'94 KACC (1994. 10. 17 ~ 20)

Modeling and Prediction of Rapid Pollution of Insulators in Substations Based on Weather Information

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Abstract

Mathematical model of the pollution rate of substation insulators is constructed, taking the model parameters as wind speed, wind direction, typhoon conditions and rainfall in an hourly basis. The main feature of model construction is to distinguish the effect of each parameter by separately analyzing the positive and negative pollution causing factors. Model parameters for the insulators of Karatsu substation, Saga, Japan were estimated and model validation was done using the actual data, in which the pollution deposits on the insulators were measured using a pilot insulator and 'salt meter'. The proposed model of the pollution rate [mg/cm^2/hr] enables the identification of the effective parameters and prediction of the pollution rate so that it helps for the automatic decision making for insulator cleaning or the model can be used as a tool for the substation engineers to make precautionary measures.

1. Introduction

High voltage insulators of substations near the coastal areas are subjected to rapid pollution because of the large salt content in the wind. It has been experienced that the pollution rate comes to hazardous levels within two or three hours, especially at the times of high winds and typhoons. Therefore frequent measurements of pollution deposits are extremely important, and depending on these measurements, substation engineers decide on the time for insulator washing. In practice the decision making for insulator washing is entirely dependent on the measurements of pollution levels and to a certain extent on past experience. Some substations are fully automated and the correct time for the decision of insulator washing becomes impracticable.

Extensive studies on the electric fields around a HV insulator [2], modeling of pollution flashover [3] and critical levels of flashover [1] has been done worldwide. But, identification of the pollution causing factors and a model construction for the pollution content using weather related parameters have not been done so far to the knowledge of authors. Therefore this problem still prevails and sometimes adhoc rules to decide the time for insulator washing are followed at certain substations. For example, Nishi Kyushu Substation in Saga prefecture, Japan follows the rule that if the measurements of pollution records exceeds .03 mg/cm^2 or the pollution difference of consecutive records exceeds .003 mg/cm^2/hr, then the decision for washing is made. Further, if the pollution level goes beyond .06 mg/cm^2 then the substation has to be shut down and insulators to be washed because the hot-line washing may ignite flashover.

This work is aimed at the identification of the critical factors and their threshold values for the insulator pollution, and proposes a model of the pollution rate [mg/cm^2/hr] of high voltage insulators. Basic concepts of the model construction and the identification of the most influential parameters were originated from the analysis of the actual data of the pollution deposits collected at three hour sampling interval (sampling interval of measurement was reduced to one hour at the hazardous times) and measurements of wind speed, wind direction, rainfall, temperature, humidity and sea level data in an hourly basis collected over a six month period from the Karatsu Substation in Saga prefecture of Japan. The Karatsu Substation is just one kilometer range from the sea and it is one of the badly hit substations from salty winds.

The proposed model of this paper is a generalized model and it is validated for the insulators in Karatsu substation. The proposed algorithm can be applied to any insulators, to find out the pollution rate at given wind speeds, wind directions, rainfalls and knowing whether the atmosphere is stable or unstable (presence of typhoons). Finally, the estimated pollution rate and the estimated accumulated pollution deposits can be made use for the automatic decision making for insulator washing and to find out the critical times. Further, just by predicting the wind speed and rainfall, the pollution rate can be predicted. This is a very valuable information for substation engineers to make precautionary actions at the times of hazardous situations.

2. Collection And Allocation of Data

The available data are, average wind speed [m/s], wind direction, accumulated rainfall [mm/hr], mean temperature [°C], humidity [%] and sea level [mm] in hourly basis, and pollution deposits [mg/cm^2] collected at variable sampling intervals, depending on the criticality of weather conditions. The data of pollution deposit have been collected at every three hour interval at normal winds and every one hour interval at the times of typhoons.

2.1 Collection of pollution data

The pollution deposits of the substation insulators were measured by using a pilot insulator and a salt meter. The measuring parameter is the leakage current at a particular D.C. voltage (10kV) and a particular humidity level (70%). Afterwards, the corresponding pollution deposit is determined from the standard graphs of the leakage current vs the pollution deposit. At first the pilot insulator is immersed in the salt meter and the humidity level in the containment is raised to 70% using vapor, to have a sufficiently wet insulator. After that 10kV D.C. voltage is applied across the electrodes in the pilot insulator and the leakage current is measured. The corresponding pollution deposit in mg/cm^2 is taken from the available graphs. After having finished the process, the insulator is dried and lifted out of the salt meter and positioned at the same height of other insulators. The entire process takes approximately 30 minutes.

Despite some small errors in the measurements due to the non-uniform distribution of pollution deposits [1] and no effect of pollution during the period in the compartment of the salt meter, this method is widely adopted to get continuous measurements because there is no other reliable method to get the pollution deposit data of the substation insulators.

2.2 Data allocation and identification of influential parameters

As the pollution deposits were measured at three hour sampling interval under normal conditions and the other data were collected at one hour sampling interval, proper matching of the parameter values were impossible while getting the maximum possible information from the available data.

At first the data collected just after the manual washing were removed as the objective of analysis is to find out a relationship between the pollution rate and the weather related parameters. The correlation analysis of the data revealed that the correlation coefficient between the pollution rate and each of the parameter was less than .5. The low correlation was mainly due to the complex relationship of the parameters with the pollution rate. For example, it is a fact that rapid pollution occurs at high winds and natural washing happens in rains. But, neither of these phenomena will be revealed if simultaneous rains and high winds are present. This really happened in the actual data analysis. Therefore, some kind of subdivision of data were required to identify the effect of parameters for insulator pollution.

Since the prominent parameters are wind speed, wind direction, typhoons and rainfall, at first the data were subdivided into two: the data with the effect of rainfall (negative pollution causing factors) and the data with no rainfall (positive pollution causing factors). As the pollution data at rainfall are a combination of the negative effect due to rainfall and the positive effect caused by wind speed, typhoons and other factors, it was understood that the phenomenon of positive pollution causing factors has to be fully understood first, and then the data with the effect of rainfall should be dealt with.

Presence of typhoons was guessed to be an important factor to be considered because the pollution rate at the times of typhoons were different from the normal situations even under the same conditions of the other parameter values. Therefore, typhoon conditions was also taken as a parameter.

Wind direction happens to be an another influential parameter for pollution because the salt content in the wind differs with the distance between the substation and the nearest point to the sea. Therefore wind direction can be divided into groups by considering the geographical situation and the average distance from sea.

Preliminary analysis of the data (Sept, Oct of 1992 and Sept-Dec. of 1993) collected from Karatsu substation were analyzed after excluding the data with the effect of rainfall and allocating them into a two dimensional distribution formed by wind direction (four divisions) and typhoon conditions (two divisions: whether a typhoon is present or not). The analysis revealed that the wind speed has a clear effect on the pollution rate but atmospheric temperature, humidity and sea level had a correlation less than .3 with the pollution rate. Therefore, wind speed, wind direction, typhoon and rainfall are taken for the model construction of the pollution deposit rate on insulators.

3. Model of The Pollution Rate

As mentioned in the previous section, at first the phenomenon of positive pollution causing factors has to be identified before being constructed a complete model of the pollution rate. The proposed method of the separation of the positive and negative pollution causing factors can be mathematically expressed as

$$\hat{P} = \hat{P}^{+}(V_w, V_d, Ty) + \hat{P}^{-}(R), \qquad (1)$$

where $\hat{P}$ is the estimated pollution rate [mg/cm^2/hr], which is a function of wind speed (V_w), wind direction (V_d), typhoon (Ty) and rainfall (R), $\hat{P}^+$ is the positive pollution rate which is only a function of V_w, V_d and Ty, and $\hat{P}^-$ is the negative pollution rate which is the effect of natural washing due to rainfall, R.

Next step is to find out the functions $\hat{P}^+$ and $\hat{P}^-$ of (1) separately. The proposed algorithm is to collect P^+ data, at first, by excluding the data at the times of rainfall. As P^+ is a three dimensional distribution of V_w, V_d and Ty, it is proposed to allocate the data of P^+ and the corresponding V_w data into groups formed by the two dimensional distribution of V_d and Ty. This enable to find out a general expression of the positive pollution rate in terms of V_w, V_d and Ty using the available small number of data.

3.1 Model of positive pollution rate

Since the effect of wind direction depends on the geographical situation of the concerned substation, let's assume that the wind direction is divided into m groups $V_d(1), V_d(2), \cdots V_d(m)$, concerning the location of the substation and distance from the sea in each direction.

The parameter 'typhoon', Ty can be divided into two groups as, presence of typhoons, $Ty(1)$ and no typhoon $Ty(0)$, because the actual data revealed that the pollution differs whether a typhoon is present or not even under the same conditions of other parameters. This fact can be explained as, turbulent intensity of wind is very much higher at typhoons than normal situations. Therefore, the measured one hour average wind speed is quite different from the extreme wind speeds during the one hour period. Further, due to the high turbulence of wind and instability of air and sea, the salt content of wind is high at the times of typhoons.

Since the approach is to identify the relationship between each groups of parameters and finally construct a general model of the positive pollution rate, the appropriate expression can be represented by

$$\hat{P}^{+}(V_w, V_d(i), Ty(j)) = W_d(i)\, W_{Ty}(j)\, \hat{P}^{+}(V_w, V_d(1), Ty(0)) \quad (2)$$

where $W_d(i)$ is the weighting element corresponding to the ith group of wind direction, with reference to the selected $V_d(1)$ group. Similarly, $W_{Ty}(j)$ is the weighting element corresponding to the jth group of typhoon, with reference to the $Ty(0)$ group. $\hat{P}^+(V_w, V_d(1), Ty(0))$ is a function of the positive pollution rate in terms of wind speed, V_w corresponding to the data in the group of $\{V_d(1), Ty(0)\}$.

There are several methods for the functional fit of $\hat{P}^+(V_w, V_d(1), Ty(0))$, but this paper proposes general least square method. The proposed model of $\hat{P}^+$ can be found in the form of

$$\hat{P}^{+}(V_w, V_d(1), Ty(0)) = \begin{cases} f_1(V_w) & : \quad V_w \geq V_1 \\ f_2(V_w) & : \quad V_1 > V_w \geq V_2 \\ f_i(V_w) & : \quad V_{i-1} > V_w \geq V_i \\ f_n(V_w) & : \quad V_n > V_w \end{cases} \qquad (3)$$

where the threshold values of wind speed, V_1, V_2, $\cdots V_i$ and V_n depend on the type of data and location of the substation.

After having determined the function of $\hat{P}^+(V_w, V_d(1), Ty(0))$ of (3), the pollution data in any group of $\{V_d(i), Ty(0)\}$ can be used (The weighting element $W_{Ty}(j)$ becomes unity in the level of $Ty(0)$) to get the weighting element $W_d(i)$ corresponding to the i th level of the parameter, V_d, by the expression

$$\hat{P}^{+}(V_w, V_d(i), Ty(0)) = W_d(i)\, \hat{P}^{+}(V_w, V_d(1), Ty(0)), \qquad (4)$$

where $\hat{P}^+(V_w, V_d(1), Ty(0))$ is the estimated P^+ from (3) for a given values of V_w, V_d and Ty. The optimum $W_d(i)$ can be estimated by minimizing the error between the actual data of the pollution rate, P^+ in the group of $\{V_d(i), Ty(0)\}$ and the estimated pollution rate, $\hat{P}^+$ for the same values of V_w, V_d and Ty. The general least square method gives the estimate of $W_d(i)$ from

$$W_d(i) = \left(\frac{\sum^N \{ P^+(V_w, V_d(i), Ty(0)) \; \hat{P}^+(V_w, V_d(1), Ty(0)) \}}{\sum^N (\hat{P}^+(V_w, V_d(1), Ty(0)))^2} \right) \quad (5)$$

where N is the total number of data in the group of $\{V_d(i), Ty(0)\}$. Likewise, the weighting element $W_{Ty}(j)$ of (2) can be found by using the data in the group of $\{V_d(1), Ty(1)\}$. In the level of $V_d(1)$, the weighting element, $W_d(1)$ is equal to one and the equation (2) is reduced to the form of

$$\hat{P}^+(V_w, V_d(1), Ty(j)) = W_{Ty}(j) \; \hat{P}^+(V_w, V_d(1), Ty(0)). \quad (6)$$

Similar to the estimation of $W_d(i)$, the weighting element, $W_{Ty}(j)$ can be estimated using the expression (5), for the data sets in the group of $\{V_d(1), Ty(j)\}$.

3.2 Model of negative pollution

Having known the actual pollution rates P, and with reference to (1), the data of the negative pollution rate can be constructed from

$$P^-(R) = P - \hat{P}^+(V_w, V_d, Ty) \quad (7)$$

where $\hat{P}^+(V_w, V_d, Ty)$ is estimated from (2) at the given wind speed V_w, wind direction V_d and typhoon condition Ty. With the assumption that the natural washing or the negative pollution rate $P^-(R)$ is proportional to the content of water falling onto the insulator within an hour, the model of the negative pollution rate can be represented by the linear relationship of ,

$$\hat{P}^-(R) = b_0 \, R \quad (8)$$

where b_0 is the parameter to be estimated from the data of $P^-(R)$ and the accumulated rainfall within an hour, R. This can be determined using the same least square method done, to find out $W_d(i)$, as in (4) and (5). It is to be noted that the maximum value of $|P^-(R)|$ is subject to the constraint of the net pollution deposit $(\sum P)$ at the time of estimation.

The generalized expression of the pollution rate can be determined by substituting (2) and (8) in (1).

4. Model Estimation and Validation

The data collected at the Karatsu substation for a period of six months were used for the estimation of the parameters of the models. At first, wind direction was divided into four groups (m=4), considering the location of the Karatsu substation, as shown in Fig. 1. The four groups are accordingly, wind from the direction covered by N-NE ($V_d(1)$), NEE to E ($V_d(2)$), SEE to SW ($V_d(3)$) and SWW to NWN ($V_d(4)$). As seen from the map in Fig. 1, $V_d(1)$ has the minimum distance from the sea and $V_d(3)$ is practically infinite distance from the sea.

4.1 Model estimation

To find out the model of the positive pollution rate, as given by (3), the data, excluding the rainfall, were allocated into eight groups formed by the two dimensional distribution of wind direction ($V_d(1), \cdots V_d(4)$) and typhoon ($Ty(0), Ty(1)$).

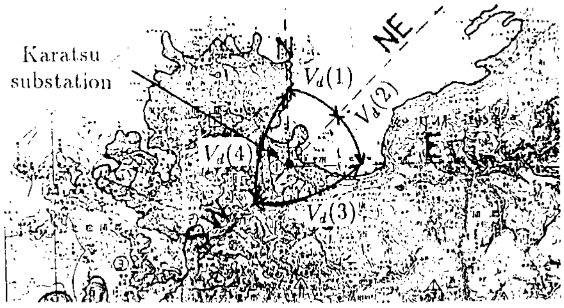

Figure 1 The geographical situation of the Karatsu substation

Since the rapid pollution is the concerned factor in this analysis, only the data with the positive pollution $P^+ \geq .0002$ mg/cm^2/hr were considered for model estimation. According to (2) and (3), the estimated model in the group of $\{V_d(1), Ty(0)\}$ is

$$\hat{P}^+(V_w, V_d(1), Ty(0)) = \begin{cases} .000038V_w^2 \; -.000355V_w + .0011 \\ \qquad : \quad V_w \geq 5. \\ .000025V_w \\ \qquad : 5 > V_w \end{cases} \quad (9)$$

The optimum values of the weighting elements $W_d(i)$ of (2) were estimated from (5), to be $W_d(1)$=1, $W_d(2)$=.79, $W_d(3)$=.40 and $W_d(4)$=.57. Similarly, the weighting element associated with typhoons, $W_{Ty}(1)$ was estimated as 2.15. The values of $W_d(2)$, $W_d(3)$ and $W_d(4)$ really comply with the relative distances to the sea (Fig. 1), with respect to that of the group $V_d(1)$.

The plot of the data of pollution rates and associated models, estimated from (2) are shown in Fig. 2.

By following the procedure described in the Section 3.2, the model of the negative pollution rate $P^-(R)$ was estimated and b_0 of (8) was found to be equal to -.0001075 when the rainfall, R is in mm. Now, we are in a position to calculate the pollution rate at any given values of wind speed, wind direction, knowing the presence of typhoons and rainfall.

4.2 Model validation

Data collected from the Karatsu substation during the month of Nov., 1993 were used for model validation. Even though the model construction was done using a selected set of data and grouped them into different levels, the model validation is done for the continuous set of time series data.

As the measurements of pollution deposits were not taken at every hour and the proposed model of (1) estimates the pollution rate per hour [mg/cm^2/hr], the estimated pollution difference during the period of the measurements of pollution deposit has to be obtained by summing up the estimated pollution rates over the period of consecutive measurements. Fig. 3 shows the results of the model validation for the actual data of wind speed, wind direction, typhoon conditions and rainfall data in an hourly basis. The actual data of the pollution difference (ΔP) over the measurement interval of pollution, and the estimated pollution difference ($\hat{\Delta P}$) , by summing up the estimated pollution rate (P^+) over the sampling interval, were also shown. The model error

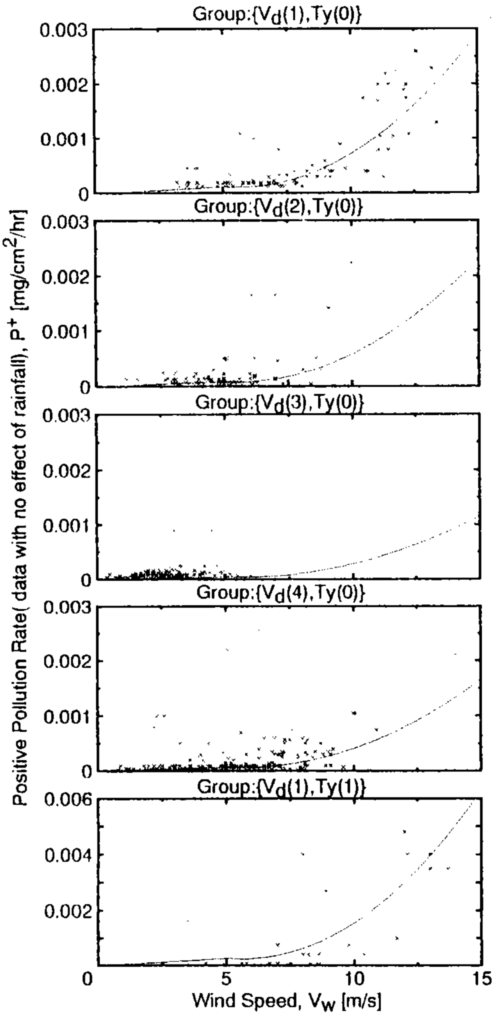

Figure 2 The estimated models and the actual data of the positive pollution rates (excluding the data with the effect of rainfall) with wind speed in four groups of the two dimensional distribution with the parameters, wind direction ($V_d(1)$, $V_d(2)$, $V_d(3)$, $V_d(4)$) and typhoon ($Ty(0)$ and $Ty(1)$).

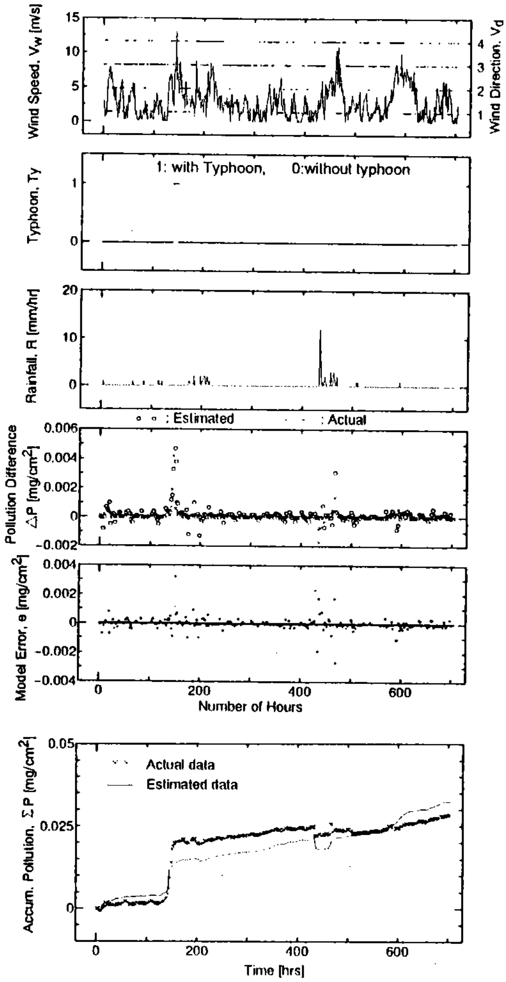

Figure 3 Model validation for the data collected from Karatsu substation in November, 1993.

shown in Fig. 3 was defined by

$$e(i) = \Delta P(i) - \sum_{t=t-T_i}^{t} (\hat{P}(v_w, V_d, Ty, R), \qquad (10)$$

where $\Delta P(i)$ is the actual pollution difference of the ith measurement at time t, and T_i is the time between the $(i-1)$ th and i th measurement of the pollution deposit.

The results (Fig. 3) of the accumulated pollution ($\sum P$) and model error (e) indicate that the model is reasonably good and give satisfactory results over the frequently available range of the wind speed and rainfall. The standard deviation of the model error, σ_e was .00046 [mg/cm^2] compared to $\sigma_{\Delta P}$=.00055 of that of the actual data of pollution differences. This implies that the overall performance of the estimated model is satisfactory. Model validation was done for the other sets of time series data and the results were summarized in the Table. 1. The results show that σ_e was less than $\sigma_{\Delta P}$ for all the data except for Sept.,1992.

There are some mismatches with the estimated model and the actual results, especially at the times of typhoons with low hourly average wind speeds. Validation results of Fig. 3 had a discrepancy at around the 150 hrs point. At that time, there existed a typhoon and the hourly average wind speed was less than 5 m/s, but there experienced a pollution difference of .0047 mg/cm^2 within three hours and .0038 mg/cm^2 within two hours, compared to the estimated values ($\hat{\Delta P}$) of .0006 and 0.0006 respectively. This error has caused the difference of the actual and estimated values at 150 hour point of the accumulated pollution graph. In fact, even under typhoons, such a large pollution was not experienced with other available data, at very low wind speeds. It was presumed that there must have very high wind speeds lasting for few minutes, but they were not reflected in the hourly average wind speed.

5. Discussion

This paper proposes a model construction of a still untouched area of the pollution rate, in terms of weather related information. It is true that the estimated model of pollution rate has to be improved further, enable it to be applied for the final goal of automatic decision mak-

Table 1 Results of the model validation: standard deviation of the model errors (σ_ϵ) and the standard deviations of the actual pollution difference ($\sigma_{\Delta P}$) for each month of data

Month	$\sigma_{\Delta P}$ [mg/cm^2]	σ_ϵ [mg/cm^2]
Sep./92	.00090	.00100
Oct./92	.00150	.00130
Sep./93	.00050	.00050
Oct./93	.00076	.00075
Nov./93	.00055	.00046
Dec./93	.00037	.00032

ing for insulator washing. The improvement can be made if more information about typhoons are available, especially the characteristics of wind speed at small sampling intervals rather than the hourly average wind speed.

In this paper, authors wish to stress on the approach and new concepts used for the model construction, which enable to make the path for a generalized model of pollution rate. The analysis in this paper, takes only distance from the sea to divide the wind direction into groups. As revealed from the model construction using the actual data, the wind from the land side has a different impact on the pollution. This has to be investigated further in the future works.

Since the proposed model can be applied on-line for time series data, the pollution rate can be predicted if the wind speed and rainfall are predicted for few steps. Autoregressive models of winds and rainfall can be constructed and few steps ahead prediction can be done. But at the times of typhoons, constructed time series models do not match with the violent characteristics of wind and rainfall. Therefore, at those times weather information should be taken into account to predict the wind speed and rainfall. The predicted pollution rate is a very valuable information for the decision making process of insulator washing.

6. Conclusion

Model construction for the pollution rate of insulators in terms of wind speed, wind direction, typhoon conditions and rainfall were done. This paper proposes the separation of the positive pollution causing factors and negative pollution causing factors, and in turn, model construction for them separately. The grouping of the wind direction in accordance with the geographical situation was proved to be accurate as the values of the weighting elements comply with the distance from the sea. Finally a satisfactory model of the pollution rate was constructed for the insulators in Karatsu substation, Saga, Japan and model validation is done using the actual data.

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