shown in Fig. 3.

D. Standard Deviation of Flashover Voltage

The standard deviation σ of flashover voltage was about 0.05 (5%) in artificial contamination tests [15]. About 0.20 (20%) was obtained for naturally contaminated and wetted insulators [15]. Thus, both 0.05 and 0.20 are adopted as the values of σ.

E. Truncation of Flashover Voltage Distribution

When flashover voltage is expressed with a normal distribution, flashover probability approaches zero with a decrease in voltage but does not become exactly zero, even at an excessively low voltage. This does not agree with empirical facts. Here, this normal distribution is truncated mathematically to elucidate the effect of flashover probability on the low-voltage side on flashover risk. For example, a normal distribution is considered above the 1st percentile value, and the frequency is forced to be zero below the 1st percentile value. This distribution is denoted as "1% cut." Similarly, 3% and 5% cuts are considered. The concept of truncation is shown schematically in Fig. 4. A normal distribution without truncation (0% cut) is used as a reference.

The area between a truncated normal distribution curve and the horizontal axis shall be equal to 1, but the removed area of a truncated normal distribution is not compensated because of difficulty in establishing a persuasive normalization method. This is an issue in the future.

IV. CHARACTERISTICS OF FLASHOVER RISK

In this section, flashover risk in a year is calculated under various conditions using probabilistic distribution functions obtained in the previous section. The objective is to verify if characteristic behavior of flashover risk obtained by calculation shows the same trend as that of on-site and experimental results.

Provided that ESDD and RH are independent of each other, assessment is conducted for an assumed 500 kV transmission line with insulator strings of N = 8616. A number of insulator units per string larger than 60 is not appropriate to a typical 500 kV ac transmission line, but numbers up to 180 are assumed here to evaluate characteristics of flashover risk calculated by the proposed method. Non-linearity between flashover voltage and creepage distance in a very long insulator string is not considered.

Excel 2016 is used for calculation of flashover risk. The integration in (4) is performed numerically using the trapezoidal rule.

A. Effect of Insulator Contamination Severity on Flashover Risk

Fig. 5 shows 3- and 2-dimensional plots of $P_N(U_x,w,h)\ f(w)g(h)$ for a normal flashover voltage distribution (0% cut) as an example, where the number of insulator units per string is 46. The 2-dimensional plot is obtained by viewing the corresponding 3-dimensional plot from right above. High numerical values of $P_N(U_x,w,h)\ f(w)g(h)$ are obtained in a limited region of ESDD and RH. This is explained by their statistical distributions shown in Figs. 1 and 2. Because of the RH dependence of 50% flashover voltage shown in Fig. 3, the numerical value of $P_N(U_x,w,h)\ f(w)g(h)$ is zero below RH<0.75. In the case of $\sigma = 0.20$, the value is not zero for the wider range of ESDD and RH values, which is attributed to the broad distribution of flashover voltage.

The values of flashover risk, which can be obtained as the volume integral of the solid region of 3-dimensional plots in Fig. 5, are 0.020 and 0.270 for σ values of 0.05 and 0.20, respectively. If flashover is assumed to occur once a day as described in Section II, flashover risk of 0.020 means that flashover will occur in about seven days in a year ($365 \times 0.020 = 7.3$).

B. Effect of Number of Insulator Units in String on Flashover Risk

Fig. 6 shows flashover risk as a function of the number of insulator units per string when the flashover voltage follows a normal distribution (0% cut). Flashover risk decreases gradually with an increase in the number of insulator units per string, which is a reasonable result. Flashover risk is higher for a larger σ for a given number of units. This is attributed to the fact

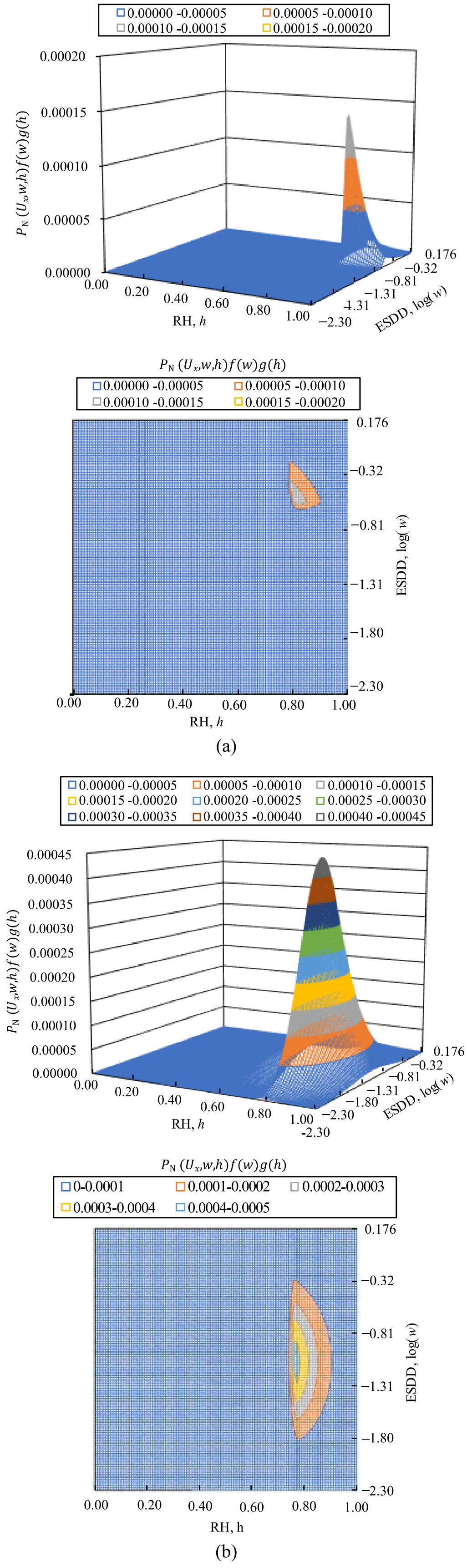


Fig. 5. $P_N(U_x, w, h)\ f(w)g(h)$ for 0% cut distribution. Number of insulator units per string is 46 and N = 8616. (a) $\sigma = 0.05$. (b) $\sigma = 0.20$.

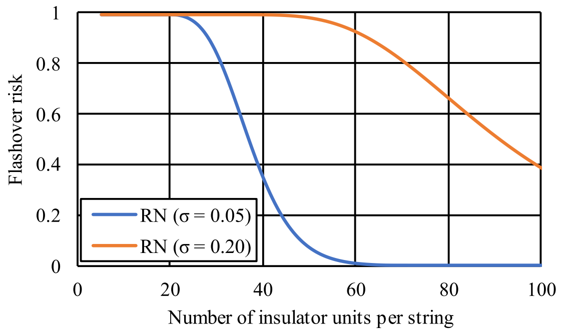


Fig. 6. Flashover risk as function of number of insulator units per string (N = 8616).

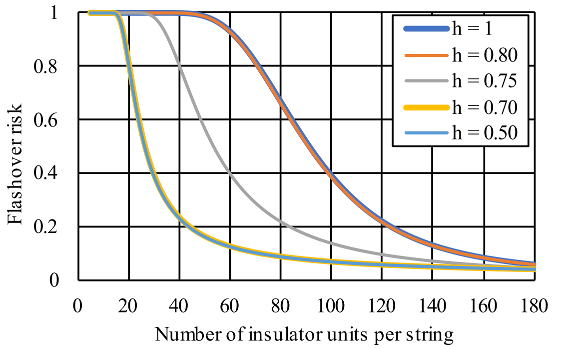


Fig. 7. Effect of h on flashover risk in case with 0% cut distribution, $\sigma = 0.20$ (N = 8616).

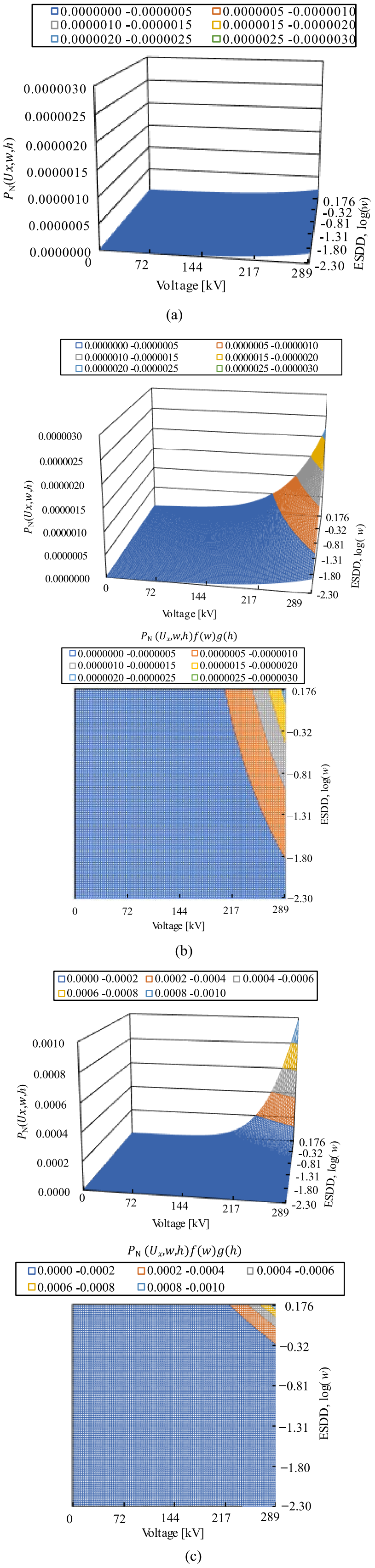
that $P_N(U_x, w, h)\ f(w)g(h)$ is not zero for the wider range of variables, as shown in Fig. 5(b).

C. *Effect of Insulator Surface Wetting on Flashover Risk*

The effect of RH on flashover risk is discussed here using a sample case where flashover probability follows a normal distribution (0% cut) with $\sigma = 0.20$. Fig. 7 shows that flashover risk for a given number of insulator units changes at an RH of 75% and remains almost the same above 75%. This is attributed to the assumed RH dependence of the 50% flashover voltage, as given by (7) and shown in Fig. 3. Fig. 7 also shows that a higher RH leads to a higher flashover risk for a given number of insulator units. Fig. 8 shows the flashover probability for 60 insulator units per string as an example. $P_N(U_x, w, h)$ is higher at a higher RH, resulting in an excessive flashover risk.

D. *Effect of Standard Deviation of Flashover Voltage on Flashover Risk*

Fig. 9 shows flashover risk as a function of the number of insulator units per string when flashover probability follows a 1% cut distribution. Flashover risk decreases gradually with an increase in the number of insulator units and is higher for a larger σ. This is because $P_N(U_x, w, h)\ f(w)g(h)$ is not zero for the wider range of variables. Compared with the case with a normal distribution (0% cut), flashover risk is lower for a given number of insulator units, especially for a large σ.



(a)

(b)

(c)

Fig. 8. Effect of RH on $P_N(Ux, w, h)$ in case with 0% cut distribution and $\sigma = 0.20$. Number of insulator units per string is 60 and N = 8616. (a) $h = 0.7$. (b) $h = 0.75$. (c) $h = 1$.

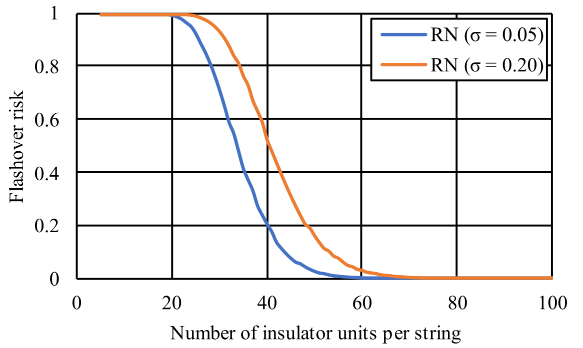


Fig. 9. Flashover risk as function of number of insulator units in case with 1% cut distribution (N = 8616).

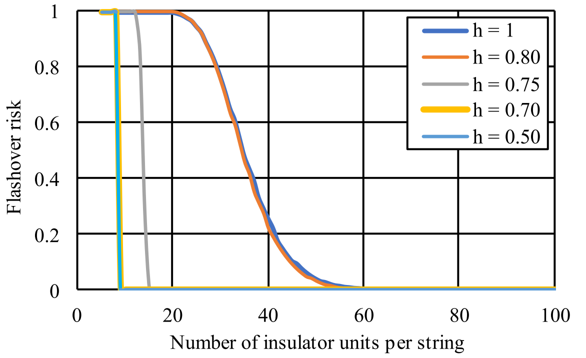


Fig. 10. Effect of RH on flashover risk in case with 3% cut distribution and $\sigma = 0.20$ (N = 8616).

TABLE II

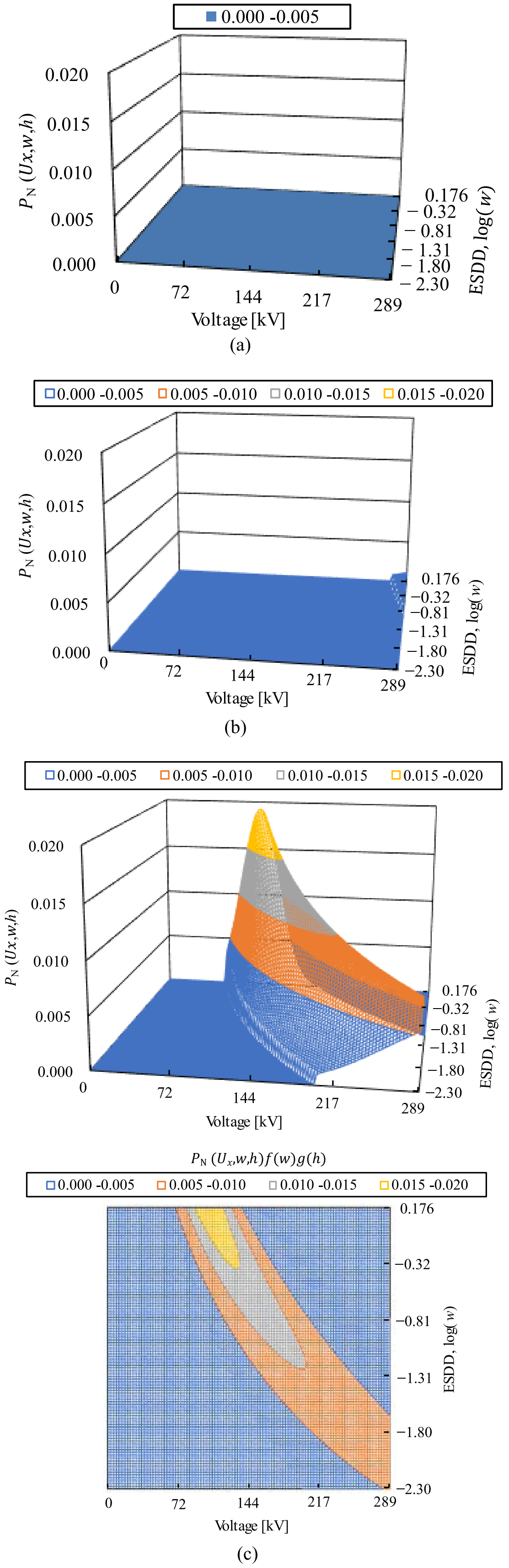
EFFECT OF RH AND TRUNCATION ON $P_N(Ux, w, h)$

Wetting h	Normal distribution (0% cut) (60 insulator units)		3% cut (14 insulator units)	
	σ = 0.05	σ = 0.20	σ = 0.05	σ = 0.20
0.50	0	0.125	0	0
0.70	0	0.127	0	0
0.75	0	0.398	0	0.291
0.80	0.005	0.924	0.994	0.994
1	0.007	0.926	0.994	0.994

E. Effect of Truncation of Flashover Probability on Flashover Risk

The effect of truncation on flashover risk under various RH conditions is shown in Fig. 10, where a 3% cut distribution of flashover probability and $\sigma = 0.20$ are used for calculation. Compared with the case with a normal distribution (0% cut; Fig. 7), flashover risk is considerably lower for a given number of insulator units. This is due to the fact that $P_N(U_x, w, h)$ is low even for a small number of insulator units, as shown in Table II. Fig. 11 shows $P_N(U_x, w, h)$ for 14 insulator units.

The characteristic behavior of flashover risk obtained by calculation shows the same trend as that of on-site and experimental results. Statistical distribution functions used in the present study are not universal, but the flashover risk assessment is available for any other statistical distribution functions.



(a)

(b)

(c)

Fig. 11. Effect of RH on $P_N(Ux, w, h)$ in case with 3% cut distribution and $\sigma = 0.20$. Number of insulator units per string is 14 and N = 8616. (a) $h = 0.7$. (b) $h = 0.75$. (c) $h = 1$.

TABLE III
INSULATION DESIGN OF EXISTING 500 KV AC TRANSMISSION LINE [16]

Nominal voltage (kV)	500	
Diameter of cap-and-pin insulator unit (mm)	280	
Expected ESDD (mg/cm^2)	0.063	0.50
Correction factor of ESDD	1.0	1.0
Coefficient of overvoltage	1.0	1.0
Designed withstand voltage of insulator (kV/unit)	10.8	7.2
Required number of insulator units per string	34	51

TABLE IV
CONDITIONS FOR CALCULATION OF FLASHOVER RISK

Applied voltage (kV)	289 (500 kV/$\sqrt{3}$)
Coefficient of contamination withstand voltage: k	6.74
Diameter of cap-and-pin insulator unit (mm)	280
Number of insulation strings: N	100, 600
99th percentile ESDD: w_{99} (mg/cm^2)	0.063, 0.50
Standard deviation of ESDD: σ_w	0.377 [18]
Range of ESDD: w (mg/cm^2)	0.0003-0.2 0.003-2
Standard deviation of flashover voltage: σ	0.05, 0.20
Truncation rate on low-voltage side of flashover voltage distribution (%)	0, 1, 3, 5

V. TRIAL INSULATION DESIGN OF 500 KV AC TRANSMISSION LINE

The proposed probabilistic method is applied to the insulation design of a 500 kV ac transmission line. The required numbers of cap-and-pin insulator units per string under assumed acceptable flashover risk levels are calculated, and the results are compared with those obtained by the conventional deterministic method. Five levels of flashover risk (10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, and 10^{-6}) are considered. If a flashover event is assumed to occur once a day as described in Section II, then a flashover risk of 10^{-2} means that flashover will occur once in 100 days. Likewise, flashover risk levels of 10^{-4} and 10^{-6} mean that one flashover event will occur in about 27.4 years and in over 100 years, respectively.

A. Calculation Conditions

Table III lists the details of the deterministic insulation design of an existing 500 kV ac transmission line in Japan [16]. The expected ESDD is set to 0.063 or 0.50 mg/cm^2, depending on the location of the transmission line. The designed withstand voltages of the insulator for w_{99} values of 0.063 and 0.50 mg/cm^2 are 10.8 and 7.2 kV/unit, respectively, which are obtained experimentally for 280 mm cap-and-pin insulators by fog and contamination tests [16].

Table IV summarizes the calculation conditions for the probabilistic insulation design. When relation between withstand voltage of an insulator unit Y kV and salt deposit density X mg/cm^2 is expressed as $Y = k*X^{-0.2}$, k is denoted as coefficient of contamination withstand voltage. For a 280 mm cap-and-pin insulator unit, $k = 6.74$ is obtained experimentally [17]. The length of transmission line is about 2 km in the case of N = 100, assuming one-circuit three-phase lines, four parallel insulator strings for one phase at one tower, and span of towers of 300 m.

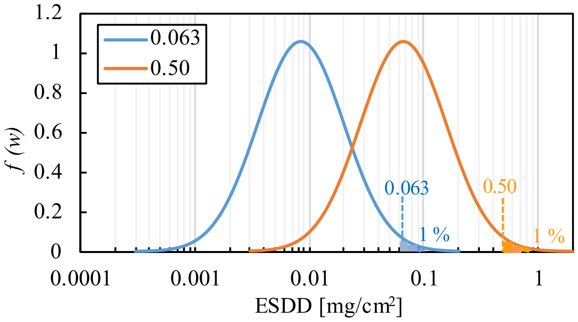


Fig. 12. Assumed distribution of ESDD for flashover risk calculation.

TABLE V
REQUIRED NUMBER OF INSULATOR UNITS PER STRING ($N = 600$, $w_{99} = 0.063\ \mathrm{mg/cm^2}$, $\sigma_w = 0.377\ \mathrm{mg/cm^2}$)

Flashover risk	Standard deviation $\sigma = 0.05$				Standard deviation $\sigma = 0.20$			
	Truncation (%)				Truncation (%)			
	0	1	3	5	0	1	3	5
10^{-2}	27	27	27	25	70	31	27	25
10^{-3}	31	31	30	29	151	35	31	29
10^{-4}	***34***	***34***	***33***	31	N/A	38	***33***	31
10^{-5}	***35***	***35***	***34***	32	N/A	40	***34***	32
10^{-6}	36	36	***34***	32	N/A	40	***34***	32

TABLE VI
REQUIRED NUMBER OF INSULATOR UNITS PER STRING ($N = 600$, $w_{99} = 0.50\ \mathrm{mg/cm^2}$, $\sigma_w = 0.377\ \mathrm{mg/cm^2}$)

Flashover risk	Standard deviation $\sigma = 0.05$				Standard deviation $\sigma = 0.20$			
	Truncation (%)				Truncation (%)			
	0	1	3	5	0	1	3	5
10^{-2}	41	41	40	37	102	46	40	37
10^{-3}	47	47	46	43	N/A	53	46	43
10^{-4}	***52***	***52***	***51***	48	N/A	59	***51***	48
10^{-5}	55	55	54	***50***	N/A	62	54	***50***
10^{-6}	57	57	54	***50***	N/A	62	54	***50***

Because of the unavailability of the statistical distribution of the ESDD in the area of the studied transmission line, a normal distribution is assumed; the 99th percentile value is set to 0.063 or 0.50 mg/cm^2. The resulting condition is less severe than that when the ESDD is fixed at 0.063 or 0.50 mg/cm^2 because the distribution contains smaller ESDD values. Fig. 12 shows the ESDD distribution, and its probability density function is expressed by

$$f\ (w) = \frac{1}{\sqrt{2\pi}\sigma_w}\, exp\left\{-\frac{1}{2}\left(\frac{log_{10}w - log_{10}\mu}{\sigma_w}\right)^2\right\}, \quad (8)$$

$$\sigma_w = \frac{log_{10}w_{99} - log_{10}\mu}{2.33}\ , \quad (9)$$

where

σ_w	: standard deviation,
μ	: average,
w_{99}	: 99th percentile value, and
2.33	: z value corresponding to a 99% probability in a standard normal distribution.

The average and standard deviation values of ESDD are calculated from raw data, which were measured monthly for 250 mm cap-and-pin insulator strings in an exposure test at Takeyama, Japan [17].

Three truncations (1%, 3%, and 5% cut) are used for flashover voltage distribution, and a normal distribution (0% cut) is used as a reference. Surface wetting h is set to 1 in the present study considering enough insulator surface wetting.

B. Results and Discussion

Table V lists the calculated required number of insulator units per string for $N = 600$, $w_{99} = 0.063$ mg/cm^2, $\sigma_{\mathrm{w}} = 0.377$ mg/cm^2, and five levels of flashover risk (10^{-2} to 10^{-6}) are provided. Table VI summarizes the results calculated under the same conditions except that w_{99} is changed to 0.50 mg/cm^2.

When the standard deviation σ of flashover voltage is 0.20, a larger number of insulator units is required compared with that under $\sigma = 0.05$ in the cases of 0% and 1% cuts. For a broad distribution with $\sigma = 0.20$, the value of $P_N(U_x, w, h)f(w)g(h)$ is not zero, even at low voltages, so the truncation of the normal distribution affects the calculation results. On the contrary, 3% or 5% truncation slightly affects the calculation results. The normal distribution (0% cut) is not suitable for the evaluation of flashover risk because the required number of insulator units is unreasonable in some cases. This is attributed to the fact that flashover probability is not exactly zero even at low voltage. Therefore, a higher w_{99} results in a larger required number of insulator units.

The required number of insulator units is mostly the same for $N = 100$–600 under the present calculation conditions, but it depends on N at a higher applied voltage.

The Italic and bold characters in Table V refer to cases where the calculated required number of insulator units is equal or close to 34. The value is obtained by the deterministic method for an ESDD of 0.063 mg/cm^2, as shown in Table III. The Italic and bold characters in Table VI are for an ESDD of 0.50 mg/cm^2, where the deterministic method gives 51 as the required number of insulator units.

In the case of $w_{99} = 0.063$ mg/cm^2, a comparison of the probabilistic and deterministic calculation results shows good agreement for flashover risk levels of 10^{-3} to 10^{-5} in the case of the 3% cut, regardless of the value of σ. An increase of one or two cap-and-pin insulator unit(s) per string leads to a one-digit-lower flashover risk. Under $w_{99} = 0.50$ mg/cm^2, regardless of the value of σ, the 5% cut findings generally agree well with the result obtained by the deterministic method for acceptable flashover risk levels of 10^{-5} to 10^{-6}. Flashover risk is decreased by an order of magnitude by increasing the number of cap-and-pin insulator units by two or three.

The NSDD is also an important factor affecting flashover risk. Since an appropriate distribution of the NSDD is unavailable, its effect on the number of insulator units per string is discussed using fixed values of 0.01, 0.1, 1, and 10 mg/cm^2. In the calculation of flashover risk, the coefficient of contamination withstand

TABLE VII
REQUIRED NUMBER OF INSULATOR UNITS PER STRING ($N = 600$, $w_{99} = 0.063\ \mathrm{mg/cm^2}$, $R_N = 0.01$)

NSDD ($\mathrm{mg/cm^2}$)	Standard deviation $\sigma = 0.05$				Standard deviation $\sigma = 0.20$			
	Truncation (%)				Truncation (%)			
	0	1	3	5	0	1	3	5
0.01	21	21	20	19	51	23	20	19
0.1	26	26	25	24	65	29	26	24
1	33	33	32	30	81	37	32	30
10	41	41	40	37	102	46	46	37

TABLE VIII
REQUIRED NUMBER OF INSULATOR UNITS PER STRING ($N = 600$, $w_{99} = 0.50\ \mathrm{mg/cm^2}$, $R_N = 0.01$)

NSDD ($\mathrm{mg/cm^2}$)	Standard deviation $\sigma = 0.05$				Standard deviation $\sigma = 0.20$			
	Truncation (%)				Truncation (%)			
	0	1	3	5	0	1	3	5
0.01	32	32	32	30	81	37	32	30
0.1	41	41	40	37	102	46	40	37
1	51	51	50	47	128	58	50	47
10	64	64	63	59	161	73	63	59

voltage k is replaced by k' as

$$k' = \left(\frac{w_n}{0.1}\right)^{-0.1} * k, \tag{10}$$

where w_n is the NSDD. The other calculation conditions in Table IV remain unchanged.

Tables VII and VIII show the required number of cap-and-pin insulator units to achieve a flashover risk of 0.01 when w_{99} is 0.063 and 0.50 $\mathrm{mg/cm^2}$, respectively. As the NSDD increases, more insulator units are required to avoid flashover. Thus, the statistical distribution of the NSDD should be obtained to improve the proposed method in the next step.

The results of this study indicate that the proposed probabilistic method offers potential as a design method for transmission line insulators. The results of the probabilistic method and the deterministic method cannot be fairly compared. Nonetheless, an economical design can be developed if a certain level of flashover risk is accepted realistically. The deterministic method offers a flexible margin between the withstand and target operating voltages in insulation design, but the probabilistic method provides an advantage that lies in the rationale of its flashover risk–based decision.

VI. CONCLUSION

A flashover risk-based probabilistic approach is discussed for an insulation design of transmission line under contamination conditions.

The proposed approach seems useful and promising for evaluating contamination performance of insulators quantitatively, because (i) the characteristic behavior of flashover risk obtained by calculation shows the same trend as that of on-site and experimental results, (ii) an economical design is enabled depending on the required reliability of a target transmission line, because the required number of insulator units per string can be calculated if a certain level of flashover risk is accepted, and (iii) in the case study on some assumptions, the number of insulator units per string is close to that obtained by the traditional deterministic method.

Further investigation will be necessary to establish an advanced probabilistic method reliable enough for practical insulation designs against contamination. Reliable statistical distributions of flashover voltage, insulator contamination severity, and insulator surface wetting should be acquired. This may be achieved by assessing the performance of existing transmission line insulators by considering, for example, the number of insulator units per string, applied voltage, contamination, years of operation, and number of flashover events.

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REFERENCES

[1] G. Karady, D. Dallaire, and D. Mukhedkar, "Statistical method for transmission line insulation design for polluted areas," in *Proc. IEEE PES WM Conf.*, Portland, OR, USA, 1976, pp. 18–23.

[2] J. Kucera and M. Plechanova, "A probability choice of insulators for alternating voltage and electric strength at switching impulse in the areas with pollution," *CIGRE Session*, Paris, France, pp. 1–6, Sep. 1982.

[3] M. Sforzini, R. Cortina, and G. Marrone, "A statistical approach for insulator design in polluted areas," *IEEE Trans. Power App. Syst.*, vol. PAS-102, no. 9, pp. 3157–3166, Sep. 1983.

[4] K. Naito, Y. Mizuno, and W. Naganawa, "A study on probabilistic assessment of contamination flashover of high voltage insulator," *IEEE Trans. Power Del.*, vol. 10, no. 3, pp. 1378–1384, Jul. 1995.

[5] Y. Suzuki, T. Fukuta, Y. Mizuno, and K. Naito, "Probabilistic assessment of flashover performance of transmission lines in contaminated areas," *IEEE Trans. Dielectrics Elect. Insul.*, vol. 6, no. 3, pp. 337–341, Jun. 1999.

[6] L. O. Barthold and L. Paris, "The probabilistic approach to insulation coordination," *Electra*, vol. 13, pp. 41–58, 1970.

[7] Y. Nagano, M. Igarashi, Y. Yagisawa, and S. Kitamura, "Estimation of polluting rate and effect of periodical cleaning for insulator by computer simulation," (in Japanese), *Trans. IEEJ*, vol. B-98, no. 11, pp. 887–894, 1978.

[8] Y. Mizuno, H. Nakamura, and K. Naito, "Dynamic simulation of risk of flashover of contaminated ceramic insulators," *IEEE Trans. Power Del.*, vol. 12, no. 3, pp. 1292–1298, Jul. 1997.

[9] IEC, "Selection and dimensioning of high-voltage insulators intended for use in polluted conditions - Part 1: Definitions, information and general principles," IEC, Geneva, Switzerland, Tech. Specification 60815-1, 2008.

[10] A. Pigini and R. Cortina, "Evaluation of the performance of polluted insulators under DC: A statistical approach," in *Proc. 17th ISH*, Hannover, Germany, Aug. 22-26, 2011.

[11] A. Pigini and I. Gutman, "Evaluation of the performance of polluted insulators: The IEC simplified approach against the statistical approach," presented at the INMR World Congr.: Insulators, Arresters, Bushings, Cable Accessories, Vancouver, BC, Canada, Sep. 8–11, 2013.

[12] L. Cui and R. S. Gorur, "A statistical model for predicting flashover of outdoor insulators," in *Proc. IEEE Conf. Elect. Insul. Dielectric Phenomena*, Toronto, ON, Canada, 2016, pp. 837–840.

[13] Y. Imao, T. Sugimoto, and T. Taniguchi, "Natural pollution tests on insulators for 500 kV transmission line: Part I salt deposit characteristics," (in Japanese), Central Res. Inst. Electric Power Ind., Tokyo, Japan, Rep. 71112, 1972.

[14] T. Kawamura and K. Isaka, "Humidity dependence of absorption density of moisture, leakage current and flashover voltage upon the polluted surface of the insulator," (in Japanese), *Trans. IEEJ*, vol. 93-b, no. 9, pp. 426–433, 1973.

[15] K. Naito, R. Matsuoka, and H. Shinokubo, "Investigation of the insulation performance of the insulator covered with lichen," *IEEE Trans. Power Del.*, vol. 5, no. 3, pp. 1634–1640, Jul. 1990.

[16] Electric Technology Research Association, “Rationalization of insulation design,” (in Japanese), *Soc. Elect. Cooperative Res.*, vol. 44, no. 3, pp. 1–285, 1988.

[17] Electric Technology Research Association, “Design of transformation facilities against salt contamination,” (in Japanese), *Soc. Elect. Cooperative Res.*, vol. 35, no. 3, pp. 1–129, 1979.

Yukio Mizuno (Member, IEEE) was born in Nagoya, Japan, in 1958. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from Nagoya University, Nagoya, Japan, in 1981, 1983, and 1986, respectively.

From 1986 to 1993, he was a Research Assistant with the Toyohashi University of Technology, Toyohashi, Japan. In 1993, he joined the Department of Electrical and Computer Engineering, Nagoya Institute of Technology, Nagoya, Japan, as an Associate Professor. He is currently a Professor with the Department of Electrical and Mechanical Engineering, Graduate School of Engineering, Nagoya Institute of Technology. His research interests include electrical insulation diagnosis, high voltage insulation, superconducting power cable, quantification of power frequency electric, and magnetic fields.

Dr. Mizuno is a Fellow of the Institute of Electrical Engineers of Japan and a member of Cryogenic Association of Japan and CIGRE.

Motohiro Maeda was born in Nagoya, Japan, in 1984. He received the B.Sc. and M.Sc. degrees in electrical engineering from the Nagoya Institute of Technology, Nagoya, Japan, in 2006 and 2008, respectively.

In 2008, he joined NGK Insulators, Ltd. He has been engaged in insulator contamination. He is currently a Manager of Engineering section, Energy & Industry Business Group.

Mr. Maeda is a member of the Institute of Electrical Engineers of Japan, and CIGRE.

Kuniaki Kondo (Member, IEEE) was born in Nagoya, Japan, in 1967. He received the B.Sc., M.Sc., and Ph.D. degrees in electrical engineering from the Nagoya Institute of Technology, Nagoya, Japan, in 1990, 1992, and 1997, respectively.

In 1992, he joined NGK Insulators, Ltd. He has been engaged in insulator contamination. He is currently a Manager of NGK High Voltage Laboratory, Energy & Industry Business Group.

Dr. Kondo is a Senior Member of the Institute of Electrical Engineers of Japan, and a Member of CIGRE.