ELECTRICAL CHARACTERISTICS AND PROPERTIES OF A STUB (DAMAGED TOUGHENED GLASS INSULATOR)

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Abstract: Overhead line insulators can be damaged for various reasons during their service life. Porcelain or composite insulators once damaged can display a large variety of conditions and aspects. On the other hand, damaged toughened glass insulators always appear as a stub thanks to the properties of toughening. While the mechanical residual strength of a stub is covered by standard tests, its electrical performance is not always fully understood by the users. This paper presents a comprehensive approach to the electrical characteristics of a glass stub taken individually or in a string of insulators. A model of a stub is being proposed in an equivalent electrical circuit. Test results on stubs tested individually or in full strings are analysed and will help to understand their behaviour in situations in line with normal service conditions as well as during over voltages. The influence of environmental elements (dry, wet or humid conditions) is also presented through selected pre-stress conditions. Finally, the electrical behaviour and characteristics of a stub are studied after mechanical and thermal mechanical preconditioning. The electrical properties of a stub offer a significant contribution to the utilities in their maintenance, inspection and live line work strategy.

1 INTRODUCTION

While the performance of overhead line insulators is well described through standard test procedures, there is much less information relative to the performance of damaged insulators. In reality the only standard test existing in this category is the mechanical residual strength test which exists with various procedures for cap and pin suspension or tension insulators [1] [2]. Unfortunately, given the large diversity of possible damage modes on polymers such an approach does not exist for composite insulators.

The results described in this paper do not focus on mechanical aspects of damaged toughened glass insulators, already largely described [3], [4], but more specifically on the electrical performance and behaviour of a broken glass insulator.

The electrical characteristics and main parameters of a stub (broken glass shell) are defined. Electrical properties of a stub have been evaluated as a single unit as well as part of a complete string through tests simulating the diversity of stresses which can be encountered in service.

2 BRIEF DESCRIPTION OF A STUB

The common designation of “stub” (figure 1) applies to any toughened glass insulator damaged on the shell. The thermal toughening of the glass shell during manufacturing introduces a mechanical pre stress in the glass which will be instantly released when any overwhelming damage is done to the dielectric.

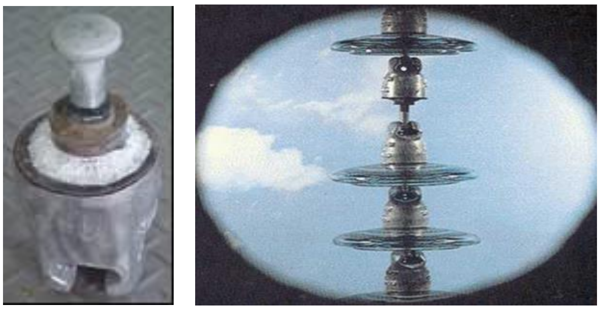
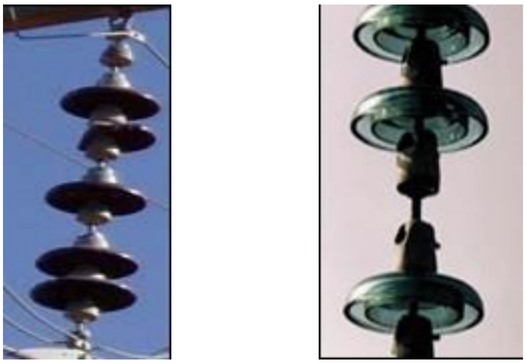


Figure 1: Typical aspect of a toughened glass stub

As a result, and unlike porcelain which can break in large pieces with randomly distributed cracks (figure 2a), a broken glass insulator systematically becomes a stub (figure 2b). The aspect and properties of stubs can therefore be predicted with consistency given the reproducibility of the end condition of the insulator once damaged [5], [6].

3 MAIN ELECTRICAL CHARACTERISCS OF A TOUGHENED GLASS INSULATOR

The characteristics of a cap and pin insulator dielectric are mainly defined through the electrical resistance (R) and capacitance (C). Unlike for porcelain, the nature of glass (amorphous material) produces inherently very stable values since it is not affected by micro cracks, micro structures and crystallographic structure or defects which cannot exist in toughened glass dielectric [7].



a: Porcelain discs

b: Toughened glass

Figure 2: Damaged cap and pin units in a string.

In this regard, and unlike for porcelain dielectrics the values of R and C are strictly defined by the chemistry of the glass itself and the size of the dielectric (geometric considerations like thickness of the head in a cap and pin insulator) and are not affected by ageing or time.

Figure 3 gives an example of the body resistance of similar toughened glass insulators for AC applications and DC applications. To be correctly measurable, the resistance is tested at high temperature. The resistance of a typical insulator unit at ambient temperature can be estimated from 10GΩ to 500GΩ for AC and DC glass respectively. The difference in values between AC and DC is strictly the result of the bi-alkali effect in the chemistry used for the DC glass.

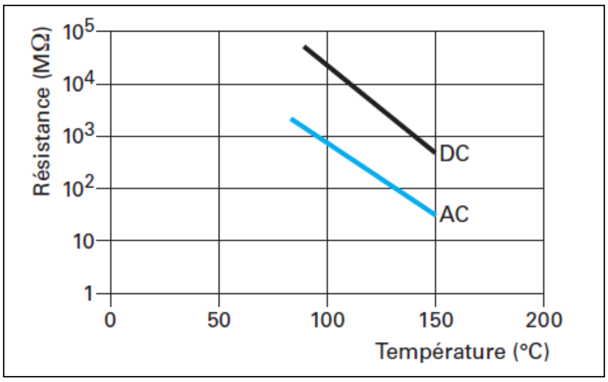


Figure 3: Example of body resistance measured at high temperature for AC and DC insulators as per IEC 61325 [8] [9].

The value of the capacitance of a toughened glass insulator is almost constant and is only slightly dependent on the size of the glass head inside the cap.

A median value of C around 70pF can be considered for a complete glass insulator corresponding to a mechanically mid-range product, as can be seen in figure 4.

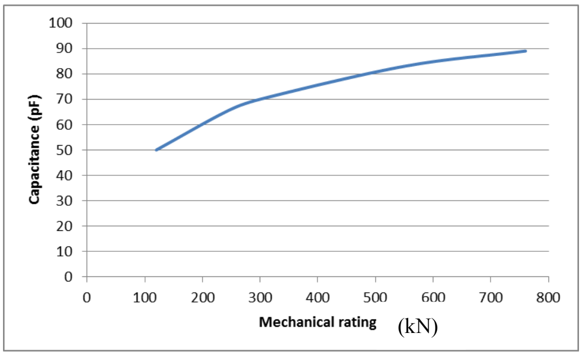


Figure 4: Example of capacitance values of toughened glass insulators.

The surface resistance of the insulator (meaning the electric resistance along the surface of the skirt) is largely a function of the environmental conditions; this surface resistance is considered as variable.

Concentrating strictly on dielectric material behaviour we will not focus on this variable resistance. The equivalent circuit in dry and clean conditions can therefore be represented by 5a, and to the extent that the body resistance is very high, cap and pin insulator units can be simplified as represented by 5b.

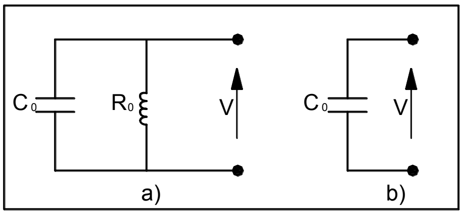


Figure 5: Equivalent circuit of a cap and pin suspension insulator. a) Full circuit. b) Simplified circuit.

4 STUB SCHEMATIC ELECTRICAL CIRCUIT

Doing the same exercise with a stub requires the understanding that, once broken, the remaining glass stub will not see internal arcing during a voltage increase but rather flashover by an arc externally crossing the section of broken glass between the cap and the pin as can be seen in figure 6. This external air gap is short compared to the longer distance for an arc to find its way internally between the glass fragments compressed between the cap and the pin once the insulator is broken.

Figure 6: Flashover across the remaining section of broken glass of a stub. (Left AC, right DC).

The thickness of the glass is slightly variable but in a narrow range (we will consider 12mm as a reference value), we can assimilate this external and constant distance to an air gap operating precisely as such. Tests have shown that 12kV is a typical discharge value for this phenomenon in AC in dry and clean conditions. For DC average values around 14kV were found for both polarities. The capacitance and resistance of the stub will be changed by the fact that the glass is broken. We can therefore consider that both C and R will change leading to the equivalent electric circuit shown in figure 7.

Cs is the additional capacitance and Rs the resistance arising from the interfaces in the broken glass inside the head of the insulator. The equivalent capacitance of a stub is thus defined by:

$$C = Co + Cs \quad \text{and} \quad 1/R = 1/Ro + 1/Rs$$

Where C, Co and Cs = capacitance in Farad (F) and R, Ro and Rs= resistance in Ohm (Ω)

C = 200 pF; R = 20 MΩ

These values are defined for normal atmospheric conditions in clean ambient laboratory conditions. It is extremely important to understand the behaviour of the air gap corresponding to the distance over the glass between the cap and the pin at the bottom of the stub. This distance is constant and represents the shortest distance for an arc to take place. While for a complete insulator the flashover is defined by the arcing distance, in the case of a stub the arcing value is strictly defined by the air gap between the internal edge of the cap and the cement around the pin.

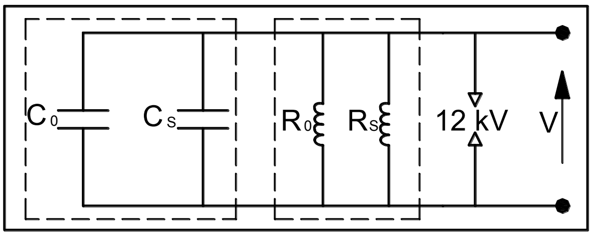


Figure 7: Equivalent electric circuit of a stub in dry and clean conditions

The following section describes the values of C and R of a stub under various preconditioning circumstances as well as the stub behaviour.

5 INFLUENCE OF ENVIRONMENTAL STRESS CONDITIONS TO THE ELECTRICAL PROPERTIES OF A STUB

The electrical behaviour of a stub was determined after various pre-stress conditions as explained below. For each case the stubs were tested after being subjected to one or the other preconditioning parameters (figure 8). The tests presented in the following sections will cover most frequently asked questions relatively to the electrical behaviour of stubs in service.

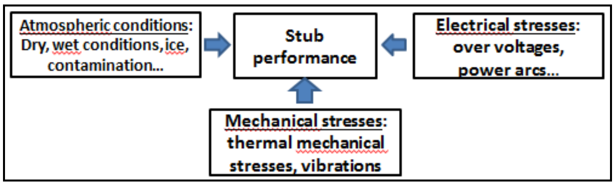


Figure 8: Possible stresses for a stub in service.

5.1 Atmospheric conditions

5.1.1 Stubs in water

Stubs were immersed in salt water for one hour. Electric tests were performed 2 hours after being removed. All stubs flashed externally.

Additionally, the electrical resistance of the stubs was measured highlighting a reduction of the resistance to around 0.1 MΩ compared to the initial value of 20 MΩ while the capacitance increased to reach values around 600 pF compared to the initial value of 200 pF.

5.1.2 Stubs in dry air conditions

Samples of stubs were preconditioned for 24h in a climatic chamber at 40°C and 22% humidity. All samples were electrically tested confirming an external flashover. Figure 9 shows the evolution of C and R at various times after being introduced from ambient conditions into the climatic chamber. It is interesting to note that during the drying process the resistance is slightly increased while the capacitance is slightly decreased. Despite these changes it is important to note that the behaviour of the stub is not changed, always showing systematic external arcing.

5.1.3 Stubs under icy conditions

Stubs have been frozen for 24h after being immersed in water for 48 h The stubs were electrically tested immediately after being removed from the freezer, and all stubs flashed externally after the leakage current on the surface of the stub had melted the ice.

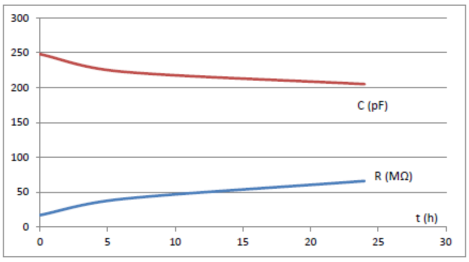


Figure 9 : Evolution of R and C as a function of time after introduction of a stub into a dry air climatic chamber.

5.2 Mechanical pre stresses on stubs

While the mechanical strength of stubs has been largely demonstrated over the last decades and clearly described through standard tests [1], [2], some additional mechanical stresses were considered.

5.2.1 Vibration stresses

Stubs were tested after having been subjected to 11 million cycles where the applied load varied from 40% to 50% of the mechanical rating of the insulators at a frequency of 12Hz. All the stubs were tested electrically and in all cases the arc was observed in the air gap outside the stub. (A verification of their mechanical integrity showed that all failing loads were above mechanical rating).

5.2.2 Thermal mechanical stresses

Full strings of stubs have been tested in thermal mechanical conditions corresponding to the most severe testing conditions [10] as shown in figure 10.

Figure 10: Left: Thermal mechanical test on stubs. Right: electromechanical test at 70% of rating.

Applied load was 70% of the rating, temperature cycles were from -50°C to +50°C. After thermal mechanical stresses were applied all the stubs were electrically tested resulting in systematic external flashover.

In a final stage, all stubs were electrically tested under a permanent mechanical load of 70%, again leading to systematic external flashover.

5.3 Electric stresses on stubs

5.3.1 Steep front tests on stubs

Stubs were subjected to a steep front wave test which was as severe as possible given the short air gap on the stub (figure 11). A steepness in the range of 1000 kV/µs was reached during these tests. All stubs flashed externally. Additionally after the steep front test the stubs were subjected to a 3h withstand test at 11kV as shown in figure 11. All the stubs in this test displayed systematic external flashover in a retest after this sequence.

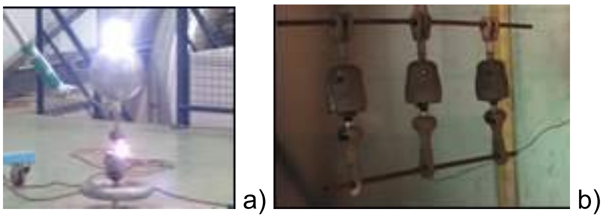

a) b)

Figure 11: (a) Steep front on stubs and (b) power frequency withstand test after steep front test.

5.3.2 Power arc on stubs

Stubs were subjected to a power arc following the set up and test conditions of IEC 61467 [11]. The tests were performed simulating various configurations of a string made of 6 units. The stub was placed once at the bottom, once in the middle and once at the top of the strings. Each string was submitted to two consecutive shots of 6kA/0.2s. The same test was performed with strings which stubs had previously been immersed for 48h in a 10g/l salt solution. An additional test of 6 consecutive shots was made on a string constituted only of 6 stubs.

The choice of the applied current was made to ensure that the test would optimize the chances to keep the arc on the surface of the stub rather than moving away from the insulator string. This detail reinforces the severity of the applied stress on the stub itself.

Figure 12 shows the tested strings. Figure 13 shows the string made of 6 stubs during the power arc. The presence of 6 separate arcs crossing the external distance outside the stubs indicates clearly that the stubs do not behave like punctured discs, and as such illustrates clearly the difference with porcelain discs which, once punctured, could lead to a string separation resulting from internal arcing along the puncture path leading to excessive energy accumulation inside the cap.

Figure 12: Strings with stubs after power arc testing.

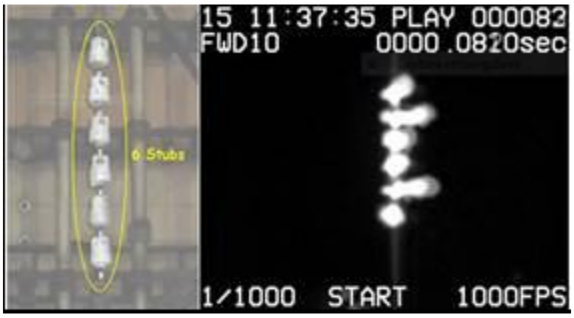


Figure 13: String of stubs during a power arc test showing systematic external arcing.

6 ELECTRICAL PROPERTIES OF STRINGS CONTAINING STUBS

The predictability and strength of a damaged toughened glass insulator has been largely demonstrated over the past decades from a mechanical point of view [3].

From an electrical point of view as well, there is no hidden risk or unpredictable behaviour to fear [12], making toughened glass insulators the preferred type of insulator from a live line work point of view [12]. Specific rules relatively to clearance distance and national standards differ from one country to another in terms of number of damaged units allowed in a string [13] before a maintenance action is required.

The following aspects of performance of strings with stubs have been selected to form a rational understanding of the string behaviours.

6.1 Dielectric tests on 138 kV strings

Typical 138 kV strings of 8 units (ANSI class 52-5) were tested under lightning impulses as well as dry and wet power frequency. Intact units were replaced with stubs in various locations along the string. The results in figure 14 show that the most critical case is the wet power frequency performance. When 6 out of 8 units are in a stub condition (75 % of the string being broken), the remaining leakage distance of the two last complete insulators falls below what is required to withstand the operating voltage. However, with half of the string broken the operation of the line (80kV phase-ground) is still maintained (except for cases where pollution is present, for which leakage distance is the prevailing factor). These tests were performed with line end units 1 and 2 always broken.

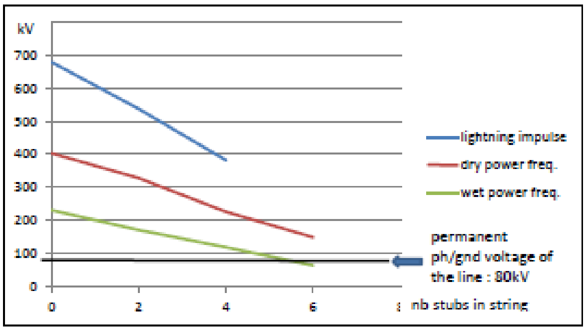


Figure 14: Withstand values of a 138kV string with stubs.

6.2 Switching impulse on 500kV strings

At 500kV the switching impulse behaviour becomes a major focus for line performance.

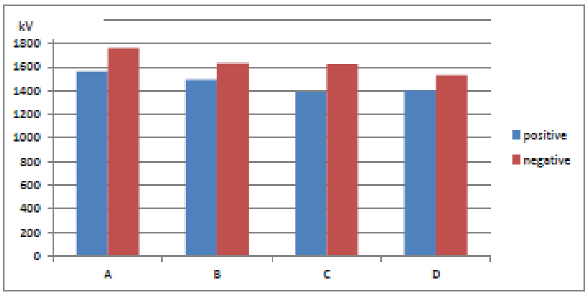


Figure 15: U50 dry switching impulse performance of 500kV string with 5 stubs (A: full string B: 5 stubs in 3-7-11-15-19 from line end C: 5 stubs in 1-7-11-15-19 D: 5 stubs in 1-7-11-15-22).

The tests were performed with a string of 22 units ref. B12/140. A string having 5 stubs distributed in positions 1-7-11-15-22 was tested under dry switching impulses. Figure 15 shows the comparative results between this configuration and a complete intact string. It is interesting to note that the performance of a string containing about 22% of stubs maintains about 90% of its original performance.

6.3 RIV on 500kV strings

The following RIV test was performed according to ANSI C29-1 [14] on a 500kV string made of 25 ANSI 52-5 glass units, equipped with normal hardware configuration, having a stub at the live end. At nominal voltage the RIV levels are similar both with or without a stub.

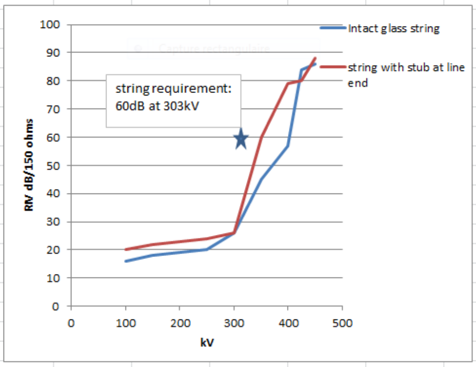


Figure 16: RIV results of a 500kV string containing a stub in the glass string at the live end.

The actual behaviour of a string containing a stub is the result of the voltage distribution along the string. The voltage distribution measured on a 500kV string composed of 20 glass ANSI 52-5 class insulators is shown in Table 1.

Insulator position conductor end	String of 20 toughened glass insulator units				
	With NO stubs	With a stub in position			
		1	2	3	4
1	11.5	2.5	11.8	12.0	11.7
2	9.1	12.0	1.9	9.6	9.7
3	7.6	9.4	9.2	1.6	8.1
4	6.4	7.6	6.9	7.7	1.3
5	5.5	6.3	6.0	5.8	6.5

Table 1: Percent voltage distribution of a 500kV string of toughened glass insulators with a stub in various positions.

It is interesting to note that during this test there was no partial arcing on the stub and the voltage distribution is similar to a string with only intact discs everywhere else. The drop of potential of the stub in various positions is stable for whatever position in the string. This is the result of the difference of the capacitance of a stub versus a complete disc (about 4 times more for a stub as explained earlier).

7 CONCLUSION

The geometry and nature of stubs provide unique properties to a damaged toughened glass insulator. The benefit of repeatability in the condition of a stub and the specific values of resistance and capacitance make that over voltages under the variety of circumstances encountered in service will systematically generate an external arc and not a puncture as may be the case with porcelain. The predictable and safe behaviour of a stub in a string allows maintenance crews to forecast easy and low cost maintenance while ensuring the most reliable service conditions. The absence of urgency resulting from the behaviour of stubs makes toughened glass the most effective solution for live line work and full cycle cost.

8 REFERENCES

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