Advantages of Composite Insulators in Comparison to Porcelain Insulators and new solutions with Composite Insulators

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Abstract

This paper focuses on hollow-core insulators used for high-voltage equipment such as bushings for transformers, GIS or circuit breakers, measuring transformers, cable terminations and surge arresters. In particular, the most common materials and production methods will be described. Additionally, the main features will be enlightened in comparison to conventional porcelain insulators. Furthermore, the expected future developments resulting from increasing requirements (higher voltages and/or higher currents), and integrated functionality in insulators will be discussed.

Keywords: High-Voltage Equipment – Insulator – Composite Material – Porcelain – Mechanical Properties – Electrical Properties – Hydrophobicity

1. Introduction

Hollow-core composite insulators are in use for more than thirty years now [1], [2]. For line insulation the time-period during which plastic materials are used as an alternative to ceramic rods or glass chains is even longer. However, due to the different fields of application of instrument insulators and line insulators the requirements and thus the demand on the quality is largely different. This may be the reason why the materials used and the production methods are not comparable for these two types of insulators.

In the following only hollow-core insulator will be discussed although for line insulators also a substitution of porcelain and glass has taken place and is still going on.

1.1. Shed Materials

1.1.1. Silicon Rubber

Nowadays, the most common materials used for the sheds are different types of Silicon Rubbers (SIR) [6]. Their chemical structure consists of a chain of alternating silicon and oxygen ($-Si-O-Si-O-$) while the Si-atoms carry two organic substituents (e.g. methyl groups). The binding energy of Si $-$ O is comparably high. Thus, silicon elastomers have a high resistance against radiation, chemical attack, and high temperatures. By adding fillers the electrical and mechanical properties can be adjusted within a wide range.
The key feature of SIRs in comparison with particularly porcelain is their hydrophobicity. Due to a certain content of low-molecular weight components (LMW) which accumulate on the surface, the energy of the surface is very low. Hence, no continuous water film can be formed on the surface. Dirt particles (e.g. dust or salt) are normally flushed away with rain. Even if a durable dirt layer remains on the sheds (e.g. under very heavy environmental conditions near to the coast or in extremely polluted industrial areas) the LMWs are able to migrate through the layer and transfer the hydropho-

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bicity to the surface of the dirt layer [7]. In case of a flashover the hydrophobicity could temporarily be suppressed but after a rather short period of time (i.e. hours up to a few days) the hydrophobic properties are the same as for the new material since the LMW migrate from the bulk material to the surface (hydrophobicity recovery) [2]. From the current state of knowledge there is no indication that hydrophobicity reduces even after 40 years in service [8], [9]. Hydrophobicity can be classified according to the level of water repellence [10] into six so-called hydrophobicity classes. Class 1 means many small separate water droplets and class 6 refers to a continuous water film.

Silicon rubbers can be divided into high temperature vulcanizing (HTV), room temperature vulcanizing (RTV), and liquid silicone rubber (LSR). The main differences between these types are the processing conditions (i.e. the viscosity), the mixing ratio, the curing mechanism (peroxidic or condensation polymerization), and the curing temperature. The choice of the appropriate type of SIR depends strongly on the production process (cf. sec. 1.2).

1.1.2. Other organic materials

Additionally to the silicone materials described above organic materials are used for the sheds of composite insulators. The two most common types are EVM (Ethylene-Vinylacetate-Rubber) and EPR (Ethylene-Propylene-Rubber). The latter one is a generic term for Ethylene-Propylene-Copolymer (EPM) and Ethylene-Propylene-Diene-Terpolymer (EPDM).

The main chain of the organic materials is a *–C–C–* bonding with a low bonding energy compared to the SIR-types. Therefore, their resistance against environmental influences is lower. However, the properties can be varied in a wide range by adding fillers like lubricants, UV-stabilizer, ATH, etc.

Although the organic materials exhibit a certain level of hydrophobicity as well, mechanisms like the transfer to dirt layers or the recovery of the hydrophobic properties are not valid for EVM and EPR.

Tab. 1 compares qualitatively the properties of the silicon rubber types and the organic materials.

1.2. Application of the Sheds

In industrial practice, currently four different methods are used to apply the sheds onto the GFRP tube:

- **Spiral Extrusion**
  The material is extruded circumferentially onto the surface of the GFRP-tube. At the same time the tube is moving in direction of its longitudinal axis. Therefore, the silicone forms one single shed with a spiral shape (cf. Fig. 1).
  The advantage of this method is the continuity of the process and that it is in principle applicable for insulators of an arbitrary length. Due to the extrusion process a spiral-shaped bond results which leads from one end of the insulator to the other. As it will be explained later in more detail, bonding interfaces in insulating materials are a general issue and should be avoided if possible.

Property	EVM	EPR	SIR
Heat resistance	+	+	++
Elongation at break	0	+	++
Low temp. flexibility	0	+	++
UV resistance	+	+	++
Ozone resistance	++	++	++
Creepage current strength	0	++	++
Arc resistance	0	++	++
Hydrophobicity			
- New condition	++	++	++
- Recovery and transfer	–	–	++

Tab. 1: Properties of the shed materials in comparison [6].
++ very good/high, + good/high, 0 sufficient, – not applicable

Another potential problem could be that due to the spiral shape water can run from the top to the bottom and form a continuous water track which could lead to electrical problems (i.e. a high leakage current).

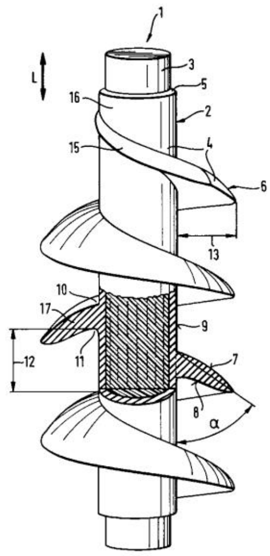

Fig. 1: Schematic view of an insulator with spiral sheds [11]

- **Shed-by-Shed Moulding**
  Fig. 1 shows the principle of Shed-by-Shed moulding. The liquid raw material is poured into the shed mould which is mounted around the core tube. After curing the mould (or the tube, respectively) moves and the process starts again for the next shed.

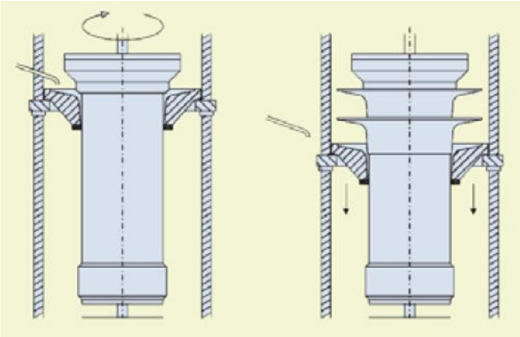

Fig. 2: Moulding shed by shed [12]

The costs for the equipment are comparably low. However, the processing times are long and thus the production of large quantities is very time consuming. Furthermore, each shed has to be vulcanized onto the foregoing one. Therefore, there are many bounding surfaces which could potentially act as inlets for water if they are not totally tight. Furthermore, interfaces are generally possible entrapments in the presence of high electrical fields, because they are regions where e.g. voids or weak bonding can occur with a higher probability than in the bulk material

- **Application Shed-by-Shed**
  Single sheds are pre-produced and then drawn mechanically onto the GFRP core. Similar to the Shed-by-Shed process described above, the tooling costs are very low. But instead of vulcanizing the sheds to each other, the joint has to be created separately. This is another potential source for defects.

- **Moulding**
  In this process almost exclusively Liquid Silicone Rubber is used. The GFRP tube is placed in between two mould halves. The two components of the LSR are blended in a static mixer and injected into the mould. The mould contains the shape of the sheds (cf. Fig. 3). After the injection the silicon is cured inside the mould for a certain time depending on the volume of the sheath. This process provides the shortest processing times compared with the production methods mentioned above. For insulators not exceeding approx. 2.7 m in length all sheds can be applied in one shot. For longer types the moulding process has to be repeated. Since all sheds are produced in one step there are no bounding surfaces between the sheds[1]. As already mentioned interfaces are potentially weak spots with respect to the electrical strength. Hence, the reduction of interfaces generally helps to minimize the risk of partial discharges or flashovers. Although the moulding process exhibits many advantages it should be noted that the costs for the moulds and the machines are significantly higher compared to the Shed-by-Shed methods.

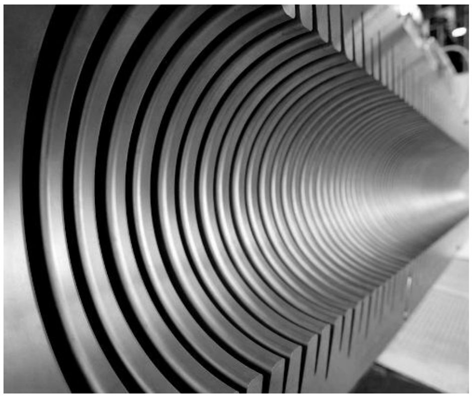

Fig. 3: One half of the mould

2. Major Differences between Porcelain and Composite Insulators

2.1. General Features

Generally, there is no difference with respect to the shape between porcelain and composite insulators. Regarding the production costs, for smaller types porcelain is slightly cheaper than composite but the ratio changes when the dimensions of the insulator increase. This effect is due to several reasons:

- There are only a few manufacturers of ceramic insulators which have the capability (i.e. a sufficient large furnace) to build products with large dimensions.
- With growing dimensions the kiln process involves an increasing risk of failure
- The possible tolerances with respect to dimensions and form for porcelain are generally comparably large. Therefore, with increasing size the absolute deviation from the nominal dimensions is also increasing. This leads to a large number of rejections.
- Because of their brittle material behavior porcelain insulators are vulnerable to impacts or shocks. With increasing weight the number of failures during production goes up.

The aforementioned issues do not apply to composite insulators. Hence, the production costs for larger types are in most cases lower for composites than for porcelain insulators. Additionally, due to the reasons mentioned above most porcelain producers only supply insulators up to a length of about 3 m. For composites lengths up to 12 m in one piece are already common.
Many types of hollow-core insulators (composite and porcelain) can be provided with an alternating shed profile as illustrated in Fig. 4.

[1] Exception: If two shots are necessary there is one single bounding surface between the first and the second part of the sheath.

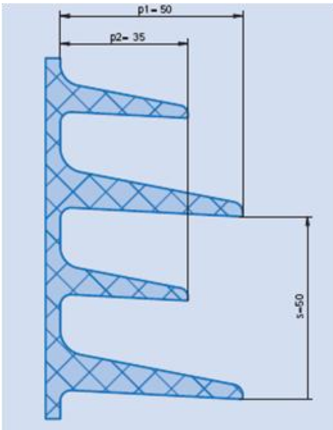

Fig. 4. Alternating shed profile

By keeping the distance between the large sheds constant and placing an additional small shed in between the creepage distance can be increased significantly. However, due to the brittleness of porcelain the sheds of ceramic insulators are generally thicker in comparison with rubber sheds. This leads to a smaller effective shed distance in case of porcelain and thus to a higher probability of surface discharges.

2.2. Mechanical Properties

Porcelains or ceramics, respectively, have in general a higher mechanical strength than plastics. This results in a higher stiffness of porcelain insulators compared to composites with identical dimensions (diameter, length, wall thickness). In particular the deflection of the porcelain type under a certain bending load is smaller what could be an advantage in certain applications.

However, due to the higher density of ceramics ($\rho_{Porcelain}\approx 2.5$ g/cm3, $\rho_{GFRP}\approx 2.0$ g/cm3) the porcelain type will have a remarkably higher weight what is inconvenient regarding the handling and the transportation. Furthermore, as a consequence of the high stiffness the porcelain behaves brittle in case of an impact or a shock wave. It has been reported that the damage tolerance during natural catastrophes or in case of vandalism is much better for composite insulators [13].

Therefore, in applications where deflection does not play the dominant role the lower mechanical properties of composite can be overcompensated by its advantages.

2.3. Electrical Properties

In section 1.1 it has already been described that due to the hydrophobic properties of the silicon elastomers and the organic shed materials no continuous water film can be formed on the surface of the shed. This effect can be seen in Fig. 5.

Fig. 5: Water droplets on SIR sheds

Consequently, the magnitude of leakage currents occurring during service is significantly lower compared to porcelain insulators [2]. Furthermore, the long term performance of composites is better because due to the low leakage currents tracking and erosion effects are at a very low level.

From these points follows that it is possible to use a shorter creepage distance in case of composite insulators compared to porcelain types for the same application.

2.4. Behavior in Polluted Areas

In a surrounding with a moderate pollution level there is no need to clean composite insulators because due to the low surface energy dirt and salt particles do not adhere to the sheds. Normally these particles are flushed away with rain. In case of porcelain it could be necessary to clean them from time to time. The necessity and the frequency of washing increases with increasing pollution level. This is a very costly operation.

In heavy polluted regions near to the coast or in industrial areas salt and dirt will accumulate on the surface of both types porcelain and composite, although the formation of an adhering pollution layer takes much more time in case of silicone rubber. However, as porcelain insulators have to be cleaned much more frequently than in moderate polluted areas, at least for SIR the hydrophobicity transfer (cf. section 1.1.1) results in a hydrophobic surface of the pollution layer as it is shown in Fig. 6. Therefore, even in highly polluted surroundings SIR composite insulators normally need not to be cleaned during their life time.

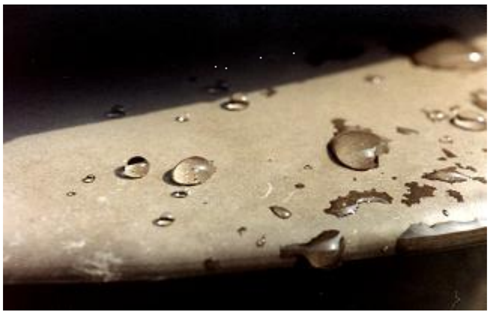

Fig. 6: Water droplets on a pollution layer on a SIR shed [2]

2.5. Behavior in Case of Failure

It has already been reported in section 2.2 that porcelain behaves significantly more brittle than composite materials. Consequently, composites insulators are expected to be more reliable during an impact caused by vandalism, improper handling or earthquake. However, due to the higher strength of porcelain it can stand higher forces. Therefore, it could be argued that porcelain types perform better e.g. during very strong earthquakes, what could be valid in certain cases.

Nevertheless, composite insulators exhibit an excellent damage tolerance due to their ductile material behavior and the high damping of plastics in general.

If a serious failure occurs (e.g. an explosion) porcelains will be completely destroyed and in most cases shivers will be catapulted within a large circumference. Surrounding equipment is usually damaged and if people are in the vicinity heavy injuries or even death will be the consequence. Composites on the other hand do normally fail in forms of rupture and even after an internal explosion they remain in one single piece [2], [13].

3. New Solutions with Composite Insulators

Despite the technological predominance of composite insulators it is possible to integrate new sophisticated features due to the very flexible production process and to the variable composition of the parts.

3.1. Insulators with GFRP flange

In Fig. 7 an insulator with a polymeric flange is displayed. Particularly the (upper) flange is made of a non-metallic and non-ferromagnetic material. This design has the following advantages:

1. Increased arcing distances
2. Even lower weight compared to a “conventional” polymeric insulator
3. Higher flexibility of the flange design
4. Suppression of eddy currents in the flange and therefore lower losses for e.g. reactor coils

Fig. 7: Composite insulator with GFRP flange

Using a smart design for the GFRP flange and an optimized laminate structure the mechanical properties are comparable to a metallic flange as it is widely used for all kinds of insulators. For outdoor applications the flange has to be coated with an e.g. weather and UV resistant paint.

3.2. Insulators with integrated optical fibers

Composite Insulators offer the possibility to integrate functionality beyond electrical insulation. One example is shown in Fig. 8. The picture demonstrates a hollow insulator with integrated optical fibers for current transformers. The fibers allow the galvanic isolated transmission of measuring signals from the high-voltage site to ground potential. Furthermore, depending on the nature of the fibers it is also possible to transport power along the fibers from the bottom to the top in order to provide energy for the measuring device.

Fig. 8: Insulator with integrated optical fibers

The number of fibers and the design of the connectors are up the customer’s needs and there is generally no limitation. If the insulator is only used as a support (e.g. for optical CTs) the interior can be filled with an insulating medium such as SF_6, mineral oil, or a solid silicon material. The latter solution provides the advantage that no maintenance or monitoring of the part is necessary during its lifetime.

Of course it is still possible to leave the interior of the insulator hollow that it can be used as a housing for electrical equipment. In this case the fibers are fixed in a groove in the outer surface of the tube and they are protected by a sealing and by the silicone sheds.

3.3. Conical Insulator

Especially for larger parts (>420kV) it could be useful to change the shape of the insulator from cylindrical to conical. Fig. 9 shows an example for this design.

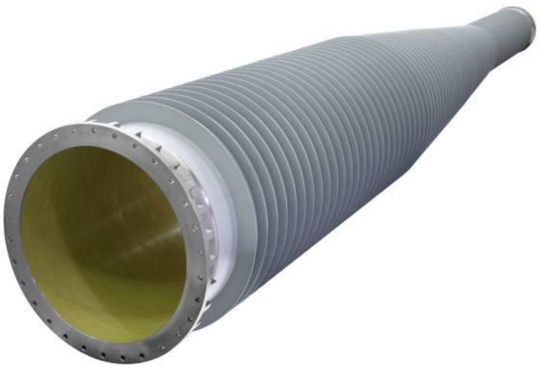

Fig. 9: Conical design

The conical insulator needs less insulation medium inside (oil or gas) due to its smaller interior volume. Consequently the equalizing containers could also be smaller. And finally the phase to phase distance is largely increased since the metallic parts on the top of the insulators have a significantly smaller diameter compared to the cylindrical solution. Particularly the latter feature helps to save space in the installation and gives more flexibility in the design of the substation.

4. Summary

Polymeric insulators in general and hollow core composite insulators in particular provide an outstanding performance with respect to the mechanical and electrical properties. The predominance in comparison to conventional porcelain types is substantiated in the hydrophobicity of the sheds from silicon rubber (or the other organic materials) and in the superior damage tolerance in case of vandalism or natural catastrophes.

Primarily, for UHV and HVDC applications porcelain insulators are not suitable in the future since it is not possible to produce them in the dimensions needed at a competitive price level.

Due to the easy handling and the flexible production process of composite insulators the design can be varied very easily and the properties can be adjusted exactly to specific requirements.

The integration of sophisticated functions such as signal and/or power transmission can be realized in a large variety.

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