Relation between Motion of Water Droplets and Dielectric Property of Silicone Rubber under AC High-field Application

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Abstract: The relation between motion of water droplets and their dielectric property on a silicone rubber surface is studied under AC high-field application. Both water droplets and inter-digital stainless steel electrodes are put on the silicone rubber surface and AC high field with superposition of DC offset voltage is applied to the electrodes. The vibration of water droplets, which is related to the hydrophobicity of the silicone rubber surface, is evaluated by both the image data analysis of the shape of water droplets and its dielectric measurement using unbalanced operation method of a capacitance bridge. These data are useful to determine the small changes of hydrophobicity classes with combine the usual contact angle and STRI methods.

INTRODUCTION

Polymeric insulating materials are widely used in the manufacture of weather-sheds of outdoor insulators. Silicone rubber (SIR) especially has excellent hydrophobic property in addition to its excellent electrical, mechanical and chemical characteristics. The usage is expanding rapidly as an electric insulation material typically under the heavy contaminated environment. Therefore, it is very important to study the degradation of hydrophobicity of polymer surface as one of the indices of its initial deterioration process.

The hydrophobicity of the material is usually measured by contact angle of a droplet of distilled water on the sample surface. However, it sometimes shows hysteresis, time dependence and location dependence during the measurements. Therefore, hydrophobic image of the specimen surface after spraying of water mist, which includes many water droplets, is recently used to determine the hydrophobicity class of the surface (STRI's HC level from 1 to 7) [1]. A digital image processing method for estimating the level of hydrophobicity class of specimens is reported in [2, 3].

This paper studies the motion of the water droplets on the SIR surface during AC high field application. AC ramp voltage and AC high field with superposition of DC offset voltage are applied to the inter-digital stainless steel electrodes on the SIR surface. Between the electrode fingers one or three water droplets are set on the SIR surface. Image data indices such as size and position of the water droplets are evaluated to discuss the change in HC levels from vibration behavior of the water droplets [3]. This phenomenon is also detected by the change in dielectric property measured by using the same electrode system on the SIR surface [4]. Electric field dependence of dielectric properties, such as AC loss current, Ixr, and the change in capacitive current from the bridge balance, dIxc, with superposition of DC offset voltage are measured. Dipoles and charges of the sample may show different behaviors under with and without the superposition of DC high field to AC field application.

This dynamic motion study of water droplets on the polymer surface under AC high-field application with DC offset voltage can diagnose the hydrophobicity of polymer surface more accurately. This vibration may initiate the flashover on the insulator surface and, thereafter, the degradation of the material starts.

SAMPLE AND EXPERIMENTAL PROCEDURE

HTV-SIR sample of size 60x50x6 mm is used. A pair of inter-digital electrodes which was made by stainless steel is set on the sample surface. Between the inter-digital electrodes, water droplets were put on the sample surface. The photographic view of the sample and electrodes are shown in Fig. 1. Width and height of



Figure 1: Inter-digital electrodes and water droplets on HTV-SIR sample surface. M; Main electrode, HV; High Voltage electrode, WD; Water droplets, LED+ and LED– are monitoring the phase of applied AC field for image analysis.



Figure 2: Typical result of image data analysis of a water droplet under AC ramp voltage application. AC ramp voltage; 30 Hz, Max 4 kVp-p, 0 to peak and peak to 0 are 1.5 s each. Image rate: 500 FPS, 512x240 pixels. 8bit. Change in size of a water droplet is measured for 1,500 image frames. Volume of the water droplet is 20 μ L.

the electrode finger are 4mm and 3 mm, respectively. The separation of M(Main) and HV(High Voltage) electrode fingers are 6 mm. The volume of water droplets are 20 μ l for AC ramp voltage application and 10 μ l for DC superposition measurements.

AC high field is applied to the electrodes and the motion of the droplets are measured by the image analysis using high speed digital camcorder and also by the dielectric measurement of AC loss current (Ixr) and deviation of capacitive current (dIxc) for each one cycle of AC field application. These dielectric properties are evaluated by using the unbalanced operation method of high-voltage capacitance bridge[4]. DC offset voltage is also superposed to the AC field to clear the hydrophobicity class of the sample surface.

RESULTS AND DISCUSSIONS

Motion of Water Droplet

Figure 2 shows a typical result of the image data analysis of a water droplet under AC ramp voltage application. Change in the size of a water droplet is almost corresponds to the shape of applied AC ramp voltage waveform. At lower field region, however, it cannot detect the change in applied field magnitude from image data analysis by this experimental condition.

Applied AC Field with Superposed DC Ramp Voltage

Figure 3 shows an applied voltage pattern with superposition of DC high field to AC field. At first, only AC ramp voltage of 33.3333 Hz is applied from 0 to 0.9 s (30 AC wave cycles). Thereafter, superposition of DC ramp voltage is started. 0.6 s (20 cycle) is from 0



Figure 3: Typical applied voltage pattern of this measurement. Only AC ramp voltage of 33.3333 Hz is applied from 0 to 0.9 s and 3.3 to 4.2 s (30 AC cycles each). Superposition of DC ramp voltage is 0.6 s (20 AC cycles) for each ramp condition. Maximum and minimum values of DC ramp voltage are 2kV and -2kV, respectively.



Number of applied AC wave [cycles]

Figure 4: Evaluated AC and DC components from superposed applied electric field shown in Fig. 3. AC; Maximum value. DC; Average value.

to 2kV, 1.2 s is from 2kV to -2kV and 0.6 s is from -2kV to 0 V. Finally, AC applied voltage is reduced from 4 kVp-p to 0 V using 0.9 s. Therefore, 140 cycles of AC waves are applied, totally. The maximum DC offset voltage is 2kV; therefore, 50th and 90th AC cycles are only positive and negative field application to the HV electrode, respectively.

Figure 4 shows evaluated AC and DC components from superposed applied electric field shown in Fig. 3. AC amplitude is maximum value of the AC wave component and DC amplitude is average value of superposed DC voltage. Even with superposition of DC high field, the measuring system can evaluate dielectric properties for every one cycle of AC field.

Dielectric Properties of SIR before Aging

Figure 5 shows an evaluated AC loss current, Ixr, during superposed field application. HTV-SIR sample is before aging and dried naturally at room temperature. is with three water droplets. is without water droplets. The SIR sample is dried and hydrophobic. Therefore, without water droplets it shows small Ixr. This loss current flows both on the sample surface and in the sample volume.



Figure 5: Evaluated AC loss current, Ixr, during superposed field application. HTV-SIR sample is dried naturally at room temperature. ; With three water droplets. ; without water droplet. Volumes of water droplets are 10 μ l. Distilled water, 3 μ S/cm, is used.



Figure 6: Same as Fig. 5 except evaluate the deviation of capacitive current, dIxc, from its balanced condition without water droplet.

With three water droplets Ixr increases, slightly. This small increase in Ixr is caused by dielectric loss, which is corresponds to the motion of water droplets. From Fig.5, DC offset voltage slightly increases the Ixr.

Figure 6 shows the evaluated dIxc. The measurement conditions are same as Fig.6. Before set the water droplets capacitance bridge is balanced. Therefore, shows no signal during the measurement. This means the capacitance of the experimental specimen dose not change by the amplitude of AC field. It also means that capacitance of the specimen does not affected by DC field.

With three water droplets, however, Fig. 6 shows the change in capacitive current. The effect of superposed DC field to dIxc is, however, still small for hydrophobic samples. Figs. 5 and 6 also show small time dependence of hydrophobicity during AC field application of 30 to 110 cycles.



Figure 7: Evaluated AC loss current, Ixr, before and after aging in distilled water of HTV-SIR. Sample is without water droplet on the surface. During aging, sample is immersed in distilled water at room temperature for 55 days. ; Before immersing in distilled water.



Figure 8: Evaluated dielectric properties of Ixr and dIxc after aging in distilled water of HTV-SIR. Sample is with one water droplet on the surface. Aging condition is same as Fig.7. Applied field patterns of AC and DC are also indicated in the figure.

Dielectric Properties of SIR after Aging

HTV-SIR sample is aged by immersing the sample in distilled water at room temperature. The immersing period is 55 days and increase in sample weight is 0.08 %. After this aging, SIR sample surface slightly looses its hydrophobicity.

Figure 7 shows the evaluated Ixr during superposed field application without water droplets on HTV-SIR surface.

is before aging and is after aging. After immersing the sample in distilled water, sample absorbs water and increases the Ixr. This means the dielectric loss caused by water absorption is increased. It dose not affected by DC superposition. Therefore, conductive loss does not affected to dielectric loss.



Figure 9: Evaluated Ixr of HTV-SIR with one and three water droplets. Sample was aged in distilled water Aging condition is same as Fig.7.



(a) Flashover to Main electrode at DC- peak.



(b) Flashover to HV electrode at DC+ peak.

Figure 10: Typical flashover between water droplet and electrode. LED is lighted when at (a) DC- peak, (b) DC+ peak.

Dielectric Properties of SIR with Water Droplets after Aging

Figure 8 shows dielectric property of a HTV-SIR surface with one water droplet. SIR was aged by immersion in distilled water. The SIR sample is aged; therefore, even without water droplet it shows larger Ixr (Fig.7). With one water droplet Ixr increases more, typically around high DC field region. The capacitive current, dIxc, also becomes larger compared to the sample with three water droplets and before aging (Fig. 6). In Fig. 8, dIxc at larger positive DC superposition region shows small decrease. These results mean DC superposition increases the dielectric loss caused by conductive carrier and DC high field limits the motion of water droplet. Around minus peak of DC offset voltage water droplet is just before flashover to Main electrode.

Figure 9 shows Ixr of a HTV-SIR surface with one and three water droplets. Conditions are same as Fig. 7.

Increasing the number of water droplets, it increases the Ixr. The effect of DC superposition increases the loss current drastically. At -2 kV DC offset region, 3 droplets measurement occurs flashover.

Flashover between Water Droplet and Electrode

Figure 10 shows typical flashover between water droplet and electrode. Fig. 10 (a), corresponds to Fig. 9, shows flashover occurred at Main electrode. Water droplet seems to move toward the High voltage electrode, however, flashover occurred at Main electrode. From LED- lighting, this flashover occurs at the negative peak of superposed DC applied field. Fig. 10 (b) shows the flashover occurred to HV electrode. LED+ indicates the positive peak of the DC offset voltage.

SUMMARY

Inter-digital electrodes on SIR surface can detect the water absorption of the sample and, therefore, it can detect the degradation of the hydrophobicity of the sample surface from the dielectric properties. Water droplets on the sample surface, which set between the electrodes, increase both Ixr and dIxc of the dielectric property. When the sample surface decreases its hydrophobicity, both Ixr and dIxc increase more. Water droplets enhance these increases.

These changes in dielectric properties corresponds to the hydrophobicity and, therefore, to the motion of water droplets during electric high-field application. Superposition of DC electric field to the AC field also enhances the increase of dielectric property, which caused by the change of hydrophobicity class.

Image data analysis of the motion of water droplets under AC or DC superposed field application is also useful to recognize the hydrophobic condition of the sample surface.

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