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Study on Leakage Current Waveforms of Porcelain Insulator due to Various Artificial Pollutants

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***Abstract*—**This paper presents the experimental results of leakage current waveforms which appears on porcelain insulator surface due to existence of artificial pollutants. The tests have been done using the chemical compounds of NaCl, Na_2SiO_3, H_2SO_4, CaO, Na_2SO_4, KCl, Al_2SO_4, $MgSO_4$, $FeCl_3$, and TiO_2. The insulator surface was coated with those compounds and dried. Then, it was tested in the chamber where the high voltage was applied. Using correspondence analysis, the result indicated that the fundamental harmonic of leakage current was very close to the applied voltage and third harmonic leakage current was close to the yielded leakage current amplitude. The first harmonic power was correlated to first harmonic amplitude of leakage current, and third harmonic power was close to third harmonic one. The chemical compounds of H_2SO_4 and Na_2SiO_3 affected to the power factor of around 70%. Both are the most conductive, due to the power factor drastically increase among the chemical compounds.

***Keywords*—**Chemical compound, harmonic, porcelain insulator, leakage current.

I. INTRODUCTION

OVERHEAD transmission or distribution lines are widely used in present power system to transmit electric power from generation stations to customer points. Their proper function depends to a large extent on the insulation system with the supporting structures [1]. The performance of outdoor insulators is affected by some parameters. One of these parameters is environmental contamination. To approach the real condition of pollutant effects on an insulator surface, it has been conducted leakage current measurement of outdoor insulator with the artificial pollutants experimentally. However, the compounds of pollutants theirselves were based on the elements from the coastal region site, i.e. Na, Mg, Al, Si, S, Cl, K, Ca, Ti and Fe [2]. For this moment, based on such elements, tests have been done using the compounds of Na_2SO_4, $MgSO_4$, Al_2SO_4, Na_2SiO_3, H_2SO_4, KCl, NaCl, CaO, TiO_2 and $FeCl_3$.

The objective of this research is to obtain the significance of correlation among parameters. The main parameters to be analyzed are leakage current amplitude related to its first, third, fifth and seventh harmonic amplitudes and powers. Also to determine which chemical compound(s) influence significantly to the leakage current using statistical correspondence and correlation analyses.

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II. EXPERIMENTAL AND ANALYSIS METHODS

The chemical compounds were dissolved or emulsified in the fresh water, and sprayed on the porcelain insulator surface overlapped with one by one of compound emulsions. The porcelain insulator was dried under sun ray, and then put in the chamber, with the humidity and temperature were in room condition. It was subjected to high voltage, where the voltage and leakage current waves were recorded by a two-channel digital storage oscilloscope. The recorded data were transferred to pc for further analysis. The experimental setup schematic diagram is shown on Fig. 1.

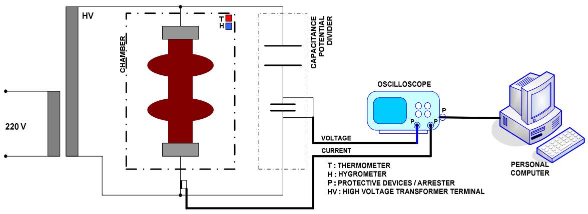

Fig. 1 Schematic diagram of experimental setup

For analysis, it has been done using correspondence analysis with basic rule as follows [3]:

$$P = \frac{1}{n} K \quad (1)$$

where K is the row data matrix, and n is the sum of total components of K. V is the matrix of P divided by the sum of each column and U is the matrix of P, which is divided by the sum of each row. D_k is the matrix with the diagonal components; sum of each row of P and D_m is the matrix with the diagonal components; sum of each column of P. Their non-diagonal components are zero. Furthermore, the analysis on R_k follows

$$T_1 = V\, D_m\, V^t \tag{2}$$

$$T_1\, D_k^{-1} \vec{u}_k = \lambda_i\, \vec{u}_i, i = 1,2,\ldots,q \tag{3}$$

and

$$\vec{c}_i = V_t\, D_k^{-1}\, \vec{u}_i \tag{4}$$

and analysis on R^m will result in

$$S = U\, D_k\, U^t \tag{5}$$

$$S\, D_m^{-1}\, \vec{v}_i = \lambda_i\, \vec{v}_i, i = 1,2,\ldots.,q \tag{6}$$

$$\vec{d}_i = U_t\, D_m^{-1}\, \vec{v}_i \tag{7}$$

Analysis on both R_k and R_m simultaneously are:

$$d_{ij} = \sum_{l=1}^{m} \frac{1}{\sqrt{\lambda_i}} \frac{P_{jl}}{P_{j\bullet}} . c_{il}\, ;\, j = 1,2,\ldots.,k \tag{8}$$

$$c_{ij} = \sum_{l=1}^{k} \frac{1}{\sqrt{\lambda_i}} \frac{P_{lj}}{P_{\bullet j}} . d_{il}\, ;\, j = 1,2,\ldots.,m \tag{9}$$

It is also analyzed using correlation matrix base on covariance matrix to understand how much level of correlation among parameters base on these research with basic formulae as follows [4]-[5]

$$Cov(X,Y) = \frac{1}{n} \sum_{j=1}^{n} (x_j - \mu_x)(y_j - \mu_y) \tag{10}$$

Thus, the components of correlation matrix as below.

$$\rho_{x,y} = \frac{Cov(X,Y)}{\sigma_x, \sigma_y} \tag{11}$$

It was also used fast Fourier transform for analysis the leakage current waveforms [6]. Therefore the frequency spectra were obtained. These implementations used the **Danielson-Lanczos** method [7]. The FFT of the sampled data is:

$$V[k] = \sum_{n=0}^{N-1} w[n] x[n] \exp(-i 2\pi F_k n),\ 0 \le n \le N-1 \tag{12}$$

and the estimate of the power spectrum is:

$$P[k] = \frac{1}{\sum_{n=0}^{N-1} (w[n])^2} |V[k]|^2 \tag{13}$$

III. RESULT DATA AND ANALYSIS

Fig. 2 shows the applied voltage and leakage current waveforms of insulator due to 1 gr NaCl solution. It is shown that the leakage current waveform is not pure sinusoidal, i.e. on the peaks, this experiences deformed decrease. This phenomenon indicates that the wave has harmonics. The phase difference between the leakage current and applied voltage waves is 63.4 degree.

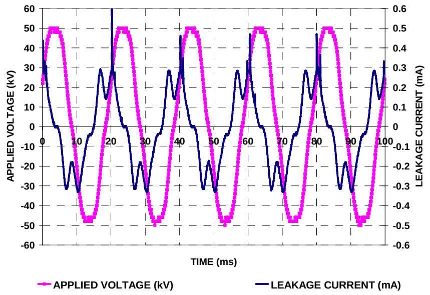

Fig. 2 The waveforms due to 1 gr NaCl solution

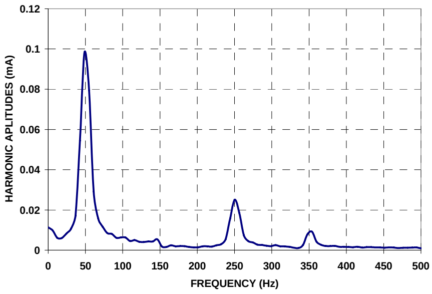

Fig. 3 The leakage current spectrum due to 1 gr NaCl

Thus, it was analyzed in some harmonic frequencies of leakage current waveform, as shown on Figure 3. The highest amplitude, of course, is the fundamental, followed by 5th harmonic, 25.55%, and 7th harmonic, 9.35%. This is also presented the power of harmonics, as shown on Figure 4. The highest is also the fundamental, and followed by 5th and 7th harmonics respectively, or 6.53% and 0.87% of the fundamental.

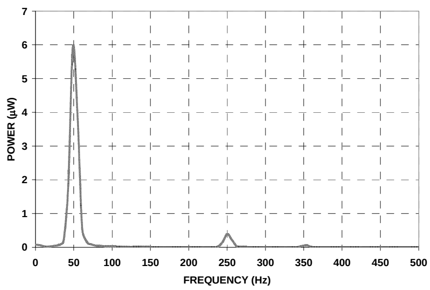

Fig. 4 Power of leakage current spectrum due to 1 gr NaCl solution

The second coating was 1 gr Na_2SiO_3. The leakage current waveform was still similar with previous one. It had 58.3 degree of phase difference to the applied voltage. The highest amplitude of harmonic frequency spectrum was the fundamental, and 5.77%, 19.96% and 6.10% of the fundamental for 3rd, 5th and 7th harmonics respectively. The highest of harmonic power was 11.1 μW, and 3rd, 5th and 7th harmonics were 0.33%, 4.00% and 0.37% respectively.

Fig. 5 shows the applied voltage and leakage current waveforms of insulator due to 1 gr H_2SO_4 solution. The leakage current waveform is strictly different from previous ones, only one peak on the wave. The phase difference is smaller than the formers, 34.6 degree. This is also shown that the leakage current amplitude is very high, for low applied voltage. For moment, these phenomena indicate that H_2SO_4 solution is very conductive.

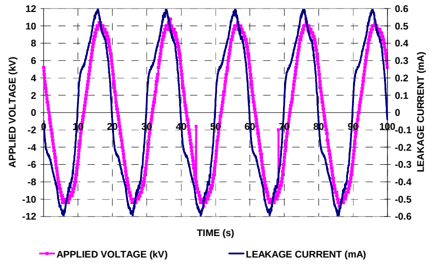

Fig. 5 The waveforms due to 1 gr H_2SO_4 addition

Fig. 6 shows the harmonic frequency spectrum of leakage current waveform. After the fundamental frequency, the second highest amplitude is 3rd harmonic, 11.12%, and followed by 5th, 7th and 9th, those are 8.09%, 3.64% and 1.06% of the fundamental respectively.

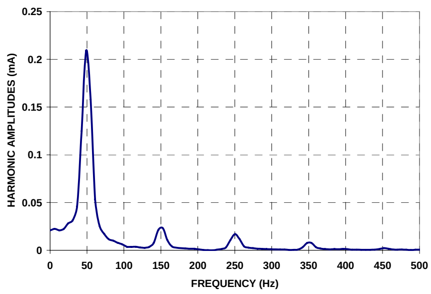

Fig. 6 The leakage current spectrum due to 1 gr H_2SO_4

Whereas Fig. 7 shows the power of harmonic frequency spectrum of leakage current waveform. On this condition, the fundamental power is 26.8, μW, and the 3rd, 5th, and 7th harmonic powers are 1.24%, 0.65% and 0.13% of the fundamental.

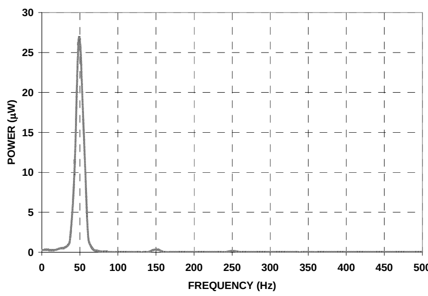

Fig. 7 Leakage current power spectrum of 1 gr H_2SO_4

Whereas, on the addition of 1 gr CaO, the leakage current waveform were still similar with Na_2SiO_3 one. The leakage current wave had the phase difference of 62.6 degree. After the fundamental frequency, the second highest amplitude was 5th harmonic, 20.16%, and followed by 3rd and 7th, those were 6.41% and 4.63% of the fundamental respectively. On this condition, the fundamental power was 9.62 μW, and the 3rd, 5th and 7th harmonic powers were 0.41%, 4.06%, 0.21%, of the fundamental.

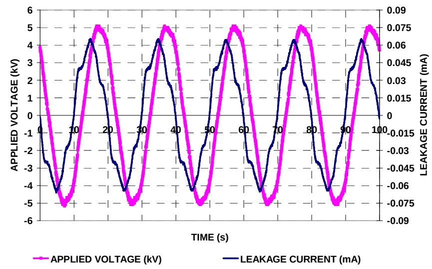

Fig. 8 The waveforms due to 1 gr Na_2SO_4 addition

Furthermore, Fig. 8 shows the applied voltage and leakage current waveforms of insulator due to addition of 1 gr Na_2SO_4 on previous coating. The leakage current waveform tends to similar to that of H_2SO_4 coating, rather than the others. The leakage current wave has 46.1 degree of phase difference. It is smaller rather than that of CaO, and larger rather than that of H_2SO_4.

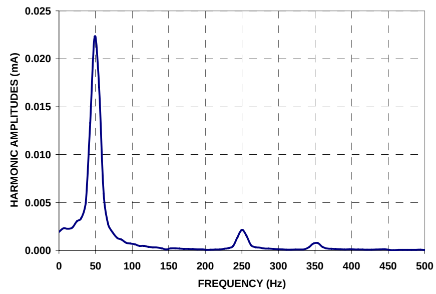

Fig. 9 The leakage current spectrum of 1 gr Na_2SO_4

Fig. 9 shows the harmonic frequency spectrum of leakage current waveform. It is indicated that after the fundamental frequency, the second highest amplitude is 5th harmonic, 9.64%, and followed by 7th and 3rd, those are 3.40% and 0.94% of the fundamental respectively.

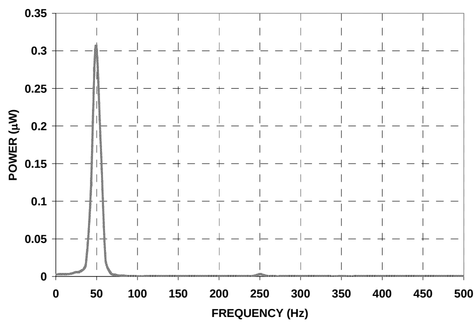

Fig. 10 Power of leakage current spectrum due to 1 gr Na_2SO_4 addition

Fig. 10 shows the power of harmonic frequency spectrum of leakage current waveform due to 1 gr Na_2SO_4. On this condition, the fundamental power is 0.306 μW, and the 3rd, 5th and 7th harmonic powers are 0.000319 μW or 0.01%, 0.92% and 0.10% of the fundamental.

Otherwise, the leakage current waveform due to KCl was not so significantly different from that CaO coating. The leakage current wave had 56.2 degree of phase difference from the applied voltage. It was larger than that of Na_2SO_4 or H_2SO_4.

Whereas, the harmonic frequency spectrum of leakage current waveform indicated that after the fundamental frequency, the second highest amplitude was 5th harmonic, 21.54% and followed by 3rd and 7th, those were 5.24% and 4.60% of the fundamental respectively. On this condition, the fundamental power of harmonic frequency spectrum of leakage current waveform due to KCl was 8.47 μW, and the 3rd, 5th and 7th harmonic powers were 0.28%, 4.64% and 0.21% of the fundamental.

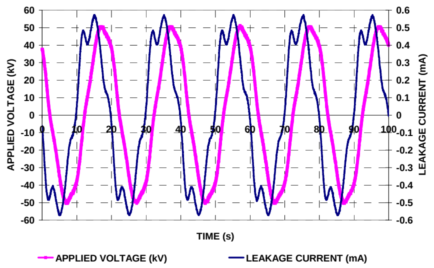

Fig. 11 The waveforms due to 1 gr Al_2SO_4 addition

Fig. 11 shows the applied voltage and leakage current waveforms of insulator due to addition of 1 gr Al_2SO_4 on previous coating. The leakage current waveform is similar to that of NaCl or Na_2SiO_3 coating. The leakage current wave has considerable phase difference from the applied voltage, 44.6 degree, and smaller than that of KCl.

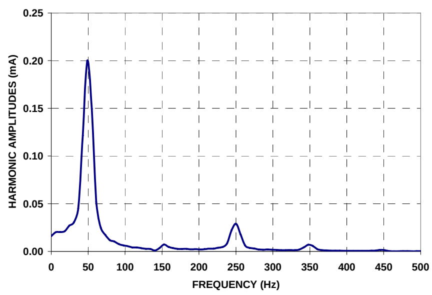

Fig. 12 The leakage current spectrum due to 1 gr Al_2SO_4 addition

Whereas, the harmonic frequency spectrum of leakage current waveform due to 1 gr Al_2SO_4 addition is shown on Fig. 12. After the fundamental frequency, the second highest amplitude is 5th harmonic, 14.48% and followed by 3rd and 7th, those are 3.57% and 3.47% of the fundamental respectively.

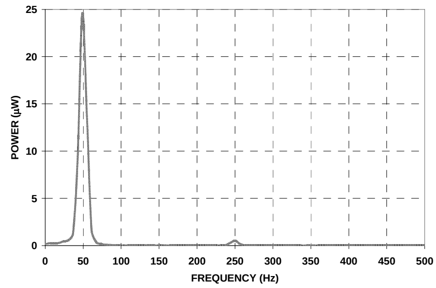

Fig. 13 Power of leakage current spectrum due to 1 gr Al_2SO_4 addition

The power of harmonic frequency spectrum of leakage current waveform due to Al_2SO_4 is shown on Fig. 13 above. On this applied voltage, the fundamental power is 2.46 μW, and the 3rd, 5th and 7th harmonic powers are 1.27%, 20.93% and 1.20% of the fundamental respectively.

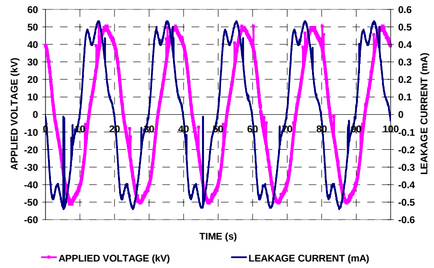

Fig. 14 The waveforms due to 1 gr $MgSO_4$ addition

Fig. 14 shows the applied voltage and leakage current waveforms of insulator due to addition of 1 gr $MgSO_4$ on previous coating. The leakage current waveform is similar to Al_2SO_4 coating. The leakage current wave has considerable phase difference, 48.2 degree.

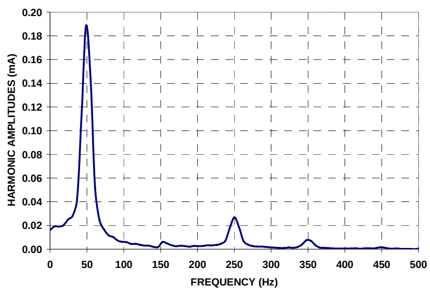

Fig. 15 The leakage current spectrum due to 1 gr $MgSO_4$ addition

The harmonic frequency spectrum of leakage current waveform due to 1 gr $MgSO_4$ addition is shown on Fig. 15. After the fundamental frequency, the second highest amplitude is 5th harmonic, 14.24% and followed by 7th and 3rd, those are 3.99% and 3.16% of the fundamental.

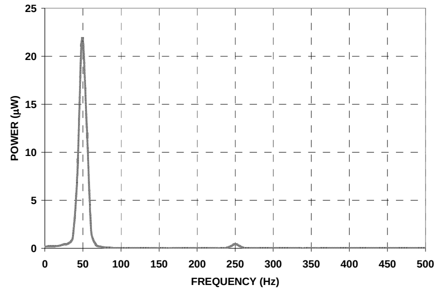

Fig. 16 Power of leakage current spectrum due to 1 gr $MgSO_4$ addition

Whereas the power of harmonic frequency spectrum of leakage current waveform due to $MgSO_4$ is shown on Fig. 16 above. On this applied voltage, the fundamental power is 2.18 µW, and the 3rd, 5th and 7th harmonic powers are 1.00%, 20.28% and 1.59% of the fundamental.

The leakage current waveform due to 1 gr $FeCl_3$ is similar to $MgSO_4$ coating. The phase angle is also nearly same as 47.5 degree. Whereas the second highest amplitude of leakage current waveform is 5th harmonic, i.e. 13% and followed by 3rd and 7th, those are 4.38% and 3.35% of the fundamental amplitude respectively. The fundamental power of leakage current harmonic frequency spectrum due to $FeCl_3$ is 7.5 µW, and the 3rd, 5th and 7th harmonic powers are 1.91%, 16.93% and 0.74% of the fundamental respectively.

The leakage current waveform due to 1 gr TiO_2 is similar to that of $FeCl_3$ coating. Its phase angle is also nearly same as that one, 47.5 degree. After the fundamental frequency, the second highest amplitude is 5th harmonic, 13.84% and followed by 3rd and 7th, those are 5.91% and 3.59% of the fundamental amplitude respectively. Whereas the fundamental power of leakage current harmonic spectrum is 156 µW, and the 3rd, 5th and 7th harmonic powers are 0.35%, 1.92%, and 0.13% of the fundamental amplitude respectively. These harmonics are very small comparing to other ones.

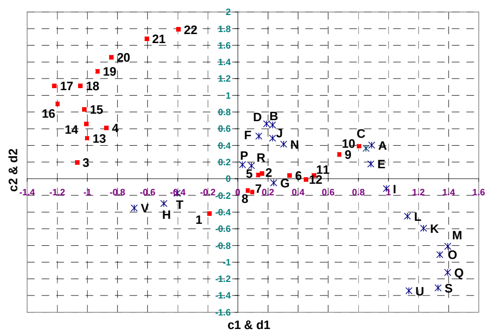

Fig. 17 Correspondence analysis result of experimental data

Fig. 17 shows the scatter plot of correspondence analysis of experimental data. To make shorter of variable names, it is used capital letter. V_{max}, I_{max}, ϕ, $\cos(\phi)$, $1^{st}{}_{max}$, $3^{rd}{}_{max}$, $5^{th}{}_{max}$, $7^{th}{}_{max}$, $1^{st}p$, $3^{rd}p$, $5^{th}p$, $7^{th}p$, NaCl, Na_2SiO_3, H_2SO_4, CaO, Na_2SO_4, KCl, Al_2SO_4, $MgSO_4$, $FeCl_3$, TiO_2 are signed by A, B, until V. However, individuals or components using numeral indicate different quantities, i.e. on each condition; there are two values, small and large values.

From this scatter plot, it can be obtained some information of experimental data. It is shown components 1 until 12, except 3 and 4, are correlated closely to variable A up to J. This case is indicated that those plots close each other.

For closer view, amplitudes of applied voltages are close to leakage current, phase, power factor, harmonic amplitude and harmonic power. Thus, these quantities are influenced significantly by applied voltage magnitudes.

The amplitude of applied voltage is very correlated with first harmonic amplitude of leakage current. Thus, the first harmonic amplitude increases as the applied voltage to insulator under test rise very significantly. Besides that, it is also influenced by chemical compound of CaO.

From these data, the third harmonic amplitude of leakage current is very close to amplitude of yielded leakage current. Thus, such third harmonic amplitude is influenced by the leakage current amplitude significantly. On rather far from applied voltage amplitude or yielded leakage current, it is shown the fifth harmonic amplitude of leakage current. Therefore, it is rather correlated or influenced by applied voltage or yielded leakage current. The fifth harmonic amplitude of leakage current is also influenced by Na_2SiO_3 tightly. The latest is seventh harmonic amplitude that is very far from either applied voltage or yielded leakage current. On other word, it is not influenced by either applied voltage or leakage current significantly. However, it is correlated to chemical compounds of $MgSO_4$ and TiO_2 closely.

The fundamental or first harmonic power is very close to first harmonic amplitude of leakage current. Therefore, both quantities are influenced each other. The first harmonic amplitude rises make the first harmonic power increases, and vice versa.

The third harmonic power is very close to the yielded amplitude of leakage current and third harmonic amplitude of leakage current. Therefore, such three quantities are influenced each other. The yielded leakage current influences third harmonic amplitude and third harmonic power very significantly.

However, the fifth and seventh harmonic powers are very far from either fifth or seventh harmonic parameter. Therefore, both quantities can be said that they are influenced by those harmonic amplitudes slightly. On other hand, both harmonic powers are close to chemical compounds of NaCl, H_2SO_4, Na_2SO_4, Al_2SO_4 and fairly of $FeCl_3$. Thus, it is concluded that the fifth and seventh harmonic powers are influenced by those chemical compounds.

Table I shows correlation matrix that correlate among variables, those have been normalized, so that the correlation between its own self is unity as maximum. The columns from the left to the right, and the rows from the top to the bottom are V_{max} (maximum applied voltage), I_{max} (maximum leakage current), phi (phase angle), cos-phi (power factor), $1^{st}{}_{max}$, $3^{rd}{}_{max}$, $5^{th}{}_{max}$, $7^{th}{}_{max}$ (maximum leakage current frequency

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spectrum harmonics amplitudes 1^{st} to 7^{th}), 1^{st}p, 3^{rd}p, 5^{th}p, 7^{th}p, (maximum power of leakage current frequency spectrum 1^{st} to 7^{th}), NaCl, Na_2SiO_3, H_2SO_4, CaO, Na_2SO_4, KCl, Al_2SO_4, $MgSO_4$, $FeCl_3$ and TiO_2 (kind of chemical compounds for insulator surface coating).

TABLE I
CORRELATION MATRIX AMONG THE PARAMETERS

	V_{max}	I_{max}	phi	Cos(phi)	1^{st}_{max}	3^{rd}_{max}	5^{th}_{max}	7^{th}_{max}	1^{st}_{P}	3^{rd}_{P}	5^{th}_{P}
V_{max}	1	.69	-.22	.25	.67	.54	.83	.79	.47	.30	.58
I_{max}	.69	1	-.42	.40	.99	.92	.96	.96	.93	.83	.92
phi	-.22	-.42	1	-.99	-.42	-.43	-.33	-.35	-.32	-.37	-.27
Cos(phi)	.25	.40	-.99	1	.39	.38	.33	.34	.29	.32	.26
1^{st}_{max}	.67	.99	-.42	.39	1	.92	.95	.95	.93	.84	.92
3^{rd}_{max}	.54	.92	-.43	.38	.92	1	.84	.88	.86	.95	.82
5^{th}_{max}	.83	.96	-.33	.33	.95	.84	1	.97	.87	.73	.91
7^{th}_{max}	.79	.96	-.35	.34	.95	.88	.97	1	.85	.76	.88
1^{st}_{P}	.47	.93	-.32	.29	.93	.86	.87	.85	1	.89	.98
3^{rd}_{P}	.30	.83	-.37	.32	.84	.95	.73	.76	.89	1	.83
5^{th}_{P}	.58	.92	-.27	.26	.92	.82	.91	.88	.98	.83	1
7^{th}_{P}	.56	.90	-.28	.27	.90	.85	.89	.90	.95	.88	.97
NaCl	-.03	.13	-.43	.41	.13	.07	.07	.10	.12	.10	.09
Na_2SiO_3	-.06	.20	-.68	.70	.20	.14	.09	.06	.18	.16	.12
H_2SO_4	-.09	.22	-.71	.70	.22	.16	.09	.05	.21	.20	.14
CaO	.04	.13	-.59	.61	.13	-.02	.10	-.03	.20	.02	.19
Na_2SO_4	-.02	.17	-.58	.57	.18	0	.11	.01	.25	.07	.22
KCl	.14	.30	-.42	.43	.31	.13	.26	.15	.33	.15	.32
Al_2SO_4	.11	.37	-.43	.43	.38	.19	.29	.23	.41	.22	.37
$MgSO_4$	.09	.40	-.31	.31	.41	.26	.32	.28	.46	.30	.42
$FeCl_3$	.07	.47	-.26	.26	.48	.38	.39	.35	.57	.43	.53
TiO	.05	.42	-.16	.16	.43	.41	.38	.36	.57	.53	.57

	7^{th}_{P}	NaCl	Na_2SiO_3	H_2SO_4	CaO	Na_2SO_4	KCl	Al_2SO_4	$MgSO_4$	$FeCl_3$	TiO
V_{max}	.56	-.03	-.06	-.09	.04	-.02	.14	.11	.09	.07	0.5
I_{max}	.90	.13	.20	.22	.13	.17	.30	.37	.40	.47	.42
phi	-.28	-.43	-.68	-.71	-.59	-.58	-.42	-.43	-.31	-.26	-.16
Cos(phi)	.27	.41	.70	.70	.61	.57	.43	.43	.31	.26	.16
1^{st}_{max}	.90	.13	.20	.22	.13	.18	.31	.38	.41	.48	.43
3^{rd}_{max}	.85	.07	.14	.16	-.02	0	.13	.19	.26	.38	.41
5^{th}_{max}	.89	.07	.09	.09	.10	.11	.26	.29	.32	.39	.38
7^{th}_{max}	.90	.10	.06	.05	-.03	.01	.15	.23	.28	.35	.36
1^{st}_{P}	.95	.12	.18	.21	.20	.25	.33	.41	.46	.57	.57
3^{rd}_{P}	.88	.10	.16	.20	.02	.07	.15	.22	.30	.43	.53
5^{th}_{P}	.97	.09	.12	.14	.19	.22	.32	.37	.42	.53	.57
7^{th}_{P}	1	.10	.07	.07	.06	.11	.21	.29	.36	.45	.57
NaCl	.10	1	.67	.52	.42	.35	.29	.24	.19	.15	.10
Na_2SiO_3	.07	.67	1	.77	.62	.52	.43	.36	.29	.22	.15
H_2SO_4	.07	.52	.77	1	.81	.67	.56	.46	.38	.29	.19
CaO	.06	.42	.62	.81	1	.83	.69	.57	.46	.36	.24
Na_2SO_4	.11	.35	.52	.67	.83	1	.83	.69	.56	.43	.29
KCl	.21	.29	.43	.56	.69	.83	1	.83	.67	.52	.35
Al_2SO_4	.29	.24	.36	.46	.57	.69	.83	1	.81	.62	.42
$MgSO_4$	.36	.19	.29	.38	.46	.56	.67	.81	1	.77	.52
$FeCl_3$	.45	.15	.22	.29	.36	.43	.52	.62	.77	1	.67
TiO	.57	.10	.15	.19	.24	.29	.35	.42	.52	.67	1

From correlation matrix above, it is shown that the different parameters those yield values 0.9 and above are maximum amplitude of leakage current with maximum first, third, fifth and seventh harmonics, and maximum power of leakage current of first, fifth and seventh. This means the maximum amplitude of leakage current influences very significantly to those parameters. Those parameters rise as the leakage current increase very considerably. However, power of third harmonics is influenced by 83% of leakage current. It is significant. Whereas, the chemical compounds of H_2SO_4 and Na_2SiO_3 are affected to the power factor of 70%. This is significantly enough. Base on this correlation matrix, among these chemical compounds, both are the most conductive, because the power factor drastically increase. It means the conductivity increase more rapidly, rather than those due to other chemical compounds. Otherwise, applied voltage amplitude contributes only 69%, to the amplitude of leakage current. In other word, although the leakage current is almost influenced by the applied voltage, there are any other parameters for affecting the leakage current, i.e. in this experiment is artificial pollution. The correlation components of other parameters are so small, so that their influential levels are not so significant.

III. CONCLUSION

Base on the data and analyses, it can be concluded that the fundamental harmonic leakage current amplitude is significantly influenced by the applied voltage. The leakage current amplitude influences the parameters with maximum first, third, fifth and seventh harmonics, and maximum power of leakage current of first, fifth and seventh very considerably. The second one is for maximum power of third harmonic leakage current.

Whereas, the chemical compounds of H_2SO_4 and Na_2SiO_3 affected to the power factor around 70%. This is significantly enough. Among these chemical compounds, both are the most conductive, because the power factors drastically increase.

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