Dielectric Parameters of Unimpregnated Mica Tape under Humid Condition

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Abstract—**At the white stage—i.e., after taping and installing coils/bars in slots but prior to vacuum pressure impregnation (VPI), also called green coils/bars—the integrity and capability of insulation systems could be affected by various stresses related to the manufacturing process of winding. Consequently, assessing potential in-process defects in stator winding insulation systems prior to impregnation requires conducting various high-voltage tests. However, the moisture content of mica tapes, unimpregnated insulated coils and assembled windings is influenced by storage conditions, which may lead to failure during high voltage testing. Although proper preheating could dry the insulation materials sufficiently to pass the high voltage tests, preventing humidity- and moisture-induced insulation failure during high-voltage testing still depends on defining and applying an appropriate voltage level. To evaluate the effect of moisture contents on the dielectric behavior and breakdown voltage of insulation systems, various samples were prepared. The samples consisted of mica paper and mica tapes stored under a variety of humidity and temperature conditions. The dielectric properties of the mica sheets were analyzed by dielectric spectroscopy, and parameters such as dielectric constant, tan δ and insulation resistance were evaluated under a range of frequencies. Finally, the breakdown voltage test was implemented using AC and DC voltage.**

I. Introduction

Insulation defects in VPI systems can lead to insulation failure and, ultimately, financial losses for customers. Detecting insulation defects at an early stage of manufacture would go a long way to preventing these problems. Because factors such as mechanical stresses during winding manufacture affect the integrity and proper functioning of insulation systems, diagnostic testing during winding is of substantial utility. In particular, high voltage imposes electrical stresses on the insulation system—in this case, unimpregnated mica tape—of green coils/bars at the white stage, which results in insulation failure. Applying an appropriate voltage detects insulation problems without the electrical stress.

One common diagnostic test for identifying weaknesses in insulation is surge testing. IEEE Std. 522 recommends specific voltage levels for surge testing impregnated and cured insulation systems. For unimpregnated coils, however, IEEE Std. 522 suggests a reduced voltage, i.e., 60 to 80% for VPI and 40 to 60% for resin-rich insulation systems [1]. To reduce electrical stresses on the main insulation during the surge test, the stator should be at floating potential (i.e., not grounded) [2].

IEEE Stds. 95 and 1043, on the other hand, recommend AC and DC hipot (high potential) tests to assure the integrity of the insulation system with different voltage levels for newly impregnated windings (Table I) [3–5]. For maintenance evaluations, 75% of the values shown in Table I is recommended. For green coils at the white stage, however, there is no recommendation [5].

TABLE I
Hipot Voltage Level

Voltage type	Frequency (Hz)	Voltage level
AC	50	$2E^{*}+1$
DC	–	1.7 (2E+1)
VLF**	0.1	1.63 (2E+1)

* E: Rated line–line voltage
** VLF: Very low frequency

To determine the optimum level of testing voltage at the white stage, researchers have investigated the correlation between the number of insulation layers and the breakdown voltage of unimpregnated coils [2]. Their findings show that the deviation in breakdown voltage is rather low. Furthermore, applying an appropriate voltage during high voltage testing raises the likelihood of detecting insulation defects [2].

For coils, bars and stators at the white stage (prior to impregnation), storage conditions such as temperature and humidity affect the moisture content of mica tapes. The moisture content in turn changes the tapes' dielectric properties. Moisture also affects the breakdown voltage of unimpregnated windings during diagnostic testing. Moreover, the moisture content of green coils/bars affects the dissipation factor, capacitance and partial discharge behavior of the insulation system [6]. Finally, proper drying prior to impregnation enhances the performance of the insulation system after impregnation and curing.

In the work described here, we investigated the effects of humidity and temperature on the dielectric properties of unimpregnated mica sheets and also subjected them to AC and DC high voltage testing. Parameters such as polarization current, insulation resistance, permittivity, capacitance and tan δ were evaluated. We also examined the effect of taping tensile strength on humidity absorption at different temperatures and, consequently, the AC and DC breakdown voltage of the green coils. Finally, we measured capacitance and insulation resistance for each condition and the relationship between them.

II. Dielectric Properties of Mica at Different Humidity and Temperature Conditions

A. Test Sample and Test Setup

Mica sheets with adequate dimensions (10 cm × 10 cm) consisting of woven glass fabric with impregnated muscovite mica paper, without accelerator (Table II), were prepared.

TABLE II
Mica Sheet Specifications

Properties	Units	Value	Test norm
Thickness	mm	0.15 ± 0.025	IEC 60371-2

These mica tapes are used in VPI insulation systems for slot and end-winding of coils and bars for high-voltage motors and generators. The mica sheets were stored at 23°C and two levels of relative humidity: 50 and 80%.

To eliminate surface leakage and ensure a uniform electrical field inside the mica sheet during measurement of the dielectric properties, ring electrodes were employed. The values measured by the dielectric material analyzer were sent to a computer (Fig. 1).

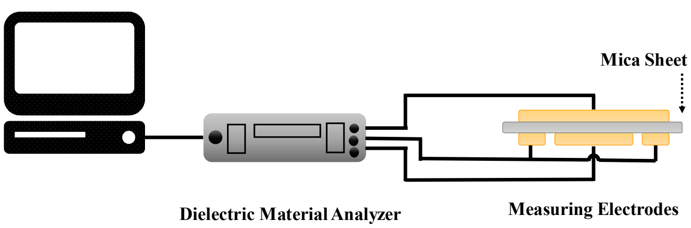

Fig. 1. Test setup for measuring dielectric properties.

B. Test Results

The dielectric parameters were measured on the sample after 24 h under 50 and 80% r.H. The measurements were conducted in a frequency range of 5 Hz to 5 kHz.

The results show considerable variation between the resistance of the mica sheets at different relative humidity. Increasing moisture enhances conductivity. Consequently, samples with higher moisture content (80% r.H.) demonstrate lower resistivity values (Fig. 2). Moreover, because conductivity is inversely related to frequency (R~1/f), resistance values decrease as frequency increases.

The measured polarization currents of the samples confirm the differences in sample conductivities due to variation in moisture content (Fig. 3). The steady-state polarization currents of the samples show a noticeable difference.

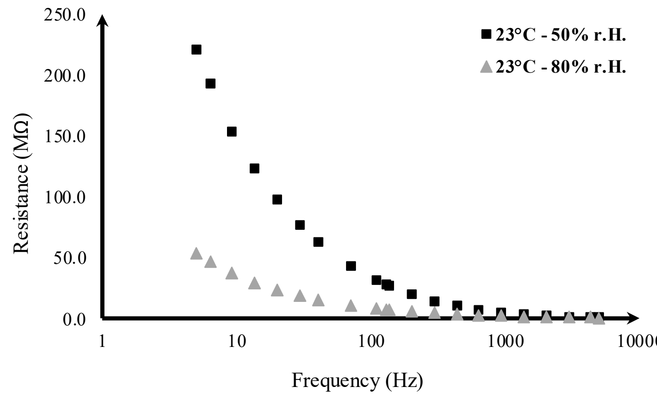

Fig. 2. Resistance of mica sheets with different moisture content.

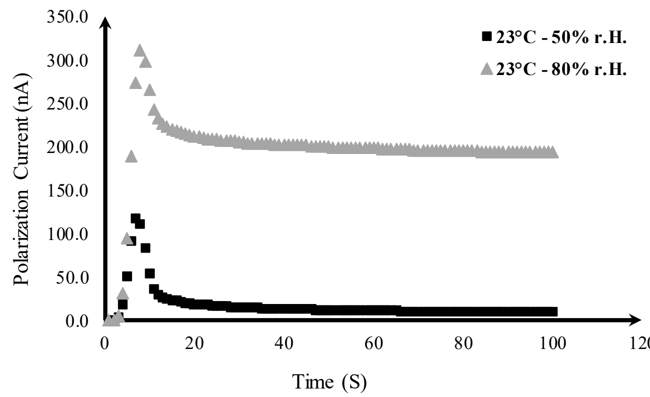

Fig. 3. Polarization current of mica sheets with different moisture content.

We also measured the capacitance of the samples over the frequency range (5 Hz to 5 kHz). The results show the effect of increasing the moisture content of the mica sheets (Fig. 4). Measuring the permittivity of the samples (Fig. 5) showed that increasing relative humidity raises capacitance due to higher permittivity of water against mica (ε_r = 80 @ 20°C). Increasing the frequency by factor of f^{-2} decreases the permittivity.

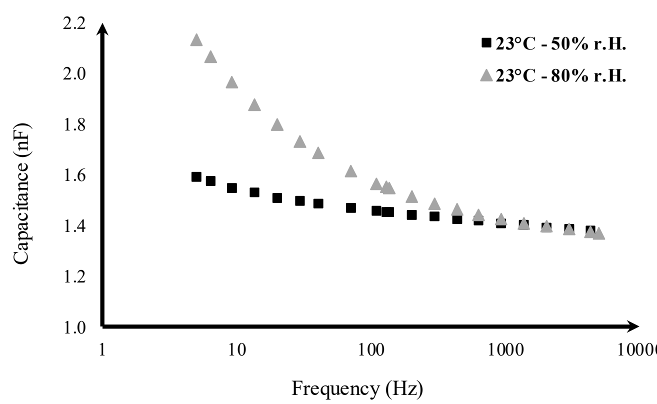

Fig. 4. Capacitance of mica sheets with different moisture content.

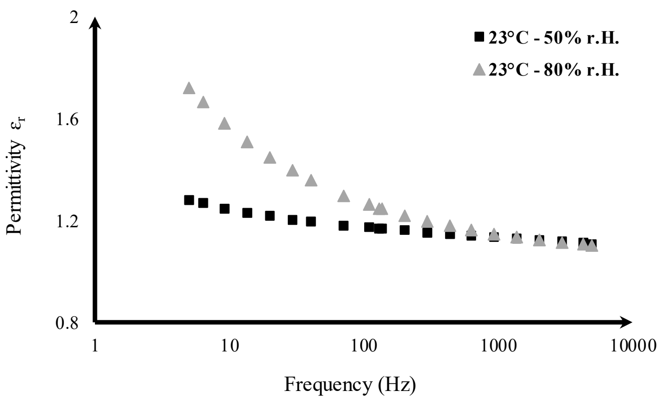

Fig. 5. Permittivity of mica sheets with different moisture content.

Measurement of the dissipation factor (tan δ) over the frequency range (5 Hz to 5 kHz) confirms all the previous measurements and shows the effect of the moisture content of the mica sheets (Fig. 6). Increasing the moisture level leads to losses enhancements due to the increased conductivity of the mica sheets. Increasing the frequency reduces the dissipation factor due to the inverse relationship of conductivity and permittivity to frequency.

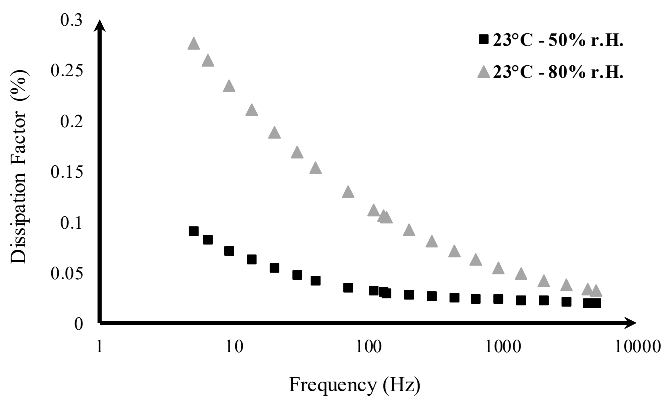

Fig. 6. Dissipation factor of mica sheets with different moisture content.

III. Green Bars at Different Humidity and Temperature Conditions

A. *Test Sample and Test Setup*

Steel bars with identical dimensions (10 mm × 30 mm × 900 mm) and a 1 mm corner radius were taped with mica tapes (five layers, half-overlapped) consisting of woven glass fabric with impregnated muscovite mica paper, without accelerator (Table III). Slot sections, as well as the overhangs of high-voltage motors and generators, are taped and insulated with this type of mica tape. The tape's resin content makes it suitable for VPI systems. The taping tensile strength was set to 50 N. In addition, U-shaped steel forms were used to simulate slots (Figs. 7, 8).

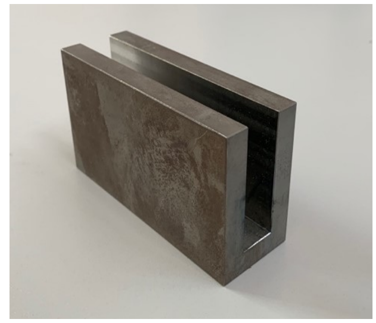

Fig. 7. U-shaped steel for simulating the slot.

Fig. 8. Green bars in the slot simulator.

TABLE III
Mica Tape Specifications

Properties	Units	Value	Test norm
Thickness	mm	0.15 ± 0.025	IEC 60371-2
Total weight	g/m^2	195 ± 15	IEC 60371-2
Mica paper	g/m^2	160 ± 10	IEC 60371-2
Glass fabric	g/m^2	23 ± 2	IEC 60371-2
Resin content	g/m^2	12 ± 3	IEC 60371-2

B. *Testing Procedure*

To evaluate the effect of relative humidity on the breakdown voltage, step-up AC and DC dielectric testing was implemented. Testing started at 4 kV and increased in 2 kV steps (250 v/s) until insulation breakdown. Each step took 10 s. The samples were stored at 20 and 40°C. For each temperature, four levels of humidity were selected (30, 50, 70, and 85%). For instance, two samples were stored for 24 h at a temperature of 40ºC and 85% r.H. This procedure was employed for each set of parameters listed in Table IV and followed with AC and DC dielectric testing.

TABLE IV
Environmental Conditions – 24 H

Temperature (°C)	20				40			
Humidity (% r.H.)	30	50	70	85	30	50	70	85

C. *Test Results*

AC high-voltage testing was implemented on the samples after 24 h under the various environmental conditions detailed in Table IV.

To assess the moisture content of the insulation system of green bars at the white stage, we investigated two factors: insulation resistance and capacitance.

As the moisture content of the green bars increased from 30 to 85%, the insulation resistance of the bars at the white stage decreased from 900 GΩ to 2 to 20 GΩ. However, differences in temperature had no significant effect on this trend (Fig. 9). Moreover, after drying the bars for 24 h at 90°C, insulation resistance increased to 2.2 TΩ. The minimum acceptable value for insulation resistance of coils/windings at the white stage is 1 GΩ (which is not a useful diagnostic criterion).

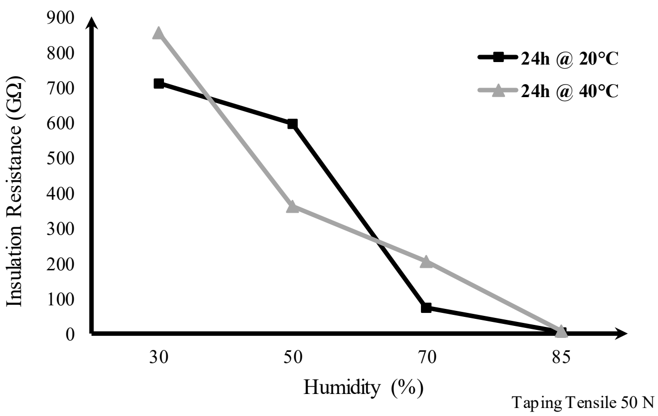

Fig. 9. Insulation resistance of green bars at different humidity and temperature.

Capacitance measurements of green bars at the white stage show that increasing moisture content raises capacitance (Fig. 10). The capacitance of green bars dried for 24 h at 90°C was almost 13 pF. Thus, capacitance measurement is not a useful indicator of moisture content.

The breakdown voltage results under AC voltage show that varying moisture content and temperature also has no significant effect (Fig. 11). Increasing the humidity from 30 to 85% r.H. results in no significant change in the AC breakdown voltage, with values in the range of 14 kV. The AC breakdown of green bars dried for 24 h at 90°C is almost 16 kV. This finding suggests that drying could enhance the function of insulation systems at the white stage.

The results of the DC breakdown voltages differed markedly from those for the AC breakdown voltages. Increasing the humidity (from 30 to 85% r.H.) led to a considerable decrease in DC breakdown voltage (to almost to 14 kV from 22 kV) (Fig. 11). Moreover, ambient temperature did not appear to have any substantial effect on the reduction trend. In contrast, the sample dried at 90°C for 24 h shows a huge increment—up to 25 kV—in the DC breakdown voltage.

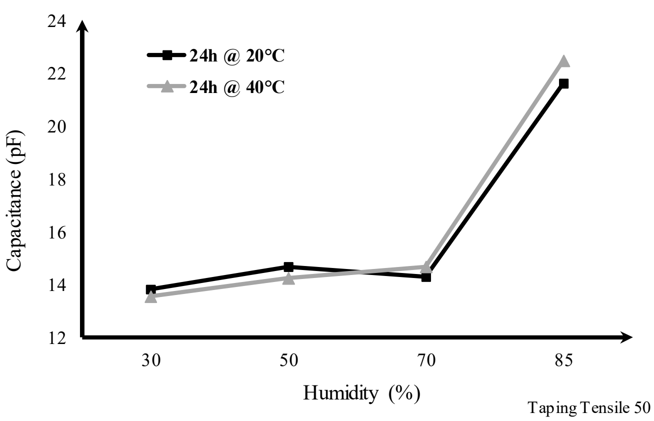

Fig. 10. Capacitance of green bars at different humidity and temperature.

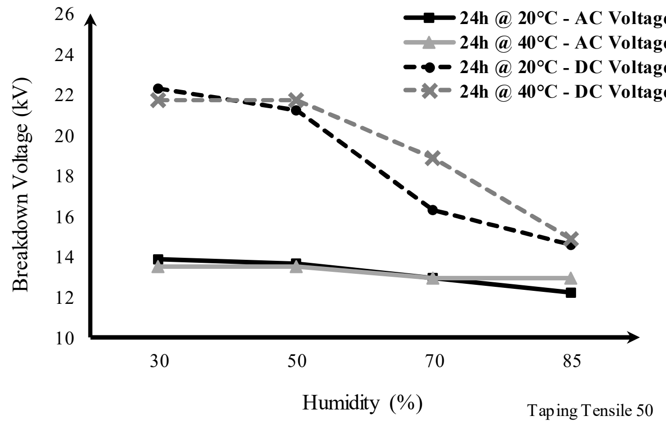

Fig. 11. AC and DC breakdown voltage at different humidity and temperature.

Furthermore, samples with tape tensile strength of 30 N were prepared and followed with dielectric tests. The results show an almost 20% increment in the breakdown voltage level after drying. However, the breakdown voltage of the bars with differing values of moisture content show a slight decrease. This could be because decreased tape tensile strength allows more space to absorb and release moisture.

IV. Summary

Increasing the moisture content of mica sheets reduces insulation resistance and increases the polarization current, capacitance and dissipation factor at low frequencies. However, because conductivity and permittivity are inversely related to frequency, increasing the frequency leads to decreasing the values of these factors.

The DC breakdown voltage of green coils at the white stage is considerably reduced by increased humidity and moisture content. However, the AC breakdown voltage shows no significant variation under the same environmental conditions. Thus, moisture content is an important consideration in setting appropriate voltage levels for diagnostic testing. The findings presented here highlight the importance of DC dielectric voltage testing, taking into account the moisture content of green coils/stators.

Measuring insulation resistance could provide a useful indicator for evaluating moisture content in unimpregnated coils/bars. However, current standards consider 1 GΩ to be an acceptable threshold value for initiating dielectric testing of insulation resistance, whereas our results show that insulation resistance is considerably higher than 1 GΩ for elevated moisture content. While the capacitance due low variation regards to different humidity levels could not be a proper index to define the moisture content of green coils/bars.

V. References

[1] IEEE Guide for Testing Turn Insulation of Form-Wound Stator Coils for Alternating-Current Electric Machines, IEEE Standard 522-2004 (Revision of IEEE Standard 522-1992), 2004.

[2] M. Stranges, D. Snopek, A. Younesi, and J. Dymond, "Effect of surge testing on unimpregnated ground insulation of VPI stator coils," *IEEE Trans. Ind. App.*, vol. 38, pp. 1460–1465, Sep./Oct. 2002.

[3] IEEE Recommended Practice for Voltage-Endurance Testing of Form-Wound Bars and Coils, IEEE Standard 1043-1996, Aug. 1997.
[4] IEEE Recommended Practice for Insulation Testing of AC Electric Machinery (2300 V and Above) With High Direct Voltage, IEEE Standard 95-2002 (Revision of IEEE Standard 95-1977), Apr. 2002.
[5] B. K. Gupta, G. C. Stone and J. Stein, "Stator winding hipot (high potential) testing," *2009 IEEE Electrical Insulation Conference*, Montreal, QC, 2009, pp. 409–413.
[6] W. Grubelnik and C. Stiefmaier, "Un-impregnated VPI tape testing and effects on dielectric performance of VIP insulation systems," in *IEEE Electr. Insulation Conf. (EIC),* Philadelphia, USA, 2014, pp. 359–362.