Fiber-reinforced composites – extra mechanical and electrical strength for transformer tap-changers

Fiber-reinforced composite materials are making strong inroads in the electrical engineering industry. A new factor driving this trend is the recent improvement in the properties of composites used for electrical insulation. These enhanced materials have already established themselves in transformer tap-changers, while another application area with considerable growth potential is high-voltage switchgear. The combination of improved properties and advances in the production area is contributing to more cost-effective manufacture of composite products designed to withstand high mechanical and electrical loading.

A joint development programme undertaken by ABB Plast and ABB Components has produced fiber-reinforced composites with improved properties that increase the dielectric and mechanical strength of the end-products. The material specifications were based on the demands that typically have to be met by the cylinders used in transformer tap-changers. These cylinders are subjected to high electrical loads, and the material must ensure that there is no risk of flashover.

Composite materials for tap-changer cylinders are made of an epoxy resin matrix and glass fibers **1**. Several of the properties of this material are closely associated with the boundary layer, or interface, between the fibers and the matrix. During the development of the new, higher-strength material, the focus was therefore on optimizing this interface. Factors which contributed to the improved end-product included testing of many different combinations of materials and optimization of the impregnation process during production.

Anders Strömbeck
ABB Plast AB

Tommy Larsson
ABB Components AB

Transformer tap-changers – operation and mounting

Load tap-changers for transformers have been manufactured by ABB since 1910. Their task is to ensure that the secondary voltage of the transformer remains at the required level despite the daily fluctuations in load. The tap-changers do this by adjusting the primary/secondary turn ratio.

The turn ratio is adjusted by connecting or disconnecting taps on the regulating winding of the transformer. Tap-changing has to be carried out without interrupting the load current.

When mechanical tap-changers are operated arcing occurs, leading to the oxidation of particles, which contaminates the surrounding insulating oil. Since the transformer cannot function properly with contaminated oil, the part of the tap-changer in which the arcing occurs has to be placed in a separate tank.

Tap-changers are located either inside the transformer tank **2** or outside, on one of the tank walls **3**.

Mounting the tap-changer outside the transformer creates a natural insulating barrier between it and the insulating oil in the main tank. When the tap-changer is located inside the transformer it is necessary to provide a separate oil tank made of an insulating material. Over the past twenty years it has been common practice to use fiber-reinforced composites for such vessels.

Growing use of fiber-reinforced composites

Fiber-reinforced composite materials are also being used increasingly for other parts of the tap-changers, mainly as a result of the improved mechanical and electrical properties of the newer composites.

Nevertheless, fiber-reinforced composites submersed in pure transformer oil remain a weak spot simply because of the outstanding electrical properties of the oil. Every improvement in the electrical properties of the composites therefore brings about a direct improvement in the operating behaviour and a more compact end-product.

Standard type and routine testing is not enough for tap-changers with the new composite materials; what is also needed is statistical verification that the composite material agrees closely with the specified nominal data (ie, only a very small scatter is allowed), and that the composite material fulfils all the requirements.

Cylinder made of fiber-reinforced composite material, for use in transformer tap-changers **1**

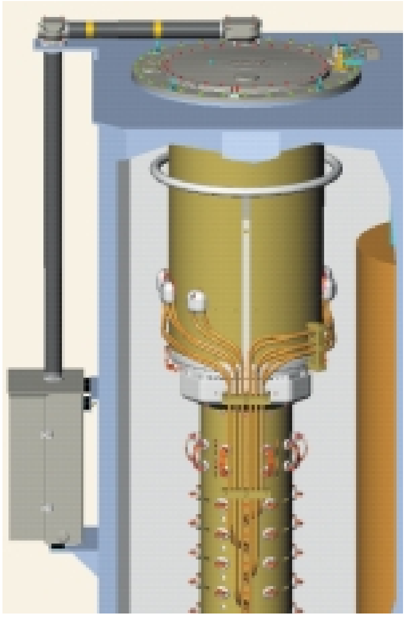


ABB tap-changer, type UC, mounted inside a transformer tank **2**

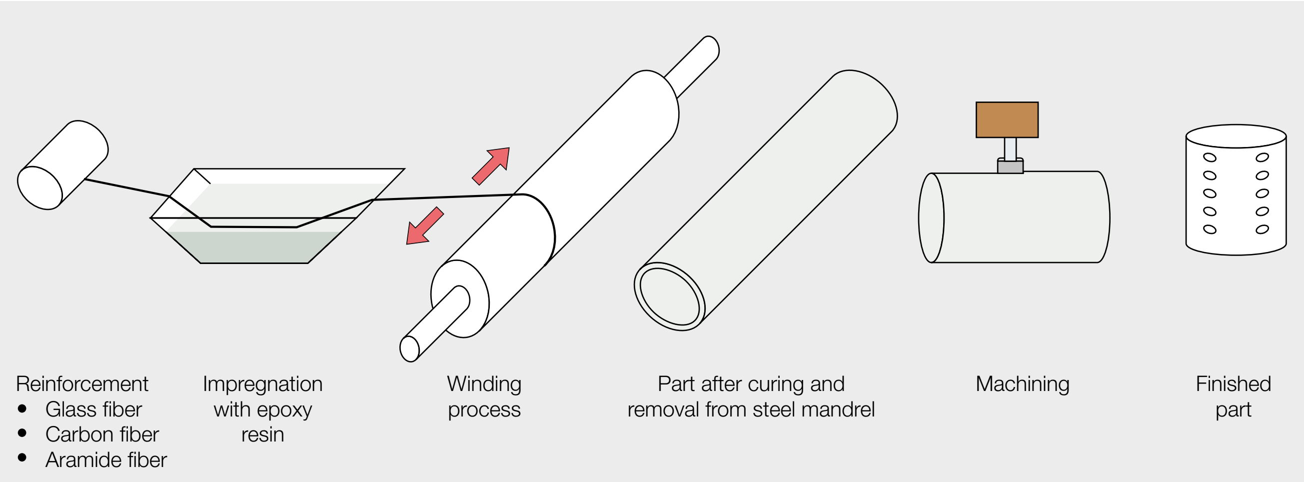
Composites for tap-changer cylinders – design and production

Tap-changer cylinders are manufactured using a filament winding process **4** and have epoxy resin and glass fibers as their main components. In this process the filaments, bunched into a fiber bundle, are wound around a rotating mandrel. The position of the fibers, ie the angle of winding, as well as the fiber tension can be precisely controlled. The high fiber content and predefined fiber direction ensures very high mechanical strength for the material. A critical part of the process is the impregnation of the fibers with liquid epoxy resin. To achieve the highest quality for the material, the surface of the fibers has to be completely wetted and air pockets in the resin have to be kept to a minimum.

ABB Plast has developed its own method for solving these problems. Among the key parameters influencing the impregnation are the viscosity of the resin, the winding speed and the compatibility of the fibers and resin. An optimum boundary layer will ensure strong bonding between the matrix and the fibers, while the region close to the interface also has to be able to withstand local stress concentrations.

The impregnated and cured blanks then have to be machined to produce the fin-

ABB tap-changer, type UZ, mounted on the outside of a transformer tank **3**



Basic principle of the filament winding process used to manufacture composite cylinders for tap-changers **4**

ished tubes **5**. A high-quality material, and therefore a first-class end-product, is ensured by electrical testing of every individual blank.

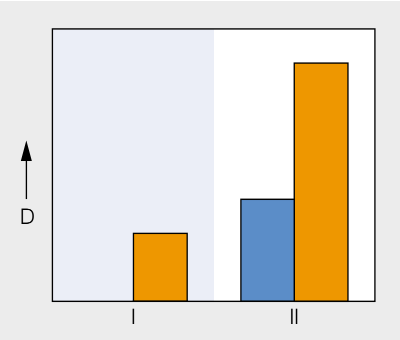
Development of composite materials

The successful development of products made of composite materials requires a multi-disciplinary effort and depends on know-how in the manufacturing, materials and design areas. Composite materials are characterized by their anisotropy and the fact that parts are manufactured from material straight off the production line. This leads to one of the most important benefits of composites, which is the opportunity they offer to define and optimize the material properties in a given direction for each individual product.

The rigidity and strength of a composite material depend in the first place on its fiber content. The matrix – often a moulding material which can be hardened – has several other important functions; for example, it fixes the fibers in position in the material and distributes the load equally amongst the fibers. In addition, the matrix ensures a smooth, uninterrupted surface and a uniform density. In the case of electrical insulating materials the matrix and the fibers also have to absorb enough of the electrical load to prevent damage being caused to the material.

The properties at the boundary layer between the fibers and matrix can have a large influence on the general characteristics of the material. For example, these properties can dictate the load level at which microcracks could occur in the matrix. In components for applications in which the main task is to absorb load, microcracks can be permitted to a certain extent. On the other hand, they can cause certain other variables – eg, resistance to aging and fatigue, or density and electrical properties – to deteriorate strongly. In the case of the new materials described, the development engineers concentrated on improving the boundary layer between the fibers and matrix so that microcracks do not occur for a defined load. The overriding

Testing the dielectric strength of parts made of composite materials **5**



Diffusion test results for optimized (I) and standard (II) composites **6**

D — *Measured diffusion*

Blue — *After 1 hour*
Orange — *After 4 hours*

goal was to ensure an electric strength which was higher than for a comparable standard material.

Improved material properties

Besides testing the electric strength it was also necessary to measure the differences in the boundary layer for various fiber/matrix combinations. For this, ABB developed a special test which is based on measurement of the diffusion in the composite material, especially along the fiber surface and in the adjoining region (ie, the interface). This test enables quantitative results to be obtained which are a measure of the diffusion, and also provides qualitative information that allows conclusions to be drawn about the electric strength.

As the diffusion tests showed **6**, the different combinations of materials have widely varying characteristics.

To test how different materials resist cracking, a method was chosen which is commonly used to carry out tensile tests on cross-ply laminates. These tests also showed when the first cracks occurred in the material and that the load at which cracking begins differs widely from material to material. The results are of great interest, since changing the type of fiber while leaving the matrix and production method unchanged has a large influence on crack initiation **7**. Also, it was confirmed that the chemical composition of the glass fiber surface strongly influences the boundary layer in the composite, which in turn is a determining factor in crack initiation.

Filament winding process

The technology developed for filament winding is especially well-suited for manufacturing enclosed, symmetrical products, such as tubes and cylinders, and offers several important advantages:

- High strength for the composites
- A wide choice of fibers and matrix materials
- Highly reproducible production process, made possible by computer control

Due to these benefits, filament-wound products belong to the composites with easily the best strength properties. *Table 1* gives examples of material characteristics of samples made from cylinders wound using this technology.

Table 1
Some of the material properties of samples made from filament-wound tube material

Material property		
Modulus of elasticity	GPa	45
Tensile strength	MPa	1,100
Density	kg/m³	2.0

Alternative production processes for composite cylinders

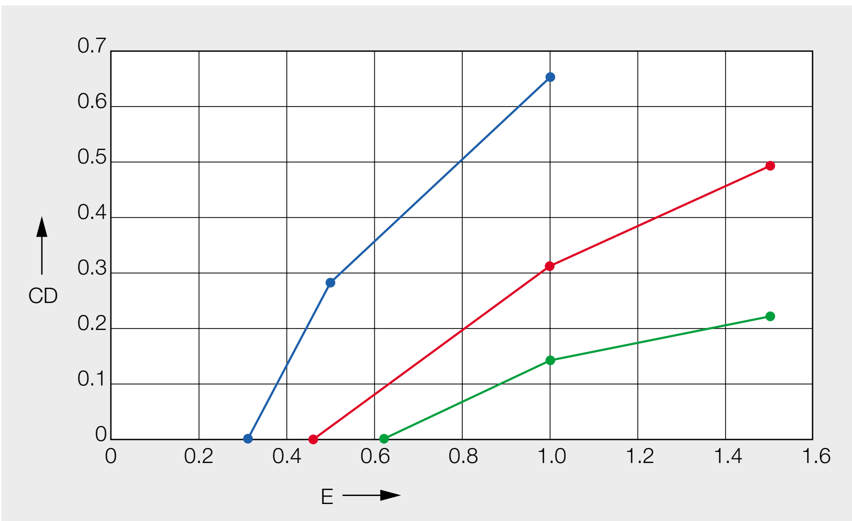
ABB Plast employs a range of procedures for manufacturing products made of composite materials. Besides filament winding, the other main method used to produce high-strength tubes is vacuum injection **8**.

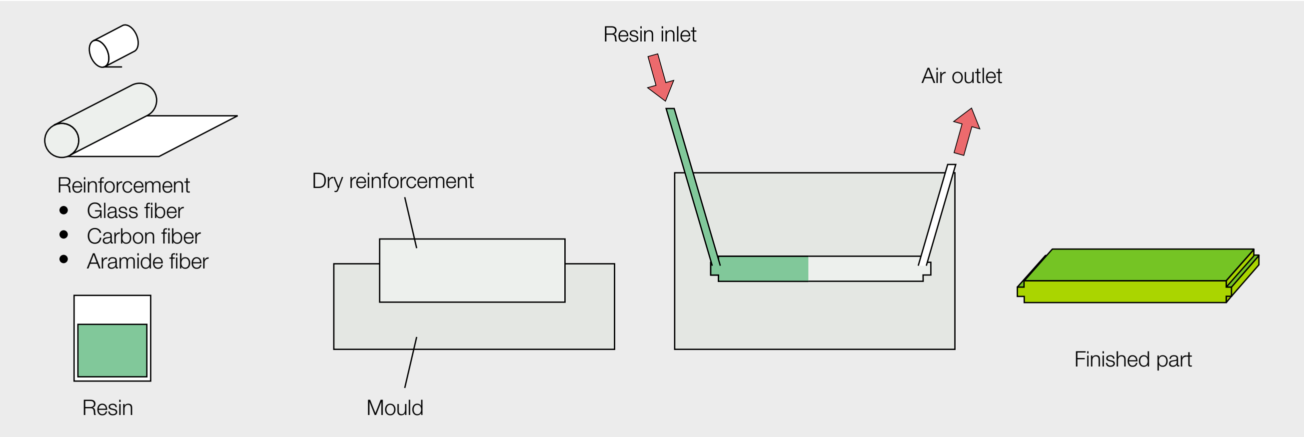
Whether filament winding or vacuum injection is used depends on, among other things, the geometry of the final product. Although suitable for straight, cylindrical tubes, filament winding is less well suited

Results of tensile tests carried out to determine the resistance to cracking of different materials. The tests also show when cracking is initiated. **7**

CD — *Crack density*
E — *Elongation*

Blue — *Resin A*
Red — *Resin B*
Green — *Resin C*





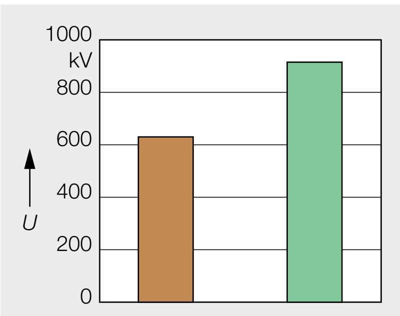
Vacuum injection process 8

for products with complex geometries. Vacuum injection, on the other hand, can be adapted for complicated geometries without impairing the good strength properties of the material in any way.

In vacuum injection the dry reinforcement, made of fiber material, is preformed and then placed in an enclosed mould, in which it is impregnated with polymer resin. The vacuum existing in the mould during the impregnation process pulls the resin into the mould and ensures complete impregnation of the fibers (in the micro-range). The vacuum further ensures that any inclusions contained in the finished composite are negligible.

Relative impulse withstand capability of normal (brown) and optimized (green) composites 9

U Voltage



Electrical testing of transformer tap-changers

A whole series of tests was carried out under real-world operating conditions. The purpose of the tests was to investigate how well the optimized composite material withstands surge voltages, eg in the event of lightning striking in the vicinity of the transformer.

The tests were designed to check the limit rating capability of the tap-changers. A large number of units were subjected to voltages far higher than their rated levels until flashover occurred. Commercially available composites used in the electrotechnical industry also had their surge voltage withstand capability tested and compared with the value for the optimized composite material 9.

The verified improvement shows that this material further increases the performance capability of tap-changers, allowing even more compact units to be manufactured.

Bright outlook for composites in HV applications

Demand for efficient insulating materials continues to grow, especially for insulating components used in state-of-the-art switchgear. The composites developed jointly by ABB Plast and ABB Components exhibit the high dielectric strength required of materials for transformer tap-changers. These materials, plus optimization of the manufacturing processes, enable components satisfying the highest technical requirements to be produced. By improving the properties of the composites, ABB has considerably widened their area of application in high-voltage installations.

Authors

Anders Strömbeck
ABB Plast AB
P.O. box 273
SE-941 26 Piteå
Sweden
Telefax: +46 911 663 75
E-mail:
anders.stromback@sepla.mail.abb.com

Tommy Larsson
ABB Components AB
SE-711 80 Ludvika
Sweden
Telefax: +46 240 800 78
E-mail:
tommy.larsson@se.abb.com