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A Method to Estimate Leakage Current of Polluted Insulators

***Abstract**. The effects of the applied voltage(U), equivalent salt deposit density (ρ_{ESDD}) and relative humidity density(RH) on the leakage current (LC) are studied based on the least squares algorithm (LSA) in this study. Experiments' results show that, the maximal amplitude of LC I_h increases with the increase of ρ_{ESDD} by an power function with a positive index 0.451, while increases with the increase of both U and RH by an exponential function with a positive index 0.017 for U and 9.751 for RH. The result can be used to evaluate the pollution condition of insulators based on LC.*

***Streszczenie.** Zbadano prąd upływu zabrudzonych izolatorów uwzględniając przyłożone napięcie, względne zasolenia i względna wilgotność. Stwierdzono, że prąd upływu rośnie wraz z zasoleniem ze współczynnikiem potęgowym 0.45. (**Metoda określana prądu upływu zabrudzonych izolatorów**)*

Keywords: Leakage current; Insulators; equivalent salt deposit density; relative humidity density; least squares algorithm.
Slowa kluczowe: prądu upływu, izolatory,

1 Introduction

During long term operation, the pollution deposited on the surface of insulators can result in a reduction of their dielectric strength, then the flashover of polluted insulators is a serious threat to the safe operation of overhead power lines [1-4]. To avoid pollution flashover, several measures, such as adjusting creepage distance, coating hydrophobic dope on the surface of insulators and cleaning the insulator regularly, have been adopted. The effect of these measures is not very good, because they are dependent on the detected results of contamination state of the insulators. The equivalent salt deposit density (ESDD), the surface conductance and the non-soluble deposit density (NSDD) are commonly recommended to express the contamination levels [5-7], but they are are limited to represent the pollution degree of insulators. So, it is urgent to develop a reliable system to evaluate contamination state on insulators to take precautions against possible accidents due to pollution. The leakage current (LC) on surface of insulators is closely related to the developing process of pollution flashover, affected by many factors, such as wetting degree, system voltage and structures of insulators [1-9]. At the same time, the LC is easy to be monitored on-line continuously [10]. Hence, as one of on-line monitoring methods for polluted insulators, the measurement and analysis of LC has attracted many researchers attention in recent years [4, 9-16].

Laboratory studies and industrial experience showthat the LC is not only related with contamination degree on the surface of insulators, but also with environmental factors and applied voltage. The humidity is one of key factors which result in the LC. The research papers of [4, 15] pointed out that the LC increases with the increase of relative humidity. The experimental results in the paper [17] show that, the LC increases with the increase of applied voltage. The equivalent salt deposit density (ρ_{ESDD}) is another key factor which affects the LC, an the research papers of [7, 11] point out that the LC increases with the increase of the ρ_{ESDD}. The relationship between LC and ρ_{ESDD} are non-linear relationship in [11] while approximate liner relationship in [7], these different conclusion may be due to the different test methods. As is known to us, the relations between the flashover voltage of insulators (Uf) and ρ_{ESDD} is a power function [1-3]. but the relationship between LC and ρ_{ESDD} in different RH has not been found.

To sum up, there have been many qualitative researches on the relationships between the LC and its influence factors, while there are few studies on the mathematical model of LC expressed by its influence factors. In this study, the insulator strings are taken artificial pollution test, the specific mathematical relationship of the U, ρ_{ESDD}, RH and the LC are studied based on the LSA. A regression model (RM) for estimating the LC is established, the performance of estimating the LC by RM is compared with the that by artificial neural network (ANN).

2 Test facilities and procedures

2.1 Test facilities and Samples

The tests were performed in the multi-function artificial climate chamber (MACC) in the High Voltage and Insulation Technological Laboratory of Chongqing University [1-4, 13-15]. The MACC has a diameter of 2 m and a length of 3.8 m, in which the relative humidity (RH %) can be controlled between 40% and 100%. The test circuit of the artificial contamination test is shown in Figure 1. In the circuit, the source components are a voltage regulator T (TDJY-1000/10) and a test transformer B (YDJ-900 KVA/150KV). The rated current is 6 A, and the maximum short circuit current is over 30A. The equipment meets the requirements for the power source of artificial pollution tests on high voltage insulators [18]. The high voltage source is connected to MACC through a 110 kV wall bushing H. The high voltage end is connected to an AC capacitive voltage divider F (SGB-200 A) with the divider ratio of 1:1000 which records the applied voltage in real time. The protective resistor R_0 is about 15 kΩ, OSC is a TDS5052B digital oscilloscope, by which the LC wave acquired from the potential difference across the R_i (100 Ω) can be measured and displayed. A bipolar transient voltage suppressor (TVS) G should be connected in parallel with R_i for protection the oscilloscope from over-voltages. A glass door (1.2 m × 2.5m) of the fog chamber is used for visual observation purposes.

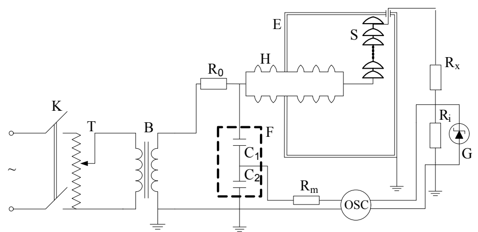
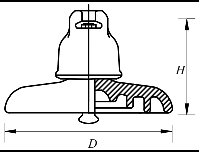


Fig.1. Test circuit of the artificial pollution experiment

The tested insulators were IEC standard suspension insulators (IEC U160BL). The main dimensions, parameters and configuration are shown in Table 1. The insulator string of 3 units was used to simulate the 35 kV power line.

Table 1. Main dimensions, parameters and configuration of IEC standard suspension insulator

Main Dimensions and Parameters	Configuration
Diameter(D)= 305 mm	
Height(H)=155 mm	
Leakage distance=295 mm	
Rated Failing Load=70 kN	
Routine Tension Load=160 kN	

2.2 Test procedures

Based on the IEC-60507 standard [18], the test procedures in this study were designed as follows:

(1) Before tests, all samples were carefully cleaned so that all traces of dirt and grease were removed and dried naturally in the laboratory.

(2) After preparation, the solid layer method was used to produce uniform pollution layers on the surface of the insulators. The sodium chloride and kieselgur were conductive and inert materials, respectively. The Non-Soluble Deposit Density *NSDD* (in mg/cm^2) was 2.0 mg/cm^2, five kinds of *SDD* (in mg/cm^2) levels of 0.05, 0.10, 0.15 and 0.20 mg/cm^2 to simulate four pollution levels, respectively. The sodium chloride and kieselgur were mixed with a little distilled water uniformly. Then the pre-contaminated samples were suspended vertically in MACC, and completely dried for 24 hours.

(3) The pressure of MACC was constant, which was equal to the atmospheric pressure of 99.5 kPa. The temperature was about 26 °C, which was the indoor temperature of spring in the city of Chongqing. The *RH%* was controlled by the fog generator and the desiccant. In the chamber, a hygroscope was used to measure the *RH%*. When the *RH%* was lower than the proposed value, the fog generator was used, when *RH%* was higher than the proposed value, the desiccant was used.

(4) The polluted insulator string of 3 units was hung up in the MACC about 5 hours after the *RH%* was controlled well. Then a 50 Hz AC voltage U was applied to the insulator string quickly to ensure avoidance of flashover of the insulator string. At the same time the LC were sampled at a rate of 2 Ms/s, and the sampling length was 0.2 s. Then the LC and test voltage signal were transferred to a data buffer and stored. The data acquisition system mainly consisted of potential dividers, a TDS5052B digital oscilloscope, and a computer.

3 Test results and analysis

3.1 Test results

157 groups of measured amplitude of the LC are shown in Table 2 (a), (b), (c), (d), with different values of applied voltage and humidity, NSDD is 2.0 mg/cm^2, ρ_{ESDD} is 0.05, 0.10, 0.15 and 0.20 mg/cm^2, respectively. 142 random samples were selected to find the experiential formula between the amplitude of LC I_h and applied voltage U, ρ_{ESDD} and RH by regression analysis, and the remaining 15 groups of data will be used to validate the formula.

Table 2. The test results (t=26±2℃), (a) (ρ_{ESDD} =0.05mg/cm2)

No.	RH/%	U/kV	I_h/mA	No.	RH/%	U/kV	I_h/mA
1	71%	27.66	1.00	24	49%	24.69	0.32
2	74%	21.96	1.14	25	50%	25.77	0.42
3	74%	25.65	1.24	26	50%	18.54	0.32
4	74%	24.69	1.20	27	67%	30.60	0.36
5	74%	22.5	1.50	28	67%	23.10	0.3
6	72%	28.02	1.70	29	67%	13.86	0.24
7	73%	25.2	1.34	30	69%	32.64	0.68
8	60%	27.42	0.42	31^{test}	71.%	31.20	1.10
9	57%	27.51	0.40	32	72%	31.20	1.70
10	62%	28.38	0.38	33^{test}	85%	27.00	4.20
11	55%	23.1	0.34	34	84%	31.20	3.00
12	55%	29.85	0.40	35^{test}	87%	30.39	5.60
13	58%	26.73	0.32	36	87%	30.84	6.00
14	58%	31.80	0.36	37	89%	32.19	6.10
15	59%	29.70	0.40	38	92%	29.46	6.00
16	59%	24.90	0.38	39	59%	36.00	0.46
17	58%	25.77	0.32	40	59%	30.84	0.42
18	57%	27.66	0.34	41	59%	22.59	0.34
19	56%	28.98	0.36	42	59%	15.54	0.28
20	51%	30.00	0.40	43	73%	30.18	2.20
21	49%	21.78	0.34	44	92%	31.23	7.00
22	49%	17.52	0.30	45	100%	32.16	7.60
23	49%	19.44	0.36				

(b) ρ_{ESDD} =0.10mg/cm2

No.	RH/%	U/kV	I_h/mA	No.	RH/%	U/kV	I_h/mA
46	78%	28.05	3.48	73	55%	34.38	0.38
47	83%	27.42	11.30	74	67%	27.27	0.61
48	83%	21.60	9.00	75	69%	26.1	0.61
49	83%	24.18	8.00	76	69%	24.24	0.63
50	83%	28.86	7.60	77	69%	29.58	0.8
51	83%	23.4	2.80	78	69%	36	0.94
52^{test}	80%	27.33	2.50	79	69%	20.49	1.44
53	77%	31.5	2.90	80	69%	30.39	1.92
54	78%	21.78	2.10	81	69%	19.35	2.12
55	79%	18.48	1.00	82	63%	33.6	1.04
56	71%	31.35	1.61	83	58%	31.74	0.52
57	65%	30.93	0.75	84	50%	33.90	0.55
58	69%	29.46	0.96	85	48%	33.75	0.44
59	69%	23.25	1.16	86	47%	33.51	0.48
60	69%	21.96	2.04	87	47%	31.92	0.44
61	70%	25.86	2.52	88	47%	34.08	0.56
62^{test}	71%	28.65	0.92	89	82%	32.04	19.00
63	74%	26.34	2.56	90^{test}	88%	33.03	21.00
64	76%	27.96	2.16	91	80%	32.07	6.20
65	75%	26.34	2.08	92	62%	41.13	1.02
66^{test}	76%	29.58	2.44	93	57%	28.68	0.42
67	71%	28.68	3.48	94	53%	27.03	0.38
68	71%	25.62	3.24	95	53%	29.85	0.42
69	74%	27.15	3.52	96	85%	26.88	10.5
70	70%	29.91	2.44	97	89%	30.09	14.00
71	55%	30.06	0.44	98	89%	31.65	23.00
72	52%	26.61	0.36	99^{test}	100%	32.13	70.00

(c) (ρ_{ESDD} =0.15mg/cm2)

No.	RH/%	U/kV	I_h/mA	No.	RH/%	U/kV	I_h/mA
100	80%	30.69	2.80	112	51%	30.72	0.38
101	74%	34.53	1.40	113	53%	27.60	0.36
102	66%	25.35	0.50	114	62%	25.74	1.73
103	66%	24.00	0.44	115	85%	31.41	12.00
104	68%	31.29	0.60	116	88%	30.6	18.00
105	69%	30.54	0.72	117	92%	31.2	22.00
106	67%	18.69	0.44	118	93%	28.71	25.01
107	67%	36.63	0.60	119^{test}	92%	28.41	35.00
108	67%	28.68	0.56	120	82%	30.75	10.01
109	63%	31.17	0.50	121^{test}	86%	28.56	19.00
110	61%	28.92	0.40	122	86%	29.46	20.00
111	52%	31.05	0.42	123	86%	28.62	25.00

(d) (ρ_{ESDD} =0.10mg/cm2)

No.	RH/%	U/kV	I_h/mA	No.	RH/%	U/kV	I_h/mA
124^{test}	82%	33.48	5	141	71%	27.42	2.08
125	83%	28.23	30	142	71%	31.44	2.72
126	72%	22.56	8	143	68%	27.33	0.56
127^{test}	68%	23.61	4.4	144	75%	24.09	3.22
128	77%	27.24	4.8	145	77%	29.04	1.06
129	78%	27.03	4.6	146	73%	30.60	3.41
130	79%	30.72	4.6	147	58%	31.32	1.08
131	69%	29.52	1.12	148	66%	26.67	0.84
132	69%	26.28	1.04	149	62%	31.11	0.42
133	68%	25.83	0.74	150	67%	29.76	0.81
134	69%	20.88	1.28	151	80%	32.67	1.34
135	70%	20.85	1.58	152	87%	31.83	12.03
136	71%	32.01	2.32	153^{test}	88%	28.38	20.00
137	71%	22.83	2.84	154	86%	24.33	40.00
138	74%	26.43	3.6	155^{test}	89%	30.99	62.00
139	74%	32.37	4.24	156	89%	26.22	78.00
140	69%	27.93	1.04	157^{test}	99%	32.40	190.0

3.2 Modeling of I_h using regression analysis

Based on the analysis of large amounts of artificial pollution test results, it is found that, the relations between I_h and the parameters of U and RH are exponential functions, the relation between I_h and ρ_{ESDD} is a power function. Therefore the form of regression model (RM) for estimation of I_h can be written as:

(1) $$I_h = Ke^{aU}\rho_{ESDD}^{b}e^{cRH}$$

Where K is a coefficient correlated with the type and length of insulator, a is the characteristic exponent characterizing the influence of U on I_h, b is the characteristic exponent characterizing the influence of ρ_{ESDD} on I_h, c is the characteristic exponent characterizing the influence of RH on I_h. By linearization, the equation (1) can be written as:

(2) $$\ln I_h = \ln K + aU + b\ln\rho_{ESDD} + cRH$$

To determine the four coefficients in equation (2), the sum of deviation squares (Q) should be keep smallest according to the least squares algorithm (LSA) [19], so as to obtain the best regression curve. The Q can be written as:

(3) $$Q = \sum_{i=1}^{n}\left[I_{hi} - \left(\ln K + aU_i + b\ln\rho_{ESDDi} + cRH_i\right)\right]^2$$

Where, Q can be regard as the function of the independent variables of K, a, b and c; I_{hi}, U_i, ρ_{ESDDi} and RH_i are the amplitude of LC, the U, the ρ_{ESDD} and the RH in the i^{th} test; n is total group of tests used to regression analysis.

If $I' = \ln I_{hi}$, $K' = \ln K$, $\rho' = \ln\rho_{ESDD_i}$, to ensure Q be the smallest, then K', a, b and c should be satisfied with:

(4) $$\begin{cases} \dfrac{\partial Q}{\partial K'} = -2\sum_{i=1}^{n}\left(I' - K' - aU_i - b\rho' - cRH_i\right) = 0 \\ \dfrac{\partial Q}{\partial a} = -2\sum_{i=1}^{n}\left(I' - K' - aU_i - b\rho' - cRH_i\right)U_i = 0 \\ \dfrac{\partial Q}{\partial b} = -2\sum_{i=1}^{n}\left(I' - K' - aU_i - b\rho' - cRH_i\right)\rho' = 0 \\ \dfrac{\partial Q}{\partial c} = -2\sum_{i=1}^{n}\left(I' - K' - aU_i - b\rho' - cRH_i\right)RH_i = 0 \end{cases}$$

When 142 groups of test data are input to equation (4), the solution of partial differential equation can be found. The result of K, a, b, c is 0.003, 0.017, 0.451 and 9.751, respectively, then the equation (1) can be renewed as:

(5) $$I_h = 0.003e^{0.017U}\rho_{ESDD}^{0.451}e^{0.9751RH}$$

3.3 Multiple correlation coefficient (R) and F examination

The Multiple correlation coefficients (R) and the F examination are introduced to verify the feasibility of regression equation (5). The R can be calculated by:

(6) $$R = \sqrt{\frac{S_R}{L_{I'I'}}}$$

Where, $S_R = \sum\left(\ln\hat{I}_{hi} - \ln\bar{I}_h\right)^2$ is the sum of regression squares, $L_{I'I'} = \sum\left(\ln I_{hi} - \ln\bar{I}_h\right)^2$ is the sum of deviation squares. Calculation results show that R is 0.99 in this model, so the linear relationship between $X(U, \rho_{ESDDi}, RH)$ and $Y(I_h)$ is significant. The F can be calculated by:

(7) $$F = \frac{S_R/3}{S_S(n-3)}$$

Where, S_S is the residual sum of squares as a result of $L_{I'I'}$ subtracted from S_R. Calculation results show that F is 166 695 and the critical value $F_{0.001}$ (3, n-3) is 5.42 according to statistics database of F examination. It is obvious that F is far bigger than $F_{0.001}$(3, n-3) even if the alpha is 0.001. So the RM is statistically significant, and can be used to evaluate the pollution condition of insulators.

3.4 The estimation results of RM compared with ANN

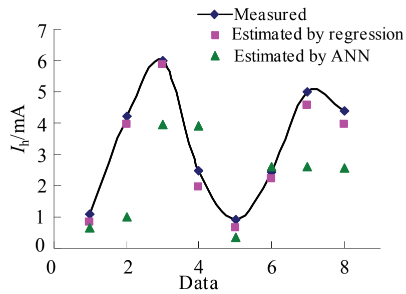
The artificial neural network (ANN) has excellent performance of approximating to the optimal nonlinear mapping between input and output vectors after learning, so ANN can be applied to identify the nonlinear models. The training process of ANN can be regard as the process of seeking for the optimal nonlinear function. In this paper, a BP ANN is designed to estimate the I_h, the BP ANN has 3 input neurons, 1 hidden layer including 9 nerve neurons and 1 output neurons, the input vectors are ρ_{ESDD}, U, and RH, respectively, the output vector is I_h, and the algorithm of Levenberg-Marquardt (L-M) is applied to train the BP ANN. In this study, 157 groups of experimental data were collected, 142 of them are selected randomly and normlized to train the BP ANN, the left 15 groups are used to test the performance of the BP ANN. Then the value of I_h can be estimated by established BP ANN.

The 15 groups of estimated values of I_h calculated by RM and BP ANN are listed in Table 3.

Table 3. The test results and calculated results by model

No.	Test results /mA	RM /mA	Relative error /%	ANN model /mA	Relative error /%
1	1.10	0.8455	-23.1%	0.6344	-42.3%
2	4.20	3.9730	-5.4%	1.0031	-76.1%
3	6.00	5.8768	-2.1%	3.9351	-34.2%
4	2.50	1.9541	-21.8%	3.9345	57.3%
5	0.92	0.6384	-31.2%	0.3669	-60.1%
6	2.44	2.2293	-8.6%	2.5989	6.5%
7	5.00	4.5743	-11.4%	2.6168	-47.6%
8	4.40	3.9661	-9.8%	2.5550	-41.9%
9	21.00	21.7132	3.4%	21.7161	3.4%
10	70.00	70.7526	1.1%	69.3392	-0.9%
11	35.00	35.7322	2.1%	31.5574	-9.8%
12	19.00	19.7079	3.7%	21.3940	-9.8%
13	20.00	20.4469	2.2%	23.4148	11.3%
14	62.00	63.4416	2.3%	60.4148	-2.5%
15	190.0	191.5592	0.8%	190.0000	0.0%

a) I_h <10mA



b) I_h >10mA

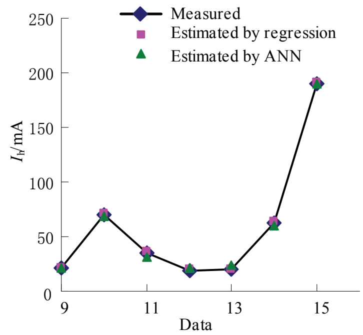


Fig.2. Comparison of the experimental results, the calculation results by ANN and RM

The 15 measured values of I_h, which are applied to to test the trained BP ANN, can be compared with the estimated results calculated by the ANN and RM. The measured values of I_h come from experiments, the values of I_h estimated by BP ANN and RM are plotted as shown in Fig.2. It can be seen from the Fig.2 that, as a whole, the estimated values of I_h by BP ANN and RM can keep well in accordance with the experimental results.

When the I_h is smaller than 10mA, the relative error of I_h estimated by RM reaches as high as 31.2%, as shown in Fig.2 (a), while the absolute error is smaller than 1 mA (test No.1~8 in Table 3). The error of I_h estimated by RM has nearly no influences on evaluating the contamination condition of insulators because I_h is in the interval of from 0 mA to 25mA, in which the insulator is in safe operation [13,14]. At the same time, and the relative error of I_h estimated by ANN is much higher than that of I_h estimated by RM yet. When the I_h is bigger than 10mA, the relative error of I_h estimated by RM and ANN is smaller than 3.4% and 5%, respectively, as shown in Fig.2 (b). So the estimated results by RM and ANN all match the experimental results well.

All in all, the estimated values of I_h by RM shower higher precision and accuracy than that of I_h by BP ANN. So the RM shows more excellent performance of estimating the LC of contaminated insulators than BP ANN. The estimated values of I_h by RM is a excellent tool for evaluating the contamination condition of insulators.

Conclusions

(1) The maximal amplitude of LC I_h has a correlation with U, ρ_{ESDD} and RH, the latter two have vital influence on I_h. The maximal amplitude of LC I_h increases with the increase of ρ_{ESDD} by an power function with a positive index 0.451, while increases with the increase of both U and RH by an exponential function with a positive index 0.017 for U and 9.751 for RH. The result can be used to evaluate the pollution condition of insulators based on LC.

(2) The non-linear RM for estimating the LC can be written as: $I_h = Ke^{aU} \rho_{ESDD}^{b} e^{cRH}$, where K is a coefficient correlated with the type and length of insulator, a is the characteristic exponent characterizing the influence of U on I_h, b is the characteristic exponent characterizing the influence of ρ_{ESDD} on I_h, c is the characteristic exponent characterizing the influence of RH on I_h.

(3) The estimated values of I_h by RM shower higher precision and accuracy than that of I_h by BP ANN. So the RM shows more excellent performance of estimating the LC of contaminated insulators than BP ANN. The estimated values of I_h by RM is a excellent tool for evaluating the contamination condition of insulators.

This work was supported by Key Project of Chinese National Programs for Fundamental Research and Development (973 Program) (2009CB724503).

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