About the Breakdown and Partial Discharge Behavior of Different Heat-resistant Cast Resins

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Abstract: Experimental investigations concerning the breakdown and the partial discharge behavior of six heat-resistant cast resin systems are presented and discussed in this paper. The tests were performed with two epoxy resin and an epoxy modified isocyanate system in combination with two different fillers. The breakdown strength of the materials was measured in a uniform as well as in a non-uniform electrical field. Furthermore the partial discharge inception voltage (PDIV) was determined by using a highly inhomogeneous electrode arrangement. All tests were performed in dependence on the temperature. The contribution reveals that wollastonite as filler can lead to a lower electrical strength of the molding material than silic flour. Furthermore it will be displayed that above the glass transition temperature (Tg) the electrical strength diminishes significantly and that resin systems with a high Tg can have nearly constant electrical properties over a large temperature range.

Keywords: cast resin, breakdown strength, partial discharge inception voltage, silic flour, wollastonite

I. INTRODUCTION

In electrical applications cast resins are widely used as a solid insulating material with excellent electrical, dielectrical and physical characteristics. By variation of the molding material components and the processing parameters, respectively, the properties of the insulating material can be adapted to the application requirements. Besides the microscopic interfaces between filler and resin matrix in most devices with resin-insulated components, like e.g. dry type transformers, also macroscopic interfaces between the resin system and encapsulated materials exist. These interfaces are often regarded as a weak point of the insulating system [1] because among others especially thermal strains can lead to internal mechanical stresses due to the different coefficients of thermal expansion of the insulating material and the enclosed electrode. As a consequence cracks along the interfaces can occur. These defects can lead to partial discharges and finally to an electrical breakdown of the insulating system. By using solid materials with a good resistance against high temperatures and a good crack resistance it would be possible to realize more compact and economical constructions of cast resin insulated apparatuses.

With regard to the outlined problem the breakdown and the partial discharge inception voltage (PDIV) of heat-resistant cast resin systems have been determined. The investigations were performed in a temperature range between -20 and 200 °C in a uniform and in a highly non-uniform electrical field.

II. EXPERIMENTAL SETUP

1) Tested Materials

The presented investigations were carried out on six different cast resin systems. These insulating materials were composed of two epoxy resin and an epoxy modified isocyanate system, respectively, either filled with silic flour or silic treated wollastonite. All employed components with the chosen parts by weight (pbw) are listed in Tab. 1. In order to investigate the influence of the filler on the properties of the cured resin compounds it is advisable to realize comparable parts by volume of the fillers.

The applied epoxy resin systems are a fluid Bisphenol A (Araldite) and a Bisphenol-A/F (Rütapox) based resin system each used in combination with an anhydride hardener and an amine accelerator. The epoxy modified isocyanate system is composed of two different isocyanates each based on diphenylmethane diisocyanate (MDI) and an amine

<table>
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<tr>
<th>system</th>
<th>resin</th>
<th>pbw</th>
<th>hardener</th>
<th>pbw</th>
<th>accelerator</th>
<th>pbw</th>
<th>filler</th>
<th>pbw</th>
<th>vol.-%</th>
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<td>100</td>
<td>HY918</td>
<td>85</td>
<td>DY062</td>
<td>1</td>
<td>silica flour</td>
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<td>85</td>
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<td>1</td>
<td>silane treated wollastonite</td>
<td>324</td>
<td>42</td>
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<tr>
<td>3</td>
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<td>100</td>
<td>Rütapox VE4518 CB</td>
<td>82</td>
<td>Rütapox VE4518 CC</td>
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<td>4</td>
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<td>82</td>
<td>Rütapox VE4518 CC</td>
<td>1</td>
<td>silane treated wollastonite</td>
<td>318</td>
<td>42</td>
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epoxy modified isocyanate system

<table>
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<tr>
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<th>hardener</th>
<th>pbw</th>
<th>accelerator</th>
<th>pbw</th>
<th>filler</th>
<th>pbw</th>
<th>vol.-%</th>
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<tbody>
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<td>Blendur TP KU3-4523</td>
<td>3</td>
<td>silica flour</td>
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<td>45</td>
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<tr>
<td>6</td>
<td>Blendur TP KU3-4516 / 50 / 50</td>
<td>Blendur TP KU3-4523</td>
<td>3</td>
<td>silane treated wollastonite</td>
<td>177</td>
<td>42</td>
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The epoxy modified isocyanates consist of special isocyanates and a Bisphenol A epoxy resin.

In Tab. 2 the measured glass transition temperatures ($T_g$) as well as the fracture toughness ($K_{IC}$) of the tested materials are listed.

<table>
<thead>
<tr>
<th>system</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<td>$T_g$</td>
<td>[°C]</td>
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<td>114</td>
<td>88</td>
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<td>308</td>
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<tr>
<td>$K_{IC}$</td>
<td>[MPa·m$^{1/2}$]</td>
<td>1.96</td>
<td>2.26</td>
<td>2.57</td>
<td>2.83</td>
<td>1.85</td>
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</table>

2) Electrode Arrangements and Test Procedures

For the electrical investigations two electrode arrangements were used. The uniform field was realized by the application of two brass electrodes with Rogowski profile which were completely encapsulated by the tested cast resin material. The gap distance was chosen to 1 mm. In order to ensure a best possible contact to the resin matrix the electrode surfaces were roughened. The investigations in a non-uniform field were carried out with a needle-plate electrode arrangement. The needle was made of tungsten with a tip radius of 2 μm and the gap distance was adjusted to 2 mm. All required test specimens were produced by conventional vacuum casting.

The experiments were performed with 50-Hz-AC-voltage. The breakdown strength was determined in ramp-tests with a constant voltage rising rate of 2 kV/s until breakdown occurred. The PDIV was determined with the needle-plate electrode configuration in ramp-tests, too. By using a coupling device parallel connected to the specimen in combination with a narrow-band detection system the PD signals were acquired. For these investigations the voltage was increased with a reduced speed of 0.5 kV/s. The PDIV was reached when discharges with an apparent charge of ≥ 1 pC occurred. All measurements were carried out in a temperature range between -20 and 200 °C.

III. RESULTS AND DISCUSSION

In the following figures the arithmetic means and the standard deviations of the results are shown. In each diagram the obtained curves for the silica flour and the corresponding wollastonite filled resin system are compared. For a better lucidity the outlined values are slightly shifted against each other with respect to the temperature. The means of the breakdown voltage are based on at least six readings whereas the PDIV was determined with more than eight test specimens.

1) Uniform Electrical Field

In Fig. 1 the breakdown voltages of the investigated materials are shown in dependence on the temperature. It can be taken from the diagrams that in a uniform electrical field a rise of the temperature is for the filled epoxy resin systems first combined with an increase of the electrical strength up to a local maximum. Above a temperature of about 90 °C for system 1 and 2 and approx. 30 °C for system 3 and 4 the breakdown voltages decrease continuously so that a bell-shaped curve characteristic appears. In contrast to this the breakdown voltages of the filled epoxy modified isocyanate systems 5 and 6 increase continuously with rising temperature in the whole investigated temperature range.

The bell-shaped characteristic of the curves can be explained by two opposing effects. On the one hand internal mechanical stresses are “frozen” in the specimens during the manufacturing process because of the different coefficients of thermal expansion of the resin matrix and the encapsulated electrode material. These tension stresses are responsible for an increased electrical conductivity due to the stretching of the molecular structure of the cast resins whereby empty spaces are created which cause a higher charge carrier mobility and hence a lowering of the electrical strength [2]. With rising temperature the mechanical stresses are reduced resulting in an augmentation of the breakdown voltages. On the other hand it has to be considered that an elevation of the temperature leads in accordance with Van’t Hoff’s law to an increasing electrical conductivity due to the growing thermal perturbation energy k·T and thus to a charge carrier activation already at lower field strengths. This effect is to be claimed responsible for the observed decline of the breakdown voltages in the upper temperature interval [3]. The shift of the strength-maximum to lower temperatures for the Rütapox resin systems relative...
to system 1 and 2 can be explained with the lower $T_G$ of these materials (Tab. 2).

Because of the comparably high $T_G$ and nearly constant dielectric properties in a wide temperature range no decrease of the electrical strength can be observed for the epoxy modified isocyanate systems when the temperature is increased [4]. On the contrary a slight improvement of the breakdown values with rising temperature occurs as a result of the diminishing internal mechanical strains. In this respect it may be suggested that also for the modified isocyanate systems a bell-shaped curve characteristic of the temperature dependent electrical strength exists with the maximum being shifted to temperatures in the range of $T_G$ at about 300 °C.

Furthermore it can be taken from Fig. 1 that the wollastonite filled epoxy resin systems 2 and 4 are less affected by the temperature than the silica filled materials. This effect is particularly pronounced in the upper temperature range above the local maximum of the curves. The breakdown values of both wollastonite filled epoxy systems lie in a voltage range between 40 kV and 55 kV for the whole investigated temperature interval. In contrast to this the electrical strengths of the silica filled epoxy systems are reduced from a maximum of approx. 65 kV for system 1 and about 55 kV for system 3 to minima at 200 °C of nearly 40 kV and 20 kV, respectively. This means a decrease of the electrical strength by 40 and even 65 %, correspondingly.

With regard to the Araldite epoxy resin systems should be noted that the wollastonite filled material can have slightly lower breakdown values than system 1. Considering the margins of error this effect is not recognizable for the two other resin systems. On the contrary for system 4 at high temperatures even higher breakdown values than for system 3 could be measured.

2) Non-uniform Electrical Field

The breakdown behavior of the investigated cast resin systems determined in a non-uniform electrode arrangement is shown in Fig. 2. It can be seen that the breakdown values of all epoxy systems decline with rising temperature with the maximum reduction in the range of $T_G$ of the respective material. From Fig. 2 it can also be derived that for system 5 an increase of the temperature is combined with a slight and nearly constant decline of the breakdown values. The breakdown strength of the corresponding wollastonite filled system 6 is with a constant value of about 27 kV not influenced by the temperature at all.

Furthermore it becomes obvious that the used kind of filler has a significant impact on the breakdown behavior of the cast resins. The application of wollastonite instead of silica flour is for all resins combined with a pronounced decrease of the electrical strength especially at low temperatures. The breakdown strength of the wollastonite filled cast resins, however, are less affected by a variation of the temperature. This finds its expression e. g. in the fact that at room temperature the breakdown value of system 1 is with about 50 kV more than 65 % higher than for system 2 with approx. 30 kV. But at 200 °C this difference is reduced to approx. 20 % because the electrical strength of system 1 is declined to about 30 kV whereas for system 2 still a breakdown voltage of approx. 25 kV could be measured.

The reducing electrical strength of the examined materials with increasing temperature can again be explained with the temperature dependent conductivity of the solid dielectrics. Above $T_G$ the purely thermal charge carrier activation is associated with a release of secondary valence forces which loosen the morphologic structure of the cured resin compounds [3]. Additionally above $T_G$ an exponential growing of ionic conduction occurs. These effects lead to the observed more significant reduction of the breakdown voltages in the range of the glass transition temperature. The fact that the breakdown characteristics of system 5 and 6 are less dependent on the temperature and do not show a pronounced gradient in the investigated temperature interval as can be perceived for system 1 to 4 near $T_G$ is related to the comparably higher $T_G$ of the epoxy modified isocyanate systems. Their glass transition temperatures amount to more than 300 °C so that a significant gradient in the breakdown-temperature-characteristics has not to be expected within the investigated temperature interval.

Considering that the interface between filler and resin matrix is often regarded as a weak point of cast resin insulating materials the acicular grain structure of the wollasta-
nite could be responsible for the low breakdown values of the systems 2, 4 and 6. This structure may perhaps facilitate the propagation of the discharge after being initialized at the needle tip.

In Fig. 3 the results of the PDIV measurements as a function of the temperature are summarized. As can be derived from the diagrams all epoxy molding materials show a comparable curve characteristic starting with an area of nearly constant PDIV at low temperatures which is followed by a more or less significant decrease of the PDIV with rising temperature. The PDIV values of the epoxy modified isocyanate systems experience only a slight reduction by an elevation of the temperature.

Moreover it can be pointed out that the used filler either has a slight impact like for the Araldite epoxy resins or even no influence on the PDIV like for the other systems. A comparison between the two epoxy resins reveals that obviously the used resin type determines the PD behavior. The measured PDIV for the systems 3 and 4 are in the lower temperature range more than two times higher than the corresponding values of the Araldite resin. For higher temperatures the PDIV of the systems 3 and 4 decreases dramatically because of the rising conductivity and the changed morphologic structure of the cured resin compound above \( T_G \) already observed and described for the breakdown behavior in a non-uniform field.

The high PDIV of the Rutapox resin systems can be explained among others with the comparatively high critical stress intensity factor \( K_{IC} \) of these materials (Tab. 2). A high fracture toughness \( K_{IC} \) means that more energy is needed to initialize cracks which can be responsible for partial discharges and this finds its expression in higher PDIV [5]. The only slight reduction of the PDIV of the epoxy modified isocyanate systems is attributed to the high \( T_G \) and the stable dielectrical properties of these materials in the whole investigated temperature interval. But it becomes obvious that up to a temperature of about 150 °C the PDIV values of the modified isocyanate systems are even 40 to 55 % lower than the corresponding values of system 1 and 2 what is in coherence with the low \( K_{IC} \) for these dielectrics.

IV. CONCLUSIONS

The presented short-time investigations have revealed that above the glass transition temperature the electrical strength of a mineral filled epoxy resin system decreases significantly. Moreover it can be said that silica fillers lead to a better electrical breakdown behavior of the employed epoxy resin than wollastonite above all for lower temperatures and in a non-uniform field. The PDIV, however, is not significantly influenced by the used filler. The PD behavior seems to be determined by the resin matrix. Additionally it can be deduced from the investigations that mineral filled epoxy modified isocyanate systems show a comparatively stable electrical strength over a wide temperature range but it has to be noted that these materials can have significantly lower partial discharge inception voltages than the corresponding epoxy resin systems especially in the lower temperature range.

V. ACKNOWLEDGMENT

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VI. REFERENCES