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Safety Considerations Favour Hollow Composite Insulators on High Voltage Apparatus

The selection of hollow composite insulators to replace porcelain on HV equipment such as bushings, surge arresters, breakers (both live & dead tank) and instrument transformers is increasing worldwide. Indeed, for certain applications where reduced weight or superior pollution performance are the key decision criteria, the majority of such apparatus is now being ordered equipped with this type of insulator.

Hollow core composite insulators are also a prerequisite in the move toward UHV DC since they permit creepage distances to be reduced compared to porcelain. This makes production of very long insulators more feasible given the mechanical needs, especially in areas with seismic activity.

But a growing requirement that also makes them the preferred option is safety – not only for personnel but also for nearby substation equipment that could be destroyed in the event of failure. For example, the explosive shattering of an old circuit breaker at a 400 kV near Geneva during the mid 1990s caused such extensive damage to the substation that it plunged the entire city into a blackout.

This article, based on a contribution by Anders Holmberg and Mattias Lundborg at ABB and Dan Windmar (now at STRI), reviews this issue of safety as it applies to hollow composite insulators.

Bypass breaker at ± 800 kV converter station in China

Safety and reliability are increasingly important considerations for power utilities and are therefore becoming one of the most important advantages offered by composite insulators in place of porcelain housings on pressurized substation equipment.

Insulators filled with compressed gas can store great amounts of energy (typically anywhere from 100 to 1000 kJ depending on size and pressure). To reduce the risks associated with explosive failure, current international standards prescribe minimum requirements for materials, design and construction as well as validation of these by full-scale testing and routine manufacturing inspection.

Typically, all such vessels must be subject to a routine pressure test to verify structural performance prior to delivery. In the case of composite insulators, this routine test pressure is twice the highest pressure expected in service, i.e. the design pressure or maximum service pressure (MSP). The failure or burst pressure of these vessels is generally required to be at least twice the test pressure.

There are four different parts of a typical modern design hollow core composite insulator that will govern mode of failure due to an internal pressure overload:

1. The inner barrier layer (or liner)
This protects the load-carrying composite in the tube from corrosive degeneration products from the insulating gas, e.g. SF6. A new insulator must be able to sustain an internal pressure of at least 4 times the MSP with no visible damage to this liner.

2. The load-bearing composite in the tube.
The tube must be able to a carry pressure of at least twice the MSP without damage and at least 4 times MSP without rupture during validation tests under ambient conditions.
The tube must also be designed to withstand all relevant mechanical, thermal and electrical loads over the entire service life.

3. The joint
This is the adhesive joint between the tube and the metal flanges.

4. The flange
The metal flange transfers mechanical loads to other parts of the assembly.

The insulator norm does not specify which modes of failure are or are not acceptable during a pressure test. Still, for safety reasons it is preferable that the failure mode is by leakage

420 kV disconnecting circuit breakers at substation in Sweden.

through the tube wall or by excessive deformations of the flange that lead to leakage. These are clearly better than e.g. failure of the adhesive joint. For insulators whose tube fibers are wound either in or close to the circumferential direction, axial strength is very low and sensitive to variations during manufacturing. In the event of excess pressure loading, such insulators can separate into two parts in quite a catastrophic manner. Therefore, such designs should be avoided.

Failure in the adhesive joint is another undesirable failure mode. For this reason, this joint should be designed to have a greater safety margin than the other insulator components. To verify that insulators have safe behaviour, even if loaded to failure, one optional test to consider is to pressurize to failure once type tests have been completed. Such failure should then ideally occur only by leakage through the tube wall.

Modeling can also be used to optimize design of the tube and adhesive joint prior to manufacturing prototypes and verifying by means of type tests. Stress analysis is performed to determine the local stress state in a single layer of the composite and adhesive as a function of applied thermal and mechanical loads. The margin of safety is then assessed using conservative failure criteria given the strength parameters of the particular raw materials and manufacturing process.

It is important that these properties are determined for the material combination and manufacturing process of each particular supplier. This is because certain properties may prove sensitive to design details of the manufacturing equipment and process. In other words, *material properties determined to be relevant for insulators produced by one supplier cannot be expected to be valid for those produced by all other suppliers.* For this same reason, the performance of similar-looking composite tubes can also differ significantly among different manufacturers.

TABLE 1: TEST OBJECT DATA

Test object	
Description	Live tank circuit breaker 245kV
Filling gas	Helium
Filling pressure	15 bar (abs)
Insulator test object	1 Porcelain (brown)
Insulator test object	2 Composite insulator with silicone rubber sheds (grey)

Shatter Test of HV Breakers
To compare the failure mode of pressurized porcelain versus composite housings, a shatter test was performed on live tank circuit breakers equipped with both types of insulators. The different failure modes were then carefully investigated.

Data for the two test objects are provided in Table 1.

The methodology selected to investigate the different failure modes was by shooting with a 7.62 mm caliber hunting rifle (Figure 2) at a distance of 100 m from the test object. This simulated the possible effects caused by typical real-life events such as:

- internal fault/over-pressure in the equipment
- external shock during transport, installation or maintenance
- environmental influences e.g. earthquake, landslide, tornado
- vandalism e.g. rock throwing, shooting

Figure 1: Live tank circuit breaker tested.

TABLE 3: COMPARISON BETWEEN PORCELAIN AND COMPOSITE INSULATOR

	Porcelain Insulator	Composite Insulator
Time after impact for pressure release	<< 1 s	> 150 s
Maximum weight of fragment	31.3 kg	Not applicable
Maximum distance of fragment from test object	57 m	Not applicable
Mechanical intact (load bearing) after impact	No	Yes

Figure 2: Shatter test of insulator by rifle shot.

TABLE 2: DISTRIBUTION OF PORCELAIN FRAGMENTS

Distance from test object [m]	Weight of fragment [kg]
57 m	3.0 kg
35 m	14.3 kg
35 m	9.5 kg
35 m	16.0 kg
30 m	6.1 kg
29 m	11.0 kg
25 m	10.0 kg
40 m	4.1 kg
23 m	11.4 kg
30 m	31.3 kg
35 m	20.3 kg
40 m	11.4 kg

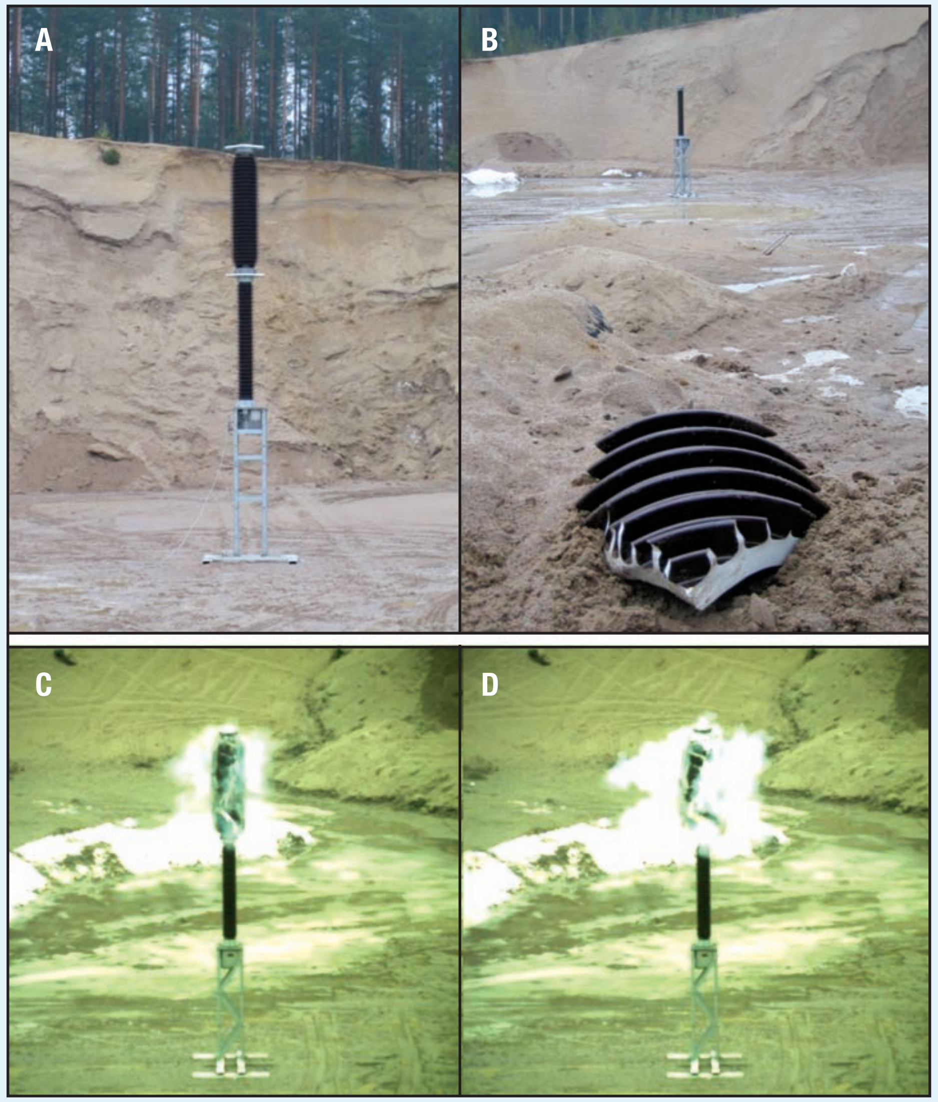

Figure 3: Porcelain insulator, a) before shatter test, b) after shatter test, c) 6 ms after impact, d) 12 ms after impact.

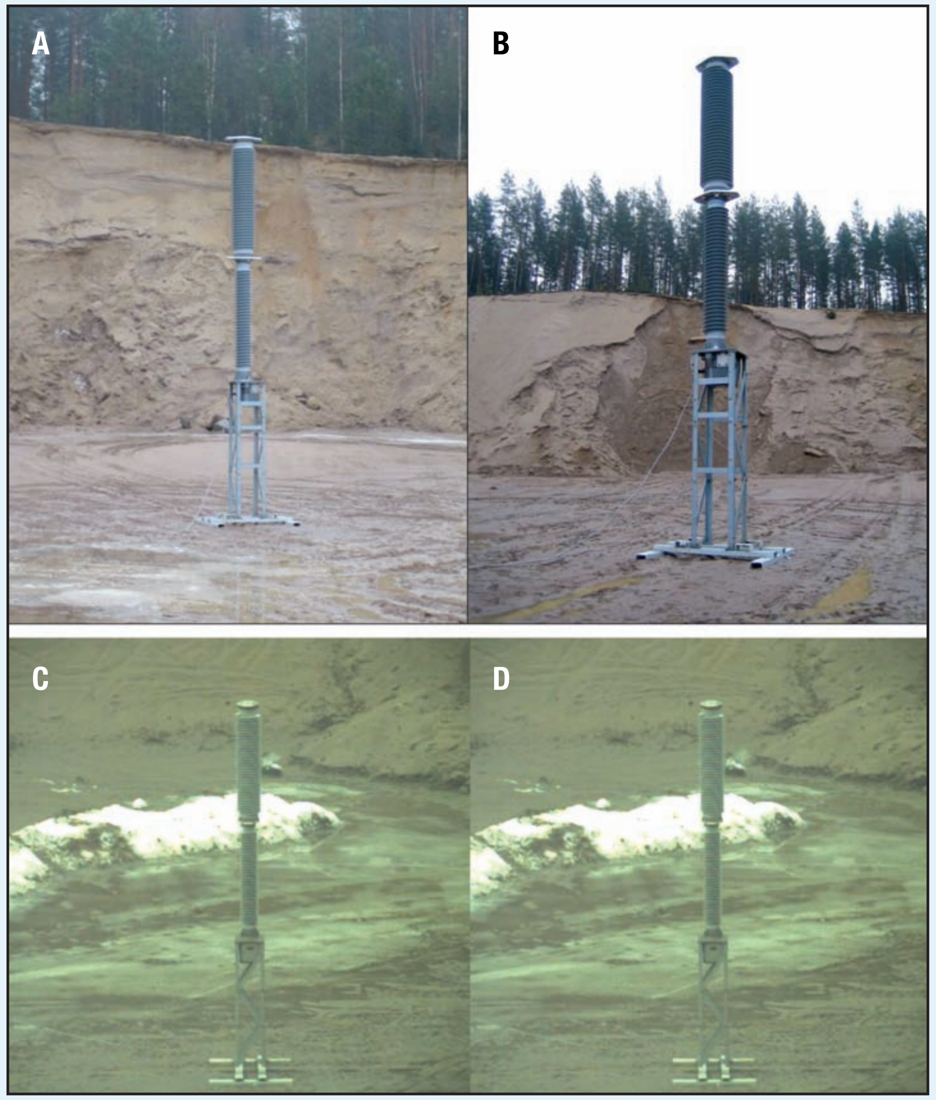

Figure 4: ABB composite insulator, a) before shatter test, b) after shatter test, c) 6 ms after impact, d) 12 ms after impact.

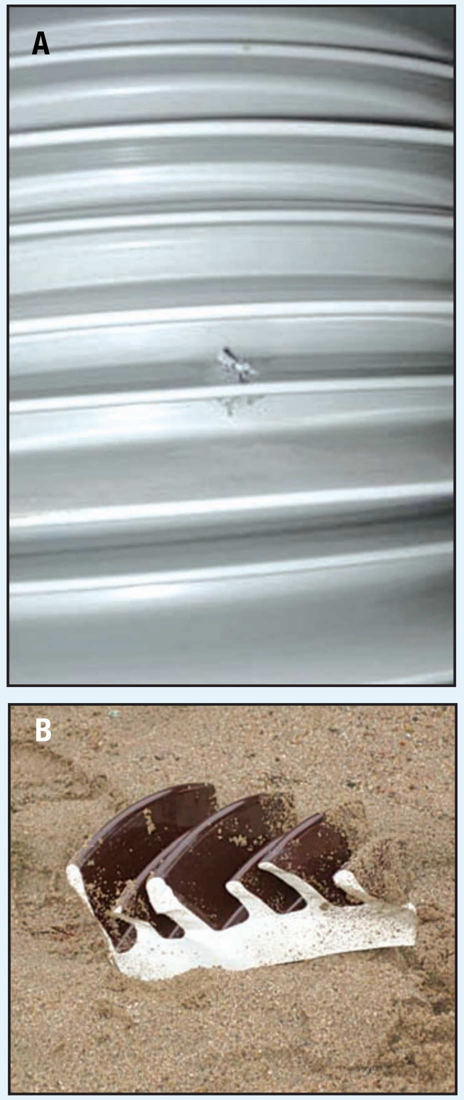

Figure 5: a) Puncture of composite insulators, b) jagged porcelain fragment

The live tank breaker having porcelain insulators experienced failure with a violent explosion. The upper breaking chamber where the impact of the bullet occurred was completely destroyed and sharp porcelain fragments were ejected at high speeds. Figure 3 illustrates the results before and after the impact. High speed photos of the event are also shown.

The main concentration of porcelain fragments landed in the range of 23 to 57 m from the test object and had a weight of between 3.0 and 31.3 kg (see Table 2).

By contrast, test object 2 (the live tank breaker with composite insulators) remained mechanically intact after the impact of the bullet. A small puncture occurred at the point of entrance, which was the upper breaking chamber. There was no launching of destructive fragments in the air.

Figure 4 shows the results before and after impact and includes high speed photos of the event. The time needed to release the overpressure through the puncture was >2.5 minutes.

Conclusions
The photos in Figure 5 above show these different failure modes. The porcelain insulator explodes into sharp fragments spread over a wide area. The composite insulator, by contrast, remains mechanically intact and with only a small puncture from the bullet.

In the event of an internal fault/inner over-pressure or external influence such as vandalism, a porcelain insulator will experience violent failure (explosion) with dangerous fragments thrown about at high speed.

The failure mode of a composite insulator, however, is by de-lamination/puncture without launching of any dangerous fragments. There is therefore no possible damage to surrounding equipment and no danger for persons in the vicinity. This assures maximum safety for both personnel and other equipment at the substation. ☒