Comparative Assessment of Impregnating Agents in Electrical Insulation Systems

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Introduction

Winding systems are distinguished by type or by application, as round-wire conductors (low-voltage range, i.e. less than 1000V), which are coated with insulating enamel, and flat copper wires with rectangular cross section for high-voltage machines. These flat copper wires are wound with fine mica, and may additionally be coated with insulating enamel.

With low-voltage machines, the insulated wires are “trickled in” to the slots of the laminated core. Additional insulating materials are also used for the slots, such as slot liners, separators, drive strips, and in the winding head region phase insulation and tapes for reinforcement.

The slots are additionally lined with insulating paper, which mostly comprises a temperature-resistant multi-layer material. The name insulating paper is derived from the method of production, because these multi-layer materials are made, or laminated, on “paper machines”.

The insulation effect of the impregnating resin is not taken into account in calculation of the parameters for insulation of an electrical machine. However, that should not lead to the assumption that the machines could be operated in “dry” state even for a short period. On the contrary, the quality of the impregnation (as far as possible air-free filling of the winding with insulating resin) is critical for the service life of a machine.

The major functions of the resin are mechanical fixing of the winding and insulating materials, thus ensuring good vibration resistance of the machine, and sealing of the winding, for protection from environmental influences such as moisture, dust, salt, etc. Heat dissipation is also improved by good impregnation.

What resin systems are suitable for the windings of electric machines?

The following points give a brief overview of problems and insights in the assessment of impregnating agents.

Temperature index

An important criterion in use of insulation materials is the temperature index. But the sum of all temperature indices of the insulating materials used is not enough to draw conclusions about the temperature index of an electrical machine.

The assignment of a temperature index to a certain insulating material is often not as clear-cut as it seems; it is no coincidence that the temperature indices of various materials have been changed from time to time, although there has been no change in the materials themselves.

Nevertheless, the temperature index continues to be an important criterion for assessment of service life, and alongside the technical data it is one of the most important parameters of a machine.

Unfortunately, the temperature index is hard to determine, despite the fact that precise figures are often given. Life depends on a number of factors which can be represented only very roughly by tests. And the further away a model is from reality, the harder it is to assess the temperature index or to derive life duration from it. Even test series with simulations of windings (also known as “motorettes”) can only be a partial simulation of real conditions. It is only possible to do approximate “modelling” of voltage, vibration and temperature loads and environmental influences that prevail locally in a rotating machine. But parameters which may otherwise be neglected can become decisive factors in large machines or generators.

To take the example of just one case out of the many that occur in practice: magnetic slot wedges which were available for a long time as Class H material were downgraded to Class F although no change was made in the wedges.

Resin types

The following table gives a rough overview of all chemical types of resin that are available. UP resins on polyester imide basis, or epoxy resins are almost always used due to the mechanical characteristics required for electric machine construction. Silicone resin is mainly used for the traction machine area (railway and tram motors), although the disadvantage of poor mechanical characteristics versus the advantage of higher thermal stability is a matter for discussion.

	Alkyd	Urethane	Phenol	Polyester	Polyester-imide	Epoxies	Silicone
Temperature index	155	130	180	180/200	180/200	180	220
Peak temperature	180	155	200	240	280	240	260
Mech. properties	–	–	+	o	+	++	–
Elasticity	+	++	–	–	+	+	++
Chem. stability	+	o	++	+	+	++	o
Dielectric strength	1 kV	1 kV	1 kV	6.6 kV	15.8 kV	25 kV	6.6 kV

Table 1: Comparison of principal properties of various chemical families of resins. Specific resin formulations may have properties differing from those shown in this table

The polyester resins (known as UP resins for short) can be subdivided roughly into resins mainly containing styrene or styrene derivatives (especially vinyl toluene), acrylates, diallyl phthalates or oligomer cross-linkable substances. The main component in all cases is maleic or fumaric acid (whereby the relationship of these two isomers has a decisive influence on the physical properties). All currently used temperature-resistant UP resins contain imide structures (mostly of a cyclical nature). It must be noted that the distinction between UP and UPI resins is generally not used, or else it is used inaccurately. Thus in the motor and generator industry, the description UP resin is generally used for polyester imide resin.

In general terms, polyester imide resins are used in the low-voltage area (round-wire machines), and epoxy resins in the high-voltage area (machines with form coils and fine mica insulation). In the event that this rule of thumb is not observed, the following should be noted:

Application of UPI resins for series-wound motors

High-voltage coils which are impregnated with polyester imide resins mostly exhibit very high tan δ values, especially at higher temperatures (which are in the area of the operating temperatures of high-voltage machines). It is suspected that the extreme softening (modulus of elasticity) of most resins can be associated with that. In order to get acceptable tan δ values, it would probably be necessary to resort mainly to UP resins with styrene or vinyl toluene (e.g. Dobeckan FT2015).

Application of EP resins for shunt-wound motors

Epoxy resins are less suitable for application in the low-voltage area, i.e. specifically for round-wire windings with polyamide imide enamelled wire, and specifically for large motors or generators.

Tests using models normally show failures after ageing by temperature and vibration. The cause is probably that the adhesion of EP resins on the wire enamel is so great that if there are gaps or cracks in the resin (caused by mechanical loads and/or temperature expansion) they reach down to the blank copper, i.e. they also tear away the enamel insulation of the copper wire.

Physical properties of polyester imide resins

The glass transition point of polymers gives important indicators for the form stability of the polymers on heating, and thus indications of the temperature range in which the polymers can be used. The glass transition point is the temperature at which amorphous or partially crystalline polymers change from the liquid or rubber-elastic condition to the hard-elastic or glass state, or vice versa. The reason for the phenomenon of the glass transition temperature is to be found in the freezing or thawing of the Brownian molecular movements of longer chain segments of the polymers. When the glass transition point (also known as the softening or fusion point) is reached, there is a drastic change in the physical parameters such as hardness, modulus, volume, enthalpy and entropy.

With complex structured polymers, determination of the glass transition temperature is often difficult or even impossible, because there are often several transition points and/or the ranges of the conversion interval may be very great.

Dobeckan FT2015 is a vinyl toluene resin with a fairly simple structure, so its glass transition point can easily be measured and is around 140°C. Dobeckan MF8001 is a monomer-free resin with quite a complex structure, and its transitions can only be recognised at quite low temperature; as different measurement methods produce different results, it is reasonable to assume that these transitions have different causes, or are due to components within the resin that do not characterise the properties of the resin itself.

Comparison of glass transition points obtained from the different methods:

Resin	3PC-DMA	SC-DMA	DMTA	DSC
Dobeckan FT 2015	≈ 0 / 142	141	137	119 to 120
Dobeckan MF8001	≈ 0 / 54 to 59)[1]		60	24 / 55 to 63
Acrylate resin 1	≈ 0 / 73	)[2]	60	19 / 73
Acrylate resin 2	_13 to _17		115	50
High-temperature EP resin	_3 / 92	131	106	20 / 105
EP resin single-component	≈ _3 / 73 to 77			30 to 60 / 67 to 85
EP resin Araldite type	130	131		
Silicone resin	_32 / 59	_30 / 67		35 / 136

)1… The transition in this range can be observed only with half the samples tested
)2… Measurement from 80°C, no further transitions to be observed

Table 2: Glass transitions (Tg) of various reaction resins (UP resins, EP resins and a silicone resin) in °C, determined by different measuring methods, i.e. 3-Point Cantilever DMA, Single Cantilever DMA, DMTA (Dynamic Mechanical Thermal Analysis) and DSC (Differential Scanning Calorimetry). Transitions in the temperature range around 0°C could also be related to water, split products of initiators or other compounds added to the resin, which are not evaporated during curing. Where two transitions are found in one measurement, these are separated by a stroke.

The table shows that there are only a few cases where unequivocal and reproducible results are obtained. This makes it clear that it is problematic to discuss or compare physical properties without indication of the test method. In addition, the same test methods can produce different results if conducted with different test equipment.

Another interesting characteristic of thermosetting plastics is that there are temperature ranges where the thermal expansion coefficient changes.

The coefficient of thermal expansion may be measured by means of TMA (Thermal Mechanical Analysis): the degree of curing of the samples has little influence on the coefficient of thermal expansion. For thermosetting plastics it is in the range from 75 µm/mK to 180 µm/mK. Compare: α (copper) = 18 µm/mK, α (iron) = 12 µm/mK.

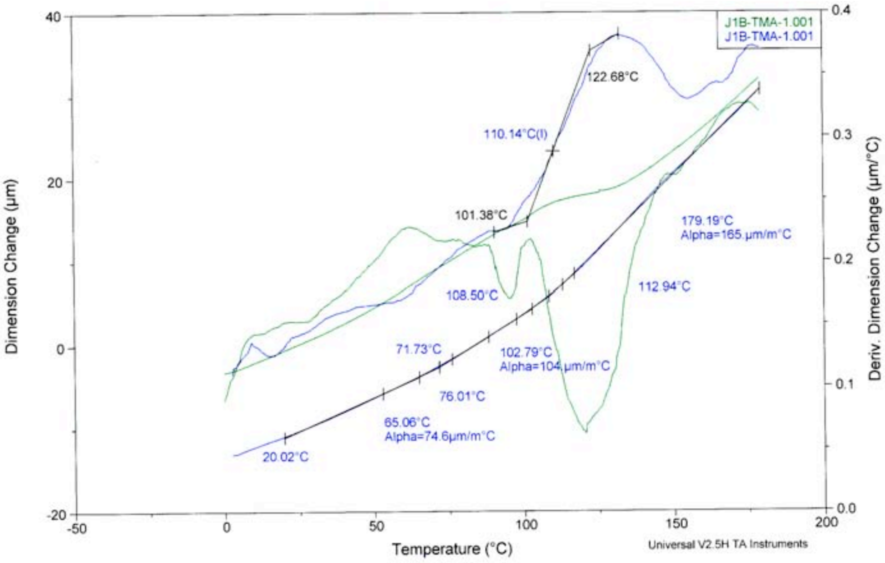

Fig. 18:

TMA plot of resin Dobeckan FT 2015.

This shows three linear ranges of thermal expansion.

Another important point in assessment of reaction resins is the loss of weight that occurs in curing. Styrene resins in particular (or resins with styrene derivatives) exhibit major weight loss, because the styrene component has very low vapour and evaporates on temperature increase before this component can be incorporated in the network as a result of cross-linking and polymerisation reactions.

Table 3 gives information on the weight loss as a percentage, with emission on cross-linking and curing.

Resin designation	Resin type / Remarks	Weight loss after curing [%]
Dobeckan FT 2015	UPI / Vinyl toluene	40.5
Dobeckan MF8001	UPI / Monomer-free	5.5
Rhenatech TH 3800	UPI / Oligomers	12.5
Acrylate resin	UPI / Acrylate	12.1
Epoxy resin	EP / Single-component resin	3.9
Wacker H62C	Silicone resin	1.6

Table 3: Overview of weight loss (%), occurring as emission on cross-linking and curing (160°C) of very small sample volumes (20-30 µg). Measured by TGA (Thermogravimetric Analysis).

Influence of impregnating technology

A very frequently used method for impregnation of round-wire windings of low-voltage electrical machines is the VPI (Vacuum Pressure Impregnation) method borrowed from high-voltage technology. Trickle methods are also in widespread use for impregnation of round-wire windings.

The demand for ever smaller construction of motors (and generators) is causing designers to go ever closer to the limits of what is possible with these motors, for example in terms of temperature load. Inverters are used more and more in motor operation, which means increasing voltage load, so that the insulating systems are subject to greater load than before.

This means that the quality of impregnation of the machine with impregnating resin is more important than ever before.

Tests have shown that the VPI method, which is still very popular, leaves only about 72% of resin (related to wet resin retention) in the winding. The winding is completely filled with resin due to the previously applied vacuum, but as long as the gelling temperature is not yet reached it can flow unhindered out of the winding again. It is different for high-voltage motors, because the fine mica tapes contain an accelerator which causes the resin to gel and thus prevents resin from flowing out of the winding in the curing oven.

If the impregnating process is done without a vacuum, resin retention is only insignificantly less. The impregnation process with vacuum increases resin retention only by about 5% compared with normal pressure. The use of pressure, as prescribed in the VPI process, seems to be more a question of faith for round-wire windings.

An alternative to the impregnating methods currently used is the current-UV method, a method that works without vacuum and pressure. This method also involves heating/curing the coils by use of the Joule effect, using only little energy input. There is no requirement for an oven. The resin retention achievable with this technology is around 95%. Increase of resin retention by use of a vacuum may be possible, but in view of the resin retention levels achievable without a vacuum it is no longer advisable.

The current-UV method not only gives a high level of resin retention, but also gives many further advantages, e.g. enormous power savings, emission reductions, reduction of throughput time, space saving, and a very high degree of automation, so that despite the high plant purchase cost it seems likely that conventional impregnation methods will be replaced by this method in the long run.

The range of resins that can be processed with this method is much greater than with conventional methods, because it is also possible to use very high-viscosity resins.

The emission reduction that can be achieved with the current-UV method is due to the fact that the coils warm up so quickly, which means that gelling temperature is reached very rapidly. Aerosols are formed only in a time window of about 5 minutes, in the period when the gelling temperature is exceeded and the resin begins to cure; these escape due to the high temperature and are not retained by the resin surface (because it is still liquid). As soon as a skin is formed, this prevents evaporation of VOCs (Volatile Organic Compounds). As the VOCs or aerosols are present for a short period, and thus in high concentration in a small air volume, they can be deposited again very easily. Only very few of them can get into the environment. By contrast, oven curing particularly of large objects often means that it will take hours until gelling. During this period, all evaporating organic compounds are taken up by the circulating air in the oven, and diluted so much that they can no longer be deposited. Then exhaust air cleaning can only be achieved by thermal afterburning, which is expensive both in purchase and operation.