The Effect of Impulse Rise–Time on the Breakdown of Composite Ester–Polymer Insulation

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***Abstract*— This paper reports and discusses the breakdown behaviors of composite insulation formed from insulating fluids and practical polymers, under test conditions representative of electrical stresses experienced within pulsed power machines. Interfaces formed from the synthetic ester fluid, MIDEL 7131 (M&I Materials, UK) and the natural ester fluid, EnviroTemp FR3, (Cargill, USA) and solid polymers (NYLON 6,6 and PMMA) have been stressed with discrete negative impulses until breakdown; with measured parameters compared to those gathered for identical composites utilizing transformer oil (Shell Diala S4 ZX). Dissimilarity in the behavior of the composite insulation systems has been observed; with those formed of the Nylon polymer shown to possess a tendency to experience bulk polymer breakdown rather than surface flashover; the predominant form of breakdown seen in tests conducted on liquid-PMMA samples. Regardless of the type of breakdown experienced, both ester fluids offer comparable levels of dielectric strength to that of transformer oil under the test conditions applied. It can also be reported that a clear sensitivity to the impulse parameters (rise-time) was experienced by all PMMA interfaces, with a reduction in dielectric strength observed as impulse rise-time was increased; with no such trend witnessed in the behavior of composite systems utilizing the Nylon polymer.**

Keywords—Dielectric breakdown; liquid-solid insulation; impulse breakdown; ester liquids; ester-polymer breakdown.

I. Introduction

Environmentally-friendly ester dielectric fluids have been the subject of active research within the power industry for over 80 years [1]. Given the nature of such research, focusing on ester fluids as an alternative to conventional transformer oil, test methodologies were developed which are based on the application of a standard 1.2/50 μs lighting impulse, which represents the transient electrical stress which insulating liquid may experience within a typical power transformer [2-4]. While such an approach may yield suitable data for the operators of power systems, it does not fully extend to pulsed power technology. For example, large pulsed power machines [5] typically generate impulsive voltages with nominal parameters (rise-time, fall-time) which are not reflected within standard tests, IEC 60897. Representation of pulsed power systems is also lacking in published research surrounding breakdown of interfaces between liquid and solid dielectrics. As with bulk liquid breakdown, work in this area has focused on breakdown of interfaces formed with typical dielectrics used in power transformers: mineral oil and kraft paper, [6-8]. However, kraft paper is not commonly used in pulsed power machines, where different solid polymers are typically employed. Consequently, efforts must be made to increase understanding of the dielectric behavior of solid polymer-insulating fluid interfaces stressed with non-standard HV impulses.

II. Materials & Methods

A. Dielectrics used in Experimental Study

To that end, an investigation was conducted into the breakdown of composite insulating systems formed from the synthetic ester fluid, MIDEL 7131 (M&I Materials, UK) and the natural ester fluid, EnviroTemp FR3, (Cargill, USA) and solid polymers (NYLON 6,6 and PMMA) under a number of discrete negative voltage impulses of various wave-shapes, characterized by rise-times of 0.4 μs, 1.2 μs and 7 μs; with all data measured against a benchmark of the same interfaces formed with a mineral oil (SHELL Diala S4 ZX). Key parameters of the investigated dielectric fluids have been given in Table I. The obtained breakdown parameters will yield important information to increase confidence in the use of environmentally-friendly ester fluids within the pulsed power industry.

TABLE I; Key parameters of investigated dielectric fluids

	Shell Diala S4 ZX	**MIDEL 7131**	**Enivrotemp FR3**
Composition	Mix of hydrocarbons	Pentaerythritol tetra ester	Plant based ester
Water Saturation	70ppm [9]	2600ppm [10]	1100ppm [11]
Flash Point	191°C [9]	260°C [10]	316-330°C [11]
Relative Permittivity	2.2 [9]	3.2 [10]	3.2 [11]
Dielectric strength (AC)	60kV [9]	75kV [10]	56kV [11]

TABLE II; Key parameters of investigated polymer dielectrics

	Nylon 66	PMMA
Composition	Polyamide	Polymethyl-metacrylate
Density	1.14g/cm³ [12]	1.19g/cm³ [13]
Dielectric strength (AC)	27kV/mm [12]	20kV/mm [13]
Dielectric constant	3.8 [12]	3.5 [13]
Tensile strength	82MPa [12]	80MPa [13]

B. Testing Methodology

Five individual 8 mm thick samples of each solid material, the parameters of which have been summarized in Table II, were immersed in the chosen dielectric fluids, and stressed with HV impulse voltages until the occurrence of interfacial breakdown, or breakdown through the bulk of the solid dielectric. For each Liquid-polymer sample breakdown parameters (breakdown voltage and time to breakdown) were logged for 10 individual interfacial flashovers, or a single bulk breakdown of the polymer dielectric. Applying such a methodology allowed for determination of both the level of voltage required to cause complete breakdown of the composite insulation system, as well as providing an indication of the likelihood of the different types of breakdown to occur.

III. Experimental Setup

The breakdown tests were conducted in a needle-plane electrode configuration. A gramophone needle with a nominal tip radius of ~35 µm was used as the HV electrode, with a 40 mm diameter mild steel ground electrode. Comprehensive analysis of the electric field distribution within the test cell resulted in the use of a recess, 'ring', design for the grounded electrode.

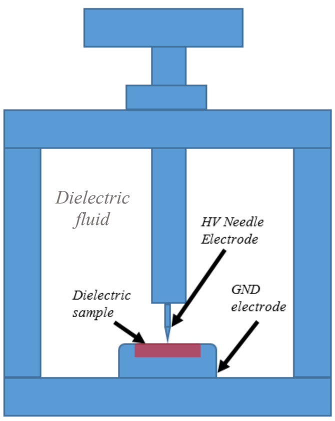

Fig. 1. Schematic of test cell used for all breakdown experiments.

The discrete negative voltage impulses used for the breakdown measurements were generated with a Marx-type impulse generator. A DC charging voltage of 25 kV was used in all tests, producing HV impulses with a nominal peak amplitude of 125 kV. The nominal rise-time of the generated impulses was controlled through alteration of the *RLC* parameters of the pulsed power driving circuit; specifically, the wave-front resistance and capacitance.

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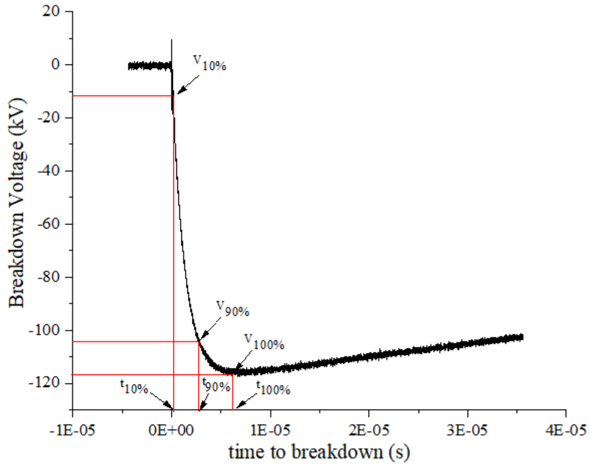
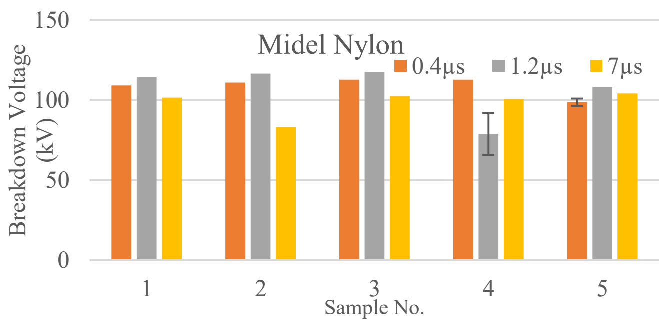


Fig. 2. Example of one of the discrete voltage wave-forms (nominal rise-time 0.4 µs) applied during breakdown tests. Nominal rise-time of the impulse was taken as the time for the magnitude to increase from $V_{10\%}$ to $V_{90\%}$ with a multiplication factor of 1.25 applied [14].

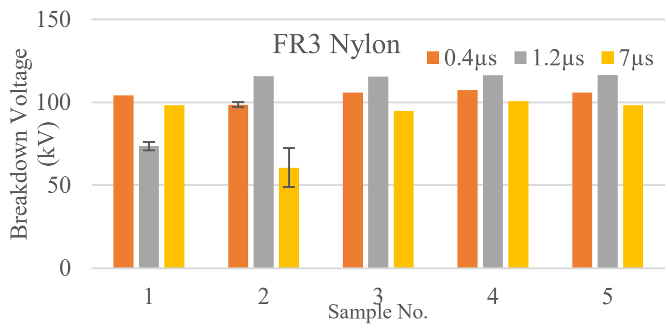
To measure the HV wave-forms during the breakdown tests, a HV divider was connected in parallel with the test cell. This custom-built divider, a $CuSO_4$ water solution filled column, was coupled to a commercial HV probe, NorthStar PVM5, with a nominal bandwidth of 80 MHz. All experimental voltage signals were captured and recorded using a Textronix TDS3054C digitizing oscilloscope (500 MHz, 5 Gs/s).

IV. Experimental Results

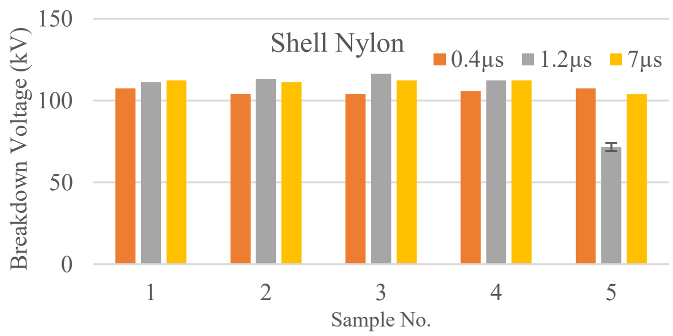
The measured breakdown voltages for each liquid-polymer sample when stressed with the three discrete negative voltage impulses are presented in Figure 3. The average breakdown voltages for surface flashover of the interface, or for bulk breakdown of the polymer, have also been provided. Data devoid of error bars represents an insulation system that experienced bulk polymer breakdown, with all others showing samples which underwent 10 individual surface flashover events. Each value of the breakdown voltage shown in Figure 3 was obtained as an average of the measured individual values of this parameter, and the error bars in the diagrams and (±) error values in the tables represent the standard deviation in these parameters. Table entries devoid of data show that no test samples experienced a given type of breakdown; i.e. if an entry is absent under the 'bulk breakdown' sub-heading only surface flashover was observed for the five test samples when a particular impulse was applied, as is the case for surface flashover of the Midel-Nylon samples when stressed with the impulse of 7 µs rise-time.



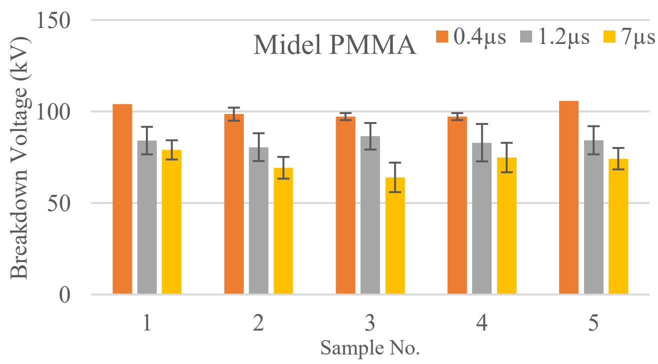
Impulse rise-time	$V_{average}$ – Midel Nylon	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4 µs	111.32 ± 1.69	98.61
1.2 µs	114.14 ± 4.19	78.83
7 µs	98.34 ± 8.55	



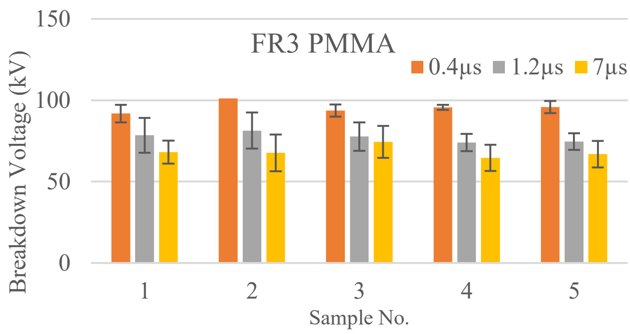
Impulse rise-time	$V_{average}$ – FR3 Nylon	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4 µs	105.84 ± 1.37	98.62
1.2 µs	116.01 ± 0.44	73.65
7 µs	97.97 ± 2.39	60.65



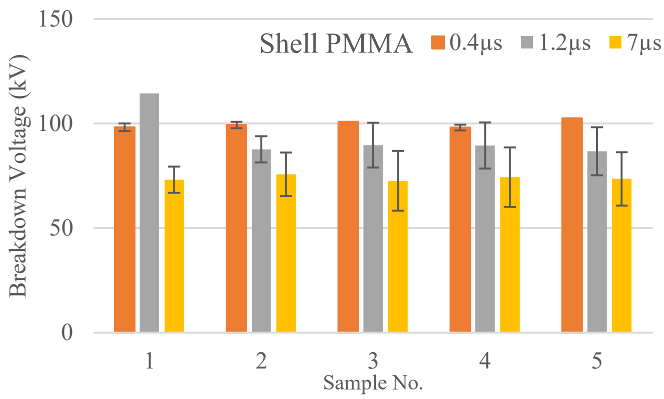
Impulse rise-time	$V_{average}$ – Shell Nylon	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4µs	105.84 ± 1.68	
1.2µs	113.36 ± 2.25	71.72
7µs	110.45 ± 3.63	



Impulse rise-time	$V_{average}$ – Midel PMMA	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4 µs	105 ± 1.19	97.72 ± 0.78
1.2 µs		83.71 ± 2.19
7 µs		72.29 ± 5.79



Impulse rise-time	$V_{average}$ – FR3 PMMA	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4 µs	101.09	94.26 ± 1.88
1.2 µs		77.27 ± 2.98
7 µs		68.36 ± 3.63



Impulse rise-time	$V_{average}$ – Shell PMMA	
	Bulk Breakdown (kV)	***Flashover (kV)***
0.4µs	101.64 ± 1.19	98.56 ± 0.64
1.2µs	114.4	88.4 ± 1.41
7µs		73.86 ± 1.24

Fig. 3. Measured breakdown voltages for tested liquid-solid interfaces. Data absent of error bar represent samples which experienced bulk breakdown of the solid dielectric; all other data points represent the mean of 10 individual surface flashover events. Error bars represent standard deviation.

It is evident from the obtained data that dissimilarity exists in the breakdown behaviour of the investigated composite insulation systems. Examination of the Liquid-Nylon insulation systems clearly shows that, irrespective of impulse rise-time, bulk breakdown of the polymer is the most likely type of breakdown to occur; observed in almost all tested samples.

The chosen liquid is seen to have little effect on the propagation path of the breakdown streamer, however, interfaces formed from the natural ester fluid EnviroTemp FR3 do exhibit a slightly lower probability of bulk breakdown of the polymer samples (80% of tested samples) as compared with both the synthetic ester and transformer oil; 87% and 93%, respectively.

No clear upward or downward trend in the breakdown voltage was witnessed for the composite insulation systems with a Nylon solid - the measured values were seen to fluctuate for all investigated fluids, irrespective of the applied impulse rise-time; though it can be stated that bulk breakdown of the polymer consistently occurred at a higher level of voltage than flashover across the liquid-polymer interface.

Evaluation of the data obtained from testing of liquid-solid interfaces consisting of the chosen liquids and the PMMA polymer showed contrasting behaviour to those of the Nylon interfaces. Firstly, the breakdown predominantly took the form of interfacial flashover rather than bulk breakdown of the polymer. Flashover across the liquid-PMMA interface was observed in almost all test samples; with this occurring in 93% of samples immersed in the natural ester, 87% of those in synthetic ester and reducing to 80% for those submerged in mineral oil.

Furthermore, unlike the Liquid-Nylon interfaces, composite insulation systems utilising the PMMA polymer showed a clear sensitivity to the applied impulse rise-time; with the breakdown voltages seen to reduce for all liquid-PMMA samples as the impulse rise-time was increased (providing that surface flashover of the interface was the breakdown mechanism). Again, the highest levels of breakdown voltage were recorded for samples which experienced bulk breakdown of the polymer dielectric. When comparing like for like breakdowns for the two polymers, it can be said that the highest breakdown strength was observed for composite systems consisting of the Nylon polymer, though when accounting for standard deviation of the data, these cannot be thought of as exhibiting statistical significance. What is clear, however, is that the tested ester fluids offer comparable dielectric performance to the investigated mineral oil in all test cases; both when bulk breakdown of the polymer and interfacial flashover occur.

V. CONCLUSIONS

Results have been presented, and findings discussed, from breakdown experimentation performed on liquid-polymer interfaces formed from engineering polymers and dielectric fluids under testing conditions applicable to pulsed power apparatus. Dissimilarity in the behaviour of the interfaces has been observed, with those formed from a dielectric fluid and a nylon polymer seen to favour bulk polymer breakdown, irrespective of the applied impulse rise-time; while those using PMMA exhibit sensitivity to impulse rise-time. A clear downward trend in breakdown voltage of liquid-PMMA interfaces was observed as the rise-time of the applied impulses was increased; coupled with a reduced likelihood of polymer breakdown. No such trend appears in the data from Nylon tests; attributed to the wide variation in streamer propagation path when polymer breakdown occurs. It is evident from the experimental data provided that ester fluids behave comparably with transformer oil when in contact with both Nylon and PMMA polymers, however, the specific mechanisms responsible for variations in polymer behaviour require further investigation.

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