DC Voltage Endurance of Capacitor BOPP Films at High Temperature

Mikael Ritamäki, Ilkka Rytöluoto, Kari Lahti
Electrical Energy Engineering
Tampere University of Technology
Tampere, Finland
mikael.ritamaki@tut.fi

***Abstract*—A large-area method for determining the voltage endurance of capacitor films is presented. The method was used to characterize the high field – high temperature performance of a commercial biaxially oriented polypropylene film. Following IEC standard 61251, an inverse power law model was fitted to the Weibull-distributed times-to-breakdown data. The insulation life increased rapidly as either field or temperature was decreased. Even at mildest stresses used, the failure rate was still increasing with time, implying that the conditions were above reasonable design limits. Determining the threshold conditions below which the failure rate starts to decrease with time may open up new paths for development of dielectric for higher energy density film capacitors.**

Keywords— Dielectric measurement, materials reliability, capacitors, materials testing, life testing

I. INTRODUCTION

High voltage direct current (HVDC) transmission is indispensable in utilizing distant renewable energy sources, such as offshore wind power. Voltage source converters (VSCs) offer a smart, new way to connect HVDC networks to the existing AC power transmission grid. Especially when combined with stationary energy storage both power quality and grid stability are improved. Capacitors are key components in VSC systems, thus ensuring extreme technical performance and uncompromised reliability is of great importance. New high energy density dielectrics could open up paths to improved VSC systems. However, the reliability and long-term properties of any new dielectrics needs to be verified before their use in these often reliability-critical applications. Repeatable and reliable voltage endurance test methods are needed for early screening of novel would-be dielectrics, before expensive industrial scale production, which is the prerequisite for tests using wound capacitor elements.

Biaxially oriented polypropylene (BOPP) is the current state of the art technology for high energy density film capacitors, offering high dielectric breakdown strength, low dielectric losses, and stable capacitance with temperature. The Achilles knee of BOPP is their low permissible operating temperature around 100 °C. The reliable life decreases with increasing temperature, thus for highest reliability their operating temperature is limited. Preliminary measurements on new nanostructured dielectrics have demonstrated improved high temperature characteristics [1], therefore highlighting one possibly way to develop better film capacitors.

Various self-healing multiple breakdown measurement methods have been developed and utilized in TUT high voltage research group to study the DC [2], AC [3] and long-term [4] properties of various oriented capacitor films. These methods utilize self-healing metallized film electrodes to continue the measurement beyond the first breakdowns, enabling rapid gathering of large amounts of data. In [4] it was proposed to extend this methodology to times-to-breakdown "voltage endurance" tests, an implementation of which is reported in this paper. This method is used to evaluate the high field – high temperature endurance of an industrially produced capacitor-grade BOPP film.

II. EXPERIMENTAL

A. Measurement methods

Three types of DC breakdown measurements were conducted: single breakdown ramp tests in oil at room temperature using polished brass electrodes, and large-area multiple breakdown ramp tests and times-to-breakdown measurements in air at various temperatures. The film studied is a smooth commercial 10 µm BOPP film for capacitor applications. A list of test conditions is given in Table 1.

Large-area samples had an active area of 81 cm2, and used a Zn-Al metallized 12 µm BOPP film as the electrodes, similar to as described in e.g. [2]. High temperature tests were done in an oven with forced air circulation. The test fixture had been pre-heated, and the system was given at least 10 minutes to reach thermal equilibrium before test voltage was applied. Temperature stability was around 3 %.

After temperature stabilization, a DC voltage ramp was applied, during which the electrostatic force compressed the

TABLE 1 DC BREAKDOWN TESTS WERE DONE IN THE FOLLOWING CONDITIONS

Temperature (°C)	Constant stress test (kV/mm)	Ramp test (V/s)
ambient		500, 50, 10, 5 (small-area)
80	500, 450, 400	
100	500, 450, 400	50, 10, 2.5 (large-area)

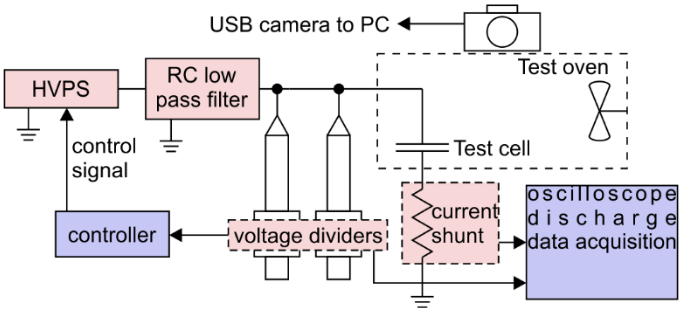

Fig. 1. Large-area breakdown measurement system utilizing a feedback control for voltage stability

film layers, pushing air from between them. Nevertheless sometimes major pockets of air remained initially between the electrodes and the film being tested, in these cases a DC voltage below the intended test voltage was applied for a several seconds, and then a soft cloth was used to swipe the air bubbles out. Despite the sample being not energized during this “swiping” no major air bubbles were seen as the full test voltage was applied afterwards, and any small bubbles disappeared rapidly. Since insulation life is highly dependent on the applied field, the influence of this pre-stressing on the measured times-to-breakdown values was deemed non-significant.

In large-area tests, the voltage ramp was applied until either no discharges were detected (in ramp tests) or until the intended voltage was reached, after which a constant voltage was maintained using closed-loop feedback control. Discharge current and voltage waveforms were recorded using a high-resolution 12-bit oscilloscope, and an USB camera was set up to photograph the sample after each discharge. The measurement system is depicted in Fig. 1.

B. *Times to breakdown data qualification*

The discharge energy and breakdown voltage –based qualification procedure explained in e.g. [5] was modified for tests at constant voltage, and used in combination with the recorded photos to validate each recorded event. The selection criteria is based on the dependency of the self-healing energy E_{sh} on the breakdown voltage U_{bd} and the capacitance partaking in the self-healing C [6]:

$$E_{sh} = a \times C \times U_{bd}^{b}$$

with a and b being factors that can be assumed remain constant during a measurement at constant voltage. The self-healing energies should follow a (slowly) decreasing trend as other factors remain constant and the capacitance decreases as the active area is reduced. Any discharges were excluded as non-independent or non-breakdown discharges if their energy deviated notably from this trend, or if they occurred at lower voltages, the latter being a sign of successive self-healings. The first events were also reviewed using the photographs to exclude edge discharges, and finally to harmonize the results only the 10 first qualified events for each sample were used in further analyses. Four parallel samples in each condition were measured, yielding 40 data points in total.

C. *. Statistical analysis*

The breakdown data was fitted with two-parameter Weibull-distributions using maximum likelihood estimation, and confidence bounds were calculated using a Fisher Matrix –based method. The Weibull distribution for breakdown times t (or electric fields) is written as [7]:

$$F(t) = 1 - \exp\left\{ -\left(\frac{t}{\alpha} \right)^{\beta} \right\}$$

where $F(t)$ is the Weibull distribution with scale and shape parameters α and β. The scale parameter α is the characteristic life, that is the time (or electric field in progressive stress tests) after which 63.2 % of samples have failed.

An inverse power law (IPL) model, as recommended by IEC 61251 was fitted to the Weibull times-to-breakdown data:

$$L = c \times E^{-n},$$

where L is the characteristic insulation life (Weibull α), E is the electric field stress and c and n are constants. Parameter n is also known as the voltage endurance coefficient (VEC). Of the IPL parameters, the VEC is the most interesting, as it describes how rapidly the insulation life decreases as electric field is increased. [8]

The Weibull electric field and time parameters were extracted from ramp tests results using the statistical methods described by Dissado & Hill in e.g. [9], similarly as in [10]. The time parameter is equivalent to the β in Weibull times-to-breakdown distribution. This enabled the results from ramp tests to be converted to equivalent times-to-breakdowns values using the formula from IEC-61251:

$$t_{\text{equivalent constant voltage}} = \frac{t_{\text{ramp test}}}{n+1}$$

where n is the power law exponent of the IPL model.

III. RESULTS AND DISCUSSION

The Weibull parameters and the voltage endurance coefficients are reported in Table 2. The characteristic insulation life (Weibull α) as a function of DC field and temperature is visualized in Fig. 2. The VEC calculated from room temperature ramp tests is extremely high, but the trend

TABLE 2 WEIBULL PARAMETERS.

Ramp tests converted to constant voltage equivalents

Tamp.	RT ~22–24°C				100 °C			
Ramp rate Vs-1µm-1	50	5	1	0.5	5	4.65	1	0.25
α (s)	0.4	4.4	21.5	40.0	6.2	6.5	28.6	108.2
β	0.23	0.31	0.41	0.30	2.84	2.83	2.80	2.78
VEC	34				21			

Tests at constant voltage

Temp.	80 °C			100 °C		
E-field (V/µm)	500	450	400	500	450	400
α (s)	403	1330	4960	240	325	2122
β	2.88	1.99	1.62	3.28	3.10	2.49
VEC	12			10		

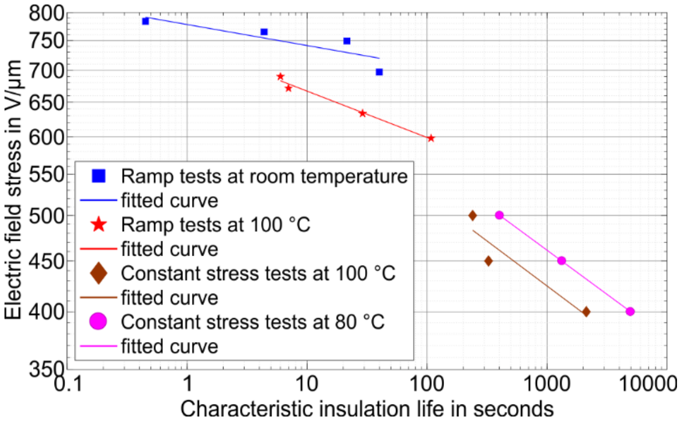

Fig. 2. Characteristic insulation life reduces as either DC electric field or temperature is increased.

appears to decrease towards longer times. This type of behavior is also mentioned in IEC 61251. From a practical point of view, this means that the insulation life at lower fields cannot be extrapolated from high field data, as the predictions would be overly optimistic. Less evident VEC curvature may also be seen between ramp and constant stress tests at 100 °C, but this may originate from differences in data qualification between large-area ramp and constant stress tests. In general, the VEC of 10–12 in constant voltage tests is within the expected range of 8-15 [8] for dielectrics. An interesting observation is also that the VEC appears to increase with decreasing temperature, as explained in [11], based on which values as high as 15–20 might be expected at room temperature for polymeric dielectrics.

It would be extremely beneficial in steering the development of new capacitor dielectrics if the VEC of the film itself could be correlated with life test results done on actual capacitors. Even more if the VEC can be determined using a simple and repeatable method like the one reported in this study. A proper comparison would require capacitors wound from the same type of film, which is, however, not within the scope of this study. In general, care should be taken to distinguish between AC and DC life test results, especially since preliminary measurements indicate space charge accumulation in BOPP thin films in typical operating conditions [1] while DC ageing is dominated by space charge effects [12]. These effects should be negligible under AC excitation. Moreover, it needs to be ensured that accelerated ageing does not bring phenomena uncommon in real capacitors, such as partial discharging at electrode edges.

In Fig. 3, the confidence contours for Weibull parameters are shown in 5 % increments from 75 to 95 %. Weibull β is crucial for understanding the failure characteristics in constant stress tests, as three regimes can be identified [7]:

1. if $\beta < 1$ the failure rate decreases with time, representing early failures

2. if $1 < \beta < 2$, the failure rate increases with time, but at a decreasing rate, representing end of life (EOL) wear out

3. if $\beta > 2$ the failure rate increases at an increasing rate, signifying rapidly approaching EOL.

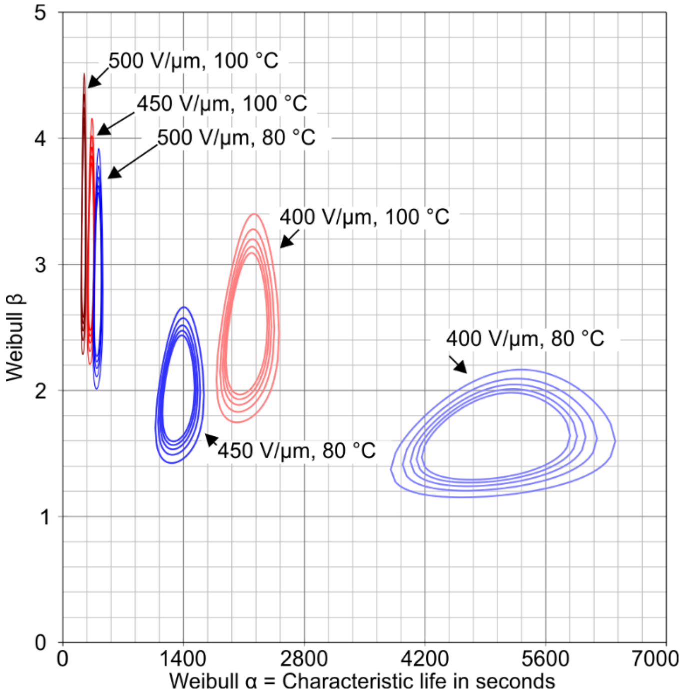

Fig. 3. Weibull parameters visualized using confidence contours, the rate at which the failure rate increases with time decreases with temperature and DC field, approaching constant at β=1.

When combined these three regimes can be used to model the whole bathtub curve of failure rate for capacitors [7], [13]. Obviously, if β is above one in short-term voltage endurance tests such as the ones reported in this study, the film is not reliable in the test conditions. Looking at Fig. 3 Weibull β decreases with decreasing temperature and field, but even with the confidence bounds considered remains above one in all high temperature measurements. However by extrapolating from the available data towards lower fields and the room temperature points in Table 2 where $\beta < 1$, it can be postulated that a threshold exists, below which the failure rate starts decreasing with time. This threshold marks the highest allowed stresses and is a function of temperature and field.

To determine this threshold the large-area constant stress measurement methodology can be extended to longer measurement times, but doing so requires an inert atmosphere to limit oxidation, as was done in e.g. [4]. Capacitors are usually sealed to prevent the ingress of oxygen, as at least their ageing under AC stresses is influenced by the presence of oxygen [14]. Ageing in atmospheric air in may be significantly accelerated due to the presence of oxygen [15], or the phenomena, such as antioxidant conversion [16] may not be representative of those occurring in capacitors during normal operation. However, since the duration of the measurements reported was in the range of hours, oxidation was not considered a major issue. Also for longer measurement times the absence of DC PD shall be ensured.

IV. CONCLUSIONS

The large-area multiple breakdown method was extended to DC voltage endurance tests, and then used in high field – high temperature characterization of a capacitor BOPP film. The large-area approach was beneficial in gathering large amounts of data for improved statistical accuracy. As long as the absence of PD and oxygen is controlled, this test method is also suitable for longer tests.

The failure rate decreased with field and temperature, thus a threshold presumably exists, below which the film is “stable”, that is, has a decreasing failure rate. Determination of this threshold may prove beneficial in R&D work aiming to produce better capacitors for high field HVDC applications.

ACKNOWLEDGMENT

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 720858.

REFERENCES

[1] G. C. Montanari, P. Seri, M. Ritamäki, K. Lahti, I. Rytöluoto, and M. Paajanen, “Performance of Nanoparticles in the Electrical Behavior of DC Capacitor Films,” in *2018 IEEE 12th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, 2018 (*In Press*).

[2] I. Rytöluoto, “Large-Area Multi-Breakdown Characterization of Polymer Films: A New Approach for Establishing Structure–Processing–Breakdown Relationships in Capacitor Dielectrics,” D.Sc. thesis, Tampere University of Technology, 2016.

[3] M. Ritamäki, I. Rytöluoto, M. Niittymäki, K. Lahti, and M. Karttunen, “Differences in AC and DC large-area breakdown behavior of polymer thin films,” in *2016 IEEE International Conference on Dielectrics (ICD)*, 2016, pp. 1011–1014.

[4] M. Ritamäki, I. Rytöluoto, K. Lahti, T. Vestberg, S. Pasanen, and T. Flyktman, “Large-area Approach to Evaluate DC Electro-thermal Ageing Behavior of BOPP Thin Films for Capacitor Insulation Systems,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 24, no. 2, pp. 826–836, Apr. 2017.

[5] I. Rytöluoto, K. Lahti, M. Karttunen, and M. Koponen, “Large-area dielectric breakdown performance of polymer films – Part I: Measurement method evaluation and statistical considerations on area-dependence,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 22, no. 2, pp. 689–700, Apr. 2015.

[6] Y. Chen, H. Li, F. Lin, F. Lv, M. Zhang, Z. Li, and D. Liu, “Study on Self-Healing and Lifetime Characteristics of Metallized-Film Capacitor Under High Electric Field,” *IEEE Trans. Plasma Sci.*, vol. 40, no. 8, pp. 2014–2019, Aug. 2012.

[7] ReliaSoft Corporation, “Life Data Analysis Reference Book.” [Online]. Available: http://reliawiki.org/index.php/Life_Data_Analysis_Reference_Book.

[8] “IEC 61251:2015 Electrical insulating materials and systems - AC voltage endurance evaluation Edition 1.0.” IEC, 2015.

[9] R. M. Hill and L. A. Dissado, “Examination of the statistics of dielectric breakdown,” *J. Phys. C Solid State Phys.*, vol. 16, no. 22, pp. 4447–4468, Aug. 1983.

[10] I. Rytöluoto, M. Ritamäki, K. Lahti, and M. Karttunen, “DC ramp rate effect on the breakdown response of SiO2-BOPP nanocomposites,” in *2015 IEEE 11th International Conference on the Properties and Applications of Dielectric Materials (ICPADM)*, 2015, pp. 496–499.

[11] G. C. Montanari, “Notes on theoretical and practical aspects of polymeric insulation aging,” *IEEE Electr. Insul. Mag.*, vol. 29, no. 4, pp. 34–44, 2013.

[12] G. C. Montanari, “Relation between space charge and polymeric insulation ageing: cause and effect,” *IEE Proc. - Sci. Meas. Technol.*, vol. 150, no. 2, pp. 53–57, Mar. 2003.

[13] R. Gallay, “Metallized Film Capacitor Lifetime Evaluation and Failure Mode Analysis,” Proceedings of the CAS-CERN Accelerator School: Power Converters , Geneva, 2014.

[14] B. Gosse, J. P. Gosse, S. Saïd, A. Gadoum, and M. Nemamcha, “Electrical Degradation of Polypropylene: A Study by FTIR Microspectroscopy,” *J. Appl. Polym. Sci.*, vol. 46, no. 6, pp. 1121–1124, Oct. 1992.

[15] T. D. Huan, S. Boggs, G. Teyssedre, C. Laurent, M. Cakmak, S. Kumar, and R. Ramprasad, “Advanced polymeric dielectrics for high energy density applications,” *Prog. Mater. Sci.*, vol. 83, pp. 236–269, Oct. 2016.

[16] J. Ho, R. Ramprasad, and S. Boggs, “Effect of Alteration of Antioxidant by UV Treatment on the Dielectric Strength of BOPP Capacitor Film,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 14, no. 5, pp. 1295–1301, Oct. 2007.