VOLTAGE UPGRADING OF OVERHEAD LINES – AN INSULATION COORDINATION CHALLENGE

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Abstract: When voltage upgrading overhead lines, the lightning, switching- and pollution performance of the insulators and air gaps play a very important role. The dielectric dimensioning procedure is different and technically more challenging from those of new lines. The available margins are much smaller and, therefore, the engineering needs to be done more precisely. Against this background, Statnett (the Norwegian TSO) has considered different types of insulators, and also the pollution, lightning and switching performance of the most frequently used glass insulator and air gaps. Gap factors have been determined theoretically and measured in full scale experiments at Graz University of Technology. Moreover, tools for the determining the exact air clearances have been applied. The studies and its results are assumed to be of general interest to other utilities that consider upgrading or compacting of towers, and some of them are presented in this paper. It showed that voltage upgrading is possible, but precise engineering is needed.

1 INTRODUCTION

Statnett which is the Norwegian transmission system operator (TSO), is currently upgrading and rebuilding some 5000 km of its 300 kV network to 420 kV. The line configurations considered are simplex lines (ca 3500 km) and duplex lines (ca 1500 km). Each of these has its own specific set of challenges. However, common to both configurations are the insulation coordination issues.

The dielectric dimensioning procedures used when upgraded overhead lines are in several respects different and technically more challenging compared to those used when building new lines. Among other things, the air gap margins available in voltage upgrading are much smaller and therefore, the engineering needs to be done more precise.

The dielectric dimensioning / insulation coordination comprises different issues, including matters related to:

The length and type of the insulator strings

- The air clearances
- The lightning performance
- The switching overvoltage performance
- Wind loads under different load conditions
- Clearance to ground

This paper primarily addresses gap factors (i.e., air clearances) for duplex lines, engineering tools and the insulation coordination procedures.

2 TYPICAL TOWER CONFIGURATION

A typically overhead line tower used in 300 kV lines is shown in Figure 1. Such a tower has just sufficient insulation distances to make upgrading a viable option, depending on the mechanical and thermal loads (wind, ice, and conductor temperature), topography and line angles. Every tower is a unique case and therefore each tower need to be studied in detail. , For some towers voltage upgrading can readily be performed, whereas in other special solutions have to be implemented.

As it can be expected when considering Figure 1, the majority of the problems with clearances are related to the centre phase.

Figure 1. A typical 300 kV tower with duplex arrangement and single I-strings before upgrading.

3 INSULATION COORDINATION PROCEDURE

The procedures for determining insulator lengths, air clearances, whether or not to use surge arresters, the occurrence of single phase or three phase switching, acceptable icing, pollution and lightning outages, are very complicated. All parameters tend to interact. For a new line this is already complicated, but for voltage upgrading, it is even more complicated and very detailed and accurate engineering calculations are required since the margins available are so small. Quite often, an iterative engineering process must be carried out to get everything on place.

Statnett has been dealing with many aspects of insulation coordination when upgrading overhead lines [7], [8], [10], [11], [12]. In the following sections the work on air clearances is described.

Before starting, information about climatic loads, failure rates and lightning statistics of the considered line are collected. These data are then later used to determine the actual air clearances, and also for line performance estimator (LPE) calculations [9] to predict future line availability estimates.

At first a very accurate geometrical model of the existing overhead line is made in PLS CADD. In the first ‘upgraded’ i.e. the 420 kV version, the insulators are extended to the required length. Using this length and the three different required clearances for the three different load cases, “problem towers” are identified. It turns out that most of the problems can be solved by shortening the insulator string to the middle phase conductor. However, it not all issues are resolved by this, alternative solutions such as V-chain insulators are considered. In some cases also smaller distances can be acceptable if the influence to the total line performance is not significant. The first solution chosen is studied closer by using LPE that besides the accurate distances obtained from PLS CADD in every tower, is using the real gap factors as found in the study presented in the next chapters. More about this can be found elsewhere [2].

The used procedure will now be described by an example. In Figure 2 the estimated risks associated with the different failure types and the successful auto reclosing rate are presented for a line without surge arresters. It can be seen that when the deviation from the selected insulator length is zero (this means applying the standard insulator, e.g. 17 discs), 8% of the failures will be caused by ice flashovers, 35% of the failures by pollution flashovers and the remaining 57% by lightning flashovers. The successful auto reclosing rate is 55%, which is by the way unacceptable.

First, by lengthening the insulators, the total number of expected failures decreases. In this example from 2.5 to 1.5 failures per 100 km per year. From Figure 2 it can be seen that by extending the insulator string with one disc (i.e. 17 cm), the number of pollution and ice failures decreases, whereas the portion of failures due to lightning increases. Lightning failures are of short duration while outages caused by ice and pollution last longer, so this is an advantage. From the same figure it can be seen that increasing the insulator lengths has almost no effect on the successful auto-reclosing rate. This problem can be solved by introducing surge arresters, as can be seen in Figure 3.

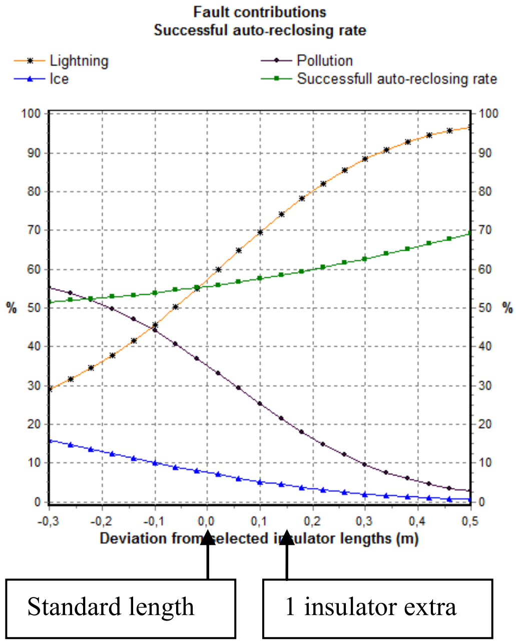

Figure 2. Failure contributions of the different failure types and the rate and successful auto reclosing rate, with no surge arresters on the line.

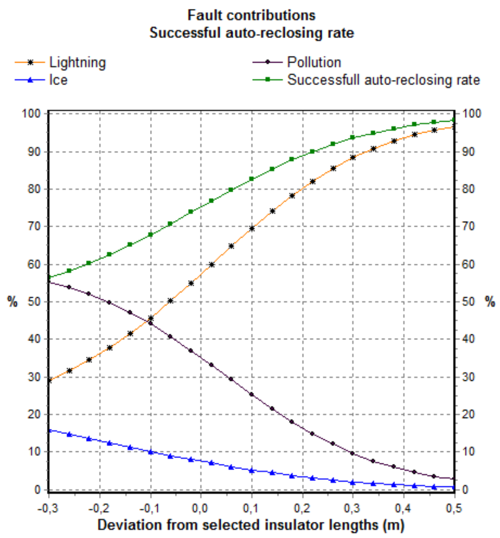

Figure 3. Failure contributions of the different failure types and the rate and successful auto reclosing rate, with two surge arresters installed.

4 AIR CLEARANCES

4.1 Load cases

When considering the required air clearances three load cases are considered [1]:

1) Still wind conditions
2) 3-year-return-time wind conditions
3) 50-year-return-time wind conditions

For each of these conditions different air clearances are required, and must be determined for each tower, see next section and [2] for more details.

The three load conditions and their distance requirements are visualized in Figure 4.The swing angle of the conductors/insulators for the three load cases is different, as can be seen in the figure.

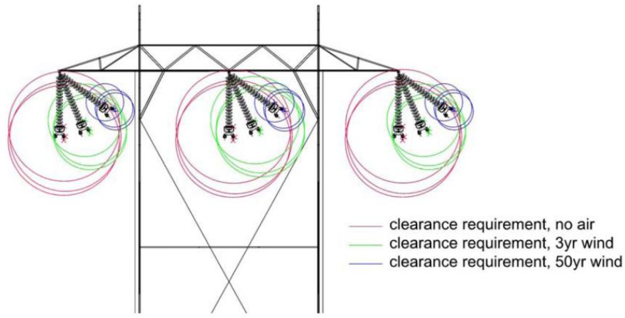

Figure 4. Sketch of a typical tower with the insulators in three different swing angles, due to three different wind load cases.

4.2 Required air clearances

For each of the three wind load cases there are different requirements on the air clearances.

According to [1] the minimum clearance for still wind condition is as given by equations (1) or (2), whichever is greater. Since the typical line length to be upgraded is 50 km, and the most frequent type of switching operation is single phase autoreclosure, the switching overvoltages are not that high [11]. Furthermore, overvoltages can be limited by using surge arresters. Consequently, for still wind condition lightning surges should be used for the dielectric dimensioning of voltage upgraded lines.

Since the 3-year-return-time wind load condition only occurs for less than 4 hours per year, the probability of lightning to occur at the same time is very low [1]. Hence, the distance requirement only considers switching overvoltages, i.e. the requirement given by (2). The requirement for the extreme wind condition that only occurs for 2-5 seconds during every 50 year, is of obviously that it can withstand AC overvoltages given by (3).

$$D_{el} = \frac{1}{K_a} \cdot \frac{K_{g\_ff\_is}}{K_{g\_ff}} d_{is} \tag{1}$$

$$D_{el} = \frac{1}{0{,}46} \cdot \left(e^{\frac{K_{cs} \cdot U_{e2\%\_sf}}{1080 K_a \cdot K_{z\_sf} \cdot K_{g\_sf}}} - 1 \right) \tag{2}$$

$$D_{pp} = \frac{1}{0{,}55} \cdot \left(e^{\frac{\cdot U_s}{750\sqrt{3} \cdot K_a \cdot K_{z\_pf} \cdot K_{g\_pf}}} - 1 \right) \tag{3}$$

Note that the requirements given by (1), (2) and (3) only consider external clearances. Internal clearances might be reduced since they only have an effect on the system outages.

As can be seen from (1) the insulator length chosen has a direct effect on the required/needed air clearances. A 15 cm shorter insulator will result in a 15 cm shorter required clearance and therefore 30 cm total reduction in distance will be obtained. For new lines this is within the construction tolerances, but when in the context of voltage upgrading this is the difference between feasible and unfeasible.

4.3 Determination of actual air clearance

One important task is to determine the actual air clearance using a particular insulator configuration in each tower. At Statnett this is done by using PLS CADD [15]. A complete overhead line and terrain model is made in PLS CADD using topographic maps, results from helicopter scans, photographies, detail tower drawings, insulator string lengths, etc. Studies have been made about the inaccuracy of PLS CADD and on the deviations between drawings and as built. It shows that this is a good tool to use for the estimating air clearances. However, PLS CADD is not intended for high accuracy dielectric design, so the usage is somewhat cumbersome.

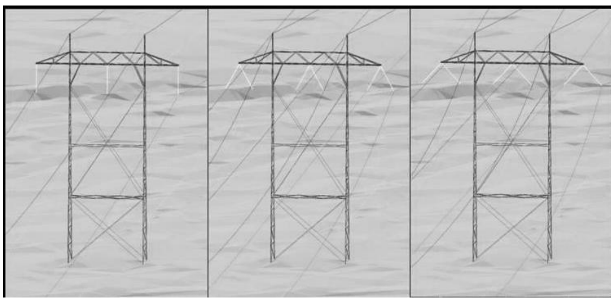

Figure 5. The determination of the distances for the three load cases using PLS CADD. To the left, the still wind condition, in the center the 3-year-return-time wind condition and to the right the 50-year-return-time wind condition.

5 GAP FACTOR

5.1 The importance of the gap factor

When doing voltage upgrading it turns out that the gap factor has a significant influence on the whole design procedure. The required clearances are proportional to the gap factors, as can be seen in (1) and (2). In [3] it is discussed that compacting towers (or upgrading towers) has a positive influence towards the real gap factors, this implies that it would be possible to decrease the ar distances. Since the distances used in [1] where assumed to be somewhat conservative and since Statnett did not want to take any high risks, a study was initiated to determine the exact margins, or more precisely the correct gap factors for the towers to be upgraded. A theoretical study was performed, followed by full scale experimental testing at Graz University of Technology.

5.2 Results of the theoretical study

The air space inside the tower "window" may be seen as multiple air gaps with a strike distance d. The tower window can mainly be divided into three air gaps: conductor-cross arm, conductor-tower pole and conductor-guy wire.

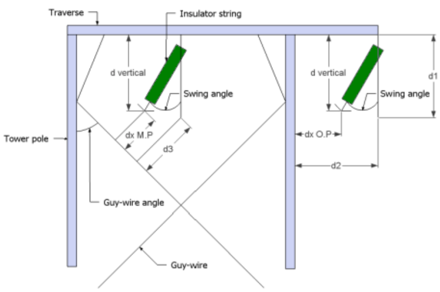

Figure 6. The different airgaps in the tower window and tower.

When designing new transmission lines, it makes sense to use one common gap factor, which would be the lowest one of the three, for the whole air space within the tower window When it comes to voltage upgrading, the air clearances within the tower is limited, making it neccessary to examine all relevant air gaps within the tower window to get a more accurate description of the characteristics of the air gap and hence the various withstand strengths.

The theoretical study performed by NTNU, showed that previously performed tests (at STRI and at SINTEF) have shown that the lightning performance of insulators is around 12% higher than it would be expected. The switching performance is about 5% better than the values obtained from the standard.

Furthermore, it showed that when determining the gap factors accurately (instead of using the standard values given in [1]) the dielectric strength of the air gap to the guy wire would be 7-8% higher than across the insulator string.

This gave enough clues to make it interesting to perform full scale tests. Among the reasons for performing full scale test and not down-scaled tests are that the insulators and accessories are difficult to scale down.

5.3 Results of experimental full scale study

The full scale tests were performed at the High Voltage Laboratory of the Graz University of Technology [6]. Most of the difficulties in terms of insulation coordination are expected to appear at the centre phase of the steel tower. Consequently, a full scale model of the centre phase of a relevant tower was built, see Figure 7. With this model it was possible to investigate the effect of varying the distances between the centre phase conductor and the tower structures and guy wires, respectively (corresponding to relevant swing angles).

The test program included both lightning and switching impulse voltages. Two different types of corona rings were evaluated, see Figure 8. The first one consists of one horizontal ring, the second type of two vertical rings. The total length of the insulator string (number of cap-and-pin insulators) depends on the type of corona ring and the number of insulators in the string.

Figure 7. Full scale test model, here simulating displacement of insulator due to wind, an angle in the line or temperature - or ice load.

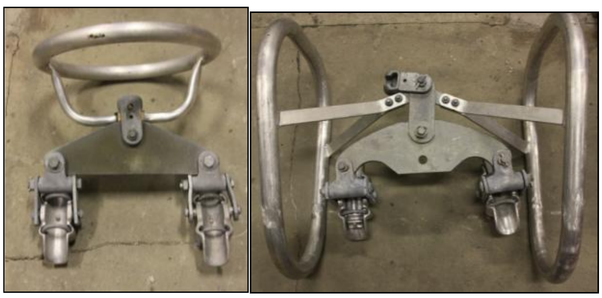

Figure 8 Corona ring – Type I (left) and type II (right)

The experimental results and the outcome of the theoretical study, explained in detail in [5], [4] and [6], are summarized in the sections that follow below.

5.3.1 Results for lightning impulse tests

Tables1 to 4 show the most relevant results for the lightning impulse tests and the gap factors that are calculated.

With these gap factors, the required distances can be calculated with good precision. This results in a distance requirement that reduced with approximately 23 - 42 cm compared to the conventional approach. These 23 - 42 cm makes a big difference as it can be the difference between a feasible and not feasible solution. It can also allow for one additional insulator disc to be used in the chain, leading to fewer failures caused by pollution and icing.

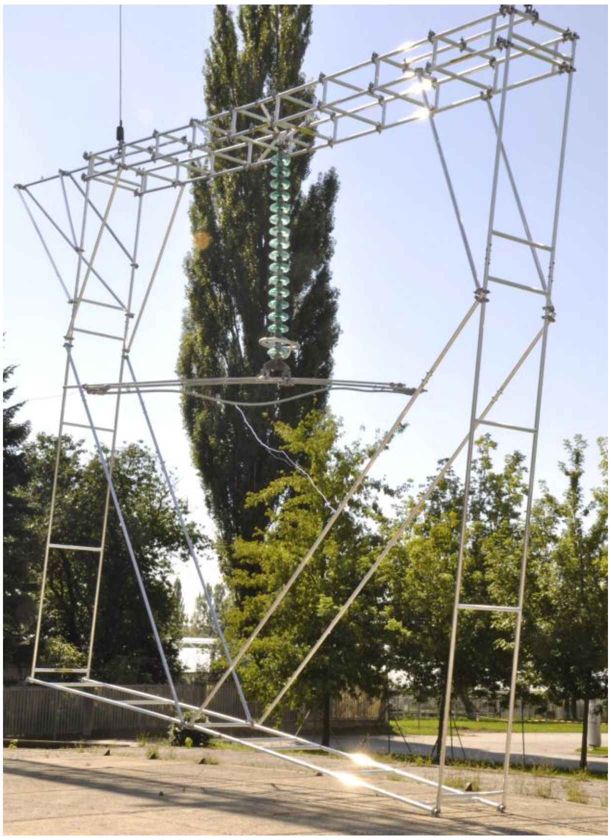

Figure 9. Flashover from the conductor to the guy wire (when using a vibration/damper loop).

Table 1. Flashover strength of the two insulator strings.

Type of corona ring	Shortest striking distance[m]	Corrected voltage value [kV]	
		U50%	*U90%*
1	2.73	1515.62	1574.73
2	2.60	1483.44	1541.30

Table 2. Gap factors for the two insulator strings.

Type of corona ring	Gap factor: Test TU Graz	Gap factor: Standard[a, b]	Gap factor: Literature[c,d]
1	1.052	1.07 (1.12)	0.99 (1.08) [c]; 1.10 [d]
2	1.081	1.07 (1.12)	0.99 (1.08) [c]; 1.10 [d]

a. Standard EN 50341-Part 1 [1]
b. Standard IEC 60071-Part 2 [13]
c. see [14] d. see [4]

Table 3. Gap factors for the airgaps.

Type of corona ring	Interpolation striking distance[m]	Gap factor Test TU Graz	Gap factor Standard[a,b]
1	2.476	1.15	1.07
2	2.317	1.21	1.07

a. Standard EN 50341-Part 1 [1]
b. Standard IEC 60071-Part 2 [13]

Table 4. Implication for the required distances

Type of corona ring	Required Distance Test TU Graz [m]	Required distance Standard[a,b] [m]
1	2.51	2.74 (2.87)
2	2.45	2.74 (2.87)

a. Standard EN 50341-Part 1 [1]
b. Standard IEC 60071-Part 2 [13]

5.3.2 Results for switching impulse tests

The most relevant results for the switching impulse tests and the corresponding gap factors are presented in the tables below.

With the obtained gap factors, the required distances can be calculated. For a required $U_{50\%}$ withstand voltage of 780,9 kV the gap can be reduced from 1,70 m to 1,36 m.

Table 5. Flashover strength of the two insulators strings.

Type of corona ring	Shortest striking distance[m]	Corrected voltage value[kV]	
		U50%	*U10%*
1	2.73	1098.25	1012.59
2	2.60	1101.51	1015.59

Table 6. Gap factors for the two insulator strings.

Type of corona ring	Shortest striking distance[m]	Gap factor Test TU Graz	Gap factor Standard[a,b]
1	2.73	1.26	1.25 (1.45)
2	2.60	1.31	1.25 (1.45)

a. Standard EN 50341-Part 1 [1]
b. Standard IEC 60071-Part 2 [13]

Table 7. Implication for the required distances.

Type of corona ring	Shortest striking distance[m]	Gap factor Test TU Graz	Gap factor Standard[a,b]
1	1.55	1.50	1.25
1	1.40	1.48	1.25

a. Standard EN 50341-Part 1 [1]
b. Standard IEC 60071-Part 2 [13]

6 CONCLUSIONS

The engineering efforts associated with dielectric design are simpler when dealing with new overhead lines than when upgrading existing lines. One of reasons is that margins in air clearances available are much smaller. The main goal of the reported work was to establish methods and tools to carry out the tasks using the best possible knowledge, Moreover, developing the tools needed for comprehensive voltage upgrading programs was also an important objective. Upgrading as much as 1500 km lines makes it necessary to have suitable tools that can provide technical support to the engineers.

The theoretical estimates as well as the full scale experimental work have shown that the air gap distances can be reduced significantly without introducing any unacceptable risk for dielectric failures.

The air clearances to the guy wires during still wind conditions can be reduced from 2.8 m to about 2.5 m. For the 3-year-return-time wind condition it was found that the air gap to the guy wires can be reduced from 1.9 or 1.7 m to 1.4 m. This implies that one can use one more insulator disc in the string, which means a reduced risk of having faults on the line. Or instead of having to use a V-chain one is able to keep the configuration with an I-chain configuration.

In conclusion, the results show that precise engineering is needed when voltage upgrading, since small change in parameters have large consequences on the final solution.

7 FUTURE WORK

In the spring of 2011, additional tests have been performed at Graz Technical University to investigate the influence of vibration loops in suspension towers. In September 2011 tests will be performed there for determining accurately the required insulation distances in tension towers.

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