Stressing Factors Impact on Surface Erosion of Epoxy Resin Exposed to Electrical Discharges

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Abstract

This paper investigates the influence of electrical as well as environmental stresses on surface erosion of polymeric materials used in high voltage insulation like epoxy resin. The analyzed electrical factors are test voltage magnitude TVM and frequency TVF; whereas environmental factors are temperature and humidity of discharge medium. Suitable electrode arrangement is applied in order to produce measurable erosion and guarantee the control of the analysed factors of influence. Also, the influence of UV stresses induced from electrical discharge is investigated in terms of surface erosion. From the obtained results, a dependence of erosion severity on the stressing factors can be concluded. A strong correlation also exists between discharge parameters and surface damage.

1 Introduction

As a matter of fact surface erosion mechanism of polymeric insulating materials is of high interest to the scientific community. Actually, there is still a lack of knowledge concerning the routes leading to polymer surface erosion while being under the influence of electrical surface discharge. For the development of new insulating materials or the improvement of existing insulating materials, it is mandatory to understand the mechanisms of erosion and hence to identify the main stressing factors of influence and to quantify their effect.

As a matter of fact discharge intensity depends mainly on the test voltage, electrode arrangement and electric field distribution. However discharge gas characteristics may also have an impact on discharge intensity and in turn on erosion behavior. In most of the previous work [1-3], there is almost no elucidation for the correlation between the environmental stresses and surface discharge intensity as well as surface erosion. The effect of the stressing factors on discharge intensity and discharge gaseous byproducts is expected to play an important role in material erosion [4]. Therefore discharge environment should be controlled to investigate the impact of each factor and the interaction in between (if exists).

In order to obtain clear elucidation of surface erosion phenomena the main sources which may contribute to the material surface erosion need to be studied separately. Surface discharge induced erosion processes fall broadly into three categories: those initiated by ion bombardment, chemical reactions or photon bombardment (UV) [5]. Hence, material surface irradiation by UV from electrical discharge is expected to take part in erosion.

Up to now, usually an experimental set-up according to IEC 60343 [1] is used to test for this performance although the standard has a quite different scope. This arrangement is mainly used for determining insulating material resistance to breakdown by surface discharges. The flat sample, located in a rod-plate electrode arrangement, is stressed by surface discharges. One of the cons against this setup is that it applies normal electric field on the sample between the electrodes which is convenient to test breakdown strength. However the associated gliding discharge is not sufficient to test surface erosion.

This paper presents a test setup capable of producing measurable erosion and enables the control of different factors of influence. This test setup in contrast to IEC 60343 introduces a tangential field on material surface; which is comparable to service stresses and permits erosion analysis. Both electrical and environmental factors of influence are studied in order to quantify its effect. Influence of all factors on polymeric material is investigated in terms of discharge, erosion and UV characteristics. Thanks to used test setup UV impact on material erosion is investigated.

2 Experimental Setup

2.1 Specimen

The used material for the specimens is epoxy resin 60% by wt. silica micro-filled of dimensions 60 mm x 50 mm x 2 mm. The number of samples used for each test series is 5 samples. For each test series the median value of the resulting data set is reported.

2.2 Electrode Arrangement

Schematic view of the applied electrode arrangement is illustrated in **Figure 1**. High voltage electrode is a sewing needle made of stainless steel with tip diameter of 0.4 mm. On the other hand an Aluminium sheet, whose dimensions are 50 mm x 20 mm x 0.2 mm, is used as ground electrode. Both electrodes are placed on sample surface with a distance of 15 mm in between.

The whole arrangement is placed in 18.5 liter desiccator in order to allow controlling the environmental conditions. During the investigation of environmental factors of influence, the cell is sealed in order to enable the analysis of both temperature and humidity of discharge medium and facilitates their control.

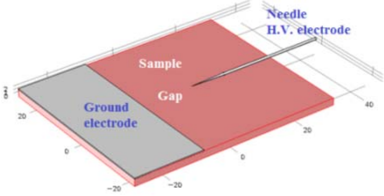


Figure 1 Electrode arrangement

2.3 Electrical Stresses Control

The test voltages are generated primarily using Agilent 33220A signal generator. The output of the signal generator is then passed through a high voltage amplifier (Trek 20/20C), whose output AC voltage range is up to 20 kV_{peak} and output current up to 20 mA_{peak}. The output of the amplifier is then connected to the needle electrode via a double-insulated cable.

The value of test voltage magnitude is taken via a voltage monitor signal supplied by the high voltage amplifier. The current measurement is performed indirect via a 300 Ω series resistor, which is connected in series with the plane electrode in its ground path. Hence all the signals to be measured are transferred in sequence via 8 channel relay to an oscilloscope. The oscilloscope is connected to a computer via RS-232 port to support communication interface in between. The whole schematic circuit diagram of the test setup and measurement system is illustrated in **Figure 2**.

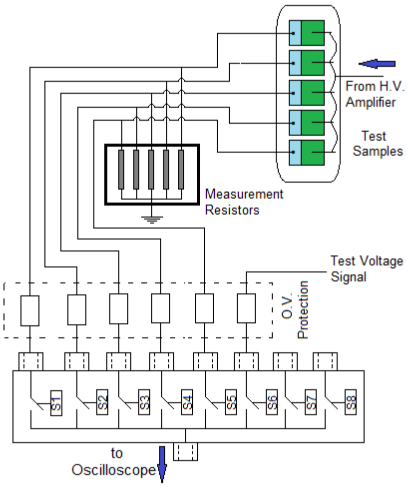


Figure 2 Test setup with the measurement system

2.4 Environmental Factors control

Temperature is raised using two (300 mm x 120 mm x 0.4 mm) thermo self-adhesive heating foils attached to the inner surface of the test cell. The power requirement for each foil is 65 W at 230 V and surface temperature range is up to 90°C. The inner surface temperature is adjusted through using an ON/OFF temperature control circuit connected to the heating foils. The circuit activates the heating foils through temperature switch, when the measured temperature via the temperature sensor (NTC 5kOhm @ 25°C) is lower than a pre-set temperature. The sensor is mounted inside the vessel at sample level.

With the aid of saturated salt solutions the relative humidity inside the vessel is controlled. A certain amount of the saturated solution is introduced in the closed vessel after placing the samples and electrodes. After 12 hours the system hence adjusts to equilibrium and then the test voltage can be applied at the desired relative humidity. The fabrication of these saturated solutions is performed according to DIN EN ISO 483.

2.5 UV irradiation Impact Identification

In order to study the effect of induced UV irradiation on material surface erosion, suitable electrode arrangement is applied in order to investigate UV irradiation separately. In other words the sample surface is under the influence of UV stresses only; where almost no electrical stresses exist.

Thanks to the applied tangential field stress on sample surface, the following setup could be achieved. Both electrodes are placed on the main sample surface; which empty the space above the test setup. Therefore, another sample can be inserted parallel to the main one with 4 mm normal distance in between (see **Figure 3**).

In this way, direct influence of discharge on the secondary sample surface is limited, whereas UV radiation is sufficiently arriving. This can be also proven by electric field simulation for the modified test setup. **Figure 4** shows the electric field distribution on the lower surface of the secondary sample. The electric field is obviously too weak to result in any discharge on the surface of the secondary sample. The modified test setup is applied during the first test series in order to study the effect of electrical factors on induced UV radiation.

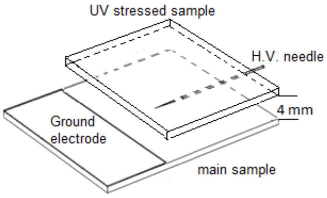


Figure 3 Modified test setup for UV stress analysis

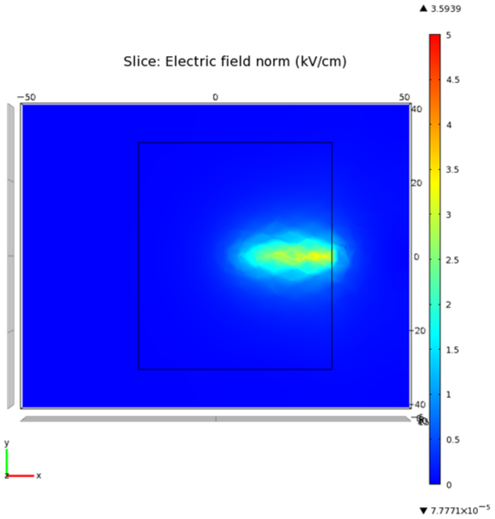


Figure 4 Electric field distribution on the lower surface of the secondary sample

2.6 Testing Procedure

Factorial analysis is performed on four test series in term of discharge parameters, erosion severity of sample surface and UV radiation characteristics. The first factorial analysis is performed between test voltage magnitude (TVM) and frequency (TVF), whereas the second one is between the temperature and humidity of discharge medium. While investigating a certain test series, the settings for the factors of influence in the other one are kept constant as shown in table 1. Therefore, it is possible to correlate between the factors of influence under study and the resulting damage. It is also possible to perform an interaction analysis between those factors.

Test Series	TVM (kV_{peak})	TVF (Hz)	Temp. (°C)	Humidity (%RH)
1,2	10, 12, 14	50, 250, 500	20	33
3,4	12	500	20, 40, 60	11, 33, 53, 70

Table 1 Test parameters setting for each test series

3 Impact Quantification

3.1 Discharge Parameters

Discharge parameters are total discharge energy E_{total}, cumulative charge Q_{cum} over the whole test period and the average number of pulses per cycle N_{cycle}. Total discharge energy E_{total} is determined from the sum of all discharge pulses energies. The pulse energy is calculated by multiplying the discharge magnitude Q_i by the instantaneous value of the test voltage V_i at which the discharge occurs. Similarly, cumulative charge Q_{cum} is calculated from the sum of charge magnitudes for all pulses.

$$Q_{cum} = \sum_{i=1}^{n} Q_i \quad (1)$$

$$E_{total} = \sum_{i=1}^{n} V_i . Q_i \quad (2)$$

3.2 Erosion Characteristics

During sample treatment, the material surface attains some morphological changes in the surface in the form of erosion. The magnitude and the shape of that erosion are measured with a high resolution laser profilometer. Then erosion parameters are determined using Matlab.

The main idea in calculating erosion parameters is that it defines the set of points as triangles, whose vertices are those data points. Once the triangles are obtained for the scanned data points the area can easily be calculated from the summation of individual triangles areas. Hence the volume can be determined with the aid of the vertices of each triangle (i.e. erosion depths) and calculated areas. In the calculation procedures of erosion characteristics, three parameters were used for identifying the erosion severity on the insulator surface; surface eroded area, maximum erosion depth and eroded volume.

3.3 UV Irradiation Characteristics

UV imaging was performed in the absence of the secondary sample to in order to get the complete UV on the main sample surface. Here, a PCO UV sensitive digital camera was used, with which it was possible to capture images in the UV range in addition to the visible region of the electromagnetic spectrum. Daylight filter UG11 is mounted on the lens in order to confirm the complete darkness in the surroundings of the discharge zone.

The captured image is stored in a PC as a matrix of pixels in a JPG file. The pixels' intensities (represented by the elements of the image matrix) are summed up to obtain the cumulative intensity [6]. The noise level in the obtained image is defined as the threshold intensity above which UV intensities are clearly separated from the background image. In the resulting UV image, pixels that have intensities higher than the noise level are considered illuminated. UV radiation parameters are illuminated ea, A_{UV} (mm^2) and cumulative UV intensity I_{UV} (a. u.).

The area is calculated by calculating the number of pixels that are part of UV irradiation spectrum as followed in (3). Where the number of illuminated pixels is N_{UV} and A_{UV} is the whole illuminated area of the image. The area A_{UV} is calculated from dividing N_{UV} by the square of image resolution (i.e. 72 pixels per inch). Then it is calculated in mm^2 and divided by the square of lens magnification ratio, which is 5 times the size in reality.

UV intensity is calculated by performing weighted sum of all pixels that are part of UV emission spectrum. The pixel intensity is measured relative to I_{noise} the base noise threshold level as followed in (4).

$$A_{UV} = \frac{N_{UV}}{(\text{Resolution,pixels/inch})^2} \times \frac{(25.4)^2}{(\text{magnification ratio})^2} \quad (3)$$

$$I_{UV} = \sum_{n=1}^{N_{UV}} I_{pixel}(n) - I_{noise} \quad (4)$$

4 Results

4.1 Factors of Influence versus Discharge

4.1.1 Interaction between TVM and TVF

The influence of electrical factors of influence on discharge parameters is presented in **Figure 5**. It was found, that increasing either of TVM or TVF results in a certain increase in discharge parameters under analysis.

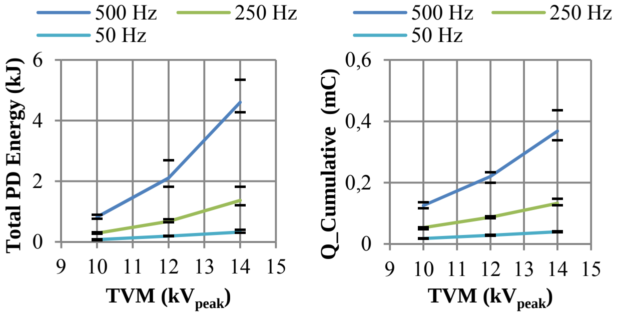


Figure 5 Discharge parameters for electrical factors (median, span), other settings see table 1 (Test series 1, 2)

It can be also seen from Figure 5 that at lower values of either of those factors (i.e. TVM or TVF), the increase in discharge parameters with the other factor is almost linear. However any enhancement in either of those factors introduces nonlinearity in the discharge parameters change with the other factor. There is a synergism between electrical factors in terms of discharge parameters.

4.1.2 TVM and TVF interaction in terms of UV characteristics

The interaction between TVM and TVF can be also proven in other forms of energy such as UV radiation associated with the surface discharge. It was found that, the enhancement in any of electrical stresses results in an increase in UV radiation strength. **Figure 6** displays the interaction plots in terms of both illuminated area and cumulative intensity.

It can be observed that, the effect of TVM on radiation characteristics is more significant with the increase of TVF. It can be concluded that the impact of both electrical factors is higher than the addition of both separate impacts; because an interaction exist between them.

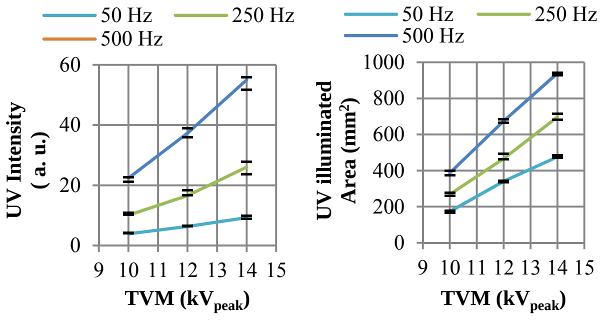
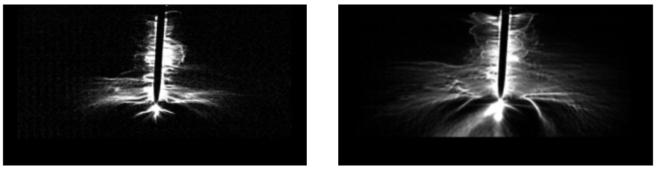
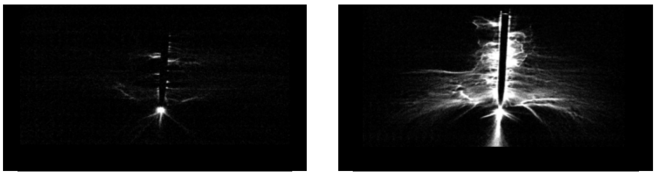


Figure 6 Interaction between TVM and TVF in terms of UV characteristics



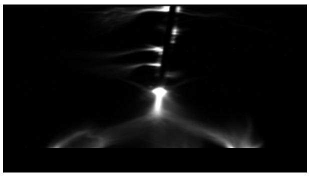
a. 10 kV$_{peak}$, 500 Hz

b. 14 kVpeak, 500 Hz



c. 12 kVpeak, 50 Hz

d. 12 kVpeak, 500 Hz



e. 12 kVpeak, 50 Hz

- a, b, c and d are captured with 2 seconds exposure time
- e is captured with 20 seconds exposure time

Figure 7 UV images at different electrical stresses

The change in UV intensities and irradiation area on the sample surface is apparent to be TVM and TVF dependent (see **Figure 7**). Both UV cumulative intensity and illuminated area is dependent on test frequency at fixed exposure time. The difference in illuminated area between high and low frequencies is referred to:

- UV intensity in some regions for low test frequency is too small to be distinguished; which can be obviously proven by increasing the exposure time to 20 seconds.
- The increase in supply frequency enhances discharge intensity per second (i.e. number of pulses and discharge magnitude). This results in faster avalanches and higher probability of discharge; which in turn leads to further extension of discharge streamer (i.e. larger UV area).

4.1.3 Temperature and humidity interaction

The effects of environmental factors of influence on discharge parameters are studied and the response of each discharge parameter is calculated. It is clear from **Figure 8** that temperature rise increase discharge parameters but with a slow rate of change. The reason is temperature rise of charged particles in discharge zone, which results in and higher probability of generating more charged particles.

On the other hand, it can be seen from Figure 8 that discharge parameters are slightly affected by humidity change in inverse proportional relationship. This could be attributed to the fact that, under humid conditions scattering and absorption of UV results in a reduced percentage of UV reaches surface (see **Figure 9**). Those results are consistent with those from [6].

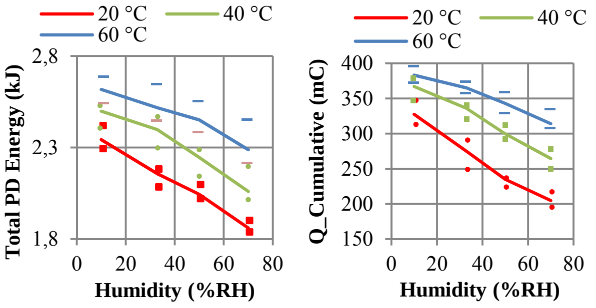


Figure 8 Discharge parameters for environmental factors (median, span), other settings see table 1 (Test series 3, 4)

The rate of decrease in discharge parameters with humidity increase is higher at lower temperature degrees. This can be explained as an interaction between both environmental stresses in terms of discharge intensities. This interaction occurs because each factor is compensating the impact of the other one; where the impact of each on discharge parameters is the opposite of the other.

Each coloured region in Figure 9 represents a change in UV characteristics due to humidity change. Boundaries of the coloured regions are given by median values. The upper boundary represents UV characteristic value at 11 %RH; whereas the lower boundary is for 70 %RH. UV characteristics are influenced by humidity increase to a certain extent independent from TVM and TVF.

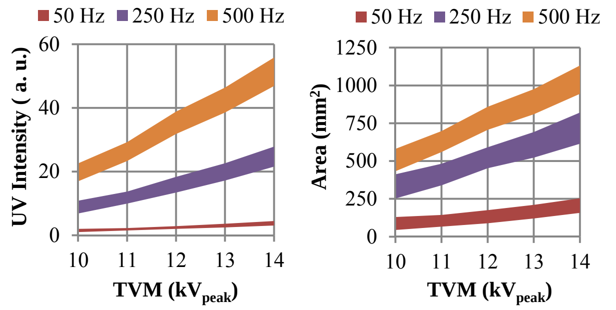


Figure 9 Humidity impact on UV characteristics in form of interaction plots between TVM and TVF

4.2 Factors of Influence versus Erosion

4.2.1 Interaction between TVM and TVF

From **Figure 10** it can be noticed that erosion severity is dependent on TVM as well as TVF. That is nearly correlated to discharge behavior under the effect of increasing electrical stresses. Surface erosion severity is hence significantly dependent on surface discharge parameters.

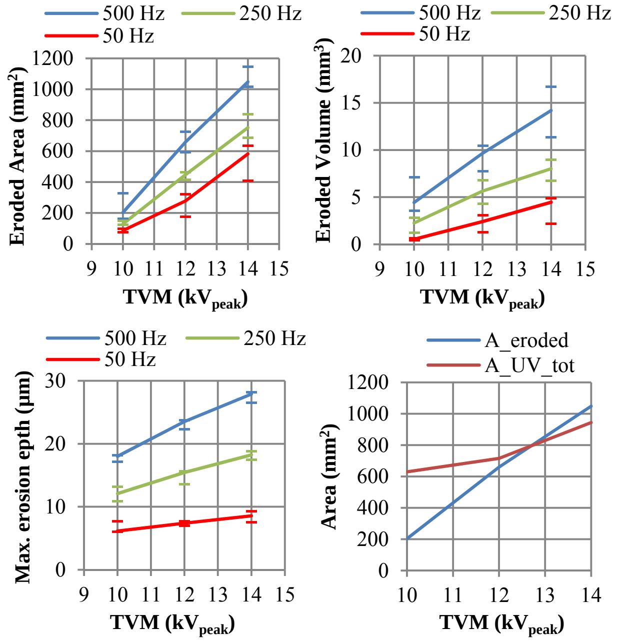


Figure 10 Erosion characteristics for electrical factors (median, span), other settings see table 1 (Test series 1)

The interaction between TVM and TVF can be also observed in terms of the resulting surface damage. For example the rate of change in erosion characteristics with respect to TVM increases at higher values of TVF. This confirms the fact that there is an interaction between both stresses in terms of erosion characteristics.

Eroded area of the stressed samples is compared to UV illuminated area, as shown in Figure 10, under different TVM values and 500 Hz TVF. It can be seen that under low values of TVM, UV illuminated area is increasing with a lower rate compared to eroded area.

For TVM lower than 12.5 kV_{peak}, UV illuminated area is larger than eroded area. This means that, only a portion of the illuminated area has enough intensity (i.e. enough photon energy) to take part in material erosion. Whereas working at higher stresses (i.e. TVM higher than 12.5 kVpeak) result in eroded area larger than UV illuminated area. Even if all UV radiation possesses enough photon energy to cause erosion, but UV is not the only stress that influences erosion phenomena.

4.2.2 Erosion from UV irradiation

The results of this study (i.e. erosion from UV radiation) are presented in **Figure 11**. It can be seen that, both eroded area and volume, of the secondary sample, are increasing nonlinearly with both stresses. Concerning maximum erosion depth, it is found to be TVF dependent, whereas it is nearly independent of TVM.

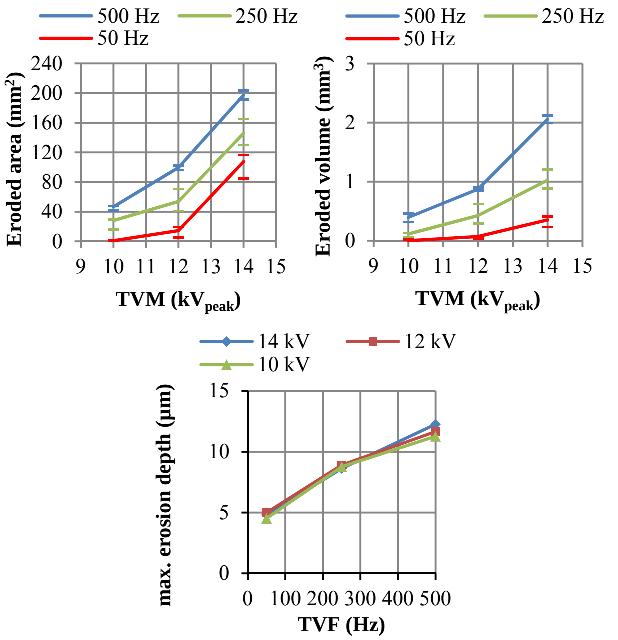


Figure 11 Erosion characteristics for secondary samples from UV radiation (median, span)

In order to quantify the impact of UV on surface erosion, two parameters are calculated to correlate between UV characteristics and its relative damage. UV erosion yield (Y_A) is the ratio between surface eroded area (A_{eroded}) and UV illuminated area (A_{UV}). UV erosion yield (Y_V) is the ratio between eroded volume (V_{eroded}) and cumulative UV intensity (I_{UV}).

$$Y_A = \frac{A_{eroded}}{A_{UV}} \qquad (6)$$

$$Y_{V1} = \frac{V_{eroded}}{I_{UV}} \qquad (7)$$

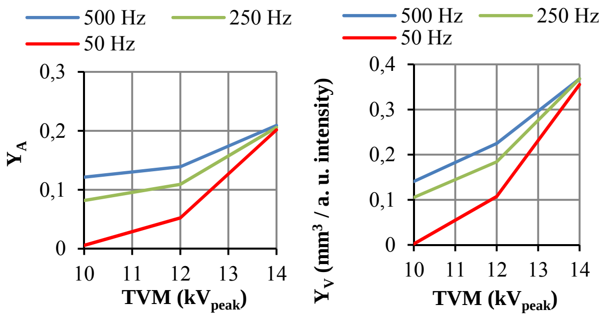


Figure 12 UV erosion yields (Y_A and Y_V) at different electrical stresses (median)

Both UV erosion yields increase under the influence of either stresses (i.e. TVM or TVF) as shown in **Figure 12**. In other words, electrical stresses increase UV stress, in terms of both spread and intensity, and hence enhance its ability to cause more damage on material surface. However, at higher stresses of TVM, both erosion yields Y_A and Y_V are TVF independent. This could be due to domination of high TVM stress on erosion process, which makes the impact of the other stress unobserved.

Figure 13 compares erosion of the main samples under the influence of all stresses including UV to that from secondary samples under the influence of UV. Clearly, it can be noticed that the gap between the lines increases with increasing the electrical stresses. This means that UV radiation impact, as a percentage of total damage, is the highest at low electrical stresses and decreases with enhancing the stresses**.**

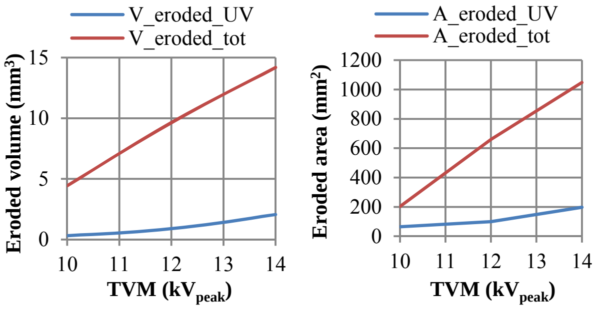


Figure 13 UV induced erosion versus of the main samples under the influence of all stresses at 500 Hz.

4.2.3 Temperature and humidity interaction

The environmental factors of influence were found to be directly correlated to material erosion as shown in **Figure 14**. The rate of change in eroded area and volume is nearly constant with respect to the change in the involved influencing factor.

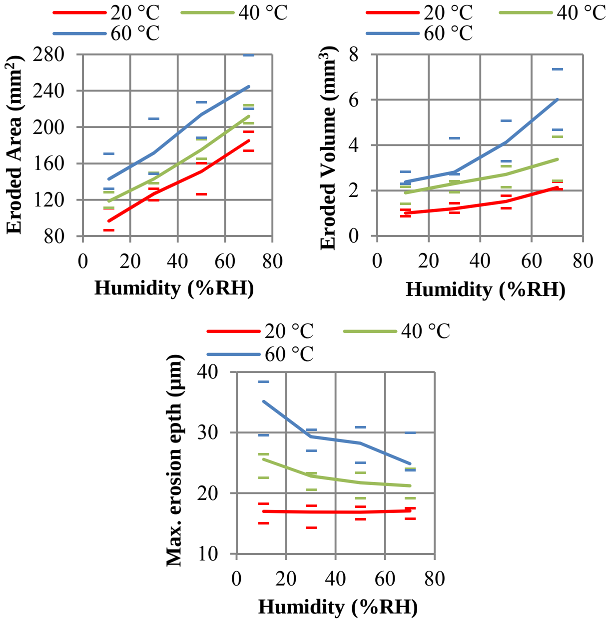


Figure 14 Erosion results for environmental factors (median, span), other settings see table 1 (Test series 3, 4)

On the other hand, maximum erosion depth is nearly constant with humidity increase at low temperature degrees. At high temperature it exhibits a decreasing trend with humidity increase. It is referred to humid conditions impact on discharge parameters (see Figure 8).

5 Conclusion

Epoxy resin containing 60 % micro filler was investigated considering erosion due to surface discharges. This analysis was performed under the impact of test voltage magnitude, frequency, temperature and humidity as influencing factors. It was found that:

- Discharge parameters are direct correlated to electrical influencing factors (voltage magnitude and frequency).
- Temperature rise increase discharge parameters, but with a slow rate of change. However, discharge parameters are reduced with a small extent by humidity increase. This can be explained by UV radiation characteristics which are inversely proportional to humidity increase.
- Surface erosion severity is significantly dependent on discharge parameters on the sample surface and direct correlated to the investigated factors of influence (i.e. V, f, T and %RH).
- Erosion resulting from UV radiation is a small percentage of erosion under all stresses. This percentage is significantly reduced with electrical stress enhancement. The reason for that is charged particle bombardment taking part in erosion, whose influence is dominant at higher electrical stresses. Therefore, its share from total erosion increases with enhancement in electrical stress.

6 References

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