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A compact 420 kV line utilising line surge arresters for areas with low isokeraunic levels.

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SUMMARY

This report describes the work carried out to develop a delta 420 kV compact line with 5 m phase spacing, utilising line surge arresters and eliminating shield wires. Long term audible noise measurements were taken on a full-scale outdoors test line. Special grading rings were developed and tested. The design is based on tension towers only, to overcome the clearance problems of short insulator strings on compact towers.

KEY WORDS

Compaction – Upgrading - Corona test - Surge arrester – Magnetic field

1 INTRODUCTION

In the Nordic countries there is expected an increase in the demand for compact 420 kV lines in suburban areas in order to reduce magnetic fields and visual impact. Such lines would be utilised on line sections (<5 km) close to or within towns and cities, for either new lines, voltage upgrades or even direct replacements of existing lines.

One of the characteristics of the Nordic countries is a low isokeraunic level (<20 days/year), this led to consideration of removing the shield wire and using line surge arresters. This would result in a further reduction of tower height, reduced tower loading and consequently reduced visual impact. An additional benefit for areas prone to icing was to eliminate the risk of the shield wires sagging between the phase conductors and causing flashovers.

The line surge arresters would be placed on the top phase of every tower, thus converting the top phase to a shield wire. The surge arresters prevent backflashovers, while the tight phase spacing ensures increased coupling between all phases, reducing the risk of phase-phase and phase-tower flashovers. Because of the reduced tower dimensions and low isokeraunic level it is easier to design surge arresters with a sufficiently low probability of damage due to lightning.

The visual impact of the line was examined before full scale testing by use of a 3D CAD drawing which enabled comparison with standard tower designs and an evaluation of the use of inter-phase spacers.

The report also describes design criteria for the towers and arresters including energy stresses due to lightning, insulation co-ordination, mechanical stresses and connection of arresters to the tower and phases. Finally the results of testing on corona rings are presented.

The different towers referred to in this report are shown in

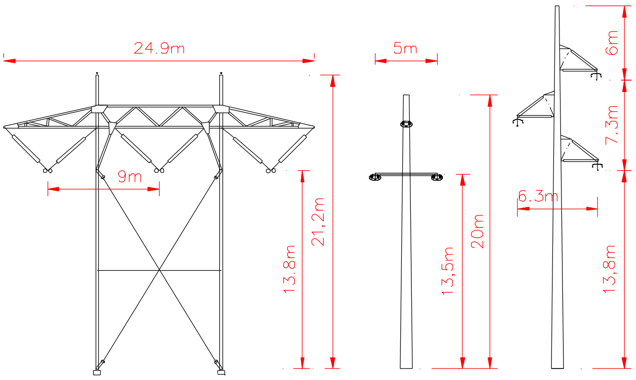

Figure 1.

Figure 1. 420 kV towers, standard 9m horizontal, 5 m delta and 7.3 m horizontal delta

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Background

In the early 1990s there was a great deal of pressure on authorities to set limits on magnetic fields from transmission lines. In 1993 this led to the start of a project to investigate and prove the feasibility of low magnetic field tower designs. The project was divided into three parts:

- 69-145 kV evaluation of designs
- 220 kV evaluation and full scale testing [1]
- 420 kV evaluation and full scale testing

Compaction and phase splitting were chosen as the main techniques to reduce magnetic fields. Phase splitting is especailly beneficial as the magnetic field varies inversely with the third power of the radial distance. Such a design was chosen for 220 kV, however at 420 kV it was feared that the need for multiple sub conductors in all phases would lead to a “spaghetti” of conductors which would lead to more protests from the general public than the magnetic fields. As a result of this belief the 420 kV only utilised compaction to achieve reduced magnetic fields.

Compaction of lines results in higher surface gradients that lead to increased audible noise (AN), radio noise (RI) and corona loss (CL). Audible noise is probably the most important corona phenomena as this is what the general public encounters most frequently. Present recommendations/regulations for transmission lines in an urban environment require an average (L50) audible noise in rain of 50 dB(A) or less. Many empirical methods are available [2, 3], however none of the lines used in the database for these methods included a split phase 220 kV or a 420 kV with 5m phase spacing. Therefore confirmation of the corona performance by full-scale testing was felt necessary. Increased surface gradients can also lead to corona from fittings and grading rings, as 3-D field calculations are still rather difficult, a full-scale corona test was considered the best way to confirm the suitability of fittings.

The full-scale corona studies were carried out at STRIs outdoor span utilising 420 kV, using phase spacings of 7,3m, 6m and 5m. The results showed acceptable AN, RI, and CL down to 5 m phase spacing, and confirmed the accuracy of the AN calculation method in [3]. The corona measurements also provided a timely reminder of the importance of ageing to new conductors as reported in [4]. It took approximately 9 months for the AN to stabilise.

Two different grading rings were tested at phase separations of 7,3m and 6m. Standard grading rings for 550 kV proved unsatisfactory, but a set of specially designed grading rings / arcing horns performed well.

At phase spacings of 5m a significant problem arises, insulators become very short while grading rings become very large, this can result in unacceptably low switching surge withstand or pollution withstand. To overcome these problems a compact line based on tension towers was adopted.

2 DIMENSIONING

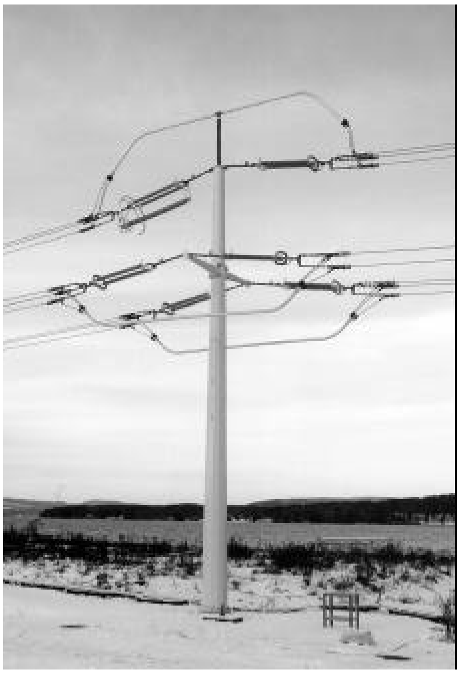
2.1 Pole

The pole is designed for the following:

• Maximum span length	250m
• Maximum ice	6 kg/m
• Maximum wind	32 m/s
• Lightning impulse withstand	1175 kV
• Phase spacing	5m
• Conductors	triple A2

For the conductor used the ice load is approximately equivalent to 25mm (one inch) radial ice. A lower than normal wind speed was used because of the shielding available from buildings in an urban environment. The above design criteria led to a pole diameter of 1 m at the base, tapering to 0,6 m at the top. A photo of the tower can be seen in Figure 2.

Figure 2. Photo of tower, delta with 5 m phase spacing



2.1.1 Clearances

The minimum phase-phase clearance in mid span is 4,5m, however at the tower this is reduced to 3,2m between the top phase and lower phases on the arrester side and 4,2m between all other phases. The reduction in clearance is due to the grading rings, especially for the arrester which is 1,8m in diameter. The phase to ground clearance is 7,8m at 80 ºC and 5,8m at maximum ice.

2.1.2 Reduction of tower / pole height and ROW

The height of the poles with triangular conductor configuration is approximately 20m; this is less than 1m shorter than a comparable standard suspension tower with horizontal conductor configuration, this is partly due to the need for a post insulator to lead the upper phase over the tower top. Due to the slim pole and the short phase spacing, savings of at least 13m in ROW can be achieved.

2.1.3 Reduction of magnetic field

Figure 3 shows that it is possible to achieve more than a 50 % reduction in magnetic field at the ROW with 5m triangular phase spacing compared to 9m horizontal phase spacing. The reduction is obtained in spite of reduction of the ROW for the compact configuration. It is interesting to note that directly under the centre of the lines the 7,3m horizontal delta has the same magnetic field as the 5m delta, this is because of the height difference of the two uppermost phases in the horizontal delta.

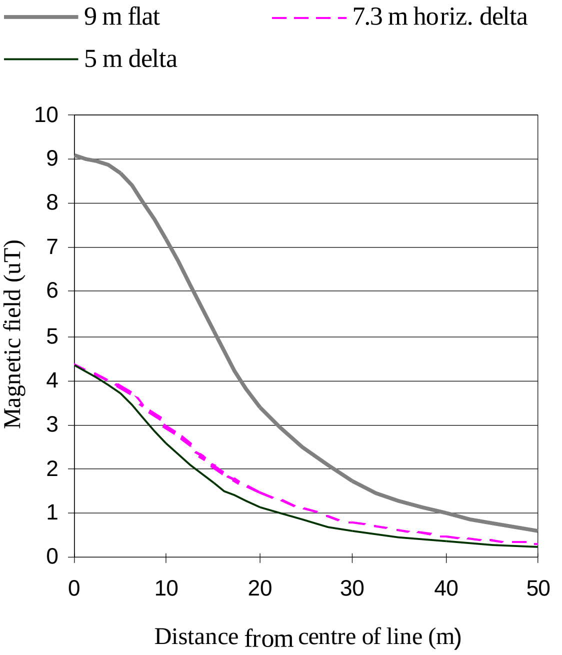


Figure 3. Magnetic field for different configurations, for 500 A

2.2 Design for lightning protection

2.2.1 Lightning performance of conventional and compact lines

The prospective lightning outage rate for the compact line may be estimated by comparison with existing lines of similar height. For such a comparison, the most appropriate line type is a 220 kV line design that has been used in Sweden for more than fifty years. For an unshielded line in this voltage range, the outage rate is a good approximation of the number of strokes to the line, since practically all lightning strokes will cause a flashover of the line insulation. The recorded lightning outage rate for the 220 kV line, without shield wires, is around 3 per 100 km per year. It can therefore be expected that the number of lightning strokes to the compact 420 kV will be around 3 per 100 km per year. To account for the additional attracting effect of the top phase at the tower of the compact line (see Figure 2), the expected number of strokes is increased to 4 per 100 km per year for the subsequent study.

Nordic 420 kV lines of conventional design, with horizontal phase configuration and double shield wires, have a lightning outage rate of about 0,2 - 0,4 per 100 km per year. Thus, without any form of lightning protection, the compact 420 kV line would have an outage rate about ten to twenty times higher than the conventional 420 kV lines. This is not in general for this new concept considered as a satisfactory lightning performance, even though the compact line sections will only constitute fractions of the total line length.

2.2.2 Transmission line surge arrester application

The traditional way of improving the lightning performance by means of shield wires would hamper an optimised design of the compact line with regard to environmental impact. Instead, it was decided to study the feasibility of using surge arresters installed in the top phase of each tower along the compact line to protect it from outages caused by direct lightning strokes. In this way, the top phase acts like a shield wire with a shielding angle of 30° with respect to the outer phases.

With a shield angle of 30°, the EGM method [5] yields that the shielding failure rate will be completely negligible, i.e. the top phase acts as an efficient lightning shield for the outer phases. Thus, the major source of lightning outages would be direct strokes to the top phase of the compact line. Therefore, the surge arrester must provide a sufficient protection of the line insulation in order to achieve an acceptably low line outage rate. Furthermore, when the top phase acts like a shield wire for the compact line, the whole lightning surge current is conducted to ground through the surge arresters. This means that the arresters must have a certain energy absorption capability to keep the risk of arrester failure at a sufficiently low level. Both aspects of the surge arrester application are treated in the following sections.

2.2.2.1 Modelling for flashover performance calculations

In order to study the risk of flashover due to direct lightning strokes to the top phase, a typical section of a compact line with a length of about 5 km was modelled in EMTP. At both ends, the compact line is connected to conventional 420 kV line sections with a horizontal conductor configuration and double shield wires. The conventional line sections are terminated in substations equipped with surge arresters and a low grounding resistance of 1 Ohm. The length of the conventional line sections were chosen as 3 km to reduce the computation times. The tower grounding impedances were chosen as 52 Ohms to account for the worst grounding conditions. A continuous counterpoise (c.c.) was assumed for the compact line section as well as for the conventional line.

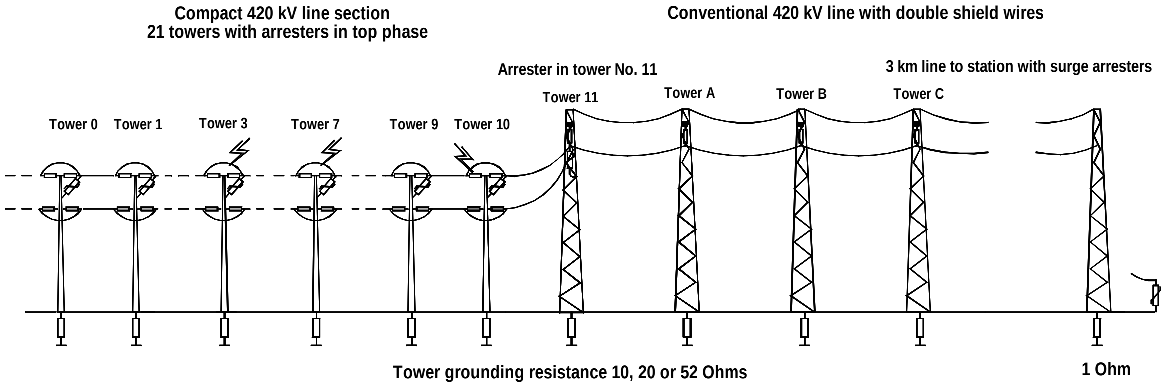


Figure 4. Line model for EMTP calculations of flashover performance and arrester energy requiremen

Figure 4 shows one half of the line model used. For the calculations, a surge arrester with a rated voltage of 330 kV was chosen since it is a voltage rating commonly used on 420 kV systems in the Nordic countries. Arresters were positioned in the top phase of each compact line tower and in the middle phase of first tower of the adjacent conventional line sections. The protective characteristics of the arrester are shown in Table 1.

Table 1. Electrical data for transmission line arrester

Rated voltage	Residual voltage vs. current amplitude			
	10 kA	20 kA	40 kA	65 kA
kV_{rms}	kV_{peak}	kV_{peak}	kV_{peak}	kV_{peak}
330	776	854	954	1050

The residual voltages given in Table 1 are valid for current wave shapes of 8/20 µs. When positioned in the line towers, the arresters may be subjected to much steeper currents. Therefore, the protective characteristics were increased by 11% corresponding to a steepness of at least, ten times the steepness of the 8/20 µs current impulse. Furthermore, to model the effect of the arrester length and the connection leads, an inductance of 4 µH was introduced in series with the arrester.

To model the lightning overvoltage withstand of the line insulator on the compact and conventional line sections, flashover models based on voltage-time curves were introduced, assuming a phase-to-ground LIWL of 1175 kV for all insulators. The lightning current was modelled as a double-exponential impulse with a concave front [5], with varying values of amplitude and maximum steepness.

2.2.2.2 Results of flashover performance calculations

The risk of flashover due to direct lightning strokes to the top phase of the compact line was estimated by varying the values of stroke current amplitude and steepness in such a way that a limiting curve could be established as shown in Figure 5. Combined values of stroke current amplitude and steepness above the limiting curve will cause flashover of a line insulator on the compact or conventional line sections. The corresponding risk of flashover can be estimated by taking into account the statistical distributions of stroke current amplitudes and steepnesses.

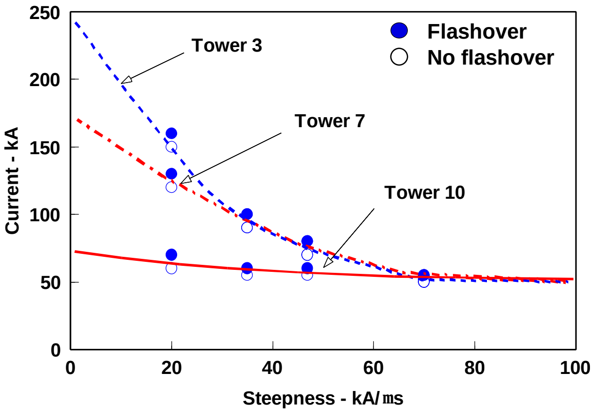


Figure 5. Limiting curves for insulator flashovers

Assuming that both distributions are lognormal with a certain correlation coefficient, the bivariate lognormal distribution can be determined [6,7,8]. Furthermore, the conditional lognormal distribution for one of the parameters, keeping the other parameter constant, can also be established. This means that the conditional probability that the amplitude exceeds the limiting curve can be calculated for a given value of the steepness. By repeating this calculation for each steepness ranging from the lowest to the highest value considered, and summing up the probability contributions, the total risk of exceeding the limiting curve is obtained.

The limiting curves for different towers (No. 3, 7 and 10 in Figure 4) are indicated in Figure 5. Only the negative first stroke amplitudes and steepnesses were considered in the study. The statistical data on mean values, standard deviations and correlation coefficient were obtained from [5] and [9]. The calculated risks of exceeding the limiting curves are given in Table 2. The resulting outage rate, assuming 4 strokes per 100 km per year to the compact line as discussed above, is also given in Table 2.

Table 2. Calculated outage rate for compact line

Tower	3	7	10
Risk of flashover	0,070	0,071	0,12
Outage rate per 100 km per year	0,28	0,28	0,48

As seen in Table 2, the average outage rate can be estimated to about 0,4 per 100 km per year, which is in the same order as for the conventional line. The higher values for strokes to tower 10 is due to the proximity to the conventional line section, where flashovers have a tendency to occur in towers not protected by surge arrester. It should be noted that no ”back flashovers” to the outer phases take place on the compact line. This is because the transient tower voltage is greatly reduced by the voltage drop created by the protective level of the surge arrester.

2.2.2.3 Modelling for arrester energy absorption calculations

For the energy absorption calculations, the same EMTP model was used as in the flashover studies. The energy stress on the surge arresters was calculated by injecting a single current impulse having a concave front with an amplitude and duration chosen in order to obtain a certain charge, including the effect of multiple strokes. Apart from the flash charge, the energy stress on the arrester depends also on the tower grounding conditions. Therefore, the calculations were carried out using grounding impedances of 10, 20 and 52 Ohms, with and without a continuous counterpoise.

The specific energy withstand capability of transmission line surge arresters is preferably expressed as a required MTBF (Mean Time Between Failure). In this study, the MTBF was chosen as 25 years for the complete installation of 23 arresters along the 5 km line section. The procedure for finding the required energy capability of the arresters from the required MTBF is described in detail in [10] and [11]. In short, the method is based on finding the total flash charge, including multiple strokes, which has a statistical return period equal to the desired MTBF. By calculating the energy stress on the arresters for this ”design charge”, it is possible to select an arrester type which yields the required MTBF.

To determine the design charge, the corresponding ”design probability” is calculated first:

$$p = 1 / (MTBF*N)$$

where N is the number of flashes per year to the line section with arresters.

2.2.2.4 Results from energy absorption calculations

With a requested MTBF of 25 years and 0,2 of strokes per year to the 5 km line section, the design probability is 0,20. From the statistical distribution of total charge of negative flashes, this probability of exceedence corresponds to a total flash charge of 17,4 As [12].

In order to reflect a similar probability for the current amplitude as for the design charge, the current amplitude was chosen as 55,4 kA, corresponding to an exceedence probability of 0,20 for negative first strokes. The duration of the current impulse was adjusted to obtain the design charge of 17,4 As.

The maximum surge arrester energy absorption, expressed in kJ/kV (rated voltage), is shown in Figure 6 for current strokes to towers 3, 7 and 10, for various tower grounding impedances, with and without a continuous counterpoise. As seen in the figure, the energy absorption for strokes to tower 10 is significantly higher. This is caused by the proximity of the conventional line section, which has a lower effective grounding impedance due to the shield wires. It can also be seen that the presence of a continuous counterpoise makes the effective grounding impedance more uniform, thereby making the energy stresses more even among the surge arresters.

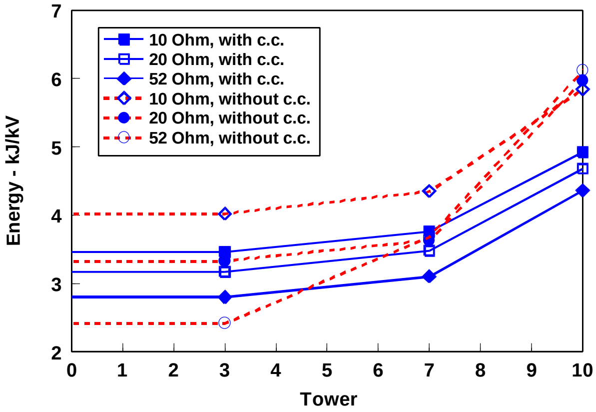


Figure 6. Arrester energy absorption

The required MTBF of 25 years for the complete installation of surge arresters along the 5 km compact line section is satisfied by installing arresters with a specified energy capability equal to the values shown in Figure 6. In practice, the same arrester type is chosen for all towers. Thus, the mean energy capabilities required for the arresters range from 3,1 to 4,4 kJ/kV for varying grounding conditions.

2.2.3 Design and installation of surge arrester

The surge arrester is shown in Figure 7. It is built-up of 6 separate mechanical and electrical modules connected in series. The design of each module includes an HTV silicone rubber insulator moulded directly onto the internal structure with the ZnO block column. The internal cage-style mechanical structure provides high mechanical strength and well controlled short-circuit capability in the event of arrester overloading.

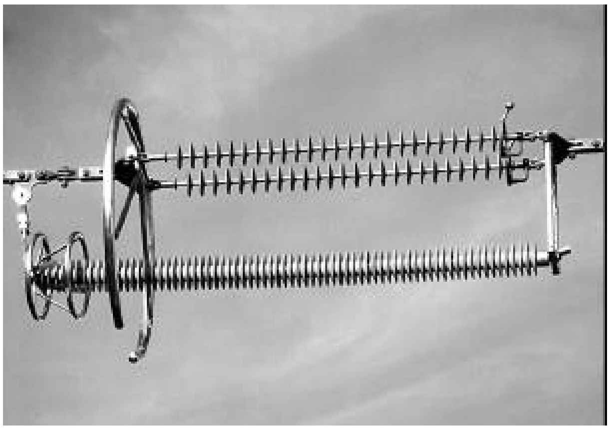


Figure 7. Surge arrester positioned under the insulator strings in top phase of the compact line

The special location of the arrester in the tower has required extensive 3D electrical field calculations to determine necessary grading rings to control the voltage distribution along the arrester. The mass of the arrester including the grading rings is 128 kg or approximately one third of the mass of an equivalent arrester with porcelain housing. The creepage distance of 27 mm/kV corresponds to IEC class III.

A number of tests in accordance with draft standards from IEC TC 37 on testing of polymer-housed arresters have been performed to verify the design. Some of these tests are as follows:

- Weather ageing test - 1000h salt-fog
- Tightness tests
- Short-circuit current test
- Operating duty tests as per requirements for 10kA line discharge class 3 arresters

In addition, a lightning energy withstand test has been carried out to determine the capability of the arrester to withstand lightning current impulses of sinusoidal shape with a duration of approximately 200μs which is intended to cover the combined effect of multiple lightning strokes [10, 11]. This type of test has verified an energy capability of the arrester of at least 4,5 kJ/kV rated voltage. This exceeds the energy capability required to meet the desired MTBF, as discussed above.

To the top terminal of the arrester a disconnecting device is connected which shall operate in the case of an arrester overloading to avoid a permanent ground fault. The disconnector has been carefully designed and tested to ensure its function only on arrester failure. All other possible stresses in terms of energy and current, which the arrester would withstand, will not cause a disconnector operation. It has e.g. been verified that disconnection will not take place for the following current impulses:

- 130 kA, 4/10 µs
- 3 kA, 4 ms, rectangular
- 28 kA, 200 µs, sinusoidal

3 FULL SCALE TESTING IN TEST SPAN

3.1 Corona testing of hardware

The corona tests were carried out in order to verify that no corona activity was present on any of the hardware, with the exception of the conductor, that always has some background corona. Certain parts of the hardware, such as the line fittings and clamps were from conventional 420 kV transmission lines, whereas other parts were specifically designed for this application. The final objective was to obtain a complete set of corona free hardware by, if necessary, re-designing or modifying the available fittings.

The corona measurements were carried out on an outdoor test span at night in dry conditions, using a regulated 3-phase voltage supply. Corona activity was registered by an UV-sensitive image intensifier and recorded on video.

Three different sets of grading rings for the high voltage side were tested. The third set proved to be corona free at 420 kV phase-to phase.

In order to achieve an artificial ageing of the rings' surfaces, several of the grading rings, with new, smooth surfaces, were coated with a layer of fine grade sand, and fixed with a thin layer of silicon grease. The sand was sieved in order to achieve a grade of 0.25 - 0.50 mm.

The grading rings tested are desribed in the following sections.

3.1.1 Grading ring type 1

The first type tested was a factory made double ring with arcing horn, where one ring was used for each separate insulator in the tension strings. The maximum outer diameter was 417 mm, and the thickness of rod material in the double ring was 32 mm. All grading rings of this model were artificially aged before the test in the manner described above.

3.1.2 Grading ring type 2

For the second test, a larger single ring was used to surround both insulators in the tension string. The rings were made from 76 mm standard steel-tube at a local workshop. The outer dimensions were given by a maximum width (W) 880 mm and a maximum height (H) 495 mm, see Figure 8. Tests were carried out with and without sand coatings, to assess the effect of the artificial aging.

Table 3. Results from the corona tests on the grading rings. A = left side of the tower (surge arrester side), B = right side, 1 = top phase, 2, 3 = outer phases

Grading ring	U_{inc} and U_{ext} measured on position	Inception voltage phase-ground kV	Extinction voltage phase-ground kV	Comments
Type 1	A2	160	150	With sand coating
Type 2	B1, B2, B3	140-190	130-180	No sand coating
Type 2	B3	190	180	No sand coating
Type 2	B3	170	160	With sand coating
Type 3	A2, A3, B2, B3	> 243	-	No sand coating

Table 4. Results from corona test for other parts of the hardware.

Object	Comments
Large grading ring on surge arrester/tension string	No corona
Small grading rings on surge arrester	No corona
Insulator sealing in string above the surge arrester	Corona of low intensity on one insulator end
Aluminium rods and the rod fittings	No corona
Split pins and bolts on conventional hardware	Corona on some points

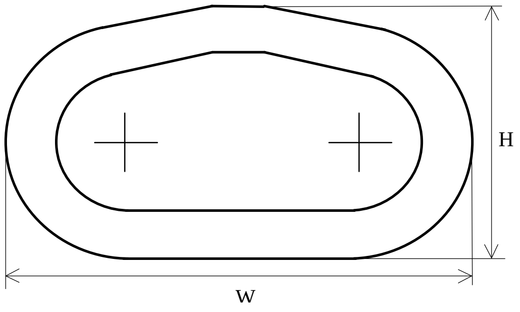


Figure 8. Sketch of ring type 2 and 3

3.1.3 Grading ring type 3

In the third and last test, single rings of the same type as type 2 were used, but the ring thickness was increased to 104 mm. The width and height were 960 mm and 530 mm respectively. No artificial ageing was necessary for these rings, because a coarser grinding was used during manufacture, resulting in a greater surface roughness.

3.1.4 Results of corona test

The main results from the measurements of corona inception and extinction voltages are shown in table 3.

The dispersion in results (U_{inc} 140-190 kV) for the rings of type 2 is mainly a result of individual differences in the rings due to the fact that the rings are handmade. The effect of the sand coating on the ring type 2 in position B3 was a 20 kV decrease in the inception and extinction voltages. The results also show that for ring type 2, there was no improvement over type 1.

The main dimensions needed for a grading ring, for the short phase to phase distance in this 420 kV compact-line design, have thus been established by the test on ring type 3, which proved to be corona free.

Corona was observed on the line end of the insulators above the arrester and on certain split pins and bolts, see table 4. Except for this, no significant corona activity was present. The corona on the insulator ends could easily be eliminated by using small grading rings at the line end. Corona activity on split pins and bolts could be eliminated by showing greater care in bending split pins and using caps on bolt ends.

3.2 Insulation coordination and impulse tests

The insulators are selected for a lightning-impulse withstand voltage phase to ground greater than 1175 kV. The distance between the grading rings of the tension strings is 2,3m. The arcing distance of the post insulator on the top of the tower is 2,1m. The minimum air clearance between aluminium tubes (jumper loops) on the outer phases and the tower is also 2,1m.

According to published results [13] from switching impulse tests, the expected switching impulse withstand voltage is about 950 kV phase to ground. Results from bipolar switching impulse tests with $U_{Pos.} = U_{Neg.}$- indicate a withstand voltage of about 1500 kV for the shortest phase to phase distance of 3.2 m. Earlier tests on short phase to phase distances carried out at STRI gave approximately the same results. Estimates and comparisons of withstand levels are uncertain due to lack of knowledge about the differences between the gap factors.

Impulse tests in the test span are planned in order to optimise the insulation design with respect to air clearances, and to verify the insulation levels. The following tests will be carried out:

- Lightning impulse test, phase to ground
- Switching impulse test, phase to ground
- Bipolar switching impulse test, phase to phase

4 ADDITIONAL AESTHETIC CONSIDERATIONS

From Figure 3 it is clear there is little to gain in magnetic field reduction in going from a 7,3m horizontal delta to a 5m delta configuration, therefore some non traditional concepts were utilised in an effort to optimise the appearance of the 5m delta. The removal of the shield wire and use of an arrestor instead has been covered earlier, in addtion,

- aluminium tubes for jumper loops
- painting of pole
- composite insulators

were used. The top jumper loop as a triplex bundle gave a very untidy, non-symmetrical appearance to the tower, however the tube jumpers would probably be improved by matting, as would all the other aluminium parts. It was not considered necessary to matt any galvanised steel fittings as they already had a mattish appearance. In contrast it was considered best to paint the tower light gray, as more appropriate to an urban environment, this can of course vary depending on the structures around the tower. The light gray proved especailly suited to snow conditions. Composite insulators were chosen because of their slim design and mattish appearance.

During the project two methods were suggested to avoid the necessity of a post insulator on top of the tower to lead the jumper loops over. The first proposal was for a large polymer post insulator of diameter 0,6m to replace the tension strings. Such a post insulator could presumably also replace the crossarms and tension strings on the lower phases. Unfortuneately no such post insulators with sufficient mechanical strength were available at the time. A second alternative was to use a tripod of post insulators to obtain the same effect, time limitiations prevented further investingation of this concept.

5 COSTS

The total costs for a compact tower will be higher than for a standard tower with 9 m horizontal phase to phase spacing. The costs for a compact tower including, structure, conductors, fittings, insulators, surge arrester, painting of pole, installation and construction are calculated to approximately 320.000 US$/km (four spans of 250m). Costs will be lower for 10-20 poles, and a conservative cost reduction of approximately 20 % should be possible to achieve for an actual line. This leads to approximated cost of 250.000 US$/km. Typically a tower with horizontal configuration in a suburban area costs 190.000 US$/km, i.e. 30% more for a compact line compared with a standard line. The increased cost for the compact line should however be compensated by the reduced cost for purchasing ROW, which can be significant in suburban areas. The extra costs can better be put into perspective when the alternatives to a compact tower maybe cabling or a forced detour in planned ROW.

6 CONCLUSIONS

- Compact lines of 5 m phase spacing can be used with acceptable corona.
- A 5 m delta can reduce the ROW by 13 m in comparison to a standard horizontal configuration.
- A 5m delta offers a 50% reduction in magnetic field in comparison to a 9 m horizontal configuration.
- Without any form of lightning protection the compact line would have an outage rate about ten to twenty times higher than the conventional 420 kV line.
- With surge arresters installed in the top phase of each tower the estimated outage rate would be in the same order as for a conventional line.
- With a requested MTBF of 25 years for a typical application with a 5 km line section the mean energy capabilities for the arresters range from 3,1 to 4,4 kJ/kV depending on varying grounding conditions.
- Single grading rings have been successfully tested for compact lines down to 5 m spacing.
- It is expected that a 5 m delta will cost 30% more than a 9 m horizontal tower, exclusive ROW costs.

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