High Strain Insulation Systems for Compulsator Rotors

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Abstract - As the power density requirement for new compulsator (CPA) designs increases, designers are driven to use more composites to reduce mass, spin the rotors faster to store more energy, and operate the machine at higher voltages to increase machine power output. In any particular compulsator design, the rotor windings are subjected to high strain levels as the rotor is spun and experiences radial growth. A critical component in the rotor winding design is the high voltage insulation. As the rotor is spun, the induced strains are applied to the insulation system on the coil conductors. This implies that over the operating life of a compulsator, the coil structure and the high voltage insulation must remain structurally intact, while undergoing repeated cyclic loading.

This paper presents the design and testing of a compulsator rotor winding that has been recently fabricated at the Center for Electromechanics at The University of Texas at Austin. The paper focuses on the testing done both at room and elevated temperature to evaluate the winding structure and high voltage insulation system under both tensile and transverse strain conditions. Data presented suggests a factor of safety of at least five for strain to failure values and high voltage insulation good for at least twice line voltage after testing to strain failure.

INTRODUCTION

In general, potential military uses require that proven compulsator (CPA) technology be taken to higher performance levels. To make these pulse power units attractive, their power density must be increased from present performance levels. Essential parameters that must be addressed to increase CPA power density are the rotor tip speed, operating voltages, and excitation flux density. Recent advances in composite technology combined with high strength titanium and aluminum alloys have allowed designers to reduce CPA mass [1], [4]. Increasing tip speed, making the machine lighter, generating higher voltages, and reducing losses are all relatively easy when viewed individually, but together these parameters have a unique relationship that must be balanced carefully.

For this paper, the authors will limit discussions on machine mass to the rotor only. Reducing rotor mass means the rotor must be spun to higher tip speeds to store the same initial kinetic energy. Spinning the rotor faster means the electric coil on the rotor (whether it be the field coil or armature) is subjected to higher strain fields during operation. These strain fields are seen in two different areas in a coil mounted to a spinning rotor. The coil can be represented with active turn regions that run parallel to the machine axis and end turn regions that join active turn segments. Spinning such a coil will induce hoop strain transverse to the coil conductors in the active region and tensile strain parallel to the conductors in the end turn regions.

The main area of concern involves the strain seen in the gaps between coil conductors. Typical high voltage coils mounted to a rotor consist of tightly packed conductors separated with an insulation layer and some type of E-glass reinforcing overwrap. The coil is fully assembled and insulated, wrapped with glass, and then vacuum pressure impregnated with an epoxy. Any induced strain on the coil distributes itself inversely proportional to the different moduli of the materials. The higher modulus conductors see less strain while the lower modulus insulation and epoxy/glass matrix between conductors sees the bulk of the strain. Excessive strain in the epoxy/glass matrix between conductors may start to form small cracks or "crazing" that can propagate through insulation layers and eventually cause a voltage breakdown. One easy way to reduce the strain seen in the gaps between conductors is by enlarging the gap between conductors. Larger gaps between conductors are also attractive due to higher generated voltages desired in high performance CPAs, thus allowing more insulation between conductors. However, to maximize energy storage and minimize resistive losses in the coil, the conductor cross section must be maximized. Small changes in conductor cross section (A) can have significant effects on conductor heating, which scales with $1/A^2$. With present material technology, the insulation and epoxy/glass matrix between conductors have an upper temperature limit of 90˚C.

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With limits on conductor heating and strict requirements on generator output, the relationship between rotor speed, induced strains, generated voltages, insulation requirements, gap size, and conductor heating define the scope of the problem for a designer.

The remainder of this paper will focus on a point design with defined parameters for gap width, voltage holdoff, and both transverse and tensile strain limits. An extensive analytical and experimental test program was completed to evaluate insulation and reinforcing systems to achieve required insulation and strain levels. The data from this test program and associated results and conclusions are presented.

COIL DESIGN PARAMETERS

Past experience with high voltage insulation systems at the University of Texas Center for Electromechanics (UT-CEM) had proven that a multi-layered approach, each layer capable of holding full design voltage, was a safe design approach. If any one layer is violated due to a manufacturing imperfection or damaged during high voltage operation, there is a backup layer to provide insulation.

The first insulation layer to be applied to this rotor coil was Limitrak®. Limitrak® (a Westinghouse trademark product) is a semi-conducting enamel coating used to smooth electric field concentrations caused by small imperfections on the surface of a high voltage conductor. Smoothing electric fields in a high voltage system will lengthen the cycle life of an insulation system [2].

In this design, the Limitrak® layer was not considered a part of the primary insulation system. An extensive product search was done to investigate possible insulating coatings that could be applied to this particular rotor geometry which were relatively tough and durable, and that could hold off the required voltage. The original insulation scheme involved the thin Limitrak® layer and then a thin insulation coating. Following the thin coating would be a single half-lap wrap with polytetrafluoroethylene (Ptfe or Teflon®) tape. The Teflon® tape provides a good insulation layer with demonstrated dielectric strength at 2,000 V/mil, and its 300% elongation at failure provides an excellent barrier to prevent the propagation of cracks should any form in the gaps between conductors. Then a final layer was composed of some type of glass tape overwrap.

The type of glass tape and the exact amount to wrap around each conductor was determined to be an important parameter in the coil design. The glass wrap reinforcement was used for several reasons. First, the glass acts as a filler to provide the proper spacing between conductors in the coil during assembly. Second, the glass acts as reinforcing member when the coil is potted with epoxy. The presence of the glass greatly increases the mechanical properties of the epoxy filler and the glass also helps to inhibit the formation and propagation of cracks in the cured epoxy. A DOW® epoxy system used on these coils has a strain to failure limit of approximately 4% when cured with no reinforcement. However, past experience with this epoxy at UT-CEM has shown it is prone to crack formation and propagation without the presence of glass reinforcement. With the goal of increasing the strain capabilities of the potted coil structure, it was proposed that a reduced glass content in the coil would raise the strain to failure limit in the coil to levels closer to that of raw neat epoxy.

An extensive product search was performed to identify one or more candidate insulation films that could be applied to the coil. After reviewing numerous products and evaluating such parameters as dielectric strength, maximum operating temperature, toughness, and application method, the only acceptable thin film coating found was parylene [3]. Parylene is a polymeric conformal coating that is applied under vacuum to provide a very thin and uniform insulation layer. Parylene's excellent dielectric strength and ability to be applied in a pinhole and stress free manner make it a very attractive insulating layer.

TEST SAMPLE DESIGN

It was obvious at this point during the coil design phase that, with the unfamiliar parylene coating, the secondary Teflon® layer, and the unknown relationship between glass content and strain to failure limits in the conductor gap, a set of test samples had to be designed to experimentally verify the strain capabilities of any proposed insulation and reinforcing designs. Custom Analytical Engineering Solutions Inc. (CAES) provided consultation on the design of these test samples. The goal was to design a tensile sample to represent the longitudinal strain parallel to the conductors in the coil end turns and a transverse sample to represent the transverse "hoop" strain perpendicular to the conductors in the active turn regions.

The longitudinal sample design (Fig. 1) utilized two 6061-T6 aluminum test specimens individually wrapped with candidate insulation and reinforcing schemes. The 2.54 cm (1 in.) long gauge section in the middle of the sample was sized to represent the actual conductor size. These wrapped samples were then mounted in a potting mold with the representative gap between aluminum pieces and then potted with epoxy to form a monolithic test sample. The holes in the aluminum bars were for attaching a pulling fixture to apply the tensile load. The reduced area gauge section was designed to strain first as the test piece was loaded. The test piece was designed to have a very small strain gauge mounted along the midplane of the gap between the conductors in the gauge section.

The transverse sample (Fig. 2) utilized two similar aluminum bars to represent the coil conductors. These bars had two deep grooves cut into their back sides to minimize edge effects and better define a gauge section in the middle of the bars. As with the tensile test samples, the transverse samples had the candidate insulation systems applied and then were placed in a potting mold. The samples were then potted with epoxy. Because there was no apparent way to accurately measure the actual strain in the gap between aluminum bars while under load, small strain gauges were mounted along the midplane of the gap between conductors in the gauge section. It became apparent at this time that a finite element model of the

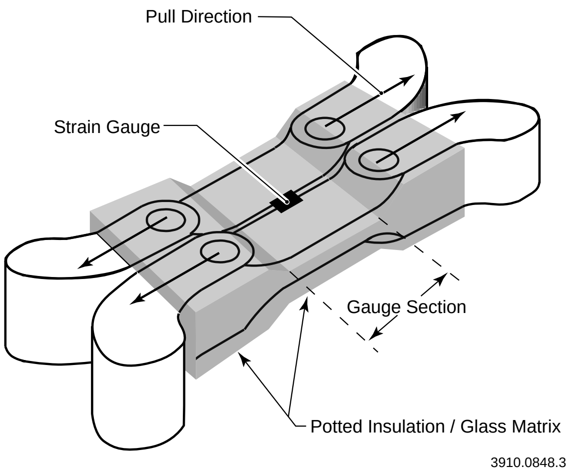

Fig. 1. Longitudinal (end turn) test specimen.

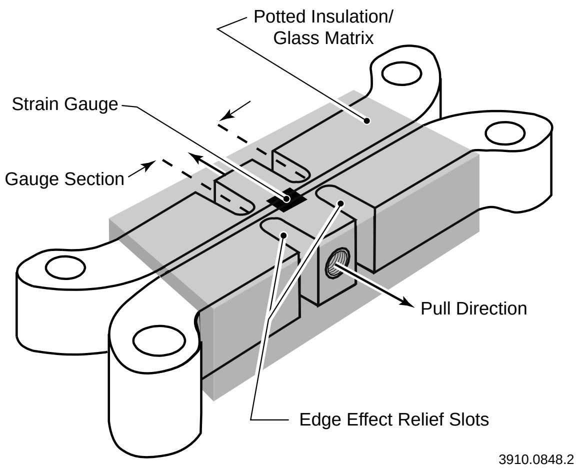

Fig. 2. Transverse (hoop) test specimen.

transverse test specimen would be required to establish a relationship between strain measured at the "free" edge of the sample and the actual strain in the gap between conductors.

FINITE ELEMENT MODEL

The goal of the finite element model and the analysis was to obtain an accurate correlation between the strain measurement at the free surface of the sample and the induced transverse strain in the gap between conductors. The significance of this analysis focused on the primary intent of the transverse test, which was to establish the strain capabilities of the conductor/insulation system as it is configured for the field coil design. However, the complexity of the insulation system, which utilizes highly compliant materials, results in a severe strain gradient from the middle of the gap to the free edge. Therefore, to establish a level of confidence in the allowable transverse strains deduced from the transverse samples, it was imperative that a model reflect an appropriate representation of the complex interaction between various material components of the test specimen.

Two finite element models (Figs. 3 and 4) were used to evaluate the tensile specimen. The model in Fig. 3 represents a cross section through the thickness and across the width of the specimen, while the longitudinal model in Fig. 4 reflects a cross section along the length and through the thickness of the specimen. The specimen geometry inherently has two planes of symmetry, lending itself to limiting model size by focusing on one quarter of the specimen. For rapid analysis, a plane stress model was incorporated in lieu of a full three-dimensional model. This simplification was justified on the basis of analysis conducted using the plane stress model representing the longitudinal section of the specimen. Results from the longitudinal model indicated that approximately 90% of the total load applied to the specimen was induced as a normal stress in the 1 in. gauge section. By limiting the longitudinal depth of the cross-sectional plane stress model to one-half the gauge length, the induced normal stresses in the gap region would be conservatively higher than that in the actual specimen tested.

The models embody all major components of the transverse test specimen including the conductor, Limitrak®, Teflon®, E-glass overwrap, the triangular resin pocket formed at the free edge in the gap region, and the additional thin ply of glass cloth to prevent cracking under the strain gauge. Experience from numerous correlations between analytical results and measured data provides confidence that an accurate material representation of the potted glass layers was achievable in the model. However, the material properties for the Limitrak®/Teflon® system were not accurately known. Consequently, the methodology established for conducting the analysis began with an investigation to determine appropriate material stiffness to be used for Teflon®. Given that the applied load and the measured strain at the free edge of the specimen represented actual data, it was reasoned that for a given load applied to the model the appropriate stiffness selected for the Limitrak®/Teflon® layers should result in a match between the predicted and measured strain at the free edge. Results of the investigation indicated that the effective modulus resulting in a correlation between predicted and measured strain at the free edge was 13.8 MPa (20,000 psi) for the Teflon®. This correlation resulted in a predicted value of strain of 6% in the gap, which is five times the average strain value (1.2%) measured at the free edge. With a predicted strain of 1.0% in the gap between conductors during a 5% overspeed condition, the transverse samples tested to date show a comfortable factor of safety for strain to failure.

INSULATION AND GLASS WRAP SELECTION

A set of transverse test samples was defined to experimentally evaluate the strain to failure limits with different combi-

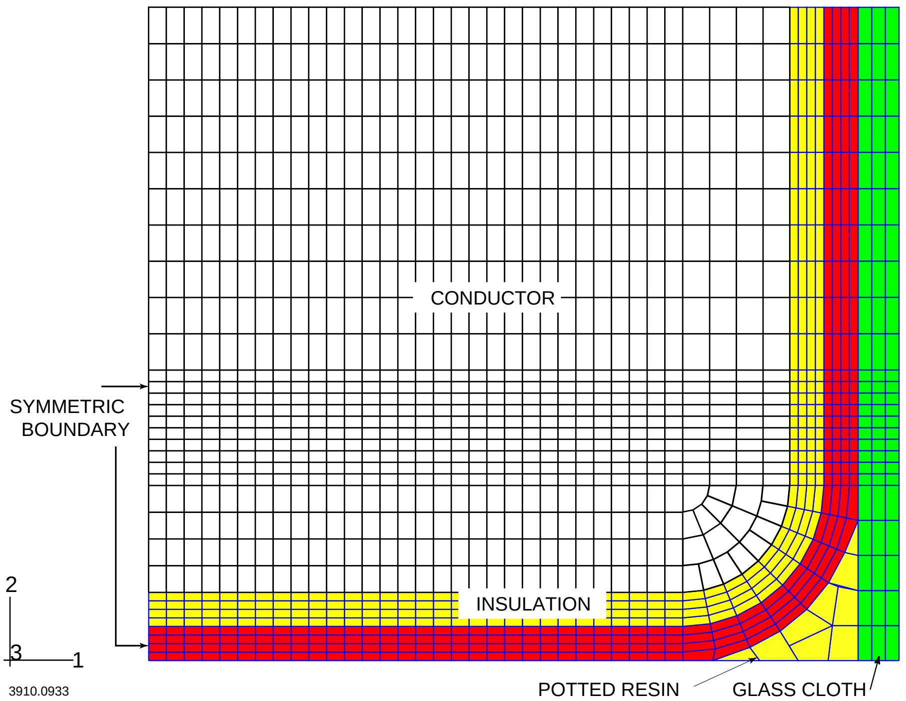

Fig. 3. Plane stress cross-section model.

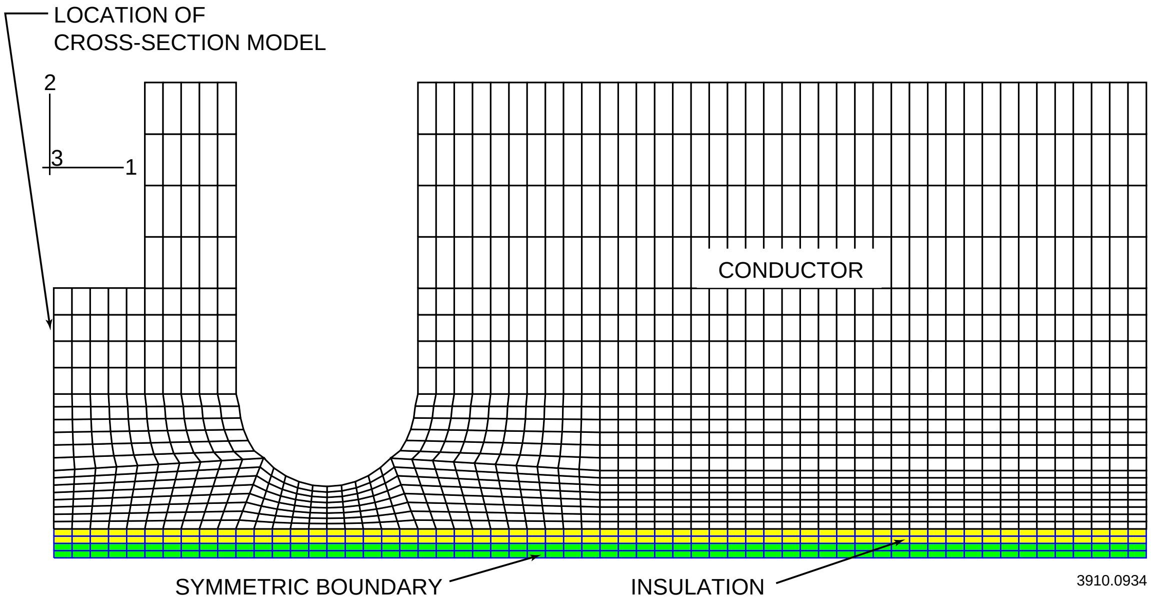

Fig. 4. Plane stress longitudinal model.

nations of insulation and glass wrappings on the conductors. All samples were to have a layer of Limitrak® applied. The parylene insulation coating was included in this initial set of tests because of its excellent dielectric and mechanical properties. One set of samples was coated with a 0.004 in. thick layer of parylene and a single half lap wrap of Teflon® tape. At this point in the test program there was some uncertainty concerning the feasibility of coating this particular coil design with parylene. The remaining three sets of transverse samples had an additional half lap wrap of Teflon® applied to substitute for the parylene layer.

Three types of E-glass tape were identified as potential reinforcing wrap around the conductors. The first glass candidate, which has been widely used at UT-CEM in the past, was a 58-36A plain weave E-glass tape with a $170 g/m^2$ weight. The second glass candidate was a BGF-1659 Leno weave scrim tape with a $54.4 g/m^2$ weight. An extensive search was conducted to find an additional 2.54 cm (1 in.) wide E-glass tape with a weight between the first two E-glass candidates. This mid-range weight was desired to test the percent glass content versus allowable strain. Only one tape, Mutual Industries C-150 E-glass tape with a $136 g/m^2$ weight was found. To get a true comparison with the different glass candidates, the three different glass wraps were applied to the samples with the double Teflon® layers.

The transverse samples were pulled on an Instron tensile tester. A digital storage scope was used to simultaneously record the applied load and measured strain. The Instron machine was configured to pull with a constant displacement of 0.001cm/s (0.0004 in./s). This displacement rate resulted in a time to peak strain of two to three minutes, which closely matches the strain rate to which the actual coil was to be subjected. Failure for these samples was defined as when the applied load was no longer linear with applied strain.

Table 1 shows the strain to failure data for the first set of transverse test samples, four samples of each type. The free edge strain is the strain measured by the strain gauge mounted on the surface of the sample. The gap strain is scaled by a factor of five based upon the previously discussed finite element analysis (FEA) done by CAES.

All these samples were successfully dc hi-potted after being pulled to failure. With the schedule constraints of applying parylene to the actual coil geometry and the excellent results from the other candidate systems, the preliminary selection for the coil design was the two layers of Teflon® wrap with the C-150 E-glass overwrap.

Expanded Data on Chosen System

After selecting the insulation and reinforcing system to be use on the coil, another set of transverse tests was conducted to further qualify the systems strain to failure limits. Additional strain to failure tests were done at room temperature as well as at elevated temperature. Table 2 shows the expanded strain to failure data for the transverse samples. The fifteen transverse samples in the second set were successfully dc hi-potted after being pulled to failure.

Table 1. First set of transverse data.

Wrapping Scheme	Measured Free Edge Strain (%)	Gap Strain (%) Based on FEA
Limitrak® 2 half-lap wraps of Teflon® 58-36A E-glass	1.25	6.25
	1.28	6.40
	0.98	4.90
	1.60	8.00
Limitrak® 2 half-lap wraps of Teflon® C-150 E-glass	1.38	6.90
	1.08	5.40
	1.14	5.70
	1.26	6.30
Limitrak® 2 half-lap wraps of Teflon® BGF 1659 Scrim	1.02	5.10
	0.70	3.50
	0.50	2.50
	0.40	2.00
Limitrak® Parylene Teflon® 58-36A E-glass	1.14	5.70
	1.34	6.70
	1.14	5.70
	1.50	7.50

Table 2. Second set of transverse data.

Sample	Measured Free Edge Strain (%)	Gap Strain (%) Based on FEA
Room Temperature	1.48	7.40
	1.50	7.50
	1.60	8.00
	1.10	5.50
	1.60	8.00
	2.20	11.0
	2.00	10.0
70 ˚ C	1.57	7.85
	1.13	5.65
	1.05	5.25
	0.95	4.75
	1.27	6.35
	1.00	5.00
90 ˚ C	1.10	5.50
	1.00	5.00

Fatigue and Longitudinal Test Samples

A set of 14 transverse samples was tested to evaluate the insulation systems fatigue characteristics. The fatigue tests were configured to load the transverse samples to predicted peak gap strains seen in the actual coil over 1,000 cycles. These tests were done at room temperature as well as at predicted operating temperatures, 70 and 90˚C. After the samples were subjected to the 1,000 cycles at peak operating strain, they were then pulled to failure as previous transverse samples to observe the residual strength after cyclic loading. These data are presently being reviewed and evaluated.

The set of 12 longitudinal test samples were also pulled with recorded strain and load data. The geometry of these samples is more complex and the data are still under evaluation. Strains measured on the free edge were in excess of predicted strains in the coil and all the samples did dc hi-pot after being pulled.

CONCLUSIONS

Using the finite element model from CAES as a guideline, the transverse samples tested to failure suggest a large factor of safety for the strain to failure properties in the active "hoop" region of the coil, both at room and operating temperature. This factor of safety is enhanced by the fact that after pulling these samples to failure, they still passed the dc hi-pot test to twice operating voltage plus 1 kV. The fatigue data and longitudinal data must be evaluated before complete conclusions can be made about this high strain insulation system, but this insulation/reinforcement system has demonstrated very good high voltage insulation and crack resistant properties after being pulled to strain failure.

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