Two-dimensional numerical modeling of electric field and correlation to dielectric breakdown

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***Abstract*—An attempt is presented to estimate the intrinsic breakdown characteristics of a dielectric by using ramp-to-breakdown experimental values and numerical simulations. The method presented illustrates the stressed-area(value) approach can be implemented to better understand the breakdown properties of different materials and remove influence of measurement/electrode topology in the breakdown physics.**

Dielectric breakdown properties of materials determine the size and lifetime of a high voltage system due to their direct influence on the clearances and tolerance, and performance [1]. Performing breakdown experiments is a straight forward experiment that requires only a voltage source and voltmeter with a voltage divider; there are various commercially available systems to perform the job with all the required parts embedded. The results of the breakdown measurements on the other hand require some analysis. There are methods developed to analyze the breakdown data, see Tuncer et al. [2], which are based on pure mathematical models to better represent the data. In all the analysis approaches the data collected usually performed with a *well-defined* electrode structures which are mainly using plane-to-plane electrode geometry where the electric field is highly uniform, but not perfect; for perfectly uniform fields one needs to use Rogowski profiles [3]. There are other electrode arrangements that can be employed, *i.e.,* sphere-to-sphere or needle-to-plane or needle-to-needle geometries, but it would make the analysis hard due to non-linear fields. The current study is aiming to remove the influence of non-linear electric field effects from the breakdown measurements, we considered that the material considered in the study was linear, meaning the electrical properties do not change with electric field.

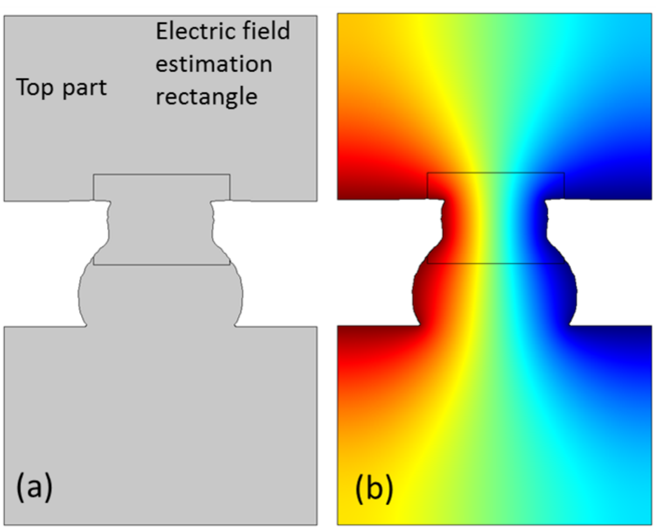


Fig. 1. Computational domain (left) and the potential distribution in the medium (right). The red and blue scales indicate full and ground voltage levels; the voltage is applied to the left pad and the right pad grounded.

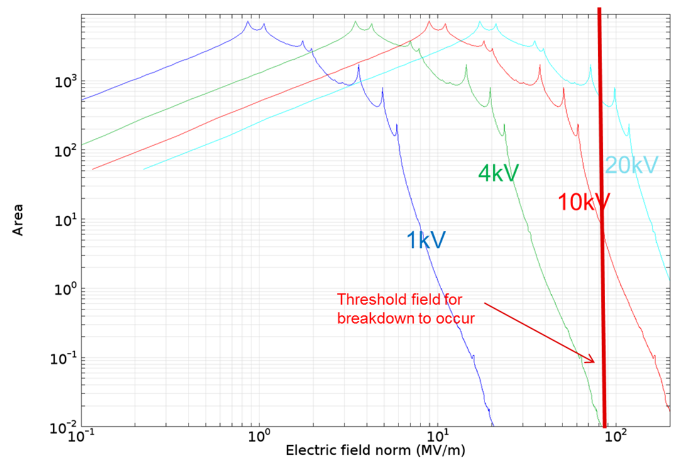


Fig. 2. Electric field histograms for a given potential difference between electrodes.As the difference increases the curve shifts to high indicating increase in stressed area.

The influence of the electric effects are removed using the numerical simulations and estimating the percentage of high field regions in a given test (electrode) geometry. In the simulations an effective medium approach was used. The method implemented to determine breakdown from the simulations is based on the stressed area approach which was first illustrated by Tuncer and Sauers [4] and later published for a particle-in-a-box simulation by Tuncer et al. [5], which contains the details of the method.

The computational domain and the results from the finite element solver are shown in Fig. 1, where the region of interest for the calculations are shown. Notice that one can use the whole computation domain for the calculations, however due to the electrode geometry, the area that has low field would be high in over all area calculation and compared to the

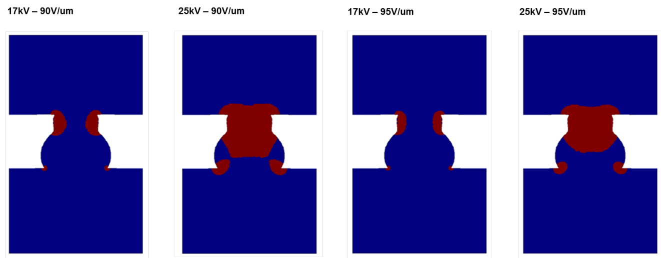


Fig. 3. Areas of interest for the electric field strength are shown for two different voltages and two different stress thresholds.

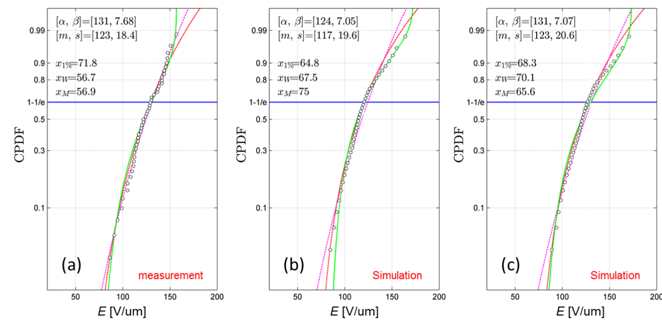


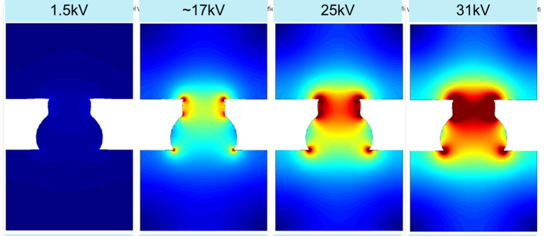
Fig. 5. Actual ramp-to-breakdown cumulative probability distribution function (CPDF) from the same electrode geometry arrangement (a) and the stress area estimates from simulated results for 95V/μm (b) and 100V/μm (c) are shown above. The lines and parameters are obtained from different breakdown expressions, see Tuncer et al. [2] for details.

interested electric field values which are located in a small area located at the top of the computation domain Fig. 1b. The region of interest therefore selected as shown in Fig. 1, which only includes the upper part of the electrode geometry, which is the anticipated to initiate the breakdown due to short clearance distance. One can estimate the stressed area for a given potential difference in a nonlinearly distributed field [5] as shown in Fig. 2.

Example of the simulated field distribution for different voltage levels are presented in Fig. 3. Notice that the dark regions between the top part of the electrodes increase with increasing voltage difference between them. At low voltages, 1.5kV the field is low enough to initiate any electric field hot spots, while as the voltage is increased the pointed corners illustrate field enhancement. The table in Fig. 4 also shows the percentage of area in the box-of-interest from Fig. 1 that is stressed with 90V/μm and 95V/μm, where at 31kV potential difference nearly 100% of the box is seeing 90V/μm. Using a procedure to estimate the electric field strength for a given voltage level and correlate it to the measurement results would be straightforward after estimating stress area for any given applied voltage and threshold field, which is estimated by comparing the calculation results with the measurement values. The approach can be further illustrated in Fig. 3.

The actual dielectric breakdown measurements performed using the same electrode geometry are plotted in Fig. 5a with Weibull representation [2]. The lines in the figures illustrate different fit model with parameters listed in the plots to

	1.5kV	~17kV	25kV	31kV



Threshold E-field				
95V/um	0%	~20%	90%	99.8%
90V/um	0%	~28%	95%	99.9%

Fig. 4. Electric field distributions at different voltage levels and corresponding stress area in table above presented to describe the proposed method. The stress area develops with increased voltage difference between electrodes as expected.

the experimental data, which are outside the scope of this manuscript. The concept of using the field simulations and plotting the stress area for breakdown analysis is presented for the two threshold voltages 95V/μm and 100V/μm in Fig. 5b and 5c, respectively. Notice that the area plot with respect to electric field shows a similar trend as the ramp-to-breakdown measurements in Fig. 5a. Therefore, one can in practice use an optimization to match simulation results to measurements which will output *intrinsic electrical breakdown field* for a given material. Here no optimization procedure was adopted, only the curves overlapped to check for similarities as shown in Fig. 6.

The proposed method is able to represent the ramp-to-breakdown data for threshold fields of 100V/μm, see Fig. 6b at low fields. At high stress fields there is a discrepancy, which is not significant for high voltage design since one needs account for low breakdown probabilities rather than high breakdown field, which is not practical for long lifetime and reliability. One can in principle improve the method by better selecting the region of interest by using the flux lines, which would actually show a better definition for the stressed area of interest.

The comprehensive understanding of breakdown in solid materials are limited due to the complexity of the measurement arrangements, the micro-structure of tested materials and charge transport and polarization phenomenon. One should not disregard the manufacturing defects, which is actually included in the micro-structural information. It is usually considered that the defect initiated breakdown in solids. However the proposed model/method provide a macroscopic approach where an effective medium within a electrode arrangement can be employed to estimate a breakdown phenomenon by considering stressed area approach. In this method the threshold electric field which is assumed to be the breakdown initiation field and considered an absolute dielectric breakdown field. Simulations using an exact electrode geometry employed in materials testing in our labs was able to explain the ramp-to-breakdown behavior with 100V/μm threshold fields for the effective medium. The correlation between simulations and the measurements is a good indication for the usefulness of the method and how one can perhaps transfer measurements from one electrode arrangement to another. Notice that the method presented here considered only linear material properties with respect to electric field.

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REFERENCES

[1] T. W. Dakin, "High voltage insulation applications," *IEEE Transactions on Electrical Insulation*, vol. EI-13, no. 4, pp. 318–326, Aug 1978.

[2] E. Tuncer, I. Sauers, D. R. James, A. R. Ellis, and M. O. Pace, "On dielectric breakdown statistics," *J. Phys. D: Appl. Phys.*, vol. 39, pp. 4257–4268, 2006.

[3] P. D. Thacher, "Optical effects of fringing fields in kerr cells," *IEEE Transactions on Electrical Insulation*, vol. EI-11, no. 2, pp. 40–50, 1976.

[4] E. Tuncer, "Strategic dielectric r&d for hts and other oe applications," June 28-July 1 2010, the document was presented at 2010 Department of Energy Peer Review in Alexandria, VA.

[5] E. Tuncer, C. Calabrese, and W. Yin, "Preliminary numerical study on dielectric mixtures under lightning impulse conditions," in *Power Modulator and High Voltage Conference (IPMHVC), 2012 IEEE International*, June 2012, pp. 184–186.

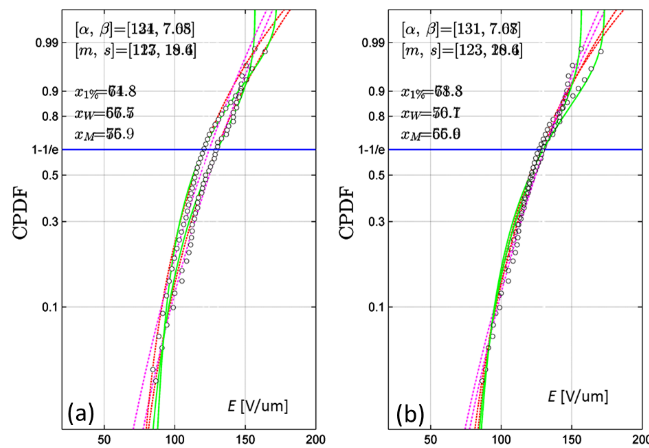

Fig. 6. Illustration for how good the proposed method matches actual ramp-to-breakdown results for threshold stress fields of (a) 95V/μm and (b) 100V/μm.