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Design considerations for modern 400 kV AC substation in coastal area: what is missing in IEC/CIGRE requirements

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SUMMARY

This paper presents the results of a pre-study for refurbishment of a 400 kV AC substation located at the West coast of Sweden, i.e. in polluted environment. The existing insulation design is based on porcelain insulation for both apparatus and support insulators supported by automatic washing system, which is applied on energized insulators. Careful statistical dimensioning of different new modern types of insulators included all options, i.e. porcelain, composite, Room Temperature Vulcanized (RTV) silicone rubber coated porcelain and hybrid porcelain/composite. Each possible insulation option was investigated in detail taking into account:

- Estimated service experience
- Estimated service life in Swedish West coast environment
- Level of standardization in IEC/CIGRE.

A number of missing IEC/CIGRE requirements was identified and is discussed in the paper.

For RTV-coated porcelain insulators these were requirements on how to evaluate the pollution performance of RTV-coating and end-of-life criteria (ageing or tracking and erosion).

For composite station post and apparatus insulators these were requirements for the maximum E-field on the composite surface close to the high-voltage end. Also, there is no test method for evaluation of pollution performance.

For composite station post insulators these were also requirements for the rigidness, influencing the deflection in service (depending on layout of the substation).

For hybrid insulators, the IEC Technical Specification is only recently issued which just open the way for the application of this interesting new type of insulation (combining the best features of porcelain mechanically and composite electrically). Also, there is no test method for evaluation of pollution performance.

KEYWORDS

Substation, pollution, insulation, service experience, composite insulators, RTV-coating.
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BACKGROUND AND GOAL

The Swedish TSO Svenska Kraftnät is planning to refurbish a number of its older substations built along the West coast of Sweden, i.e. in polluted environment. One of such typical substations is 400 kV AC substation at Barsebäck. The present insulation design is based on porcelain insulation for both apparatus and support (station post) insulators supported by automatic washing system, which is applied on energized insulators. The results of careful statistical dimensioning of all available at present types of insulators (porcelain, composite, Room Temperature Vulcanized silicone rubber coated porcelain (RTV-coated porcelain) and hybrid porcelain/composite) were presented in [1]. The goal of this paper is to discuss possible application of each of these insulation options specifically taking into account level of present standardization in IEC/CIGRE. Missing IEC/CIGRE requirements are identified and discussed in this paper followed by some practical examples.

RESULTS OF STATISTICAL DIMENSIONING OF INSULATION

General

Taking into account that the substation is located in polluted environment and that the results obtained for this substation later can be used for other similar projects, a comprehensive statistical method for insulation dimensioning according to IEC 60815-1 [2] has been decided. This method allows more accurate dimensioning than deterministic (simplified) method, however amount and quality of input data for this method should be high [3]. The location of Barsebäck substation is shown in Figure 1 (left), while principles of statistical dimensioning are shown in Figure 1 (right). The principles of dimensioning are as follows [2]. The environmental stress $f(\gamma)$ should be defined (normally described as soluble/non-soluble deposit density ESDD/NSDD, i.e. pollution parameters measured/estimated at the insulator). A cumulative distribution function $P(\gamma)$ describing the strength of the insulation, should also be defined. These data normally come from laboratory tests, service experience or field tests. The two functions $f(\gamma)$ and $P(\gamma)$ are subsequently multiplied to give the probability density for flashover, and the area under this curve expresses the risk for flashover during a pollution event. Thus, based on required Mean Time Between Flashover (MTBF), the insulation length and the creepage distance of insulator in question can be calculated.

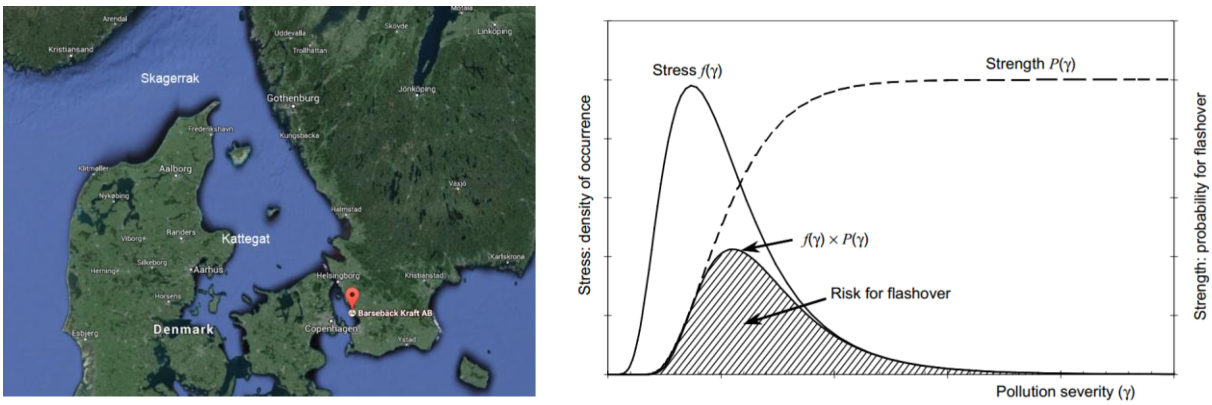

Figure 1 Left: location of Barsebäck substation (red marker); Right: principles of statistical dimensioning according to Annex G of IEC 60815-1 [2].

Estimation of pollution stress

To obtain a reliable amount and quality of input data for the pollution stress, a few parallel investigations have been performed and some of them are still running. These included the following:

1. Analysis of service experience at the existing substation including data from Automatic Pollution Monitor (APM) permanently installed at the substation, see Figure 2 (left). This sample insulator (porcelain post) is periodically dipped into the tank with water and the automatic equipment measures accumulated pollution on a section of the insulator by dissolving accumulated salt in the water and measuring its conductivity. Samples are normally taken at intervals determined by average wind speeds (more speed, more salt bringing onto the

insulator), but at least every 3 days. Sampling can also be triggered by the operator, which is typical at events with high accumulation rates such as salt storms.

2. Analysis of earlier performed pollution measurements along the West coast of Sweden.
3. Pollution measurements using Directional Dust Deposit Gauge (DDDG) techniques recommended by IEC 60815-1, see Figure 2 (middle). This evaluation was complemented by application of new-developed ESDD model taking into account natural contamination by wind and natural self-cleaning by precipitation of different character [4].
4. Additional pollution measurements (ESDD/NSDD) recommended by IEC 60815-1 and hydrophobicity measurements according to IEC 62073 on special set of composite insulators with different diameters, see example of installation in Figure 2 (right).

Figure 2 Left: Automatic Pollution Monitor; Middle: Dust Deposit Gauge; Right: de-energized test station for pollution/hydrophobicity measurements on composite insulators with different diameters.

Using smart analysis (which means considering the accuracy of different pieces of data) of all four parallel investigations mentioned above, the design ESDD/NSDD level for Barsebäck can be preliminary and conservatively estimated as: 0,1/0,1 mg/cm^2. Investigations 3-4 will be finished in 2016, allowing for potential correction of the design pollution severity before final dimensioning of chosen insulation option.

Estimation of strength of insulation

Generic pollution performance curves for different insulator options (created from literature references) were obtained for the calculations in Insulation Selection Tool (IST) software program [5] which follows the principles of statistical dimensioning according to IEC 60815-1. Three different curves were used to represent 1) porcelain, 2) RTV-coated porcelain, and 3) composite and hybrid insulators. All curves were corrected to the typical average diameters for different insulation options. This work was similar to what was made earlier for ESKOM, but in ESKOM's case all pollution performance curves were obtained in the laboratory for the specific insulators of interest [6]. Such testing will be also needed for the final dimensioning of the specific insulators chosen for Barsebäck.

Statistical estimation of insulators length and creepage distance

Estimated pollution severity and generic pollution performance curves for different insulator options were used for the calculations in IST program to obtain the specific creepage distance and insulation length for insulators. The following parameters were used for the calculations in the IST program:

- Maximum operating voltage 420 kV
- Number of parallel insulators: 35 insulators/bay × 7 bays = 245 insulators
- Number of pollution/wetting events per year: 10 (conservative upper limit)
- Mean Time Between Flashover (MTBF): 50

Examples of calculations for porcelain and composite insulators are presented in Figure 3. Depending on the insulation option it was possible to obtain insulation length in the range of 2,8-3,2 m. The corresponding unified specific creepage distance will be 43-58 mm/kV (25-34 mm/kV according to older version of IEC 60815 using phase-to-phase voltage). Thus, from perspective of insulator length, all types are considered as feasible options. More details can be found in [1].

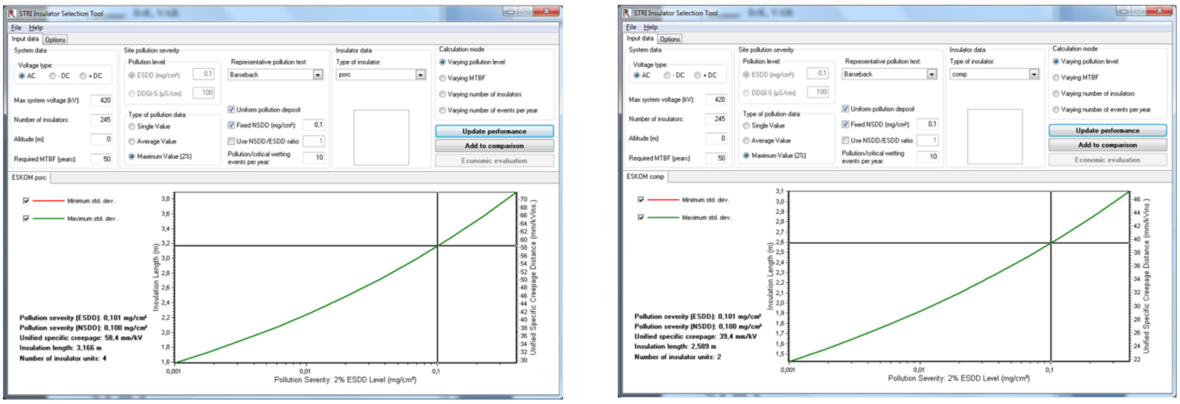

Figure 3 Left: example of IST calculation for porcelain insulator; Right: example of IST calculation for composite insulator.

CONSIDERATIONS FOR APPLICATION

Preliminary matrix for different insulation options is presented in Table 1, where "traffic light" principles are applied: GREEN is the optimal option; YELLOW is applicable option; RED is not recommended.

Table 1. Possible insulation options at Barsebäck. The "traffic light" principles are applied: GREEN is the optimal option; YELLOW is applicable option; RED is not recommended.

Function of insulator	Apparatus insulators	Station support insulators	Earthing switch
Porcelain			
RTV-coated	Note 1		
Composite		Note 2	
Hybrid			

Note 1: Possible option. However, Svk's technical policy is to use composite insulators only.
Note 2: Possible option. This option is rejected due to Svk's concern of mechanical properites of composite station support (post) insulators.

To compare further different insulator options, the following criteria have been used: estimation of service experience, rough estimation of service life and level of international IEC/CIGRE standardization. Porcelain insulators represent mature technology and are well standardized, but they are questionable from pollution point of view in the area of interest.

The following was considered regarding service experience and service life. The RTV-coating is at present a mature and approved countermeasure against pollution and is recommended in both CIGRE Guidelines for insulation dimensioning in pollution conditions, i.e. for AC [7] and DC [8]. For DC RTV-coating is considered not only as a countermeasure, but also as an insulation option at the design level. Estimated volume of service installations is tens of thousands. One of the recent examples was complete refurbishment of ESKOM's transmission and distribution substations located close to the coast. All porcelain insulators were covered by RTV with additional booster sheds to reach desired creepage distance. Based on test station evaluation in a few locations in Sweden the life time of RTV in Sweden is estimated as 20 years.

There are most probably a few hundreds of thousands of composite station post (support) insulators installed all over the world, however majority of them (about 200000) are installed in Russia. The service life is estimated the same as for composite apparatus insulators, i.e. 40-50 years.

It is complicated at present to estimate a number of hybrid insulators in service. There are a few companies producing such insulators. The total number of hybrid insulators installed in the world might be from hundreds to a couple of thousands. The estimated life time for hybrid insulators should be the same as for composite apparatus and post insulators, i.e. 40-50 years.

Composite apparatus insulators are well-proven insulation option both world-wide and in Sweden. The volume of service experience is estimated as 1,2 mln. all over the world and the experience is very positive even when having a closer look by service inspections [9]-[11]. The average duration of service for apparatus composite insulators is approaching 10-15 years and thus it can be considered that their service life, especially in lightly polluted Swedish conditions, can be up to 40-50 years.

The summary of comparison of different insulator options related to composite insulators (coated and complete) is presented in Table 2. In the next section of the paper detailed discussion on missing IEC/CIGRE requirements also summarized in this table is presented.

Table 2. Comparison of different insulation options

Insulator option	Number in service	Standardization world-wide	Estimated service life in Sweden, years	Additional issues to consider
RTV-coated	Tens of thousands	No IEC, only partially CIGRE/IEEE	15-20	Pollution, ageing, adhesion, E-field limits
Composite support	Hundreds of thousands	Yes, IEC	40-50	Pollution, deflection, E-field limits
Hybrid	Hundreds	On the way, IEC	40-50	Pollution, E-field limits
Composite apparatus	More than one million	Yes, IEC	40-50	Pollution, E-field limits

MISSING IEC/CIGRE REQUIREMENTS

RTV-coated porcelain insulators

At present there are no IEC standards for RTV-coating. There is, however, an IEEE Standard [12] and RTV-related general CIGRE Technical Brochure TB [13]. Recently more CIGRE TBs were issued (TB 488, 489, 520, 595), but they are related to material and not complete products. Typical requirements for RTV-coated insulators shall cover the following:

- Pollution performance (there is no standard test method for pollution test except described in CIGRE TB 555 [14]). This statement is also valid in general for all types of composite insulators.
- Tracking and erosion performance (reflecting ageing performance and in a way end-of-life estimation).
- Adhesion performance (RTV-coating to porcelain in this case).

Typical approach for investigations in this direction, covering the majority of the issues above was recently presented in [15]-[16], but this data is related to RTV-coated glass cap and pin insulators.

Composite station post insulators

Such insulators can be manufactured as a solid core concept, when there is a solid fibreglass rod bearing the mechanical strength (IEC standard [17]) or as a hollow core concept, when a hollow fibreglass cylinder is bearing the mechanical strength (IEC draft standard [18]). At present in both of these standards there are no requirements for the rigidness of specific insulators, influencing the deflection of insulation column and the whole bus bar in service (depending on layout). Influence of deflection on possible fatigue effect on connections to the bus bar is also questionable. Recently published paper [19] illustrates how IEC standards for post insulators will be harmonized when all of them will be published. This is illustrated in Figure 4 and according to [19] this figure is called “The link to the existing station post world”.

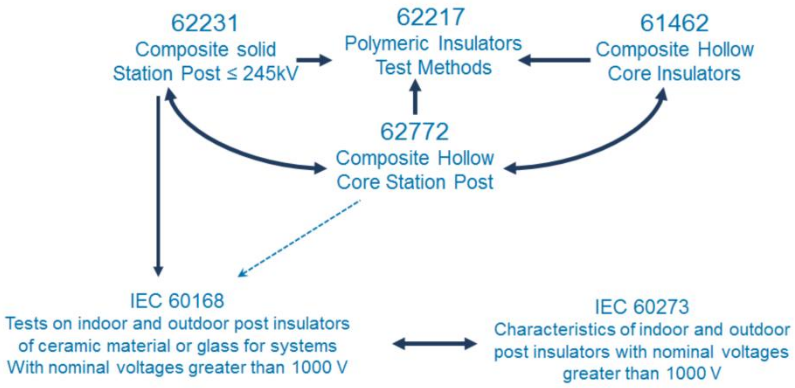

Figure 4 Adopted from [19]: The link to the existing station post world”.

Another important issue for composite station post insulators is the limit of E-field on the surface close to high-voltage end of the insulator. Recently (in 2015) typical limits for line composite insulators were presented and internationally agreed [20], [21]. They describe recommended limits for both metal parts and composite parts. The most important criterion is based on water drop corona, which may in long-term influence the hydrophobicity of the silicone rubber close to the high-voltage end and even further deteriorate the insulator. Therefore, depending on voltage class, AC line composite insulators are normally equipped by appropriate grading/corona rings. This is sometimes not taken into consideration for station post insulators, which may not differ much in average diameter from line insulators. In Figure 5 the results of practical inspection/calculations are presented as an example illustrating need for grading rings for 400 kV composite station post insulators. It is important to note that for apparatus composite insulators no activity was observed at the same substation. Partially this can be explained by difference in design [9] and partially by better knowledge of apparatus insulators manufacturers.

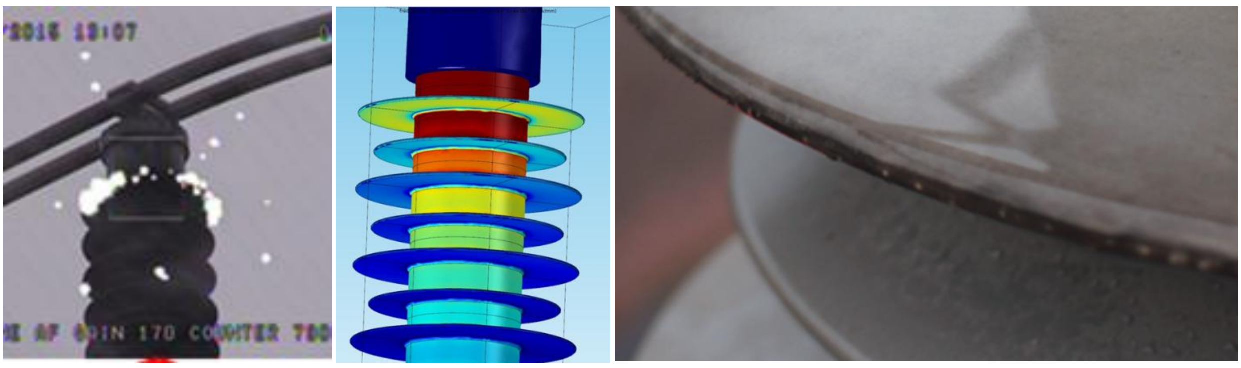

Figure 5 Left: corona observed in service; Middle: too high E-field leading to corona in service and loss of hydrophobicity; Right: reduction of hydrophobicity close to the high-voltage ends in service.

Hybrid insulators

Very recently (2015) the first Technical Specification for this type of insulators was issued [22]. This opens the way for the application of this interesting new type of insulation (combining the best features of porcelain mechanically and composite electrically). However, as for all other composite insulators, there is no test method for evaluation of pollution performance. Adhesion properties may also be tested more carefully.

Composite apparatus insulators
At present there are a plenty of IEC standards for different types of apparatus insulators and their recent versions include composite insulators. These include arresters, bushings, current transformers, circuit breakers and disconnecting circuit breakers.

SUMMARY

Modern AC substation in polluted environment can be designed with different insulation options, and many of them include composite insulators. Insulators can be different such as composite, RTV-coated porcelain and hybrids. Based on comprehensive statistical dimensioning, requirements for insulation length and creepage distance are obtained showing that all options are preliminary feasible.

Possible practical application of each of insulation options was investigated in detail taking into account service experience, estimated service life in Swedish environment and level of standardization at IEC/CIGRE. A number of missing IEC/CIGRE requirements was pointed out and discussed.

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