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Improved Core Insulation Schemes for Multi-Terawatt Magnetic Switches

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Abstract

The operation of multi-terawatt magnetic switches was successfully demonstrated in the CometII pulsed power module in 1984. Those switches, however, had short lifetimes (< 100 shots) due to inter-lamina dielectric breakdowns at electric-field levels far lower than expected. Since then, experiments have been conducted to gain an understanding of this problem.

We found that the breakdowns occurred at low electric-field levels, because the thin dielectric film (Mylar) was abrasively degraded by the relatively rough surface of the magnetic tape (Metglas) during the core winding process. This problem can be solved by modifying the Metglas surface before winding. A factor of 2 improvement in breakdown level, from .8 MV/cm to 1.6 MV/cm, has been demonstrated on the MSTF module (a Marx driven, 500 kV, 2 Ω, 50 ns PFN) in 18" OD switches wound with Electrodag coated Metglas (nominal coating thickness ~ 6 μm). Even better performance has been achieved in smaller scale tests with an electrophoretically applied plastic-coated Metglas. A description of these experiments and a discussion of the results will be presented.

Introduction

The large multi-megavolt, multi-terawatt, pulsed power modules which were developed for the Particle Beam Fusion program at Sandia National Laboratories (SNL) presently use self-closing water switches in the final stages of pulse compression. These switches produce damaging shock waves upon closure and, when operated with the large gaps that are required at high voltages, become significant sources of timing jitter. In the next generation machine, modules with higher reliability, reduced jitter, faster shot repetition rate, and, possibly, pulse shaping capability will be required. To accomplish this, improved water switches must be developed or alternatives must be found.

One possible alternative is the magnetic switch (ie. saturable reactor) which because of its passive nature of operation, has the potential of being a very reliable, low jitter, repetitive switch. In a magnetic switch, pulse compression is accomplished by using the non-linear magnetic properties of ferrimagnetic or ferromagnetic materials in a way which is described in detail in the literature [1]. Briefly, the switch is a nonlinear inductor whose inductance is very high in the open state while the switch's magnetic core is unsaturated. When the core saturates, the switch inductance drops by 2-3 orders of magnitude, and the switch enters its closed state. In an application such as the one described above, the best suited magnetic materials are the amorphous magnetic alloys (Metglas) because of their low eddy current losses at high frequencies and large ΔB swings [2]. Magnetic switches which use Metglas are constructed in a tape wound geometry because of the way Metglas is manufactured (cast in tape form). In any magnetic switch it is desirable to minimize the thickness of the inter-lamina insulation to enhance the performance of the switch (ie. reduce the saturated inductance).

Magnetic switches have been reliably used in many sub-TW peak power, repetitive modules [3,4]. In addition, the feasibility of using magnetic switches for pulse compression in a large pulsed power module was demonstrated on the CometII module where a 2.7 MV, 3.7 TW, 35 ns pulse was delivered to a 2 Ω matched load [5]. However, the Comet switches had unacceptably short lifetimes (< 100 shots). The first Comet switch that failed, MS2A, was constructed in a tape-wound geometry with ~ 10,000 spiral windings of 25 μm Metglas 2605SC and 2 layers of 6 μm Mylar insulation. It had a volt-sec product of .054, had 720 kg of Metglas, was 1.7 m in diameter and was vacuum impregnated with Fluorinert FC-77. The switch failure was characterized by multiple (> 10,000) inter-lamina dielectric breakdowns uniformly distributed throughout the core. At peak voltage, the estimated average inter-lamina electric field in the core was 237 kV/cm which was an order of magnitude below the expected breakdown field of the insulation.

In preliminary investigations of this problem [6], we found that the dielectric strengths of thin insulating films (< 25 μm thick) are significantly degraded when the film is wound against the relatively rough surface of Metglas. For example, in Fig. 1A the DC breakdown distribution of 27 tape wound, 2.54 cm ID, .2 μF capacitors with Metglas conductors and 2 layers of 6 μm Mylar insulation is shown. The mean DC breakdown field (E_b) was 1.6 MV/cm, the standard deviation (σ) was 56%, and 20% of the samples were shorted during the winding process. In contrast, the breakdown distribution of a similar set of 20 capacitors with aluminum conductors, shown in Fig. 1B, had a mean of 4.27 MV/cm, a σ of 19%, and no winding shorts. Our subsequent investigations, which are described in this report, have been directed at obtaining a better understanding of the film degradation and finding ways to prevent it. These investigations have included three types of experiments: (1) unwound insulation experiments which were designed to gain a better understanding of the degradation mechanism, (2) coating experiments which were designed to test solutions to the problem in capacitors on a small scale, and (3) core experiments which were designed to test solutions in a magnetic switch environment on a moderate scale.

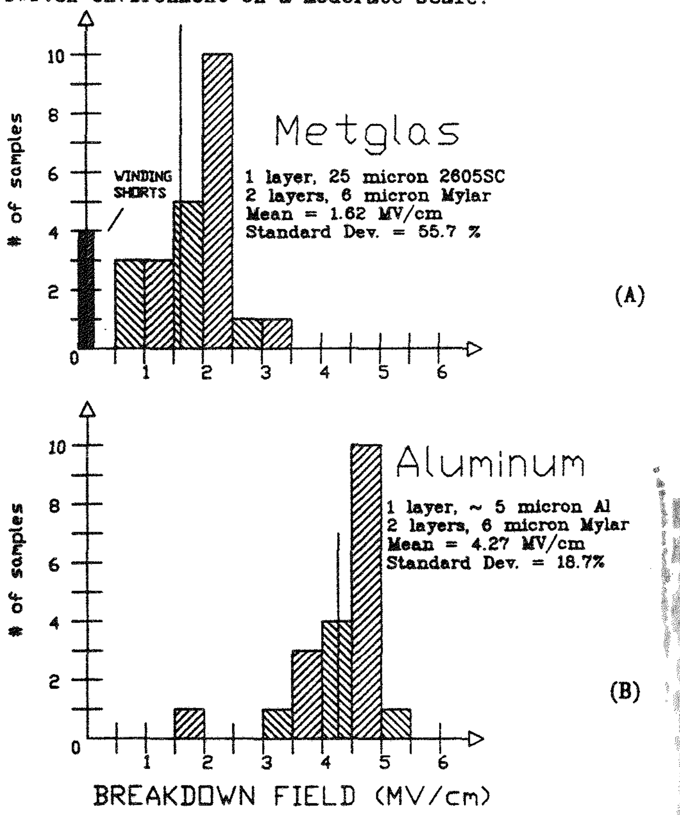


Fig. 1. Breakdown distributions for wound capacitors

Unwound Insulation Experiments

This degradation in dielectric field strength was observed in capacitors in a wound geometry with Metglas conductors. It seemed plausible to attribute the degradation to the surface roughness of Metglas, however, there was still some question about the role of the geometry. If the degradation was primarily due to an electrostatic field enhancement about the sharp protrusions on the Metglas surface, then the geometry should have little effect. If, however, the degradation was primarily due to abrasion (tearing, puncturing, etc.) of the film during the winding process when it slides over the Metglas surface, then the geometry should have a significant effect. To answer this question, a series of tests were performed in unwound geometries (point to plane and parallel plate) on several types of thin insulations with Metglas and aluminum (for a reference) conductors. The experimental arrangements for these tests are shown in Fig. 2. All tests were conducted in a Fluorinert bath. Early in the testing we observed that it was necessary to take great care during the assembly of a test sample to ensure that there was no slippage between layers. If any slippage was detected, the probability of having a shorted sample was > 50%. Consequently, special fixtures were constructed to eliminate the possibility of slippage.

It was also necessary to do the parallel plate tests with a 5 μs rise, 10 μs fall applied voltage pulse rather than DC to avoid applying excessive pressure to the dielectric. The pressure due to the electostatic attraction between the plates of a parallel plate capacitor scales with the applied voltage squared and at 1000 V with a separation of 12 μm, it is ~ 30 PSI. In a parallel plate capacitor with aluminum conductors, this pressure reduces the mean DC failure voltage of a 12 μm Mylar dielectric from its normal level of 5 kV to ~ 2 kV. With Metglas conductors the pressure effect is a bit more severe.

With the special fixtures and the pulsed voltage for the parallel plate test, there was no significant difference in performance between samples with Metglas conductors and those with the reference aluminum conductors. For example, in Fig. 3 the pulsed breakdown distributions from the parallel plate tests on samples with 2 layers of 6 μm Mylar insulation are shown. The mean pulsed breakdown field (E_p) of 10 samples with Metglas conductors (Fig. 3A) was 4900 kV/cm with a σ of 11%. The E_p for 10 samples with aluminum conductors (Fig. 3B) was 4760 kV/cm with a σ of 7%. The results from all of the point to plane and parallel plate tests are summarised in Table I. The lack of any noticeable degradation in the Metglas samples implies that there is no significant insulation degradation caused by field enhancement about surface protrusions. Consequently, these results, along with the qualitative observation concerning slippage during sample assembly, are strong indications that the insulation is primarily degraded mechanically during the winding process.

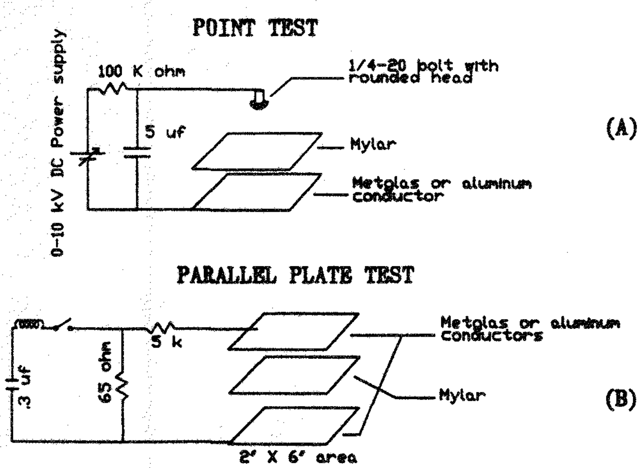


Fig. 2. Test setups in unwound geometries.

Coating Experiments

Once the winding process was identified as a problem area, a series of experiments directed at improving the winding process were conducted. These included; wet winding with Flourinert, removal of all nonessential rollers on the winding machine, winding tension minimization, among others. With these techniques, only minor improvements of 20-30% were achieved. This test series indicated that greater improvements would probably only be achieved by modifying the Metglas surface so that it would be less abrasive to thin dielectric films during the winding process. One way to do this would be to planarize the Metglas surface by applying a coating (ie. fill in the valleys with a coating). The resulting smooth surface might then allow thin dielectric films to be wound with Metglas without degradation. In order to test this

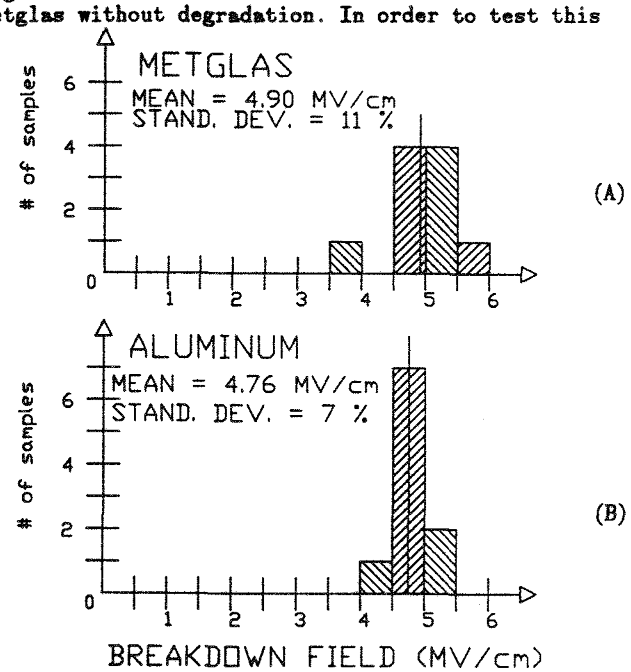


Fig. 3. Breakdown distributions for parallel plate capacitors with 2 layer 6 μm Mylar insulation.

TEST TYPE	CONDUCTOR TYPE	DIELECTRIC TYPE # of layers / layer thick. , TYPE	MEAN BREAKDOWN FIELD (Mv/cm)	STANDARD DEVIATION (%)
pt	AL	2 / 6 μm , MY	4.45	25
	MET shinny		3.84	21
	MET dull		3.73	23
	AL	1 / 10 μm , MY	3.67	44
	MET shinny		5.09	19
	MET dull		3.60	41
	AL	1 / 12 μm , PC	4.11	34
	MET shinny		2.34	64
	MET dull		3.91	39
	AL	1 / 12 μm , K	3.73	29
	MET shinny		3.99	17
	MET dull		3.65	18
par	AL	2 / 6 μm , MY	4.76	7
	MET		4.91	11
	AL	1 / 10 μm , MY	4.82	12
	MET		5.55	4
	MET	1 / 23 μm , MY	3.67	12

Table I. Results from tests in unwound geometries (MY=Mylar, PC=Polycarbonate, K=Kapton).

idea, we adapted a small transfer winding machine, as shown in Fig. 4, to dip coat Electrodag 154 (solution similar to Aerodag) onto Metglas. Electrodag was selected for this initial coating experiment primarily for convenience. A SEM photograph of a typical location on an electrodag coated Metglas sample, shown in Fig. 5A, reveals that, even though the coated surface appears rough, the largest protrusions from bare Metglas (pips) are well masked. A SEM photograph of a typical pip on the surface of bare Metglas is shown in Fig. 5B. Pips are the result of small indentations that develop in the casting wheel during the manufacture of Metglas. As these indentations erode during the casting process, correspondingly larger mirror image protrusions result on the casting wheel side (dull) of the Metglas ribbon. Pips range in size from insignificant to > 20 μm in height depending on how far into a run the Metglas was cast.

With the coated Metglas, 1" ID, .2 μF capacitors were wound with 12 μm thick Mylar insulators and a DC breakdown distribution was obtained. The results of this 14 sample test series are shown in Fig. 6. The E_b was 4570 kV/cm and the σ was 20%. The improvement in E_b over the best comparable uncoated Metglas conductor capacitors was 71%, there were no dropouts and the breakdown distribution was very much like the comparable aluminum conductor capacitor distribution shown in Fig. 1B (E_b=4270 kV/cm and σ=19%). With the coating, a 12 μm Mylar dielectric can be wound with Metglas with no significant degradation.

To determine the relative importance of coating composition versus coating surface quality, the next coating type that was tested was an electrophoretically applied plastic coating. In the electrophoretic coating process [7], a small DC bias voltage is used to control the deposition rate in a manner analogous to electroplating. After application, the coating must be cured in an oven at ~ 200 C for about 20 minutes. In order to produce sufficient quantities for testing, the electrodag coating machine of Fig. 4 was modified slightly. With this machine, a thin coating (nominal thickness ~ 6 μm) was applied to field annealed 2605CO Metglas at a rate of ~ 10 m/hour. Nine capacitors with 12 μm Mylar insulators were then wound and tested. The resulting DC breakdown distribution, shown in Fig. 7, has a σ of 5% and an estimated E_b of 4000 kV/cm. The breakdown field could only be estimated because the dielectric thickness in the capacitors was not spatially constant. With the nominal 6 μm thick coating, the largest pips on the Metglas surface and the Metglas edges were not completely covered. In these areas, the nominal dielectric thickness would be ~18 μm if one assumes that uncovered areas on adjacent conductors did not align. For lack anything better, it was this, somewhat arbitrary, value for dielectric thickness that was used to estimate the breakdown fields. However, even with the uncertainty in E_b, the tightness of this distribution shows that the Mylar insulation was not degraded during the winding process. In addition, a postmortem on the capacitors revealed that all breakdowns occurred on a conductor edge, which is the typical failure mode for aluminum conductor capacitors. All previous tests with Metglas conductor capacitors had demonstrated randomly distributed breakdown sites without preference for edges. The surface quality of Metglas with this coating is so good that a SEM photograph of a typical location, shown in Fig. 8, reveals virtually no surface features. This seems to indicate that the surface quality of a coating on Metglas is more important than the composition of the coating. With a high quality coating like the Electrophoretically applied plastic, the performance of test capacitors with Metglas conductors is essentially indistinguishable from comparable capacitors with aluminum conductors.

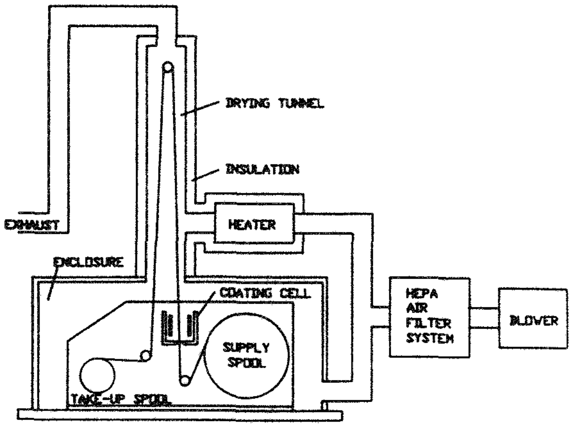
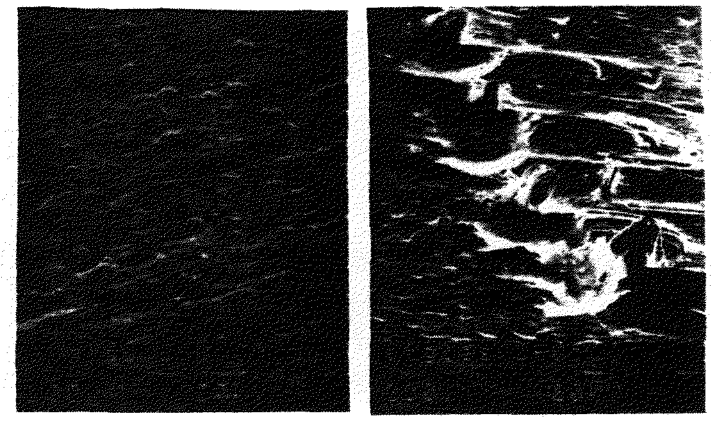


Fig. 4. Coating machine setup.



(A) (B)

Fig. 5. SEM photographs of (A) dull side of electrodag coated Metglas and (B) Pip on the dull side of bare Metglas.

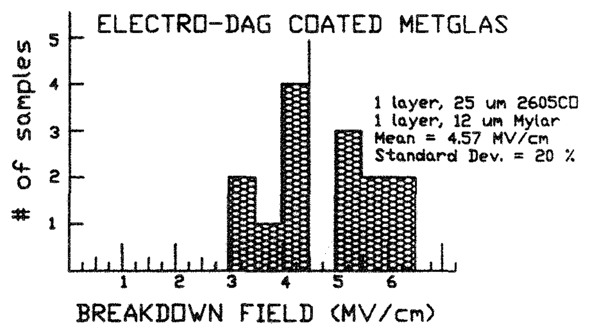


Fig. 6. Breakdown distribution for wound capacitors with electrodag coated Metglas.

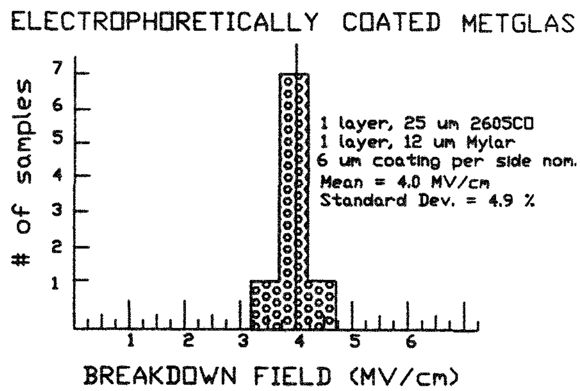


Fig. 7. Breakdown distribution for wound capacitors with electrophoretically coated Metglas.

Core Experiments

To assess the scalability of the improvements observed in CBT tests, 2 magnetic switches wound with electrodag coated Metglas and a single layer 12 μm Mylar insulation were tested on the magnetic switch test facility (MSTF). Unfortunately, it was impractical to produce enough plastic coated Metglas on the small coating machine for such a test. MSTF was constructed to duplicate, on a smaller scale, the switch-core conditions that existed in the Comet switch, MS2A. It consists of a 1 MV Marx which drives a coaxial, 2 Ω, water dielectric PFN, as shown in Fig. 9 , and can deliver a 500 kV, 50 ns pulse to a matched load. The switches tested in MSTF were 43.4 cm ID, ~45.7 cm OD, 10 cm wide, and vacuum impregnated with Flourinert FC-77. The testing procedure was as follows. An operating point well below the expected breakdown field of the switch was selected, and a series of 25 shots was taken at that point. If the switch did not fail, a new operating point at slightly higher fields was selected, and another series of shots was taken. This process was repeated until the switch failed or until the limits of MSTF were reached. The switches wound with electrodag coated Metglas both failed after 150+ shots at ~ 1600 kV/cm; by far the highest level ever achieved in MSTF tests. For comparison, the failure levels of all the switches with 12 μm of Mylar insulation that have been tested on MSTF are plotted in Fig. 10. The mean failure level for uncoated switches (circles) was ~ 800 kV/cm with a σ of 17% and the highest failure level that had been observed was 1100 kV/cm. The coated switch data points (squares) are 6 standard deviations above the mean for the uncoated switches and, thus, represent a significant advance.

Conclusions

The breakdown strengths of thin dielectric films are significantly degraded when wound against the rough surface of Metglas. The degradation occurs during the winding process and can only be prevented by modifying the Metglas surface prior to winding, so that the thin insulating film does not see the rough Metglas surface. With two coating techniques, we have been successful in planarizing the rough Metglas surface and trading a little in packing factor for improved breakdown characteristics. The composition of the coating is not as important as the surface quality of the resulting coated surface. The value of these techniques in achieving improved breakdown performance in full size magnetic switches needs to be demonstrated, but the cause of the low level failures of the CometII magnetic switches and possible solutions have been identified.

Fig. 8. SEM photograph of the dull side of electrophoretically coated Metglas.

Acknowlegments

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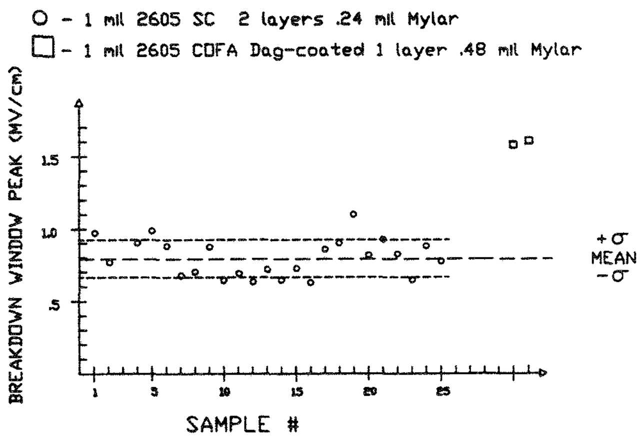

Fig. 10. Pulsed breakdown on MSTF magnetic switches.

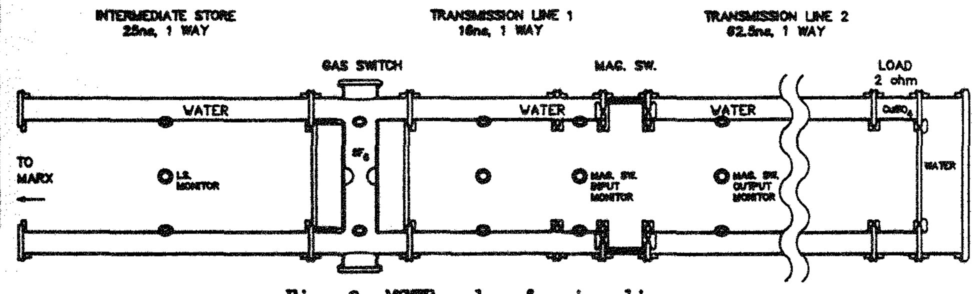

Fig. 9. MSTF pulse forming line.