MECHANICAL AND ELECTRICAL BEHAVIOUR OF A DAMAGED TOUGHENED GLASS INSULATOR

IMPACT ON MAINTENANCE STRATEGY FOR OVERHEAD LINE CREWS

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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 and require specific approach for inspection or live line work. Today major questions are still open for polymer insulators assessment and live-line work techniques given the diversity of situations encountered and the difficulty to have a reliable inspection technique in service. 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 mechanical and 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 a string are analyzed and will help to understand their behavior 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 behavior 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

Toughened glass insulators have been used for more than 60 years in overhead lines thanks to the mechanical strength imparted by the toughening process. Today, this technology is widely used for AC or DC lines up to 1000kV AC or 800kV DC. Through a rapid cooling process using air jets specifically located around the glass shell all along the surface of the dielectric, and as the temperature is rapidly decreasing, the “skin of the glass (approx. 1/10” of thickness from the surface, (about 2mm)) is rigidified like it were “frozen” while the bulk volume inside remains warmer for a longer period of time (figure 1). When finally the inside cools down it tends to contract in volume, which is no longer possible since the “skin” is rigid. As a consequence, a balance of internal forces is being established. The inside volume keeps permanently its extension forces while the “skin” is under permanent compression This balance of internal forces give the strength to the glass body.

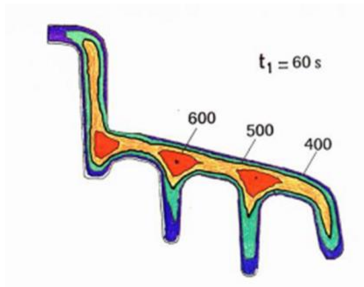


Figure 1: temperature gradient during the cooling process imposed by the toughening.

Toughening is applied to the glass when it is still hot. This property is permanent and can only be modified if the glass is being broken (in which case the internal energy of the toughening is instantly released and the glass breaks in thousands of small fragments), or by exposing the glass body for several hours to a temperature which is not realistic in service conditions (>1300 F (> 700°C)) .

Several major consequences are resulting from this property:

- Toughened glass does not age (figure2). (4).

Figure 2: compressive strength measured on a new glass insulator (left) compared with the strength of a 50 year old unit (center) removed from service. Indentation measures (right) show a compressive stress in surface in the range of 200MPa to 210 MPa (approx. 30kpsi)

- Whenever and for whatever reason a toughened glass shell is being broken, it always breaks the same way, with a complete destruction of the glass shell (figure 3)

Figure 3: binary condition of a toughened glass insulator either intact or shattered. Right: a ”stub”

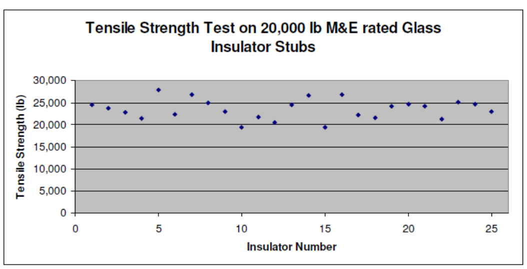
The discussion below will address the mechanical and electrical behavior of a stub under various stress conditions and environmental situations. The characteristics of a stub will also be described in the context of string performances.

2. Mechanical aspect of a stub

What is left from the glass insulator once the shell is broken is called a stub, as shown in figure 3. Inside the cap the small pieces of glass are contained between the cap and the cone of the pin like a wedge.

The mechanical strength of damaged insulators (called residual strength) is fully described in standards. While ANSI is the least demanding test, IEC or CSA ask for more stringent test conditions, adding a thermal preconditioning prior to the mechanical test itself.

With respect to ANSI C29 2B (2), the strength of a damaged porcelain or glass unit is considered as acceptable if the criterion described below is met (based on test results of a sampling of 25 units).Figure 4 shows the results on a 20kips design. The failing loads remain close or above the rating of the insulator.



$$\overline{X}_R \geq (1.2\times \text{tension-proof load}) + 1.645\ S_R$$

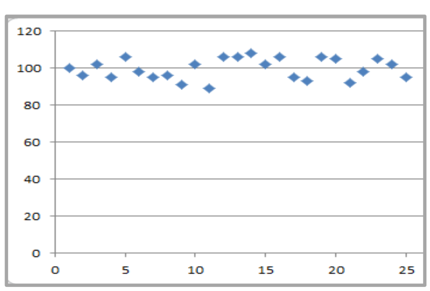
where,

$\overline{X}_R$ = average residual strength of 25 units

S_R = standard deviation of residual strength of 25 units

Figure 4 : typical residual strength test and acceptance criterion according to ANSI C29 2 (tests performed in ASU, Arizona) (7)

For IEC (8), the strength of a damaged porcelain or glass unit (tested after thermal preconditioning) is considered as acceptable if the the factor "k" calculated as described below is higher than 0.65 (based on test results of a sampling of 25 units). Figure 5 shows results for a 40kips design. Values remain around the rated value of the intact insulator and systematicaly above 80% of the rating.



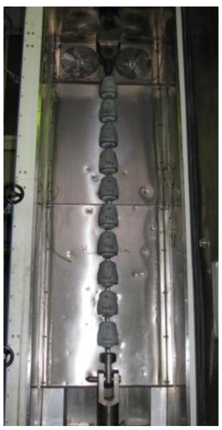
$$k = \frac{\overline{X} - 1.645\ s}{R}$$

($\overline{X}$ is the average value of the test sampling, R is the guaranteed failing load, s is the standard deviation)

Figure 5: residual strength test as per IEC 60797 (8) on 40kips toughened glass insulators (results on 25 units expressed in % of rating)

Similar tests have been performed on insulators after more than 30 years of service (4) either in AC or DC. The results do not differ from recently made insulators, and there is no further degradation to expect given the fact that once broken the stub is in a final stage with no further cracking or crack propagation to expect (unlike for porcelain where a crack can propagate internally and lead to unexpected mechanical consequences).

The mechanical strength of stubs has also been tested under a variety of situations including thermal mechanical tests. Below is an example for such a test performed according to CSA 411.1 (3) which is the most severe standard with a requirement at 4s (4x standard deviation). The load is set at 70% of the rating and cycled for 96 h with temperature variations going from -50°C to +50°C. Figure 6 shows the tests and mechanical results of such stress tests



Average failing load: 56 kips

Min value : 55 kips

Acceptance criteria : $\bar{X} \geq R + 4s = 52$ kips

Figure 6: thermal mechanical tests on stubs (left) and final mechanical pull test after the thermal mechanical test (center), pin broken during the test (right). Tested units: 50kips ANSI 52-11.

Another stress test was performed with the application of cyclic load. Figure 7 shows such a setup. The load was oscillating between 40% and 50% of the rating at a frequency of 12Hz, with an overall duration equivalent to 11 million cycles. At the end of these tests, the failing load of the stubs was established by a mechanical pull test. All the results were found above the initial rating of the insulators.

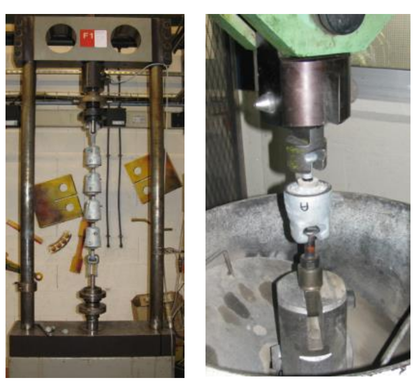


Figure 7: cyclic mechanical load test on stubs

All these tests demonstrate that the mechanical strength of a stub is stable and above the mechanical requirements of the line during operation. Such tests support the fact that in service the presence of a stub does not require any urgent need for replacement. Besides the fact that the ease of inspection provides a 100% sure diagnostic of the condition of a string, line crews know that a stub is not a mechanical weak link in a string of insulators.

3. Electrical aspect of a stub

Given the design of a toughened glass insulator and the fact that the glass shell is systematically disappearing when damaged, the shortest distance for an arc to take place is between the cap and the pin externally as shown in figure 8. The average flashover value of a stub has been measured around 12kV (with possible fluctuation of one or two kV depending upon the size of the insulator).

Figure 8: flashover of a stub

The binary aspect inherited from the toughening as explained in section 1 makes that this value is equivalent to an actual design characteristic for a damaged toughened glass insulator. Therefore, and given the fact that the insulator itself has a certain resistance, and capacitance, the equivalent circuit of a stub can be represented by figure 9 and compared to the equivalent circuit of an intact insulator. The electrical values R, and C of a toughened glass insulator and a stub have been established in previous publications (5) under normal service conditions or under a variety of environmental conditions. We can consider that the value of the equivalent resistance and capacitance of a stub are:

R= 20MΩ and C= 200pF

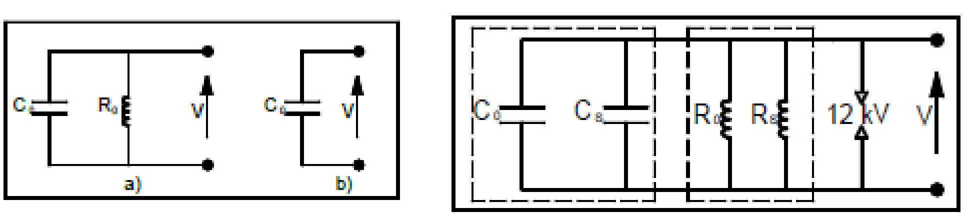


Figure 9: equivalent electric circuit of a toughened glass insulator (left) and of a stub (right)

The 12 kV air gap being the shortest distance for an arc to bridge the distance between the electrodes represented by the cap and the pin, we can consider that the equivalent circuit of a stub contains a built-in external protection calibrated to more or less 12 kV. One of the major consequences is the fact that toughened glass insulators do not present the risk of string separation like it is the case for porcelain where punctured heads subjected to power arcs can lead to cap or pin ejection.

To go beyond the electrical characteristics of a stub, additional stress tests have been applied to validate the fact that the arc is consistently external.

Among these tests, the previously described thermal mechanical and vibration stress tests were used. At the end of these tests, and prior to mechanical verification, all the samples were electrically tested, leading to a systematic external flashover. This demonstrates that neither mechanical vibrations nor thermal cycles are disturbing the integrity of a stub.

Several additional tests were performed.

<u>Power arc tests:</u>

Stubs were subjected to a power arc following the set up and test conditions of IEC 61467 (9). The tests were performed simulating various configurations. 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 10 shows the tested strings. Figure 11 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 possible internal arcing along the puncture path leading to excessive energy accumulation inside the cap.

Figure 10: strings with stubs

Figure 11: power arc on stubs

Steep front tests:

Stubs were subjected to a steep front wave test which was as severe as possible given the short air gap on the stub (figure 12). 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 12. All the stubs in this test displayed systematic external flashover in a retest after this sequence.

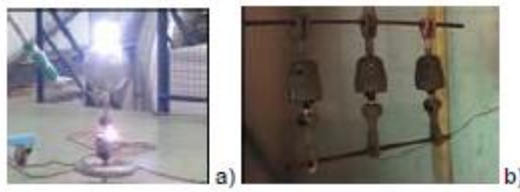


Figure 12: a) steep front test on stubs. b) withstand test after steep front test

All these electrical verification tests demonstrate the safety level represented by a stub in a string. Therefore, and like in the previous section, there is an interesting feature for maintenance crews who do not need to rush replacing a damaged glass insulator since there is no risk for the operation of the line. Furthermore, the diagnostic being visually reliable at 100%, such strings are compatible with live line work (provided the number of broken bells remains in the limits of the safety rules of the utility) (6).

4. Electrical performance of insulator strings containing stubs

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

4.1 Dielectric tests on a 138kV string with stubs

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 13 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.

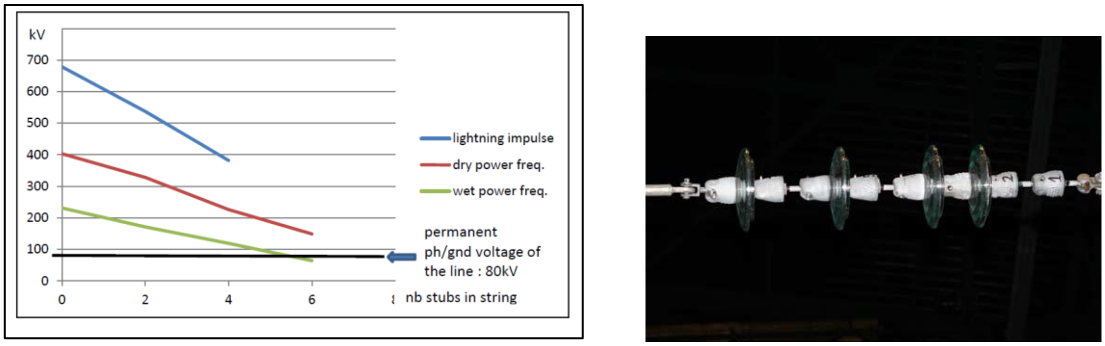


Figure 13: dielectric tests on a 138 kV string with various cases of stub locations and number of stubs in the string

4.2 Switching impulse on a 500kV string with stubs

At 500kV the switching impulse behavior becomes a major focus for line performance.
The tests were performed with a string of 22 units ref. B12/140. A string having 5 stubs distributed in positions 1 or 3 -7-11-15-19 or 22 was tested under dry switching impulses. Figure 14 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.

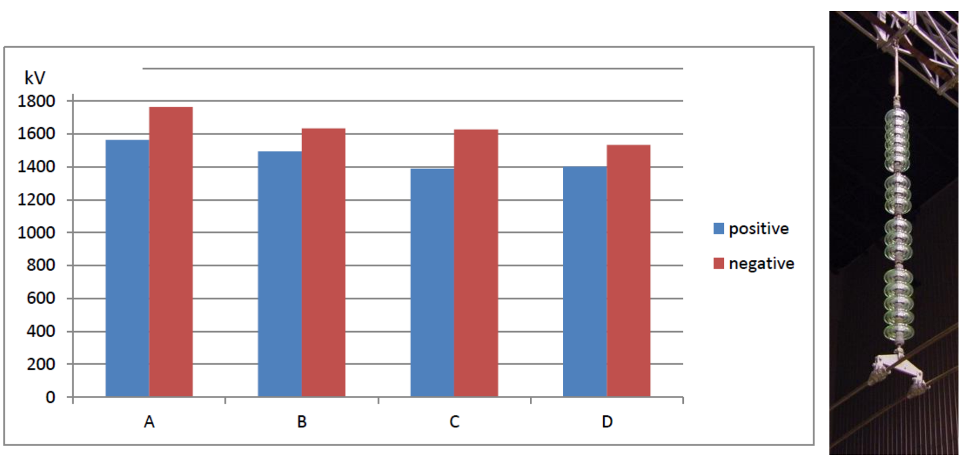


Figure 14: U50 dry switching impulse performance of a 500kV string with 5 stubs
(A: full string B: 5 stubs in 3-7-11-15-19 from line end C: 5 stubs in 1-7-11-15-19 D: 5 stubs in 1-7-11-15-22).

4.3 RIV on a 500kV string with stubs

The following RIV test was performed according to ANSI C29-1 (1) 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 and without a stub (figure 15).

The actual behavior 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 figure 16. 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 mainly due to the value of the capacitance of a stub versus a complete disc.

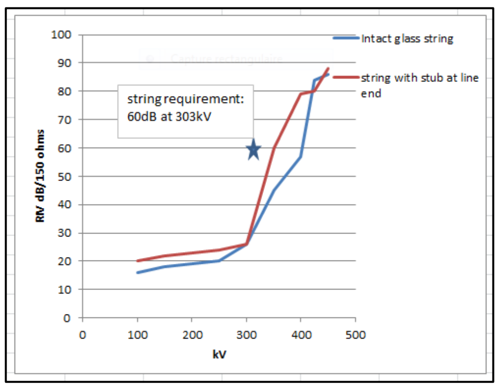


Figure 15: RIV results of a 500kV string containing a stub in the glass string at the live end.

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

Figure 16: Voltage distribution (in %) of a 500kV toughened glass string with a stub in various locations

5. Conclusion

Toughened glass insulators offer a binary behavior being either intact or shattered. This can be spotted visually from the ground or by helicopter through an obvious and simple naked eye inspection. Besides the fact that the diagnostic of toughened glass insulators is 100% sure and reliable, this report shows that the presence of a stub in a string of toughened glass insulators does not represent any risk for the operation of a transmission line. Among the advantages of this technology, the fact that there is no urgent need for maintenance crews to replace a damaged string of glass insulators reduces maintenance costs (10). This unique attribute of toughened glass insulators has been the major reason also for crews and utilities worldwide to select glass insulators whenever live line wok is required.

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