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ABSTRACT

Pulsed power engineers have used transformer oil as the high voltage insulator for their transmission line pulse forming networks since work initially began in this area in the 1950's. It exhibits good bulk breakdown properties and can recover its dielectric strength following catastrophic failure, although not as quickly as some gases. However when one of the driving design parameters for a pulsed power system is size, aiming for a compact, high energy density system the use of oil can limit the potential size reductions. Water has also been extensively used in such systems when transmission line length is important and the high relative permittivity can result in length reductions over oil by a factor of 4-5. However when another of the system requirements is high repetition rate the use of water is generally ruled out due to its polar properties leading to conduction under extended repetitive operation.

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Abstract

Pulsed power engineers have used transformer oil as the high voltage insulator for their transmission line pulse forming networks since work initially began in this area in the 1950's[1]. It exhibits good bulk breakdown properties and can recover its dielectric strength following catastrophic failure, although not as quickly as some gases[2]. However when one of the driving design parameters for a pulsed power system is size, aiming for a compact, high energy density system the use of oil can limit the potential size reductions. Water has also been extensively used in such systems when transmission line length is important and the high relative permittivity can result in length reductions over oil by a factor of 4-5. However when another of the system requirements is high repetition rate the use of water is generally ruled out due to is polar properties leading to conduction under extended repetitive operation. Solid insulation is generally considered to be non-recoverable in the event of dielectric breakdown, however there are pulsed power applications where its use is warranted. This can result in increased system capacitance with the possibility of operating at increased energy levels or reduced system volumes. Although capacitor manufacturers have employed these techniques successfully for a number of years[3] solid insulation failure under pulsed power conditions is not fully understood by the majority of system designers. This paper reports on the results of a recent test programme, the object of which was to investigate the material limits of solid dielectric insulation at potentials in excess of 100kV. This comparative study of various materials was not an attempt to optimise the material breakdown voltage but to make a direct sample comparison under identical, representative pulsed power conditions.

The electrical breakdown characteristics of various materials were studied using HV pulses which are representative of those generated in a typical high voltage transmission line system. The investigation was carried out for both dc and pulsed voltages, the latter operating at repetition rates of up to 100pps. The broad aims of this test programme were to compare the flashover and breakdown performance of different materials in air and in oil, to compare the voltage characteristics of insulating tubes and insulating films for different materials and to investigate the effect of repetitive operation and pulse charging upon solid insulation.

The breakdown voltage of PTFE, acrylic, Pyrex glass and polycarbonate tubes was measured and compared using a standard test arrangement. This enabled direct comparison to be made between the different materials. The flashover potential of these materials was also measured as a function of gap spacing in silicone oil and air. Breakdown tests were also carried out for tubes made from many layers of polypropylene and polyester films. These were wound under vacuum and impregnated with silicone oil to minimise trapped air effects. Electrostatic modelling of the test set up was also carried out to provide a more accurate value for the breakdown field[4].

Introduction

The high voltage flashover and bulk breakdown properties of various insulating materials have been investigated for both dc and pulsed voltages at repetition rates of up to 100pps. The tests were conducted for solid dielectric tubes (PTFE, acrylic, Pyrex glass and polycarbonate) and for tubes made from many layers of polypropylene and polyester film. The solid tubes are currently used in pulsed power transmission line systems however the potential increase in permissible E-field stress which the thin film option brought warranted its inclusion in this programme as a future material technology for this field. The thin film samples were wound round the former of a test jig to ensure compatibility with the solid tube tests. The films were wound under vacuum and impregnated with silicone oil to prevent air bubbles remaining in the test piece. A schematic of the test set up is depicted in Fig.6.

The surface flashover properties of insulating tubes is an important consideration in the engineering design of compact high voltage transmission line pulsers. Since repetitively rated Marx generators operate at voltages of ~40kV per stage, it is appropriate to consider insulator spacings required to withstand this potential. The present investigation was designed to compare the surface flashover voltage of insulating tubes in air, as a function of electrode separation and material. A ramped voltage waveform rising from 0V to 40kV in 4ms was applied to the test piece and a high voltage probe (1000:1) was used to monitor the test piece inter-electrode potential. The voltage would rise until either flashover occurred or the 40kV limit was reached.

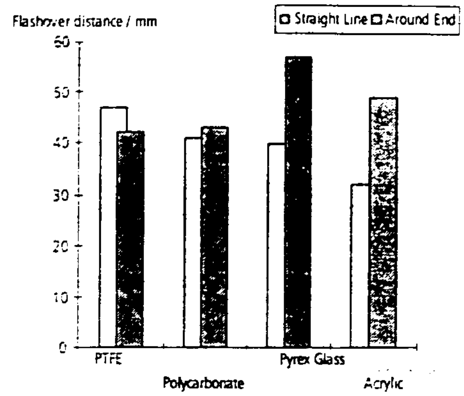
The HV electrodes were formed from the outer conducting sheath of semi rigid cable in order to minimise field distortion. The flashover voltage around the ends of the tube was measured for different materials and different path lengths to simulate the effect of flashover fins. The dc tests were only carried out up to 40kV whereas the impulse tests were carried out up to 160kV using a 10 stage Marx Generator.

Electrostatic modelling of the test set up was carried out using the Boundary Element Program Electro. This modelling showed an effective field enhancement of about 1.3, a value typical of pulsed power systems. This enhancement was consistent for all test pieces and therefore direct material comparison was valid. Such a field enhancement would have contributed to the measured breakdown values being significantly less that the quoted figures although applied waveform and material thickness would have a contributing effect.

Air Insulated Surface Flashover

The aim of this investigation was to evaluate which material resulted in the minimum distance required to prevent flashover of potentials up to 40kV. This measurement was carried out for both a linear flashover and also an "around end" flashover. Fins are often use to improve the surface flashover performance and therefore the 'around end' figure was measured to produce the effect of high voltage insulating fins on pulsed power systems. Fig.1 shows the electrode spacing required to insulate 40kV for both linear and simulated fin flashovers (around end). The shorter the column height the better the insulator performance.

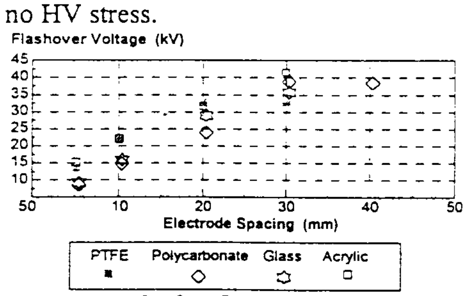
Acrylic seems the better material for a design with no fins, whereas PTFE seems the better material to use as an anti-flashover fin. Polycarbonate is a good compromise material in that it has a fairly consistent breakdown performance for both straight line and around edge flashover. The more detailed surface flashover results are shown in Fig.2 for the straight line flashover and in Fig.3 for the around edge flashover.



Electrode spacings required to hold off 40kV
Fig.1

Oil Insulated Surface Flashover

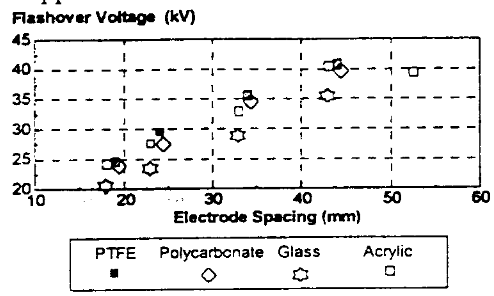
The air insulated flashover tests were then repeated under silicone oil insulation with a 10 stage Marx generator operating at 40kV per stage, shown in Fig.4, used as an impulse voltage source. The Marx generator was an ambient air insulated device capable of operating at repetition rates of up to 100pps. This repetitive operation was achieved by the use of a battery powered fan situated below the first stage of the generator. This enabled the hot, arced gas to be transported away from the inter electrode region between pulses, allowing the air to recover its dc breakdown voltage level. The voltage recovery of the gas was aided by the use of a capacitor charging power supply which could be inhibited between pulses, allowing the gas to recover for a period of a few ms with no HV stress.



Surface Flashover in Air
Fig.2

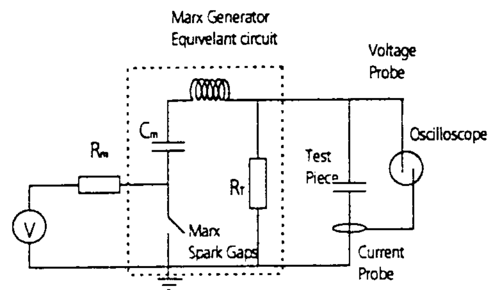
A current probe was used in the ground return to monitor the test piece flashover. At each electrode spacing, the Marx stage to which the high voltage electrode was connected was increased until flashover occurred. The electrodes used here were stainless steel Jubilee clips which enabled the separation to be accurately determined. Although these are far from being optimised electrodes, their profile is representative of that found in typical pulsed power transmission lines.

For each electrode separation, a clean, not previously discharged section of the tube's surface was used. This arrangement was also employed to measure the single shot and repetitive breakdown voltage of the various materials. The applied voltage was progressively increased until breakdown occurred with the repetitive tests being carried out over the range 10 to 100 pps for burst duration's of 1 to 5 seconds.



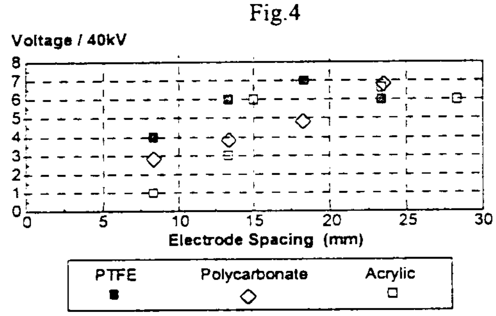
Around Tube End Flashover in Air

Fig.3



Surface flashover in oil & dielectric breakdown circuit

Fig.4



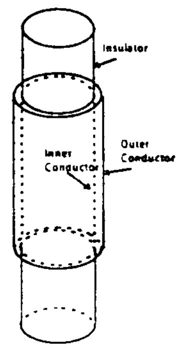
Surface Flashover in Oil

Fig. 5

The surface flashover results for the different materials are shown in Fig.5. For electrode spacings of less than 20mm, PTFE significantly outperformed the other materials. However for spacings in excess of 25mm all materials were found to posses similar flashover voltage levels.

Bulk Breakdown Measurements

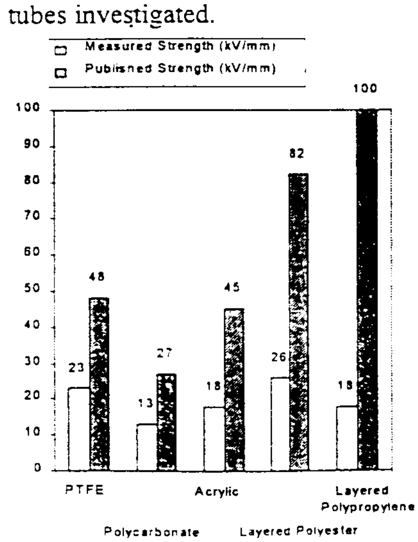
Each material sample was subjected to tests at voltage levels of 40kV, 80kV, 120kV and 160kV in turn using the surface flashover experimental set up. At each of these voltage levels, the samples were subjected to a single shot impulse, a burst of 10pps for 1 second, followed by 10pps for 5 seconds, 50pps for 1 second, 50pps for 5 seconds, 100pps for 1 second and 100pps for 5 seconds.



Test Jig for bulk breakdown material tests

Fig.6

The level at which solid dielectric breakdown occurred was noted and the tests repeated for 5 samples. The average results of the dielectric breakdown tests are shown in Fig.7 for the single impulse case and this is compared with published breakdown data for the different materials. The measured breakdown voltages are significantly lower than the published values. The thickness of the materials used in this study was in the range 3-4.2mm whilst standard breakdown data is quoted for much thinner materials (several mm) and should therefore not be used in a direct comparison. The general trend is however the same for the published figures and the results of this study. Fig.7 shows that PTFE has the highest bulk breakdown field followed by acrylic with polycarbonate exhibiting the lowest breakdown field of the three tubes investigated.



Comparison of measured and published dielectric intrinsic breakdown for test materials

Fig.7

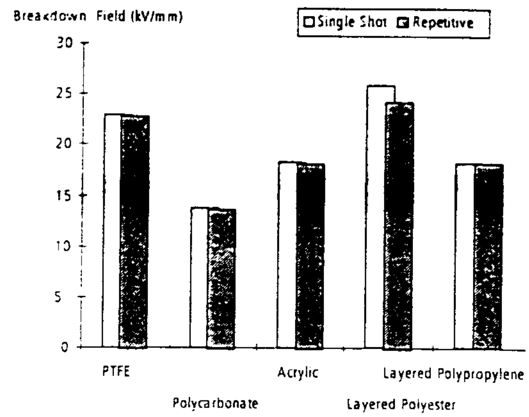
The results from the repetitive breakdown experiment are shown in Fig.8. The dielectric loss factor of the materials investigated being low enough to cause little thermal variation at repetition rates up to 100pps over a 5 second period. The results from the repetitive study revealed very little variation in the bulk breakdown data with that taken during the single shot measurements. The layered polyester sample failed at a slightly lower value under a 1 second, 10pps burst, this should be investigated in more detail to fully understand such differences. The overall test results suggest that at the repetition rates investigated little or no additional stress was placed on the materials which would have led to a reduction in bulk breakdown voltage.

Conclusions

No one material exhibits excellent linear flashover, "around end" flashover and dielectric breakdown properties. However Polycarbonate seems to be a good compromise material for flashover in air while PTFE exhibits the best properties under oil. PTFE and the layered polyester seem to have the highest dielectric breakdown strength of all the materials tested. The workhorse pulsed power material is acrylic and this represents a good compromise material if the user is unsure as to the specific voltage waveform and electrode geometry to be used. There seems to be little deviation between the repetitive and single shot failure at the repetition rates studied here. The dielectric loss factor is not great enough to result in significant thermal variation at 100pps for a 5 second burst although this may be a concern at higher prf's. A more stringent repetitive testing of these materials could be carried out for higher pulsed repetition rates (100-1000pps) and longer burst duration's.

The greatest discrepancy between the measured and the quoted figures was for the polyester and polypropylene film. The measured breakdown voltage of about 30% of the expected value suggests that the preparation and storage of such materials is critical to achieving best performance. Although these samples failed at a significantly lower level than had been predicted, the failure E-field for these materials was slightly higher that for the solid dielectric tubes. This suggests that with careful and optimised fabrication and packaging this route would give the optimum energy density for high voltage pulsed power transmission lines.

The repetitive tests were not carried out for Pyrex glass due to its poor (and catastrophic) performance during the flashover testing. Although this material was initially chosen due to its potential for fabrication into complex geometries, it was felt that its tendency to shatter even under flashover conditions made it a potentially dangerous choice which could have serious design implications to any transmission line system. If used at E-fields significantly below the failure threshold it may have limited applications.



Repetitive Dielectric Breakdown Results
Fig.8

The packaging and handling of insulating materials is important and it may be that the handling procedures employed in the manufacture of high voltage capacitors will have to be adopted in order to minimise poor flashover performance through contamination.

The surface and bulk breakdown properties of other materials such as Alumina and other high value permittivity materials requires to be investigated for potential high capacitance, low frequency transmission line systems. They were not considered for this programme due to the shortening effect of the relative permittivity on the transmission line length. Extensive electrostatic modelling of such systems would also be required due to the field compression experienced in high ε_r materials. This may enhance high field stress at the system triple points.

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