Surface Discharge Current Pattern Properties of Porcelain Insulator Specimen on Various Pressures

Waluyo, N. I. Sinisuka, Suwarno, and M. A. Djauhari

Abstract—This manuscript presents the patterns of surface discharge currents due to pressure influence on the porcelain insulator specimen. It was subjected by the high voltages in a hermetically sealed chamber, where the pressure could be adjusted and measured simultaneously. The applied voltage and discharge current waveforms were recorded by a storage digital oscilloscope, transferred and saved to a computer. The discharge current waveforms were analyzed by using FFT, correlation coefficient and principal component analyses.

The yielded discharge currents were in intermittent conditions. After the fundamental, the second highest harmonics was third. The discharge current amplitude increased significantly as the pressure reduced. The characteristics between discharge current and applied voltage magnitudes were more extremely non-linear as the pressures reduced, especially they were lower than the atmospheric pressure. The discharge breakdown voltage increased as the air pressure rose. It required a voltage magnitude threshold to be discharge. Almost harmonics had the negative correlation coefficients on the pressure, except the THD which had 0.45. The increasing THD was more dominantly caused by the increasing first harmonics which was slighter than the increasing remaining harmonics.

Index Terms—Discharge current, harmonics, non-linear, porcelain specimen, pressure.

I. INTRODUCTION

O
VERHEAD transmission or distribution lines are widely used in present power system to transmit electric power from generation stations to customer points. Their proper function largely depends on the insulation system with the supporting structures [1]. The performance of outdoor insulators, as main insulating materials, is influenced by some parameters, one of them is atmospheric pressure.

The study of flashover process very important for electric power supply reliability, efficiency and serviceability. The main events leading to flashover of polluted insulators under service voltages are the formations of conductive layer on the insulator surface, leakage current surging with associated dry band formation and partial arc development and arc propagation along the insulator surface eventually spanning the whole insulator [2]-[7]. The third harmonic components of leakage currents are indications of dry-band arcing rather than a threshold value [8]. According to [9], the relation flashover voltage and pressure is

\[
\frac{V}{V_0} = \left( \frac{P}{P_0} \right)^{\frac{c}{(c+1)}} = \left( \frac{p}{p_0} \right)
\]

Until now, \( m \) are various values, 0.31 upto 0.81. While the theoretical value is 0.2. Little attention to temperature during the experiment may be a possible reason for the scatter of the value. This equation can be written as

\[
\frac{V}{V_0} \approx 1 - m \left( \frac{\Delta p}{p_0} \right)
\]

It shows a linear relation between contamination flashover voltage and pressure. It was stated that under constant temperature, a 5% reduction in contamination flashover voltage per 1 km of altitude is anticipated.

At high altitude areas, reduction of both temperature and pressure occurs, so that it is necessary to evaluate simultaneously the effect of both temperature and pressure on contamination flashover voltage of insulators [9].

A flashover voltage increased asymptotically as the pressure rose [10], [11]. Nevertheless, the flashover voltage decreased parabolically as the pressure reduced below normal condition. However, the impulse flashover voltage rose linearly as the pressure increased [12]. The dependence of line and substation insulators, which had the range of pollution density from 2 to 14 \( \mu \text{s} \) at \( p/p_0 \), from 1 to 0.7, is approximately identical at various air pressure [13], [14]. The flashover voltage increased as linear logarithmic with pressure increased too [15].

Almost cited references discussed regarding magnitudes of flashover or discharge voltages or their gradients. Only few references discussed influence of pressure to flashover or discharge voltages. It was minus in discussion concerning the current patterns of discharge or flashover on a insulator or specimen with the pressure influence. Thus, it was necessary to investigate the discharge current patterns on the porcelain insulator specimen and their behaviours due to pressure change. The objectives were to obtain the characteristics of discharge current amplitudes, harmonic patterns and total harmonic distortions (THDs). The patterns were presented by the harmonics. Finally, the parameter behaviour on the pressure was obtained by using the correlation coefficient and principal component analysis.

Manuscript received August 10, 2010; revised April 4, 2011.

This work was supported by the KK-ITB Research Grant, 2009.

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Publisher Item Identifier S 1682-0053(11)189220 © 2011 ACECR
II. EXPERIMENTAL AND ANALYSIS METHODS

The porcelain insulator specimen under test was given one water drop of dried kaolin solution as artificial pollutant for making lower threshold voltage magnitude. The leakage length was 3 cm. It was tested in the hermetically sealed chamber, where its pressure could be adjusted and measured simultaneously. The pressure could be enhanced by a compressor and reduced by a vacuum pump. It was indicated by negative and positive displays respectively on the digital manometer.

The measurements and recordings of discharge current and applied voltage waveforms simultaneously used a two-channel storage digital oscilloscope. The data were transferred to a computer by using USB and saved in softcopy forms. The waveform data were in drawing (bitmap) and numerical (csv) files. The latters were for further analyses. The schematic diagram of discharge current measurement setup is shown in Fig. 1.

Moreover, the discharge current waveforms were analyzed by using FFT (fast Fourier transform), to obtain the harmonics spectra on some pressures. These implementations used the Danielson-Lanczos method [16]. It was necessary total harmonic distortion (THD) to quantify the waveforms of discharge currents. If a THD closed zero, the waveform approached the pure sinusoidal waveform, and vice versa. THD is defined as [17].

\[
THD = \sqrt{\sum_{n=2}^{N} I_n^2} / I_1
\]  

(3)

The relations among parameters were analyzed by using correlation coefficient analyses, the derivation of covariance matrix to represent the correlations among parameters based on data [18], [19]. The component of correlation matrix is correlated by

\[
\rho_{x,y} = \frac{\text{Cov}(X,Y)}{\sigma_x \sigma_y}
\]  

(4)

Another way to assess among parameter correlations is using principal component analysis (PCA) [20]-[22]. If a set of data is presented in matrix \( X \), the main algorithm of PCA involves some steps.

First, determining the mean components of matrix \( X \), those are related by

\[
x_{i} = \frac{1}{n} \sum_{i=1}^{n} x_{i,i}
\]  

(5)

Second. determining covariance matrix using equation of

\[
C = X^T X
\]  

(6)

Third, determining eigen values and eigen vectors of covariance matrix using equation of

\[
CQ = \lambda Q
\]  

(7)

Finally, their scatters were plotted in two dimensions, for first and second principal components. Thus, the nearness of parameters indicates their correlations

III. RESEARCH RESULTS AND DISCUSSION

Fig. 2(a) shows the sample of the discharge current and applied voltage waveforms, where the chamber was exactly same as the room atmospheric pressure. The discharge current was occurred in intermittent, so that it was not continual. The applied voltage amplitude was 28 kVpeak. The discharge current and applied voltage magnitudes are shown on the left and right sides. Fig. 2(b) shows the corresponding harmonics of discharge current wave. As important points of view, the fundamental, third and fifth harmonics were 146 \( \mu \)A, 47 \( \mu \)A and 18 \( \mu \)A or the percentages on the fundamental were 32.3% and 12.1% for the third and fifth ones respectively. The THD was 75.8%. The significances were third, ninth and eleventh harmonics after the fundamental. Fig. 2(c) shows the discharge current and applied voltage magnitude chart. The property of discharge condition was in non-linear. The average negative and positive critical discharge voltage magnitudes were -25.24 kV and 24.93 kV, respectively.
Fig. 3. The discharge current characteristics on 23.5 kV_{max} and -19 kPa for applied voltage and pressure reduction; (a) discharge current and applied voltage waves, (b) discharge current harmonics spectrum, and (c) V-I characteristics.

Fig. 3(a) shows the discharge current and applied voltage waveforms on the condition of 23.5 kV_{max} and -19 kPa for the applied voltage amplitude and the pressure reduction respectively. Fig. 3(b) shows the corresponding harmonics. The fundamental, third and fifth harmonics were 1797 µA, 816 µA and 291 µA respectively. The percentages of the third and fifth harmonics on the fundamental, significances, were 45.4% and 16.2% respectively and the THD was 53.8%. Fig. 3(c) shows the relation between discharge current and applied voltage magnitude chart. The property of discharge was more drastically non-linear than that the previous one. The negative and positive averages of critical discharge voltage magnitude were -22.45 kV and 22.04 kV respectively.

Moreover, Fig. 4(a) shows the discharge current and applied voltage waves on 27.7 kV_{max} and +19 kPa for the applied voltage amplitude and the pressure addition respectively. Fig. 4(b) shows the corresponding harmonics and the fundamental, third and fifth harmonics were 228 µA, 109 µA and 124 µA respectively. The percentages of third and fifth harmonics on the fundamental were 47.8% and 54.4% respectively and the THD was 90.8%. The significant amplitudes were fifth, third, seventh, sixth and tenth harmonics after the fundamental. Fig. 4(c) shows the corresponding discharge current and applied voltage magnitude chart. The property of discharge was considerably less non-linear than that the previous ones. The negative and positive average critical discharge voltage magnitude was -27.02 kV and 26.82 kV respectively.

These figures indicate that the pressure had an important role on an electrical discharge. On the atmospheric pressure, the third harmonics of discharge current was significantly dominant after the fundamental. Nevertheless, the remaining odd harmonics were also dominant, mainly eleventh, ninth and seventh harmonics. First case was different from the lower pressure one, as an example on 19 kPa under the atmospheric pressure. On the low pressure, the third harmonics of discharge current was more dominant than that the atmospheric pressure. It was also the highest amplitude among remaining harmonics, except the fundamental. The thorough discharge current amplitude enhanced significantly, more than five times from the first. The V-I characteristics was considerably more non-linear than the first. The averages of critical discharge voltage magnitude were considerably lower than the first.

On the contrary, in the higher pressure, as an example
on 19 kPa upper the atmospheric pressure, the third harmonics was significantly less than the previous ones and the fifth harmonics. The discharge current amplitude was significantly lower and the V-I characteristics was also less non-linear than the previous ones. Therefore, the role of low pressure is very important to create an initial discharge. On the low pressure, the electron on the insulator specimen surface was easier to be released (= ionized) as subjected by a sufficient high voltage. This case was also a representation, that if an insulator is installed on a high land, where the atmospheric pressure reduces, it will tend to be discharged, as an initial fail condition.

Fig. 5 shows the average of critical discharge voltage magnitudes as function of pressure. The critical positive discharge voltage magnitude would considerably rise as the pressure increased. This case was similar as the negative one. Therefore, the critical discharge voltage magnitude would reduce as the pressure decreased to tend to a vacuous condition. In a low pressure, it needed a slightly low applied high voltage to discharge the specimen, which meant that the electron tended to be easier to discharge when subjected by a high voltage.

The third harmonics were usually dominant among harmonics, especially on the low pressures, so that the discharge currents were far away from the pure sinusoidal form. These phenomena were indicated by discharge current waveforms and the harmonics spectrum or high THDs. Usually, the fronts of discharge current waves were suppressed to the centre. After reach the peaks, the waveforms were not suppressed. These cases indicated that to be discharge, it required applied voltage magnitude thresholds.

Those phenomena were suitable as the Vosloo’s proposal, a leakage current just before discharge [23], as shown in Fig. 6(a). If this wave is compared to the above experimental results, or Fig. 6(b), those figures resembled the proposed waveform theory.

Fig. 7 shows the positive and negative peaks of discharge currents versus the pressure experimentally. Actually, the peaks of discharge current, whether positive or negative, were occurred in intermittent. So those, in the experiment, the peak values were obtained randomly. The discharge current peaks, besides depended on pressure, they also depended on applied voltage magnitude, pollutant, leakage distance, form factor, environmental condition and so on. However, it was emphasized on the pressure effects.

The discharge current peaks would significantly decrease as the pressure increased. The chart tended to be fairly hyperbola, where the empirical equations are shown. Therefore, the role of atmospheric pressure is very important on the discharge current peaks. On the low pressures, as high land representation of insulator installation, the discharge current amplitudes will be higher. For an example, if an insulator installation on 870 meter above sea level, the discharge current amplitude will be around twice.

Fig. 8 shows the odd harmonics of discharge current versus the positive and negative pressures. It indicates that the harmonics would reduce significantly as the pressure increased. The reducing phenomena were hyperbola. Nevertheless, the slopes were different, where on the negative values, they were more drastic than those on the positive ones. Furthermore, the harmonics tended to be constant values. Usually, the harmonics would be smaller as the harmonics order increased.
For further analysis, Fig. 9 shows the percentages of odd harmonics to the corresponding fundamentals of discharge currents versus positive and negative pressures. The charts tended to very slightly increase. This case means that the harmonics comparisons to the corresponding fundamental would fairly constant as the pressure increased. The third harmonics were most significantly influenced by the pressure. On the low pressures, they would increase drastically as the pressure reduced. On the contrary, on the high pressures, they would significantly reduce as the pressure increased. Nevertheless, the harmonics percentages on the corresponding fundamentals tended to be fairly constant. This case indicated that the harmonics increased as a follower of the corresponding fundamentals.

Usually, the percentages of the harmonics on the corresponding fundamentals were represented by THDs. Fig. 10 shows the THDs versus both positive and negative pressures. The THDs would increase considerably as the pressure rose. This statement means that the fundamentals would slightly increase rather than those increasing remaining harmonics on the corresponding fundamentals as the pressure increased.

The critical discharge voltages versus the pressures experimentally are shown in Fig. 11. The pressure was indicated by the digital manometer as positive, zero and negative values. Nevertheless, due to Bandung city is 768 m above sea level in average, the actual pressures had to be converted according to the pressure conversion table [24].

The critical discharge voltage would rise as the actual pressure increased. It was more difficult to be discharge as the pressure would be higher, and vice versa, as the pressure was lower, it would be easier to be discharge. In the real condition on sites, if a land of insulator installation increases above sea level, an insulator is relatively easier to be discharge or flashover occurrence than that on a lower place.

The atmospheric pressure is one of the factors that considerably influence the minimum flashover voltage of insulators. The relationship between the critical flashover voltage of polluted insulators and the air pressure was cited on the references [9], [14], [25], [26] as (1). Based on the sea level (0 meter), the actual atmospheric pressure is 101.33 kPa, so that m constant values were between 0.226 and 3.137, where m average value was 1.35. The exponent m was the constant value of which characterized by the influence of air pressure on the critical flashover voltage of insulators and depended on the several factors and parameters, including insulator profile, voltage polarity and pollution severity [11]. The atmospheric pressure has a definite effect on the AC minimum flashover voltage of insulators or specimens.
The discharge currents had some unique properties, such as the magnitude was dominantly influenced by air pressure, intermittent occurrence, tended to be far from pure sinusoidal waveform. Although like this, the third harmonics would reduce as the pressure increased.

The THD closed to the pressure, where it would increase as the pressure rose. This means as the pressure rose, the discharge currents would be fairly far away from pure sinusoidal waveform. Although like this, the third harmonics would reduce as the pressure increased.

Discharge currents were different from leakage currents. The discharge currents had some unique properties, such as the magnitude was dominantly influenced by air pressure, intermittent occurrence, tended to be far from the sinusoidal waveform, high THD (usually more than 50%), tended to be suppressed on the wave front due to the thresholds. The second highest harmonic was the third and fifth harmonics (H03) and fifth (H05) harmonics. These harmonics were highly influenced by the pressure reciprocally, where those parameters would reduce considerably as the pressure increased. These properties were also supported by the correlation coefficients as shown above, where they had high negative values.

Although the 3rd harmonics were so fairly small effect on the pressure, actually it had high values after the fundamentals as the pressure reduced. This statement was clarified by the PCA scatter plot in Fig. 12, where the third harmonics (H03) were far away in opposition from the pressures (P). The third harmonics would increase as the pressure reduced, and vice versa. It is also revealed that the far opposing parameters to the pressure (P) were the first (H01), seventeenth (H17), nineteenth (H19), sixteenth (H16) and fifth (H05) harmonics. These harmonics were highly influenced by the pressure reciprocally, where those parameters would reduce considerably as the pressure increased. These properties were also supported by the correlation coefficients as shown above, where they had high negative values.

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Fig. 12. The PCA scatter plot for the harmonics and THD on the pressure.

IV. CONCLUSIONS

Although the discharge current THD had very high values when low air pressures, they would increase as the pressure increased. These phenomena were caused more dominantly by the increasing first harmonics which were slightly rather than the increasing remaining harmonics, although these harmonics increased too.

Almost discharge current harmonics had negative correlation coefficients on the pressure. Nevertheless, the THD had 0.45 of correlation coefficient. This means as the pressure increased, the discharge currents were slightly far away from pure sinusoidal wave.

The discharge currents had some unique characteristics, such as the ambient was dominantly influenced by air pressure, intermittent occurrence, tend to be far from sinusoidal wave, very high THDs (more than 50%), tend to be suppressed on the front of wave, due to the threshold values of applied voltage magnitudes, third harmonics as almost discharge current harmonics had negative correlation coefficients on the pressure. Nevertheless, the THD had 0.45 of correlation coefficient. This means as the pressure increased, the discharge currents were slightly far away from pure sinusoidal wave.

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ACKNOWLEDGMENT

Authors herewith respectfully offer thanks to Riset KK-ITB research project for supporting the research.

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