Central Power Research Institute

Vol. 18(1)/45-51, June 2022
ISSN (Print) : 0973-0338
DOI : 10.33686/pwj.v18i1.1096

Power Research

Effect of Moisture Content on the Performance of PPLP as a Dielectric for HTS Power Cable

Maalika Sarkar[1*], Isaac De Souza[1], Abhik Sarkar[2], Abhay Singh Gour[1] and Vutukuru Vasudeva Rao[1]

[1]Indian Institute of Technology, Kharagpur – 721302, West Bengal, India; maalika.sarkar123@gmail.com
[2]SuperQ Technologies India Pvt. Ltd., Bengaluru – 560045, Karnataka, India

Abstract

For the operation of High Temperature Superconducting (HTS) power cables at high voltage levels, the electric field distribution depends on the relative permittivity of dielectric materials. In HTS cables, PolyPropylene Laminated Paper (PPLP) is used as a cold dielectric material and is wrapped helically along the length of the conductor thereby electrically insulating it. During the installation and maintenance process of HTS cables, termination units and joint boxes, the PPLP is often exposed to moisture. The presence of moisture affects the dielectric breakdown strength and dielectric losses. The effect of moisture content in PPLP at ambient and liquid nitrogen temperature has been studied to determine the breakdown strength, relative permittivity (ε_r) and dissipation factor (tan δ). Effect of moisture content on the performance of PPLP via the measurement of dielectric breakdown strength and relative permittivity for various temperatures and moisture content are discussed in this paper.

Keywords: Dielectric Breakdown Strength, HTS Cable, Moisture Content, Relative Permittivity, PPLP

1. Introduction

PolyPropylene Laminated Paper (PPLP) in the form of tape is often used as paper-based insulation for HTS power cables because of its lower dielectric loss and higher dielectric strength[1]. PPLP-HTS-125 supplied by Sumitomo Electric Industries, Ltd. has a total thickness of 120 μm. Each PPLP sheet consists of a PolyPropylene sheet (70 μm) laminated on either side by a layer of kraft paper (25 μm). PPLP strips are helically wound in layers around the conductor part of HTS power cable and are also the main insulating materials, for cables, termination units and joint boxes used for HTS power cables. During the maintenance and assembling of HTS cable segments, these PPLP layers are subjected to moisture from surrounding air. The kraft paper is a porous material and has the capability of absorbing this surrounding moisture, as a result, at Liquid Nitrogen (LN_2) temperature (77 K) this absorbed moisture will form an ice, which in turn will act as a heat load to LN_2. Due to the trapped moisture in PPLP, the conduction current forms the path in the sample between the electrodes and the leakage current increases, resulting to increased dielectric losses, which is the part of the AC losses in superconducting cables. Hence, the research on the electrical insulation of PPLP for maintenance usage is very crucial. In the reported literatures, the research mainly focuses on the AC, DC, lightning impulse voltage test on PPLP[2,3]. In recent study, Du, Hao, *et al*., have studied the breakdown characteristics of PPLP at various modes of voltage rise test[4]. Mini model cables with various arrangements of PPLP are studied by Wei, Bin, *et al.*[5]. Also, the dielectric characteristics of PPLP is graded and compared to other insulation materials for application at high voltage grid[6,7]. After the literature survey, effect of moisture content at various operating conditions on samples for high voltage applications has to be carried out in more detail.

In this paper, two different sets of experiments are conducted on PPLP as a cold dielectric for the dielectric breakdown strength measurements and capacitance measurement for computing the relative permittivity and dielectric losses. The experimental setups and procedures for measurement of AC breakdown strength and computation of relative permittivity from capacitance

*Author for correspondence

measurement are discussed in section-2. Section-3 summarizes the results and discussions. Section-4 concludes the results.

2. Experimental Setups

To determine the effect of moisture content on PPLP, two experiments were carried out. First, to measure the AC dielectric breakdown strength and second, to estimate the change in relative permittivity of the samples in dry and wet conditions.

2.1 AC Dielectric Breakdown Strength

The schematic of the setup for measurement of AC breakdown strength is shown in Figure 1 and the photograph of the setup is shown in Figure 3. The PPLP sample holder setup consists of a cylindrical copper electrode (high voltage electrode) with thickness 60 mm and diameter 25 mm and a cylindrical brass electrode which is the ground electrode, of thickness 6 mm and diameter 55 mm. The high voltage electrode has edge radius of 3 mm to avoid the edge effect[9]. PPLP samples (PPLP-HTS-125) manufactured by Sumitomo electric industries Ltd. were used for these experiments. These samples are cut with a diameter of 72 mm and placed in between the electrodes for testing. The setup is placed horizontally inside a FRP container and filled with LN_2. Layers of PUF insulation is wrapped outside the container with silicon sealant for thermal insulation. The container is placed inside the vacuum desiccator, which is connected to the rotary vacuum pump. For the measurements in $LN_{2,}$ the vacuum assisted setup is used to conduct the experiment to stabilize the LN_2 in the container and to eliminate bubble formation on the sample and electrodes at atmospheric pressure. To hold the PPLP samples at place in the LN_2 container, the weight of the high voltage electrode is used, and a cage-guarded electrode holder is designed of Bakelite as shown in Figure 2.

AC breakdown strength measurement was carried out by using a 60 kV high voltage transformer controlled by a variable transformer (variac) which is fed directly from the 230 V, 50 Hz input supply. A trip circuit is connected to trip the circuit when the leakage current exceeds the set trip current 2 mA and isolates the high voltage transformer from the input voltage supply from variac. The main copper electrode is connected directly to the high voltage terminal, and the ground electrode is connected to the neutral terminal of the transformer. The voltage across the electrode is measured by using a high voltage probe. For the measurement of leakage current, ammeter is connected in series. The current vs voltage values are plotted for different number of layers at room temperature (300 K) and LN_2 temperature (77 K) as shown in Figure 4[13]. In Figure 5, the plot shows AC dielectric breakdown strength for the PPLP, PP sheet and kraft paper at room temperature and when impregnated

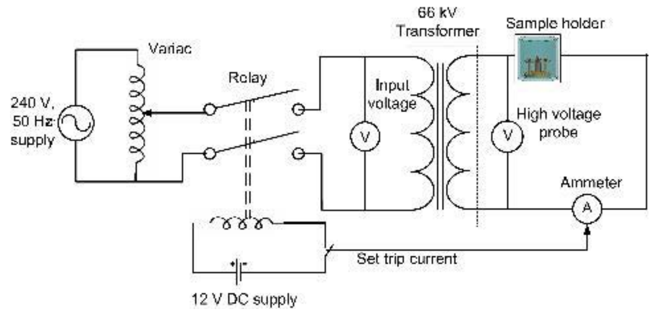

Figure 1. Schematic of the setup to measure AC breakdown strength.

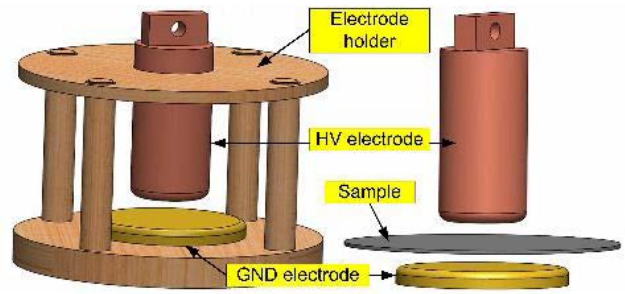

Figure 2. CAD design for HV electrodes and holder.

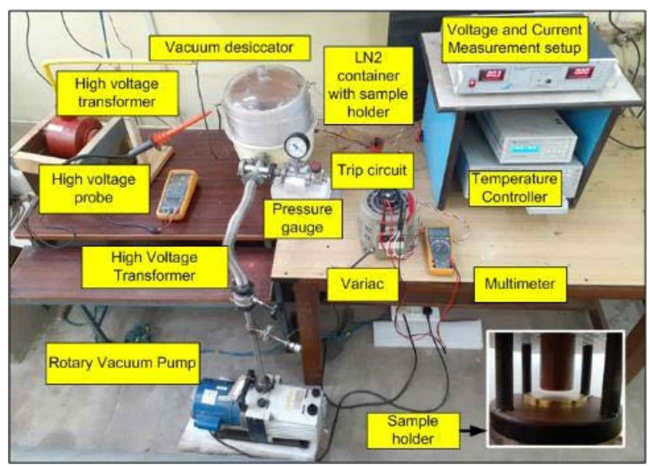

Figure 3. Photograph of the experimental setup for AC dielectric breakdown strength.

with LN_2. For the measurements, the kraft paper and PP sheet are peeled off from the PPLP and the thickness is measured using micrometer to determine the individual breakdown strength.

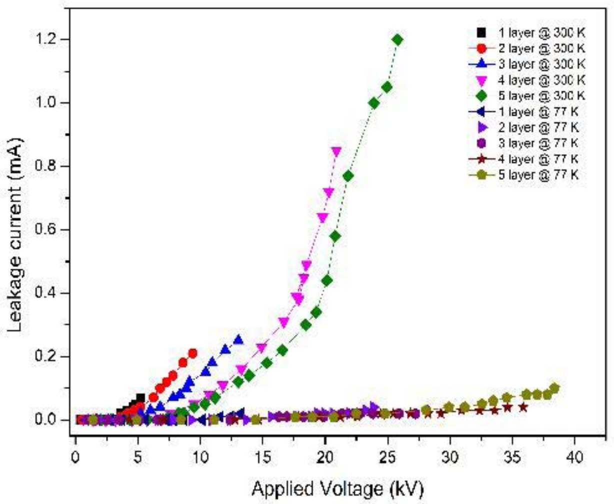

Figure 4. I-V breakdown characteristics at room temperature (300 K) and liquid nitrogen temperature (77 K).

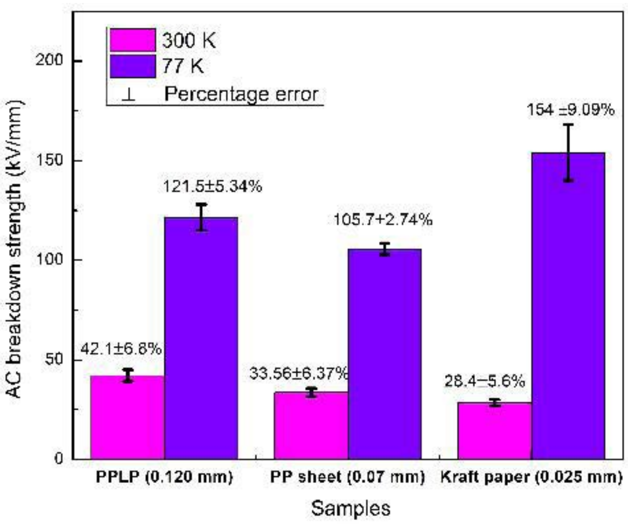

Figure 5. AC breakdown strength at 300 K and 77 K for PPLP, PP sheet and kraft paper.

The measurements are carried out 3 times for each sample. Subsequently, the mean and the standard deviation are calculated for the percentage error. It is observed that the percentage error for kraft paper (±9.09%) at 77 K is more than that of PP sheet and PPLP, because, the peeling of kraft paper degrades and weakens the fibrous bond structure of the material which changes the breakdown pattern due to uneven partial discharge phenomena for each measurement. From the graph, it is well represented that LN_2 impregnated kraft paper shows better breakdown strength than PP sheet. Since kraft paper has a frail structure which easily gets damaged during wrapping on the cables are not suitable as of its own. Therefore, the kraft paper along with PP sheet enhances its feature as a cold dielectric material for HTS cables. However the combination of PP sheet sandwiched between the kraft paper forming PPLP material has a dielectric breakdown strength of 121.5 ± 5.34% kV/mm.

2.2 Effect of Moisture Content

Three layers of PPLP samples are arranged in different combinations. The combination of the samples and electrode connections are as shown in Figure 6 where (a) Dry-Dry-Dry (DDD) (b) Dry-Moist-Dry (DMD) (c) Moist-Dry-Dry (MDD) and (d) Dry-Dry-Moist (DDM).

The I-V characteristics for all four combinations of samples are shown in Figures 7 and 8 for 300 K and 77 K respectively.

After performing the experiment, it is observed that due to the moisture content, the volume resistivity of the sample decreases and the leakage current increases. At

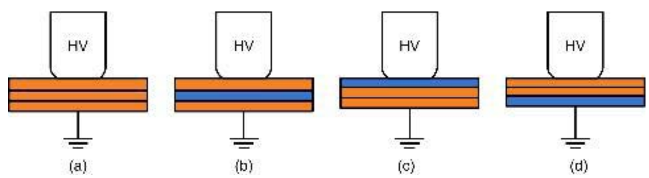

Figure 6. Arrangement of PPLP samples for the test.

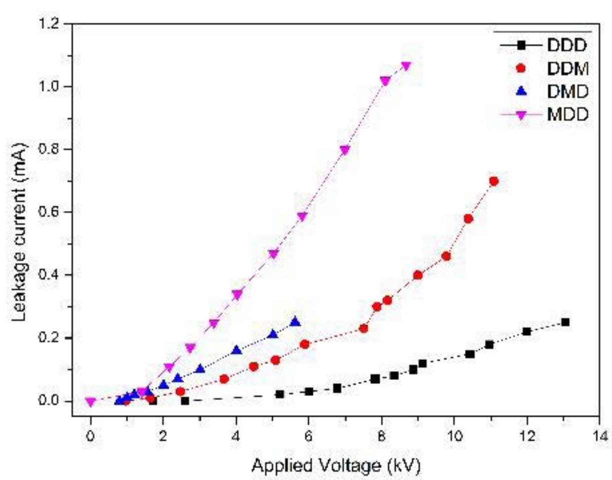

Figure 7. I-V characteristics for PPLP sample arrangements at room temperature (300 K).

room temperature, when the moist sample is in direct contact with the high voltage electrode, the rate of increase in leakage current with respect to applied voltage is more steep in compared to others due to high surface discharge. For other samples, there is a proper breakdown along with puncture of the samples. As compared to results obtained for 300 K, the breakdown characteristics are not similar in LN_2. The presence of moisture in samples does not affect the breakdown strength in LN_2.

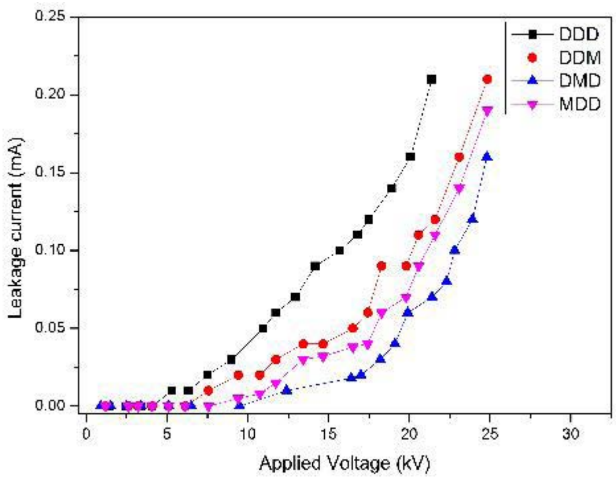

Figure 8. I-V characteristics for PPLP sample arrangement at Liquid Nitrogen temperature (77 K).

2.3 Relative Permittivity Measurement

The dielectric loss for dielectric materials is directly dependent on the relative permittivity and the dissipation factor of the material. When these paper type dielectric materials come in contact to moisture, the electrical conductivity of the material increases which in turn increases the dielectric loss. To study the effect of moisture content on PPLP, the relative permittivity is computed for wet and dry samples at 300 K and 77 K. For computation of relative permittivity, the capacitance measurement for various samples was carried out under dry and wet sample conditions. The complete experimentation involves two major steps- (a) Sample preparation and processing (b) Capacitance and dissipation factor (tan δ) measurement. The samples were cut into circular shape with a diameter of 45 mm and having a cross sectional area of 1590 mm^2. The samples must be prepared for measurement of capacitance and dissipation factor under dry and wet conditions. To do so, following procedures were followed.

1. Dry sample preparation: PPLP samples were baked in vacuum furnace at a temperature of 65°C, for a duration of 45 mins at a pressure of 10^{-2} mbar.
2. Wet sample preparation: The same dry PPLP samples were dipped in water and were shake-off in air to remove the excess amount of water from the wetted sample. Thereafter, the weight of the sample was measured using weighing machine. The weight difference between the dry and wet samples was calculated and the water content percentage was determined using (1).

$$W_{wc}(\%) = \frac{W_{wp} - W_{dp}}{W_{dp}} \times 100 \qquad (1)$$

where, W_{wc} is the water content %, W_{wp} is the weight of the wetted sample in mg and W_{dp} is the weight of the dry sample in mg.

A photograph of the weighing and positioning of the wetted sample on the polished copper electrode is shown in Figure 9.

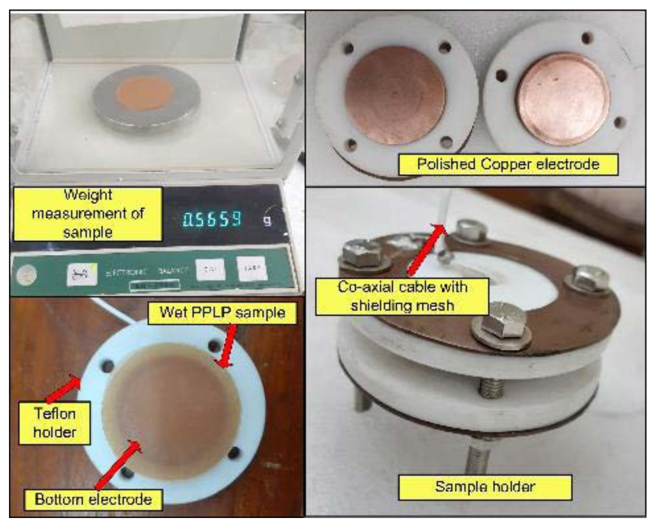

Figure 9. Photograph of weighing and positioning of PPLP sample.

An in-house test setup was developed for measuring the capacitance and dissipation factor (tan δ) of the PPLP samples at room and liquid nitrogen temperatures. An LCR precision meter APLAB 4300R was used to measure capacitance and dissipation factor for various frequencies at 300 K and 77 K under atmospheric pressure. Prior to capacitance measurement, the LCR meter was calibrated for the short circuit and open circuit test after connecting the setup. The setup consists of two copper electrodes of circular shape with a diameter and thickness of 37 mm and 5 mm respectively. The electrode diameters are smaller than the PPLP sample to reduce fringing electric field, which in turn affects the capacitance measurement. The measurements were carried out using 4-probe method with the help of shielded Teflon wires which are compatible at room and LN_2 temperatures. The PPLP sample was then placed between these copper electrodes. Teflon spacer is used to hold the copper electrodes together in position as shown in Figure 9. In addition, shielding electrodes are grounded to reduce the stray capacitance and EMI interference during measurement placed at the top and bottom of the setup.

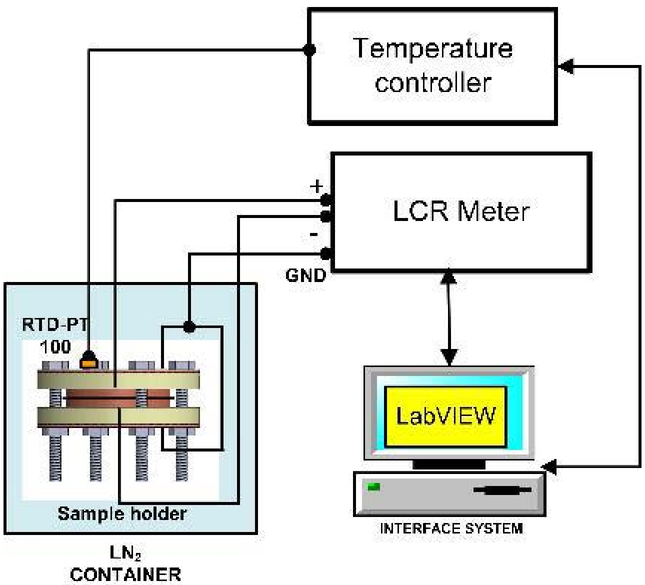

Figure 10. Schematic diagram of experimental setup.

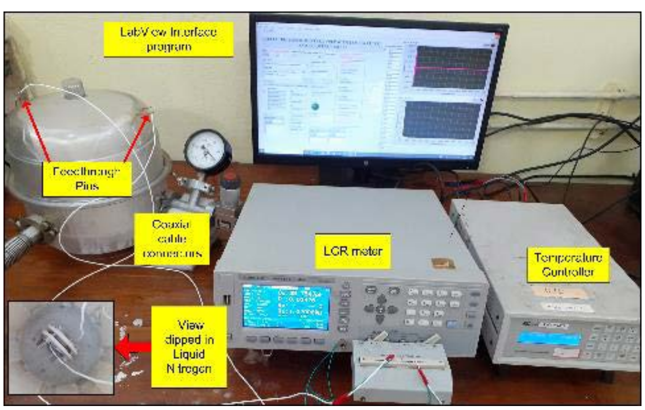

Figure 11. Photograph of experimental setup

A Lakeshore 325 temperature controller, connected to PT-100 RTD in 4-probe configuration was used to record the temperature. LCR meter and temperature controller were interfaced with the LabVIEW program and the data was logged using USB and GPIB interface respectively. A schematic and the photograph of the experimental setup are shown in Figures 10 and 11 respectively. The relative permittivity (Dielectric Constant) (ε_r) is obtained by the following:

$$\varepsilon_r = \frac{C_{ef} d}{\varepsilon_o A} \tag{1}$$

$$\frac{1}{C_{ef}} = \frac{1}{\varepsilon_o A} \sum_{i=1}^{n} \frac{d_i}{\varepsilon_{ri}} \tag{2}$$

where, C_{ef} is the effective capacitance for the stack of dry and wet PPLP samples where insertion of different layers of samples are symbolized by i and is measured by the LCR meter, d is the thickness of the PPLP sample, A ($=1.075 \times 10^{-3}\ m^2$) is the cross-sectional area of the copper electrodes, ($\varepsilon_o = 8.854 \times 10^{-12}$ F/m) is the permittivity of free space, and ε_r is the relative permittivity which is to be determined.

The dielectric power loss (W_d in W) and its value per unit volume (W_v in W/m^3) are given by (3) and (4) respectively.

$$W_d = \omega C V_o^2 \tan\delta \tag{3}$$

$$W_v = \omega \varepsilon_r \varepsilon_o E^2 \tan\delta \tag{4}$$

where, ω is the operating angular frequency, V_0 is operating voltage (V), δ is dielectric loss angle (rad), tan δ is the dissipation factor and E is the electric field strength (V/m).

The equivalent parallel capacitance C_P (F) and equivalent parallel resistance R_P (Ω) obtained from the LCR meter when the sample is connected to the LCR meter in closed circuit are used for computation of dissipation factor (tan δ) using (5), which is written in terms of conductivity and equivalent permittivity (ε) of the sample[11,12].

$$\tan\delta = \frac{1}{\omega C_P R_P} = \frac{\sigma}{\omega\varepsilon} \tag{5}$$

where, σ is the conductivity (S/m).

3. Results and Discussions

The obtained relative permittivity values at 60 Hz for dry and moist samples at room temperature (300 K) and LN_2 temperature (77 K) for 4 number of PPLP samples are plotted in Figure 12. At 300 K, the effective relative permittivity values are elevated due to the increase in conductivity of the moist samples, whereas at 77 K there is no such significant change observed for the different stack of PPLP samples. For moist samples, at 77 K, the film of moisture in the sample freezes which hardens the sample increasing the effective density of the sample and resists the polarization in it. This decreases the effective conductivity in the moist sample at LN_2 and the effective relative permittivity for the moist sample is the same as that of dry sample. The dielectric loss (W/m^3) for applied voltage of 1 V is calculated using (3) and tabulated in Table 1.

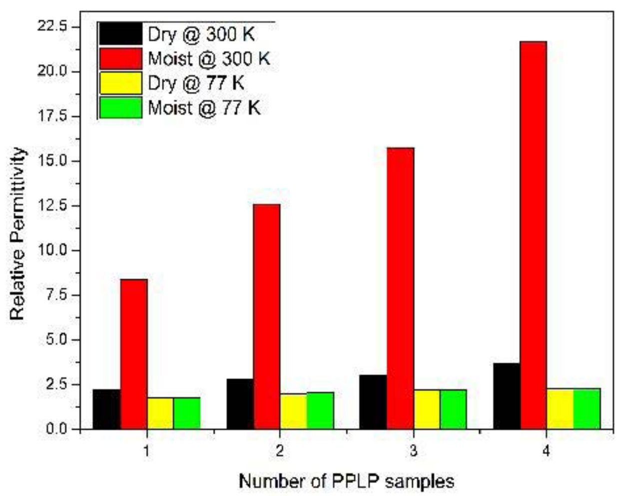

Figure 12. Relative permittivity for dry and moist samples at 300 K and 77 K.

The dielectric loss for moist samples is higher than that of dried samples at 300 K, whereas at 77 K the dielectric loss decreases for the moist samples due to the presence of hardened film moisture on the samples in LN_2. From the AC breakdown strength measurement, the moist samples are placed at different positions and compared at room and LN_2 temperature. The presence of moisture increases the breakdown strength of the sample at 77K since the moisture freezes and increases the density of the material which overall reduces the polarization and increases the breakdown voltage of the sample. To justify the phenomena, the same experiment is performed for the kraft paper which acts as the absorbent and makes it suitable as cold dielectric, at dry and moist state. The results are obtained from the AC breakdown strength measurement of moist kraft paper, which is greater than that of dry kraft paper in LN_2. Also it is observed that there are multiple punctures for moist sample due to high surface discharge both at 300 K and 77 K. The severity of puncture at 300 K is more severe than at 77 K.

Table 1. Dielectric loss (W/m^3) for Dry and moist samples at 300 K and 77 K

No. of layers	300 K		77 K	
	Dry	Moist	Dry	Moist
1	8.44×10^{-02}	18.2	1.85×10^{-03}	8.47×10^{-04}
2	3.01×10^{-02}	5.05	1.81×10^{-04}	1.24×10^{-04}
3	1.35×10^{-02}	1.09	2.87×10^{-04}	4.09×10^{-05}
4	1.07×10^{-02}	8.77	3.58×10^{-04}	2.53×10^{-04}

4. Conclusions

The cold dielectric material for high voltage HTS cables will often come in contact to moisture during installation and maintenance testing of the cable. The PPLP material, which is a paper-based dielectric material, acts as good absorbent for moisture. Dielectric properties of PPLP degrade when operated at 300 K, whereas for HTS cable this PPLP offers high dielectric breakdown strength when operated at 77 K. After a detailed study for the effect of moisture on PPLP in this paper, it was observed that the moisture content in PPLP at 77 K does not affect the dielectric properties of the material, since the moisture freezes and hardens the sample increasing the density and reducing the polarization and conductivity of the sample. Also the moisture content of the sample depends on environmental parameters which act as the heat load on the cryogen and should be avoided. On the other hand during off state, the hardened ice from moisture melts on PPLP and destroys the layer structure of kraft paper and PP sheet which degrades its overall dielectric properties and reduces dielectric breakdown strength.

5. Acknowledgment

The Authors would like to thank CPRI, Bengaluru, Karnataka, India for their funding of the HTS cable project.

6. References

1. Kwon Ik-Soo, *et al.* Comparison of the electrical conductivity of polypropylene laminated paper (PPLP) and kraft in LN 2 according to the number of layers. IEEE Transactions on Applied Superconductivity. 2016; 26(4):1–5. https://doi.org/10.1109/TASC.2016.2550182
2. Cheon HG, *et al.* A study on thickness effect of HTS cable for insulation design. Journal of Physics: Conference Series. 2006. 43(1). https://doi.org/10.1088/1742-6596/43/1/217
3. Choi J-W, *et al.* A study on insulation characteristics of laminated polypropylene paper for an HTS cable. IEEE Transactions on Applied Superconductivity. 2010; 20(3):1280–3. https://doi.org/10.1109/TASC.2010.2044235
4. Du H, *et al.* Insights on the breakdown characteristics of PPLP under different test protocols and temperatures. IEEE Transactions on Applied Superconductivity. 2020; 30(6):1–6. https://doi.org/10.1109/TASC.2020.2986450
5. Wei B, *et al.* A study of the composite insulation breakdown properties for wrapping cables in liquid nitrogen. IEEE Transactions on Applied Superconductivity. 2014; 25(1):1–6. https://doi.org/10.1109/TASC.2014.2357753
6. Gromoll D, Schumacher R, Humpert C. Dielectric characteristics of polypropylene laminated paper in liquid nitrogen for superconducting devices of the high-voltage grid. 2018 7th International Energy and Sustainability Conference (IESC). IEEE; 2018. https://doi.org/10.1109/IESC.2018.8439987
7. Garzem M, *et al.* Breakdown and partial discharge characteristics of transformer board and insulating paper materials in liquid nitrogen. IEEE Transactions on Applied Superconductivity. 2018; 28(4):1–5. https://doi.org/10.1109/TASC.2018.2805166
8. Hayakawa N, *et al.* Dielectric characteristics of HTS cables based on partial discharge measurement. IEEE Transactions on Applied Superconductivity. 2005; 15(2):1802–5. https://doi.org/10.1109/TASC.2005.849292
9. Seo I-J, *et al.* Experimental and analytical study of the DC breakdown characteristics of polypropylene laminated paper with a butt gap condition considering the insulation design of superconducting cable. Japanese Journal of Applied Physics. 2014; 53(8S3). https://doi.org/10.7567/JJAP.53.08NL04
10. Nagao M, *et al.* Dielectric breakdown mechanism of polypropylene laminated paper in liquid nitrogen. 2011 Annual Report Conference on Electrical Insulation and Dielectric Phenomena. IEEE; 2011. https://doi.org/10.1109/CEIDP.2011.6232684
11. Park C, *et al.* The characteristics of film capacitors at room temperature and in liquid nitrogen. 2018 AIAA/IEEE Electric Aircraft Technologies Symposium (EATS). IEEE; 2018. https://doi.org/10.2514/6.2018-5014
12. Available from: https://www.aplab.com/test-measurement/component-testers.html
13. Masood A, Zuberi MU, Husain E. Breakdown strength of solid dielectrics in liquid nitrogen. IEEE Transactions on Dielectrics and Electrical Insulation. 2008; 15(4):1051–5. https://doi.org/10.1109/TDEI.2008.4591227