Advanced Mica-Polymer Composites for High Voltage Insulation - An unique & essential material

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ABSTRACT: Mica is essential for high voltage (>3 kV) insulation that demands corona resistance. The mineral mica, Muscovite and Phlogopite types, abundantly available in flake form has very limited application due to its rigid and brittle nature. However, owing to its split ability into micro thin flakes, mica is processed into reconstituted mica in paper form and converted into a flexible composite material (folium and tapes) by reinforcement with glass (E grade) fabric or polyimide film bonded with a synthetic thermosetting resin (namely, Epoxy or Silicone) in B-stage to enable its application in conductor and main coil insulation in high voltage rotating machines such as motors and generators.

The article overviews the characterisation of the reconstituted mica papers and their composites that include dielectric strength, dissipation factor (Tan δ), permittivity (ε), and partial discharge (p. d./corona) behaviour under thermal and high voltage endurance. Important features of application of advanced mica-composites using the conventional resin-rich technology vis-a-vis state-of-the-art VPI (vacuum pressure impregnation) technology currently employed in the manufacture of HV rotating machines have been discussed. VPI technology leads to a void-free insulation with incorporation of maximum mica content (up to 65-70%) resulting in the better performance in terms of lower dielectric losses and partial discharges under prolonged thermal and electrical stresses.

Index Terms: **Mica, insulation, electrical, high voltage, polymer**

I. INTRODUCTION:

Since the inception of High Voltage Engineering, mica has been used as an essential component of the insulation system [1,2]. In this article we shall discuss some of the latest technology and high performance insulating materials used in high voltage rotating machines e.g., generators and motors and fire resistant cables. All electrical rotating machines operating at high voltage (≥3kV) experience corona, i.e. electrical discharges which damage the insulation and result in failure of the machine. Mica is the only dielectric material which survives corona and extends significantly the life of insulation in high voltage machines. Reconstituted mica paper due to poor mechanical strength, is reinforced using variety of backing materials and synthetic resins and converted into folium or tapes to enable insulation of conductors and coils.

Natural Micas are complex mineral silicates of different types, of which the following two types are commercially used as dielectric insulating materials.

1. Muscovite mica, also called White mica, has the basic chemical composition $KH_2 Al_3 (SiO_4)_3 .2H_2O$. Major producers are India , Brazil and USA.
2. Phlogopite mica, also referred to as Amber mica, having the basic chemical composition $KH(MgF)_3 Mg Al(SiO_4)_3. H_2O$. Major producers are Madagaskar, Canada and Mexico.

The chemical composition and electrical properties of Muscovite and Phlogopite Mica, are presented in Table 1.

II. RECONSTITUTED MICA AND THEIR CHARACTERISTICS :

By thermal, chemical and mechanical treatments, mica is transformed in to a slurry of very fine platelets which are then processed to form mica paper, also called as reconstituted mica paper. Various grades of reconstituted mica paper are produced commercially depending upon the nature of the mica mineral used and the manufacturing process. Muscovite mica undergoes calcination at about 800°C in rotary kiln thereby losing the water of crystallisation. These grades are distinguished from each other by characteristic properties such as porosity, penetration/impregnability and tensile strength. Typical characteristics of four most commonly used grades of mica papers are shown in Table 2 and are classified as follows :

Class 1 : MPM-C(C) : Mica Paper Muscovite- Calcined (chemical process) ;
Class 2 : MPM-C(M) : Mica Paper Muscovite- Calcined (mechanical process) ;
Class 3 : MPM-U : Mica Paper Muscovite- Uncalcined ;
Class 4 : MPP-U : Mica Paper Phlogopite- Uncalcined .

Table No.1
Chemical composition and Electrical properties of mica [1]

Composition (%)	Muscovite	Phlogopite
SiO_2	44.6 - 46.7	37.9 - 43.2
Al_2O_3	30.0 - 38.5	12.2 - 17.0
K_2O	8.8 - 11.8	8.7 - 11.3
MgO	0.4 - 1.5	23.4 - 29.0
Water loss on ignition (%)	4.1 - 5.0	1.2 - 3.0
Electrical Properties		
Dielectric constant	6 - 8	5 – 6
Dielectric Strength, (kV/mm)	39 - 110	51 - 118
Resistivity , Ohm-Cm	10^{15} - 10^{16}	10^{13} - 10^{14}
Power factor	1 - 3 x 10^{-4}	1 - 5 x 10^{-3}
Corona Resistance	Corona resistant	Corona resistant

Table No. 2
Characteristics of a few typical Reconstituted Mica Papers used

Mica paper grade→ Characteristics ↓	MPM-C(C)	MPM-C(M)	MPM-U	MPP-U
Thickness, mm	0.05	0.115	0.093	0.10
Unit weight, gsm	60	150	120	160
Tensile sth, N/cm	6.0 (min.)	7.0 (min.)	6.0 (min.)	8.0 (min.)
Porosity, s/100m	10000 (max)	3500 (max)	400 (max)	1200 (max)
Impregnation time, s	35 - 75	70 - 150	10 – 30	35 - 65

III. COMPOSITE MATERIALS BASED ON RECONSTITUTED MICA PAPER :

Due to inherently low mechanical strength , the mica paper is laminated with various reinforcing materials and a thermosetting resin binder to produce high quality insulating material in the form of folium or tape in a semi-polymerised state « B- stage ». Following components are used :

3.1 Mica Paper : Suitable grade of mica paper is selected according to characteristics required such as porosity and impregnability depending upon the insulation technology to be employed in the electrical machine.

3.2 Reinforcement : Low Sodium oxide content electrical grade Glass fabric, polyimide film or polyester films of different thicknesses including heat–shrinkable grades, are used as reinforcing materials.

3.3 Binder Resin System : Epoxy resins based on bisphenol-A or novolac or trifunctional and cycloaliphatic epoxy resins are commonly used as binders with carefully selected latent hardener/accelerators for Thermal class F (Temperature Index 155) materials. Silicone Resins with suitable catalyst are used to provide flexible insulation with temperature index 220.

3.4 Accelerator: Proprietary accelerator/ catalyst for specific resin system are recommended by the resin manufacturer. Boron trifluoride-amino complex from Rhein Chemie, Germany and Zinc Naphthenate from BASF Germany have been used for catalytic curing of epoxy resin binder.

Suitable combinations of mica paper grade, backing material and the binder give rise to a series of composite insulating materials which find wide application in high voltage rotating machines. We shall discuss below a few typical products.

3.5 Processing of Mica Paper-Polymer Composites:
3.5.1 Resin-rich Composites:
a) Mica paper-Epoxy rich-Glass (Mp-Er-G) rigid composite tapes : Calcined mica paper is bonded with glass cloth using pre-accelerated epoxy-novolac varnish and laminated under rollers followed by drying & semi-polymerization in a horizontal drying machines having four temperature zones ranging from 70-150°C. Important process parameters to be controlled are varnish viscosity (11-15 s by DIN/LG cup), temperature and machine speed (2-5 M/min) in order to achieve the specified characteristics in the product. The product obtained in B-stage in the form of folium or tape is characterized with resin content about 30-35%.

b) Mica paper-Epoxy rich-Glass (Mp-Er-G) flexible composite tapes : The process is similar as above except using the pre-accelerated varnish based on polyester modified epoxy resin. Process parameters are maintained in the same range as above.

3.5.2 Resin-poor Composites:
a) Mica paper-Epoxy poor-Glass (Mp-Ep-G) composites: Uncalcined mica paper is used for this composite bonded with epoxy resin about 5-10% in the B-stage product. However they may be made with or without accelerator depending upon their

Table No.3
Characteristics of typical Mica paper-Polymer-Glass Composite Tapes

Characteristics	Mp-Er-G (resin rich)	Mp-Ep-G (resin poor)	Mp-Sip-G (resin poor)
Thickness, mm	0.18±0.03	0.14±0.02	0.12±0.02
Unit weight, gsm	265±25	200±20	164±10
Mica content, %	45±3	80±8	74±5
Resin content, %	40±4	7±2	7±3
Porosity (Gurleyhill), s/100ml	-	< 900	< 700
Tensile strength, Kg/cm width	20-25	7.0-12.0	10-15
Breakdown voltage, KV	6.0-9.0	1.5-2.0	1.0-2.0

application at later stage. Often the latent accelerator is incorporated in the epoxy binder in the composite itself which permits the vacuum pressure impregnation (VPI) with epoxy resin free of any accelerator having advantage of prolonged life.

b) Mica paper-Silicone poor-Glass (Mp-Sip-G) composites : It involves uncalcined mica paper backed with glass cloth bonded with low silicone resin content and calendared into a porous composite (folium/tapes) in B-stage.

Typical characteristics of epoxy and silicone bonded composites [2, 3] are shown in Table No.3.

IV. INSULATION TECHNOLOGY:

4.1 Resin-rich Technolgy: It involves use of resin-rich tapes (Mp-Er-G) for Conductor insulation (lower thickness range), Main insulation (higher thickness tapes) and Overhangs or end-windings with flexible grade (Mp-Er-G) tapes. Main insulation straight portion of coil is hot-compressed at 2.0 – 4.0 MPa in a hydraulic press for consolidation and curing [4], followed by removal from press and further curing of end-windings and post curing of whole coil at 160°C, 8 – 12 hrs in the oven.

4.2 Resin-poor Technology & VPI processing: It involves application of porous and resin-poor composite tapes (Mp-Ep-G or Mp-Sip-G) throughout the length of the coils using automatic taping machine providing uniform tension and avoiding any damage to the tape. The dry insulated coils are inserted in the stator slots as a part of the stator assembly. Next step is the resin impregnation under vacuum followed by pressure, in order to achieve a void-free insulation system. Complete stator assembly is placed in the impregnation chamber, preheated to 50°C and evacuated to ≤1mbar. Low viscosity solventless resin (epoxy or silicone) is fed from the bottom till the submersion of the assembly and held for an hour. Vacuum is then released and a pressure of dry air or nitrogen is applied at 4-6 bars for 4-6 hrs to allow complete penetration of resin. Thereafter the resin is drained back to storage chamber and impregnated assembly is removed and cured appropriately in the oven [2].

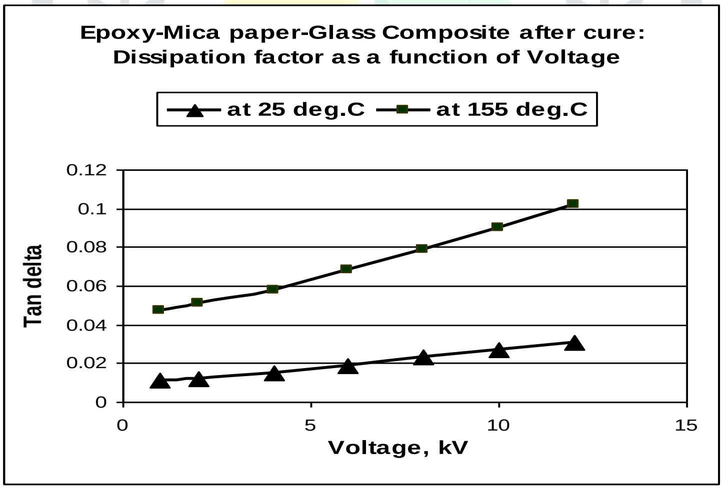

Fig.1: Plot of Dissipation factor vs. Voltage

V. CHARACTERISATION OF CURED COMPOSITE INSULATION:

5.1 Dielectric strength : The dielectric strength of cured laminate specimens rises upto 50 kV/mm with increase in mica content and becomes almost constant after about 60% mica content.

5.2 Dissipation Factor vs. Voltage: Measurement of dissipation factor (Tan δ) on insulated coil was conducted using 'Tettex' Schering Bridge model 2801 at different voltages upto 12 kV at power frequency 50Hz , and also at elevated temperatures from 25°C to 155°C. Effect of rise in voltage on Tan δ was studied and the comparative results are depicted in Fig.1.

5.3 Dissipation Factor vs. Temperature: Plots of Tan δ at 1 kV, 50Hz frequency against temperature up to 180°C shown in Fig.2 show very low values which do not increase appreciably with the rise in temperature.

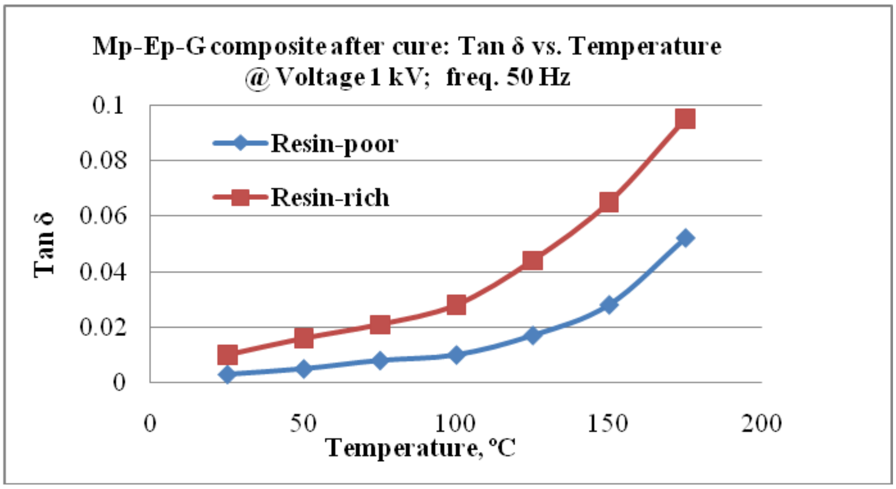

Fig.2: Plot of Tan δ vs. Temperature

5.4 Dielectric strength against thermal aging: The data on dielectric strength measurements on resin-poor Mica paper-silicone-glass composite tape insulated bars after VPI and curing, followed by heat aging at 220°C, 240°C and 270°C for 28 days is illustrated in Fig.3.

VI. RESULTS AND DISCUSSION :

Plots of Dissipation factor (Tan δ) against voltage (refer Fig.1) show very little increase with voltage upto 12 kV and temperature up to 155°C that indicates good resistance to corona and very low dissipation losses in the insulation under these conditions. It is to be noted from Fig.2 that the dissipation factor Tan δ values for the processed and cured resin poor Mp-Ep-G composite after VPI processing are far lower as compared to Mp-Er-G (resin rich) composite insulation. This indicates that the VPI processing after employing the resin-poor composites, is superior providing a void-free insulation as compared to the conventional resin-rich technology as shown by the higher Tan δ values for the later.

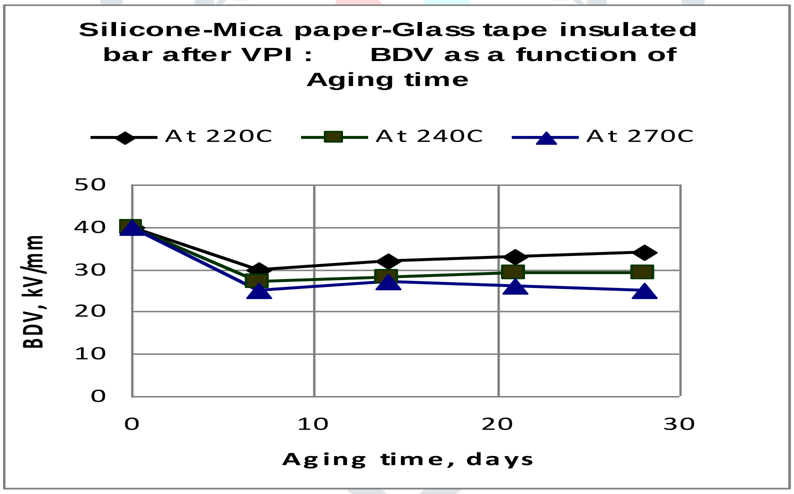

Fig.3 : Dielectric strength retention against thermal aging

Data and plots of thermal aging on insulated bars with thermal class H resin-poor composites based on mica paper-silicone-glass in Fig.3 show that initial decrease in BDV/dielectric strength may be attributed to the entrapment of residual volatiles formed during initial heating of VP impregnated insulation. Exact explanation requires further in depth study of the phenomenon. After about a weeks heat aging, a fairly good retention of the dielectric strength (between 33 and 25 kV/mm) is observed, and rather a marginal improvement in dielectric strength up to 240°C aging, has been noticed without any deterioration or discoloration, proving the healthiness of the insulation and suitability for application in Thermal class H (Th. Index 200) rotating machines such as traction motors.

VII. CONCLUSIONS:

Following conclusions can be drawn from the above studies:

i) Mica paper-Polymer-Glass composites based insulation, show a very little increase in Tan δ (0.03 and 0.10) with rise in temperature (25°C and 155°C respectively) and with rise in voltage (upto 12 kV), indicating very low dissipation losses and high resistance to corona, establishing their suitability as main insulation in high voltage rotating machines of Thermal class 155.

ii) Vacuum Pressure Impregnated (VPI) insulation system based on resin-poor Mica paper-Polymer-Glass composites, have lower Tan δ values at different temperatures than those for the Mica paper-Polymer-Glass composites processed with conventional resin-rich (hot compression) technology.

iii) Good retention of dielectric strength of VPI processed Mica paper-Silicone-Glass composite insulation after thermal aging at 220°C, 240°C and 270°C for 28 days with retained values in the range 35, 30 and 26 kV/mm respectively, show their suitability for application in high voltage machines of Thermal class 200.

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