Reliability of transmission lines resulting from insulator design selection criteria

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SYNOPSIS

The selection of the most appropriate insulator design for any given transmission line application follows rules which might not always be set on technical merits. Traditional practice, local manufacturing and nearby available supply, procurement cost considerations among other non-technical reasons can modify the initial approach from engineering, and possibly the long-term performance of a transmission line.

In each technology, either porcelain, glass or polymer, variations in design and manufacturing processes will ultimately lead to differences in long term performances. A quick review of the key technical differentiators in every design of insulators will be proposed to help understand the ultimate expectations in terms of reliability and resilience.

Likewise, technical decisions have sometime been made based on solving a specific problem and the collateral consequences are not always examined with a long-term vision. A typical example is illustrated with the classical decisions process linked to pollution management. It has appeared worldwide clearly in the last 10 years that composite insulators, especially when used in harsh conditions might fix the pollution related flashover problems, but at the cost of a much shorter life expectancy. The real challenge is then to establish the overall full life cycle cost including replacement, inspection and possible risks of failures associated.

An example will be presented showing a real field case for which pollution problems were solved with polymers with a necessity to replace the insulators after approximately 15 years. The interesting outcome is the evaluation of the TOTEX, the risk analyses in terms of reliability and how maintenance costs are impacted by short term decisions. Often utilities discover that the yearly maintenance cost for cheap purchased goods is a burden defeating the initial cost which goes unseen from the initial investment.

As an alternative, this paper will summarize the key features required to be effective in the mitigation of pollution using silicone coated insulators offering simultaneously the hydrophobicity of silicone (which mechanism will be reviewed) and the strength resilience and longevity of toughened glass insulators. Key elements in the selection of silicone coated insulators will be presented as well as performance measured in the laboratory or from the field in various environments worldwide.

Additionally, an innovative approach to preventive maintenance using smart grid solutions integrated to insulators will be presented. This technology already in place in several countries is providing a real time indicator of the pollution status of insulator strings in severe contaminated environments. These devices benefit the grid maintenance groups to forecast their actions in the field.

KEYWORDS

Toughened glass, pollution, smart grid, silicone coating, leakage current, composite insulators, porcelain, dovetail

1. INTRODUCTION

Solving specific overhead line insulation problems can lead to solutions which can have secondary negative impacts on the long-term performance and resilience of a transmission line. It is therefore interesting to review some basic concepts related to insulator design and contamination principles and definitions. Among the interesting evolutions in the approach of utilities towards pollution it is noteworthy to mention that worldwide, grid operators start to recognize the limits in lifetime and reliability of composite insulators. This technology was clearly very attractive for high contamination areas where airborne dust or salt fog were causing outages. The hydrophobic property of the silicone housing has shown clear benefits in such cases, but today there is enough field experience to understand that this technology does not have the same life span as classical glass or porcelain insulators, but also induces severe risks of catastrophic failures while inspection methods are complex expensive and not fully reliable. For that reason, in the last 20 years many utilities started to shift their attention towards glass or porcelain insulators coated with silicone in order to eliminate the risks linked to polymers. Especially for glass this solution combines the benefits of two technologies: on one side the long-term resilience of toughened glass for which there is no hidden defect, immune to ageing and operates in a binary mode, on the other side the benefits of silicone with its hydrophobicity. The performance of such insulators as well as the key properties required for the selection of the best coated insulators will be described.

Finally, in a context where more and more utilities are facing a need for predictive maintenance while reducing the risks of outage, we start to see some innovation in the smart grid contex with insulators capable to communicate in real time their levels of contamination. The technology described here integrates the measure of the leakage current directly from the insulator string but goes beyond by providing a diagnostic to maintenance for managing line washing programs with a preventive approach rather than being reactive or over conservative.

2. KEY TECHNICAL DIFFERENTIATORS BY TECHNOLOGY

For every technology, reliability is defined by the combination of design and quality. Porcelain is very sensitive to the quality and homogeneity of the raw materials and statistical distribution of the particle size of the various crystals used in the making of the porcelain body. From a design point of view porcelain performance is also driven by the shape and the design of the head of the insulators. The best porcelain insulators have a straight head while lower performers still use a so called “dovetail” shape which performances are usually found largely below current international standards. The more complex the shape of the insulator the more difficult it is to make a straight head. In this regard insulators favoured for dusty pollution such as outeribs are more sensitive. (The ribs should naturally be cleaned by the wind, which has some benefits but only in suspension. It is ineffective in tension strings). This design very often exists only in dovetail technology. Figure 1 shows typical failures of outerib dovetail porcelain insulators tested in thermo mechanical tests (string separation), steep front wave or classical electromechanical tests (risk of puncture approximately at 30% in these tests). This is the direct consequence of a shape which induces a higher density of microcracks and simultaneously a stress concentration inside the head approximately 2.5 times higher than a straight head design. Many users have discovered large quantities of punctured units as soon as in the first years of operation. This is a classical example of a design which could have benefits under pollution but leads to high operational risks in service.

Figure 1. Porcelain outerib with dovetail head. Typical failures found in testing

Toughened glass insulators, likewise are not all equal in quality and performance. Among many aspects differentiating good from bad [1], the self-shattering rate is probably the biggest differentiator. This parameter is related to the purity of glass. The industry reference is rating this number at or below 1/10000/year [2] and needs to be proven by performance certificates supplied by utilities having such products in service in countries outside of the manufacturers location).

Polymers are much more complex since more small details can breach the integrity of the insulators. Statistics from large polymer markets have shown high failure rates disregarding the design [3], [4]. Among the key parameters to consider, seals, interfaces but also chemistry of the silicone itself are critical.

While silicone housing has become very popular for pollution mitigation, it is remarkable to note that under very harsh conditions composite insulators will suffer more and age faster than expected. Many laboratory tests were designed to validate this point, but reality check shows that none of those could match the actual ageing dynamics. Even though very often their hydrophobicity is maintained, polymers will have cracks on their core with moisture penetrating down to the fiberglass rod leading to failures, including when acid resistant fibres are being used [5]. The end of life of polymers in polluted conditions estimated today between 7 years and 15 years depending upon location and environment is more the consequence of the chemical degradation of the silicone itself than the loss of functionality under pollution (figure 2).

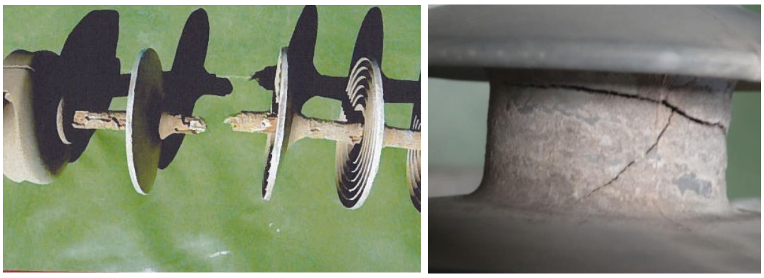


Figure 2: End of life of a polymer insulator eroded in less than 7 years [6] and less than 15 years under various polluted conditions but still hydrophobic

3. LIFE CYCLE COST

Mentioning a life cycle of 10 to 15 years for polymers should raise some questions. Beyond the low procurement cost (CAPEX) of composite insulators, one should consider the TOTEX of this technology compared to traditional toughened glass or porcelain insulators. The operational costs (OPEX) during the life of the line is impacted with composite insulators by higher inspection and maintenance costs, including 2 to 3 replacement cycles over the lifetime of a traditional glass insulator string. Figure 3 shows an example of TOTEX of a 500kV line equipped with polymers compared to the full life cycle cost of the same line using glass insulators. In this particular case severe failures occurred 15 years after installation. The polymer insulators had to be meticulously inspected and the decision was made to replace immediately 40% of the strings with glass insulators and continue the replacement progressively after. The ratio is clearly demonstrating that the low CAPEX of polymers is offset by the OPEX after 15 years. This does not include exceptional costs related to a failure which might occur during this time, knowing that polymers are very difficult to inspect.

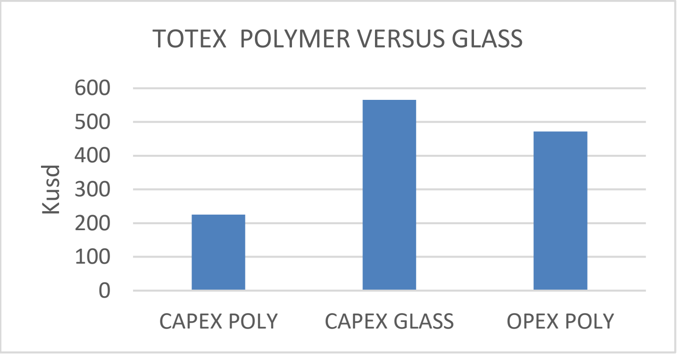


Figure 3: Summary of TOTEX for a 500kV line (actual figures from Latin America). TOTEX polymer offset CAPEX glass with the necessity to replace polymer while glass can last more than 50 years with very limited OPEX.

4. SILICONE COATED INSULATORS REPLACING POLYMERS

The large spectrum of failures of composite insulators, the difficulty for inspection and maintenance as well as an expected life expectancy of approximately 15 years or less has led to a massive shift in the selection criteria for insulators, including in high polluted environments. In many countries composite insulators are no longer selected for transmission lines despite their low cost. An alternative solution is more and more the use of silicone coated glass insulators which provide the benefit of silicone hydrophobicity combined with the resilience of a toughened glass insulator. Millions of such insulators have been installed worldwide over the last 20 years in AC and DC up to 800 kV DC (Figure 4).

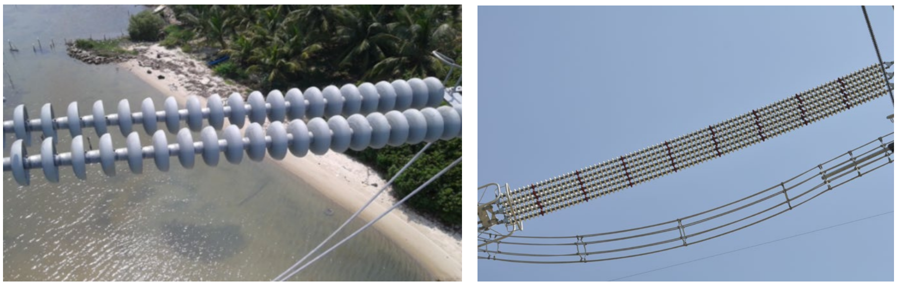


Figure 4: Coated glass insulators. Left: 220kVAC (Sri Lanka) Right: 800kVDC (China)

4.1. Coating key specification elements

Today there is a large trend for having the coating applied in a factory and not in the field. The performance of coated insulators can be severely impacted by the application process impossible to control when done on site. Optimum criteria for the selection of coatings can be summarized as follow:

From a material aspect, the silicone itself should contain at least 30% of Alumina Tri Hydrate (ATH) for a better erosion resistance. Tests to assess this performance can be a thermogravimetric analyses (TGA) and long-term ageing tests like the 2000h multi stress test largely used today and introduced by TERNA [7]. Figure 5 shows the test procedure and set up as well as different results from various types of chemistries. This test is known to be an extremely good differentiator of performance. Additionally, the coating should comply with a criterion of 1A4.5 in the inclined plan test as per IEC 60587 [8].

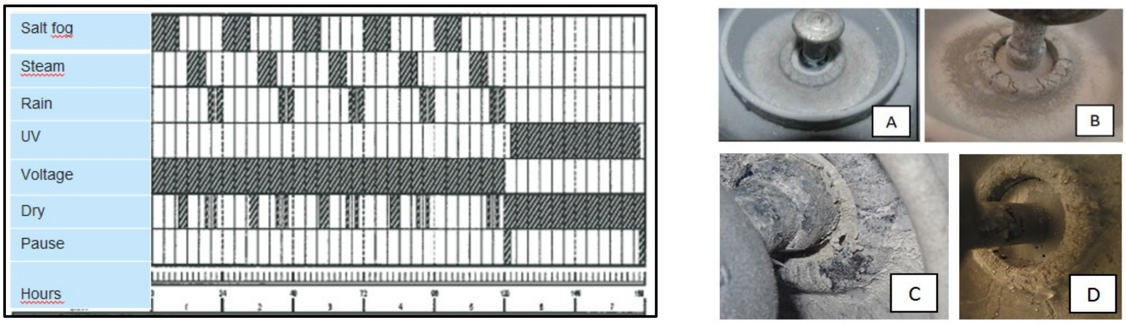


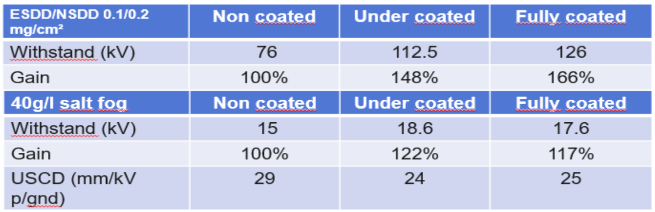
Figure 5: Multi-stress 2000h cycle procedure with various results as a function of the chemistry of the silicone. (A, B and C with different types of ATH, D with quartz fillers)

Thickness needs to be controlled between 280µm and 430µm to ensure optimum curing properties in the thickness of the coating, but also maintain the shattering ability of a glass insulator. Finally, adherence is key for electrical reasons but also for ensuring the longevity of the product. Figure 6 shows a typical adherence test as per EN-ISO 2409 using a scratch tool. Figure 6 shows also an example of field coated insulator which condition most likely is the result of uncontrolled surface cleanliness during application (difficulty to ensure a consistent adherence when dust and other airborne particles cannot be avoided).

Figure 6: Left: adherence scratch test. Right: Bad application with adherence problem [9].

4.2. Performance under pollution

Numerous reports from the field have shown that this solution offers optimum performance under severe or extreme pollution for decades [10], [11]. Pollution tests in laboratories have shown the benefits for either fully coated or only undercoated insulators [12]. Figure 7 summarizes some of these results.



ESDD/NSDD 0.1/0.2 mg/cm²	Non coated	Under coated	Fully coated
Withstand (kV)	76	112.5	126
Gain	100%	148%	166%
40g/l salt fog	**Non coated**	**Under coated**	**Fully coated**
Withstand (kV)	15	18.6	17.6
Gain	100%	122%	117%
USCD (mm/kV p/gnd)	29	24	25

Figure 7: salt fog and clean fog test results for fully and under coated insulators

5. Smart grid insulators

Leakage current along the surface of insulators is a direct consequence of the accumulation of pollution and/or moisture on the surface of the dielectric. In the laboratory, leakage current is almost systematically measured during pollution tests but in the field the instrumentation is much more complex and requires a wireless communication system. It is however one of the best indicators of the risk of flashover if the measured value can be compared to acquired data related to similar conditions and from a similar shape of insulator. It was demonstrated in earlier work that the critical leakage current value of a string is directly linked to the type of insulator under consideration [13].

With decades of testing and field monitoring, Sediver has accumulated enough data to provide a diagnostic of the potential risks linked to the actual pollution levels on a given string based on the analyses of the leakage current retrieved from such sensors. The recent evolution in IoT and communication systems has enabled new transmission protocols, such as LoRa (Long Range) wireless data communication. Figure 8 shows an application of a Smart insulator type 3S and the typical data extracted and analysed (leakage current, temperature and local humidity). This system is currently operating in South East Asia, Europe and the Middle East.

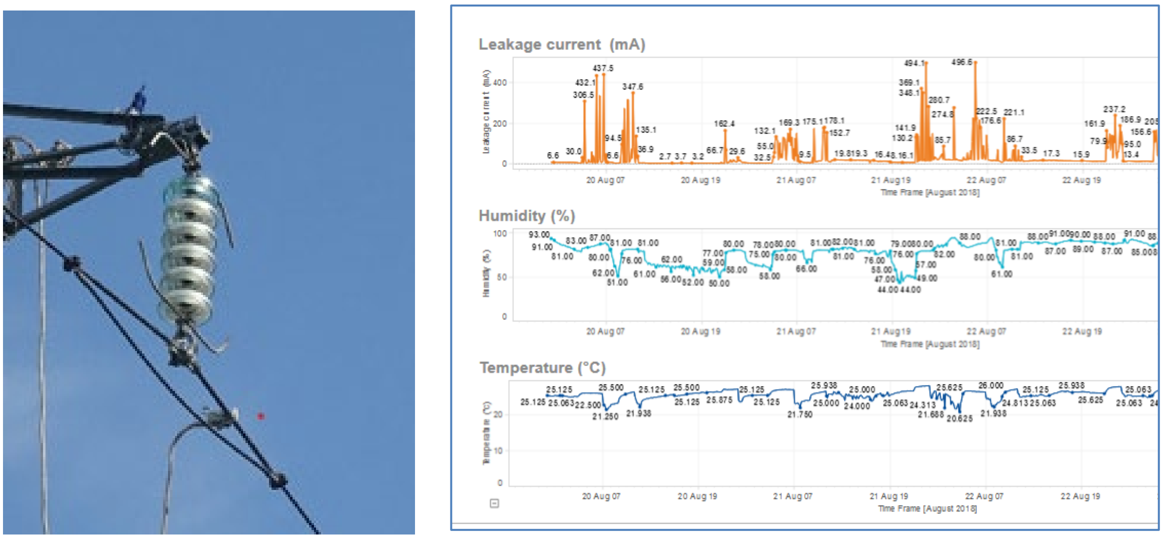


Figure 8: Example of smart insulator 3S with typical reading and analysed response

6. CONCLUSION

Pollution mitigation methods can lead to a selection of insulators reducing dramatically the resilience and reliability of a transmission line. Design and quality are key parameters to consider. While composite insulators were very popular until a few years ago for managing heavy polluted environments, the experience acquired worldwide has shown a strong reduction of life time with potential risks of unpredictable failures. In response to this inherent weakness, silicone coated glass insulators are progressively replacing polymers in very heavy contaminated environments. Furthermore, the comparative TOTEX of polymers versus toughened glass demonstrate the financial benefits of glass when considering the total life cycle cost. Among the recent innovations, Smart insulators are progressively being introduced on strategic lines to monitor the pollution condition of insulator strings in real time with a complete diagnostic process. This technology is intended to help maintenance in producing a predictive approach to line washing as well as managing real time pollution maps in the most aggressive environments.

7. REFERENCES

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