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Report

Handbook: Protective Devices in 24 kV ACC Installations

Translation of TR A4626

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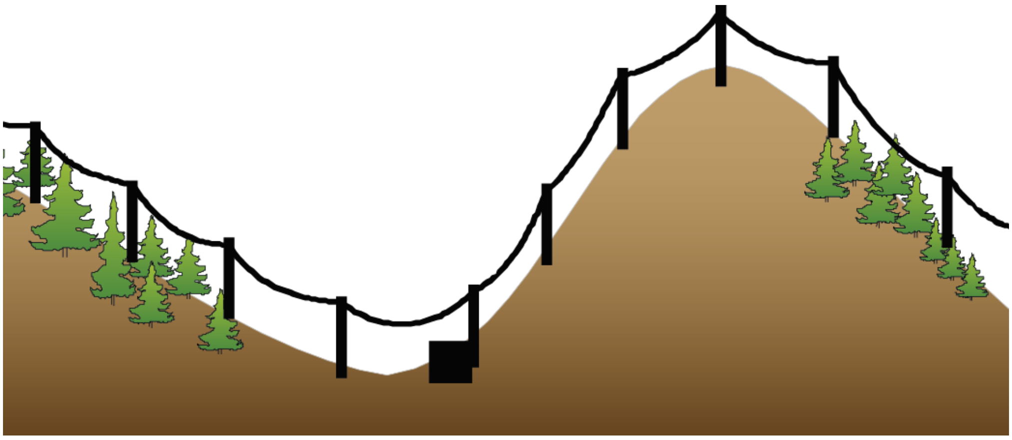

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ABSTRACT
This Handbook is revised and somewhat updated from the original issue of 1994. The Handbook gives recommendations about choices and correct use of overvoltage protection in lightning prone area, corrosion protection, and choices of open or tight ACC line configurations, and measures to protect the insulation surface against surface degradation in polluted prone parts of the line. Protection integrated in the pole top is also described.
Conditions that affect protection choices are described in appendices and references to technical reports when more details can be found are indicated.

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Table of contents

PREFACE

This handbook is an updated and partly edited version of the previous edition dating from 1994. The Handbook is intended to provide assistance, among other things in the selection and correct use of overvoltage protection in areas which are prone to lightning strikes, protection against corrosion, selection of open or sealed ACC installations and measures to prevent the degradation of the insulation surface in polluted areas. The future use of protective devices integrated in pole tops is also described. The Handbook is intended to be as simple as possible. Hence, theoretical deductions and consideration of the limitations of the results obtained have been kept to a minimum and located in appendices. Those with special interest are recommended to study published documents relating to the field. Reference may also be made to NEK Standard No. 610 (1997): “Legerte aluminiumsliner. XLPE-belagte liner for 12…24 kV” [Aluminium alloy lines. XLPE-coated lines for 12 …24 kV] and to the recommendations of Energy Norway in applicable publications of consulting company Rational Electrical Network Operations (REN, formerly REF) relating to ACC systems.

The handbook is addressed to:

1. Personnel at electricity generating stations
2. Advisors and consultants
3. Suppliers and manufacturers of line equipment
4. Line builders.

The Handbook is based on operational experience and results from the *EFFEN-Nett* project: “System for belagte liner (BLX)” [Aerial covered conductor (ACC) systems] aimed at carrying out an impartial assessment of the requirements which must be placed on ACC installations in our exposed climatic conditions, and ensuring that these requirements can be fulfilled. The participants in the Project were the Research Council of Norway, Energy Norway (the Norwegian electrical industry federation), five industrial manufacturers/suppliers and various electricity suppliers. The members of the Steering Committee of the Project are listed at the end of this Handbook.

The editorial group for this revised Handbook consisted of:
Kjell Alstad – EFI
Terje Amundsen – Energy Norway
Torbjørn Bøvre – Eidsvoll Energiverk
Sven Enger – ABB Norsk Kabel
Knut Oskar Tangen – EFI

Trondheim 31 January 1998

USING THIS HANDOOK

The Handbook consists of a main section and an appendix section.

The main section consists of:

- Chapter 1 Introduction. General information about ACC with reference to standards, regulations and recommendations.
- Chapter 2 Selection of protective devices. Conditions which determine the selection of and distance between overvoltage protection devices.
- Chapter 3 Guidelines and examples.

The appendix section consists of:

- Appendix 1 Details of conditions which influence the selection and distance between protective devices.
- Appendix 2 Terminology.

In practice, the focus should be on Chapters 2 and 3 of the Handbook, which may be supplemented from the appendix section if more information is desired. Descriptions of various protective configurations and problems connected with these can be found in Appendix 1, and should be considered essential reading, in the same way as Chapters 2 and 3.

1 INTRODUCTION

1.1 About ACC

Aerial covered conductor (ACC) systems have been in use, for example, in the US, Australia, Korea and Japan for several years. In Scandinavia, Finland was the first user in 1976, with Norway following in 1985. The proportion of ACC in the Scandinavian overhead network system is currently 3-6%, but it is expected to increase in the near future. Until now, ACC installations have been constructed using traditional wooden poles and conventional insulators, but new pole-top constructions will become available in the near future. The voltage level has until now been limited to 24 kV, with a minimum spacing of 0.5 metres between phases. However, Hallingdal Kraftnett, a Norwegian electricity network operator, has had a 66 kV ACC line in operation for more than a year, and two 110 kV ACC lines have been in operation in Finland for periods of two and five years with no operational problems. In connection with an *EFFEKT* project which commenced in 1997, the possibility of constructing ACC lines handling up to 132 kV will be considered.

ACC has the following advantages, compared with bare lines:

- Fewer operational interruptions. Contact between phase lines or trees falling against lines will not cause short-circuits or line-to-ground short circuits.
- Compacting. Reduced phase spacing and narrower power line lanes. Aesthetically more acceptable. Significant reduction of the electromagnetic field close to the ground.
- Birds, squirrels and other animals are protected better against flashover and violent death, while operational reliability is improved.

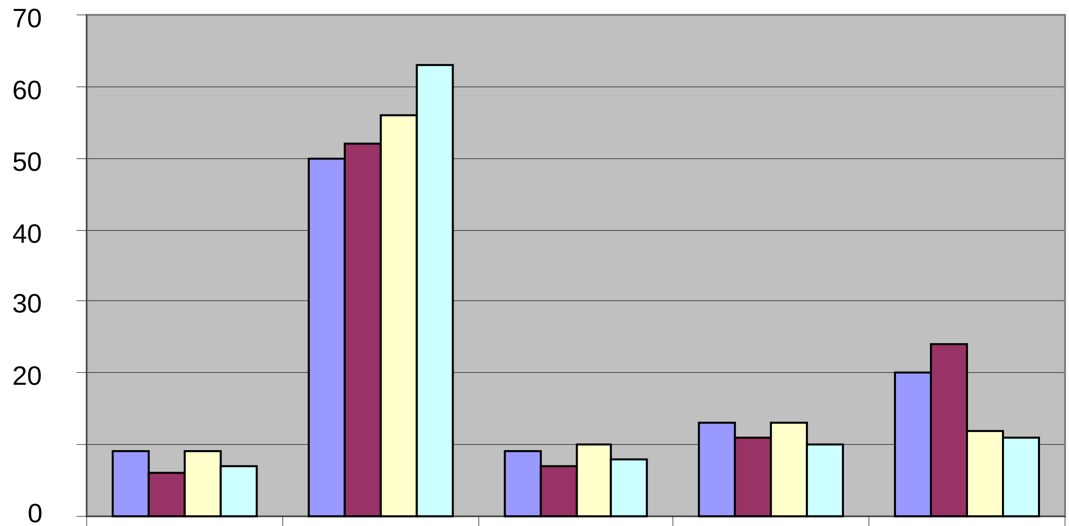
However, special attention must be paid to climatic effects:

- Overvoltages caused by lightning strikes
- Corrosion
- Leakage current caused by salt and industrial incrustation.

At present, an ACC installation is somewhat more expensive than an installation with normal, bare lines. This price difference can be recovered by way of lower costs of lane construction, lane maintenance and fewer operational interruptions.

ACC has clear advantages in forested terrain and in rural areas, where the higher investment costs can be compensated for by means of the reduced maintenance of maintaining the line lanes alone. The use of ACC lines can also be advantous in coastal areas.

Figure 1.1 shows the results of official fault and interruption statistics (FAS) in the years 1989-92. The results show causes of faults in overhead line networks using bare lines. What is particularly conspicuous is the large number of faults ascribed to “Annen natur” (other causes). This collective term includes effects such as: wind, snow, contamination of insulation surfaces, birds, squirrels and other animals, trees and tree branches.



	Thunder storms	Other causes	Man	Tech. equipment	Unknown
1989	9	50	9	13	20
1990	6	52	7	11	24
1991	9	56	10	13	12
1992	7	63	8	10	11

Figure 1.1: Causes of faults in an overhead network.

When the ACC system was introduced it was expected that the number of faults ascribed to “other causes” would be reduced. This is confirmed by the fault statistics for 1995 and 1996, since in these two years the numbers of faults per 100 km per year were 4.0 and 4.8 respectively for conventional 24 kV overhead lines, while the corresponding fault frequencies for 24 kV ACC lines were 0.9 and 1.9. If insulator failures are disregarded, the fault frequency for 24 kV ACC lines in 1996 was 0.8. It must be pointed out that the ACC lines are newer than the majority of conventional overhead lines and that the number of ACC lines is limited. The fault frequencies for Norwegian ACC systems are comparable with Finnish fault statistics.

In an ACC installation, protective devices must be introduced for the lines themselves and these devices will often protect other components in the supply network, such as transformers. The failure frequency of external components will thereby be reduced by the introduction of ACC systems. The increased introduction of spark gaps, which has been most common to date, can however create problems with regard to voltage quality. Arcs occurring in spark gaps must often be extinguished using circuit breakers to shut down the line, which results in operational problems. In this relation it should be mentioned that the French electricity supply industry has decided to replace spark gaps in its supply networks with surge arresters. A protection concept has been developed which handles overvoltage problems caused by lightning strikes without the use of circuit breakers.

No special consideration has been given to the practicality of Energised Electrical Work (EEW) when designing the various types of overvoltage protection used in ACC lines at present. Similarly, functionality with regard to the size of short-circuit currents and bird protection has yet to be satisfactorily dealt with.

1.2 About the Project

When launching a new generation of overhead power lines it is important to carry out an impartial assessment of the requirements which must be imposed in our hostile climate and of whether these requirements can be satisfied. A project was therefore inaugurated in 1991 as part of the *EFFEN-NETT* programme entitled "System for belagte linjer (BLX)" [A covered conductor (ACC) system] in order to investigate these issues. The Project was completed in 1997 and consisted of the following activities:

- Qualification of the most common 24 kV suspension/tension insulator types for use in, for example, exposed coastal areas.
- Clarification of the operational reliability of networks consisting of insulated lines in coastal areas.
- Preparation of guidelines for existing arc/overvoltage protection for ACC lines.
- Preparation of a protection concept for ACC lines in which overvoltage protection is an integral part of the pole-top configuration. Emphasis is placed on protection function without circuit breaker tripping and simplification of pole-top configurations. The actual development of products is a task for the industry.

International publications related to the Project

CIRED 93	A new overhead line concept based on covered conductors
CIRED 95	Lightning protection of overhead lines with covered conductors
CIGRE 97	Lightning protection means for XLPE-covered conductors as integral parts of the line insulation
CIGRE colloquium	Lightning performance of covered distribution lines. Proposed new line concept
23rd ICLP 1996	Lightning interception probability of upper conductor in proposed line concept for compact HV distribution lines

A reference list of technical reports is provided after the table of contents.

1.3 Relevant standards, recommendations and regulations

- NEK Standard No. 610 (1997): “Legerte aluminiumsliner. PEX-belagte liner for 12…24 kV” [Aluminium alloy transmission lines. XLPE-covered lines for 12 … 24 kV], which, among other things includes the following construction requirements:
  - Lines shall be of aluminium alloy, stranded and compressed.
  - Line types currently in use are of 50, 95 and 150 mm^2 cross-sections. The next standardised cross-section is expected to be 240 mm^2.
  - The coating shall be of weather-resistant XLPE with a minimum carbon black content of 2% and a nominal thickness of 2.3 mm for all voltages up to 24 kV.
  - Lines shall be longitudinally watertight. Sealing shall be continuous; in such a way that sealing is achieved without the need to come into contact with humidity. The filler material shall occupy all voids and shall be compatible with the XLPE covering. The filler shall withstand an operating temperature of 80°C without melting, and display good adhesion to the line.

- Forskrifter for elektriske anlegg. Forsyningsanlegg (FEA-F) [Regulations for electrical installations. Power supply installations] issued by the Norwegian Electrical Inspectorate on 1 January 1995.
- REF Publication No. 6 (Hålogaland Kraft, 1/90): “BLX-anlegg. 24 kV tremastlinjer. Fellesføring med lavspenningsledning og svakstrømskabel” [ACC installations. 24 kV wooden pole lines. Common routing with low-voltage lines and low-voltage cables].
- REF Standard REF-11-1994: “Forsterket oppheng. 11 og 22 kV tremastlinjer” [Reinforced suspension. 11 and 22 kV wooden pole lines].

2 SELECTION OF PROTECTIVE DEVICES

2.1 Why protect ACC installations?

2.1.1 Lightning strikes

Direct lightning strikes on a phase conductor in an ACC line results in a considerable voltage surge at the strike location, with a danger of flashover in the ACC line. In the event of flashover between phases or between a phase and a cross-arm in an ACC installation, a stationary arc will be created. In an installation with bare conductors, the arc will move in the direction of power feed, but in an ACC installation the plastic covering will generally prevent this. The stationary arc will probably burn through the phase conductors before a circuit breaker is tripped. However, a direct lightning strike on an ACC line will not result in failure of the line as long as adequate protection is provided.

In an ACC installation, it is overvoltage between two phase conductors or between phases and a directly grounded cross-arm that is critical. The protective devices employed until now have been various types of spark gaps, installed between the phase conductors and the cross-arms, as well as 24 kV insulators in combination with arcing horns. Arcing horns are used to prevent damage by a stationary arc to insulators and to the ACC lines. To date, metal oxide surge arresters have been little used because it has been assumed that the strain on such an arrester will be too great in the event of a direct lightning strike. This has resulted in the development of a new protection concept based on the assumption that most direct lightning strikes will hit the top phase conductor in a triangular or vertical suspension configuration. This phase conductor will thus function as an overhead ground line. In the event of a direct lightning strike on the top phase conductor, the current will be diverted to ground via a robust protective gap. Diverters are fitted between the lower phase conductors to prevent phase flashover and are only put under load in the few cases when lightning strikes these conductors. The aim is to use a self-extinguishing protective gap in the top phase conductor so that the protection functions without subscribers experiencing service interruption. Arresters now exist which are mechanically strong enough to permit their use as insulators, which significantly simplifies pole-top assemblies. Connecting arresters to the phase lines involves penetration of the insulating cover.

In addition to protecting the ACC lines themselves, it is necessary to protect components associated with the lines by diverting overvoltages to ground so that the potential difference between a phase and ground is minimised.

Protection of the ACC lines themselves and components associated with them can be combined.

A continuous underlying ground line is often used in combination with ACC lines, but this does not provide protection of the ACC line against lightning strikes. An upper ground conductor will function as protection if it is grounded at each pole. However, running lines to ground past the phases may present problems as regards the level of insulation. The new protection concept satisfies the intention of using an overlying ground line.

2.1.2 Corrosion

ACC lines must be fitted with internal protection against corrosion installed beneath the insulation and between the strands. It prevents the migration of moisture along the lines. Watertight ACC installations must always be used in corrosive environments.

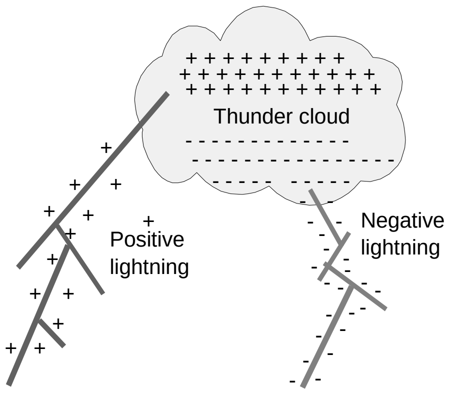
2.1.3 Leakage currents

If the surface of a contaminated ACC line is exposed to moisture, a leakage current will arise on the insulation surface, via the insulators, to ground. In adverse circumstances, this leakage current may create dry zones in the layer of contamination in which destructive discharges may occur. This problem is only observed in highly exposed coastal areas. One way of preventing this is to energise the insulator tops. However, this does introduce an exposed, electrically live point in an otherwise "sealed" installation.

2.2 Conditions influencing the choice of protection

Appendix 1 details a number of conditions which influence the choice of protective devices in ACC installations. Some of these must be addressed directly by planners when designing installations, while others may be disregarded or impossible to take into account. The following is a presentation of these conditions, with brief explanations:

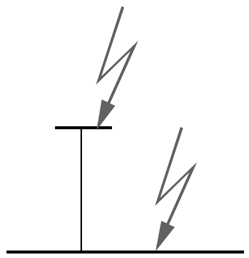
1. Lightning current



Lightning current shows considerable variations. No relation has been demonstrated between geographical conditions and the magnitude and shape of lightning currents. Based on international observations, an average lightning strike can be described as:

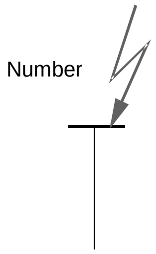
Amplitude I_m = 30 kA
Time to peak t_C = 5 µs (used instead of the IEC defined "front time")
Half-value time t_h = 80 µs
Maximum gradient S = 25 kA/µs

2. Types of strike



A distinction is made between overvoltages caused by direct lightning strikes on a line and induced voltages caused by lightning strikes close to the line. Direct lightning strikes will determine the distance between protection devices because in the event of a strike near the line, induced voltages in the phase conductors will be approximately equal and will not result in flashover between the conductors. Induced voltages relative to ground may reach about 600 kV. To prevent flashover to cross-arms, protective devices must be fitted to all poles in which the cross-arms are directly grounded.

3. Strike frequency and flashover frequency



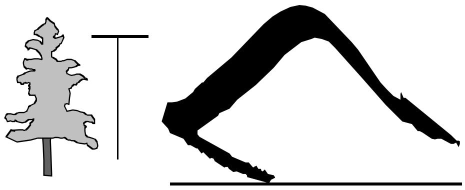
Lightning strike frequency is measured in terms of the number of direct strikes per kilometre of line per year. This will be constant for an area defined by geographical and meteorological conditions and line configuration. Considerable local variations in strike frequency may occur.

Lightning strike frequency is a function of:
Strike density: See maps in Appendix 1 (cf. Chapter 3).
Strike ratio: See maps Appendix 1 (cf. Chapters 3 and 4).

Flashover frequency is measured in terms of the number of flashovers (potential failures) in a line per kilometre per year. It will depend on the configuration of protective devices and in particular the distance between those devices.

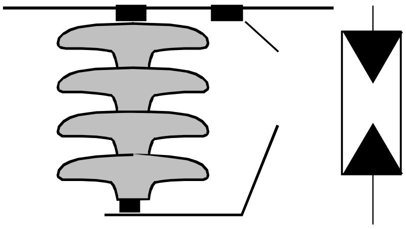
Flashover frequency is a function of:
Lightning strike frequency: See Appendix 1 (cf. Chapter 3).
Flashover ratio: See Appendix 1 (cf. Chapter 3).

4. Vegetation and terrain



Forest and elevated terrain in the vicinity of a line will have a shielding effect. The distance between protective devices may be increased when a line is not situated in open, exposed terrain. Note that forest may be cleared by subsequent felling.

5. Configuration of protective devices

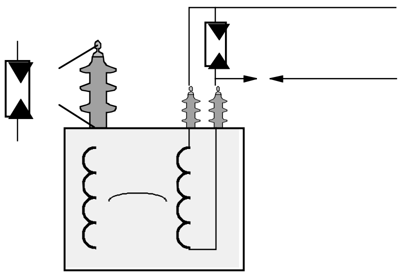


For types of protection configuration are recognised:

Spark gap:	Minimal difference between suppliers. Gaps of around 10 cm are optimal.
Insulators/arcing horns:	Arcing horns are used in combination with 24 kV insulators. The level of protection varies depending on the insulator type. Short insulators are preferable.
Arrester:	Prevents circuit breaker tripping. Must be designed in such a way that it does not fail in the event of lightning currents which expose the arrester to high energy loads.
Integrated protection:	As a consequence of excessive arrester loads, a protection concept has been developed in which the electrical loads on the arrester are minimised. The concept exploits the fact that in the case of triangular/vertical suspension most lightning strikes (more than 90%) will hit the top phase and the lightning current can be diverted to ground via a robust spark gap. Arresters are only used between phases to prevent flashover between the conductors. These arresters are only subjected to significant loads in the event of lightning strikes on the two lower phases. The protective equipment is also integrated into the pole top as a structural element.

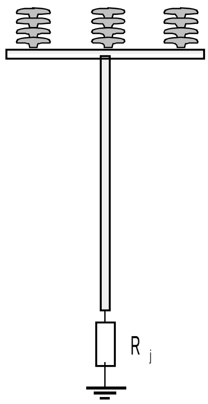
Bird protection should be fitted to insulator tops where there are electrically exposed live points.

6. Components



Components connected to an ACC line must be protected in the same way as those in a conventional bare line.

7. Cross-arm grounding

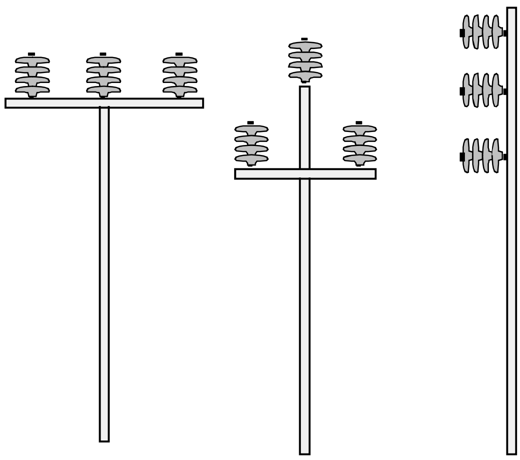


Direct grounding of cross-arms in all poles fitted with protective devices is advantageous, but not necessary to protect the ACC lines themselves. In order to protect components associated with an ACC line, the protective device and/or cross-arm must be grounded in the same way as conventional lines.

In areas particularly exposed to lightning, all poles must be fitted with protective equipment and directly grounded cross-arms. This reduces the likelihood of flashover in any particular pole and will also protect against induced overvoltages.

"Direct grounding" means a cable from the cross-arm (or the common attachment point of the insulators) down to an ground electrode. **Connection to a continuous ground line is <u>not</u> considered to be direct grounding.** When using wooden (insulating) cross-arms, protective electrodes fitted to the cross-arms must be connected to a common point.

8. Line configurations

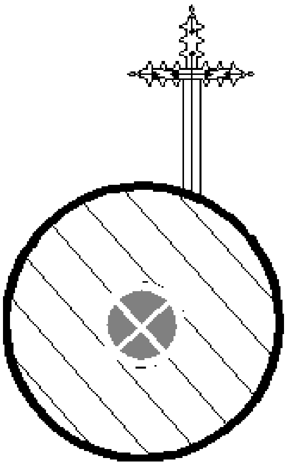


It makes little difference whether one uses flat suspension, vertical suspension or triangular suspension as regards the number of lightning discharges striking an ACC line. However, integrated protection presupposes triangular or vertical suspension because it is preferable that most lightning discharges strike the top phase.

9. Risk level and flashover frequency

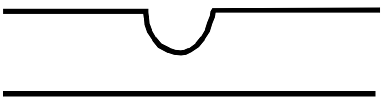
The acceptable level of risk of failure of an ACC line determines the choice of protection spacing.

10. Installation and operation



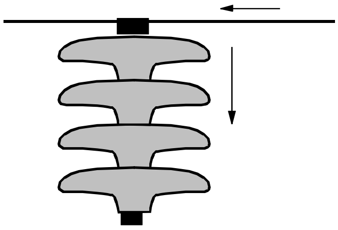
The XLPE insulation on the ACC line must not be damaged during installation. Any damage of the insulation must be repaired before the line can be put into operation. Penetrating clamps must not cause leakage of the insulation. The suspension system must be designed to avoid wear damage to the insulation. There must be no possibility of trees or branches falling against the phases, leading to damages of the insulation surface.

11. Corrosion



Long-term tests of an ACC line at Lista in Vest-Agder county (Norway) over a period of six years show that if the XLPE insulation is subjected to abrasion or shot-gun damage, any exposed aluminium strands will be to some extent attacked in coastal environments, but the use of grease will impede the spread of corrosion. The rate of corrosion at points of open abrasion damage demonstrates that uninsulated installations must not be used in a saline coastal atmosphere. In corrosive environments it is also recommended that the spacing of protective devices be especially close to reduce the development of current paths (streamers) between the phases in the event of direct lightning strikes. This will reduce the occurrence of perforation of the insulation of the ACC line.

12. Leakage currents



Salt and industrial contamination on ACC lines can, under humid conditions, result in leakage current on the surface of the insulation, with subsequent discharges in dry zones which can degrade the insulation. Maintaining a voltage at the tops of insulators eliminates this problem but introduces exposed live points which may present other problems such as bird deaths (unless bird protection measures are installed), or undesirable operational interruptions.

Table 2.1 shows the effects of the various factors on different types of ACC installation.

Table 2.1: The significance of various conditions on the design of ACC installations.

Conditions System	Strike frequency	Vegetation /Terrain	Protection arrangement	Compo-nents	Cross-arm grounding	Risk level	Corrosion	Leakage currents
Single line in-land	●	○	○	-	○	●	-	-
Single line coastal	●	○	○	-	○	●	●	●
Single line forrest	●	●	○	-	○	●	-	-
Line with components	○	-	●	●	●	●	-	-

- ● Important to take into account
- ○ Should be taken into account
- \- Not necessary to take into account

2.3 Distance between protective devices

A number of expressions are used in calculating the distance between protective devices, as follows:

Lightning strike density $\mathbf{N_g}$:	Number of lightning strikes per km^2 per year (cf. Figure 3.1)
Lightning strike frequency $\mathbf{N_S}$:	Number of direct lightning strikes per kilometre of line per year (cf. Figure 3.4)
Strike ratio $\mathbf{N_f}$:	The ratio between N_S and N_g. A function of terrain and tree height (cf. Figure 4.1)
Flashover frequency **H**:	Number of flashovers between phase lines in an ACC line per kilometre per year. Flashovers may cause failure of the line. This handbook deals with flashovers between phases spaced 50 cm apart.
Flashover ratio $\mathbf{N_0}$:	The ratio between H and N_S.

Figure 2.1 illustrates the relation between the various terms. The calculation of the distance **L** between protective devices consists of two steps: 1) Calculation of the lightning strike frequency N_S and
2) Calculation of flashover frequency H.

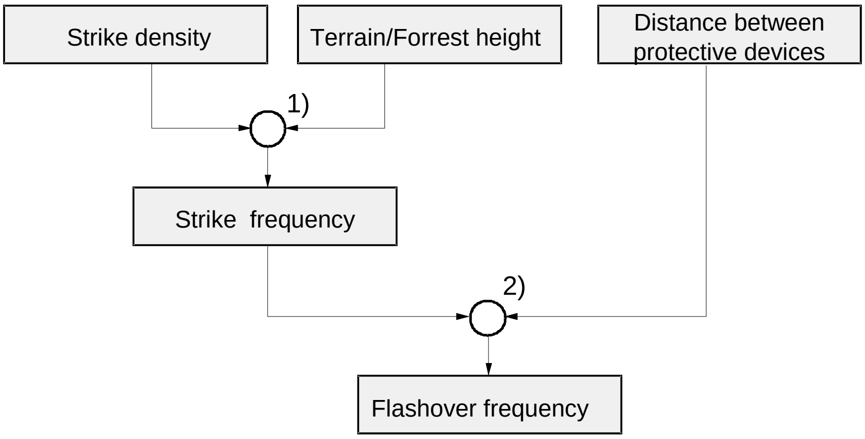


Figure 2.1: Calculation of distance between protective devices

2.3.1 Calculation of lightning strike frequency N_S

This involves a number of sources of uncertainty, partly because of the uncertainty in the strike density and also because of the lack of observations of how lightning strikes a line. The number of lightning discharges striking an ACC line is known as the lightning strike frequency $\mathbf{N_S}$ and has the units # /km/year. The number of lightning strikes on the line per kilometre per year. It can be assumed with reasonable confidence that the strike frequency will typically be in the range from 0.01 to 0.1 # /km/year.

$$\mathbf{N_S = N_g \times N_f \quad \#/km/year} \qquad (2.1)$$

N_f in Equation 2.1 depends on tree height and is given by Table V4.1 (Appendix 1).

From this table, three different tree heights **h** are selected which are used to create a diagram:

h = 0 m : $N_f = N_S / N_g = 0.07$ km

h = 3 m: $N_f = N_S / N_g = 0.05$ km

h = 6 m: $N_f = N_S / N_g = 0.015$ km

2.3.2 Calculation of flashover frequency H between phases

This is based on analysis of what happens when lightning first strikes a phase in an ACC line. The analysis is based on laboratory experiments as described in [2] and simulations in [4] and [5] in a new model of an ACC line developed in [3]. The number of flashovers and therefore potential failures in an ACC line can therefore be estimated at:

$$\mathbf{H = N_S \times N_0}\ \textbf{\#/km/year} \qquad (2.2)$$

N_O in Equation 2.2 depends on the distance between protective devices and is given in Table V3.2 (Appendix 1).

Based on Table V3.2, an average value is calculated of the flashover ratio $\mathbf{N_O}$ for three different distances between protective devices.

L = 100 m : $N_0 = H / N_S = 0.25$

L = 200 m : $N_0 = H / N_S = 0.50$

L = 300 m : $N_0 = H / N_S = 0.65$

2.3.3 Summary

The relationships developed in Sections 2.3.1 and 2.3.2 can be combined in Figure 2.2.

The basis of the left-hand side of the diagram is described in Section 2.3.1 and represents the relationship between lightning strike density in an area and lightning strike frequency on an ACC line passing through the area as a function of terrain and tree height.

The basis of the right-hand side of the diagram is described in Section 2.3.2 and represents the relationship between the flashover frequency in an ACC line and lightning strike frequency (line failure) as a function of the distance between protective devices. If there are no protective devices fitted to the line (indicated by ∞), the flashover frequency will be approximately 90% of the lightning strike frequency.

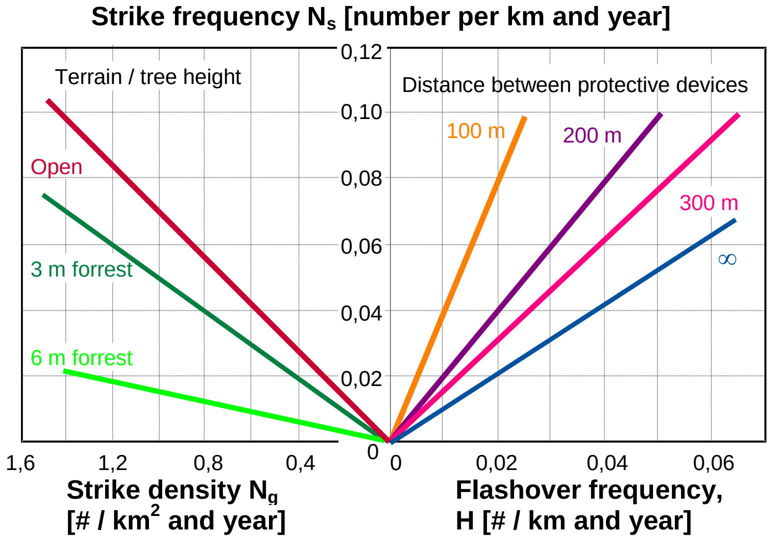


Figure 2.2: Summary of the conditions influencing the distance between protective devices.

Example

A 2 km-long ACC line passes through an area where the average tree height is 3 metres and the lightning strike density N_g = 1. One flashover/failure in 20 years is accepted for this line.

The procedure is therefore:
In the left-hand diagram, the value at the intersection between N_g =1 and 3 m tree height is read.
This gives N_S = 0.05
The flashover frequency is calculated as H = 1/2 km × 1/20 year = 0.025
In the right-hand diagram, the value at the intersection between H = 0.025 and N_S = 0.05 is read. This gives a value for the distance between protective devices L = 200 m.

3 GUIDELINES AND EXAMPLES

This chapter presents examples of the procedure for the selection of protection configuration and protection device spacing. In general it can be said that the distance between protective devices is a far more important parameter than the type of protective device used.

3.1 Selection of protection configuration

Here, only the advantages and disadvantages of different protection configurations are summarised, along with advice regarding grounding methods. Individual users must themselves assess the factors in Table 3.1 based on local conditions.

Table 3.1: Factors in the selection of protection configuration.

Factors	**Spark Gap**	**Arcing Horn / Insulation**	**Arrester in All Phases**	**Integrated Protection**
Protection of the line. Perforated by streamers	Effective protection of the line. Minimal number of perforations	Effective protection of the line. Some extra perforations	Effective protection of the line. Some extra perforations	Effective protection of the line. Some extra perforations
Protection of components	Protects the transformer if small gaps are used	Results in less protection of components	Protects transformers and cables	Protects transformers and cables
Voltage quality	During extinguish of the arc voltage disruption occurs	During extinguish of the arc voltage disruption occurs	No loss of power, High voltage quality	No loss of power, High voltage quality
Ring supply Arc wander	Might be difficult	No problems if arcing horns are installed on both sides of the insulator	No problems	No problems
Open spots (Bird problems)	The spark gap may be a weak spot. Bird protection should be installed if insulator top is energised	Bird protection shall be used	Bird protection shall be used when arrester/ insulation top has to energised	Method of bird protection is governed by the method used for line suspension / bracket
Radio interference	Problems may occur if penetrating clamp are connected too close to the insulator top, without direct connection	Spark wire in combination with not electrical insulated seizing spiral results in radio interference	Problems may occur if penetrating clamp are connected too close to the insulator top, without direct connection	None
Price	Moderate	Moderate	High	High
Failure	Do not fail. Have to be replaced after 3 – 4 arc functions	Do not fail. Have to be replaced after 3 – 4 arc functions	May fail during high lightning exposures	Low probability of arrester failure

The various types of protective device have approximately equal effect in protecting against overvoltages in an ACC line.

Grounding method

- Direct grounding of cross-arms in all poles fitted with protective devices is an advantage, but not essential, in protecting the ACC lines themselves.
- Effective grounding is necessary to protect components in the network (transformers, etc.).
- A low ground resistance is less important for protecting the ACC lines themselves.
- Protective devices must be fitted to all poles where the cross-arm and/or continuous ground line is directly grounded. This prevents damage to the line insulation in the event of insulator flashover caused by direct lightning strikes or induced overvoltages.
- A continuous ground line cannot be considered as ground in the event of lightning overvoltages!

Arc wander

Spark gaps and arcing horns must be located in relation to the direction of power feed so that any arc arising moves away from an insulator. Protective devices should therefore be located on the load side of the insulator. If spark gaps or arcing horns are fitted on both sides of the insulator, the arc will strike in the device with the smaller gap.

Special precautions should be taken for networks which operate as ring circuits.

Spark gap in:

Radial networks:	Can be used in connection with post, suspension and tension insulators.
Ring networks:	Can be used in connection with tension insulators, and also in most cases with post and suspension insulators. Arc wander has not been fully investigated.

Arcing horns and/or insulators in:

Radial networks:	Can be used in connection with post and suspension insulators.
Ring networks:	Can be used in connection with post and suspension insulators.
	Arcing horns are less suitable for use in combination with tension insulators. The shorter the flashover distance over an insulator, the more effective this type of protection will be.

Arresters:
Independent of whether the network is operated as a ring or radial circuit. No arcing.

Integrated protection:
Independent of whether the grid is operated as a ring or radial circuit.

3.2 Selection of distance between line protection devices

Protection of the actual ACC lines (but not associated components)

The following examples are based on Figure 2.2.

Example 1: Lightning-prone terrain. Lightning strike density N_g = 1.0 #/km²/year
Open terrain in south-eastern and southern Norway.
Using the left-hand side of Figure 2.2, from the value at the intersection between N_g = 1 and the line representing open terrain, we obtain a lightning strike frequency N_S = 0.07 #/km /year.

a) 1 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/1 km × 1/20 year = 0.05 #/km/year
The intersection between N_S = 0.07 and H = 0.05 on the right-hand side of Figure 2.2 gives a distance between protective devices of just over 300 m.

b) 4 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/4 km × 1/20 year = 0.0125 #/km/year
The intersection between N_S = 0.07 and H = 0.0125 on the right-hand side of Figure 2.2 gives a distance between protective devices of less than 100 m.
The accepted flashover frequency is therefore too ambitious.

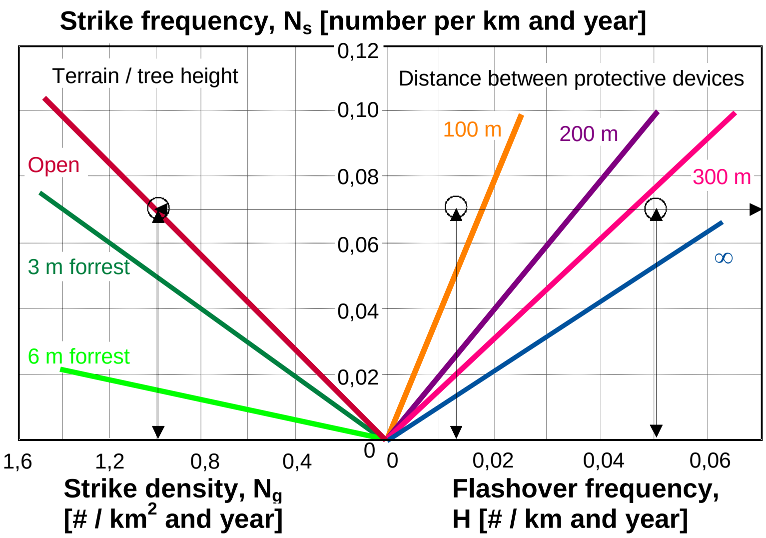


Figure 3.1: Example 1. Lightning-prone open terrain. ACC line.

Example 2: Moderately lightning-prone terrain. $N_g = 0.5$ #/km²/year
Open terrain in northern Norway, Trøndelag and parts of western Norway.
Using the left-hand side of Figure 2.2, from the value at the intersection between $N_g = 0.5$ and the line representing open terrain, we obtain a lightning strike frequency $N_S = 0.035$ #/km/year.

a) 1 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/1 km × 1/20 year = 0.05 #/km/year
The intersection between $N_S = 0.035$ and H = 0.05 on the right-hand side of Figure 2.2 gives a distance between protective devices of "greater than infinity". Hence, no protection devices at all are needed in order to satisfy the accepted flashover frequency.

b) 4 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/4 km × 1/20 year = 0.0125 #/km/year
The intersection between $N_S = 0.035$ and H = 0.0125 on the right-hand side of Figure 2.2 gives a distance between protective devices of 100 to 200 m.

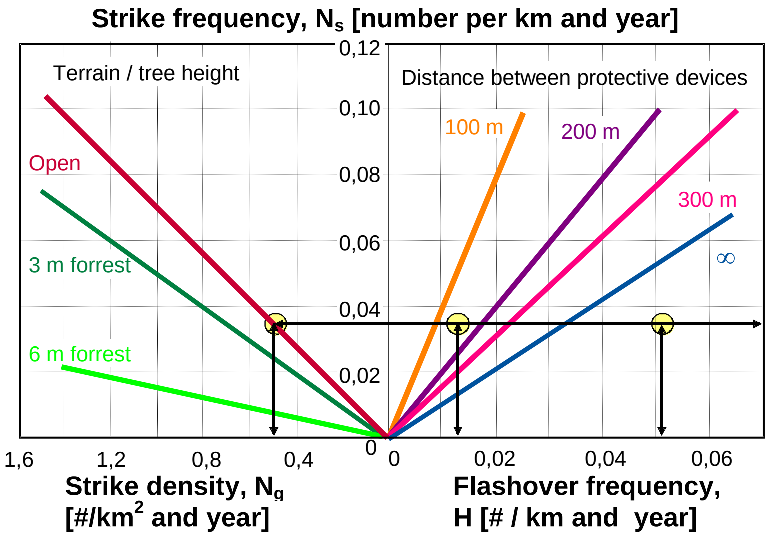


Figure 3.2: Example. Moderately lightning-prone open terrain. ACC line.

Example 3: Lightning-prone terrain. N_g = 1.0 #/km²/year
Forested terrain.
Using the left-hand side of Figure 2.2, from the value at the intersection between N_g = 1.0 and the line representing 3 metre tree height, we obtain a lightning strike frequency N_S = 0.05 #/km /year.

a) 1 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/1 km × 1/20 year = 0.05 #/km /year
The intersection between N_S = 0.05 and H = 0.05 on the right-hand side of Figure 2.2 gives a distance between protective devices equal to infinity. Hence, no protection devices at all are needed in order to satisfy the accepted flashover frequency.

b) 4 km line. One failure per 20 years is accepted.
This results in a flashover frequency H = 1/4 km × 1/20 year = 0.0125 #/km /year
The intersection between N_S = 0.05 and H = 0.0125 on the right-hand side of Figure 2.2 gives a distance between protective devices of 100 m.

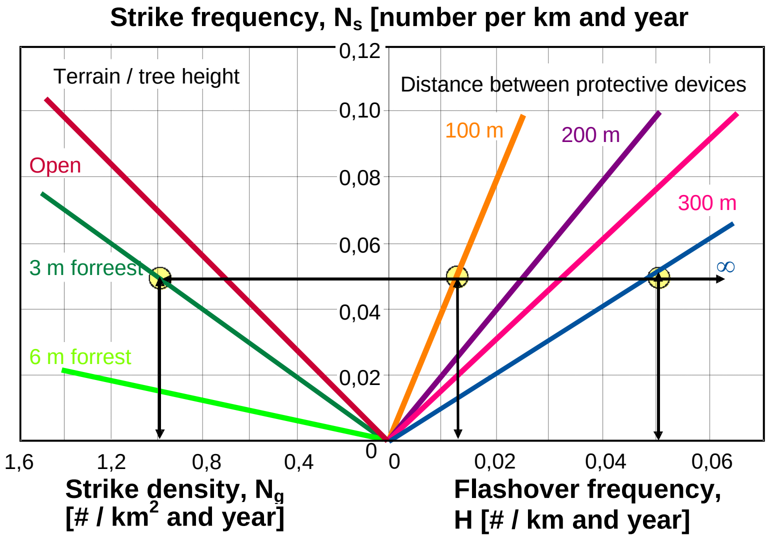


Figure 3.3: Example 3. Lightning-prone forested terrain. ACC line.

3.3 Protection of components connected to an ACC line

Components in an ACC system shall be protected in the same way as those in a bare line system.

Example 1: Transformer at end of ACC line.
Possible protection configuration:
1) Spark gap/arrester/integrated protective device on neighbouring pole.
2) Spark gap/arrester across high-voltage input.
3) Arrester across low-voltage exit point.
4) Neutral point protection between neutral point of low-voltage winding and (if necessary separate) ground.
5) Power fuse on the high-voltage side.

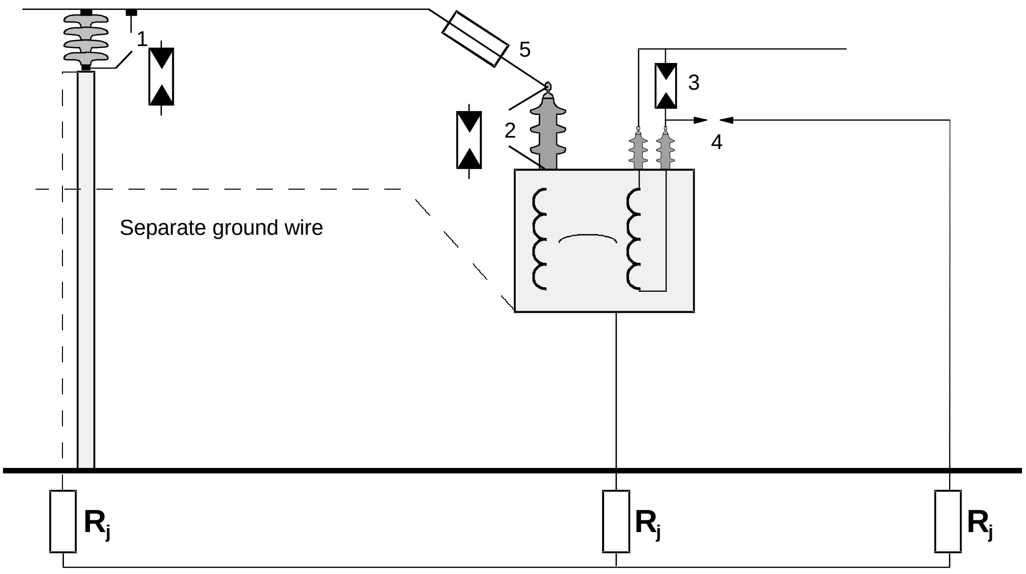


Figure 3.4: Transformer at end of an ACC line

a) Installation of spark gap/arrester/integrated protective device on neighbouring pole:
+ Effective protection of transformer and line.
+ Separate grounding of protective device and transformer. Fewer problems on the low-voltage side.
- Penetrating clamps produce weak points.
- Spark gap causes tripping of circuit breaker.

b) Installation of spark gap/arrester across high-voltage input:
+ Effective protection of transformer.
+ No penetrating clamps necessary. Eliminates the weak point at the neighbouring pole.
- Protective ground and transformer ground not separated. Greater necessity for equipment on the low-voltage side.
- Combination of spark gap and fuse prevents tripping of the circuit breaker but results in fuse failure and longer power interruption in the transformer circuit in question while waiting for fuse replacement.

Example 2: Transformer inserted in overhead line.
Possible protection configuration:

1) Spark gap/arrester/integrated protective device on neighbouring poles.
2) Spark gap/arrester across high-voltage input.
3) Arrester across low-voltage output.
4) Neutral point protection between neutral point of low-voltage winding and (if necessary separate) ground.
5) Power fuse on the high-voltage side.

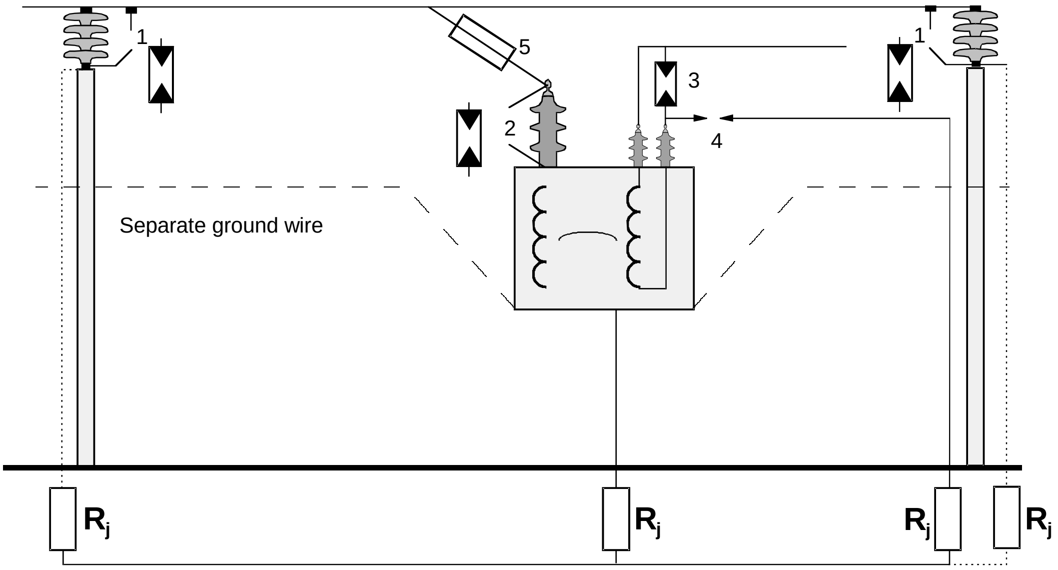


Figure 3.5: Transformer inserted in an ACC line.

Also in this case there are two alternative locations for protective devices: On a neighbouring pole and across the high-voltage input. The advantages and disadvantages of these alternatives are the same as mentioned in Example 1. In areas with low lightning activity, protective devices on both neighbouring poles will not be necessary.

Example 3: Transition between ACC and cable.
Here, arresters are fitted at the connection point between the ACC line and the cable.

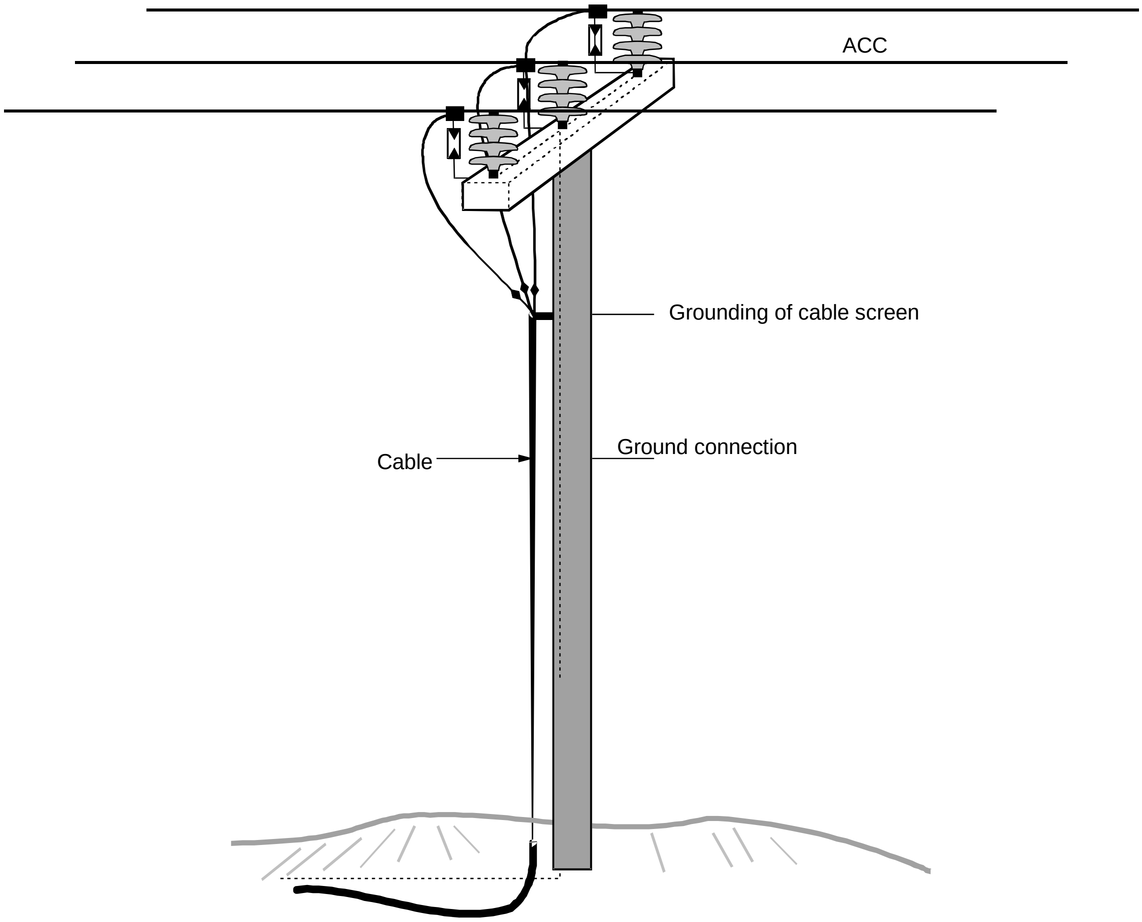


Figure 3.6: Protection of high-voltage cable connected to an ACC line.

3.4 Summary

The following is a summary of the results presented in Chapter 3.

Line protection (protection of the ACC line itself)
General:
- Install protective devices on all exposed poles (those which stand out in the terrain).
- Install protective devices at end points and branches.
- Take local variations in lightning activity into account.
- 100 - 200 metres between protective devices in lightning-prone areas.
- 300 - 400 metres between protective devices in forested terrain.

Component protection (protection of components connected to an ACC line)
General:
- Protective devices shall be located as close to a transformer as possible, on a neighbouring pole or directly across the high-voltage input.
- Arresters shall be located at cable exit.
- Protective devices must be grounded well on site.

Figure 3.7 shows a typical ACC route through an area with high lightning activity, with suggested locations of protective devices.

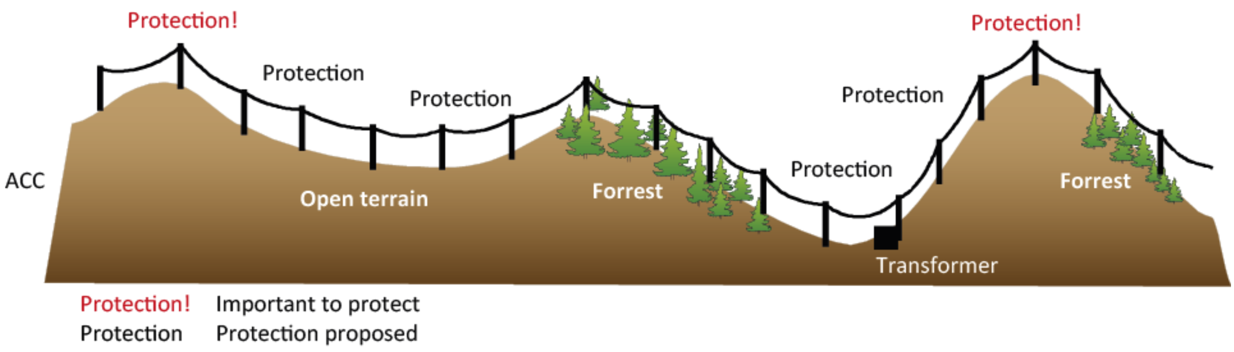


Figure 3.7: Example of location of protective devices.

REFERENCES

1. EFI TR A2025: Protection against lightning overvoltages in distribution networks (in Norwegian).

2. EFI LR F1943: Lightning strike tests on parallel ACC lines (in Norwegian).

3. EFI TR A4064: Streamer models during lightning strikes (in Norwegian).

4. EFI TR A4096: Direct lightning strikes on 24 kV ACC lines (in Norwegian).

5. EFI TR A4137: Distance between protective devices in a 24 kV ACC installation (in Norwegian).

6. EFI TR A4119: Handbook. Protective devices in 24 kV ACC installations (in Norwegian).

7. EFI TR A4203: Energy loads in overvoltage arresters during lightning strikes on ACC installations (in Norwegian).

8. EFI TR A4337: Reduction of magnetic fields in connection with the use of insulated conductors (in Norwegian).

9. EFI TR A4380: Overvoltage protection integrated in pole tops in ACC systems (in Norwegian).

10. EFI TR A4434: ACC in coastal areas (in Norwegian).

APPENDIX 1

CONDITIONS

1. Lightning current
2. Type of strike
3. Lightning strike frequency and flashover frequency
4. Vegetation and terrain
5. Configuration of protective devices
6. Components
7. Cross-arm grounding
8. Line configuration
9. Risk level and flashover frequency
10. Installation and operation
11. Corrosion
12. Leakage currents

V1 LIGHTNING CURRENT

Description of parameters which are of importance to protection strategy

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A lightning strike is modelled as an ideal current source. The shape of the lightning current is determined on the basis of given probability distributions, demonstrating the magnitude of an average lightning strike.

V1.1 Lightning strikes

Lightning consists of an electrical discharge between two clouds or between clouds and the ground. The latter is known as a lightning strike and is known to present problems, not least to the electricity supply industry. In connection with such a discharge, currents of up to several hundred thousand amperes may arise. The duration is, however, less than a thousandth of a second.

In a thunder cloud, electric charges separate, normally in such a way that the upper part of the cloud becomes positively charged and the lower part negatively charged. Static electricity arises, for example, because strong upward air currents meet cooled water droplets in higher air layers.

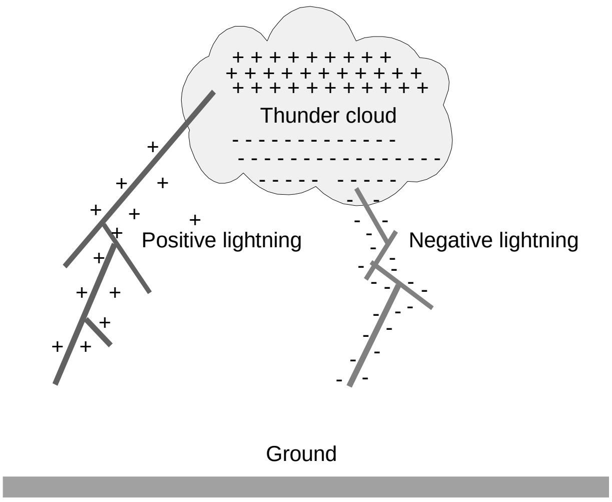

Figure V1.1: Development of a lightning strike.

Figure V1.1 is a sketch of how a lightning strike can begin. The flow of air causes electrical charges to separate in the air and cloud. A discharge originates in the cloud in the form of intermittent jumps in the direction of the ground's surface. The jumps may be 30-80 metres long and result in the formation of a lightning channel (streamer/leader), which is electrically charged. When the discharges have reached a certain height above the ground, upward discharges will commence from high points on the surface. When the downward and upward discharges meet, the main discharge, known as a lightning strike, initiates. Several consecutive lightning strikes can occur in the same lightning channel. Lightning strikes will also often occur between accumulated charges in the clouds themselves.

The location of a lightning strike has considerable effect on the overvoltages which occur in an ACC installation. Strikes are of three main types:

1. Direct strikes on phases.
2. Direct strikes on pole tops and/or cross-arms.
3. Strikes in the vicinity of the ACC installation causing induced overvoltages.

A lightning strike is modelled as an ideal current source and the current is independent of the impedance properties of the location where the lightning strikes.

Lightning current can have positive or negative polarity. Negative lightning (from negative charges in a cloud) is most common. The proportion of positive lightning is greatest during winter and appears to be greater with increasing northerly latitude. Positive lightning strikes can be of somewhat larger amplitude.

V1.2 Lightning current parameters

Four parameters are used to describe lightning current:

Amplitude I_m: The maximum value of the lightning current, measured in kA.
Time to peak t_C: The time taken for the lightning current to reach its maximum value, measured in µs. Time to maximum t_C is used instead of the front time t_f in the calculations.
Half-value time t_h: The time taken for the lightning current to sink to half of its peak value, measured in µs.
Maximum gradient S: The maximum gradient of the lightning current, measured in kA/µs. For the lightning current model used here, this occurs at the current's peak value.

All these four parameters show considerable variations in value. Measurements of the form of lightning current have been carried out for a considerable time in several countries.

Typical values for a so-called **50 %** (average) lightning strike are:

I_m = 30 kA
t_C = 5 µs
t_h = 80 µs
S = 25 kA/µs

The probability of lightning current exceeding a given value is demonstrated in Figure V1.2

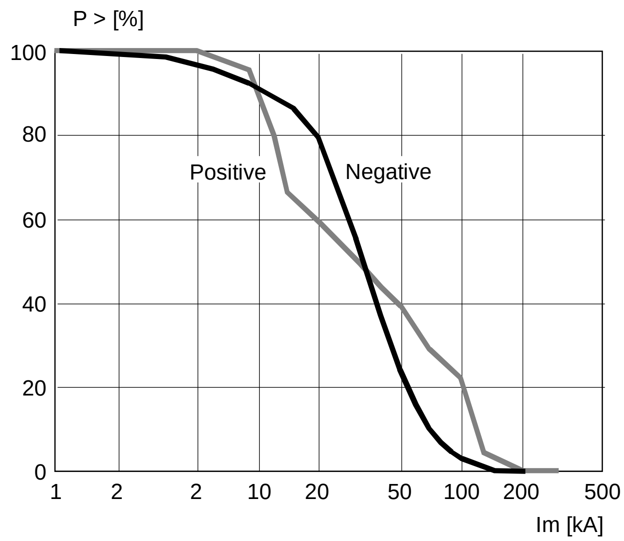

Figure V1.2: Probability distribution of lightning current amplitude.

V2 TYPE OF STRIKE

The effect of the strike location on protection strategy

Direct lightning strikes on phase lines are critical in determining protection philosophy, as compared with nearby strikes which cause induced overvoltages. Direct lightning strikes cause significant differences in potential between the phases in an ACC line, with a risk of flashover and fire.

V2.1 Direct lightning strikes on ACC lines

Direct strikes on phase lines are the most serious of events. They result in considerable voltage build-up both between the phase conductor and ground and between the conductors at the site of the strike.

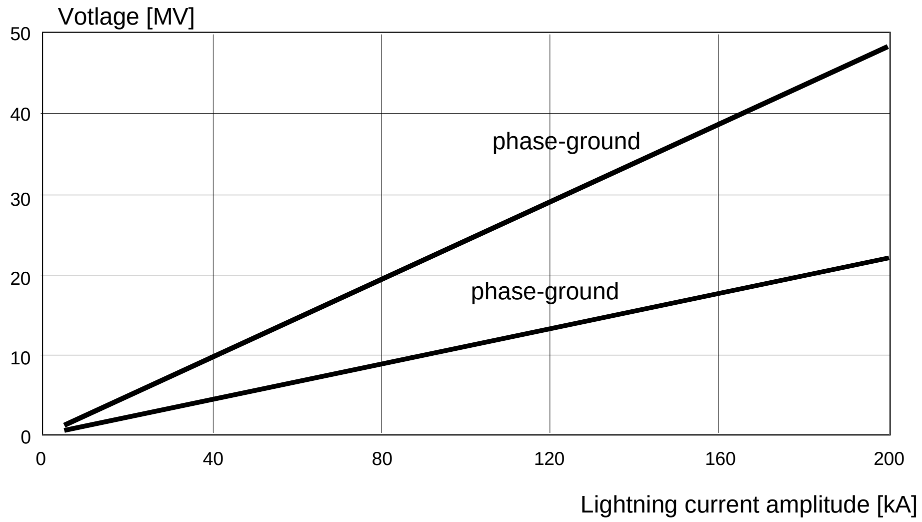

Figure V2.1: Voltage as a function of lightning current amplitude.

Phase-to-phase voltage, as shown in Figure V2.1 will be strongly attenuated by streamer development as described in [3].

V2.2 Induced overvoltages

Because the induced overvoltages caused by a lightning strike in the immediate vicinity of an ACC installation will result in an approximately equal voltage in all the phases, flashover between the conductors is unlikely. As shown in [1], the voltage induced in a line is proportional to the amplitude of the lightning current and inversely proportional to the distance from the location of the strike. Because the distance from the strike location is approximately the same for all the phase conductors the induced overvoltages will be approximately equal. Overvoltages relative to ground can, as shown in Figure V2.2, be up to approximately 600 kV. This voltage will result in flashover across insulators to a directly grounded cross-arm. Induced overvoltages occur approximately ten times more frequently than direct lightning strikes. Because of this high frequency of occurrence, it is recommended that the cross-arms are not grounded directly unless the pole in question is protected by grounding.

Generally, it is expected that if an ACC installation is protected in such a way as to prevent failure caused by direct strikes on one of the phases, this will also provide protection against the other types of overvoltage. Protection of an ACC line against induced overvoltages will be satisfactory if protective devices are installed on all poles on which the cross-arms are directly grounded.

Figure V2.2 shows the maximum induced voltage in a 24 kV ACC line as a function of lightning current. This voltage will generally be limited because lightning approaching the line will strike it directly.

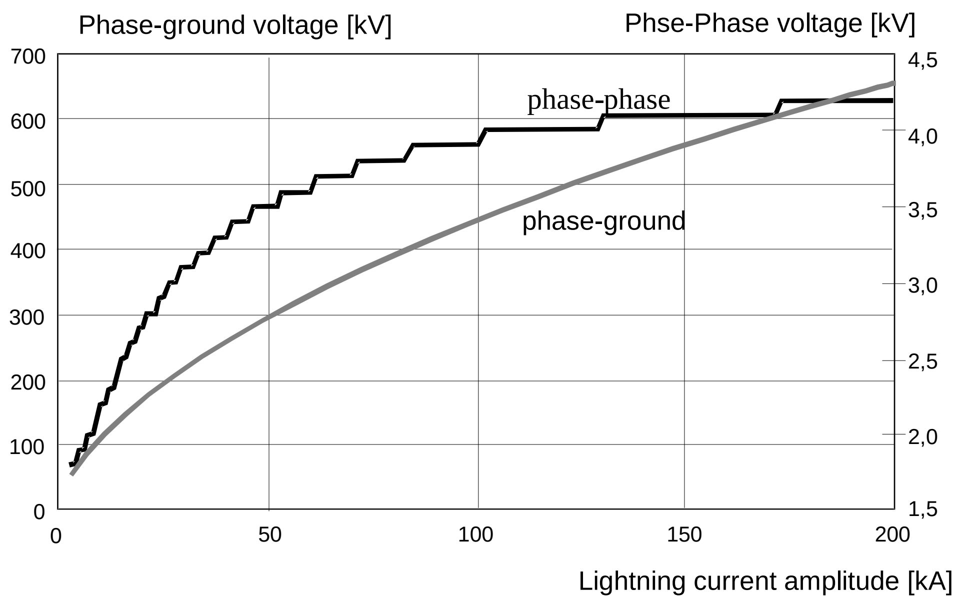

Figure V2.2: Maximum induced voltage as a function of lightning current amplitude.

Figure V2.2 shows that phase-to-phase induced voltages are limited to just over 4 kV. Hence they will not represent a problem for an ACC line. Phase-to-ground voltages are limited to just over 600 kV. This can lead to of insulation breakdown and flashover across the insulators if the cross-arm is directly grounded at the actual site and no protective devices are installed.

V3 LIGHTNING STRIKE FREQUENCY AND FLASHOVER FREQUENCY

Explanation of the relationship

Maps of strike density and the number of days with audible thunder show that there are fairly large variations in different regions of the country. An average value will be 0.5 lightning strikes per square kilometre per year. It is also important to be aware of the considerable local variations in thunderstorm activity. The lightning strike frequency is defined as 0.07 times the strike density in open terrain. The number of lightning strikes which hit a line and result in flashover (the flashover frequency) has been calculated as a function of the distance between protective devices.

V3.1 Strike density

Strike density N_g is a measure of how often lightning strikes occur at a given location, measured in number per square kilometre per year. This will be one of the most important parameters in determining the risk of flashover in an ACC line. Strike density is determined on the basis of meteorological and geographical conditions, and is assumed to be constant for a given area. Records have been kept for several years of strike density in Norway, and show variations from one part of the country to another. There are also considerable local variations.

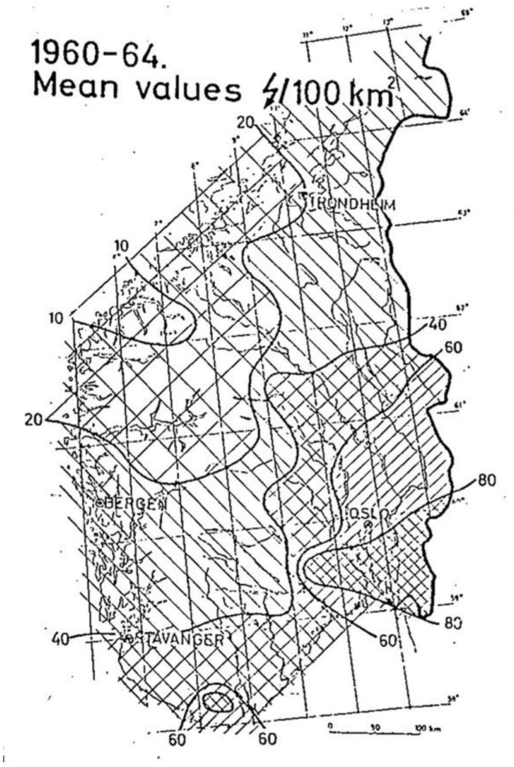

Figure V3.1: Strike density.

V3.2 Days with audible thunder

Figure V3.2 is a map of the average number of days with audible thunder recorded per year in the years 1930 to 1960. The records were produced by the Norwegian Meteorological Institute. As a general rule the figures given can be multiplied by a factor of 0.06 to give the strike density in terms of the number of lightning strikes per square kilometre per year. Figures V3.1 and V3.2 confirm each other to a certain extent, and indicate where the lightning intensity is highest.

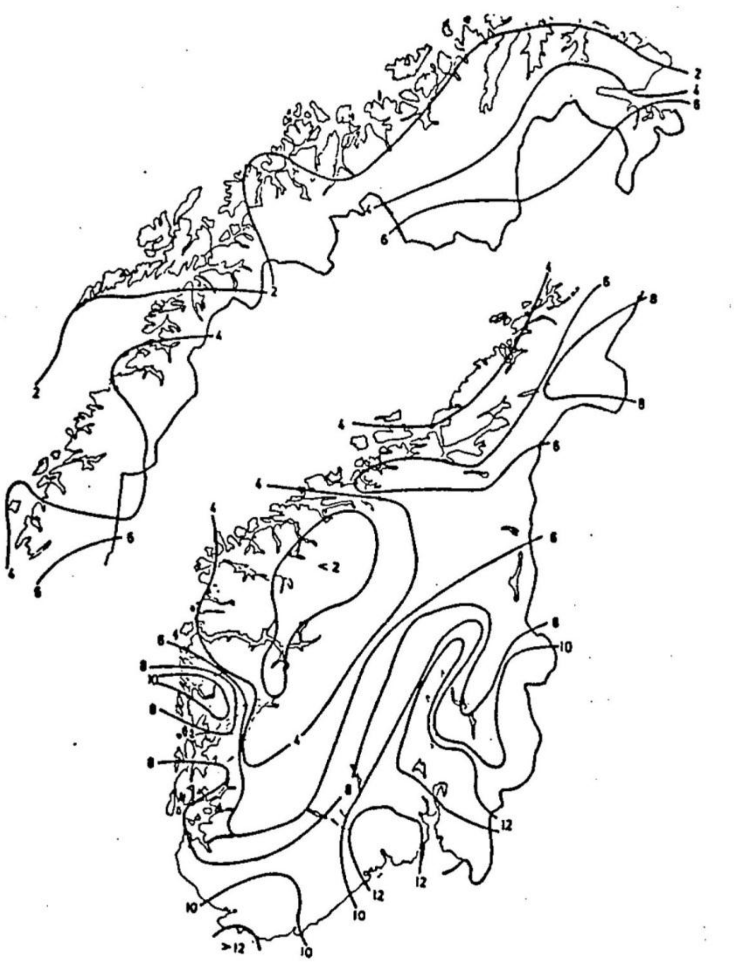

Figure V3.2: Days with audible thunder.

V3.3 Strike ratio

This chapter provides an explanation of the geometrical model used in the FLMAIN software application to calculate the proportion of lightning strikes which hit an ACC line.

FLMAIN is based on *the last jump of the lightning*, a parameter which is defined as:

$$r = 2 \cdot I_m + 30 \cdot (1 - e^{-I_m/6}) \ [m] \qquad \text{(V3.1)}$$

where I_m is the amplitude of the lightning current in kA.

Initially it is assumed that the lightning will first strike an object which comes within a distance r.

The geometrical model used in FLMAIN is shown in Figure V3.3.

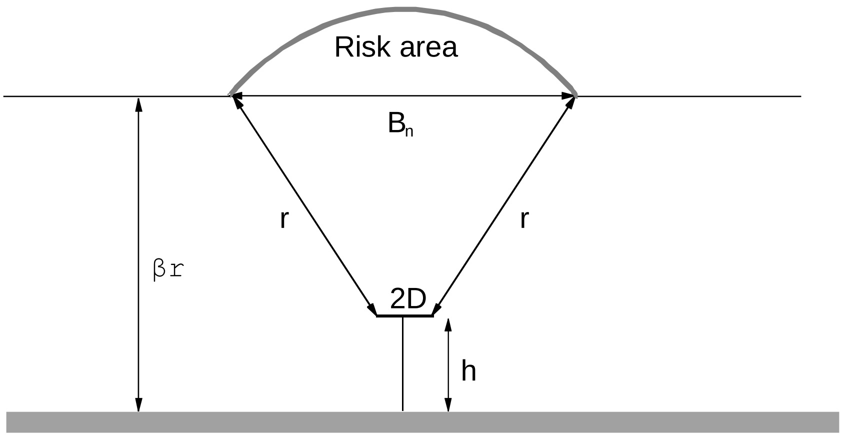

Figure V3.3: Geometrical model used in FLMAIN.

In Figure V3.3: r = the last jump of the lightning
h = pole height
D = distance between phases (in horizontal suspension)
β = attraction factor
B = width of the risk area

Lightning occurring within the area at risk, enclosed by the two radii, r, will strike the ACC line.

The attraction factor β is an adjustment factor depending on how prone the lightning is to strike the line, rather than the ground. β can be adjusted according to operational experience of how often lightning strikes hit the line. By comparing fault statistics it was found that for the 300 kV supply network, the factor is 0.8 and for system voltages exceeding 400 kV it is 0.67. In the case of 24 kV networks it is not possible to determine β in a similar way based on fault statistics, but it is reasonable to assume that it is closer to 1.0 for such an ACC installation.

A lightning strike zone is created on both sides of an ACC line, with a total width, B, of 500 metres. Based on the model shown in Figure V3.3, 10,000 lightning strikes in the strike zone have been modelled and the number of these which will hit the line directly has been calculated. Calculations have been carried out for three different values of the factor β. The line has been constructed with horizontal suspension, distance between phases of 0.5 metres, pole height 7 metres and sag 1 metre. In the first instance it is assumed that the line passes through open terrain with no shielding by trees. The number of lighting strikes hitting the ACC line is defined as the strike ratio N_f.

Table V3.1: Strike ratio for an ACC line.

β	N_f
0,8	0,145
0,9	0,115
1,0	0,070

As can be seen in Table V3.1 changing the factor β from 0.8 to 1.0 results in a considerable reduction in the number of lightning strikes hitting an ACC line.

It has been decided to continue using a factor of β = 1.0.

V3.4 Lightning strike frequency

The lightning strike frequency can now be defined on the basis of the given figures for strike density and strike ratio and is the number of direct lightning strikes per kilometre of an ACC line per year. This figure is a direct measure of the degree to which an ACC line is exposed to lightning strikes.

Lightning strike frequency N_S = Strike density × Strike ratio

$$\mathbf{N_S = N_g \times N_f} \ \textbf{\#/km/year} \qquad \text{(V3.3)}$$

Based on the choice in V3.3, $N_S = N_g \times 0.07$ #/km/year

A lightning strike frequency of 0.1 strikes per kilometre per year can be assumed to be a design parameter in open terrain.

V3.5 Flashover frequency

This is based on analysis of what happens when lightning first strikes a phase conductor in an ACC line. This analysis is based on laboratory experiments as described in [2] and simulations in [4] and [5] in a new model of an ACC line developed in [3]. The number of flashovers and hence potential failures of an ACC line is called the flashover frequency H and is measured in #/km/year.

Flashover frequency $\mathbf{H = N_S \times N_0}$ **#/km/year** (applies to flashover between phases) (V3.4)

In Equation V3.4, N_0 is independent of the distance between protective devices and is the proportion of lightning strikes which lead to flashover in a line (and possible failure). Table V3.2 shows calculated values of the flashover ratio $\mathbf{N_0}$.

Table V3.2: Proportion of lightning strikes in an ACC line which result in flashover.

Flashover ratio $\mathbf{N_0}$	Distance between protective devices L [m]		
Protection device	100	200	300
Spark gap J	0,211	0,459	0,603
Spark gap I	0,238	0,489	0,621
Arcing horn J	0,226	0,465	0,591
Arging horn I	0,286	0,542	0,630
Arrester 36 kV	0,309	0,551	0,637

Spark gap J : 10 cm spark gap, directly grounded cross-arm.
Spark gap I : 10 cm spark gap, insulated cross-arm.
Arcing horn J : Insulator NTP30097 with arcing horns, directly grounded cross-arm.
Arcing horn I : Insulator NTP30097 with arcing horns, insulated cross-arm.
Arrester, 36 kV : Metal oxide arrester (ABB EXLIM Q) 36 kV rated voltage, installed between phases.

The distance **L** between protective devices can now be expressed as a function of flashover frequency H divided by lightning strike frequency

$$\mathbf{N_S: H/N_S\,(L) = N_0\,(L)} \qquad \text{(V3.5)}$$

This is shown in Figure V3.4.

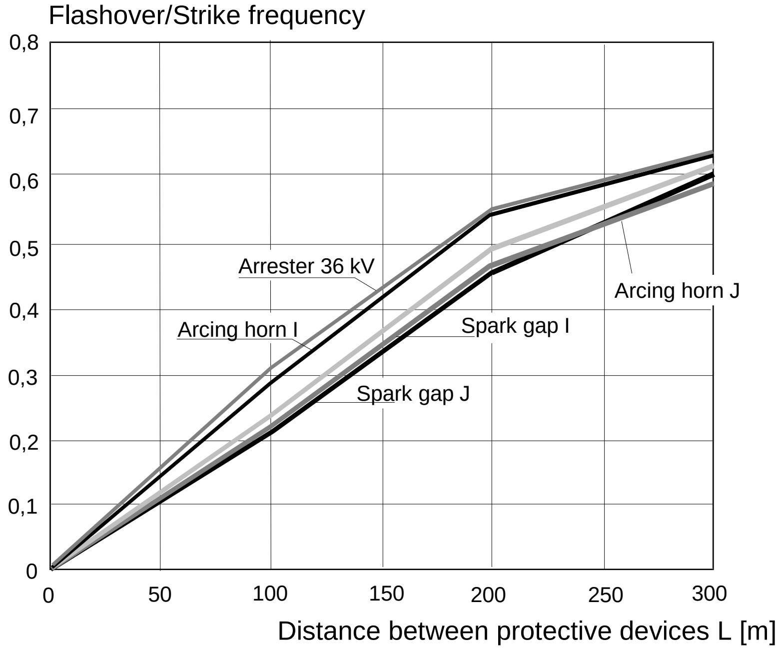

Figure V3.4: Distance between protective devices.

Figure V3.4 shows that there is minor difference between the different protection configurations. Based on this, the figure has been simplified by using an average value for the five different protection configurations. This gives:

L = 0 m : $N_0 = H / N_S = 0.00$
L = 100 m : $N_0 = H / N_S = 0.25$
L = 200 m : $N_0 = H / N_S = 0.50$
L = 300 m : $N_0 = H / N_S = 0.65$

In Figure V3.5 the average flashover frequency is plotted as a function of distance between protective devices for three values of lightning strike frequency.

An <u>exposed</u> ACC line is defined as one which passes through open, flat terrain with a high level of lightning activity. In this example, N_S is set at 0.1 lightning strikes per kilometre per year.

An <u>unexposed</u> ACC line is defined as one which passes through forested terrain or terrain with a very low level of lightning activity. In this example, N_S is set at 0.025.

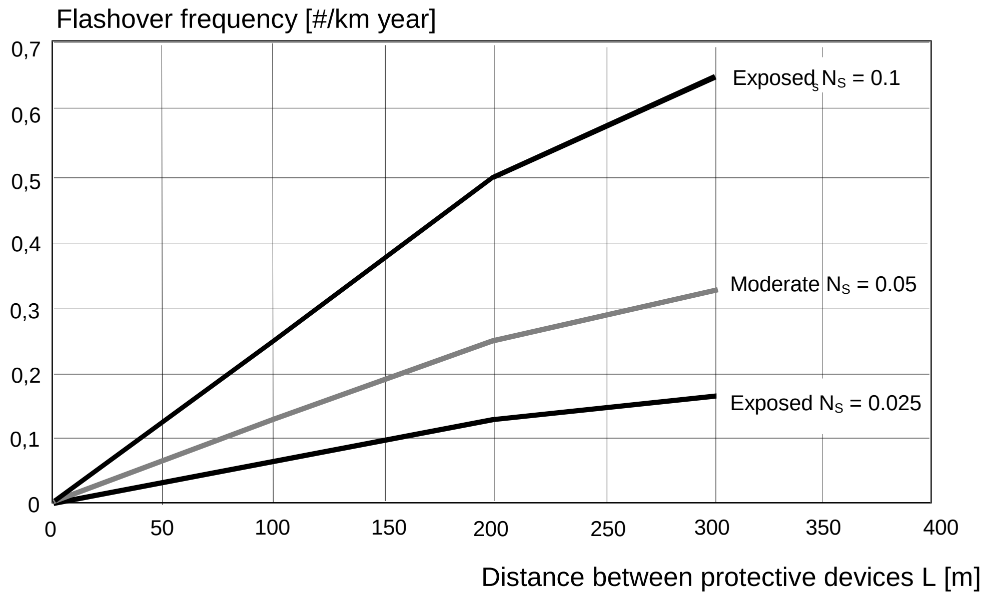

Figure V3.5: Distance between protective devices for three lightning strike frequencies.

Figure V3.4 and V3.5 may be used directly to determine the distance between protective devices for a given accepted flashover frequency and exposure (expressed by N_S) of an ACC line.

For example: Given a line of 1 km length passing through exposed terrain, N_S = 0.1 #/km/year. One flashover/failure every 20 years is accepted. The acceptable flashover frequency is given by H = 1/1 km × 1/20 year = 0.05 #/km/year. The intersection between H = 0.05 and N_S = 0.1 gives a distance L between protective devices of 200 m.

V4 VEGETATION AND TERRAIN

Description of the effect of vegetation and terrain on protection strategy

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The number of lightning strikes on a power line will be reduced by surrounding vegetation. The magnitude of this reduction has been estimated. The calculations result in an expression of strike ratio as a function of forest height.

V4.1 The effect of vegetation

The type of vegetation surrounding an ACC line has a considerable effect on the number of lightning strikes hitting the line. High trees close to the route will act as lightning conductors and thereby protect the line. The result is that the number of lightning strikes on the line is significantly reduced and the required number of protective devices can be reduced correspondingly. However, any future forest clearing must be taken into account. If the trees are lower than the height of the ACC line, the protective effect will be smaller.

Table V4.1 presents estimates of how tree height affects the lightning strike ratio for an ACC line. The calculations have been carried out by assuming that the forest takes the form of a blanket. This is equivalent to reducing the pole height.

Table V4.1: Lightning strike ratio N_f for an ACC line.

Forrest height	N_f (β=1.0)
0 m	0.07
1 m	0.06
2 m	0.055
3 m	0.05
4 m	0.04
5 m	0.03
6 m	0.015
7 m	0.007

The parameter β is explained in Chapter V3.

Values for lightning strike ratio N_f provided by Table V4.1 can be inserted directly into Equation V3.3 to determine the lightning strike frequency.

V4.2 The effect of terrain

The amount of undulation of the terrain around an ACC line will also have an effect. An ACC line at the bottom of a valley will be less exposed to lightning strikes than one located at the top of a ridge or hill.

It is therefore important, if possible, to locate the line in such a way that it is as well protected by the terrain as possible.

V5 CONFIGURATION OF PROTECTIVE DEVICES

Description of functionality

Spark gaps, insulator with arcing horns and metal oxide arresters provide approximately equally effective line protection. A new protection concept has been developed which will improve operational reliability and simplify pole-top structure.

The following is a presentation and explanation of the different configurations for the protection of ACC installations currently on the market. Although this information is available in suppliers' catalogues, it is desirable to collect all the information in one place to enable comparison between the various technical systems and to reduce the current uncertainty surrounding ACC installations. The installation of spark gaps in relation to the power feed direction will be a focus of attention, although there is still a certain amount of ambiguity with regard to this. The figures in this chapter represent schematic diagrams.

V5.1 Spark gap

A spark gap consists of two electrodes, one of which is connected to the cross-arm and the other to a penetrating clamp on the ACC line. In 24 kV installations, the gap between the electrodes is normally 10 cm. Several types of spark gap are on the market, but apart from their design there is little difference between them. Figure V5.1 illustrates the properties of types on the market.

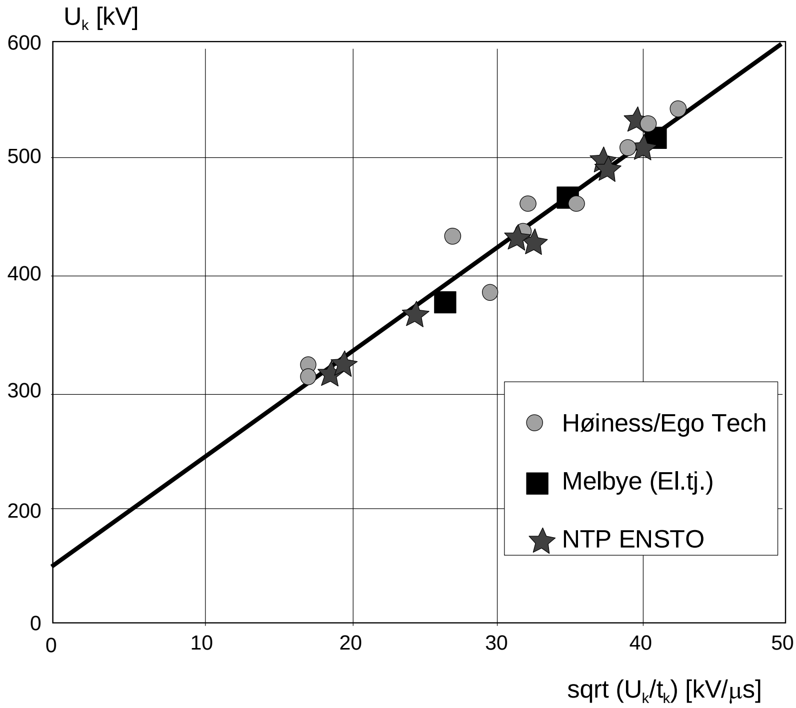


Figure V5.1: Properties of 2×10 cm spark gaps from three suppliers.

Figure.V5.1 is a plot of flashover voltage U_K against of the square root of the flashover voltage divided by the time t_K before flashover occurs. The gap is expressed as 2×10 cm because two spark gaps are connected in series.

V5.1.1 Spark gap and post insulator

General remarks:

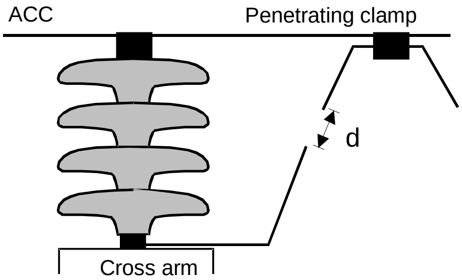


Figure F5.2: Spark gap and post insulator.

Arcing:

The arc will strike and will in most cases remain burning in the gap between the electrodes. In some cases the arc may jump so that it is between the electrodes on separate phases. When burning in the gap, the arc will be affected by magnetic fields, causing it to migrate as shown in Figures V5.3 and V5.4. If the power feed direction is from left to right, the migration will always be as shown in Figure V5.3. However, if the power feed direction is from right to left and the design of the spark gap satisfies certain conditions, the migration of the arc may be as shown in Figure V5.4. The conditions which cause such migration are not clear.

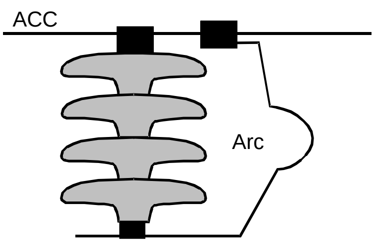


Figure V5.3: Desired arc wander.

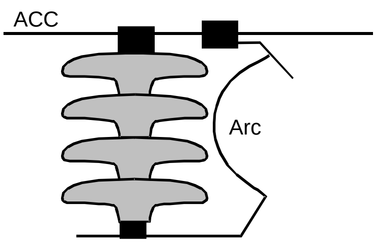


Figure V5.4: Undesirable arc wander.

Undesirable arc wander can cause the arc to remain burning against clamps and insulators, causing damage to them.

Single-sided feed. Fixed power feed direction.

In such cases, the spark gap should be fitted on the load side, as shown in Figure V5.5

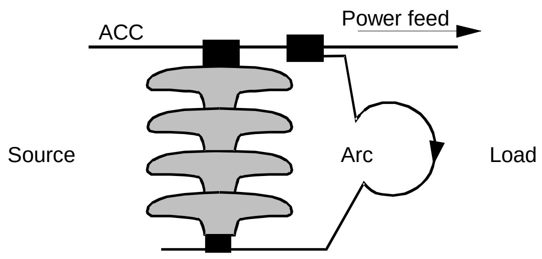


Figure V5.5: Spark gap location. Fixed power feed direction.

Double-sided feed. Ring circuit operation. Variable power feed direction.

In this network configuration the power feed can vary, resulting in either favourable (as shown in Figure V5.5) or unfavourable arc wander, as shown in Figure V5.6.

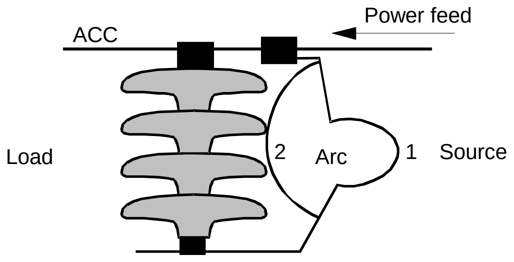


Figure V5.6: Spark gap and arc. Ring circuit operation.

So far, operational experience does not indicate that unfavourable arc wander has been a problem in networks operating as ring circuits, but one should take this into account by fitting the spark gap on the predominant load side. The distance of the spark gap from the insulator will have an effect on any damage to the insulator. In general, the distance should be as great as possible, and in the range > 20-30 cm.

If the network is being operated as a ring circuit, it will serve no useful purpose to fit spark gaps on both sides of an insulator, because which of the two gaps strikes is random.

Different categories of spark gap and post insulator

Spark gaps may be divided into three categories depending on how the electrodes are connected.

Category 1: No connection to the insulator top

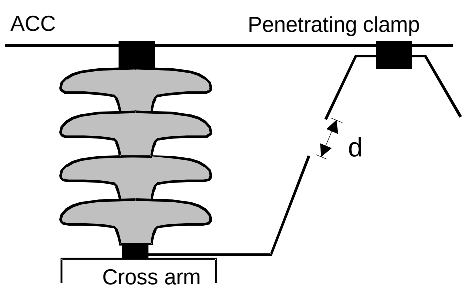


Figure V5.7: Spark gap, Category 1.

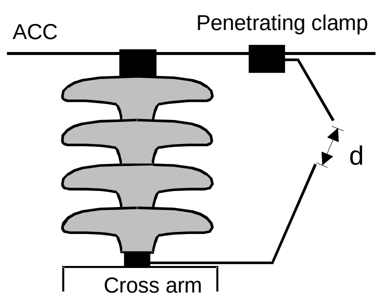


Figure V5.8: Spark gap, Category 1.

These two types will function in the same way. Flashover will occur in the gap marked "d". In Figure V5.7 the arc is also able to wander to the other side of the penetrating clamp if the electrodes and clamp are not plastic covered. In Figures V5.7 and V5.8, the recommended power feed direction is from left to right.

Category 2: Connection to the insulator top

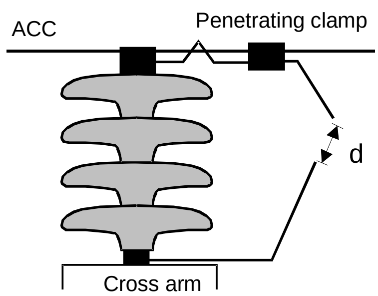


Figure V5.9: Spark gap, Category 2.

In this protection configuration, a flexible conductor runs from the penetrating clamp to the top of the insulator. This is an advantage in coastal areas where salt encrustation is a problem. Flashover will occur in the gap marked "d". If the power feed direction is from right to left the arc may wander to the top of the insulator, which is unfavourable. In Figure V5.9 the recommended power feed direction is from left to right.

Category 3: Penetrating insulator top

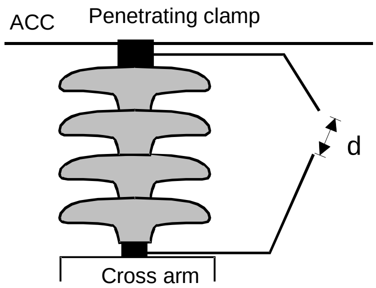


Figure V5.10: Spark gap, Category 3.

While this is a possible protection configuration it has disadvantages at a purely mechanical level because the connection of the line using a penetrating clamp can cause degradation of the line. The flashover in the gap occurs between the electrodes separated by a distance marked as “d”. In Figure V5.10, the recommended power feed direction is from left to right.

V5.1.2 Spark gap and suspension insulator

General remarks:

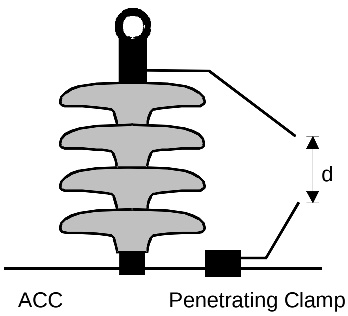


Figure V5.11: Spark gap and suspension insulator.

The spark gap electrode attached to the eye bolt of the insulator must be in good metallic contact with the corresponding electrodes on the other phases.

The problems related to arc wander and power feed direction are exactly the same in this case as for post insulators. The connection to the insulator top is identical to that for a post insulator.

V5.1.3 Spark gap and tension insulator

General remarks:

An alternative configuration is to omit the penetrating clamp and connect the spark gap directly to the bracing clamp on the insulator.

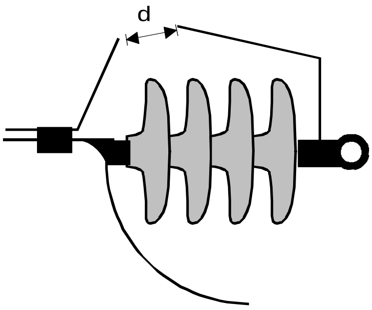
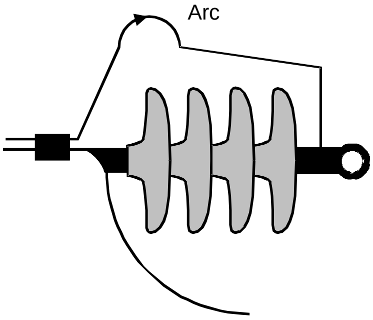


Figure V5.12: Spark gap and tension insulator.

The spark gap electrode attached to the eye bolt of the insulator must be in good metallic contact with the corresponding electrodes on the other phases.

Arcing:

A tension insulator configuration is less prone to arc wander than the other configurations are, because the arc will strike parallel to the main current direction, as opposed to at 90° to the current direction as in the two aforementioned configurations.



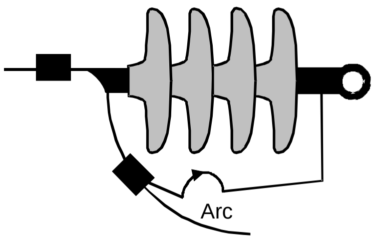


Figure V5.13: Correctly installed spark gap. Figure V5.14: Incorrectly installed spark gap.

The arcs in Figure V5.13 and V5.14 will be pushed slightly upwards because of the heat. The arc wander is not sensitive to the power feed direction.

The spark gap is fitted only to one side of the cross-arm, irrespective of whether the network is being operated as a ring circuit or not.

The connection to the insulator top is identical to that on a post insulator.

Tension insulator and overhead loop

Figure V5.15 illustrates how a spark gap can be installed by a post insulator when using an overhead loop. In this case there is normally no mechanical load on the loop, so that a post insulator with a penetrating insulator top can be used, with the spark gap fitted directly to the top of the insulator.

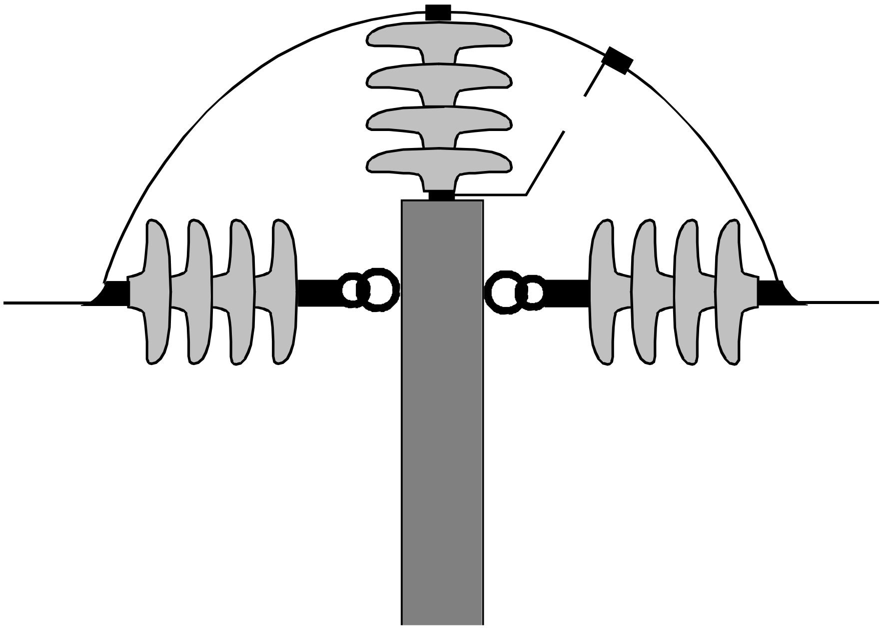


Figure F5.15: Example of installation of spark gap when using an overhead loop.

V5.2 Insulator with arcing horns

An insulator with arcing horns is a protection configuration consisting of a penetrating clamp on the ACC line and an arcing horn. The penetrating clamp is connected to the insulator top using a bare helical tie or bare, flexible conductor. The arcing horn is used to prevent a stationary arc between the insulator top or ACC line and the cross-arm. The disadvantage of this configuration is that the insulator geometry determines the level of protection. The insulator geometry varies considerably, making the efficiency of the protection unreliable. The use of insulators with arcing horns assumes that 24 kV insulators are used.

V5.2.1 Arcing horns and post insulator

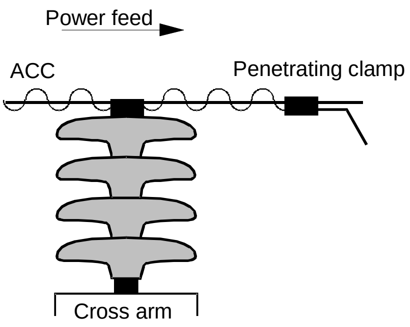


Figure V5.16: Arcing horn I. Post insulator.

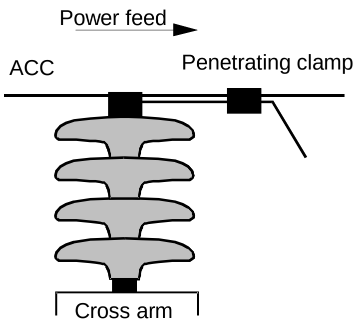


Figure V5.17: Arcing horn II. Post insulator.

Arcing:

In the configuration shown in Figure V5.16, flashover will first occur across the insulator. The arc will initially strike between the base of the insulator and the helical tie, and will then wander outwards along the helical tie to end at the arcing horn. In the final instance a continuous arc may strike between the arcing horns on two or all three phases. The process is shown in Figure V5.19. It is very important that the arc is not prevented from wandering from the insulator top to the arcing horn, something which is also important to remember when using bird protection.

According to the supplier, the configuration shown in Figure V5.16, with a bare helical tie and ignating wire is no longer being manufactured.

The configuration shown in Figure V5.17 will function as a spark gap with a large gap. Flashover will probably first occur directly between the arcing horn and the cross-arm. The connection between the penetrating clamp and the insulator top will be a flexible, bare conductor. Its flexibility is important to prevent mechanical degradation of the ACC line at the point of penetration of the clamp. It is particularly important that the connection is bare in the case of ring circuit operation in which arcing horns are installed on both sides of the insulator top.

If the penetrating clamp is enclosed in plastic, the helical tie (or the flexible, bare connection shown in Figure V5.17) must be pulled around the clamp onto the same side as the arcing horn, as shown in Figure V5.18.

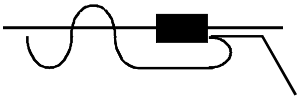


Figure V5.18: Installation of helical tie with a plastic-enclosed clamp.

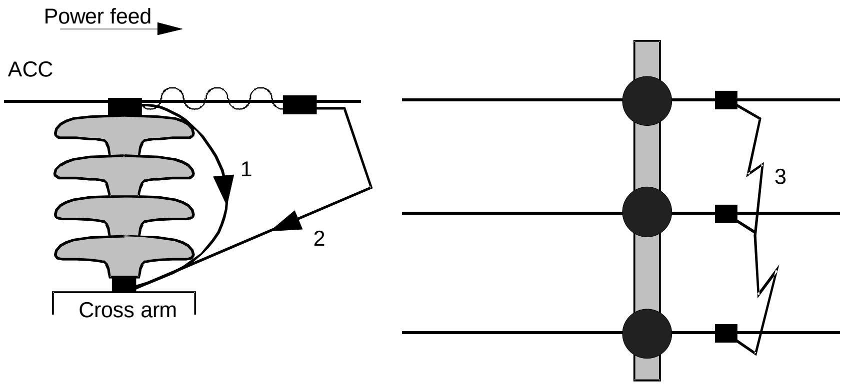


Figure V5.19: Arc wander 1) Flashover, 2) Wander in power feed direction to arcing horn and 3) Possible final state with arcing between arcing horns

If the power feed in Figure V5.19 had been in the opposite direction, the arc would have continued to burn as in Position 1, resulting in failure.

If the network is being operated as a ring circuit, arcing horns must be fitted on both sides of the insulator. The arcing horns must be connected using a continuous helical tie. This applies to both Figure V5.16 and Figure V5.17.

V5.2.2 Arcing horn and suspension insulator

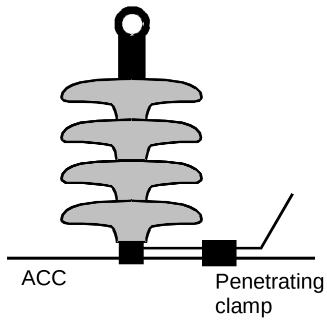


Figure V5.20: Arcing horn. Suspension insulator.

The arcing horn must be fitted pointing upwards, so that there is no obstruction between it and the cross-arm. The flashover sequence and arc wander are the same as for a post insulator. The connection between the penetrating clamp and the insulator top will be a flexible, bare conductor. Its flexibility is important to prevent mechanical degradation of the ACC line at the point of penetration of the clamp. It is particularly important that the connection is bare in the case of ring circuit operation in which arcing horns must be installed on both sides of the insulator top.

The same considerations apply as those illustrated in Figure V5.18.

V5.2.3 Arcing horn and tension insulator

The effect of using of arcing horns in combination with tension insulators is somewhat unclear. In this case it is not self-evident that an arc will move in the expected direction as in the case of post and suspension insulators. However, tests in short-circuit laboratories show that an arc will move as expected in the case of high short-circuit currents (10 kA), and that the arcing horn therefore appears to function.

V5.3 METAL OXIDE ARRESTERS

Metal oxide arresters are an alternative to spark gaps and insulators with arcing horns. The advantage of such arresters is that the fault current is limited by the resistive element, so that the lightning current is conducted away without an arc arising and without a circuit breaker needing to disconnect the line. This reduces the number of disconnections of the line and improves the supply and voltage quality. However, the disadvantage of metal oxide arresters is that they can fail in the event of strong lightning currents, and that such failures can be difficult to trace. Patents exist for methods of detecting failed arresters.

V5.3.1 Characteristics

A metal oxide arrester is a non-linear resistor whose resistance is high under the influence of low voltages. At voltages over a certain level the resistance value will be reduced drastically.

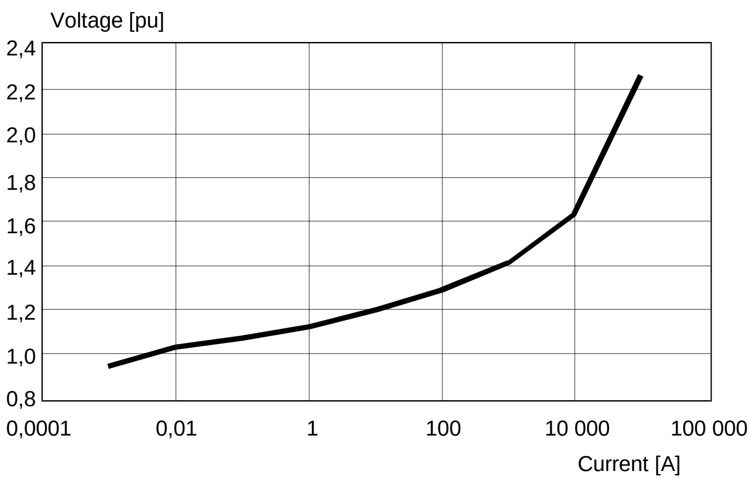


Figure V5.21: Characteristics of a standard metal oxide arrester (ABB EXLIM Q).

V5.3.2 Installation

Metal oxide arresters can be installed in two main ways:

1) Between penetrating clamps on phases and a cross-arm (common point).
   Three arresters are therefore needed to protect a three-phase line. If the cross-arm (common point) is grounded at the location this configuration will also protect against overvoltages relative to ground and therefore protect components connected to the line.
2) Between penetrating clamps on the phases.
   Two arresters are therefore needed to protect a three-phase line. This configuration will only protect the ACC lines themselves.

V5.3.3 Choice of rated voltage

The arrester must be designed so that its resistance is large for the transient overvoltages which may occur but low when subjected to voltages over a certain level. This involves selecting a rated voltage and class. Choice of rated voltage depends on the actual network configuration and will be equivalent to the case for bare lines. The choice of arrester class determines how much energy an arrester can absorb.

V5.3.4 Integrated protection

A protection concept [7, 8] has been developed which exploits the fact that in the case of triangular or vertical suspension the majority of direct lightning strikes will hit the top phase if the shield angle α between the top phase and the two lower conductors is less than 45°, cf. Figure V5.22.

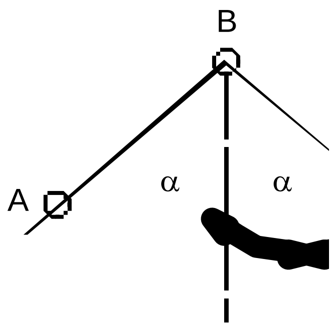


Figure V5.22: Shield angle α between top phase and the two lower conductors.

A robust protective device (spark gap) is used between the top phase and ground to divert the lightning current. To prevent flashover between phases, metal oxide arresters are fitted between the conductors. Since significant arrester loads only occur in the rare cases when lightning strikes the side phases, arrester devices of low energy class can be used. In the event of activation of the protective equipment, a normal operational situation will be restored without the consumer at lower voltage levels being aware of any operational interference. This is because in an insulated and/or coil grounded network the line voltage will be the same even if one of the phases is grounded. The protection concept is illustrated in Figure V5.23 (Alternative A and Alternative B), compared with the conventional configuration (Alternative C). In a directly grounded network, Alternative C must be used.

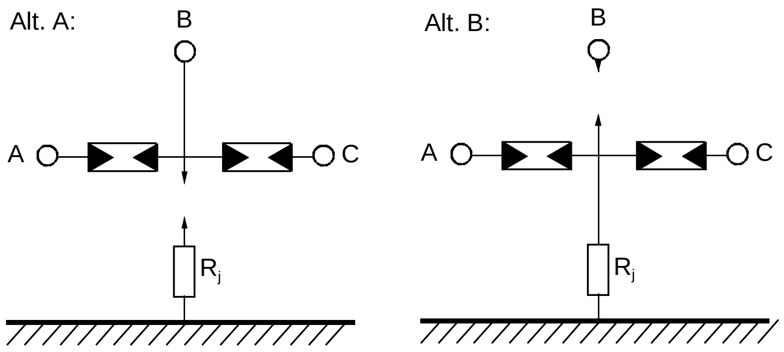


Figure V5.23: New protection concept (Alternative A and Alternative B), compared with the conventional configuration (Alternative C).

The loads on the arresters installed between the phases will not present problems in the event of a strike on the top conductor, while a strike in the side conductors will produce at least 100 times as much energy absorption in the most exposed arrester for a given lightning current.

The ground resistance at the poles will serve to distribute the lightning loads between the arresters. In the event of a strike on one of the side conductors, the arrester loads will decrease with increasing ground resistance, while in the case of a strike on the top phase the arrester loads will increase with increasing ground resistance.

The spacing of protective devices will also affect the arrester loads. When the distance between the arresters is reduced, a larger proportion of the lightning current will be distributed in the arresters in the neighbouring poles.

Computer simulations (Monte-Carlo simulations) have been carried out using a random selection of lightning strikes on an ACC line with triangular pole-top configuration. 99.4% of the lightning strikes hit the top phase conductor and 0.6% hit the side phases. The simulations show that a moderate lightning strike density of 0.3 strikes per year per km^2, with 200 metres between protective devices and zero ground resistance, results in:

- One failure per year per 6,500 km of ACC line using the new protection concept. This corresponds to an annual failure rate of around 0.002%.

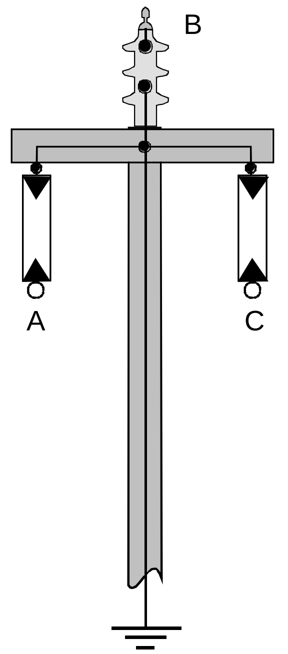
- One failure per year per 20 km of ACC line using the conventional protection configuration consisting of arresters in all three phases (Alternative C). This corresponds to an annual failure rate of around 0.3%.

Alternatives A and B provide approximately equivalent protection against phase flashover, while the conventional Alternative C provides somewhat poorer protection. For mechanical reasons, Alternative B is preferable to Alternative A.

At present, a spark gap with bird protection must be used on the top phase, but a limitation of this protection is that it is not self-extinguishing in the case of currents exceeding 25-35 A. To solve the arcing problems in networks with larger ground fault current, coil compensation devices should be considered. In some cases the arcing problem has been solved by using a shunt switch in one of the network stations to ground the top phase momentarily in connection with activation of the protection.

The use of a vacuum chamber of the type used in circuit breakers has also been considered as protection between the top phase and ground. However, according to the supplier, this type of configuration is not available.

Figure V5.24 shows a pole top with a spark gap in parallel with the top phase and metal oxide arresters used as suspension insulators in the two lower conductors. This configuration is in use in an ACC line operated by Norwegian utilities. The proposed fitting will reduce twisting and dynamic loads. Figure V5.25 shows proposals for other pole-top configurations with integrated protection devices.



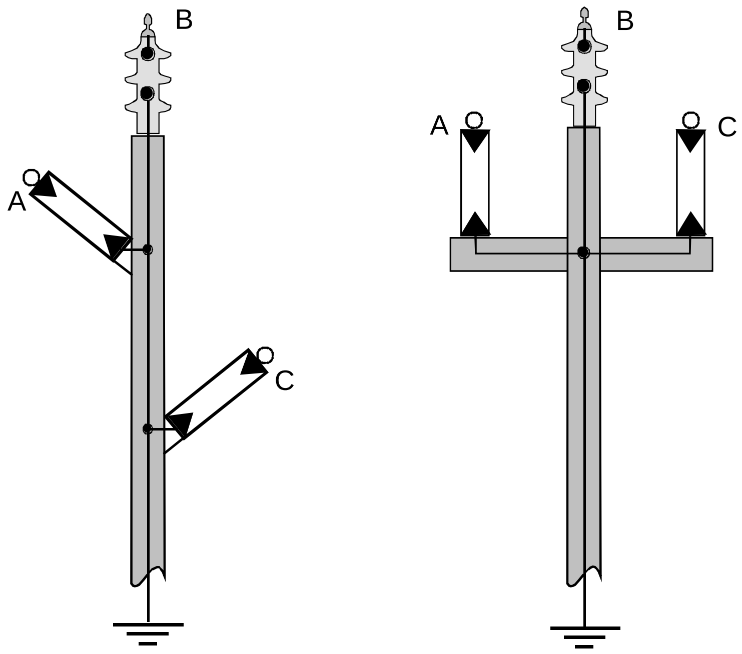


Figure V5.24: Pole top in new ACC.

Figure V5.25: Proposal for pole tops with integrated protection.

V5.4 The effect of protection

Protection must be introduced in an ACC installation to achieve the following objectives:

1) To protect the ACC line itself
2) To protect components associated with the ACC line (transformers, etc.)

Objective 2 must always be taken into account, irrespective of whether the line is ACC or not, and the main consideration here is to reduce the voltage relative to ground to an acceptable level. Earlier observations regarding protection of distribution networks [1] still apply to ACC lines.

Objective 1 is a new aspect which only applies to ACC (and AXUS). The main consideration here is to prevent flashover between phases or between a phase and the cross-arm. This type of flashover causes stationary arcs in the installation with a danger of burning through the ACC line. In the first instance it is therefore important to reduce the potential difference between the phases or between phases and cross-arms to an acceptable level. This is achieved by installing a protective device between penetrating clamps on the ACC lines and the cross-arm. It is assumed that metal or wooden cross-arms are used, with connection between the insulator attachments. To achieve the maximum effect of a protection device, the cross-arm or a common point of the insulator attachments should be grounded at the site.

Both objective 1 and objective 2 are achieved by direct grounding of a common point of the insulator attachments or the cross-arm at the site.

V5.5 Effectiveness of protection

The various types of protective device (spark gap, insulator/arcing horn and arrester) are approximately equally effective. In general it can be said that the distance between protective devices is much more important than the type of protective device selected.

V5.6 Radio interference

Radio interference in this context is defined as interfering electromagnetic waves generated by electrical discharges from electromagnetic equipment.

Radio interference from an ACC installation is an acknowledged problem, and is generally related to two sources:

1. Striking wire and arcing horn configuration. Discharges may occur between the striking wire and the helical tie if these are not properly electrically connected.
2. Penetrating clamp. Discharges may occur between a penetrating clamp fitted too close to the top attachment of an insulator and not in electrical continuity with it, because the top insulator attachment is at an undefined variable potential. A distance of more than 5 cm between a penetrating clamp and the insulator top will significantly reduce this problem.

V5.7 Bird protection

ACC lines, with their insulating covering, are in principle less prone to damage from bird contact than traditional bare lines. However, the necessity frequently to introduce protective devices compromises the ideal closed concept, since bare, live conductors are accessible at pole tops. With the reduced phase spacing in ACC lines the likelihood of birds causing short-circuits at pole tops thereby increases. This is a very serious problem which has bearing on the basic principle of introducing ACC systems. Fortunately, solutions to the problem are available, involving protecting exposed points at the pole top with insulating polymeric covers. Various suppliers offer such covers on the market, and they should be used on all pole tops with exposed, electrically live points. Polymeric covers must be designed so as not to prevent free arc wander. Line constructors must ensure that ACC lines are erected in such a way as to protect animal life.

V5.8 Reinforced suspension

Reinforced suspension is a construction and combination of components aimed at reducing the probability of phase failure. Cf. REF Standard REF-11-1994: Forsterket oppheng. 11 kV og 22 kV tremastlinjer. (Reinforced suspension. 11 kV and 22 kV wooden pole lines. (in Norwegian)).

V6. COMPONENTS

Explanation of the effect of protection strategy

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Components such as cables, transformers, substations, etc. associated with an ACC line require special protection. Protection of components is achieved by reducing the potential relative to ground. In this situation, an ACC line is treated as a bare line.

V6.1 Protection configuration

Protective devices (spark gaps or arresters) are connected between penetrating clamps on the phase conductors and a common point on the cross-arm. The common point is grounded at the location. The principle is illustrated in Figure V6.1.

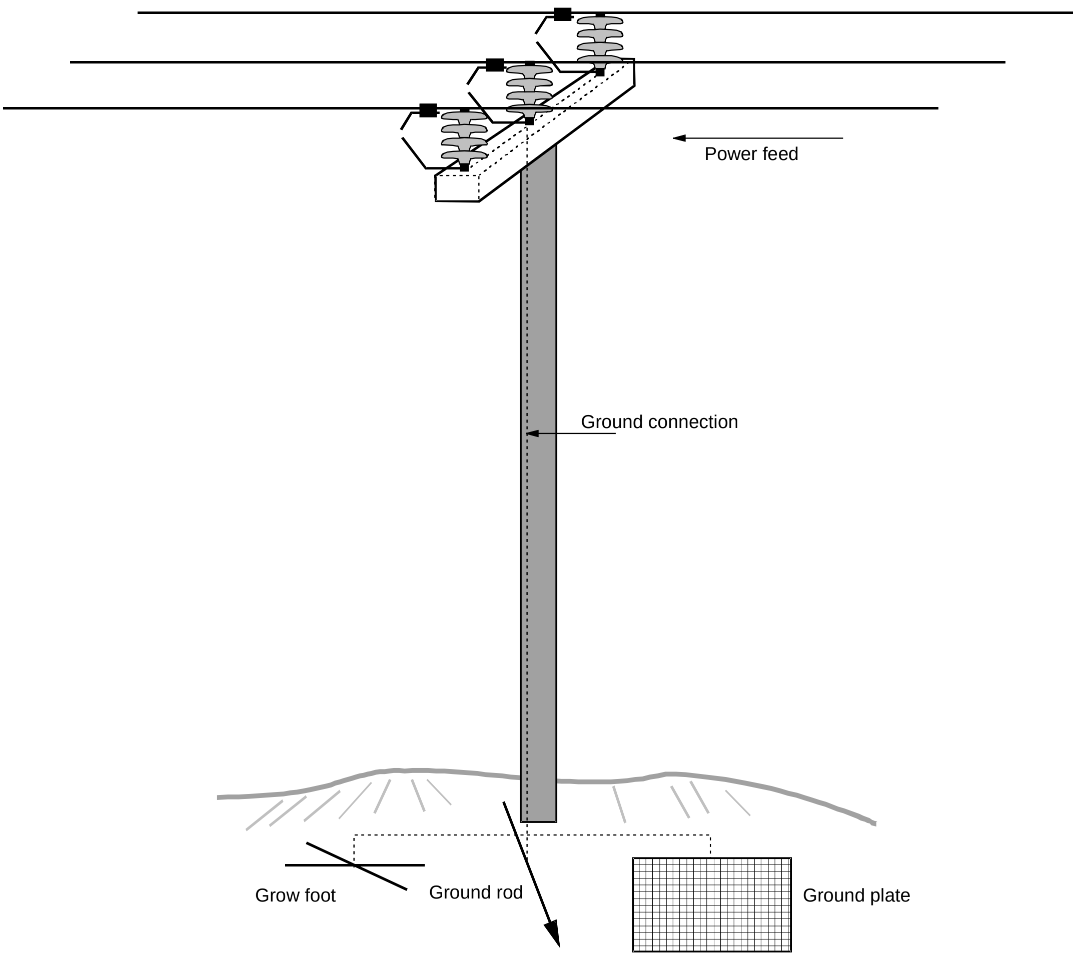

Figure V6.1: Protection configuration.

If the protection of components is to be effective, it is important that the ground resistance is kept as low as possible.

V6.2 Protection of components

Transformers

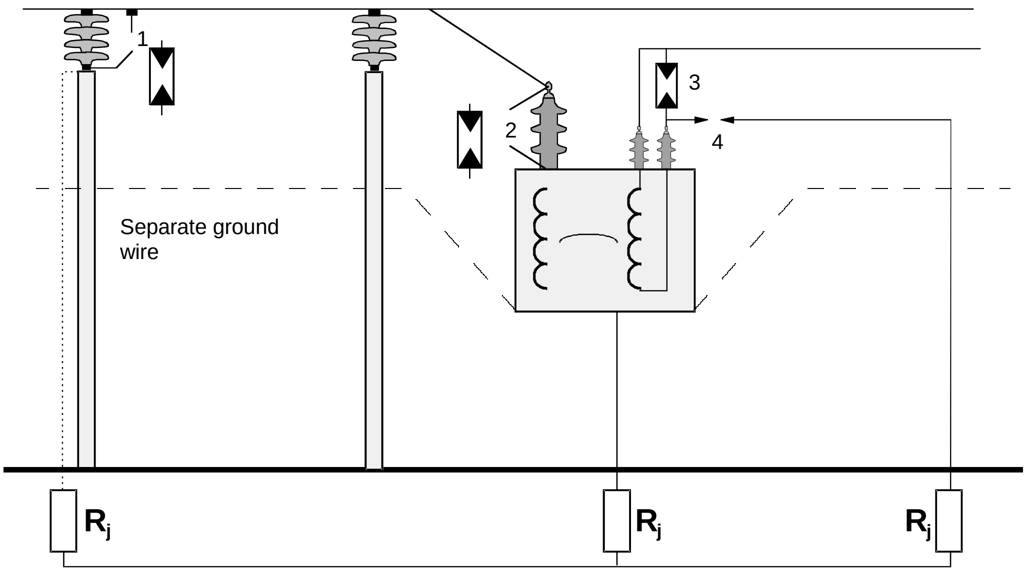

Figure V6.2: Protection of a transformer.

Figure V6.2 illustrates the location of a spark gap or arrester at the pole adjacent to a transformer 1). Also shown is additional protection of the high-voltage winding using a spark gap or arrester 2), protection of the low-voltage winding using an arrester/varistor 3), and protection of the neutral point using a separately-grounded protective device 4).

As a general rule it is recommended that protective devices be located as close to a transformer as possible. Fitting a spark gap or arrester to the pole(s) adjacent to the transformer is a common and relatively effective method which ensures separate grounding of the protective devices and the transformer but which by using spark gaps also provides many points of disconnection in the network to extinguish arcs.

Another method is to locate a spark gap or arrester directly across the high voltage input of transformer. This does not provide separate grounding of the protective devices and the transformer, with the result that high voltages can arise in the transformer casing, followed by flashover to the low-voltage winding and damage to consumers' appliances. The use of neutral point protective devices between the neutral point of the low-voltage winding and separate grounding in combination with an arrester across the low-voltage output will reduce the problem.

The use of a spark gap across the high-voltage input, combined with high voltage power fuses ensures selective disconnection of the transformer circuit and prevents the disconnection of the rest of the network. However, the fuses must be replaced, involving an extended interruption of the transformer circuit.

Cables

Inserted in an overhead line:
Here, arresters are located at each end of the cable and are grounded in combination with the cable screen.

At the end-point of an overhead line (entering a transformer, substation, etc.):
Here, protective devices are installed at the point the cable to the overhead line and are grounded in combination with the metallic screen of the cable. In the case of cables longer than about 30 metres, such protection will normally be capable of protecting both the cable and the component (transformer) at the end-point. In the case of cables longer than about 30 metres, it is recommended to fit overvoltage protection at each end of the cable.

V7 CROSS-ARM GROUNDING

Explanation of importance for protection strategy

The following rules determine the most advantageous grounding arrangement, based on the three types of grounding configuration – direct grounding, continuous ground line and insulated cross-arms.

V7.1 The effect of the grounding method

The *grounding method* in an ACC installation has an effect on the overvoltages which arise in the event of a lightning strike. "Grounding method" here means the way in which the cross-arms in the installation are connected to ground. It is assumed that metal or wooden cross-arms are used, with connection between the insulator attachments. Grounding conditions can be divided into three groups:

1) Direct grounding. Cross-arms connected to ground at the location. This also covers a situation in which the cross-arm is connected both to the ground at the location and to a continuous ground line.
2) Continuous ground line. Cross-arms connected to a continuous ground line but not connected to ground at the location.
3) Insulated cross-arm. Cross-arms are connected neither directly to ground nor to a continuous ground line.

When a continuous ground line is used, it is connected directly to ground at certain locations. However, the distance between these locations may be considerable, with the result that the grounding is not effective enough to deal with rapid events such as lightning strikes. Groups 2) and 3) will therefore be able to behave almost identically with regard to overvoltages between phases or between phases and cross-arms in an ACC installation. Groups 2) and 3) can therefore be combined, resulting in two main categories:

I) Grounded cross-arm: Cross-arm connected directly to ground at the location.
II) Insulated cross-arm: Cross-arm not connected directly to ground at the location.

In general, the following grounding arrangement can be recommended:

Pole without protective devices:
Insulated cross-arm to prevent flashover to ground caused by induced overvoltages.

Protective device fitted between phase conductor and cross-arm:
Grounded cross-arm. Because the voltage at the cross-arm is lower when it is grounded, the protective device is activated earlier. Grounding of the cross-arm will protect against both direct lightning strikes and induced voltages. In addition, components connected to the line are protected. However, there is no requirement to ground cross-arms to protect ACC lines.

Protective devices installed between phase conductors:
Insulated cross-arms to prevent flashover between phase lines and cross-arms.

It is not necessary to use a particularly low ground resistance to protect the line itself, because only the potential difference between the phases in an ACC line are to be limited.
The protection of other components in the network (transformers, etc.) depends on good grounding and low ground resistance, since it is the potential difference relative to ground which is to be limited.

V8 LINE CONFIGURATION

Explanation of the effect of selected line configuration on protection strategy

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Three different line configurations exist: Horizontal suspension, vertical suspension and triangular suspension. The following is an explanation of how exposed the different configurations are to lightning strikes.

Table V8.1 shows the estimated strike ratio for the three different line configurations using a value for β of 0.8 (cf. Chapter V3.3).

Table V8.1: Lightning strike ratio.

	Total	Outer	Mid	Pole
Horisontal	0.143	0.134	0.000	0.009
	Total	Lower	Top	Pole
Vertical	0.143	0.000	0.116	0.028
	Total	Outer	Top	Pole
Triangular	0.143	0.001	0.114	0.028

Pole height: Horizontal suspension: 7 metres
Vertical suspension: 8 metres
Triangular suspension: 7.35 metres

As seen in Table V8.1, there is no difference between the line configurations. The same number of lightning strikes will hit an ACC line, almost irrespective of the line configuration.

Neither does the line configuration have any effect on the number of lightning strikes which result in flashover (potential failure) in the line.

Increasing the phase spacing from 0.5 to 0.6 metres has almost no effect on the number of lightning strikes which result in failure of the line.

Vertical suspension is the most advantageous as regards prevailing electromagnetic fields close to the ground [8].

V9 RISK LEVEL AND FLASHOVER FREQUENCY

Explanation of the relationship between the terms

The risk level is determined by each individual planner and is a measure of how often flashover and potential failure is permissible in a line. ***Acceptable flashover frequency*** **is defined in terms of the risk level per kilometre of line.**

Calculations carried out in connection with direct lightning strikes on an ACC line provide an estimate of how many flashovers can be expected between phases in a line. Flashovers of this type may result in burning of the lines and failure before a circuit breaker disconnects the lines. Whether or not ACC lines are burnt depends on the magnitude and duration of the short-circuit current, which will depend on the location in the network. Even if flashover in an ACC line does not immediately result in burning through and failure of the line, the insulating covering of the lines will nevertheless suffer significant damage.

The "risk level" is an expression of how often flashover in a given length of ACC line can be accepted. The risk level is also referred to as *acceptable flashover frequency*, **H**, and is equal to the number of flashovers in an ACC line per kilometre per year.

For example, in an ACC line of 10 km length, one flashover (failure) every 10 years is accepted.

The acceptable flashover frequency is $H = \frac{1}{10\ km} \cdot \frac{1}{10\ years} = 0{,}01\ [\# / km \cdot year]$

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V10 INSTALLATION AND OPERATION

Description of assembly instructions and maintenance procedures

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ACC lines must be flawless before being put into operation. There must be no bare spots caused by stripping or penetration of the insulation. Contact between trees and the insulation is permissible for short periods, but must be rectified as soon as possible.

Installation

Poles, guy-wires and suspension equipment shall be designed as specified in the statutory regulations.

When pulling an ACC line, suitable pulling equipment or other arrangements must be employed to protect the XLPE covering against mechanical damage. When using greased conductors, the frog tool shall be attached to stripped conductor. Aluminium alloy conductors must be spliced using a tension-resistant ferrule compressed with a hexagonal crimping tool or using some other tension-resistant method. Any stripping or damage to the cover shall be repaired using self-amalgamating tape, heat-shrinkable tubing or similar materials.

Lines shall be tensioned to the sag corresponding to a temperature 5-10°C lower than the ambient temperature, to allow for subsequent settling or creep. The phase conductor spacing shall be at least 50 centimetres.

Insulators and/or helical ties and clamps must suit the dimensions of the ACC line. Penetrating clamps must be tightened to the specified torque and must not cause gaps in the insulation.

Operation

Because of their small lane width requirement, ACC lines can be erected in areas which were previously considered unsuitable for power distribution lines. The ACC system improves supply reliability, with no interruptions in the event of contact between lines or by trees and other grounded objects.

Following storms or bad weather the lines must be inspected to locate any damage. Repairs can then be carried out during normal working hours according to a schedule.

V11 CORROSION

Description of corrosion prevention measures

Sealed installations must always be used in coastal environments. Bare line installations must only be used in environments where they are not prone to corrosion. The choice must be made by the individual electricity supplier.

ACC lines are available as open and sealed types. Sealed lines do not allow moisture to penetrate to the inner conductors, leading to corrosion problems.

The electricity suppliers themselves must decide whether to use open or sealed lines based on an assessment of the corrosive nature of the environment at the location. Transition between areas of low and high corrosivity is, however, in most cases diffuse, making the choice difficult. However, corrosive environments can be mapped to determine boundaries between exposed and less exposed areas.

Data used in such mapping are based on three-month tests of wire-on-bolt samples developed by Bell Laboratories and as used by ALCAN (Aluminium Company of Canada). The bimetallic test uses a thin aluminium wire wound tightly around a threaded bolt. Iron bolts are used in marine atmosphere and copper in industrial environments. A Marine Corrosivity Index (MCI) or an Industrial Corrosivity Index (ICI) is calculated based on the percentage weight loss of the aluminium wire caused by the exposure. The corrosivity index is then used to classify the corrosive environment in an area.

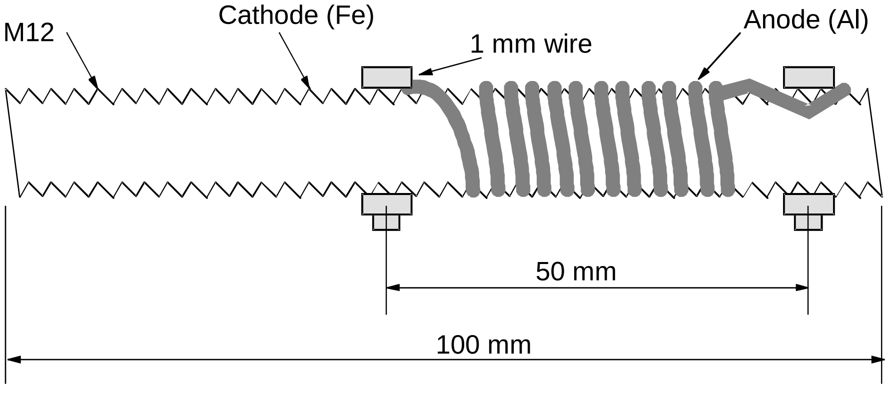

Figure V11.1: Wire-on-bolt testing in a coastal environment.

Movement of sea salt inland varies considerably with the weather conditions in different seasons of the year. A minimum test period of three months should therefore be used in the assumed most exposed period. The representativeness of the measurements is improved if the test period is extended to a year. When testing only in three-month periods, four 3-month measurements should be carried out in a number of strategically selected locations to obtain a correction factor relative to the mean.

Test locations should be selected to be representative of a larger area and so as to be relatively easily accessible. Wire-on-bolt samples are placed at each test site, for example attached to existing poles. The samples must not be shielded from exposure to the wind or sea by vegetation or structures.

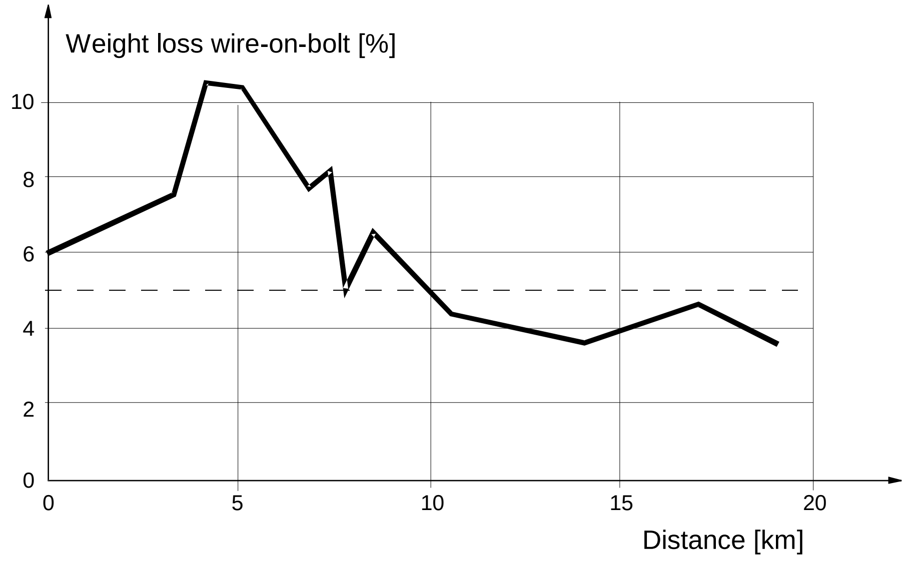

Figure V11.2: Example of variation in degree of corrosion along a 20 km distribution line.

Based on experience, a plastic-covered conductor system will be subject to leaks caused by the selected installation method or to damage in the insulation cover during construction or operation. Test lengths of ACC were therefore installed in the 24 kV network at Lista (South of Norway) in three different corrosive environments. The insulation in the test lengths was subjected to puncturing. The climate at Lista is representative of an exposed coastal area. Observations were made after one, three and six years and analyses [8] showed that the rate of decomposition was greatest in the first year and diminished towards the end of three years. At all the sites of scoring, wear and shot-gun damage, the exposed aluminium strands were to some extent corroded after six years of exposure to the coastal environment. This confirms that uninsulated installations must not be used in exposed coastal areas and that considerable caution must be exercised when erecting ACC lines. Grease impeded further spreading of corrosion of the damaged surfaces, confirming the importance of grease-filled lines in exposed coastal areas. In this connection it is extremely important to ascertain to what degree other water barriers (such as compounds and swelling powders) combat corrosion damage.

V12 LEAKAGE CURRENTS

Explanation of measures to prevent degradation of the insulation surface

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Leakage currents occur in environments prone to contamination by salt encrustation and may lead to degradation of the XLPE insulation of ACC lines. Maintaining a voltage at the tops of insulators will impede this effect.

Under special climatic conditions in exposed coastal areas, the XLPE insulation of ACC lines has been broken down close to the insulator attachment points. This is caused by contamination, causing leakage currents on the insulator surfaces in the vicinity of the attachment points, diverting current across the insulators to ground. Leakage currents in the range 2-5 mA will have the most serious degrading effect. This may lead to the formation of dry zones in the contamination coating where partial discharges may occur.

However, both operational observations and laboratory tests show that the problem can be avoided by keeping insulator attachments and internal conductors at the same potential. Penetrating clamps connecting to the insulator tops must therefore be used.

APPENDIX 2

Terminology and concepts:

Protection philosophy
With regard to protection of components connected to an ACC installation, protection of the ACC line shall be arranged in the same way as for lines with bare conductors. There is also an additional requirement to protect the lines themselves against burning.

Protection of ACC lines – Line Protection
The purpose of protection of ACC lines is to prevent flashover between phases or between phases and cross-arms, resulting in burning and failure of lines.

Arcing
When the voltage across a gap between electrodes becomes too high, the air loses its insulating properties, resulting in a discharge and subsequent arcing.

Arc wander
An arc will be affected by electromagnetic forces generated by a power line. An arc between bare lines will generally move in the direction of the line's power feed direction. The polymeric covering on ACC lines will impede arc wander and result in a stationary arc.

Power feed direction
In a radial network the power feed direction will be from the feed point towards the termination of the line. In a ring system the power feed direction will depend on the load situation.

Line burning
In the event of flashover between polymeric-covered conductors (ACC), a stationary arc will occur and the phase conductors may be burnt through.

Protection of components – Component Protection
The purpose of protecting components such as transformers, cables, etc. associated with a power line is to reduce overvoltages between phase conductors and ground and thereby prevent failure of equipment.

Direct lightning strike
This is a lightning discharge which directly strikes one of the phase conductors in a line. This results in the highest voltage load a line can be exposed to.

Induced overvoltages
These are caused by lightning strikes in the vicinity of a line. Induced overvoltages are far lower than those caused by direct lightning strikes, but they occur much more frequently.

Spark gap
Electrodes separated by a small gap, installed between phase conductors or between phase conductors and cross-arms to prevent damage to lines and insulators due to arcing.

Arcing horn
An electrode installed on a phase conductor to prevent a stationary arc from burning at a point on the ACC line and subsequently burning through the line.

Ignition wire
A conducting wire connected from an insulator top to an arcing horn, along which the base of an arc can migrate.

Penetrating clamp
A clamp attached to a conductor in an ACC line to achieve electrical contact with the conductor through the polymeric covering.

Arrester
An element installed between phase conductors or between phase conductors and a cross-arm. When exposed to high voltage an arrester will conduct current without an arc occurring.

Residual voltage
The voltage across a functioning arrester caused by the current passing through the arrester.

50 Hz residual current
Following a lightning overvoltage, the flashover location will function as a short circuit between the conductors, which carry a normal 50 Hz residual current (short-circuit current or line-to-ground short circuit current).

Continuous ground line
An ground conductor suspended between poles along an ACC line which is grounded at some poles. A continuous ground line will generally not represent an effective ground connection in the event of lightning overvoltages.

Direct grounding
“Direct grounding” here means that a cross-arm is directly connected to ground via a conductor running down the pole.

Insulated cross-arm
A cross-arm which is not directly grounded on site. In most cases such a cross-arm may also be considered insulated if it is connected to a continuous ground line.

Perforations
A direct lightning strike on a phase conductor may cause streamers, i.e. incipient flashovers between the phase conductors. This subsequently leads to the perforation of the ACC line insulation at a number of points near the strike site. Such perforations are small holes in the insulation which are rapidly filled with grease and in the short term will not result in a significant reduction in impulse integrity.

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