Untersuchung und Modellierung elektrostatischer Entladungen (ESD) von elektrisch isolierenden Oberflächen

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Durch den zunehmenden Einsatz von Kunststoffen beziehungsweise kunststoffbeschichteten Materialien treten in der Praxis verschiedene Probleme durch die Auf- und Entladung dieser Isolierstoffe auf. Zwischen der aufgeladenen Oberfläche und geerdeten Objekten, die sich in der Nähe befinden oder angenähert werden, können elektrostatische Entladungen (ESD) stattfinden. Diese führen einerseits zu einer ungewollten Beeinflussung empfindlicher Elektroniken in Geräten und Sensoren und zum anderen stellen diese impulsförmigen Entladungen eine Gefahr der Entzündung von Gasgemischen dar.

Die Auf- und Entladung von Isolierstoff-Oberflächen ist abhängig von den klimatischen Umgebungsbedingungen, wie relativer Luftfeuchtigkeit und Temperatur. Deshalb wurde der gesamte entworfene Messaufbau in einer Klimakammer untergebracht. Die untersuchten Ausgangsparameter sind die Flächenladungsdichte bzw. das Oberflächenpotential, der Entladungsabstand und das verwendete Material sowie dessen Dicke. Es wurde von einer ebenen und sauberen Anordnung der aufgeladenen Fläche ausgegangen. Auf der Rückseite stehen die Isolierstoffe in direktem Kontakt mit einer geerdeten leitfähigen Platte, wodurch um Größenordnungen höhere Flächenladungsdichten möglich sind.

Abhängig von den Ausgangsparametern können zwei Entladungsarten auftreten, die Büschel- und die Gleitstielbüschel-Entladung. Mit den vor und nach der Entladung gemessenen Flächenladungsdichte-Verteilungen auf der Oberfläche kann die sich entladende Fläche und die entladene Ladungsmenge bestimmt werden. Bei der Büschelentladung wird nur ein begrenzter Teil der Oberfläche entladen. Die entladene Ladungsmenge in einer dreidimensionalen Darstellung bildet die Form eines Kegels, mit dem Fußpunkt der Entladung im Zentrum. Die Büschelentladung kann bei höherem Aufladungspotential eine Gleitstielbüschel-Entladung einleiten, bei der viele Entladungskanäle auf der Oberfläche entstehen, die sich radial vom Entladungspunkt fortbewegen, verzweigen und somit eine große Fläche entladen. Diese Darstellung wird auch als Lichtenbergfigur bezeichnet. Durch die wesentlich größere entladene Fläche als bei der Büschelentladung ist die entladene Ladungsmenge und damit die im Funkenkanal umgesetzte Energie bei der Gleitstielbüschel-Entladung, um Größenordnungen größer. Die entladene Ladungsmenge sowie die umgesetzte Energie können mit dem gemessenen Entladungsstrom-Impuls berechnet werden.

Ein für die Praxis wichtiger Wert ist der Betrag des Oberflächenpotentials, bei dem die Büschel- in die Gleitstielbüschel-Entladung übergeht. Dieser wurde in Abhängigkeit von dem Material und dessen Dicke ermittelt und durch eine Funktion approximiert. Mit Kenntnis dieses Grenzaufladungs-Potentials kann man abschätzen, ob eine Gleitstielbüschel-Entladung, die ein wesentlich höheres Gefährdungspotential als die Büschelentladung aufweist, auftreten kann oder nicht.

Für den Bereich der Büschelentladungen wurden, ausgehend von den durchgeführten Messungen, Funktionen approximiert, welche den Entladungskegel und den Entladungsstrom-Impuls als Funktion der Ausgangsparameter beschreiben. Auch wenn aus einer Reihe von Messbeispielen, die zu den angegebenen Beschreibungsformeln führten, keine Allgemeingültigkeit abgeleitet werden kann, so sind die Approximationsformeln in der Praxis doch ein gutes Mittel, um schnell und ohne Messung die sich entladende Fläche, die dazugehörige entladene Ladungsmenge und die zu erwartende umgesetzte Energie im Funkenkanal abzuschätzen. Parallel hierzu wurde ein PSpice-Modell entwickelt, welches ebenfalls die Bestimmung der umgesetzten Leistung bzw. Energie während der Entladung ermöglicht.

Im Gegensatz zu den Untersuchungen bei Büschelentladungen, bei denen Parameterstudien für einige Parameter durchgeführt wurden, ist bei der Gleitstielbüschel-Entladung das prinzipielle Verhalten am Beispielmaterial PVC in Abhängigkeit vom Parameter Flächenladungsdichte untersucht worden. Anhand von Messungen an einem Kanal und der Betrachtung der zeitlichen Ausbreitung der Entladungskanäle wurden Kenngrößen für die Gleitentladung abgeleitet. Diese sind die mittlere entladene Flächenladungsdichte, der mittlere Radius der entladenen Fläche und die gesamte entladene Ladungsmenge. Die Abhängigkeit dieser Größen vom Parameter Flächenladungsdichte wurde ermittelt und mit approximierten Funktionen angegeben. Mit diesen Vorkenntnissen wurde ein einfaches Modell abgeleitet, welches die Bestimmung des Entladungsstromes und damit die Abschätzung der im Funkenkanal umgesetzten Energie ermöglicht. Die radiale Entwicklung der Entladungskanäle und die Startzeiten der einzelnen Kanäle sind statistisch auftretende Größen, die die Form des Stromimpulses erheblich beeinflussen. Die Voraussage der genauen Form des Stromimpulses und damit der umgesetzten Energie einer speziellen Messung ist deshalb nicht möglich. Für eine Abschätzung der maximal möglichen umgesetzten Energie ist das Modell jedoch gut geeignet.

Investigation and Modelling of Electrostatic Discharges (ESD) on Insulating Surfaces

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Due to the increasing use of plastics or plastic-coated materials different kinds of problems, like charging and discharging, can occur. Insulating surfaces are considerably charged by material separation, flowing liquids or electrical fields. For this reason discharges can develop between the charged surface and a near grounded conductive object. These transient gas discharges discharge the insulating surface in a locally limited surface area. The value of the area of the discharged surface is dependent on some physical parameters. This value defines the value of the transported charge and consequently the value of the dissipated power and energy in the discharge channel.

On the one hand, this electrostatic discharges (ESD) can influence sensitive devices and systems. On the other hand, these discharges represent a risk to generate an ignition of gas-air mixtures.

In this work, the specific aspect of the ESD, *the discharge of charged insulating surfaces* is investigated in detail. Two kinds of discharges can appear depending on the value of the surface charge density, the brush discharge and the surface discharge. For the investigation of these discharges, a measurement setup was designed. With this measurement setup, the surface charge density before and after the discharge and the discharge current can be acquired. The measured discharged charge density and the measured discharge current are analyzed for several physical parameters. For the evaluation of the ESD danger potential an easy model and an estimation of the discharge phenomena of insulating materials are derived. A criterion of the evaluation of the danger potential is the dissipated power or the energy during the discharge, respectively.

Measurement setup

The charging and discharging of insulating materials depend on the climatic conditions, like the relative humidity and the temperature. Therefore, the experimental arrangement is set up in a climatic chamber for constant climatic conditions. The conditions for all measurements are 25 % to 30 % of relative humidity and 21 °C of temperature.

All components are controlled by a PC using a program written in the computer language C. The test object and the probes are moved by a scanning system, consisting of three linear guides, driven by three stepping motors. The test object is situated on the x-axis and the probe of the electrostatic voltmeter is situated on the y-axis. With this arrangement a two-dimensional recording of the charge distribution is possible. The x-y-coordinates are determined by the pulses of the stepping motor.

The test objects, plates and foils, can be charged using the corona discharge. Therefore, high voltage, provided by a DC-high-voltage-generator, is connected to a line of corona needles. These needles are shifted over the complete surface in a distance of 5 mm, producing an uniform distribution of the surface charge.

The surface charge density distribution is calculated from the potential on the test surface, which can be measured using an electrostatic voltmeter. When the scan is completed, a grounded electrode is moved step by step or continuously in z-direction to the charged surface until a discharge occurs. The pulse of the discharge current is measured by a shunt using a 1 GHz digital oscilloscope. Then, the new charge distribution is acquired.

Finally, the measured data are analyzed. With the acquired charge distribution values before and after the discharge the transported charge and the area of the discharged surface can be calculated. Additionally, the transported charge can be determined from the current pulse.

The theoretical maximum value of the surface charge density is 2.7 nC/cm² for an one-sided charged layer. Due to a conductive layer on the back side the surface charge density can be much higher, because an electric double layer arises. Due to the higher charge density a higher danger potential is possible. Therefore, only this configuration is investigated. Furthermore, only negative surface charge density have been studied, because this charging has a higher danger potential.

Characterization of the brush discharge

Between a charged insulating surface and a near grounded conductive object with a radius of curvature of some millimeter a brush discharge can occur. Brush discharges depend on some physical parameters and occur especially for a lower value of the surface charge density. Here, a limited area around the discharge point is discharged. The difference between the measured charge density before and after the discharge is the *discharged charge density*. In a three-dimensional view, this charge density has got the shape of a cone. The discharge point corresponds to the peak of the cone.

Parameter studies and approximation of the brush discharge

For this discharge pattern, the measured discharged charge density and the measured discharge current were investigated by parameter studies for the basic parameters *initial charge density, dielectric constant , thickness of charged foil and discharge gap length*.

In a first step, the discharged surface charge density and the discharge current were approximated. These functions depend on especially defined parameters. In the case of the discharged surface charge density these parameters are the *width* and the *maximum height* of the cone. For the discharge current, the parameters are the *maximum value of the pulse*, the *time constant of rise time* and the value *of the transported charge*.

In a second step, measurements were carried out in order to describe the especially defined parameters as a function of the basic parameters *initial charge density, dielectric constant, thickness of charged foil and discharge gap length*. Thus, the discharged surface charge density and the discharge current are described by the basic parameters.

By using the discharge current and the spark law of Rompe and Weizel, the dissipated power and the energy during the discharge can be calculated. Therefore, the estimation of the dissipated power and energy depending on the basic parameters and the evaluation of the danger potential is possible, without carrying out a measurement.

Modeling of the brush discharge

Parallel to the approximation of the brush discharge an easy PSpice model for the discharge phenomenon of insulating materials was developed. The basis therefore is the geometrical setup and the parameter studies on the discharged charge density and the measured discharge current. The setup consists of the insulating surface with a groundplane on the back side and a sphere, that is also connected to the ground potential. The insulating foil is represented by a capacitance. For the simulation, this capacitance is divided into several capacitances, which represent the different areas of the insulating surface. The spark gap is realized with a switch. This element can be interpreted as a time varying resistance. The cable between the sphere and the back side of the insulating surface is taken into consideration by an inductance.

The values of these elements are determined using the already mentioned parameter studies with the discharged charge density and the measured discharge current. The results are equations, which described the values of the elements depending on the basic parameters. With this model the estimation of the dissipated power and energy depending on the basic parameter is possible.

Transition from the brush discharge to the surface discharge

For a higher surface charge density, the discharge pattern changes from the brush discharge to the surface discharge. The start condition for a surface discharge can be a brush discharge. In the case of a brush discharge, a limited area around the discharge point is discharged. This discharge shorts the charged surface to the ground plane. At the boundary between the discharged and the still charged area a high tangential electric field strength on the surface arises. If the electric field strength is higher than a critical value a surface discharge can follow.

The decisive parameter for the development of surface discharges is the tangential electric field strength. Therefore, the tangential electric field strength along the surface was investigated as a function of the *initial surface charge density*, the *foil tickness* and the *discharge length*. For the material PVC, a *critical value* of the tangential electric field strength in the range of 16 kV/cm to 20 kV/cm was determined.

Another important point is to find the value of the surface charge density or the surface potential, which defines the transition from the brush discharge to the surface discharge. For the determination of the *transition value*, measurements were carried out depending on the *tickness* and the *dielectric constant* of the foil. The initial surface potential was increased step by step until at least one small surface discharge channel occured. The result is a function, which describes the transition value of the initial surface potential depending on the parameters.

Characterization of the surface discharge

When the tangential electric field strength reaches a critical value a surface discharge can follow a brush discharge. This is possible for values of the surface charge density that are higher than the transition value. The surface discharge discharges a much larger surface area than the brush discharge. Also, the value of the transported charge and consequently, the value of the dissipated power and energy in the spark gap is much higher.

The surface discharge channels start near the discharge point and move star-shaped radial outwards. With increasing distance from the discharge point the channels can branch themselves. Furthermore, the main channels can branch at points between the discharge point and the head of the main channels. These branches are rather short compared to the main channels. The paths of propagation on the surface are statistically distributed. In the past, this arising figure was referred to as a *lichtenberg figure*.

The discharge phenomena are investigated by the example of the material PVC. The comparison of the discharge current pulse for some measurements shows, that even with constant initial conditions the shape and the rise time of the current pulse *can be different.* The reason therefore is that the surface discharge channels start at different times. When the scattering of the inception time of the channels is low the rising pulse edge is smooth and steep. For high scattering of the inception time the rising edge is stepped and less steep. Therefore, the shape is defined through the statistical distribution of the inception time of the several discharge channels.

Therefore, it is very difficult and not necessary to simulate each single discharge channel. A simplification of the complex and statistical surface charge distribution is needed.

Characteristic quantity of the surface discharge

One possibility for a simplified approach to this problem is the use of the *average discharged surface charge density in an annulus* around the discharge point. To determine this density, the difference of the measured surface charge density before and after the discharge is calculated. The result is the discharged surface charge density. From this density the average value within the area of the annulus is calculated. For the simulation, the so determined values of the average discharged surface charge density as a function of the radius of the annulus was approximated by functions.

Another characteristic quantity of the surface discharge are the transported charge and the average radius of the discharged surface area. These quantities can be derived from the average discharged surface charge density and were described by functions.

Modeling of the surface discharge

Two possible simulation models were investigated. In the case of the first model, the different inception time of the discharge channels was neglected and only *the radial propagation* of the discharge channels was considered. For the modeling of the surface discharge the model for the brush discharge was extended. The base for the simulation is the value of the average discharged surface charge density in an annulus. The rather slow and approximately linear rising edge of the surface discharge current can be explained by a continuous addition of surface elements, whereas one element represents one annulus. One element consists of a spark gap, a resistance and a capacitance. The selected step size for the annulus and the radius of the discharged surface area defines the necessary number of elements for the simulation. The parameters of the elements are defined using the geometrical setup and the average discharged surface charge density in an annulus.

For the second model, the radial propagation of the discharge channels was neglected and the *different inception time of the discharge channels* was considered. The base for this simulation was a typical discharge current of one discharge channel. This current was measured with a specific setup, which divided the surface in sectors. For this kind of model, the additional part consists of several elements which are connected in parallel. One element represents one discharge channel. Again, one element consists of a spark gap, a resistance and a capacitance. Here, the parameters of the elements were defined using the geometrical setup and the typical discharge current.

To verify these models two measurements with different current pulse shapes were simulated. The comparison of the simulated and the measured discharge current pulses show a good agreement. In the first case, the different pulse shapes are achieved by varying the start time of the elements of the anulus. In the second case, the start time of the channels was varied.

This simulation shows that the discharge current of the surface discharge can be reproduced with both models. But in practice a worst case consideration is interesting. Therefore, no specific values for the start time of the elements of the annulus and the start time of the channels are used, but worst case conditions. In this configuration the estimation of the dissipated power and energy and the evaluation of the danger potential is possible.

Conclusion

In this work, the specific aspect of the electrostatic discharge (ESD), *the discharge of charged insulating surfaces* was considered. Therefore, the two kinds of discharges, the brush discharge and the surface discharge, were investigated in detail.

By using the approximated functions of the brush discharge the discharged surface charge density and the discharge current can be calculated depending on the basic parameters. The estimation of the dissipated power and energy and the evaluation of the danger potential is possible without carrying out a measurement. With the derived PSpice model for the brush discharge it is possible, too.

The value of the surface potential where the discharge pattern changes from the brush discharge to the surface discharge was determined. A function, that depends on some parameters, describes this transition value.

In the case of the surface discharge, the discharge phenomena are investigated by the example of the material PVC. Here, with both developed models the estimation of the dissipated power and energy and the evaluation of the danger potential is possible.