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Published in:
2022 2nd International Conference of Smart Systems and Emerging Technologies, SMARTTECH 2022

DOI:
10.1109/SMARTTECH54121.2022.00037

Publication date:
2022

Document Version
Author accepted manuscript

Link to publication in ResearchOnline

Citation for published version (Harvard):
Shaukat, S, Arshad, A & Shah, WA 2022, Use of wavelet transform to analyze leakage current of silicone rubber insulators under polluted conditions. in *2022 2nd International Conference of Smart Systems and Emerging Technologies, SMARTTECH 2022.* Proceedings - 2022 2nd International Conference of Smart Systems and Emerging Technologies, SMARTTECH 2022, Institute of Electrical and Electronics Engineers Inc., pp. 118-123. https://doi.org/10.1109/SMARTTECH54121.2022.00037

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Use of Wavelet Transform to Analyze Leakage Current of Silicone Rubber Insulators Under Polluted Conditions

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***Abstract*— Leakage current is a very important parameter in the performance evaluation and monitoring of outdoor insulators. This paper presents experimental results of leakage current under different contaminated conditions of silicone rubber insulators. HTV silicone rubber sheets were utilized for tests and pollution was coated artificially in laboratory. The effect of temperature, humidity and pollution severity on leakage current of silicone rubber insulators were investigated. It was observed that leakage current magnitude increases with an increase in relative humidity, temperature, NSDD, and level of pollution severity. A discrete wavelet transforms (DWT) technique based on multi-resolution analysis (MRA) was used to study the time-frequency characteristics of leakage current. DWT-MRA technique can be used to detect frequency bands corresponding to different pollution severity levels and location of dry bands. These results can be used to predict dry band arcing activity on the surface of outdoor polymeric insulators.**

Keywords— Electric breakdown; Discharges (electric); Surface discharges; Insulation; Insulators

I. Introduction

The reliability of power system transmission and distribution system depends on the performance of outdoor high voltage insulators. Overhead insulators are exposed to many stresses such as electrical, thermal, mechanical and environmental during service conditions. Due to the improved performance of polymeric insulators in polluted conditions, their usage has increased extensively in the past few decades. The main cause of non-ceramic insulators failure as reported in [1] is the ageing of weather shed material. Polymeric insulators are organic in nature which makes them susceptible to biological degradation [2]. As the biological conditions varies from region to region, their performance also varies from one region to another. Although polymeric insulators are vulnerable to ageing and detoriation, their performance is still better than porcelain and glass insulators specially in polluted conditions [1].

Apart from ageing and degradation, flashover due to pollution deposition on high voltage insulators is another concern for utility companies. During moisture, cold fog or rain insulator surface becomes wet leading to flow of leakage current along the surface of insulator [3]. The Joule heating effect of current results in moisture evaporation and dry band formation. Electric field intensity at edges of dry bands is very high resulting in partial arcs and may lead to flashover and power outages [4]. To monitor contamination on outdoor insulators, different methods are developed based on equivalent salt deposit density (ESDD), NSDD and surface resistance [5]. However, these methods lack the capability of online monitoring and cannot be used to forecast the performance of real time insulators. So, leakage current is considered a more reliable diagnostic and monitoring technique as compared to ESDD, NSDD and surface resistance.

To improve the performance and reliability of outdoor insulators, various online and offline condition monitoring techniques were developed based on leakage current [6, 7]. The ageing and leakage current behavior of porcelain and polymeric insulators in field and laboratory conditions were evaluated in [8]. These results represents that the surface conditions at porcelain and polymeric insulators can evaluated using the time variation of cumulative charge and the corresponding element ratios. Another method for evaluating and monitoring of insulator surface conditions was proposed in [9] based on peak current and charge measurement. However, it was reported later in [10] that the value of peak current may not always match the corresponding arcing activity at the insulator surface. A new relationship between surface temperature and harmonic power of leakage current was established in [11] and a good correlation was found between the two parameters. The frequency characteristics of leakage current were studied using Fourier transform for diagnostics and monitoring of outdoor insulators [7, 12]. Because of the non-stationary nature of leakage current, the Fourier transform approach is considered inappropriate for monitoring and evaluation of outdoor insulators. An artificial neural network (ANN) approach along with fast Fourier transform (FFT) was suggested in [13, 14] to evaluate the safety conditions of insulators under polluted conditions. They suggested three basic parameters of leakage current: peak current, phase difference and total harmonic distortion (THD) for training the ANN model. In [15], it was concluded that flashover incidence in composite insulators is related to the leakage current 3rd and 5th harmonic ratio. Leakage current characteristics on naturally and artificially polluted silicone rubber insulators under field and laboratory conditions have been investigated in [16, 17]. Ageing of polymeric insulators based on leakage current characteristics and proposed ANN model were evaluated in [18]. Pattern recognition of leakage current based on ANN and other statistical tools were also proposed in [19, 20]. The pollution severity on the surface of ceramic and polymeric insulators were evaluated using the distortion of the leakage current pattern and STD-MRA [21, 22]. STD-MRA along with discrete wavelet transform have the capability to detect the width and position of the pollution layer [22]. Using this method, very interesting details about the pollution condition and the corresponding discharge can be investigated.

This paper presents experimental results of leakage current on rectangular silicone rubber sheets under humid and contaminated conditions. Tests were conducted in climate chamber to study the influence of applied voltage, pollution severity, NSDD, relative humidity, ambient temperature and dry band formation on leakage current characteristics of silicone rubber sheets. A discrete wavelet transform approach based on STD-MRA was employed to study the frequency bands of leakage current and detect those signals which indicate the occurrence of partial arcs. The authors believe that this investigation is the first of its kind considering various environmental and polluted conditions and providing a systematic study which can be used for evaluating the degree of pollution severity and monitoring of outdoor polymeric insulators.

II. MATERIALS AND METHODS

Materials Leakage current along the insulator surface is a non-stationary wave and includes transients. Wavelets offers a flexible tool for analyzing transient and non-stationary waves like leakage current [23] and allows the signal analysis of time and frequency signals simultaneously. The first step is the selection of a suitable function of wavelet called "mother wavelet" which then further investigation are performed on the dilated and shifted version of a chosen mother wavelet [24]. For the analysis of leakage current, two types of analysis techniques are generally used: continuous wavelet transform (CWT) and DWT. CWT has larger computational time and uses a continuous variety of scales and shifts while DWT use distinct range of scale and shifts. Due to its faster computational speed, DWT is the preferred choice in real time leakage current monitoring. Mathematically, DWT can be represented by the following equation.

$$DWT_x^{\varphi}(m,n) = \frac{1}{\sqrt{a^m}} \int x(t)\varphi^*\left(\frac{t-nba^m}{a^m}\right)dt \quad (1)$$

Where x(t) is the discrete signal, φ is the mother wavelet shifted by nba^m and scaled by a^m, m and n are positive integers and a, b are positive values with a>1 and b>0.

MRA of a DWT is used to produce time scale signal of discretized signal $x(n)$ at different breakdown levels. A signal is analyzed at different frequency bands and resolutions with the help of MRA. This process is continued until the required resolution is obtained. The time domain signal is decomposed by passing through successive high pass and low pass filtering. If h and g are the high pass and low pass filters respectively and $c[n]$ is the signal sequence, then the decomposition is performed by convolving $c_0[n]$ with h, g and decomposed into approximation component $c_1[n]$ and detail component $d_1[n]$. The approximation component is further decomposed into $c_2[n]$ and $d_2[n]$. This process continues until the desired resolution is obtained. Mathematically, this process is given by the following equations.

$$c_m[n] = \sum h[k-2n]c_{m-1}[k] \quad (2)$$

$$d_m[n] = \sum g[k-2n]c_{m-1}[k] \quad (3)$$

This process of decomposition enables the signal to decompose without loss of information and the original signal can be reconstructed using the inverse DWT [25].

By using multi resolution signal decomposition, two important property of leakage current can be obtained. The first property is the localization property in time which then appear as a big coefficient at the disturbance time. Another property is splitting of the signal energy into various frequency bands. To identify transition in any signal due to high frequencies, Daubechies 4 wavelet is considered very helpful [26, 27]. The leakage current signals are decomposed up to 10 levels using the Daubechies 4 wavelet and the corresponding frequency bands are obtained. Standard deviation is measured for detailed component at all decomposition levels to classify the transient energy in the signal. Mathematically, standard deviation for n^{th} level of comprehensive component is obtained using Equation (4) given below.

$$STD = \sqrt{\frac{1}{N_n-1}\sum_{j=1}^{N_n}[d_n(j)-\mu_n]^2} \quad (4)$$

Where μ_n and N_n are the mean and length of detailed component vector d_n respectively. Table 1 shows the detailed components and their corresponding frequency bands.

TABLE 1. FREQUENCY BANDS OF THE DETAILED COMPONENTS OF LEAKAGE CURRENT

Detailed Component of DWT	Frequency Band (kHz)
D1	6.25-12.5
D2	3.125-6.225
D3	1.56-3.125
D4	0.78125-1.562
D5	0.3906-0.78125
D6	0.1953-0.3906
D7	0.07656-0.1953
D8	0.04882-0.07656
D9	0.02441-0.04882
D10	0.01220-0.02441

Figure 1 shows the simplified test setup used for the experiments. Rectangular silicone rubber samples of dimensions (10 × 4 × 0.6) cm were contaminated artificially in laboratory and tested under clean fog conditions [28]. To energize the samples a variable (0kV to 100 kV, 50 Hz) transformer is placed in the experimental setup.

Fog rate, humidity and temperature were controllable within a climate chamber of dimensions 2.5m × 2.5m × 2.0 m. The protective circuit was configured at 1A and 50kV. To minimize any unwanted corona and partial discharges, very finely polished copper electrodes were used as high voltage and ground terminal. The flashover voltage was measured using a capacitive voltage divider circuit as shown in Figure 1.

Bergoz instrument CT was used to measure leakage current. Both leakage current and voltage waveforms were recorded using a National Instrument data acquisition system.

Six sample configurations were prepared in laboratory for testing. The dry and clean zone is hereafter referred to as dry band in this paper. Further details about sample preparations can be found in [29].

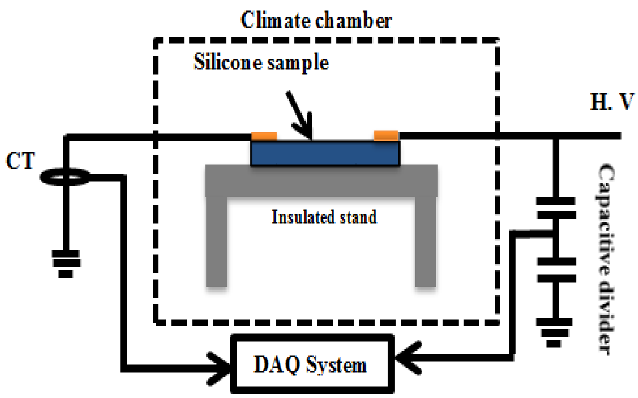

Figure 1. Test setup

III. Results And Discussions

A. *Magnitude of Leakage Current*

Magnitude of leakage current is an important parameter for the prediction of surface conditions and pollution severity of outdoor insulators. For a uniform continuous polluted sample, leakage current and applied voltage are reported to be in phase due to the resistive behavior of a uniform pollution layer [30]. In this paper various tests were carried out with different pollution severity levels (very heavy, heavy, medium and light) and various voltage level for a uniform contamination layer. An increase in leakage current with applied voltage and pollution severity was observed as shown in Figure 2. The dependence of leakage current on NSDD was investigated by changing the concentration of kaolin in the pollution suspension and keeping the NaCl concentration constant. An increase in leakage current was observed as NSDD and applied voltage were increased as shown in Figure 3. It was observed that as the concentration of inert material (kaolin) was increased in the pollution suspension, an additional uniform pollution layer was formed beside the insulator surface which lead to an increase in leakage current. Furthermore, at lower applied voltages, the distortion in leakage current reduced with an increase in NSDD. A uniform pollution layer forms as NSDD is increased and resistive leakage current increases. Leakage current magnitude at different humidity and pollution severity levels is shown in Figure 4. Three various levels of humidity were applied for experiments: low humidity (~ 50%), moderate humidity (~70%) and high humidity (~90%). At low humidity, a slight increase was observed with an increase in applied voltage. As the applied voltage was amplified, the difference in leakage current magnitude at different humidity levels increased. With an increase in humidity, the absorption coefficient of water molecule by a dielectric surface increased resulting in a more uniform pollution layer and an increase in leakage current magnitude. The effect of ambient temperature on leakage current of silicone rubber sheets was investigated and the results are shown in Figure 5. Conductivity of the pollution layer increased with an increase in temperature as reported in [31]. Ambient temperature was varied in a climate chamber from 5 to 20 °C in steps of 5 °C and tests were performed. It was found that leakage current increased with an increase in ambient temperature and applied voltage. Temperature and humidity also affected the hydrophobicity transfer characteristics of silicone rubber [32]. Therefore, enough relaxation time was allowed after each test so that a steady hydrophobicity value was achieved.

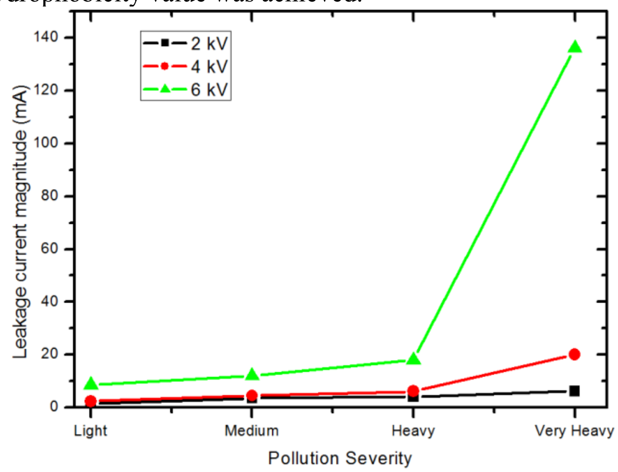

Figure 2. Leakage current magnitude at different pollution severity levels and applied voltage

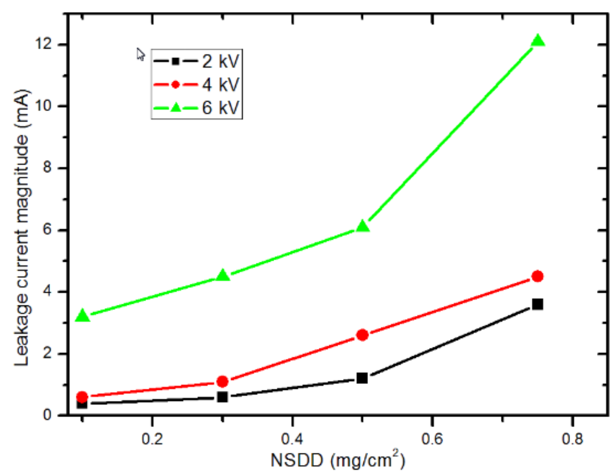

Figure 3. Leakage current magnitude at different NSDD levels and applied voltage

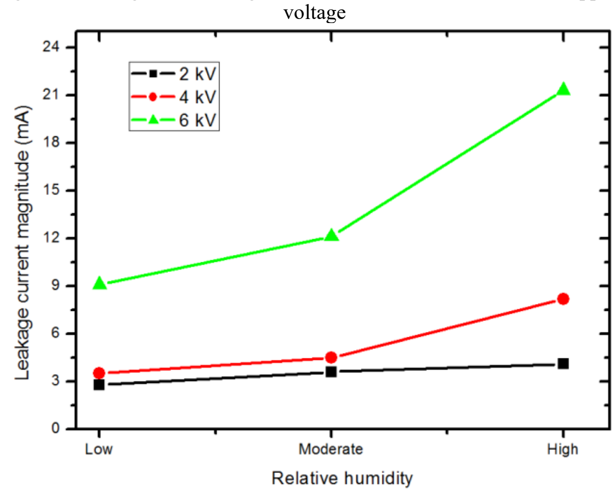

Figure 4. Leakage current magnitude at different relative humidity and applied voltage

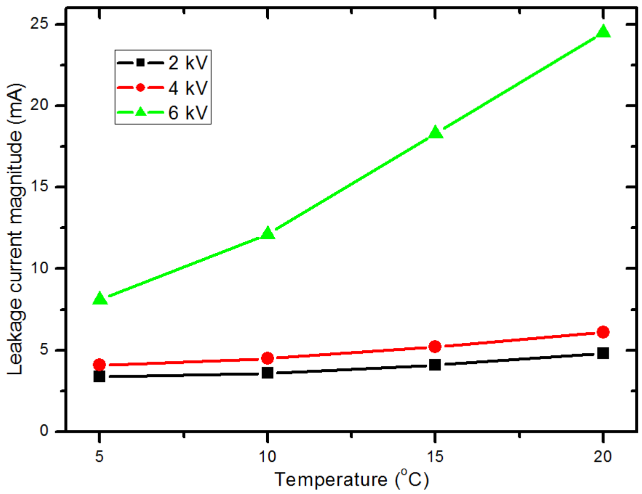

Figure 5. Leakage current magnitude at different ambient temperature and applied voltage

B. *DWT-MRA of Leakage Current*

The effect of humidity, temperature, pollution severity level and dry band formation on leakage current magnitude was studied in the previous section. In this section, leakage current pattern based on DWT STD-MRA is discussed in detail. A rectangular silicone rubber sheet uniformly polluted was used for the tests which were then placed the chamber called 'climate chamber', at moderate level of humidity and 10 °C temperature. In our previous work [29], the arc inception voltage for a very heavily polluted sample was reported to be 4.2 kV. Therefore, the applied voltage in this case was kept constant at 4 kV so that no partial arcs would appear on the insulator surface. Leakage current waveform for a sample of medium pollution severity is shown in Figure 6 when no partial arcs are present at the surface. The STD-MRA plot is shown in Figure 7 for different pollution severity. It can be observed from Figure 7 that in the absence of partial arcs, the energy content of the high frequency components D1 to D5 are closer to fundamental component D8 and increase with an increase in pollution severity.

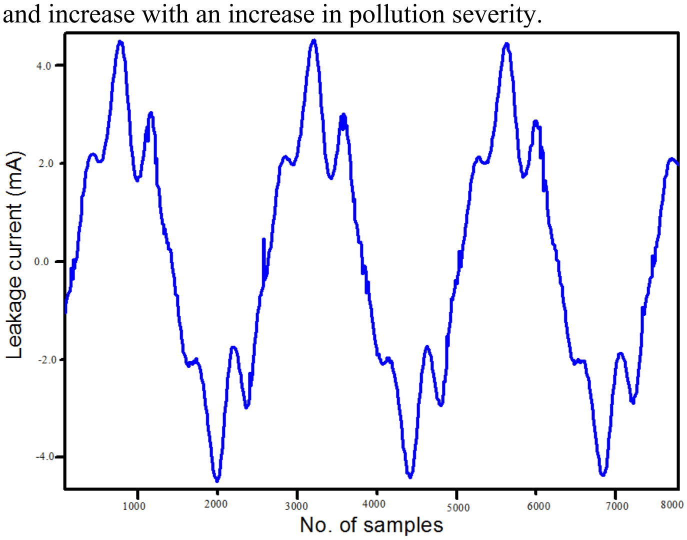

Figure 6. Leakage current waveform in the absence of partial arcs

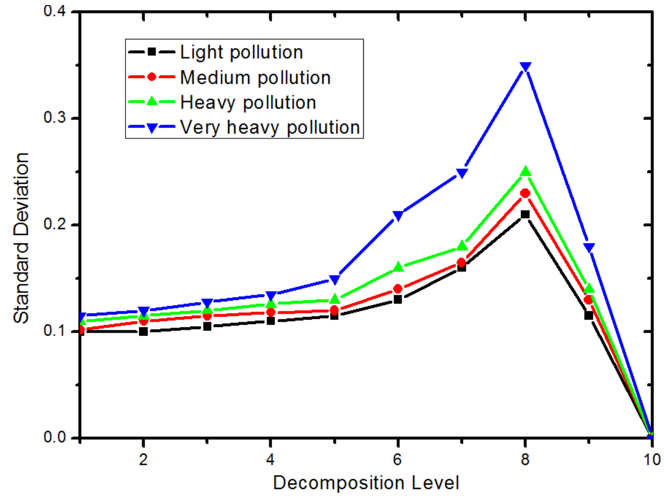

Figure 7. STD representation of leakage current at different decomposition level

To analyze the influence of partial arcs on STD-MRA, the applied voltage was increased to 6 kV. Figure 8 shows the leakage current waveform in the presence of short duration discharges along the insulator surface. The STD-MRA results are plotted in Figure 9. For light and medium pollution severity level, increase in applied voltage has a negligible effect on the STD-MRA plot. For heavy and very heavy polluted samples, an increase in STD of D8 and D6 was observed. Similarly, the high frequency components D1 to D4 STD decreased with an increase in applied voltage. The increase in D6 and D8 is associated with the inception of partial arcs along the insulator surface. When partial arcs appeared on the insulator surface, distortions in the leakage current waveform increased leading to an increase in 3rd and 5th harmonic components of leakage current.

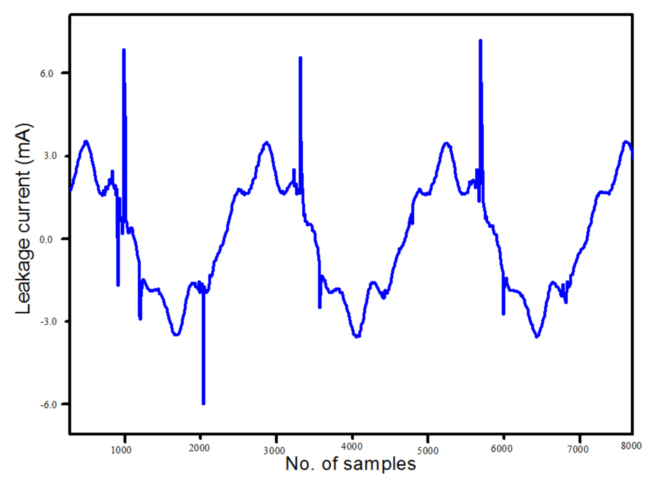

Figure 8. Leakage current waveform in the presence of partial arcs

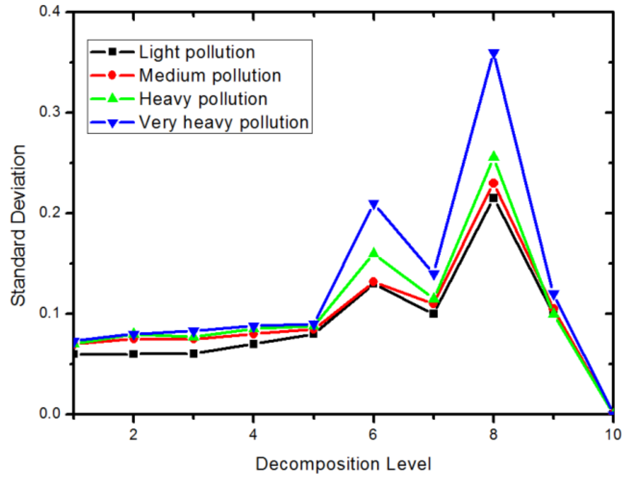

Figure 9. STD representation of leakage current at different decomposition levels in the presence of partial arcs

Change in humidity affects the performance of outdoor insulators in many ways. The magnitude of leakage current increased with an increase in humidity, as reported in previous section. Experiments were conducted under three different humidity levels (low, moderate and high) and an applied voltage of 6 kV. Visual observation revealed that no partial arc was observed at low humidity level but concentrated discharges close to the high voltage end as well as at ground end were observed in the case of moderate and heavy humidity. The STD-MRA graph is shown in Figure 10 for three different humidity levels. In the case of low humidity, the STD values for high frequency components are closer to the fundamental component D8 which indicates the absence of partial arcs along the insulator surface. However, in the case of moderate and heavy humidity, the STD value of component D6 and D8 increased as compared to the high frequency components. This increase was higher for heavy humidity than moderate humidity. These results indicate that partial arcs exist on the insulator surface which results in leakage current distortions. This distortion is more likely for high humidity than moderate humidity.

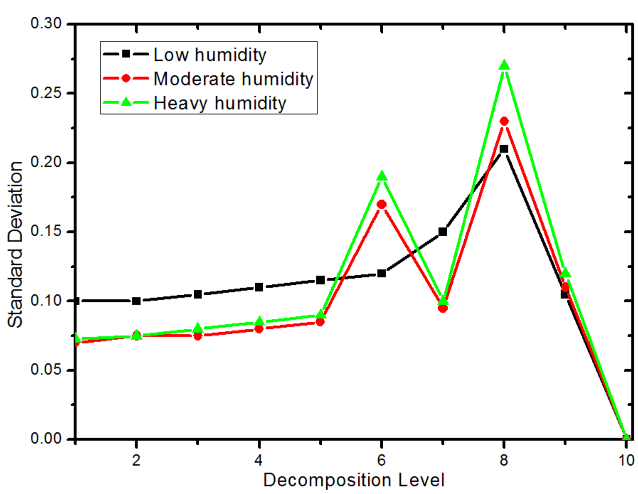

Figure 10. STD representation of leakage current at different humidity levels

IV. Conclusions

Leakage current characteristics of polluted silicone rubber sheets were investigated in this paper. The influence of humidity, temperature, NSDD, pollution severity level and dry band formation on leakage current magnitude was studied. To analyze the transient behavior of leakage current waveforms, the DWT STD-MRA technique was used. The effect of humidity, applied voltage, pollution severity level and dry band location on the detailed components of STD-MRA was investigated. The following conclusions were drawn from the experimental results:

- As pollution severity level and NSDD increases, leakage current behavior changes from capacitive to resistive leading to a decrease in harmonic distortion
- The leakage current magnitude increases with an increase in NSDD and contamination severity level
- Relative humidity and temperature have negligible effect on leakage current at 2 and 4 kV applied voltage and it increases with an increase in humidity and temperature for 6 kV applied voltage
- Magnitude of leakage current is higher for dry bands at high voltage and ground ends than for the middle dry band
- An increase in dry band width decreases the magnitude of leakage current
- In the absence of partial arcs along the insulator surface, there are only small differences between the high frequency components D1-D5 and the fundamental component D8.
- In the presence of partial arcs, STD of high frequency components decreases while those of D6 and D8 increases. The increase in D6 is an indication of the occurrence of partial arcs along the insulator surface.
- Leakage current distortions with an increase in humidity were found to be more visible for high humidity as compared to moderate humidity.
- For middle region dry band, the detailed components D1 and D2 magnitudes were higher than those of the energized and ground end dry bands. This indicates the presence of random arcs and high distortion in leakage current for the middle dry band

The results presented in this paper show that leakage current magnitude and frequency analysis could be used for the study of presence of partial arcs and the influence of various environmental parameters on leakage current characteristics. These results could also be used for the online monitoring of outdoor insulators under humid and contaminated conditions.

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