DEVELOPMENT OF INDIGENOUS ELECTRICAL INSULATION BREAKS FOR SUPERCONDUCTING MAGNETS OF FUSION DEVICES

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Abstract

Electrical insulation breaks (IB) are very critical component of large-scale fusion devices employing superconducting magnets. The electrical insulation breaks developed for the requirement of up gradation of hydraulics for the superconducting poloidal field coils of SST-1 fusion machine. The electrical insulation breaks have been installed in the hydraulic, validated and sustained the operational required temperature. It has performed in rigorous environment of many thermal cycling from 300 K to 4. 2 K of pressure 1-12 bar which induced more thermal stress in electrical insulation breaks. Main function of such insulation break is to supply cold helium to superconducting magnets and to isolate the magnets electrically from ground potential during the quench. The salient design features include bigger dimension of ½” size, breakdown voltage withstand capacity up to 5 kV, helium leak tightness ≤ 1 x 10⁻⁸ mbar-l/s at 4.5 K and needless to mention the cryogenic compatibility and flexibility issues. Success rate is about 75 % as it is new attempt with Indigenous epoxy resin system. The basic structural materials are stainless steel SS 316 L feed tube separated by a cryogenic grade G10 GFRP insulation material which bonded with cryogenic epoxy resin. The failures causes have been identified, analyses that considered and rectified during indigenous development of electrical insulation breaks. In past project, an imported cryogenic epoxy resin system was used for fabrication of small size insulation breaks. The failure was observed after the repeated 4.2 K cryogenic cycles which doubts the reliability of component and epoxy resin system. The real research & development as well as challenge are to define and develop an adequate Cryo compatible epoxy. The electrical insulation breaks and cryogenic epoxy resin are not commercially available items, not reliable, cost factor and failure was noticed after cold thermal cycles. The In-house indigenous developed electrical insulation breaks can be used for future indigenous superconducting magnet fusion machines, electrical isolation and for low temperature experiments purpose (up to 15 kV applications), bonding and sealing of dissimilar materials at cryo temperature with very much cost effective. In this paper, the design, development, fabrication, performance test at 300 K, 77 K and 4.2 K of electrical insulation breaks and highlight on development of indigenous cryogenic epoxy resin system will be presented.

1. INTRODUCTION

Large numbers of electrical insulation breaks (IB) have used in the SST-1 machine to isolate the liquid helium feeds which are at ground potential from the high voltage superconducting magnet system as shown in Fig. 1. The basic role of IB is to provide the required electrical isolation, Cryo compatibility as well as helium leak tightness. These electrical breaks are located at the superconducting magnet inlet and outlet, isolation of bus bar and current leads. As per the SST-1 requirement the basic design incorporates 5 kV isolation as break down voltage, helium leak tightness up to 1x10⁻⁸ mbar-l/s at 4.5 K and cryogenic compatibility. The maximum design pressure is 40 bar (g) which is compatible with the maximum quench pressure of the magnet system. The basic structural materials are two nos. of SS tubes separated by a high quality G-10 (FRP) tube. The bonding between the two different materials, namely, the SS and FRP is achieved by in-house developed cryogenic compatible epoxy. This component failure resulted the vacuum will be deteriorated in the machine that may resulted to have to stop the fusion experiment and needs to be open. From the past experience of failure of electrical insulation breaks, we have been able to establish the process right from the cryo-compatible material selection, fabrication procedure and understood the critical issues involved in the design of electrical insulation breaks. For the requirement of up gradation of hydraulics for the PF-3 and PF-5 SC (Superconducting) magnets of SST-1 machine, the bigger size (of ½” NB i.e. 21.3 mm Outer dia, OD) insulation breaks were in-house developed, fabricated, tested as per operational requirement and installed in the circuit as shown in Fig. 2. The electrical insulation breaks have been validated and performing as per the machine requirement. Since this component is not commercially available locally or International and used in specific application as superconducting fusion machines. Procurement from outsourcing and high cost factor influence us for development of this component.
2. TECHNICAL REQUIREMENT

As per the needs the electrical insulation breaks have developed for SC hydraulics and 10 kA current feeder systems as helium vapour insulation breaks. The in-house developed electrical insulation breaks as final product having features of optimized dimension by mechanical analysis, contour design and electrical field consideration in Paschen condition, in-house uses of cryogenic resin system, manufacturing process optimization by filament winding process and rigorous stage wise performance testing of component. The function requirement of IB listed below. Fig. 3 shows the schematic of developed electrical insulation breaks.

(a) Working condition (inside): 4 bar LHe flow at 4.5 K and with vacuum (outside): \(10^{-5}\) mbar
(b) Helium leak rate at 300 K and after 5 numbers of 77 K thermal shocks: \(\leq 10^{-8}\) mbar l/s
(c) Helium acceptable leak rate: \(\leq 10^{-8}\) mbar l/s at 4.5 K with liquid helium flow to vacuum
(d) Compatibility design pressure: 40 bar (a)
(d) Electrical Isolation: \(> 2\) kV DC
(e) Size: 5 mm ID/ 8 mm OD, \(\frac{1}{2}\)” NB, \(\frac{3}{4}\)” (SS conductor end tube OD)

3. WORK CARRIED OUT TOWARDS THE DEVELOPMENT OF ELECTRICAL INSULATION BREAKS

Different type of dissimilar materials used for bonding as Stainless steel (SS) to GFRP with cryogenic resin system, Teflon to SS with resin system etc. The joints have been fabricated and tested for fabrication of IB. The cryogenic resin system is not readily available, its reliability, higher cost factor and dependency on and reliability of imported resin induced us for in-house development. The various tasks have been carried during development of component from materials selection to final component acceptance as listed below
(a) Selection of raw materials as SS 316L for conductor materials, cryogenic resin system, S-glass fibre roving comparable with E-glass.
(b) Electrical design analysis for optimizing design parameters and electrical field strength has been analyzed at different surface and contours along with gaps considering Paschen condition.
(c) Manufacturing process of inner insulation tubes, winding process based on glass fibre content and resin ratio, fibre angle and its feed that strongly influence the final component performance. Wet Filament automatic winding process is selected for fabrication of inner insulation tubes and outer final winding over
4. MANUFACTURING PROCEDURE OF SAMPLES

The complete electrical insulation breaks consists of SS 316L stubs which is separated by glass fibre tubes of G-10 CR grade as shown in Fig. 4. Each stage of fabrication and testing, proper QA/QC aspects followed, the following are the procedure for the fabrication of the complete IB. The stage wise snaps during fabrication is shown in Fig. 5(a) to Fig. 5(g).

(a) The fabricated seamless SS 316L and GFRP tubes of optimized dimension in 10 numbers of each batch immerse into liquid nitrogen for more than 10 hr.

(b) The helium leak tightness test of each SS 316 L and GFRP tubes, acceptable leak rate < 1x10E-8 mbar –l/s.

(c) Cleaning with isopropyl alcohol the tubes samples.

(d) Prepare the resin system as per the ratio manually; the entrapped air removed by vacuum evacuation upto 1 mbar in Desiccators vessel.

(e) Apply the resin system on both external and internal mating threads of SS 316 L and G-10 tubes.

(f) Assemble SS316L tube and G-10 tube, the excess resin would be removed by applying S-glass roving at transient joint at 2-3 overlap rotation.

(g) Cure the 1st stage bonded part as per resin system curing schedule for 24 hrs at 300 K and followed by @70 °C, 3 hrs in oven.

(h) Performance test carried out of 1st stage bonded assembly as per acceptance test criteria; the passed boded assembly of respective batches is ready for outer final filament winding.

(i) The outer winding done by same resin system with optimized wet winding parameters.

(j) The complete component will be accepted after carried out and passing of all performance tests done in samples.

(k) From the measurement and test result, the density and mass of insulation tube using glass fibre roving 70-65% is higher than using glass fibre tape of 50-65%. This significantly influences the thermal contraction rate of insulation tubes.

![FIG. 4. Internals of electrical insulation breaks](image)

The wet filament winding method parameters for fabrication of inner insulation tubes and outer winding samples of IB have been shown in Table 1.

TABLE 1. WET FILAMENT WINDING PARAMETERS
The following tests were carried out from 1st stage bonded assembly to final component IB according to the technical requirement and acceptance criteria of SST-1 machine. The various performance test results are summarized in Table 2.

**TABLE 2. TEST RESULT OF ELECTRICAL INSULATION BREAKS**

<table>
<thead>
<tr>
<th>Test</th>
<th>Acceptance Criteria</th>
<th>Complete electrical insulation breaks</th>
<th>Observations /Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Helium leak test at 300 K</td>
<td>≤ 1x10^-7 mbar-l/s</td>
<td>≤ 5.0 x10^-7</td>
<td>Average reading</td>
</tr>
<tr>
<td>Thermal shock test 300-77 K (European</td>
<td>5 cycles, no crack,</td>
<td></td>
<td>No cracks found</td>
</tr>
<tr>
<td>Standard ANSI/EIA-364-32 C-200)</td>
<td>visual inspection</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium leak test at 300 K after thermal</td>
<td>≤ 1x10^-9 mbar-l/s</td>
<td>≤ 6.0 x10^-9</td>
<td>Accepted</td>
</tr>
<tr>
<td>Helium leak test @ 12 bar (g) 300 K</td>
<td>≤ 2.0x10^-9 mbar-l/s</td>
<td>≤ 3.2x10^-9</td>
<td>Sniffer mode</td>
</tr>
</tbody>
</table>
Helium leak test @ 12 bar (g) 77 K ≤ 2.0x10^{-6} mbar-l/s ≤ 3.0x10^{-6} Sniffer mode
Helium leak test @ 0-20 bar (g) 4.2 K ≤ 2.0x10^{-6} mbar-l/s ≤ 2.5x10^{-6} Sniffer mode
Helium leak testing under mechanical loading at 0-20 bar(g) helium pressure (a) Tensile and compressive load 2000N at 300 K, 77 K 5 cycles, 15 minute (b) Bending load 100 N-m (c) Torsion Load 100 N-m Avg. Helium leak rate mbar -l/s (a): 4.0x10^{-6} (b): 5.0x10^{-6} (c): 2.0x10^{-6} Load applied (a) (0-400 Kg), (b) (0-300 Kg), (c) (0-102 Kg),

Electrical test at 0-2 bar (g) He gas, in Paschen condition (1000 to10^5 mbar vacuum) (a) DC test (b) AC test (100 kV Transformer) (a) (b) 0-5 kV 0-30 kV

Tensile test ASTM D 638-1991 Deflection: 6-9 mm ASTM D 638-1991 Breaking load : 350 MPa 6523 kN (S-glass and DGEBA resin system) (S) Average tensile strength: 350 MPa (c) Insulation break failed at outer winding and inner insulation tube (i) Glass content: (68-75 %) in roving tube, (55-65%) in fiber glass tape tube, Specific gravity: 1.87 (roving), 1.63 (glass fiber tape, 10 mm width and 0.1 mm thickness) as per IS 13360 Part 8 Sec 8-A and void fraction as per ASME Sec V-2015 (ii) Chemical and microstructure of SS316L material as per ASTM 479-11 and E 562, E 407 (ASTM grain size 9-10) respectively from the Government approved laboratory. The various performance tests snaps (iii) The composite sample consists of S-glass yarn of 9 µ, 360 Tex, breakdown strength of 13 kV/mm and three component epoxy resin system of viscosity 1500-3500 cps, > 17.5 MPa shear strength, 77 K.
6. MECHANICAL AND ELECTRICAL ANALYSIS

6.1 Mechanical analysis

The mechanical design and analysis was carried out considering the static yield criteria (Von Mises stress limit) for SS 316 L material. The design stress intensity $S_m = \text{minimum}(\frac{2}{3} S_y, \frac{1}{3} S_u)$, where, $S_y = \text{yield strength}$ and $S_u = \text{ultimate strength}$ respectively. Whereas, the yield criteria for insulation material applied to the maximum allowable compressive stress for yield stress. The compressive stress in normal while the maximum allowable shear stress parallel to the glass reinforcement plane of insulation.

Mechanical analysis result of electrical insulation breaks shown in Fig. 7 and Fig. 8 for the following boundary conditions using ANSYS engineering software:
(a) Tensile force of 2000 N along axial direction
(b) Thermal stress analysis for Temperature decreasing from 300 to 4.2 K

The analysis result shows that the design is safe in working conditions of IB in machine.

6.2 Electrical analysis

The electrical analysis of insulation breaks was done using the electrostatic solid axi-symmetric model as shown in Fig. 9 by COMSOL 4.1 multiphysics software with boundary criteria [3]
(a) Design high voltage to ground: 2 kV
(b) Designed to withstand maximum voltage: > 5 kV
(c) Relative permittivity of GFRP : 3 and air and in vacuum: 1.0
(d) The maximum design electrical field strength of the insulation materials: not more than 3 kV/mm
(e) Breakdown strength of GFRP (Glass Fiber Reinforced Plastic): 20-30 kV/mm (in vacuum) and nearly 10 kV/mm (in air medium) [1]

From the test result the maximum electric field found at the arc of SS metallic tubes is 220-230 V/mm and in the gap between the metallic conductors is about 450-500 V/mm. This is acceptable value as per the design requirement. The result of electric field distribution is shown below in Fig. 10 and Fig. 11.

FIG. 7. Schematic of profile distribution of electrical insulation breaks interface
7. TECHNICAL CHALLENGES, PROBLEMS, FAILURE AND EXPERIENCE LEARNT

(a) In first phase of SST-1 machine assembly house developed and fabricated (~500 numbers) and tested at 77 K and 4.2 K for LHe and LN$_2$ services electrical IB were installed in SST-1 machine.

(b) 2-3% failure rate was reported in electrical insulation breaks.

(c) In 2nd phase of assembly of SST-1 machine, LHe and LN$_2$ insulation breaks were procured from IPP, China and replaced, the IPP breaks also observed helium leak in 6 numbers of bigger size (24 mm SS metal OD) at high pressure and cryogenic temperature whereas the smaller size (8 mm SS metal OD) insulation breaks also found leakage after cold cycle at 4.2 K. in 5 numbers, around 5 numbers breaks were reported for cold leak at 120 -130 K temperature as shown in Fig. 12.

(d) Due to the requirement in SST-1 machine SC coil hydraulic, 10 kA current lead system, supply and delivery hydraulic cryogenic transfer line to magnet system and other low temperature experiments, in-house electrical breaks were developed. From the past experience, the reasons which responsible for failure were considered more attentive, namely, the bigger size IB is more prone to leaks as induced thermal radial stress occurs is comparatively more than small sizes IB during cool down cycles,
flexibility in hydraulic and induced thermal stress during cool down to 300-4.2 K and the temperature at the transition adhesive point of SS metal and insulation material during welding. (should be < 70 °C)

(e) The availability and limited vendors experience in low temperature, interest in research and development work for formulating the epoxy resin system for cryogenic application.

(f) During development, 3 numbers of resin system failed at 77 K and pressure condition, however it works at 300 K. We learnt that at cryogenic temperature, the epoxy resin should have quality of high crack resistance, high toughness, long usable life, low viscosity for good flow and penetration and very low shrinkage on cure.

FIG. 12. IPP China LHe insulation breaks leakage in SC magnet

8. DISCUSSION AND CONCLUSION

In this development work, the electrical insulation breaks fabricated and tested in house, three kind of two and three component epoxy resin system have been used. Form the test results it found that the thermal contraction is lower in radial direction, fibre content is more than in fibre tape filament winding that results the more resin content in the composites which developed cracks and leaks at cryo temperature. Electrical insulation breaks (8 mm to ≥ ½”NB SS stub OD) for superconducting coils hydraulic have been installed, validated and performing as per the acceptance criteria of SST-1 machine. Several cool down cycles to 4.2 K have been carried out, no failure was reported in developed component. For the fabrication of IB, in-house developing epoxy resin system have used for bonding and filament winding. The developed electrical insulation breaks and resin system costs significantly less than from outside available Industries as this item is not commercially available. The insulation materials and resin system have experimentally validated upto $10^{17}$ n/m² neutron fluence irradiation environment and it is under process for $10^{22}$ n/m² radiation dose in FBTR fission Reactor. Further, more fabrication of IB in batch wise project is in-line for the repeatability of acceptance criteria. The rigorous performance tests, analysis and stringent quality controls in each stages of fabrication of IB would be the main aspects of success rate. The developed IB can be used for future indigenous superconducting magnet fusion machines, electrical isolation, dissimilar materials joining and sealing at cryogenic temperature.

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