ENERGY

Electric powertrains provide new challenges for insulation materials

By Dr David Simkin, Principal Engineer (Power Electronics and Electric Machines)

A short history of insulating materials

Since the early days of experiments with electricity, people have found ways of ensuring that they and electricity were kept apart. This involved putting an outer sleeve of insulating material around the conductor to isolate them from the voltage. In the 1800s the experience of the textile industry working with silk and cotton fibres was used to create manufacturing machines to cover the wires in thread. The Science Museum in London has some of the early winding equipment designed for covering wire on display in its galleries (Figure 1).

Figure 1: Science Museum Group. Machine used for covering wires with silk and cotton, 1837. 1939-139 Science Museum Group Collection Online, https://collection.sciencemuseumgroup.org.uk/objects/co44548/machine-used-for-covering-wires-with-silk-and-cotton-1837-winding-machine

Until the early 1900s, the materials used as insulators were naturally occurring ones, such as rubber or cotton. These cables operated successfully at voltages up to 1000V. However, a change was needed when the Edison direct current electric systems lost out to the alternating current (AC) system proposed by Westinghouse as the long-distance transmission of AC electricity required voltages of over 13,000V. The available natural insulation materials could not be used at these voltages so new insulation methods were developed. The conductors were covered with oil impregnated paper with lead outer sheaths. Cables made in this way were still in daily operation until the late 1960s, over 50 years after installation.

The effect of the aging of insulation over time in applications was not considered until the 1900s. In 1913, Steinmetz and Lamme considered how temperature affects the life of electrical insulators. Their measurements only provided a general view that the insulation in an electrical machine aged more rapidly at higher temperatures. Some early ideas from this period were rejected as more experience was gained, for instance, it was thought that insulation would recover if left at lower temperatures. Unfortunately, this isn’t the case.

As well as good electrical properties the insulation materials needed to meet mechanical, thermal and chemical requirements. These physical properties were difficult to meet with naturally occurring materials. The challenge of high voltage aging of wire insulation was solved in the 1930s when synthetic plastics became available which could replace the natural products. The physical properties of the new synthetic plastics could be tailored to the needs of the application, such as high humidity or high temperature, by changing their chemical composition. There were so many different polymers available that the selection of materials was often only based on personal experience. Standardisation was needed.

A new set of temperature classifications was defined in the 1950s to replace the material-based standards (Table 1). This was initially assigned based either on the insulation material itself or on the results of aging tests. The standards were changed to be only based on material test results in the 1980s as the complexity of the insulator needs was better understood.

These tests are expensive to perform and time consuming for a new material. However, they provide confidence that the material is a good fit for the application. The classes are based on the aging properties and the ability of the insulator to be reliably used at their required operating temperature for 20,000 hours.

IEC 60085 thermal class	Old IEC letter designation
120	B
155	F
180	H
220	R
Over 250	C

Table 1: Standardised temperature classifications of insulators

Why is there renewed interest in insulators?

To make the transition to net-zero carbon emissions for the UK economy by 2050 there must be the adoption of electrified transport. Electric cars are steadily replacing combustion engines in vehicles driven by customer demand. The UK government has accelerated this transition by banning the sale of new petrol and diesel vehicles by 2030, with hybrid vehicles facing the same fate 5-years later. Even before this, there were huge incentives for vehicle manufacturers to reduce the overall CO_2 emissions of their vehicle fleet. In the EU, large fines are imposed for not meeting average car fleet emissions. Figure 2 shows the expected emissions for vehicle fleets in 2015 and 2021. The vehicle manufacturers all need to reduce their emissions to meet the 2021 target. In 2020 Fiat paid over €300 million to purchase carbon credits from Tesla to ensure that Fiat met the overall emission standards for its fleet. Fiat does not anticipate doing this in 2022 as they are steadily reducing the emissions of their vehicle range.

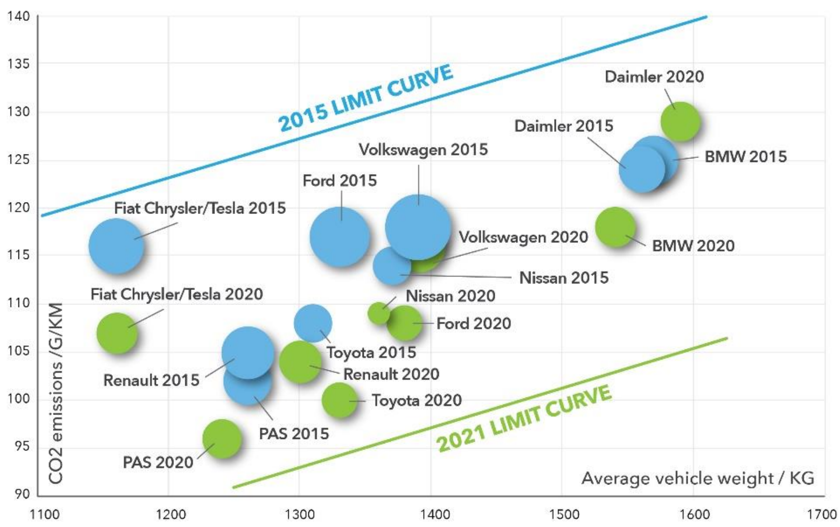

Figure 2 Emission targets 2015 to 2021

New challenges for insulation materials

Higher voltages

One of the new challenges of the insulation system in the electric vehicle market is the transition to higher electrical voltages for the electrical machines. This allows vehicles to be charged more quickly and so reduce the range anxiety many people feel when considering the transition to owning an all-electric car. For example, an 800V based system could be charged in around 20 minutes, given the appropriate charging system, whereas a 400V system would take 80 minutes to get to the same level of charge. The higher voltage systems can also be lower cost, lower weight and higher efficiency. This is principally due to less copper being used in the windings.

This increase in the system voltage results in the insulation in the electric traction system needing to survive greater electrical stresses. The unfortunate consequence of the change from a 400V to an 800V system is that at 400V the system could be considered as partial discharge free, known as Type I insulation, whereas at 800V you need to consider that partial discharges will occur, known as Type II insulation. There is also the additional consideration that above 800V coronas can form around the wires which also degrade the wire (see the separate section on partial discharge). Both of these mean the long-term reliability of the insulation material must be considered.

Silicon carbide power electronics

A second challenge for wire insulation is the transition from silicon-based (Si) power electronics to silicon carbide (SiC). Silicon carbide power electronics are more efficient than their Si counterparts. Whereas silicon power electronics are generally 96% efficient, for SiC the system losses are reduced by around 80%, and so can provide efficiencies of over 98%. This reduction is due to the reduced energy lost in the SiC switch during the “on” time of the switch, the grey area shown in Figure 3. As the SiC switch has a lower “on” resistance the energy loss due to the current is reduced. The 2% improvement in efficiency is important for a battery electric vehicle as the batteries are the largest cost item in the vehicle, being approximately 65% of the total build costs. An improvement in system efficiency allows a reduction of the battery capacity to achieve the required vehicle range. The automotive manufacturers are passionate to reduce cost to remain competitive so even though SiC electronics are several times more expensive than their Si counterparts there is still a drive to move to SiC CCOSFET technology for new designs

The challenge for the wire insulation is that it needs to cope with the rapid changes in voltage, dV/dt, that happen at each ‘switch on’ and ‘switch off’ cycle of the power electronics. The voltage differences created across each turn of wire during these switching cycles leads to degradation of the insulation and so to shorter lifetimes for the insulation in the electrical machine.

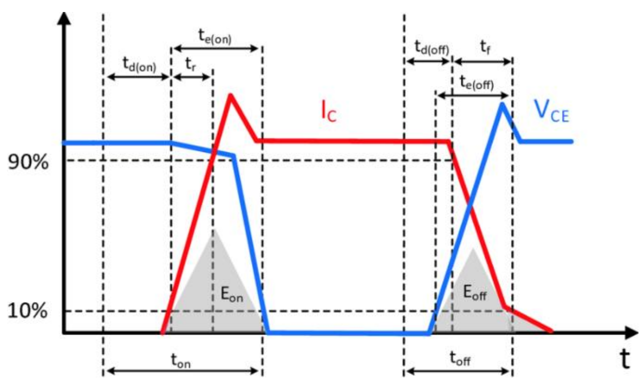

Figure 3 Switching losses in power electronics

Temperature

The third challenge is the temperature that the electrical wire needs to operate at. In many modern eMachines there is a limitation on the eMachine temperature imposed by the permanent magnet material used in the rotor. For vehicle traction, the magnet option is almost always neodymium-iron-boron (NEO) magnets. Temperatures above 150°C can lead to permanent demagnetisation of the magnets in the rotor. Temperature sensors are fitted to ensure this temperature is not reached. The current in the stator windings is reduced if the temperature becomes too high, this is known as derating.

The use of permanent magnet materials is being reconsidered as the costs can vary dramatically over time and their sourcing from China cannot be guaranteed. The challenges of NEO magnets were discussed by Dr Stuart Bradley, The Impact of Rare Earth Elements on the Transition to a Low-Carbon Economy. For an eMachine without magnets, the temperature of the eMachine is limited by the temperature the insulation system can withstand.

Consideration needs to be made of the other conditions on the wires that may cause the insulation to age. For instance, is it subject to vibration or is it sprayed with oil for cooling?

Thermal conductivity

The conductors get hot due to resistive losses which depend on the square of the current *(I^2)* in the coils. This heat must be removed so the coils do not overheat. To reduce the temperature rise of the eMachine the resistive heat from the windings must be transferred into a cooling medium. The electrical insulation prevents this heat transfer as it acts as a thermal barrier.

Material	Thermal conductivity /W/(mK.)
Polyamide/imide enamel	**0.26**
PEEK	**0.29**
PPS	**0.35**

Table 2: Thermal properties of insulating polymers

One way to reduce the thermal barrier is to use thinner insulation, which will consequently fail at lower voltages, as highlighted earlier. Another is to use an insulation material with a better thermal conductivity. This can be achieved by adding a filler to the material. However, this then makes the insulation hard to bend without cracking the insulation. If a coating material can be used which is naturally thermally conducting this will reduce the temperature of the assembly.

Partial discharge and corona discharge

The International Electrical Committee or IEC standards split insulation systems into two types, Type I (below 700V) and Type II (above 700V). Type I insulation systems are intended for use where there is no partial discharge (PD) throughout their life. The pass criterion is that PD inception occurs above the operating voltage of the eMachine multiplied by enhancement factors depending on the operating conditions, such as overvoltage or operating temperature.

For Type II insulation, partial discharge is expected during the life of the eMachine and the overall lifetime of the insulation is reduced as a result. The longer the eMachine is operated, the more likely the insulation is to fail. The IEC standards fix 20,000 hours as the expected standard lifetime.

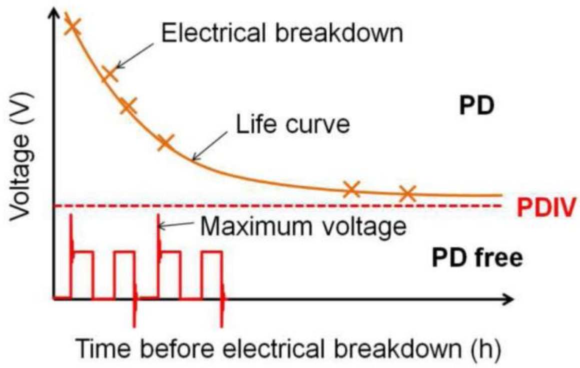

Figure 4 The effect of partial discharge on the time to failure of the insulation

If the voltages are kept below the partial discharge inception votage (PDIV) – Type I insulation – the eMachine insulation will not degrade significantly, see Figure 4. If the voltages are above the PDIV then the insulation will steadily deteriorate until it falls to the level where the insulation no longer protects the eMachine coils.

PD resistance materials can be created which have a smaller aging rate than normal insulation materials. This can be done by adding nanoparticles of polymer to the enamel when creating the wire coating. This is a forced choice as this only delays the degradation of the insulation and does not prevent it. Hence, in the initial design of the eMachine insulation system, the designer must consider the reliability of the insulation in addition to considering the electrical voltage that it needs to withstand.

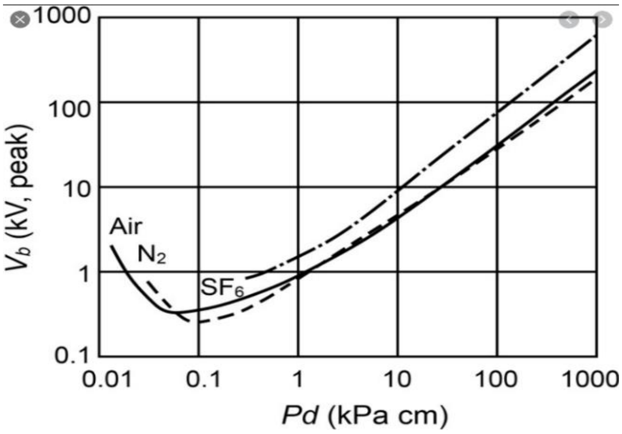

Figure 5 The electrical breakdown of air at different altitudes

Corona discharge at the surface occurs when the voltage is increased to over 800V. This is a surface effect and is due to discharges that occur on the surface of the insulation in contact with the air. Tests are made under oil to remove the surface discharge effect and measure true material parameters. In most eMachine applications, flooding the system with oil is not possible so surface corona discharge will occur. An outer layer of a corona resistant material can be applied, normally a graphite coated polyester tape. However, this is both difficult to apply during manufacture and the additional layer increases the thermal barrier between the hot copper winding and the coolant system.

For aerospace applications, PD is an even greater challenge. At the low air pressures that occur at altitude, surface corona discharge occurs at even lower inception voltages thus making aerospace applications even more challenging for high voltage eMachines. The change in PD with altitude can be estimated from Paschen's Law, a plot of which is shown in Figure 5.

The major reason for the initiation of failure of a high voltage eMachine in service is the failure of the insulation. The main contributor to this is the partial discharge that occurs as the insulation deteriorates over the life of the eMachine. As we move to higher voltage eMachines in our transport system, reducing the partial discharge in the eMachines by considering new materials will provide us with longer lasting and more reliable motoring for all.

New materials for new challenges

The standard wire insulation material for eMachines is enamel. Enamel is coated onto the wire by passing the wire either through felt pads or a nozzle. For the larger diameter wires used in eMachines, the wire is passed through multiple nozzles which each add a thin layer of enamel of less than 1µm on each pass. The enamel is then dried in a vertical tower. This manufacturing process is good for coating thicknesses up to 120µm, beyond that point, there are challenges to retain the reliability of the enamel coating. The result is that, in general, thicker enamel coatings do not give the increase in time to failure that would be expected.

An empirical expression was proposed in the 1940's by Dakin relating the PDIV to the insulation thickness;

$$V = 163 \, . \left(\frac{t}{\varepsilon_r}\right)^{0.46}$$

Where; V is the PDIV (in rms)

ε_r is the relative permittivity and

t is the insulation thickness in µm.

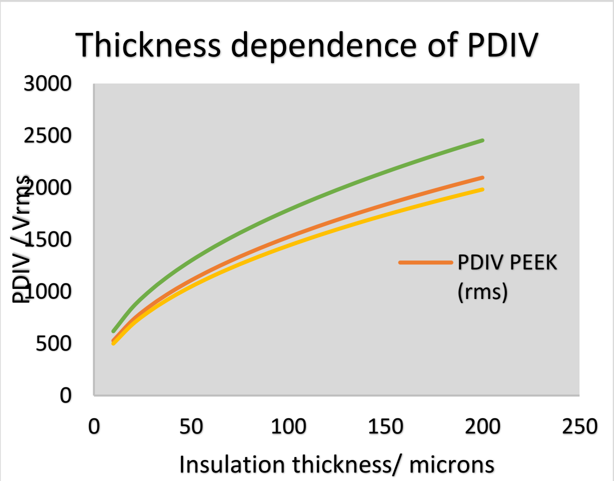

Figure 6 The effect of the insulation thickness on partial discharge voltage

The Dakin equation illustrates that as the thickness of the insulation is increased, the PDIV will increase – see Figure 6. It also shows that if the permittivity of the insulation can be reduced, the PDIV can be increased. This later effect has led to the development of foamed enamel layers to reduce the permittivity of the insulation and so increases the PDIV for a fixed thickness.

From Figure 6 it can also be seen that to give a reasonable safety factor for eMachine operating at an 800V base voltage, the insulation needs to be at least 70µm. For base voltages of over 1,200 V, which is well within the capabilities of SiC invertors, the insulation needs to be over 120µm. At this thickness, enamel coatings can be difficult to form.

Melt extrusion can be used to coat wire. In this case, a thermoplastic polymer is coated as a melt over the electrical conductor. This has the advantage that the coating thickness can be larger without creating challenges for the manufacturing process. Extrusion coatings up to 200 µm are easy to form whereas enamel layers of this thickness can be of poor quality unless additional coating stages are used.

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Summary

Over the past two hundred years, the challenges of insulation have changed as the applications of electrical equipment have evolved. Now there is a need to create more sustainable methods of mass transport by transitioning to fully electric vehicles. This has opened new opportunities for insulation, and so a mature technology has needed to reconsider the materials and coating processes it uses to meet these challenges. An exciting period lies ahead for the electrical insulation industry as it strives to supply the electric transportation market with the reliability and technical capabilities that are needed in the very competitive automotive market.

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