

268

**TRANSIENT VOLTAGES
AFFECTING LONG CABLES**

**Working Group
B1.05**

April 2005



TRANSIENT VOLTAGES AFFECTING LONG CABLES

Working Group B1.05

Composition of the Working Group:

Georg Balog (Convener)	Norway
Heinrich Brakelmann	Germany
Bjørn Gustavsen (Secretary)	Norway
Thor Henriksen	Norway
Marco Marelli	Italy
Pablo Martin,	Spain
Laurent Moreau	France
Ambrogio Orini	Italy
Wan-Ki Park	South Korea
Jean-Luc Parpal	Canada
Robert Rosevear	United Kingdom
Thomas Worzyk	Sweden

Composition of the Project sponsored by the Norwegian Research Council

Georg Balog, Ulf Baur, Bjørn Gustavsen, Thor Henriksen

Copyright © 2005

“Ownership of a CIGRE publication, whether in paper form or on electronic support only infers right of use for personal purposes. Are prohibited, except if explicitly agreed by CIGRE, total or partial reproduction of the publication for use other than personal and transfer to a third party; hence circulation on any intranet or other company network is forbidden”.

Disclaimer notice

“CIGRE gives no warranty or assurance about the contents of this publication, nor does it accept any responsibility, as to the accuracy or exhaustiveness of the information. All implied warranties and conditions are excluded to the maximum extent permitted by law”.

SUMMARY

Cables and accessories are required to be tested with standard lightning impulse voltage levels (BILs) defined in IEC 60071-1. The current practice among utilities is to choose the highest BIL within the options specified in IEC 60071-1 for the actual system voltage, and some utilities specify an even higher value. The service experience of long cables is very good with overvoltages being a rare cause of insulation failures.

This report investigates the maximum lightning overvoltage along a cable inserted in an overhead line and protected by surge arresters. The overhead line is fitted with overhead ground wires, at least at the 5 towers closest to the cable termination. The line is further assumed to satisfy certain characteristics related the grounding conditions and span length near the cable termination.

Overvoltages on the overhead lines due to shielding failures are controllable by properly shielding and this report thus considers only overvoltages resulting from close backflashovers as this gives the most severe overvoltages. The calculations are carried out for 3 different stroke currents: 100 kA, 200 kA, and 250 kA, for different system voltages and cable designs.

The calculations show that the maximum overvoltage decreases with increasing cable length. The reduction is particularly high for fluid-filled and mass-impregnated cables due to their high attenuation of lightning transients. For instance, for a 420 kV SCFF cable it was found that for cable lengths above 35 km the voltage due to a 250 kA stroke current would not exceed the arrester protective level. Thus, the actual overvoltage level is significantly lower than the adopted BILs and provides a strong opportunity to specify a lower BIL. For all studied cases involving fluid-filled cables, the attenuation caused a 20% reduction of the maximum cable voltage for cables exceeding 30 km. For all XLPE cables, a 20% reduction was obtained for cables exceeding 50 km.

In the case of very long cables, it is therefore recommended that the required BIL be subject to analysis as part of the system engineering. In some cases it may even be possible to leave out the installation of surge arresters. It is emphasised that each case should be analysed individually.

In the case of paper-oil type cables, a reduction of BIL requirements may lead to a reduced insulation thickness and thus longer cable sections (fewer joints). In the case of cables with extruded insulation, it is not anticipated that a reduced test level will affect the insulation design, as it is the AC voltage stresses that is the dimensioning factor. This may however change in the future as the insulation performance characteristics continue to improve.

CONTENTS

1	INTRODUCTION	4
2	CURRENT PRACTICE	5
2.1	Standards.....	5
2.2	Service experience.....	5
3	CABLE LIGHTNING OVERVOLTAGES	6
3.1	Cable system.....	6
3.2	Worst case lightning overvoltages.....	6
3.3	The long cable self-protective effect	6
3.4	Location of the maximum cable voltage	7
4	MODELING	8
4.1	Introduction.....	8
4.2	System configuration.....	8
4.3	Components	8
4.4	Calculation of maximum overvoltage in cable.....	9
4.5	Validation	9
5	CALCULATED RESULTS	11
5.1	Introduction.....	11
5.2	Calculated results.....	11
5.2.1	145 kV AC XLPE cable	11
5.2.2	245 kV AC XLPE cable	12
5.2.3	345 kV AC SCFF cable	12
5.2.4	420 kV AC SCFF cable	13
5.2.5	420 kV AC XLPE cable	13
5.2.6	500 kV AC SCFF Cable	14
5.2.7	400 kV DC mass-impregnated cable	14
5.3	Discussion.....	15
5.4	Relative voltage reduction	15
6	SIGNIFICANCE OF MODEL PARAMETERS.....	18
7	INSULATION CO-ORDINATION	19
7.1	Frequency of occurrence.....	19
7.2	Safety factors	19
7.3	Alternative approach by reduction factors.....	20
8	IMPLICATIONS OF REDUCED TESTING LEVELS.....	21
9	DISCUSSION.....	22
9.1	Overvoltage calculations	22
9.2	Insulation co-ordination.....	22
9.3	Insulation design.....	22
10	CONCLUSIONS AND RECOMMENDATIONS	23
11	REFERENCES	25
Appendix 1	Terms of Reference.....	27
Appendix 2	Modeling	28
Appendix 3	Computational Procedure	34
Appendix 4	Effect of Model Parameters on Maximum Cable Voltage	35
Appendix 5	Relative Voltage Reduction vs. Cable Length	44

1 INTRODUCTION

The cable insulation system is required to withstand testing with standard lightning impulse voltage. For each system voltage, the IEC standards permit to select between several test levels to account for the actual in-service overvoltage conditions. However, the common practice among utilities is to always specify the highest insulation level, thus ignoring the overvoltage reduction resulting from surge arrester instalment and the self-attenuation effect in long cables. This reluctance to adopting lower BILs leads to an excessive test voltage that may result in a more costly design of the cable and accessories. The potential advantages of reduced test levels are particularly high for long cable sections. In the last 50 years the cable lengths have grown to over 200 km, especially for submarine cables and there are several projects with lengths up to 600 – 700 km.

Study Committee 21 (later B1), decided at the 2001 SC meeting to launch a Working Group to study the transient behaviour of long cables in order to establish a firm base for the necessary transient requirements for long cable systems. The WG B1-05 was established in 2001 with members from utilities, industry, universities and research institutions. The full text of the terms of reference is given in Appendix 1.

The WG has concentrated its efforts on identifying the lightning overvoltage level in long cables (siphons) that are protected by surge arresters at both ends. No internally generated overvoltages have been investigated since those overvoltages are in general of low value. The study has considered the design of the adjacent network at the cable ends, the cable type, and the cable length. No specially bonded sheath systems were taken into consideration.

Past studies of cable lightning overvoltages [1]–[4] have mainly focused on the overvoltages at the cable ends, whereas in reality a higher overvoltage can occur *inside* the cable [5]–[7]. The available results were therefore found inadequate and a special computational procedure was developed to be able to identify the maximum voltage along the cable [8].

This report describes the modelling and computational procedure [8] adopted by the WG for calculating the maximum lightning overvoltage in cables as function of the cable length, due to backflashovers. Calculated results are shown for 7 representative cable systems, both AC and DC systems, with extruded and paper-fluid type insulation. Consideration is given to the application of the results in insulation co-ordination studies and the sensitivity to system parameters is investigated. The implications of reduced lightning impulse test levels are discussed.

The report discusses only the lightning overvoltage stresses. For a discussion on insulation withstand characteristics is referred to CIGRE Technical Report 189 [9].

2 CURRENT PRACTICE

2.1 Standards

Test voltages are described in IEC Standards such as IEC 60071-1 and IEC 60183 and in standards by IEEE/AEIC. The IEC test voltages for cable systems are shown in Table 1 in CIGRE Technical Report 189 [9].

In this report is only given consideration to the lightning impulse withstand voltage (LIWL). This voltage capability is for simplicity referred to as the “BIL” – Basic Insulation Level. The IEC norm allows choosing between a set of test levels defined for each system voltage. BILs are only defined for AC systems. For DC cables, the overvoltage requirements, including BIL, are not defined within IEC but are determined in accordance with the guidelines specified within CIGRE Technical Report 86 [16].

Historically the BIL for cable systems has been defined by the customer and specified in the customer specification. Normally, customers select the highest BIL listed in IEC 60071-1. In some cases conservative utilities specify an even higher level as an additional safety factor.

2.2 Service experience

Underground cable systems are known to be extremely reliable. Their asset value is rather significant and normally a design life of 40 years is assumed. The technological development has been gradual, incremental and based on sound experience. The predominant risk associated with cables is external mechanical damage.

There is very little published information on service experience. The last published data was produced in August 1991 and published in Electra No 137 “Survey on the Service Experience of HV AC Cable Systems, Electra no. 137, pp. 47-59, August 1991.

Service experience with DC submarine cable systems is given in reports from the CIGRE SC 14 (now SCB4) as a bi-annual report over the service experience every second year, the latest is CIGRE 2002, 14-101.

3 CABLE LIGHTNING OVERVOLTAGES

3.1 Cable system

The investigation considers a cable, which is inserted in an overhead line (siphon) and protected by surge arresters at both ends, see Fig. 3.1. The overhead line is fitted with overhead ground wires. The siphon is symmetrical; i.e. the line configuration including grounding conditions is the equal at the two ends of the cable. The objective is to calculate the maximum overvoltage that can occur in the cable due to a lightning stroke to the overhead line.

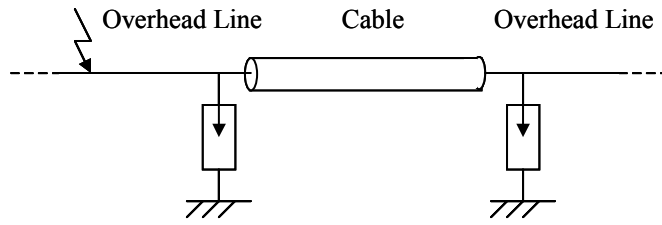


Fig. 3.1 Basic configuration used in study

3.2 Worst case lightning overvoltages

The worst-case lightning overvoltages result from either *shielding failures* or *backflashovers*, close to the cable entrance.

In the shielding failure event, the lightning current bypasses the overhead ground wires and terminates at one of the phase conductors. The lightning current is limited in peak value to a level that decreases with decreasing shielding angle of the overhead line. Thus, by reducing the shielding angle of the closest spans near the cable entrance, the current peak value and the resulting overvoltages can be controlled to a low level. Overvoltages by shielding failure are therefore not considered in this report.

In the backflashover event, the lightning stroke terminates at a ground wire or a tower top. If the voltage on the tower top becomes sufficiently high, a backflashover takes place across the insulator string to a phase conductor and causes a very steep wave front to propagate towards the cable entrance. Normally, the highest overvoltages result when the backflashover takes place at towers close to the cable terminal as the inductance associated with the distance between the cable entrance and the backflashover location reduces the steepness of the impinging voltage at the cable end. A stroke hitting a tower or a shielding wire without causing backflashover gives only insignificant overvoltages.

3.3 The long cable self-protective effect

In the case of a backflashover, multiple reflections between the (grounded) towers result in that an increasing portion of the injected lightning current is diverted to ground. This results in a strong reduction of the duration of the impinging voltage at the cable entrance, even for lightning currents with a long duration. The limited duration of the impinging voltage implies for long cables that the maximum voltage in the vicinity of the exposed

end occurs at that end before reflected waves from the remote end reaches the exposed end. In addition, the attenuation effect of long cables result in a reduction of the voltage peak reaching the remote end, thus reducing the peak value that can result from reflections from that end. The maximum voltage will therefore for a sufficiently long cable occurs at the exposed end and it is in any case limited to a value close to the surge arrester protective level.

3.4 Location of the maximum cable voltage

The maximum voltage that can occur at the cable *ends* is limited to about the arrester protective level plus inductive voltage drops along connecting leads. However, the voltage *inside* the cable can become significantly higher than this voltage due to the reflected wave from the remote cable end. This phenomenon has been investigated in detail in [8]. It is shown that the maximum in general occurs within a few kilometres from the remote end.

4 MODELING

4.1 Introduction

This section describes the model used for assessing lightning overvoltages along the cable. In general, the overvoltage conditions must be assessed for each system separately. In this report is used a model of the overhead line assembly and grounding system which gives fairly conservative (high) results for the overvoltages impinging the cable. This modelling approach is used to investigate the overvoltages on different cable systems. The main features of the model are described in this section with more details given in Appendix 2.

4.2 System configuration

The selected configuration is shown in Fig. 4.1. The five spans closest to the cable entrance are treated as transmission lines while the remainder of the line is treated as a single (infinitely long) line without towers. (The neglecting of remote towers increases the overvoltages along the cable.) It is further assumed that backflashover cannot take place within 200 m from the cable entrance. Backflashover prevention in this region can be achieved by installing additional surge arresters or shield wires. A backflashover closer to the cable would probably cause higher overvoltages in the cable and measures to prevent such backflashovers can be considered as a reasonable precaution like minimising the arrester protective level.

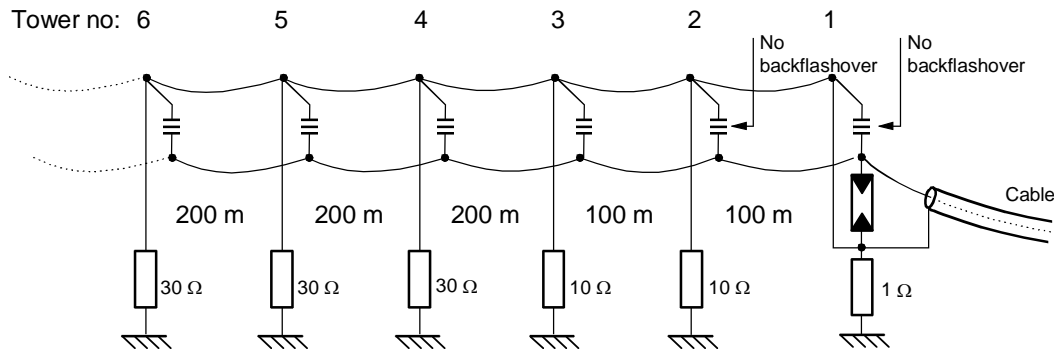


Fig 4.1 System configuration.

4.3 Components

The maximum overvoltage along the cable depends strongly on the characteristics of the actual cable, in particular for long cables. It was therefore decided to perform the computations for actual cables, using realistic frequency dependent models. Some simplified models giving too high overvoltages were used for the other components. Values for the parameters of those models were selected in a conservative way; i.e. to give an upper limit for the overvoltages when there is some uncertainty or possible variation in the actual parameter.

This section describes briefly the selected models and more details including selected parameters are given in Appendix 2. The influence of the various parameters was for one

specific cable investigated in detail, see Section 6 and Appendix 4.

Overhead line

A lossless multi conductor travelling wave type model represents the overhead line. The towers are modelled by inductances and the tower footings are represented by resistances. Five spans are modelled in this way. The rest of the line is represented by its characteristic impedance, neglecting the mutual coupling between phases.

Surge arrester

The arresters are represented by non-linear resistances with voltage-current characteristics given in Appendix 2. The arrester leads are modelled as inductances.

Cable

The cable associated with the phase with backflashover is modelled as a two-conductor (core-screen) frequency dependent phase domain travelling wave model [10]. The model takes into account skin effects in core, sheath and ground. The frequency dependent permittivity of the insulation of fluid-filled and mass-impregnated cables is taken into account using the procedure described in [11].

Lightning current

The lightning stroke is represented by a current pulse

- 1 μ s front time
- Infinite time to half value.
- Three different peak values: 100 kA, 200 kA, 250 kA

These peak values are related to different frequencies of occurrence. The significance for insulation co-ordination studies is treated in Section 7.

4.4 Calculation of maximum overvoltage in cable

The maximum overvoltage occurring in the cable is calculated using the procedure described in [8], see also Appendix 3. This procedure identifies the peak value and location of the maximum voltage by considering the sum of the forward and backward voltage wave.

4.5 Validation

The applied cable model was validated by comparison with measured voltage transients on a 6.05 km 400 kV XLPE cable section (BEWAG, Berlin, Germany) published in [12]. One of the tests [12] was to discharge a trapped voltage on the cable by closing a switch between the core and the sheath. The simulated voltage transient on the remote (open) end agreed well with that of the measurement, although the model gave too weak attenuation of the high frequency components. The consequence is that the applied cable model will produce too high overvoltages.

Comparisons were also made with open-end step voltage responses for the Fenno-Skan HVDC cable (mass-impregnated insulation), utilising measured responses in [18]. In the measurements, closing a switch discharged a trapped voltage. The computation gave a much too weak attenuation of the voltage response at the remote end, possibly due to the presence of the steel armour. It is to be noted that due to the long cable length (198 km), the frequency components relevant for lightning overvoltages were barely present in the

response, due to attenuation effects of the cable. Clearly, for this cable the long length results in that the maximum lightning overvoltage will occur on the exposed cable end.

5 CALCULATED RESULTS

5.1 Introduction

This section describes calculated results for the maximum cable overvoltage as function of cable length, for a number of representative cases. The overvoltages are calculated for lightning stroke currents 100 kA, 200 kA, and 250 kA. The probability of exceeding these stroke currents is discussed in Section 7. In addition to the overvoltages are shown by horizontal lines

- Max. BIL according to IEC 600-71 (solid line)
- Min. BIL according to IEC 600-71 (dashed line)
- Arrester protective level at 10 kA (dashed line)

Note: Where traces for maximum curves are shown by dotted lines (short cable), some uncertainty exists for the calculated voltage maximum as the effect of arrester leads is not properly accounted for.

5.2 Calculated results

A discussion of the calculated results is given in Section 5.2.8.

5.2.1 145 kV AC XLPE cable

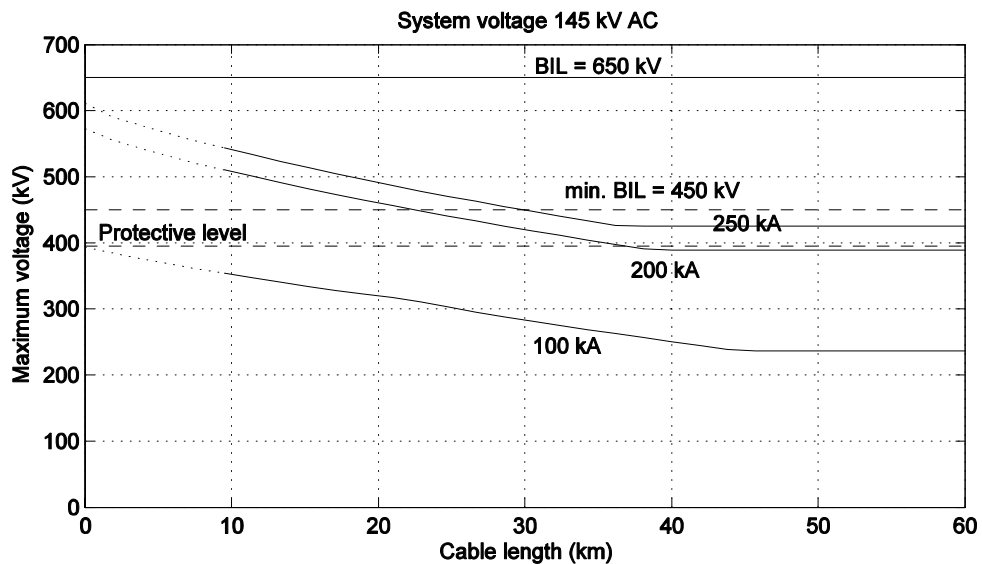


Fig. 5.1 Maximum cable overvoltage

5.2.2 245 kV AC XLPE cable

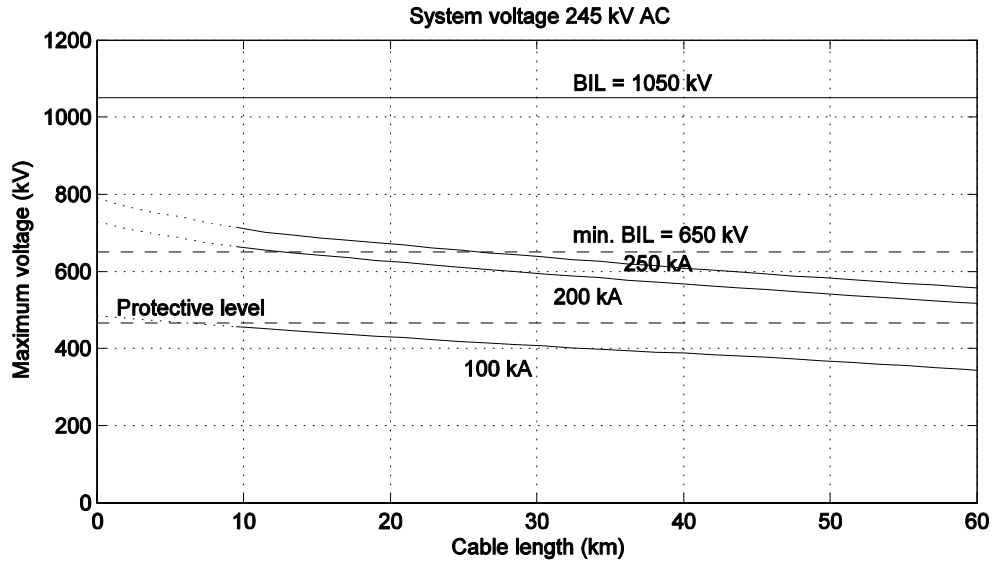


Fig 5.2 Maximum cable overvoltage

5.2.3 345 kV AC SCFF cable

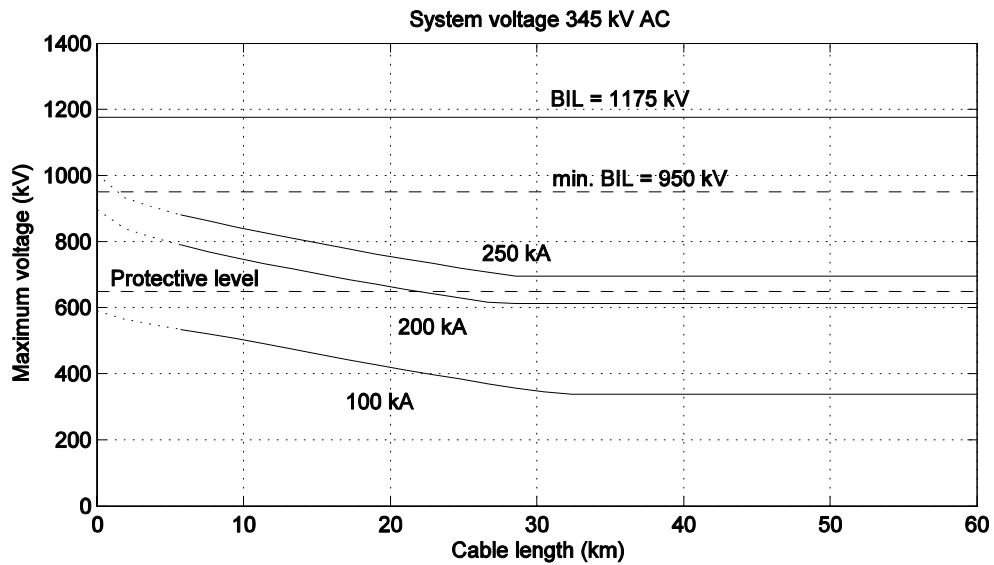


Fig. 5.3 Maximum cable overvoltage

5.2.4 420 kV AC SCFF cable

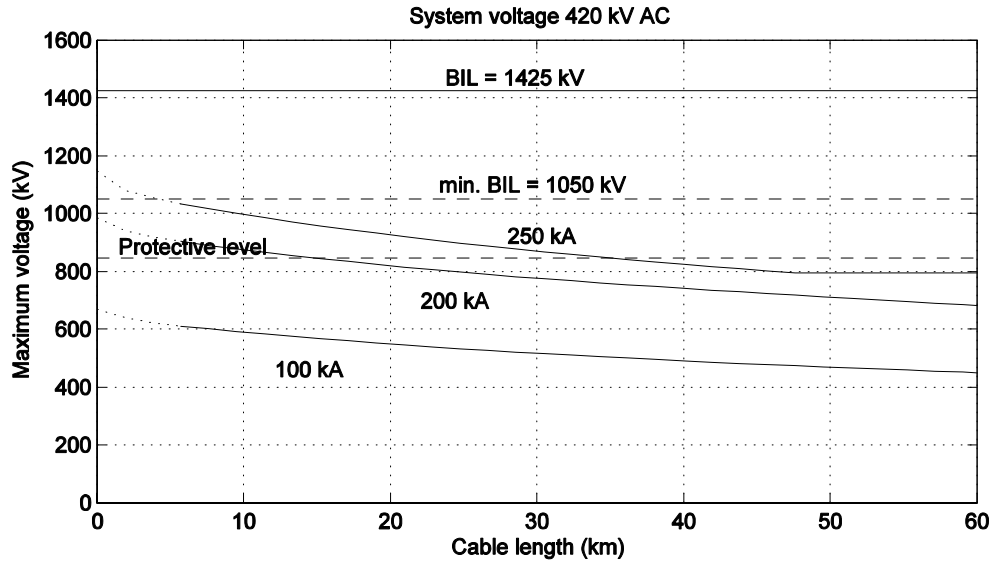


Fig. 5.4 Maximum cable overvoltage

5.2.5 420 kV AC XLPE cable

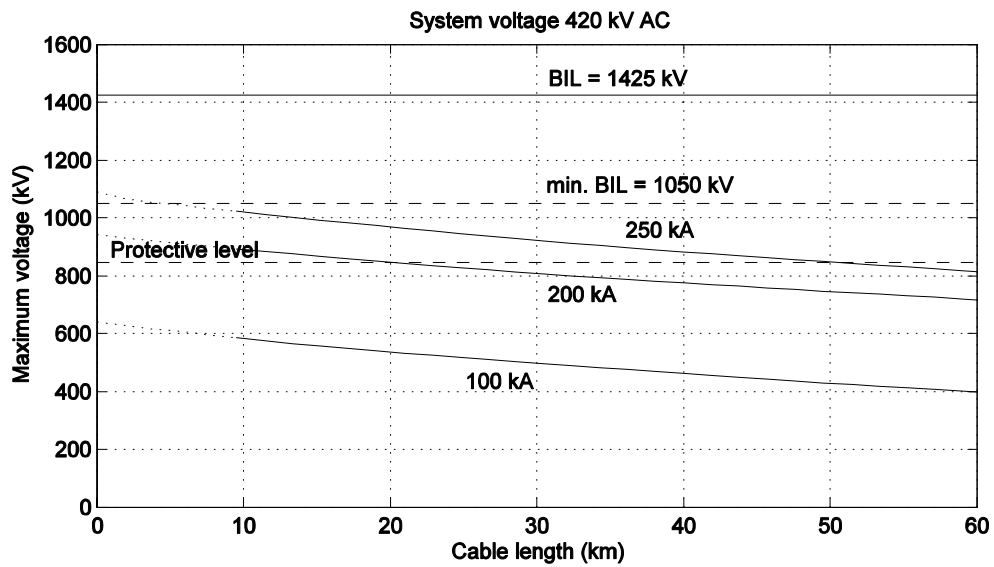


Fig. 5.5 Maximum cable overvoltage

5.2.6 500 kV AC SCFF Cable

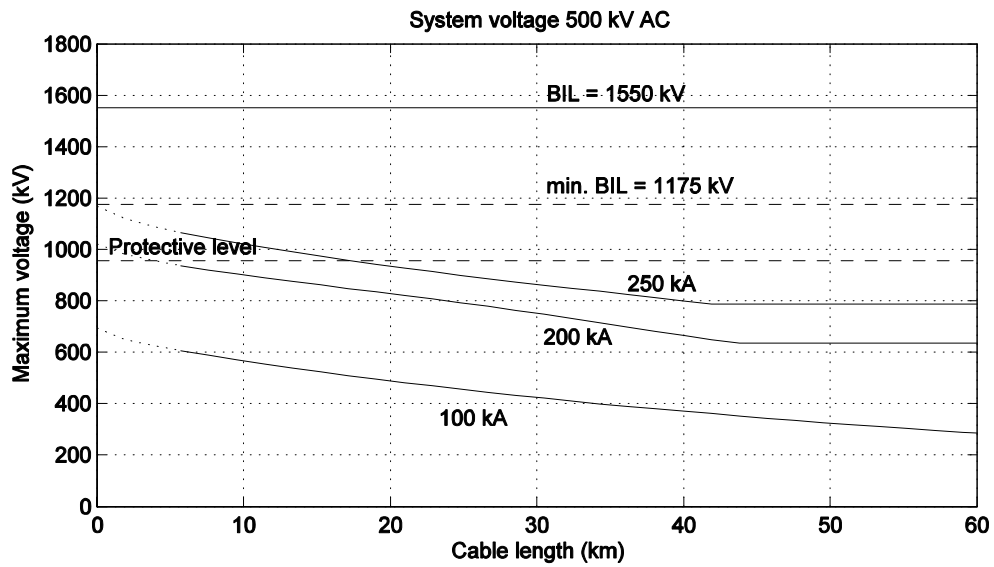


Fig. 5.6 Maximum cable overvoltage.

5.2.7 400 kV DC mass-impregnated cable

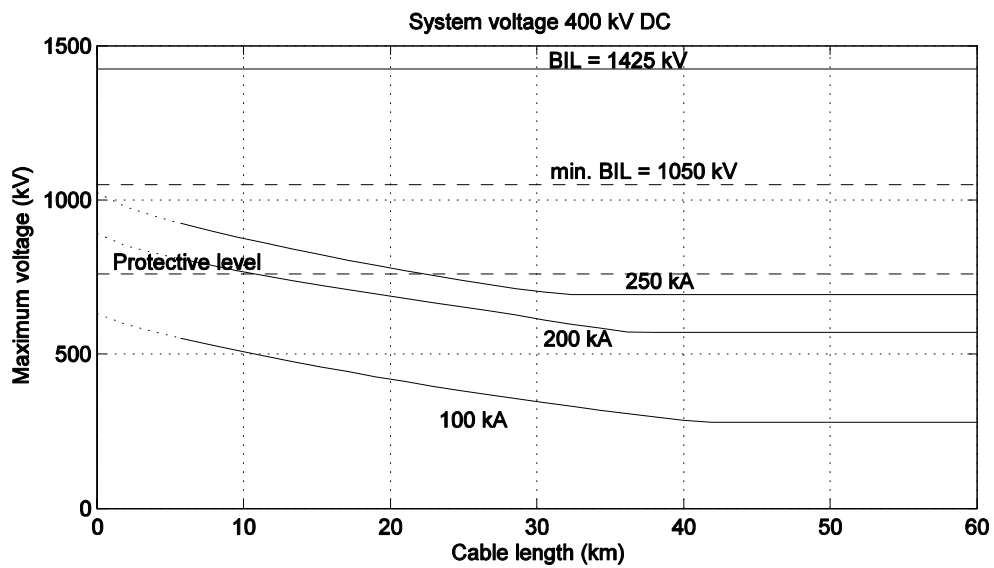


Fig 5.7 Maximum cable overvoltage

(The shown BILs are for 420 kV AC systems - included for information only)

5.3 Discussion

The traces for calculated voltages show that the maximum cable voltage decreases with increasing cable length, which is mainly a result of the cable attenuation effect. In some figures the traces for maximum voltage become “flat” at long cable lengths as the maximum voltage occurs at the exposed cable end. (The cable self-attenuation effect cannot reduce the maximum voltage below that level.) It is to be noted that each curve comprises the maximum of three curves, obtained for different values of the AC instantaneous voltage (see Appendix 3 for details).

For a given cable length, the maximum voltage is seen to increase with the lightning stroke current (100 kA, 200 kA, and 250 kA). In each figure the three voltage curves are surprisingly similar. This is taken advantage of in Section 5.4, where a concept of relative voltage reduction is described.

In addition is shown for each system voltage the maximum and minimum BIL (IEC 60071-1) and the 10 kA arrester voltage. By comparing the figures it is seen that the maximum voltage relative to the maximum BIL is lower for the higher system voltages than for the lower system voltages. For the higher system voltages (e.g. 500 kV AC), the maximum cable voltage exceeds the arrester protective level only for the combination of a high stroke current (250 kA) and short cable lengths. Thus, for such systems there is a high potential for using lower BILs.

It is to be noted that in the 145 kV case (Section 5.2.1), the system is assumed to be operated with Petersen grounding (arc suppression coils). This implies high temporary overvoltage levels (TOV) and thus a high arrester protective level. For 145 kV systems with directly grounded neutral a significantly lower protective level is attainable, which gives lower overvoltages than shown in Fig. 5.1.

5.4 Relative voltage reduction

The calculated results in Section 5.2 showed that the maximum cable overvoltage decreases with increasing cable length. It was also seen that the actual voltage level is strongly dependent on the peak value of the lightning current and it is therefore not obvious which peak value should be used when determining the required BIL. This problem is addressed in Section 7 and involves some statistical considerations. A more simple approach is to focus on the relative reduction in the maximum overvoltage and to assume that the BIL can be reduced accordingly based on a present BIL that is known to be adequate for short cables.

Fig. 5.8 shows the relative reduction for the 420 kV SCFF cables. It is seen that the peak current has only a moderate influence on the voltage reduction. This means that it is reasonable to use a single curve for the minimum reduction, independently of the peak current.

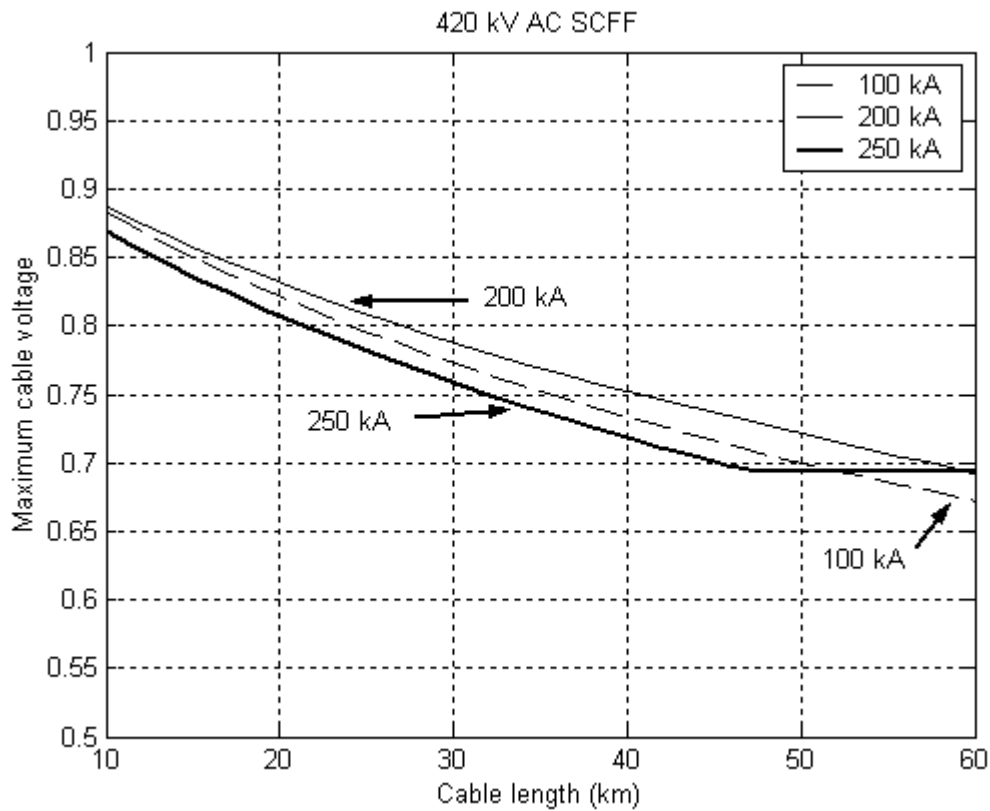


Fig 5.8 Relative voltage reduction for the 420 kV SCFF cable.

The reference voltage in the Fig. 5.8 is the maximum voltage in a long lossless cable when the voltage drop of the arrester leads at the remote end is ignored. It is to be noted that the reference voltage includes the effect of the reflected voltage wave at the remote end. (In practice, shorter cables with lengths up to 2 km may suffer greater maximum voltages because the reflected waves from the remote end may superpose and increase the wave propagating from the exposed end to the remote end).

The relative reduction was analysed also for the other cables in Section 5.2 and the curves of relative voltage reduction are given in Appendix 5. In all cases there is close agreement between the results obtained for 200 kA and 250 kA peak current. The 100 kA peak current gives somewhat deviating result. This is however less important if one assumes that the cable may be exposed to at least a 200 kA lightning current.

The minimum relative voltage reduction is summarised in Table 5.1, for all cases.

Table 5.1 Minimum relative voltage reduction

Cable length [km]	Reduction factor						
	145 kV XLPE	245 kV XLPE	345 kV SCFF	420 kV SCFF	420 kV XLPE	500 kV SCFF	400 kV DC MIND
> 10	0.92	0.94	0.86	0.89	0.95	0.89	0.87
20	0.82	0.89	0.76	0.84	0.90	0.82	0.78
30	0.74	0.84	0.70	0.79	0.86	0.74	0.69
40	0.70	0.80	0.70	0.76	0.83	0.69	0.68
50	0.70	0.76	0.70	0.73	0.80	0.68	0.68
≥ 60	0.70	0.71	0.70	0.70	0.76	0.68	0.68

6 SIGNIFICANCE OF MODEL PARAMETERS

The significance of model parameters on the maximum overvoltage is discussed in detail in Appendix 4. The main conclusions based on Appendix 4 and some additional investigations are:

The peak value of the impinging voltage at the exposed cable end

- is strongly dependent on which tower the backflashover takes place
- is significantly reduced by the presence of surge arresters, for low system voltage and high stroke current
- increases when reducing the grounding impedance of the joint grounding of the surge arrester and cable sheath
- increases when increasing the grounding impedance of towers
- increases when increasing the number of subconductors in a bundle

- increases with increasing ratio between the surge impedance of the cable and the overhead line

The voltage peak value of a voltage wave transmitted along the cable

- is reduced when decreasing the sheath thickness
- is reduced when decreasing the conductivity of the sheath material
- is reduced when replacing extruded insulation with paper-oil insulation

The presence of shunt reactors, terminations and joints has only a minor effect on the maximum cable overvoltage.

7 INSULATION CO-ORDINATION

7.1 Frequency of occurrence

CIGRE Technical Report 189 [9] describes a procedure for cable insulation co-ordination by a statistical procedure based on drawing lightning stroke parameters from statistical distributions. This procedure gives directly the overvoltage as function of the frequency of occurrence, which can be applied in insulation-co-ordination studies with appropriate safety factors to establish the most adequate insulation level.

In this report is instead used a semi-probabilistic approach with conservative stroke current shape parameters and three peak current values: 100 kA, 200 kA and 250 kA. These currents correspond to three points on the curve of overvoltage as function of frequency of occurrence. In the following is outlined how to calculate the frequency of occurrence for exceeding these stroke currents.

The probability of exceeding these stroke currents is given in Table 7.1 [13], [14]. (About 20% of all flashes are positive [14]).

Table 7.1. Lightning peak current distribution

Peak value [kA]	Probability of exceeding given value	
	Negative stroke	Positive stroke
100	0.035	
200	0.0015	
250	0.0004	0.05

If one assumes that the closest tower that can experience a backflashover (Tower no. 3 in Fig. 4.1) collects all lightning-to-ground strokes within a corridor 200 m wide and 150 m long, the tower is struck once every 33 years for a ground stroke density of 1 stroke/(km² · year).

Combining these results with the probabilities in Table 7.1 allows to calculate the frequency of occurrence for lightning strokes (to tower no. 3) that exceed the peak currents used in the calculations. E.g., negative stroke peak currents of 100 kA are exceeded on average every 950 years while positive stroke peak currents of 250 kA are exceeded every 670 year.

These results can be used together with figures 5.1–5.7 to obtain the frequency of occurrence for exceeding the calculated overvoltage for a given cable length and stroke current (100 kA, 200 kA, 250 kA).

One must be aware that there is a significant uncertainty regarding the lightning peak current probabilities in Table 7.1, as they have been determined from a relatively low number of observations. Therefore, the confidence interval is wide for high current values (see CIGRE Technical Report 63 [14], p. 13).

7.2 Safety factors

As explained in CIGRE Technical Report 189 [9], the safety factors are to be chosen such that

$$U_w \geq K_c K_s U_{rp} \quad [\text{Eq. 7.1}]$$

where U_w is the standard insulation level to be chosen and U_{rp} is the calculated maximum lightning overvoltage for a chosen frequency of occurrence. K_c takes into account uncertainties in the calculated overvoltage distribution while K_s takes into account factors, which may reduce the insulation withstand voltage. The actual value to be used for K_c will necessarily depend on the accuracy of the input data and that of the modelling procedure. Following the IEC practice stated in IEC 60071-2 Ed. 3, section 4.3.4, K_s should be chosen equal to 1.15 as the relevant apparatus committee (SC B1) has not recommended a different value.

7.3 Alternative approach by reduction factors

The need for establishing safety factors K_c and K_s can be avoided by considering the relative reduction of the cable overvoltage with increasing length, using Table 5.1 in Section 5. The table gives directly how much the BIL can be reduced for a *long cable* to achieve the same failure rate as a short cable of the same design. This allows to extend the experience gained for short cables to longer cables.

8 IMPLICATIONS OF REDUCED TESTING LEVELS

A reduction in the transient voltage performance requirements will have an impact on some cable systems. In order to evaluate the changes it is necessary to differentiate and discuss the different insulation technologies independently (see also Section 3 of CIGRE Technical Report 189 [9])

Insulation Design of AC Cables with Lapped (Impregnated /Pressurised) Insulation

In the case of Low Pressure Self Contained Fluid Filled, Low Pressure Polypropylene Laminate (PPLP) Self Contained Fluid Filled, High Pressure Oil Filled, External and Internal Gas Pressure cable systems, the cable electrical design stress level and insulation thickness is determined by BIL system requirement. Any reduction in BIL provides the opportunity to reduce the insulation thickness and increase the operating stress. Attention however must be paid to the resulting increase in capacitance and associated losses and cost of reactive compensation. Care must also be taken to ensure that the AC stress level on the outside of the main insulation does not become a limitation with respect to the performance of accessories.

As regards the design of joints the situation is the same as that for cables. The design of terminations, either outdoor or SF₆ insulated designs are generally determined by the Switching Impulse Level (SIL) and the BIL requirements, leading to some scope for change in the event of a relaxation in SIL or BIL.

Insulation Design of AC Cables with Extruded Insulation

In the case of extruded insulated cables such as cross linked polyethylene (XLPE), the cable and accessory operating stresses are generally determined by the AC operating requirement and not the transient voltages. A reduction in the SIL or BIL levels is therefore unlikely to have a significant impact on the current designs of an extruded cable system.

However it can be anticipated that as experience grows and further technological improvements are made, higher electrical stresses will be acceptable. The AC electrical stress will remain a design parameter, in particular the electrical stress on the outside of the insulation, which has a very important influence on the design, and the jointing of accessories. A reduction in impulse performance requirements will certainly facilitate such a change.

9 DISCUSSION

9.1 *Overvoltage calculations*

The calculations in this report are based on a specific configuration and all conclusions pertain to this configuration. An EMTP-type model was developed and used for calculating the maximum voltage at any point along the cable. Although conservative assumptions were made for the selected parameters and modelling procedures, uncertainties exist for both the modelling procedure and the parameters. It is therefore recommended to analyse each case individually.

A tower footing impedance of 10 Ω was used in the calculations in this report. The sensitivity analysis results in Appendix 4 show that lowering the tower footing impedance will lead to a significant reduction of the maximum cable overvoltage. Such a reduction is in reality likely to take place for the highest stroke currents due to partial breakdown in the soil. This suggests that the calculated overvoltages in this report are generally too high, in particular for the highest stroke currents (250 kA).

Comparison with field-tests (Section 4.5) shows that the currently available cable models give a too weak attenuation of lightning overvoltages. This suggests that in reality a stronger reduction of the overvoltage level with increasing cable length will take place.

9.2 *Insulation co-ordination*

The calculated curves for maximum overvoltage can be combined with the local ground flash density to obtain the frequency of occurrence for exceeding a given overvoltage. As explained in Section 7, this information can be combined with appropriate safety factors to arrive at required insulation levels. A simplified approach can also be used where one considers the relative reduction of the maximum voltage as the cable length is increased. The latter approach gives the permitted reduction of existing BILs that can be achieved while maintaining the same failure probability when the cable length increases.

9.3 *Insulation design*

The implication of a reduction in BIL has at present a lesser significance with the extruded insulation cable systems. As experience is gained and the extruded insulation thickness is reduced the BIL reduction will be of interest also for such systems. However a reduction in BIL can be utilised and the insulation thickness reduced. This leads to a smaller diameter and lighter cable, longer manufacturing and shipping lengths and fewer joints. Clearly, there is a potential for significant cost savings.

10 CONCLUSIONS AND RECOMMENDATIONS

This report considers lightning overvoltages in systems where a cable is inserted in an overhead line (siphon) and is protected by surge arresters at both ends. The overhead line is assumed to satisfy some characteristics in terms of span length, tower footing impedances and shielding angle, which are defined in the report. For such systems, the following conclusions and recommendations apply:

1. The highest cable overvoltages result from backflashover close to the cable termination. The examples in the report show results for a backflashover 200 m from the cable entrance. It is assumed that the line protection system hinders backflashovers closer to the cable terminations.
2. The maximum overvoltage along the cable is reduced with increasing cable length due to the cable attenuation and distortion effects combined with the finite duration of the impinging overvoltage at the exposed end. In the case of very long cables, the overvoltage level is limited to the arrester protective level at the exposed cable end plus the voltage drop along arrester leads. For shorter cables, the maximum voltage occurs within a few kilometers from the remote end where it may significantly exceed the arrester protective level.
3. In the case of very long cables the overvoltage level can become lower than the lowest recommended BIL in IEC 60071-1, and may even become lower than the arrester protective level. (It should however be noted that a safety factor of 1.15 is to be added to the overvoltage level when selecting the BIL). For such long cables the common practice of choosing the highest BIL is unduly excessive and it is therefore recommended that the cable overvoltage level be analysed as part of the system engineering to arrive at a more realistic BIL. Such analysis needs to take into account required safety factors for withstand voltage ($K_s=1.15$) and uncertainties in the overvoltage calculation (K_c). It may even be possible to use a lower test level than the lowest BIL in the present IEC 60071-1
4. In situations where the overvoltage level is lower than the arrester protective level, one may consider to not install arresters at the cable ends. This requires a very careful study of the overvoltage conditions.
5. In the case of SCFF cables, a reduced test level (BIL requirement) may result in reduced insulation thickness, as the lightning impulse voltage is the major design parameter of the insulation system. This may lead to longer cable sections (fewer joints) and a cheaper manufacturing process. One must however also consider practical aspects such as jointing of the cable sections.
6. Presently, the power frequency voltage is the major design parameter for cables with extruded insulation. For such cables it is with the present technology not seen that a reduced test level will affect the insulation design. However, as the insulation characteristics keep improving, one may in the future achieve reduced insulation thicknesses also for these cables.
7. This report has only considered external (lightning) overvoltages. Internally generated overvoltages (e.g. switching) are in general lower but must also be investigated. In particular, high amplitude voltage transients may propagate into the cable during fault

situations in HVDC Voltage Source Converter (VSC) systems. It is recommended that such studies be carried out within CIGRE in a future working group.

11 REFERENCES

- [1] E.W. Greenfield and W.A. Pullmann, "Transient behavior of short and long cables", *IEEE Trans. Power Apparatus and Syst.*, vol. 103, no. 11, pp. 3193-3204, November 1984.
- [2] S.A. Probert, Y.H. Young, P.K. Basak and C.P. Ferguson, "Re-appraisal of BIL for 400 kV Underground Cables using EMTP/ATP", in *Proc. Intern. Conference on Power Systems Transients (IPST)*, pp. 7-12, Rio de Janeiro 2001.
- [3] S.A. Probert, Y.H. Young, P.K. Basak and C.P. Ferguson, "Review of the Basic Insulation Level for 400 kV Oil-Filled Cable Systems: Switching and Temporary Overvoltages (TOV)", *ETEP 2003*, pp. 277-283.
- [4] P.P. Barker, "Voltage Quadrupling on a UD Cable", *IEEE Trans. Power Delivery*, vol. 5, no. 1, pp. 498-501, Jan. 1990.
- [5] J. Huse, K.Olsen and T. Ulriksen, "Lightning Overvoltages in Cable Connections", *Electra*, no. 58, pp. 81-93, 1978.
- [6] B. Gustavsen and J. Sletbak, "Transient Sheath Overvoltages in Armoured Power Cables", *IEEE Trans. Power Delivery*, vol. 11, no. 3, pp. 1594-1600, July 1996.
- [7] L. Marti and H.W. Dommel, "Calculation of Voltage Profiles Along Transmission Lines", *IEEE Trans. Power Delivery*, vol. 12, no. 2, pp. 993-998, April 1997.
- [8] T. Henriksen, B. Gustavsen, G. Balog and U. Baur, "Maximum lightning overvoltage along a cable protected by surge arresters", *IEEE Trans. Power Delivery*, TPWRD-00099-2004, accepted for publication.
- [9] CIGRE Technical Report 189, "Insulation coordination for HVAC underground cable systems", JWG 21/33, June 2001.
- [10] A. Morched, B. Gustavsen and M. Tartibi, "A Universal Model for Accurate Calculation of Electromagnetic Transients on overhead Lines and Underground Cables", *IEEE Trans. Power Delivery*, vol. 14, no. 3, pp. 1032-1038, July 1999.
- [11] IEEE Task Force on Parameter Determination for Modeling System Transients, "Part II: Insulated Cables", *IEEE Trans. Power Delivery*, TPWRD-00106-2004, paper submitted to.
- [12] M. Kizilcay, M. Ermel and S. Demmig, "Modeling of a 400 kV Cable System", in *Proc. EEUG*, pp. 83-96, Nov. 8-10, 1999.
- [13] K. Berger and R.B. Anderson, "Parameters of lightning flashes", *Electra* no. 41, pp. 23-37, July 1975.
- [14] CIGRE Technical Report 63, "Guide to Procedures for estimating the lightning performance of transmission lines", WG33-01, October 1991.

- [15] O. Breien and I. Johansen, "Attenuation of traveling waves in single-phase high-voltage cables", *Proc. IEE*, vol. 118, no. 6, pp. 787-793, June 1971.
- [16] CIGRE Technical Report 86, "Overvoltages on HVDC Cables", WG33/21/14.16, 1994.
- [17] CIGRE WG 21.10, "Survey of the service experience on HV AC cable systems", *Electra* no. 137, pp. 47-59, August 1991.
- [18] Dan Karlsson, "Overvoltages in HVDC-cables. Part 2. Measurements", STRI Report S 96-113, 96-12-09, Swedish Transmission Research Institute, Sweden. (Confidential).
- [19] L.M. Wedepohl and D.J. Wilcox, "Transient analysis of underground power-transmission systems. System-model and wave-propagation characteristics", *Proc. IEE*, vol. 120, no. 2, pp. 253-260, Feb. 1973.

Appendix 1

Terms of Reference

A1.1 Scope of Activities

- To review the literature on the subjects: transients on long cables experience with long cables, modelling of end terminations. JWG 21/33 is publishing a paper “OVERVOLTAGES IN HVAC UNDERGROUND CABLE SYSTEMS”. This paper should be used in the studies.
- To gather as much utility experience on long cables as possible.
- To define and limit the term “long cable.”
- To make recommendations regarding the transient voltage withstands levels for long cables.
- To make recommendations on testing of the system. Some parts may also have to be tested with higher stresses than others

A1.2 Interaction with other Working Groups

Other Study Committees such as SC14, SC22, SC33 and SC37 may have valuable input. In so far there is interest in this work from the other SC’s a co-operation should be established. To our knowledge there is no WG established or planned to work in this field. In the case of a parallel WG being formed, the work should be co-ordinated.

A1.3 Time Scales

A period of three years is proposed.

A1.4 Deliverables

A report to be submitted to SC21 for the 2004 meeting.

A1.5 Structure

The working group should comprise representatives from Utilities, cable companies and relevant scientific institutions.

Appendix 2

MODELING

System configuration

Fig. A2.1 shows the model that was applied when computing the impinging voltage at the exposed end of the cable (AC system configuration).

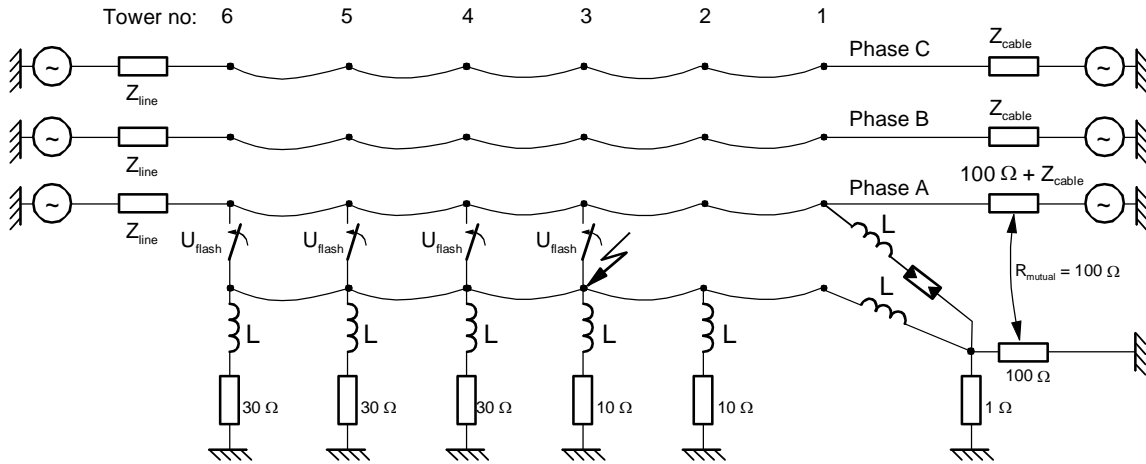


Fig. A2.1 Model

A lossless distributed parameter line model represents each span with four conductors. The two shield wires are assumed to have the same potential and they are considered as a fourth conductor.

The phase conductors are at the remote end of the last span terminated by a resistance which is equal to the equivalent characteristic impedance when neglecting the presence of the other conductors.

Each tower is represented by an inductance L . Four possible flashover locations are considered, each represented by a switch that closes when the absolute value of the voltage across the switch exceeds the voltage U_{flash} . The lightning stroke is assumed to hit tower no. 3.

Any back-flashover is assumed to take place to phase A. the cable in that phase is represented by a two-conductor model (core and screen) which is represented by a 2×2 characteristic impedance matrix

$$Z_c = \begin{bmatrix} Z_{cable} + 100 & 100 \\ 100 & 100 \end{bmatrix} [\Omega]$$

where Z_{cable} is the characteristic impedance of the core-screen loop (coaxial mode). (The overvoltages are *not* sensitive to the selected value for the screen-ground characteristic impedance ($100\ \Omega$).)

The three-phase cable is assumed to consist of three single-phase cables with individual shielding. This implies that the electric and magnetic coupling between the three cables is very small when the cable sheaths are grounded by a small impedance as shown in

Fig. A2.1 (1 Ω).

The joint grounding resistance for the cable screen, the arrester protecting the cable and the footing point of the first tower is 1 Ω . This value was selected because the overvoltages along the cable increases when the resistance decreases as explained in Appendix 4.

The model used for the bipolar DC-system configuration is basically the same as for the AC-system configurations except that the third phase is removed.

Surge arrester

The arrester is modelled as a series connection of an inductance L and a non-linear static arrester characteristic. The voltage corresponding to a given current is assumed to be proportional to the protective level, which is the voltage corresponding to a 10 kA current. Table A2.1 shows the applied characteristic when the protective level is 649 kV.

Table A2.1. Surge arrester current-voltage characteristic

Current [A]	Voltage [kV]
1.0000E-004	282.64
9.9996E-004	319.61
9.9981E-003	339.54
1.0002E-001	359.52
9.9991E-001	385.44
2.5000E+002	507.16
1.0000E+003	543.89
4.9998E+003	607.16
1.0000E+004	649.00
2.0000E+004	716.55

Voltage sources and inductances

There are six voltage sources in Fig. A2.1. They are used to provide the instantaneous value of the power frequency voltage. That voltage is assumed to be constant along the line and the cable. This is achieved by using a low value for the frequency (0.5 Hz).

The model in Fig. A2.1 contains several inductances. The symbol L is used for all inductances since they are assumed to be equal.

Cable

A full frequency-dependent transmission line model is used for the cable when calculating the voltage at remote end of the cable. Because the cable transient is dominated by high-frequency components, only the core and sheath of the exposed cable need to be included in the model. Still, the calculations included the armour in cases with armoured cables.

Series impedance

Wedepohl's closed form formulae [19] are used for establishing the series impedance matrix from the ground impedance and the inner-, outer-, transfer-, and external impedance of coaxial shields.

Shunt admittance

The insulation sandwich between the core conductor and the sheath conductor is in the case of XLPE cables modelled as a lossless insulation with permittivity $\epsilon_r=2.3$. In the case of SCFF cables, a lossy insulation is used, based on Breien/Johansen's permittivity [15]

$$\epsilon_r = 2.5 + \frac{0.94}{1 + (j\omega \cdot 6 \cdot 10^{-9})^{0.315}} \quad (\text{A2.1})$$

The obtained relative permittivity is shown in Fig.A2.2. The relative permittivity approaches 3.44 as the frequency is reduced towards zero.

In the case of mass-impregnated cables, the permittivity by (A2.1) is multiplied by the factor 4.2/3.44 in order to give a permittivity of 4.2 at low frequencies.

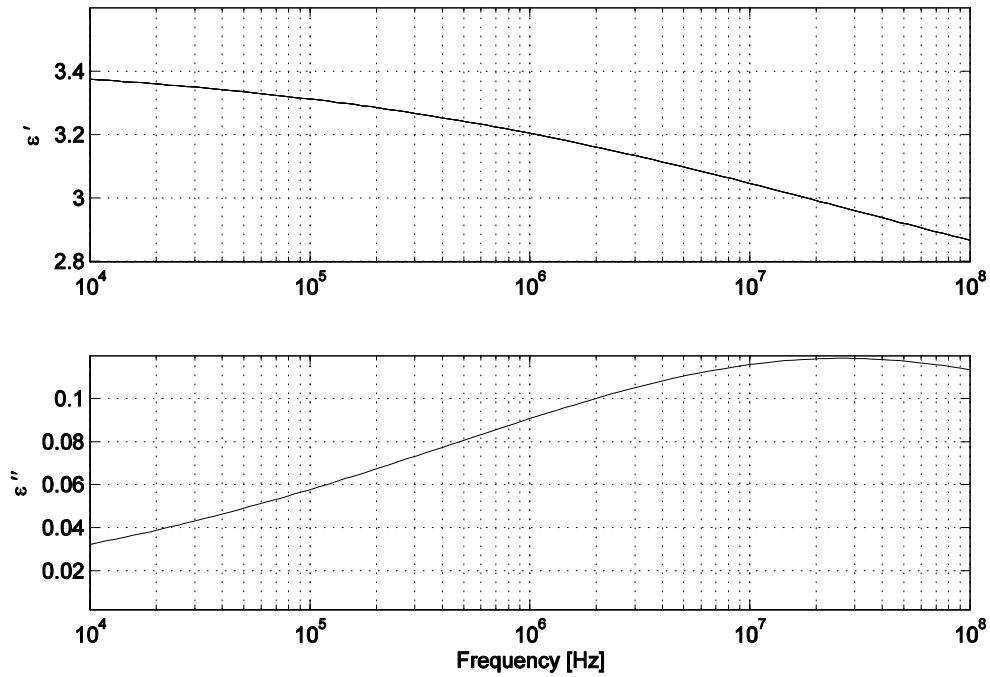


Fig. A2.2 Relative permittivity of oil-impregnated paper [15]

Time domain computation

The impinging voltage is calculated by the ATP version of EMTP (Electromagnetic Transients Program). The incoming voltage wave at the far end is calculated using a Matlab implementation of the Universal Line Model [10] with the impinging voltage as a known source at the exposed end as explained in Appendix 3. The model converts the frequency dependent series impedance and shunt admittance into propagation and surge impedance functions, which are included in the transient calculations using the travelling wave approach and recursive convolutions.

Selected parameter values

The actual parameter values are case dependent. The most important parameters related to the calculated results in Section 5 are listed below.

Overhead line geometry

Fig.A.2.3 shows the overhead line configurations used in the calculated examples.

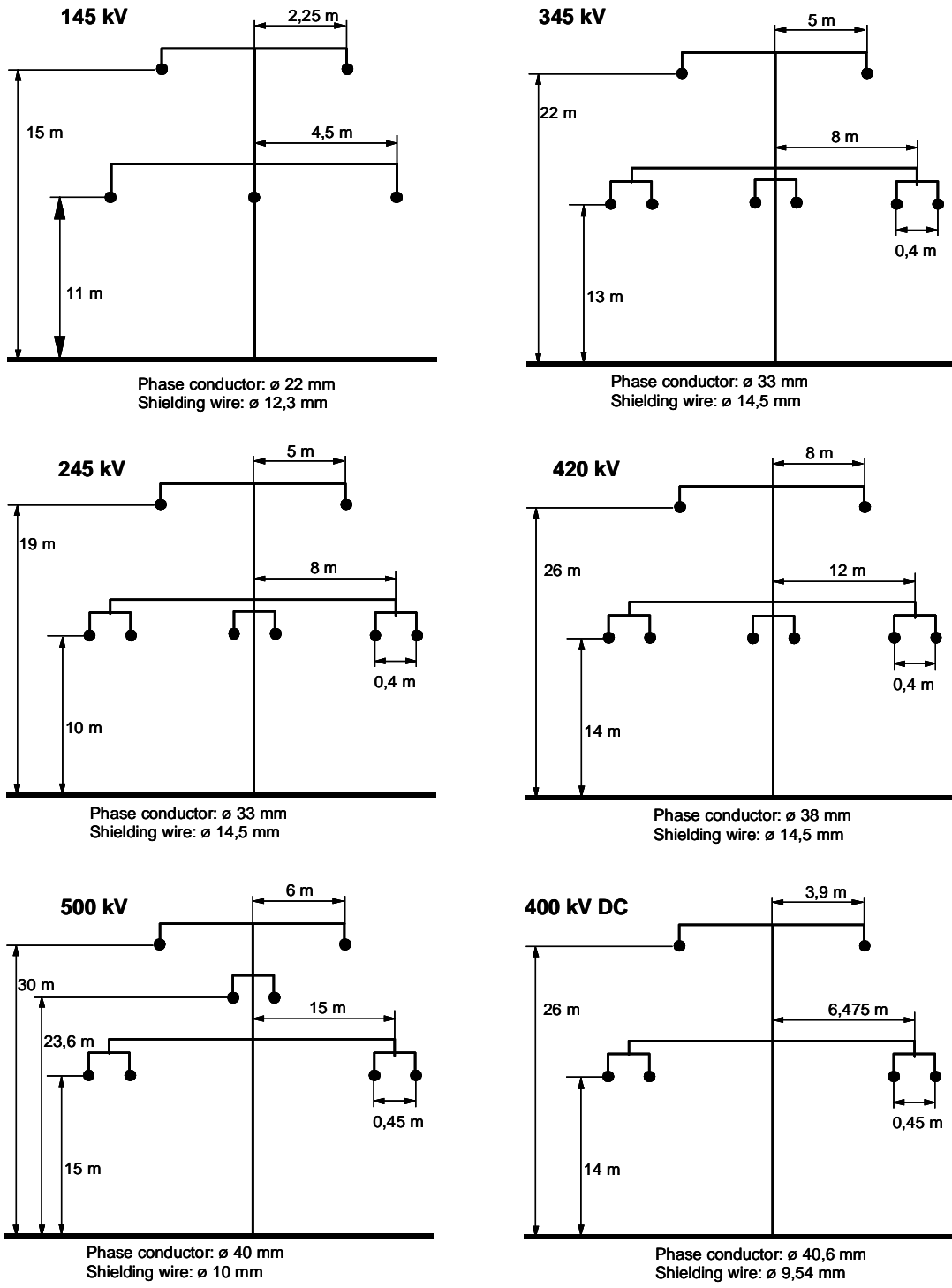


Fig. A2.3 Overhead line geometry

Cable data

The cable data used in the calculations are shown in Table A2.3.

Table A2.3 Cable data

Application	Cable	Conductor	Insulation	Sheath
Land/Submarine	145 kV AC XLPE	500 mm ² Cu	17.0 mm	Pb (2.3 mm)
Land	245 kV AC XLPE	1600 mm ² Cu	22.6 mm	Al (0.8 mm)
Land	345 kV AC SCFF	2000 mm ² Cu	21.6 mm	Pb (3.6 mm)
Submarine	420 kV AC SCFF	800 mm ² Cu	23.0 mm	Pb (3.5 mm)
Land	420 kV AC XLPE	2000 mm ² Cu	25.0 mm	Al (1.25mm)
Submarine	500 kV AC SCFF	1600 mm ² Cu	26.0 mm	Pb (4.5 mm)
Submarine	400 kV DC MIND	1200 mm ² Cu	21.0 mm	Pb (3.5 mm)

Other parameters

Table A2.2. Parameters

Cable	Flashover voltage U_{flash} [kV]	Inductance L [μH]	Z_{line} [Ω]	Z_{cable} [Ω]	Protective level* [kV]
145 kV AC XLPE	600	7	456	28.1	395
245 kV AC XLPE	850	9	330	27.4	466
345 kV AC SCFF	1000	10	346	32.7	649
420 kV AC SCFF	1280	11	346	31.3	846
420 kV AC XLPE	1280	11	346	27.2	846
500 kV AC SCFF	1400	12	345	26.9	956
400 kV DC MIND	1300	11	341	23.2	760

* the arrester voltage at 10 kA

Appendix 3

COMPUTATIONAL PROCEDURE

Several case studies with variable cable length have been performed based on selected cables with nominal voltage from 145 kV to 500 kV for AC systems and for a 400 kV DC system.

The maximum voltage was calculated based on the technique presented in [8]. The computation was carried out in three steps:

- a) Calculation of the voltage at the exposed end of the cable assuming infinite cable length.
- b) Calculation of the maximum incoming voltage wave at the remote end of the cable using the result from a) as a known voltage source at the exposed end.
- c) The maximum value of the reflected voltage wave at the remote end was calculated as outlined in [8] neglecting voltage drops along the arrester leads. The maximum value of the voltage along the cable in the vicinity of the remote end was set equal to the sum of the maximum incoming wave and the maximum reflected wave at the remote end. (This sum is greater than the voltage at the remote end when the two maxima do not appear simultaneously). The maximum voltage along the cable occurs for cables exceeding 10 km either in the vicinity of the remote end or at the exposed end as explained in [8]. The maximum voltage was determined accordingly.

The lightning overvoltages depend on the instantaneous value of the power frequency voltage and it is not obvious which value that gives the highest overvoltage. All computations (i.e. steps a – c) were therefore performed with different values for the power frequency (or DC) voltage and the highest value obtained for each cable length was taken as the result.

AC-system

The lightning current was assumed positive in all computations and three values were used for the power frequency voltage of the AC systems: maximum negative values, half of that values and zero. The back-flashover was assumed to occur to the phase conductor with the highest absolute voltage with respect to the cross arm, i.e. to the phase conductor with the highest negative voltage. This voltage varies in normal condition between 50% and 100% of the maximum negative voltage. The case with zero voltage was included because it corresponds to the situation of a disconnected line (out-of-service) without grounding of phase conductors in the vicinity of the cable ends.

DC-system

The considered DC line is bipolar and the instantaneous value of the DC voltage was assumed equal to zero and to the negative nominal DC voltage.

Appendix 4

EFFECT OF MODEL PARAMETERS ON MAXIMUM CABLE VOLTAGE

A4.1 Introduction

The maximum lightning overvoltage for a given cable depends on a large number of parameters. For the calculated results in Section 5, most of the parameters were selected with the intention to give conservative results (high voltages). However, it is not possible to guarantee such a result, as it is very difficult to predict the effect of simultaneous parameter variations.

In order to gain insight, an investigation with systematic variation of parameters was carried out. Section 4.2 shows the effect of parameter variations on the peak value, the front time and the duration of the impinging voltage for one of the cases presented in Section 5. Section 4.3 discusses the effect of cable design on self attenuation effects while Section 4.4 shows the effect of parameters that were neglected in the model used for the calculations in section 5.

A4.2 Influence on impinging voltage

Fig. A4.1 shows the impinging voltage and the corresponding arrester current for the 345 kV case presented in section 5.2. The peak value of the lightning current is 200 kA and the instantaneous value of the power frequency voltage is zero.

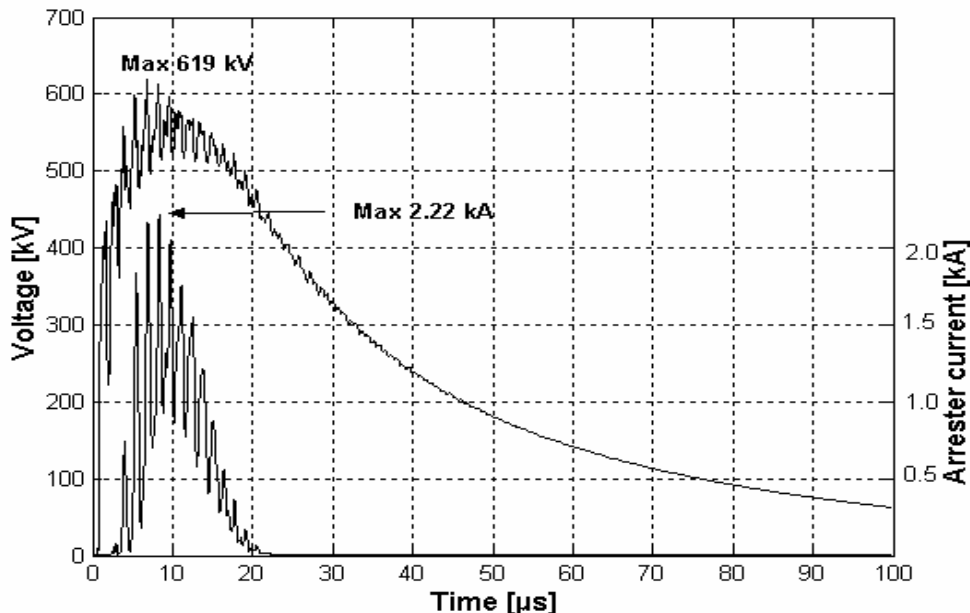


Fig. A4.1 Impinging voltage and arrester current.

The following shows the effect of parameter variations on the impinging voltage peak value. In addition is shown for some cases the effect on the front time and the duration, defined as follows:

- Front time: Time for the impinging voltage to increase from 100 kV to 400 kV.
- Duration: Time where the voltage stays above 400 kV

Both the front time and duration are influenced by a high frequency oscillation as can be observed in Fig. A4.1. A minor change in the overall response may therefore have a strong impact on the two parameters.

Table A.4.1 summarises the results of the performed parameter variations. The results are presented in % of the results obtained for the base case, i.e. the voltage shown in Fig. A4.1 where

- Peak voltage: 619 kV
- Front time: 0.8 μ s
- Duration 23.3 μ s.

Values for the front time and the duration are presented only when the variation exceeds \pm 20%.

Stroke location

The results show that the stroke location is very important. A very low peak value is obtained when the stroke hits tower no. 2 because no backflashover takes place. It is further clear that for the considered case it is sufficient to focus only on strokes that hit tower no. 3 (as long as no backflashover can take place closer to the cable entrance).

Arrester

The effect of the arrester is rather moderate. Removing it increases the peak value by 7% only. This may lead to the conclusion that the arrester can be omitted. It should in this respect be pointed out that there are some rare cases where it will cause a much stronger limitation in the cable overvoltage. It is further a general experience that the arrester at the remote end is more important except when the cable is very long.

The inductance of the arrester leads should be kept as small as possible. This inductance becomes more important when the arrester current increases. The results regarding the influence of the inductance in table A4.1 should therefore not be considered as a general result.

Table A.4.1 Influence on impinging voltage

Parameter variation	Peak voltage [%]	Duration [%]	Front time [%]
Stroke location: tower no. 2	2.4	-	-
Stroke location: tower no. 4	61	-	-
Stroke location: tower no. 5	48	-	-
Removing arrester	107		
Increasing inductance arrester leads to 15 μ H	101		
Reducing inductance arrester leads to 5 μ H	98		
Reducing inductance arrester leads to 1 μ H	96		
Reducing arrester protective level by 10%	96		78
Reducing footing resistance towers 2 and 3 to 5 Ω	75	50	390
Increasing footing resistance towers 2 and 3 to 20 Ω	116	120	48
Increasing footing resistance towers 4 – 6 to 50 Ω	101		
Increasing inductance tower 2 – 6 to 15 μ H	103		36
Reducing inductance towers 2 – 6 to 7 μ H	96		210
Increasing inductance tower 1 to 20 μ H	99		75
Reducing inductance tower 1 to 5 μ H	99		78
Increasing joint grounding resistance* to 10 Ω	92	61	
Reducing joint grounding resistance * to 0.1 Ω	101		75
Reducing characteristic impedance between cable screen and ground to 50 Ω	100		
Increasing length of spans 3 – 5 to 500m	102		
Increasing length of spans 1 – 2 to 200 m	96	180	75
Reducing flashover voltage to 800 kV	100		
Increasing the height of phase conductors and shielding wires by 5m	97		
Increasing the height of shielding wires by 5m	96		
Replace duplex conductors by simplex conductors	94		226

* joint grounding resistance of tower no 1, the arrester and the cable screen

The protective level of the arrester should be selected as low as possible. It must on the other hand be sufficiently high so that the arrester withstands the expected temporary overvoltages (TOV). The arrester characteristics selected here were based on some actual arresters, which have the following TOV capability:

Table A4.2 Arrester characteristics

Nominal voltage [kV]	Protective level [kV]	TOV capability*	
		10s	Continuous
145 AC	395	1.89	1.37
245 AC	466	1.53	1.13
345 AC	649	1.52	1.11
420 AC	846	1.55	1.14
500 AC	956	1.60	1.16

* in p.u. of nominal voltage

The 145 kV system is assumed to have an isolated neutral or arc suppression coils. This gives significantly higher temporary overvoltages compared with systems that are directly grounded. This is the reason for the relatively high TOV capability when the nominal voltage is 145 kV.

The TOV in a HVDC system is in general controlled by operation of the involved thyristors. This allows a rather fast reduction of the TOV. The protective level of the actual arrester was set equal to 1.9 multiplied by the nominal voltage without considering the TOV capability. It should further be noted that the characteristic of the DC arrester has been set equal to the characteristic of an AC arrester with the same protective level.

Grounding resistance

These resistances should be as low as possible. The results in table A4.1 show that the footing resistance of towers 2 and 3 has a strong influence on the cable voltage. Reducing these resistances from 10 Ω to 5 Ω gives 25% reduction in the peak value of the impinging voltage. Such a reduction in the resistance can be very difficult to achieve.

A sufficiently high current in the ground causes partial breakdown in the soil and thus a reduction of the apparent grounding resistance. A reduction by a factor 2 may well occur. The results obtained with 5 Ω resistance indicates that taking the partial breakdown in the soil into account would give a substantial reduction in the cable voltage.

The footing resistance of towers 4 – 6 (and towers further away) has only a moderate influence on the cable overvoltages.

Decreasing the joint grounding resistance of tower no. 1 is seen to increase the overvoltage. This somewhat unexpected result occurs because the voltage between the screen and the ground increases when the resistance increases. This voltage increase gives a reduction in the voltage between the phase conductor and the screen. It is however recommendable to keep the grounding resistance as low as possible in order to limit the screen voltage.

Tower impedance and flashover voltage

The tower impedance and insulator flashover voltages are seen to be of minor importance for the overvoltage. Despite of this, the tower impedance is of high importance as it influences the voltage on the tower top before backflashover and thus the possibility of having a backflashover. (The actual backflashover voltage is on the other hand not important).

The tower is in the calculations represented by a single inductor whose value is based on an estimated inductance of 0.5 $\mu\text{H}/\text{m}$ and the height of actual towers. This model gives probably a too high voltage at the towers and thus a too high voltage at the phase conductor after the back-flashover.

Overhead line

Table A4.1 shows that the peak voltage increases when increasing the number of subconductors in the phase conductor (bundle). The reason is that the overhead line surge impedance then decreases and causes an increase in the ratio between the characteristic impedance of the cable and the line.

The change in surge impedance is shown in Table A4.3 for the 420 kV double circuit line with quadruple conductors in Fig. A.2. (The resulting cross section per phase is kept constant in table A4.3 when varying the number of sub-conductors)

Table A4.3 Impact of phase conductor design on characteristic impedance

Characteristic impedance [Ω]		
Conductor arrangement	Phase A and B	Phase C
Simplex	435	467
Duplex	359	391
Quadruplex	310	345

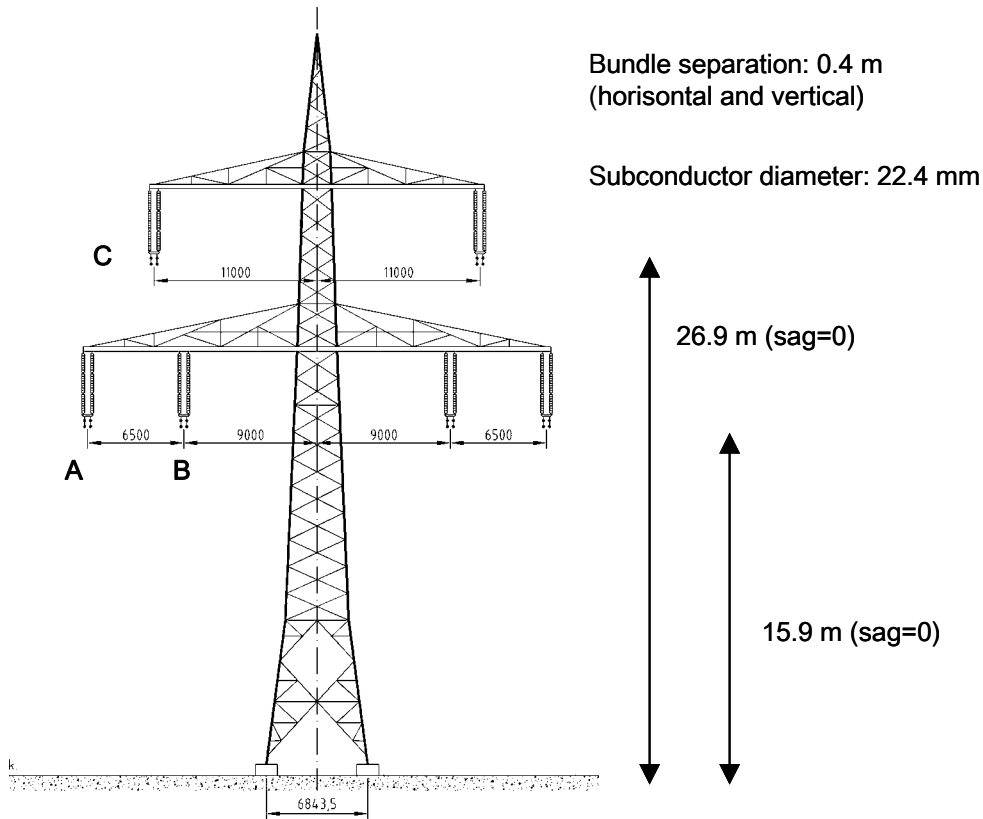


Fig. A4.2 420 kV double circuit line with quadruplex phase conductors

Cable

A two-conductor model is used for the cable with the metallic sheath as the second conductor. The impinging voltage depends on the characteristic impedance of the cable core-sheath loop (coaxial mode) whereas the characteristic impedance of the sheath-ground loop has practically no influence on the cable voltage. Increasing the cable coaxial surge impedance increases the impinging cable voltage due to the increase of the ratio between the characteristic impedance of the cable and the line.

Lightning current

Three parameters are used to characterise the current: the peak value, the front time and the time to half value. The default value for the time to half value is infinite since it represents the worst case.

Table A4.4 shows the influence from the front time and the time to half value on the impinging voltage.

Table A4.4 Influence on impinging voltage from lightning parameters

Parameter variation	Peak voltage [%]	Duration [%]	Front time [%]
Reducing time to half value to 100 μ s	99	84	
Reducing time to half value to 50 μ s	98	74	
Increasing front time to 2 μ s	94		180
Reducing front time to 0.5 μ s	106		13
Reducing front time to 0.1 μ s and peak current to 50 kA	70	-	-

Reducing the time to half value to 50 μ s reduces the duration of the impinging voltage, but the peak value is practically the same. The duration has some significance for long cables since a reduced duration gives a stronger reduction in the peak value of the incoming voltage wave at the remote end of the cable. The reduction in the duration is 16% when the time to half value is 100 μ s. It is reason to believe that a more accurate analysis regarding the decay time of the lightning current gives a moderate reduction only in the maximum cable overvoltage.

Increasing the front time reduces the peak value of the impinging voltage. The opposite effect is obtained when the front time is reduced. The steepness of the current in the base case is 200 kA/ μ s. The probability of exceeding this steepness is according to [14] less than $2.3 \cdot 10^{-4}$ for a first negative stroke. The probability increases to $3 \cdot 10^{-2}$ for the subsequent strokes, but the probability of exceeding 200 kA peak value is then less than $2.2 \cdot 10^{-5}$. The corresponding probability for a peak value of at least 50 kA or 100 kA is $4 \cdot 10^{-3}$ and $4 \cdot 10^{-5}$ respectively. The combination of 50 kA peak current and 0.1 μ s front time reduces the peak value of the impinging voltage to 70%. Combining the information above shows that it is acceptable to consider the 1 μ s front time as worst case when the peak current is 200 kA or higher.

The front time may be considerably longer than 2 μ s, which is the longest time considered in Table A4.2. Increasing the front time above 2 μ s gives some moderate reduction in the impinging voltage except when the long front time prevents backflashover.

A4.3 Cable self attenuation and distortion effects

The transient overvoltage essentially propagates as a coaxial wave between the core and sheath of the excited cable. It follows that the distortion and attenuation effects of the cable depend on the core, insulation, and sheath conductor.

Calculations were carried out to assess the significance of cable design parameters on the reduction of a voltage wave (square pulse) traveling along a semi-infinite cable. The basic cable model assumed a 145 kV cable with copper core and 17 mm insulation thickness. A 1 p.u. square pulse of width 10 μ s or 20 μ s was applied to the cable end and the reduction of the peak value was calculated as function of position along the cable.

Fig. A4.3 shows the significance of the sheath design on the cable voltage. It is seen that reducing the thickness of the cable lead sheath from 4 mm to 2 mm results in a significant reduction in the cable maximum voltage. The relative reduction increases with increasing cable length. It is also seen that the short pulse is stronger attenuated than the long pulse.

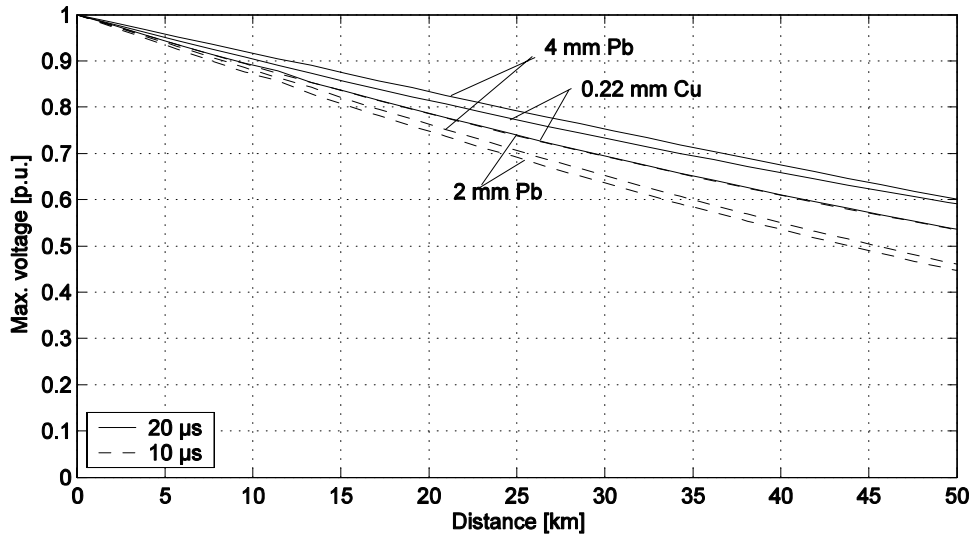


Fig. A4.3 Significance of sheath design

Fig. A4.4 shows the effect of the insulation material on the maximum cable voltage. It is seen that Paper oil insulation gives a significantly stronger attenuation than XLPE insulation, in particular when including the frequency dependent insulation losses in the calculations. The attenuation is particularly strong for the short (10 μs) pulse.

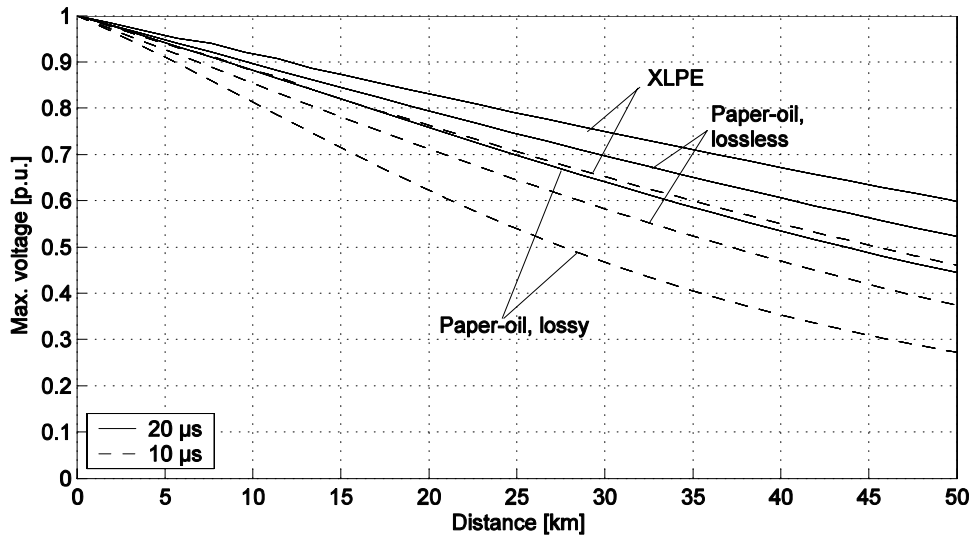


Fig. A4.4 Significance of insulation losses

A4.4 Shunt reactors

A long AC cable will normally have shunt reactor compensation at both cable ends. Such reactors will not affect the impinging overvoltage due to their high series inductance. For a specific investigation involving a 54 km cable and 300 kV nominal voltage with 50% compensation at each cable end, the effect of the reactors was only a 2 kV change to the overvoltage.

A4.5 Cable end termination

The ends of a HV cable are terminated in a special way to limit the additional stresses on the main insulation due to non-homogeneous axial condition at the end of the cable. The main principle is to gradually increase the distance from the centre conductor to the screen or other components at ground potential. The termination can be modelled as a cable with variable characteristic impedance.

A voltage wave in the cable will see a gradual increase in the surge impedance as it propagates from the cable into the termination that may in principle cause an increase of the cable overvoltage. An investigation was carried out assuming 400 Ω and 30 Ω for the surge impedance of the overhead line and the cable, respectively. The termination was 5 m with a linear variation in the characteristic impedance from 90 Ω to 30 Ω . An arrester was placed in the cable overhead line joint. It was found that with an incoming wave with a 2 μ s linear front, the presence of the end termination increased the cable voltage with only 1%. With a 1 μ s front time the voltage increase was about 2%. When considering the front time of the impinging voltage (Fig. A 4.1) and the distortion and attenuation effect of long cables, it can be concluded that the effect of the end termination on cable overvoltages is negligible.

A4.6 Cable joints

Cable joints can have significantly higher surge impedance than the cable and may therefore result in a higher cable overvoltage. The cable voltage increases with increasing value for the joint/cable surge impedance ratio and with increasing joint length. In practice, the joint/cable surge impedance ratio will be smaller than 1.45 and joints are usually shorter than 5 m.

In order to assess the effect of joints on the cable overvoltage, calculations were done assuming 5 m joint length and 1.45 for the joint/cable surge impedance ratio. With the impinging voltage at the cable end shown in Fig. A4.1, the voltage increase was found to be smaller than 1%. Thus, joints can be neglected when assessing cable overvoltages for the configuration considered in this report.

Appendix 5

RELATIVE VOLTAGE REDUCTION VS. CABLE LENGTH

The figures show the relative reduction of the maximum cable voltage, for the different cases investigated in Section 5.2. These figures complement the results given in Section 5.4.

