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Silicone Based Electrical Insulation Material for High Speed/Voltage Rotating Machines

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Abstract

This paper introduces the key requirements for resin rich electrical insulation materials for rotating machinery. The key requirements, or stresses that insulation are subject to, are summarized as T.E.A.M. (thermal, electrical, ambient, and mechanical). Resin rich insulation materials can be based on silicone, epoxy, polyester, polyesterimide, and other polymers. Among all of these insulation materials, silicone based insulation best fits into many rotating machinery applications because of stability across a wide temperature range and the ability for highly thermally conductive designs. However, many medium and high voltage rotating machinery applications do not utilize resin rich silicone based insulation because of concerns about dielectric integrity and voltage endurance, especially with highly thermally conductive designs. Arlon has recently developed improvements in highly thermally conductive insulation designs with greater dielectric integrity and voltage endurance. These improvements coupled with temperature stability and elasticity provide an excellent design platform for electrical insulation to be utilized in a next generation of rotating machinery.

Content

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1. Introduction

Electrical insulation materials are pervasive in our life and work. Every piece of electrical equipment contains an insulation material. In the past century, the large-scale use of polymeric materials for electrical insulation purposes has resulted from the excellent electrical properties and process ability of polymeric material [1-2].

Electrical rotating machinery rated at >1 KW is classified into two categories: 1) motor, which converts electrical energy into mechanical energy, 2) generator or alternator, which converts mechanical energy into electrical energy. Motors and generators can be either alternating current (AC) or direct current (DC). Most motors and generators consist of a stator winding and a rotor winding which require electrical insulation materials [3].

The basic stator insulation system components are shown in **Figure 1**. These insulation components together ensure that an electrical short does not occur, that the heat from the conductor losses are transmitted to a heat sink, and that the conductor does not vibrate in spite of the magnetic force [3].

- Strand insulation – to reduce skin effect of copper strands
- Turn insulation – to prevent electrical short between turns. In some applications, there is no strand insulation. In those applications, turn insulation can be also called conductor insulation.
- Groundwall insulation – to prevent ground fault from high potential.

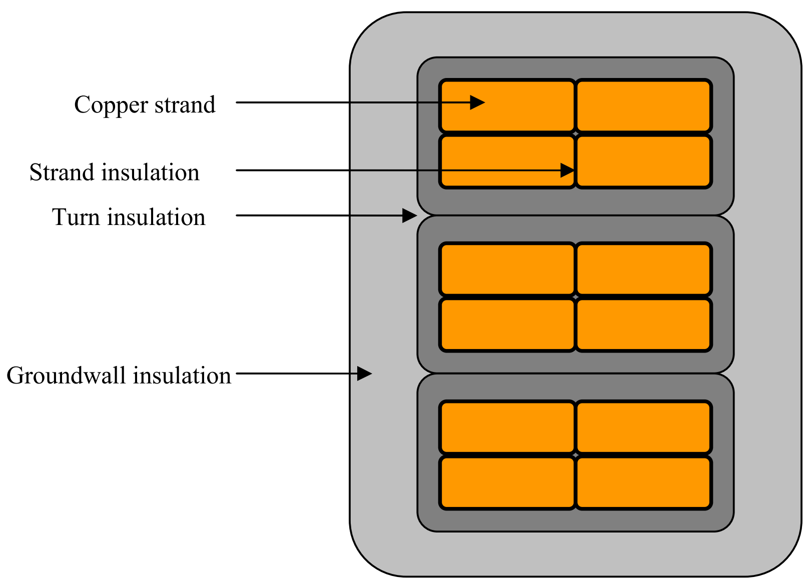

Figure 1 The cross section of a typical insulated stator coil

The insulation materials of a rotor winding include turn insulation and ground wall insulation. Turn insulation and groundwall insulation in a rotor can be relatively thin since the voltage in a rotor is typically lower than that in a stator. However, the rotor winding insulation must have very high compression strength, good abrasion strength and be supported to prevent distortion due to high rotational force in the rotor [3].

2. Overview of Insulation Materials for Rotating Machinery

The selection of electrical insulation systems for rotating machines depends on the materials available, cost, and the technical requirements in machine design. Since the industry began a century ago, insulation materials have been evolving from natural materials to mainly synthesized polymeric materials. The following insulations currently dominate the industry.

2.1 Mica

The outstanding dielectric and thermal endurance, inertness, and nonflammable characteristics of mica separate it from all other insulating materials [6]. For more than a century mica as a natural inorganic material has proven to be a reliable and persistent insulating material for groundwall insulation, although its application requires some elaborateness [4]. Mica is unique amongst materials in having a high resistance to partial discharge therefore increasing the voltage endurance and prolonging the life of insulation materials. It is generally believed that the mechanism responsible for this protective behavior is electrical in nature and not physical. The high energy electrons resulting from partial discharge are slowed down and de-energized by the strong positive fields generated by the array of K^+ ions held within the silicate lattice galleries. It is this effect which is apparently primarily responsible for the protective nature of mica in high voltage insulation system [5].

Since mica as an inorganic flake material lacks integration and flexibility, mica has to be combined with other insulation materials like polyester, epoxy and silicone as a resin rich tape or via vacuum pressure impregnation.

2.2 Polyester

Polyester can be used as a coating for strand/conductor insulation and a resin rich mica tape for groundwall insulation. Polyester has limited application in the VPI process. Polyester has a relatively low thermal class (less than class F). However, polyester is a good low cost option as an insulating polymer.

2.3 Epoxy

Epoxy resin is mainly used in high voltage insulation systems as binder resin for resin rich mica tapes in groundwall insulation or as an impregnating resin in the VPI process. Its main function includes: [4]

- Laminates the mica tape
- Fills the voids in mica flakes
- Provides good adhesion to the conductors
- Provides mechanical strength
- Protects against chemicals, dirt and humidity

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With a decent thermal class of F to H, solventless epoxy resin with low viscosity, <300cps, is dominating the VPI process.

2.4 Polyimide

Polyimide or polyesterimide can be used as a coating for strand/conductor insulation and as the polymer resin in the resin rich mica tape for groundwall insulation. Polyimide has a higher thermal class than epoxy resin. With the trend toward higher voltage motors with higher thermal classes (class F → H or higher), low viscosity polyesterimide resin has become more and more popular in the VPI process as an epoxy resin replacement.

2.5 Silicone

Silicone rubber can be used as turn insulation and groundwall insulation. Silicone resin can be used as a coating for strand/conductor insulation and impregnating resin in the VPI process. Silicone rubber and silicone resin have the best-in-class thermal rating (>class H). Silicone rubber is the only available insulation material which is elastic and flexible. The elastomeric property is very important for thermal mechanical decoupling and anti-vibration.

3. Key Requirements for Insulation Materials in High Speed/Voltage Rotating Machines

High speed, high voltage rotating machines operate in harsh industrial environments. These machines have higher requirements for electrical insulation materials than the conventional rotating machines. These requirements may include:

- **Enhanced electrical properties**. Since the operation voltage is higher, the electrical insulation materials must be able to handle higher voltage as well. The improvement in dielectric breakdown strength, voltage endurance, and partial discharge resistance will result in a thinner insulation material. Then, the rotation machines' power density or power to weight ratio can increase as well. Thinner insulation materials also result in a faster heat transfer rate so the machines can operate at cooler temperature. Furthermore, if the dissipation factor (loss tangent or $\tan\delta$ which provides an indication of the dielectric loss within insulation) of the insulation material is lower, it generates less heat, and consequently thermal stress on the insulation material will be reduced.

- **Higher thermal stability**. At high speed and voltage, the rotating machines generate more heat than conventional rotating machines and therefore electrical insulation materials may be required to operate at higher temperature. This requires that the electrical insulation materials have higher thermal stability to meet operational life requirements of the rotating machines. In general, a thermal class greater than H is necessary for these types of rotating machines.

- **Higher thermal conductivity**. All metal parts in rotating machines have very high thermal conductivity (Tc>50W/mK). Insulation materials based on polymers are the weak link for heat transfer since all polymers have relatively lower thermal conductivity (Tc<0.5W/mK).

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Higher thermal conductivity of insulation material can help heat to transfer faster and minimize thermal stress on the insulation materials. Consequently, rotating machines can be designed with smaller size, higher speed, and higher power density.

4. Arlon NG Silicone Based Insulation Materials

Arlon's 51228R*** product has been widely used as traction motor coil insulation in the locomotive industry. Decades of real-world experience have proven the reliability of this resin rich, silicone impregnated fiberglass insulation. However, targeted design upgrades can dramatically improve electrical properties, thermal stability and thermal conductivity. Recent technology advances have led to a next generation coil insulation product, labeled as "Arlon NG" in this paper. The "Arlon NG" properties are compared to the 51228R*** product, labeled as "Arlon incumbent".

4.1 Dielectric breakdown strength

In this study, dielectric breakdown strength is tested by Arlon test method--SQA-TMS-020 which is similar to ASTM D149. Test equipment is Hipotronics Model 750-2/D149-15A. Both "Arlon NG" and "Arlon incumbent" specimens are the fully cured, silicone rubber sheets (0.25 mm thick). Dielectric breakdown strength (unit=kv/mm) of "Arlon NG" is much higher than that of "Arlon incumbent", as shown in the Weibull probability plot of **Figure 2**. This indicates that thinner insulation material with "Arlon NG" can perform the same function as a thicker "Arlon incumbent".

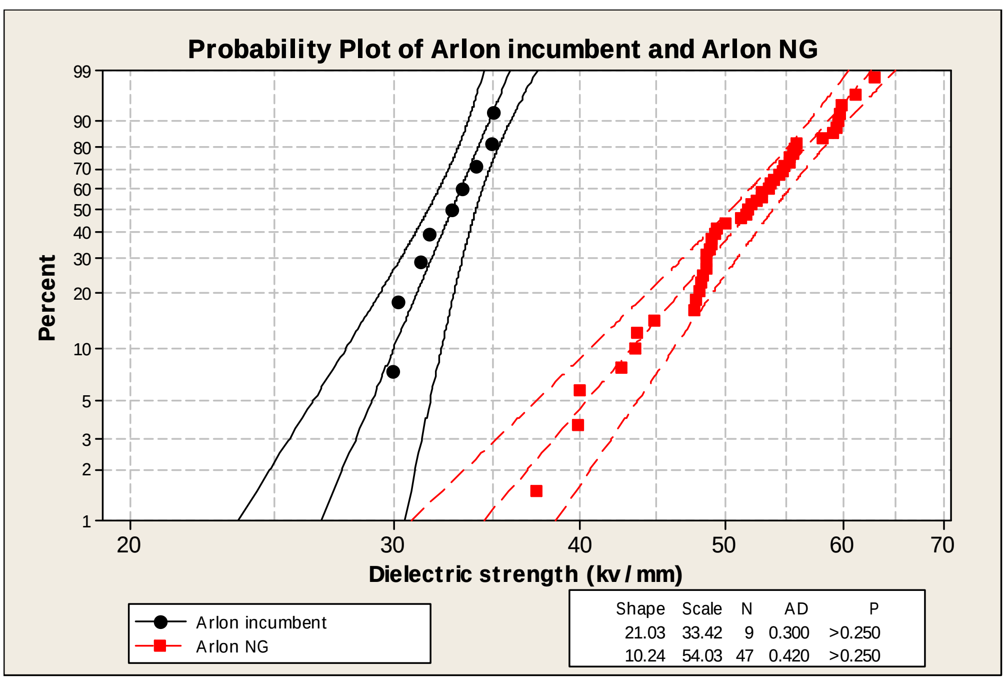

Figure 2 Dielectric Breakdown Strength of "Arlon incumbent" and "Arlon NG"

4.2 Voltage endurance

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A voltage endurance test is closer to a real world application analysis than a dielectric breakdown strength test. IEC 61251 describes that the relationship between voltage and voltage endurance time is given by the **Equation (1)** as follows [9]:

$$L = cE^{n} \quad \textbf{(1)}$$

Where, "L" is voltage endurance time;
"E" is voltage;
"c" and "n" are constants dependent on temperature and other environmental conditions.

The voltage endurance test in this study is based on ASTM D2275 and IEC 61251. Test equipment is Hipotronics Model 750-2/D149-15A. Ambient temperature is room temperature (~20ºC). The longest test cycle time is 178 min. Both "Arlon NG" and "Arlon incumbent" samples are 0.25 mm thick, fully cured, silicone rubber sheets. Five points are tested for each voltage. The median voltage endurance time is used as recorded result. The results are shown in **Figure 3**. At the same voltage, "Arlon NG" can last much longer than "Arlon incumbent". This result is consistent to the result of dielectric breakdown strength analysis. Higher dielectric breakdown strength correlates to longer voltage endurance time.

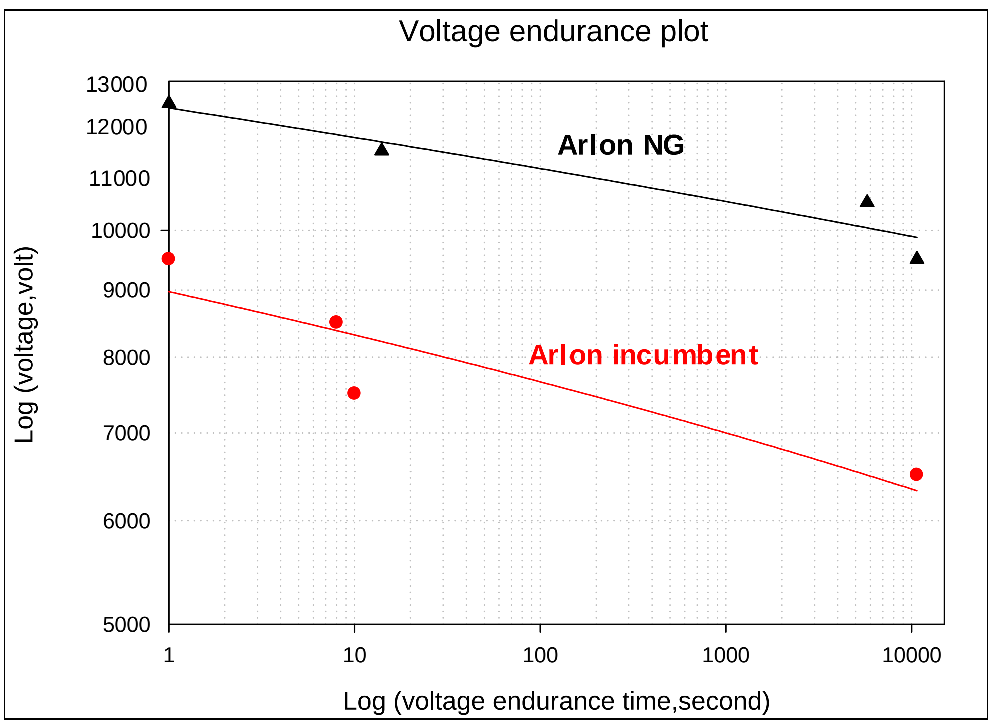

Figure 3 Voltage endurance plot based on Equation (1)

4.3 Thermal Conductivity

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Thermal conductivity is analyzed using Arlon test method SQA-TMS-022, which is based on ASTM E1530. Test equipment—TCA-300. **Figure 4** shows that the thermal conductivity of "Arlon NG" is much higher than "Arlon incumbent". This will allow heat to transfer away from copper strands much faster. Consequently, the insulation material can operate at a relatively lower temperature and have a longer service life. This becomes more important for the high speed/voltage rotating machinery which generates much more heat than the conventional rotating machinery. Thermal conductivity (1.2 W/mK) is much higher than the results in recent literature [7-8].

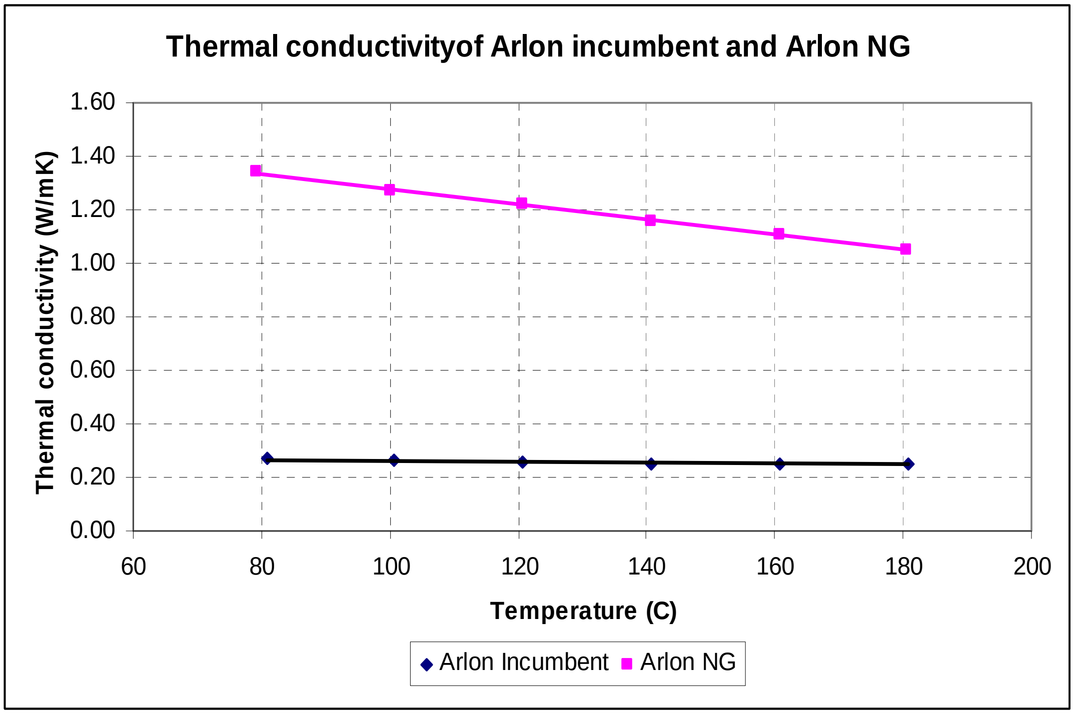

Figure 4 Thermal conductivity of "Arlon incumbent" and "Arlon NG"

4.4 Thermal Stability

Thermal stability is characterized by tensile strength retention, elongation retention, and durometer change before and after thermal aging at 300ºC air-circulated oven for 24 hr. "Arlon NG" is specially formulated for much better thermal stability than "Arlon incumbent", as shown in **Table 2**. This indicates that "Arlon NG" can have a much longer service life than "Arlon incumbent". Although they are not compared with other materials like epoxy polyester based insulation in this paper, silicone based insulation materials are well known for excellent thermal stability.

Table 2 The thermal stability test result of "Arlon incumbent" and "Arlon NG"

Property change after 300ºC*24hr	Arlon incumbent	Arlon NG
Tensile strength retention (%)	63%	102%
Elongation retention (%)	4%	30%
Durometer change (Shore A)	+27	+4

5. Conclusion

Silicone-based, resin rich coil insulation materials have been widely used in rotating machinery due to best-in-class thermal stability, flexibility, anti-vibration, and excellent electrical properties. Arlon has designed a next generation, resin rich, coil insulation material with: 60% higher dielectric breakdown strength (51 kv/mm versus 31 kv/mm); significantly longer voltage endurance; a factor of four increase in thermal conductivity (1.2 W/mK versus 0.3 W/mK); and better thermal stability versus the incumbent insulation material. These properties provide a good design platform for high speed/high voltage rotating machinery insulation systems.

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