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Management Insulator contamination problems, mitigation methods and innovative predictive maintenance of overhead lines.

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SUMMARY

Insulators represent a very small fraction of the cost involved in the construction of an overhead line, especially at the level of transmission class. However, insulators represent more than half of the maintenance problems and up to 70% of the maintenance costs, not mentioning line interruption and losses of revenue. Among the maintenance aspects, pollution related outages are often an important cost item. Airborne dust or coastal salt contamination of overhead line insulators can seriously compromise the performance of a transmission line, either AC or DC. Understanding basic concepts of the contamination process as well as the tools available for their evaluation can help finding the most appropriate sustainable mitigation methods. Among the diverse options offered in the relatively large spectrum of possibilities we will review the rules for the selection of the most appropriate specific creepage distance (CIGRE and IEC have established guidelines), as well as the most appropriate shape of insulators. We will also address questions related to the use of hydrophobic materials with a review of the physico-chemical processes at work in silicone rubber, their ageing mechanisms on either polymer insulators or coated ceramics. Comparative pollution performance results will be discussed.
Some new materials start to appear in the field of pollution mitigation using nano or micro treatments of ceramic surfaces. A review of the state of the art of these developments will show the risks and expected performance levels of these solutions with results from the laboratory as well as from the field.
While these parameters are introduced here for AC applications, a specific mention for DC is necessary since the polarized effect around the conductors will act like a magnet amplifying the level of pollution compared to an AC line on the same route. Examples will be shown to better demonstrate the specificities of a unidirectional field on the performance of a DC overhead line. A review of some key elements of string design rules for DC application will be addressed especially in relation to the CIGRE and IEC guidelines. Examples of actual line design performance versus the theoretical models will be shown and discussed.
Classical evaluation and mitigation methods require an outage during which samples are periodically taken down to measure the pollution level and often maintenance crews will produce preventive line washing at predefined intervals. Ideally information on the condition of the string of insulators should be more useful if provided on a real time basis. This would allow maintenance action at the proper time without any risk or unnecessary premature spending.
Innovative techniques for real time evaluation of the condition of a string of insulators are now possible thanks to smart insulators capable to communicate in real time their pollution condition. This paper will describe the fundamental aspects of this IoT technology where the insulator itself produces a diagnostic. Instead of measuring the level of contaminants through physical sampling on a string,

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this development will concentrate directly on the consequence of the environment on the performance of the string by measuring the actual leakage current.

KEYWORDS

Smart grid, Glass insulator, Contamination, Leakage current, Monitoring, AC, DC, Overhead transmission lines, Pollution.

I. CONTAMINATION OF INSULATORS

Insulator pollution problems have been a central point of discussion among engineers and maintenance crews for as long as overhead lines have existed. Today the accumulated knowledge and field experience provide tools, methods and solutions which can vary from one case to another based on the type of environment and the amount of contamination. The strings of insulators should then be designed with the most appropriate materials and specific leakage distance. Defining the type of contamination (coastal or dusty environment) is the easy first step in the evaluation. Airborne dust however needs to be qualified given the diversity of types of pollutants and the speed at which they might come on the insulator surface, building a solid crust. More critical is the determination of the amount of deposits. IEC 60815 [1] and CIGRE brochures [2] and [7] offer a comprehensive set of definitions. For coastal areas, the site severity needs to be established through leakage current monitoring on a sample string to define the Site Equivalent Salinity (SES) which later can translate in salt fog tests for the performance evaluation of a string of insulators designed for such conditions. It is more complex when solid airborne particles either salts or non-soluble elements combined end up on the surface of the insulators. In such case the measure of the pollution on site (typically before the dominant rain season and at the peak of the accumulation time) will provide two important numbers called ESDD and NSDD defined here after and as shown in figure 1 for pollution class definition:

ESDD: Equivalent Salt Deposit Density (in mg/cm²) corresponding to the amount of soluble salts contained in the deposit and responsible for an increase of the surface conductivity.
NSDD: Non-Soluble Deposit Density (in mg/cm²) which is made of sand, soil and non-soluble dust acting like a sponge during foggy or muggy periods of time.

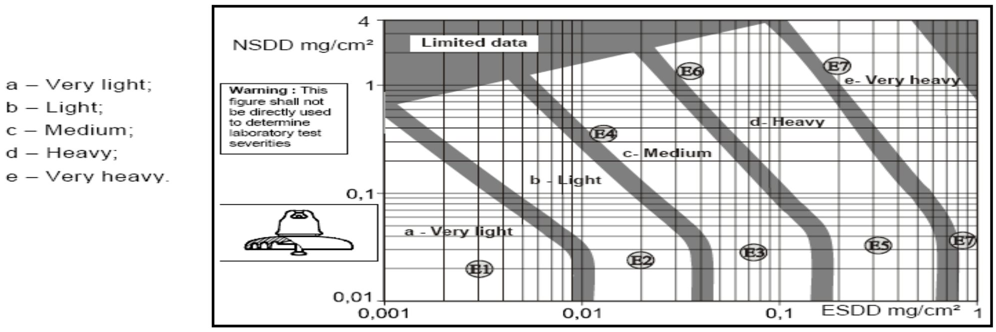


Figure 1: ESDD and NSDD chart for pollution class definition by severity of the deposits measured on the surface of the insulator [1], [2].

II. OPTIMUM SELECTION OF INSULATORS

The type of insulators to be used for any specific application needs to take into consideration the concept of Unified Specific Creepage Distance (USCD), as defined in IEC and CIGRE [1], [2], [7]. AC and DC must be considered separately.

For AC lines a first approach to specific creepage distance is given by [1] and [7] and summarized in Figure 2 below. At this stage, the designer is making sure that the selected polymer unit or the number of glass or porcelain insulators in a string will match this number (the new revisions of IEC are giving USCD phase ground). However, there is no indication so far of the optimum shape of insulator to be used. A more detailed approach would require selecting the shape and profile which would be the most effective for a given environment. Figure 3 provides such guidelines for glass insulators [3]. It is interesting to mention that ANSI C29 2B [4] does not describe any other shape than the old standard profile; in many cases this is the reason US utilities to have insulator strings either too long or ineffective, pushing engineers to use polymer insulators, in which life expectancy and ageing can compromise the resilience of the grid. Fog types or other shapes should be introduced in ANSI.

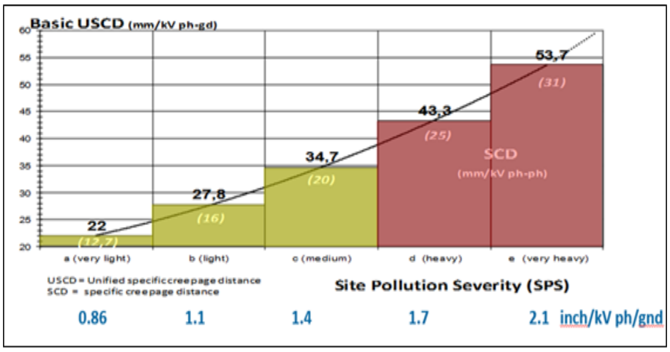
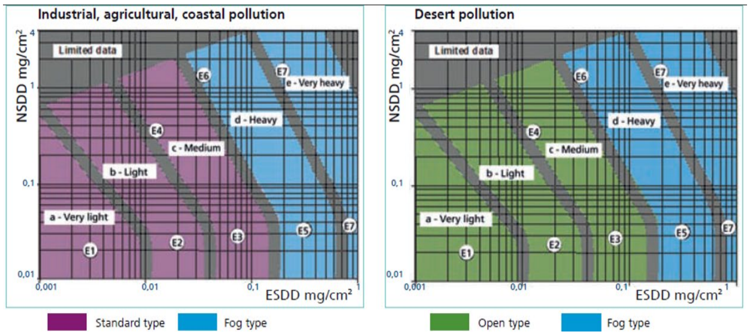


Figure 2: USCD as a function of pollution class [1], [3].

Figure 3: Shape recommendation for different pollution conditions [3].



For DC lines the unidirectional field of DC generates a higher concentration of airborne dust on the insulator strings than AC. Likewise, as shown in Figure 4, both polarities do not produce the same effect. More important, the pollution level is usually not uniformly distributed along the string of insulators as shown in Figure 5. The increased level of contaminants collected by a DC line compared to an AC line can sometimes be complex to establish. IEC 60815 [1] and CIGRE TB518 [2] have approached this question through a set of equations but more work is needed [5].

Figure 4: Difference of pollution between polarities for a 350 kV DC line (left +, right –).

The graph in Figure 6 shows the estimated increased severity in DC compared to an AC line. For these reasons DC lines will systematically need more leakage distance than an AC line. Therefore, DC lines are not designed around the classical insulation coordination methods where arcing distance and string length are defined by lightning impulse or switching but strictly by the pollution levels which are more critical in terms of string length.

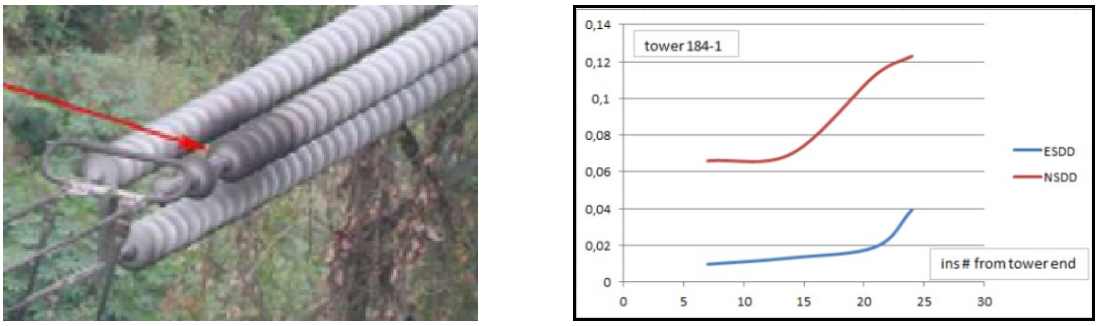
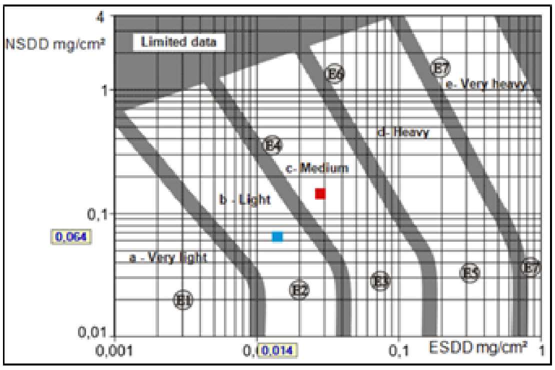


Figure 5: Left: non-uniformity of the deposit along the string (Congo 500kVDC). Right: non-uniformity of ESDD and NSDD measured on the PDCI 500kV (USA) with higher pollution measured on the conductor side (Insulator 1 on tower side, 25 on conductor side).

Figure 6: Blue dot shows the pollution measured on an AC line. The red dot shows the estimated pollution level if the line would be a DC line.



III. HYDROPHOBIC SURFACES

Polymer insulators using silicone rubber housings have made a major difference in contamination management. The reason for this success is mostly related to the hydrophobic nature of silicone. Silicone is water repellent but also can transfer this property to the contaminants on the surface of the insulator themselves (Figure 7). The main attribute is not the fact that there is less pollution on these insulators, but the leakage current developing under moist conditions on polluted surfaces will remain low enough to prevent flashovers.

Unfortunately, polymers have shown their limits especially in harsh environments where erosion will damage the housing leading to failure and possible string separations. An alternative which is developing very fast is the coating of silicone mostly over glass insulators for extreme cases where regular insulators with high creepage distances are not enough. An example of a comparative test is shown in Figure 8; the polymer is destroyed (but still hydrophobic, therefore still preventing pollution related flashovers from happening) presenting a major risk of failure (core exposed) while the coated glass is only eroded on the surface on the first bell with no risk of failure.

Figure 7: Water repellent hydrophobic property of silicone even over a polluted surface (silicone coated glass insulator after more than 10 years in a very heavy polluted environment).

Figure 8: Left and centre: comparison of ageing of a silicone polymer and silicone coated glass in Koeberg test station, South Africa, with strings having the same leakage distance tested in parallel. Right: compromised integrity of a polymer insulator that is still hydrophobic but has deep cracks after 10 years in coastal pollution.

There are millions of silicone coated insulators in service either in substations or on overhead lines. The latter sees a growing part of the market using coated toughened glass insulators given the benefits of resilience and ease of inspection and live line work combined with pollution performance in extreme environments. Originally applied mostly in substations on site, it is now clear that for overhead lines the best performance and longevity is achieved with factory pre-coated units for which cleanliness and consistency of an industrial process are much better controlled than in the field. Likewise, it is now almost a standard to use a light grey to white silicone rather than the early orange, red and brown coatings which pigments are less stable, more prone to induce an early aging of the coating.

The other key parameters considered for specifying silicone coatings, besides visual criteria (no runners, drops or lack of coating on the surface) as well as thickness and adherence. Average thickness values globally accepted are around 280µm for the top surface of the insulator and 350µm on the ribs underneath.

For adherence the most common standard is ISO 2409 [8]. It must be noted that IEEE 1523 [9] mentions a 100h boiling test for verification of adherence, but this test needs to be more detailed since silicone by nature will allow water to go through the coating. A rest time of 24h is recommended before making the assessment of adherence simply to allow the coating to dry.

Among the most important features of testing coatings for their qualification there is a need for an aging test. Classical aging tests such as those used for polymer insulators don't work for the reason that coatings are thin layers compared to the bulk thickness of polymers (3mm or more). The most commonly used accelerated aging test was brought up by the Italian TSO TERNA who introduced years ago a 2000h multistress test (figure 9) [10]. Excellent correlation with field data has been observed when comparing results of this test.

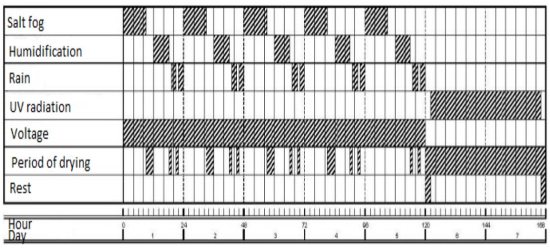


Figure 9: 2000h multistress procedure for accelerated aging evaluation of silicone coatings. (as per TERNA specification)

IV. LEAKAGE CURRENTS

One of the first consequences of pollution deposits on a string of insulators is the increase of leakage current which goes up during wetting processes, such as morning dew or moist evenings, as shown in Figure 10. This graph shows the relative evolution of leakage current during a 24h cycle of identical insulators (one coated, one not coated) installed in the same area in a coastal salty and dusty environment.

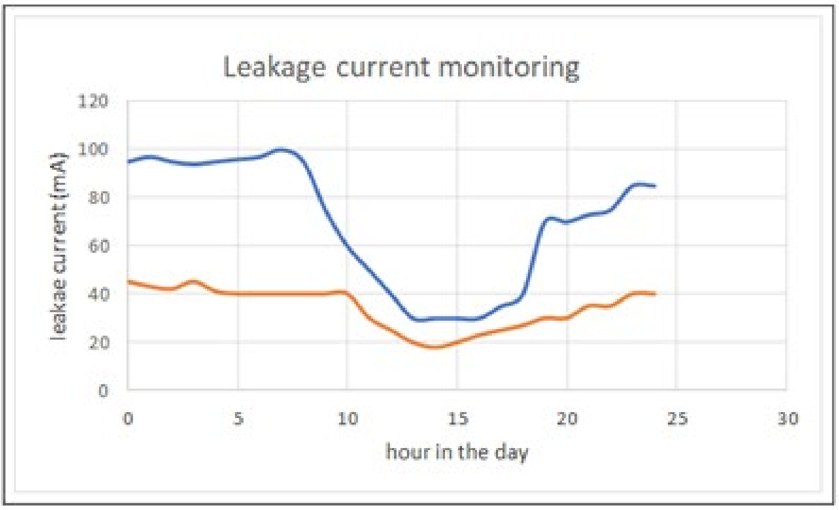


Figure 10: Relative evolution of leakage current in a 24h cycle of identical insulators. Blue curve is a regular glass insulator. Red curve is the same insulator coated with silicone RTV. Both are installed in the same area on a coastal salty and dusty environment.

Leakage currents provide a very good signature of the actual pollution condition of a string of insulators. There are many examples of leakage current measuring devices mostly used for laboratory investigations or test station monitoring. Some software applications have even been developed for assisting string designs based on theoretical equations using some reference leakage current patterns. However, the leakage current pattern and the electrical withstand characteristics of an insulator are directly linked to the shape of the insulator [6]. To run a diagnostic on the actual pollution of any given site where such sensors are installed, the knowledge of the performance under similar conditions is mandatory. Figure 11 explains how the nature of the shape of an insulator dictates its performance.

Type 1	Salt fog test 80g/l	Type 2
2725	Leakage distance (mm)	2750
80,6	Max withstand voltage (kV)	53,2
283	Leakage current (mA)	127

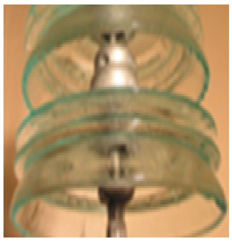


Figure 11: Different shapes, same string length and same leakage distance. Different leakage currents and flashover voltage values. Shape matters.

V. SMART INSULATORS

Taking into consideration all the previous elements, leakage current appears to be an ideal parameter for monitoring actual line pollution provided is it done in real time. It also requires the knowledge of the exact performance of the various insulator types installed on the specific lines under consideration. The recent evolution in IoT and communication systems has enabled new transmission protocols, such as LoRa (Long Range) wireless data communication. Figure 12 shows an example of an insulator which is built with a leakage current monitoring sensor in the metal cap of the insulator itself.

Figure 12: Overall smart insulator device arrangement.

Temperature and humidity are measured as well and transferred to an end-point which produces the first calculations and transfers the information directly through GSM (Global System for Mobile Communications) or LoRaWAN (Long Range Wide-area Network) to a server. The actual measures are analysed and compared to the database of similar insulators, either tested or evaluated in the field, under similar pollution conditions to provide a diagnostic. This diagnostic is immediately sent to an end, typically people responsible for servicing the lines, as shown in Figure 13. If needed this data can be examined in more detail as shown in Figure 14.

Several systems are currently installed in Europe, Asia and Middle East in AC and DC. Coastal heavily contaminated environments as well as sandy and mixed pollution locations are being monitored.

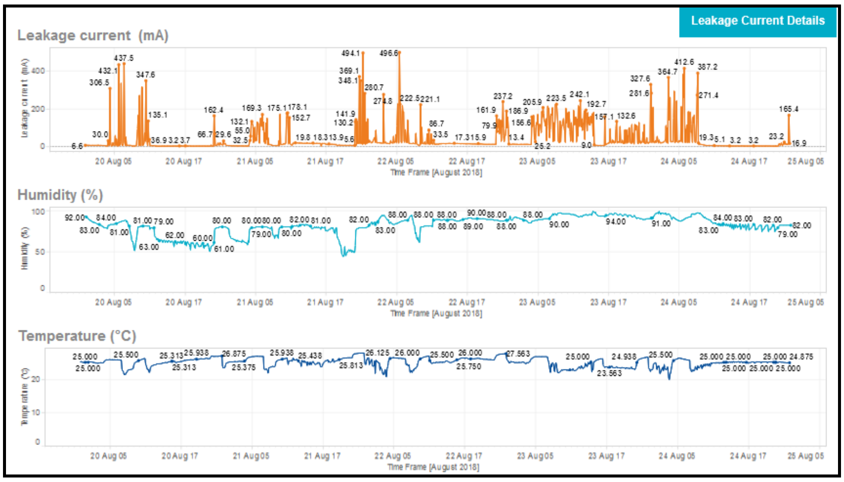


Figure 13: Information displayed

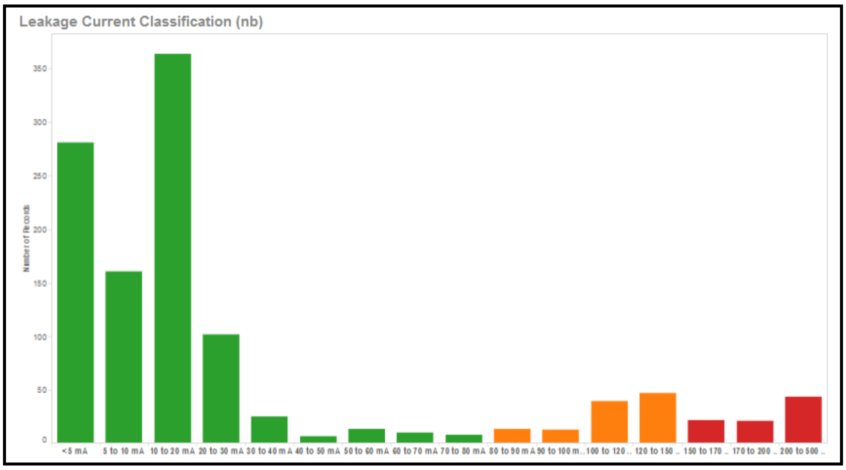


Figure 14: Detailed current bins display.

CONCLUSION

Technology is offering means and ways to improve the reliability of the grid. Insulators themselves are a central piece in the performance of a power line. The diversity of environment a line crosses requires a detailed approach in the selection of the most appropriate insulator, including AC vs DC considerations, and performance under extreme contamination without compromising reliability or expected service lifetime. Exact pollution type and quantified severity assessment is critical to select the most appropriate shape and design of insulators, including whenever necessary for extreme cases the addition of hydrophobic properties on the dielectric surface. Field experience is showing today that ageing of polymeric materials need to be addressed with specific consideration to accelerated ageing under harsh conditions. Usage of silicone coatings on traditional ceramic insulators is increasing strongly worldwide to overcome this weakness. Additionally, insulators have joined the IoT world with built in sensors capable of providing an educated diagnostic wirelessly. These diagnostics, to be meaningful, need to be based on large databases where expert analytical systems and algorithms can predict future performance from actual pollution tests and field data.

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