PRODUCTION METHODS AND QUALIFICATION OF HOLLOW CORE INSULATORS FOR UHV BUSHINGS

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Abstract: The demand for electrical power increased steadily in the past decades and this trend is not being expected to stop soon. This leads consequently to higher voltage levels in order to transmit power economically. Lines with 800 kV DC or 1000 kV AC, respectively, are already state of the art in large countries with long transmission distances like China or India. Currently an 1100kV DC project in China is in the concept stage [1]. Manufacturers of equipment have to face the challenges coming up with this development in the energy market. The present paper will discuss issues and solutions for the production of ultra high voltage bushings with composite insulators. Additional to the principal requirements for these products, several specific issues have to be taken into account if certain dimensions of the parts are exceeded. Beyond the general requirements for bushings and insulators coming from IEC or IEEE standards, it is essential to enhance the qualification procedure. This fact will be demonstrated discussing the so-called scarf joint of the housing which is necessary if parts become longer than 6 m. Although the scarf joint is a well established method for joining polymeric components, it is indispensable to regard the specific mechanical and electrical requirements in high voltage applications.

1 SPECIFIC ISSUES WITH INSULATORS FOR ULTRA HIGH VOLTAGE APPLICATIONS

Simply expressed, the higher the voltage the longer are the insulation distances. Thus, the dimensions of e.g. transformer bushings increase with the voltage level. The dependence of the dimensions on the voltage is a function of the distribution of the electrical field and must thus be determined for each specific type of bushing. Every producer has to face the problem that the existing manufacturer equipment reaches its limit at a certain dimension or voltage level, respectively. In case of insulators, produced from filament winding tubes as the core component, the length of the winding machine is the critical issue. Most tube producers are limited to a length of 6...10 m. To resolve this issue there are three possible solutions: Purchasing new equipment, stacking two or more single insulators, or assembling the tube of the required length from smaller parts. The first possibility leads in most cases to a very high investment since not only a new winding machine is necessary but also equipment for cutting and machining. Regarding the fact that the number of insulators becomes smaller the higher the voltage is it is uncertain that the amortization of the equipment takes place within a moderate period of time. Furthermore the development of future voltage levels cannot be predicted what makes it difficult to estimate the necessary size of the new machines.

The stacking is the most simple solution but it incorporates the disadvantage additional metal parts (flanges) in between the high voltage end of the bushing and the grounded end which makes it necessary two increase the insulators length compared to a one-piece part. Furthermore, at the interface between two single insulators there are additional sealing surfaces which are potentially weak spots.

Currently, many insulator producers prefer the third possibility, i.e. the joining of smaller parts to one large tube. The connection of these parts is the so-called scarf joint has already been discussed in a previous paper [2]. The design and possibilities for the qualification and monitoring will be described in detail in the following section.

1.1 Scarf joint

Figure 1 shows the principal setup of an insulator with a scarf joint. In this example the joint is located in the center of the tube but it can of course also be located at another position.

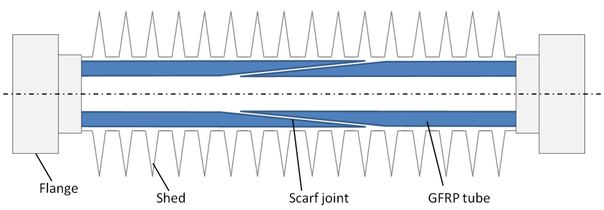


Figure 1: Principal assembly of an UHV insulator

It is already indicated in the sketch that the both partial tubes are machined conically but there are of course also other possibilities to design a joint. Three principal designs are illustrated in Figure 2.

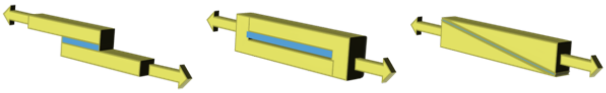


Figure 2: Different joint designs

Regarding Figure 3 it becomes obvious that in case of a single-shear connection (cf. left picture in Figure 2 the critical load is not a shear stress but a peel stress due to a deformation induced stress concentration at the edges of the joint. For the second design in Figure 2 these peel stresses are less severe but it has anyway the disadvantage that voids could occur at the edges due to the shrinkage of the glue and could thus result in mechanical and electrical problems such as partial discharges or puncture.

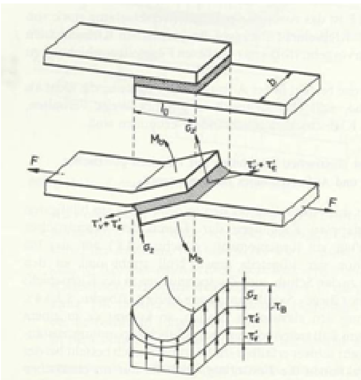


Figure 3: Stress distribution in a single-shear joint [3]

Solution number 3 from Figure 2 provides two decisive advantages: No peeling stresses at all occur [3] and the shrinkage of the glue can easily be compensated by maintaining a constant contact pressure during curing. In particular, the risk of voids inside the joint is minimized. Furthermore, as Figure 4 illustrates, if the conical joint is adapted to assemble tubes, the two parts are automatically centered when an axial force is applied and the resulting pressure on the gluing surface is uniform.

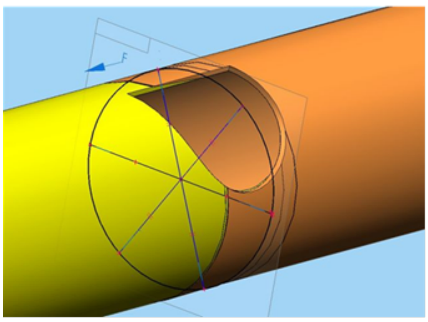


Figure 4: Scarf joint of two tubes

Therefore, the conical joint is the preferred design for the assembly of tubes due to its noncritical stress distribution and the highest process reliability.

2 DESIGN OF HOLLOW COMPOSITE INSUALTORS FOR UHV BUSHINGS

2.1 General design rules for glue joints

In Figure 5 the strength of the joint versus the thickness of the glue is illustrated. The function runs through a maximum at approx. 100 μm and decreases again for thicker joints. The reason for this effect is that the probability of large defects like voids, air bubbles, etc., is higher in a larger volume of glue. Simply spoken, a glue layer of 100 μm cannot contain an air bubble of diameter 200 μm.

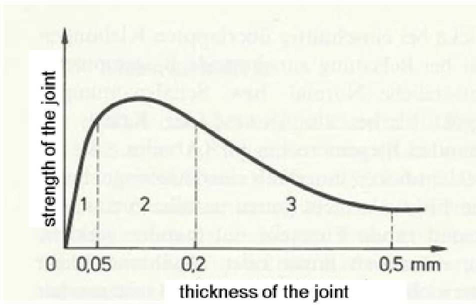


Figure 5: Joint strength as a function of the joint thickness [3]

The influence of the overlapping length on the joint strength is shown in Figure 6. Again a maximum can be observed. The position of this maximum is dependent on the thickness, i.e. the stiffness, of the parts to be joined. This feature is correlated to the deformation of the joint partners when the load is increased. Due to the increasing peel stresses at the edges, the area which contributes the joint strength becomes smaller and therefore the resulting strength decreases.

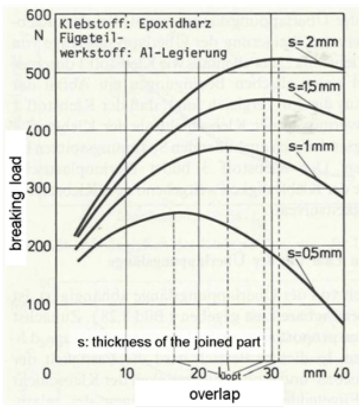


Figure 6: Joint strength as a function of the overlapping length [3]

Regarding the wall thickness of the joint partners the mechanical strength increases linearly with the

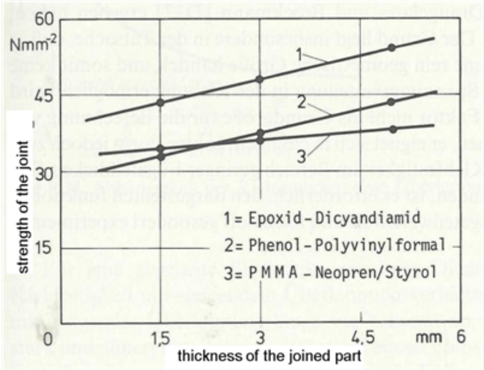


Figure 7: Joint strength as a function of the wall thickness of the parts [3]

thickness (Figure 7). Although the bending moment also increases linearly with the thickness, which lead to a higher deformation of the part, this effect is over compensated by a quadratic increase of the section modulus, i.e. the stiffness of the part.

2.2 Special design rules for insulation tubes

Generally it is of course necessary to be able to reproduce the processing parameters like temperature, tolerances of the joint partners, surface pressure during the curing, etc., reliably. For larger parts like UHV bushings this may be difficult regarding the handling. For insulators it is furthermore important to choose the position of the scarf joint carefully. As it will be shown in the following, the joint does not weaken the tube mechanically or electrically but it is however recommended in the appropriate literature to place a joint at a position with a low mechanical load. That means for an insulator exposed to bending loads a joint preferably far away from the highest bending moment which is at the fixing point. Depending on the method of siliconization there will be one to three (mixed moulding) or many (shed by shed) seams in the sheath. A properly produced seam does not lead to any problems but in order to be able to identify the failure mode in case of problems it is useful to place seams in the silicon not at the same position as the scarf joint.

3 QUALIFICATION OF JOINED INSULATORS

During development, optimization, and qualification it is of course indispensable to check the properties of the joint or the complete component. But also in serial production it can be useful to monitor the quality of the joint.

3.1 Electrical Simulation

The composite insulator is a very important component in electrical constructions. They have to fulfill several electrical and mechanical tests. Mechanical tests can be mostly achieved at the composite insulator but electrical tests are in general part of the final test of the electrical construction such as bushings, arresters or instrument transformers. Therefore it is very important to find adequate calculations or simulations for the complete design, enclose all different types of material, during the design finding process. To characterize the electrical behavior, the field simulation is one of the important tools to specify the general geometry of the product. Regarding to the type of product, AC - simulation, DC - simulation as well as transient calculation for polarity - reversal test are part of the analysis. Special areas can be improved by this method. Such as transition between different layers or joints in the filament winding tube of the insulator:

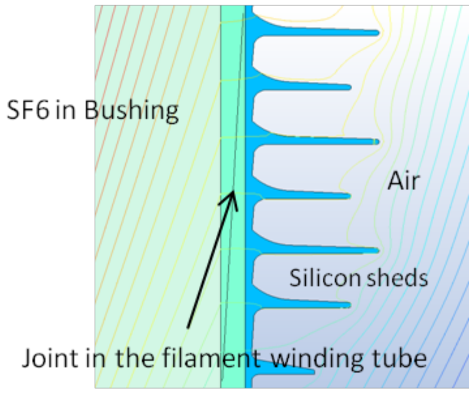


Figure 8: Equipotential plot

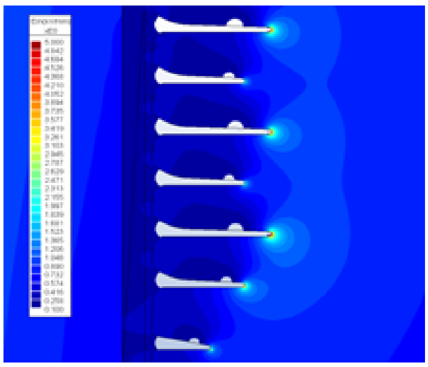


Figure 9: Equipotential plot

After a lot of calculation and additional real test in the high voltage lab we compared these results and found base design criteria for dimensioning our products and how we can improve them. We also can detect and appraise special areas in the product to come to the conclusion is it critical or not.

Started with a sharp geometry (Figure 11 and 12 left side) we switch to rounded edges (Figure 11 and 12 right side) to reduce the field strength. The best way to design this joint due to improved electric properties is as follows:

Based on these results a geometry (Figure 11 and

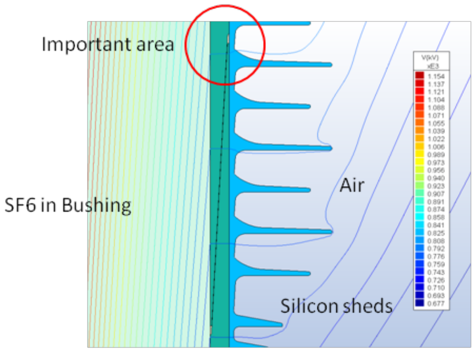


Figure 10: Equipotential plot of the joint in the filament winding tube

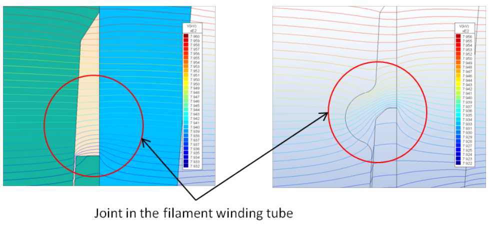


Figure 11: Equipotential plot in detail of the joint in the filament winding tube

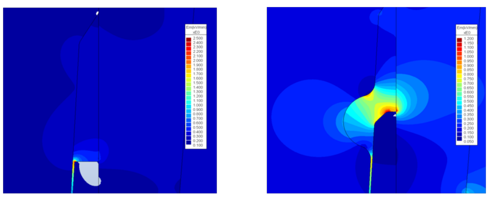


Figure 12: Field plot of the joint in the filament winding tube

12 right pictures) with improved electrical characteristics could be identified for the final product with a reduction of the maximum field strength inside of the tube from 2.5 kV/mm to 1.2 kV/mm.

3.2 Visual methods

The easiest way to control the quality of the joint after assembly is a simple backlight picture as it is displayed in Figure 13a. The bright spot in the picture is a clear indication for a lack of glue in this area. This method provides results very quickly and does not require special experience. However, there is no quantification of the dimensions of the imperfection and it is doubtful if small but already critical defects can be detected.

A more sophisticated non-destructive method to investigate the quality of the joint is Computed Tomography (CT). Figure 13b shows the cross section of a joined tube. Due to the fact that the density of the glue is almost identical to the density of the surrounding GFRP the joint cannot be seen in this picture. Nevertheless, this method provides a resolution of about 0.1 mm and an automatic picture analysis and is therefore an appropriate testing procedure for a thorough investigation. The main disadvantage are the costs for equipment which is large enough to investigate insulators for UHV (about 1.2 Mio EUR for a high end device).

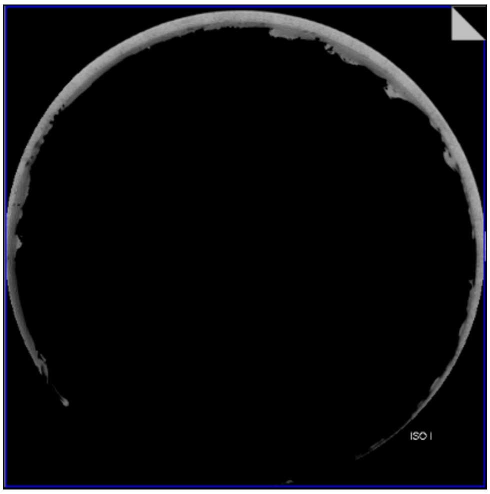
In order to quantify the number and the dimensions of imperfections in the joint samples could be cut out from the joint and investigated with a microscope. Figure 14 shows the cross-section polish of two samples with different joint dimensions. The thickness of the glue layer of the left part is 500 μm and of the right part it is 100 μm. Obviously, the thicker joint contains significantly more and larger impurities or air bubbles (black spots) than the thinner one as it could be expected from section 2.1.

3.3 Mechanical tests

The qualification of the complete part has to be performed in the type test. In case of the insulators the tests are described in the IEC 61462 [5] or IEC 62217 [6] respectively. Regarding the scarf joint particularly the mechanical requirements have to be confirmed in the bending test and if applicable in the internal pressure test.

In Figure 15 the setup for the pressure test is displayed. Both ends of the insulators are sealed with metal plates. The insulator is filled with water and the internal pressure is increased in steps according to the required service and testing pressure. In order to collect more information in most cases the pressure is increased until failure. In this particular case, an insulator was tested with approx. 9 m in length and a maximum service pressure (MSP) of

(a) Backlight picture of an imperfect joint [4]



(b) Axial CT investigation [4]

Figure 13: Visual methods

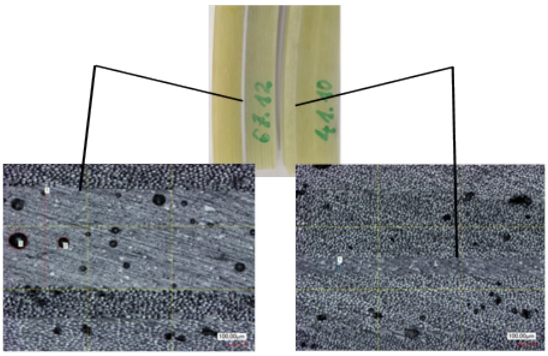


Figure 14: Microscopic investigation of two joints with different thicknesses [4]

Figure 15: Setup for pressure test

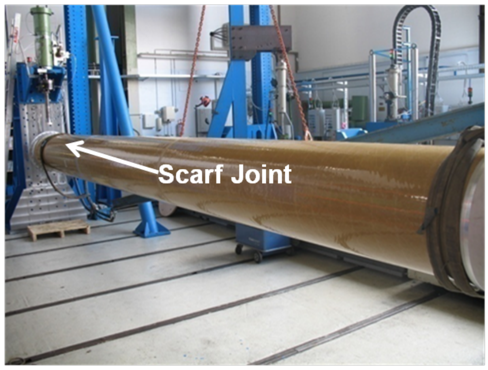


Figure 16: Setup for bending test

4 bar. According to the IEC 61462 the testing program was as follows:

- Stage 1: 8 bar (2xMSP) for 5 min
- Stage 2: 16 bar (4xMSP) for 5 min
- Stage 3: $>$ 16 bar until failure

The failure took place during stage 3 at 44 bar when one of the flanges was lifted off as it can be seen in Figure 17. Since the pressure at failure was about 2.7 bar higher than required and the failure took place at the interface between tube and flange it becomes obvious that the scarf joint did not weaken the tube.

Figure 17: Failure during internal pressure test

The cantilever bending test which is illustrated in Figure 16, is generally considered to be more crit-

Figure 18: Failure during cantilever bending test

ical than the pressure test. For this insulator the maximum mechanical load (MML) was 14 kN and the length approx. 7 m. The distance of the scarf joint to the clamping plate was approx. 4.7 m.

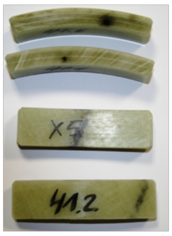
- Stage 1: 14 kN (MML) for 30 s
- Stage 2: 21 kN (1.5xMML) for 60 s
- Stage 3: 35 kN (2.5xMML) for 60 s
- Stage 4: $>$ 35 kN until failure

The actual breaking load in the cantilever test was 44 kN (=1.25xSML) and in this case the flange itself failed (cf. Figure 18). Subsequently the test was repeated with the same insulator by using the other flange to mount it on the clamping wall. The scarf joint was therefore located 2.3 m from the mounting plate and the bending moment in joint was significantly higher than in the first test. However, again the flange broke and not the joint and the breaking load was nearly the same.

3.4 Electrical tests

A joint is potentially a weak spot in a component since two new interfaces are created. Particularly regarding the dielectric strength these interfaces could be preferred paths for puncture.

(a) Tangential



(b) Axial

(c) Radial

Figure 19: Specimen after puncture tests [7]

In the Figure 19a to Figure 19c samples were tested in three different direction with respect to their dielectric strength are shown. The most important information from these pictures is that the puncture, if there is any is not along the interface GFRP - glue but in every case in the bulk GFRP. That means that the electrical strength is not declined by the joint.

4 CONCLUSION

It has been shown, that following basic design rules to optimize the mechanical properties of the joined tube and using the electrical field simulation in order to reduce the field strength at the joint and the interfaces results in a product which is at least not mechanically or electrically weaker than an insulator without a joint. Actually there is an indication that e.g. the mechanical strength of the joint is even higher than in an one-piece tube. Therefore, it becomes obvious that the application of joined insulators to UHV equipment such as bushings has no technical disadvantages compared to an one-piece solution. From a commercial point of view the purchasing of the production equipment for e.g. 12 m tubes would lead to significantly higher prices of the insulators.

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