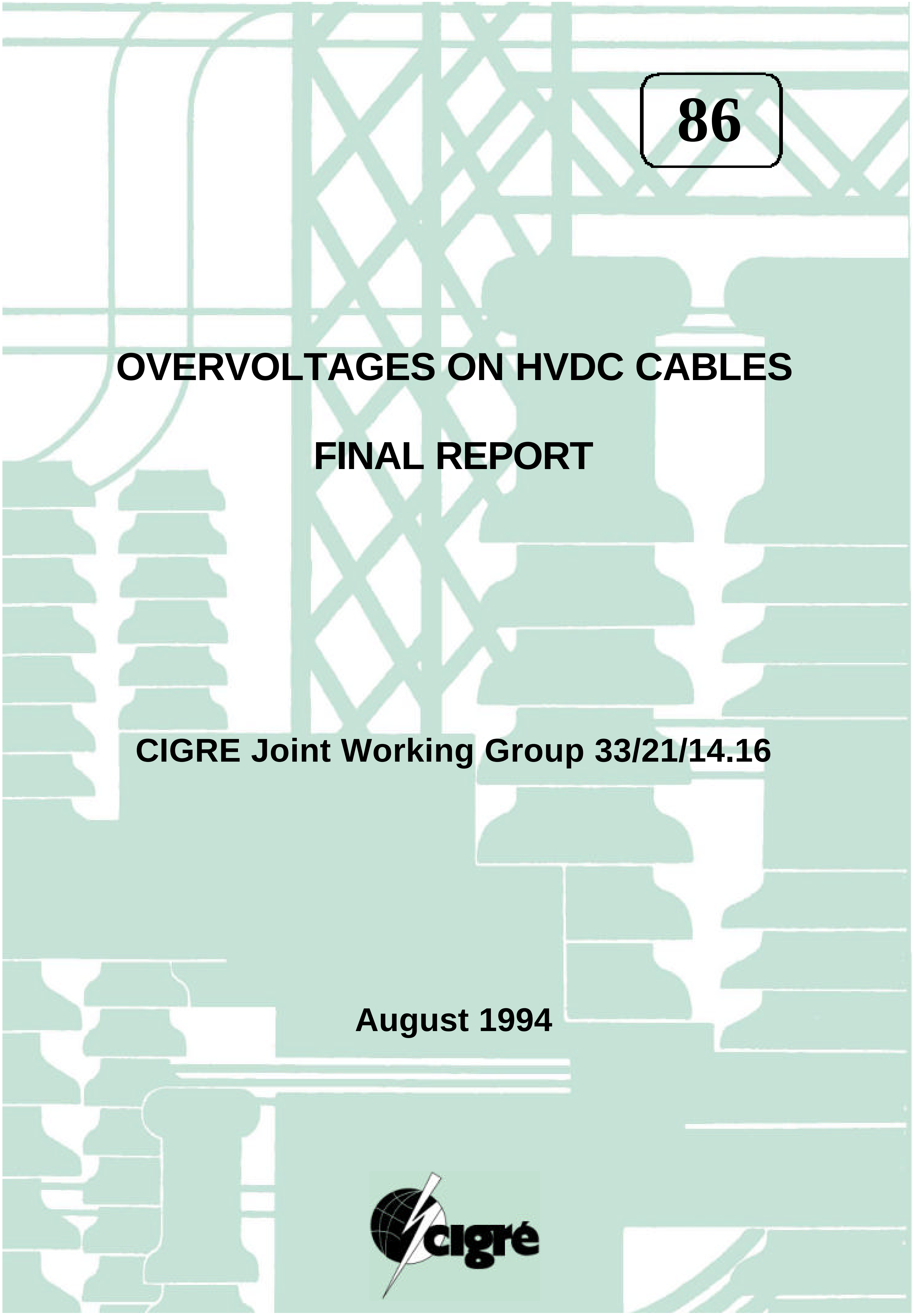

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# OVERVOLTAGES ON HVDC CABLES

## FINAL REPORT

CIGRE Joint Working Group 33/21/14.16

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## Summary

The number of HVDC Projects using long dc cables is increasing, mostly for submarine power transmission. A larger number of such HVDC schemes are already in operation or in planning stage. The economic design of dc cables is very important, because the cost of dc cables is high in proportion to the total cost of HVDC submarine cable transmission. The feasibility and economic viability of HVDC submarine cable projects can be improved if the power transmitted by a dc cable can be increased. As the current carrying capability of a dc cable is usually limited by thermal considerations the total transmission power capability can be increased only by increasing its dc operating voltage capability.

The increase in operating voltage means mostly also an increase of the voltage gradient in the insulation of HVDC cables. Besides the stresses at continuous dc operating voltage, the transient overvoltage stresses are of major concern. Therefore, the CIGRE Study Committees 14 (DC links and Power Electronic Equipment), 21 (High Voltage Cables), and 33 (Insulation Coordination) considered it important to organise a Joint Working Group (JWG 33/21/14–16) to evaluate the influence of transient overvoltages on dc cable insulation, compare the overvoltage levels with the dc cable test voltages, and investigate the applicability of overvoltage limiting devices.

This report summarizes in Table I the all important parameters of all known HVDC cables in operation or being planned up to now. DC cables using different technologies are covered, i.e. mass impregnated (MI), oil filled (OF) and gas filled (GF) cables. The gas filled cable has, however, been used only for one project, so the subjects of discussion of the report are mass impregnated and oil filled cables. Table II summarizes the test procedures used for the cables of Table I and indicates the development of test procedures through the years with regard to the loading cycles, the impulse voltages, and the dc (or dc + ac) voltages.

The insulation capability of dc cables depends on the maximum design stresses which can occur at different locations depending on load conditions, cable parameters and transient overvoltage stresses with and without superposition on the dc voltage. Representative values for relations between permissible overvoltage stresses and operating dc voltage have been evaluated. These values which are different for old and new mass impregnated cables and for oil filled cables indicate the level of stress beyond which the design of the dc cable depends on overvoltages. When overvoltages are reduced to this value the dc cable is designed

for the operating dc voltage only and then maximum economy of transmission capability per cable can be achieved. Taking into account safety margins between insulation withstand capability and overvoltage stresses, maximum overvoltage for such "optimum design" should be below about 1.9 p.u. for the new type mass impregnated cables and below 1.6 p.u. for the oil filled cables.

The report analyses internal and external overvoltages which can stress dc cables. Most of internal overvoltages (i.e. those due to switching, fault and control actions) are well below 1.5 p.u. and therefore do not influence cable insulation design. However, for some faults combined with HVDC–control failures, internal overvoltages over 2 p.u. can occur.

The external overvoltages are caused by lightning and are usually important only for mixed dc overhead line/dc cable transmission schemes. They can produce high stresses on dc cable insulation depending on the configuration and the assumptions for lightning severity.

The withstand values of dc cables are different for different types of overvoltage stresses. The typical values for mass impregnated and oil filled cables are given in the report.

The internal and external overvoltages may need to be limited by overvoltage protection equipment. Gapless metal oxide surge arresters are now mostly used. However, if overvoltage values lower than 1.9 p.u. are required special unconventional means can be used for overvoltage reduction.

Insulation coordination is based on an assessment of the maximum overvoltage stresses and the protection level of protective devices taking into account safety margins with respect to the designed withstand levels of dc cables. The paper suggests margins for external and internal overvoltages both for the cable and for associated connection equipment (including joints).

The work of the JWG can be summarized as follows:

- The maximum operating voltage of mass impregnated cables of the type now in operation is 400 kV. It can be further increased if the testing procedures are modified.
- The transient overvoltages should be limited to 1.9 p.u. for mass impregnated cables and to 1.6 p.u. for oil filled cables to permit the use of the optimum economic design of dc cables.
- Required overvoltage protection can be achieved by existing or improved protective devices.

Contents

## 1. Introduction and Scope of JWG 33/21/14–16

The number of HVDC projects using dc submarine cables is increasing. The economic design of dc cables is becoming very important, as usually the cost of dc cable is high in proportion to the total cost of HVDC submarine transmission scheme. The feasibility and economic viability of HVDC submarine cable projects can be further improved if the power transmitted by a dc cable can be increased. As the current carrying capability of a dc cable is usually limited by thermal considerations the total transmission power capability can be increased only by increasing its dc operating voltage.

The increase in operating voltage means also an increase of the voltage gradient in HVDC cables. Besides the stresses at dc operating voltages, the transient overvoltage stresses of the insulation are of major concern. Therefore, it has been considered to be of interest to evaluate the influence of transient overvoltages on the dc cable insulation, compare the overvoltages with the dc cable test voltages, and study the applicability of overvoltage limiting devices.

As the matter is of interest to three CIGRE Study Committees, namely SC 33 (Insulation Coordination), SC 21 (HV Cables) and SC 14 (DC links and Power Electronic Equipment), they established in 1991 a new Joint Working Group, JWG 33/21/14–16 with the following scope:

### Scope

- Determine the types of overvoltage that can appear on HVDC cables in service.
- Determine the parameters necessary to define the individual overvoltage of each type, taking into account their influence on the dielectric strength of the cables.
- Determine the significant values that these parameters are expected to present in service, and their dependence on the characteristics of the system.
- Examine the effect of the means of reduction of the overvoltages, evaluating the advantages of their adoption.
- Compare the results of this research with the experience of systems actually in operation or under design.
- Analyse the adequacy of the existing design and testing procedures for HVDC cables.

## 2. Data of HVDC Cable Systems

For the work of the JWG it was important as the starting point to collect all available data of HVDC cable systems installed or being planned up to now. The summarised data of Table I gives an overview of the important parameters of HVDC cables and the associated Table II gives their type test data which are discussed further in Section 3..

All known HVDC transmission cables at voltages $\geq$ 100 kV are listed. They are mainly in operation with some exceptions:

a) a few cables as noted in Table I are out of service or have been replaced by new ones;

b) Kingsnorth (No. 7) is no longer in operation;

c) Baltic (No. 21) and Kontek (No. 22) are under construction, and Hawaii (No. 18) has only been tested on short samples;

d) possibly short cables with very low power capability used for scientific purposes as well as cables for some development tests have not been included in Table I.

Nearly all systems are for submarine transmission with possibly small land sections. St. Lawrence (No. 17) is in a tunnel under the St. Lawrence river. HVDC underground transmission has been studied for urban penetration [13; 14] i.e. for bringing some GW power into large urban areas. But up to now only one such underground urban dc transmission scheme, the Kingsnorth cable (No. 7), has been in operation for a limited number of years.

The experience of dc cables spans over more than thirty years and has been satisfactory [15,16] especially from the point of view of insulation. When cables were removed from service, this was due to increased or changed power requirements and installation of new cables, and not due to ageing of the cables themselves.

The highest design voltages are 450 kV (Baltic No. 21) for mass impregnated cables and 500 kV (St. Lawrence No. 17) for oil filled cables. An increase of design voltage is considered possible. Recommendations for tests have been made up to 600 kV [17], 600 kV systems have been developed [18] and even higher voltages are considered to be attainable [19].

An unambiguous definition of maximum transmitted power capacity is not readily possible for dc systems, since many alternative schemes can be and have been used, such as monopolar with sea or metallic return, bipolar with different neutral connections, presence of spare cables and spare or backup circuits. The data of column 4 in table I are therefore given for consistency as power transmitted by a single cable even if this definition results in awkward numbers for some cases. With this definition the transmissible power value is in the range of some hundred MW (with lower values being obtained only for the very earlier dc cable projects).

As a conductor, mainly copper has been used for its good mechanical behaviour but in two instances aluminium has been preferred for its better electrical conductance to mass ratio.

Insulation [20] is in all cases made of paper tapes mainly mass impregnated or oil filled, with only one case of submarine gas filled cable (No. 4). Paper impregnated with a viscous compound without pressure assistance is especially suitable for HVDC submarine service in particular since there is no limit to the length of such cables. Up to now an insulation thickness of 19.0 mm for 450 kV is reported (No. 21), which permits a manageable overall dimension for the cable. Feeding the cable with pressurised fluids may allow a reduction in thickness but finds limitations for lengths above few tens of kilometers. The use of pressurised gas has now been superseded by mass impregnation.

Other types of insulation have been analyzed for dc cables, however without finding an application up to now:

a) extruded insulation, such as polyethylene or crosslinked polyethylene, has been studied in the seventies [21,22] and is now having a revival of interest [23,24];

b) laminated polypropylene is under development [25];

c) consideration has been given to gas (SF6) insulation [26] for land transmission.

The overall length of dc connections spans from around 35 km (No. 10) to 250 km (No. 21). There is presently no known limitation for lengths beyond 250 km. Shorter lengths than 30 km are usually covered by ac systems [27]. The only exception in Table I is St. Lawrence, as this is a short cable length for crossing a river, in the middle of a long (1500 km) HVDC overhead line.

The maximum sea depth is more than 500 m and tests have been made on cables for 2000 m depth; so no depth limitations are presently known except that heavy armour is required for deep cables with consequent influence on their mechanical design. On the contrary in shallow waters cables must be protected [28] against mechanical damage.

The above summary of the main design aspects for HVDC cables is perhaps too concise. Reference can be made to bibliography [1 to 12] for details about specific problems and how they have been overcome in particular projects.

## Table I – Some significant dc cable data for different HVDC schemes – Types and Dimensions

| | Name | Commissioning year | Voltage $U_0$ (kV) | Power (1 cable) (MW) | No. of cable | Conductor type note A | Conductor size ($mm^2$) | Insulation type note B | Insulation thick. (mm) | Length (km) | Max depth (m) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Gotland 1 (1) | 1954 | 100 | 20 | ) 1 | Cu s | 90 | MI | 7.0 | 100 | 160 |
| | | 1970 | 150 | 30 | ) | | | | | | |
| 2 | Cross Channel 1(1) sea | 1961 | 100 | 80 | 2 | Cu r | 340/390 | MI | 9.0 | 51 | 60 |
| | land | 1961 | 100 | 80 | 2 | Cu r | 605 | MI | 9.0 | | land |
| 3 | SA.CO.I. | 1965 | 200 | 100 | ) 2 | Cu o | 420 | MI | 11.8 | 119 | 500 |
| | | 1992 | 200 | 100 | ) | | | | | | |
| 4 | Cook Strait 1 | 1965 | 250 | 300 | 2+1 | Cu h | 520 | GF | 14 | 39 | 255 |
| 5 | Konti Skan: | | | | | | | | | | |
| | - Sweden Laesoe (1) sea | 1965/74 | 285 | 300 | 1 | Cu r | 625 | MI | 15 | 64 | 80 |
| | land | | 285 | 300 | 1 | Cu r | 800 | MI | 15 | 7 | land |
| | - Laesoe Jutland sea | 1965 | 285 | 250 | 1 | Cu r | 2x310 | OF(2) | 12.4 | 23 | 40 |
| | land | 1965 | 285 | 250 | 1 | Cu r | 2x310 | OF(2) | 12.4 | 1 | land |
| 6 | Vancouver 1 | 1969 | 300 | 156 | 2+1 | Cu o | 400 | MI | 18.5 | 4+27 | 200 |
| 7 | Kingsnorth (1) | 1971 | 266 | 320 | 2(4) | Cu h | 800 | OF | 10.3 | 84 | land |
| 8 | Mallorca/Menorca (3) | 1972 | 200 | 100 | 4 | Al h | 500 | OF | 8.4 | 44 | 90 |
| 9 | Skagerrak sea | 1976 | 262.5 | 250 | 2 | Cu r | 800 | MI | 16 | 125 | 570 |
| | land | 1976 | 262.5 | 250 | 2 | Cu r | 1000 | MI | 14 | | land |
| 10 | Vancouver 2 | 1976 | 300 | 185 | 2 | Cu h | 400 | OF | 11.7 | 35 | 200 |
| 11 | Hokkaido Honshu sea | 1980/93 | 250 | 300 | 2 (4) | Cu h | 600 | OF | 14.5 | 42/43 | 300 |
| | land | 1980/93 | 250 | 300 | 2 (4) | Cu h | 900 | OF | 13 | 1 | land |
| 12 | Gotland 2/3 | 1983/87 | 150 | 160 | 2(4) | Cu r | 800 | MI | 8 | 100 | 160 |
| 13 | IFA 2000 ) sea | 1986 | 270/280 | 250 | 8 | Cu r | 900 | MI | 12.3 | 50 | 55 |
| | Cross Channel II) land | 1986 | 270/280 | 250 | 8 | Cu h | 800 | OF | 10.75 | 18+8 | land |
| 14 | Konti Skan 2/3 | 1988/91 | 285 | 300 | 2 | Cu r | 1200 | MI | 15 | 64 | 40 |
| 15 | Fenno Skan | 1989 | 400 | 500 | 1 | Cu r | 1200 | MI | 17.5 | 200 | 117 |
| 16 | Cook Strait 2 | 1991 | 350 | 500 | 2+1 | Cu r | 1400 | MI | 17.5 | 40 | 260 |
| 17 | St. Lawrence | 1993 | 500 | 625 | 6 | Cu h | 1400 | OF | 26.8 | 5.1 | tunnel |
| 18 | Hawaii | tested | 300 | 250 | 2+1 | Al h | 1600 | OF | 10.9 | 67+154 | 2000 |
| 19 | Skagerrak 3 | 1993 | 350 | 500 | 1 | Cu r | 1400 | MI | 18.0 | 125 | 540 |
| 20 | Cheju sea | 1993 | 180 | 150 | 2 | Cu r | 800 | MI | 9.5 | 96 | 135 |
| | land | 1993 | 180 | 150 | 2 | Cu r | 800 | MI | 9.5 | 5 | land |
| 21 | Baltic | 1994 | 450 | 600 | 1 | Cu r | 1600 | MI | 19.0 | 250 | 60 |
| 22 | Kontek sea | 1995 | 400 | 600 | 1 | Cu r | 2 x 800 | OF(2) | 16.5 | 55 | 44 |
| | land | 1995 | 400 | 600 | 1 | Cu r | 2 x 800 | OF(2) | 16.5 | 120 | land |

Notes

A: Legend for conductor t ype
h = hollow
o = oval
r = round stranded
s = round solid

B: Legend for impregnation type
MI = mass impregnated
OF = oil filled (or fluid filled)
GF = gas filled

(1) - out of service
(2) - two cores, flat cable
(3) - tested for dc and ac, and operated at 138 kV ac
(4) - plus neutral

## Table II – Some significant dc cable data for different HVDC schemes – Type Tests

| | Name | Voltage $U_0$ (kV) | Type $U_0$ | Loading cycles | | DC and lightning impulse | Lightning impulse | DC and switching impulse | DC | DC+AC note A |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | at 2 $U_0$ | with pol. reversal at 1.5 $U_0$ | | | | | |
| 1 | Gotland 1 | 100 | MI | | | | 4.25 $U_0$ | | 4.75 $U_0$ | |
| 2 | Cross Channel 1 | 100 | MI | 10 | | | 3.5 $U_0$ | | | |
| 3 | SA.CO.I.<br>Sardinia-Italy | 200 | MI | 20 | 30 | | 3 $U_0$ | | | |
| 4 | Cook Strait 1 | 250 | GF | 40 | 60 | | 2.8 $U_0$ | | | |
| 5 | Konti Skan:<br>- Sweden Laesoe | 250 (1) | MI | 40 | 60 | | 2.8 $U_0$ | | 2.3 $U_0$ | |
| | - Laesoe Jutland | 250 | OF | 40 | 60 | | 2.8 $U_0$ | | 2.3 $U_0$ | |
| 6 | Vancouver 1 | 300 | MI | 40 | 60 | | 2.7 $U_0$ | | | 0.5 $U_0$+<br>1.5 $U_0$ |
| 7 | Kingsnorth | 266 | OF | 40 | 20 | | 3.0 $U_0$ | | | |
| 8 | Mallorca/Menorca | 200 | OF | 60 | 40 | | 3.25 $U_0$ | | | 0.5 $U_0$+<br>1.5 $U_{0(2)}$ |
| 9 | Skagerrak | 262.5 | MI | 20 | 10 | | 3 $U_0$ | | | 0+1.1 $U_0$ |
| 10 | Vancouver 2 | 300 | MI | 40 | 60 | -$U_0$+2.4$U_0$ | 2.7 $U_0$ | | | 0.5 $U_0$+<br>1.5 $U_0$ |
| 11 | Hokkaido Honshu | 250 | OF | 20 (3) | 10 | | 3.3 $U_0$ | | | |
| 12 | Gotland 2/3 | 150 | MI | 20 | 10 | -$U_0$+2.7$U_0$ | | | | |
| 13 | IFA 2000 Cross Channel II) | 270/280 | MI | 20 | 10 | | 3 $U_0$ | 0 $U_0$ +<br>2.7 $U_0$ | 3.1 $U_0$<br>2.8 $U_0$ (7) | |
| 14 | Konti Skan 2/3 | 285 | MI | 20 | 10 | -$U_0$+2.6$U_0$ | | | | |
| 15 | Fenno Skan | 400 | MI | 20 | 10 | -$U_0$+2.4$U_0$ | | -$U_0$ dc+<br>2.2 $U_0$ | | |
| 16 | Cook Strait 2 | 350 | MI | 20 | 10 | -$U_0$+2.7$U_0$ | | -$U_0$ dc+<br>2.2 $U_0$ | | |
| 17 | St. Lawrence | 500 | OF | 20 | 10 | -$U_0$+2.45$U_0$ | 2.9 $U_0$ | 0 $U_0$ +<br>2.35 $U_0$ | | 0.8 $U_0$+<br>1.1 $U_{0(4)}$ |
| 18 | Hawaii | 300 | OF | 20 | 10 | | 2.6 $U_0$ | | | |
| 19 | Skagerrak 3 | 350 | MI | 20 | 10 | -$U_0$+2.7 $U_0$ | | | | |
| 20 | Cheju | 180 | MI | 20 | 10 | -$U_0$+3 $U_0$ | | | | |
| 21 | Baltic | 450 | MI | 20 (5) | 10 (6) | -$U_0$+2.2 $U_0$ | | -$U_0$ dc+<br>1.9 $U_0$ | | |
| 22 | Kontek | 400 | OF | 20 | 10 | -$U_0$+2.4 $U_0$ | | | | |

Notes

A: The two figures give:
a) the dc level
b) the peak amplitude of superimposed ac wave
- duration is 1 to few seconds

(1) - different from operating voltage (285 kV)
(2) - also 0.5 $U_0$ + 2 $U_0$ damped oscillation
(3) - and 60 cycles at 1.5 $U_0$
(4) - add $U_0$ + 2.45 $U_0$ with high frequency oscillations and 0.5 $U_0$ + 1.37 $U_0$ at 120 Hz.
(5) - 1.8 $U_0$/1.6 $U_0$
(6) - 1.5 $U_0$/1.35 $U_0$
(7) - land cable portion

## 3. Present Practice for Tests of HVDC Cables

Equipment tests are extremely important for reliable operation. They should represent as closely as possible the stresses during operation. Therefore with increasing knowledge of cable insulation characteristics and overvoltage stresses the tests can be altered for new cable projects if they do not correspond to the conditions encountered in the system. For the discussion on the influence of tests on the design of dc cables the JWG collected the type test procedures specified for the dc cables installed or being planned up to now.

Table II contains a summary of tests carried out on the cables of Table I.

Except for the very earliest cable projects, the loading cycles and polarity reversal test have been performed on cable and accessories. The voltage test level has always been 2 $U_0$* for loading cycles and 1.5 $U_0$* for polarity reversal during loading cycles, as recommended for more than 20 years by CIGRE SC 21 [29,30,17] and the recommended total number of 30 cycles has been universally adhered to in the last 15 years.

Following the last recommendations [17] the test consists of 10 daily loading cycles with an applied voltage of $+2\ U_0$ followed by 10 cycles with a voltage of $-2\ U_0$. Each cycle consists of 8 hours heating in such a way that at the end of the cycle the conductor temperature is + 5° K above the design temperature and the temperature difference across the insulation equals the design value, followed by 16 hours natural cooling to ambient temperature. These tests are followed by 10 polarity reversal cycles at 1.5 $U_0$, where during loading cycles as above, polarity is reversed every 4 hours (one reversal coincident with cessation of heating). For testing purposes, the time span for polarity reversal is 2 minutes maximum. This test is intended to prove the adequacy of the cable for the required rated dc voltage. Testing procedure for the very latest Baltic cable (No. 21) regarding temperature and voltage levels has been modified to correspond more closely to its operating conditions. CIGRE SC 21 is now reconsidering the test requirements for the loading cycle and polarity reversal test.

Lightning impulse tests have also generally been performed, mainly at test levels from 2.7 $U_0$ to 3.5 $U_0$. The purpose of impulse test is twofold: first of all it is a very sensitive test of the good condition of a lapped insulation, both in the cable and in

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* *$U_0$ is the rated dc voltage between conductor and screen*

the accessories, with the further advantage of being widely used also for ac systems and reasonably easy to perform. The second advantage of the impulse test is that of being somewhat correlated to the withstand strength of the insulation against overvoltages of internal and external origin.

The correlation is not a direct one, because the strength of a dc cable under conditions of lightning impulse $U_p$ (to ground) superimposed on a dc voltage $U_o$ of reverse polarity is lower compared with the strength under conditions of the impulse alone $U_i$ (Fig. 1):

$$U_P = U_i - KU_o \qquad (1)$$

where:

$U_i$ = the maximum lightning impulse voltage to ground acting alone (kV),

$U_p$ = the maximum transient voltage to ground with lightning superimposed on $U_o$ (kV); it is critical when of the polarity opposite to $U_o$

$U_o$ = the rated dc voltage which is the dc preapplied voltage (kV)

K = a coefficient $0 < K < 1$ defined in appendix 1. Representative values of K are given in Chapter 4.1.

Since the test employing the impulse alone is not directly related to the insulation level to ground of the transmission system, in more recent years a lightning impulse test combined with dc voltage of opposite polarity is being performed in addition to or as an alternative to the impulse test. In this case no increase in level is needed to allow for the effect of the coefficient K, and the test level $U_p$ is directly related to the overvoltage level in the system, taking into account the wave shape or wave duration factor and a safety margin.

Other tests (in Table II) are dc voltage alone as performed in the earlier years, dc plus ac voltage in the seventies and switching impulse voltage (sometimes superimposed on dc) in the eighties.

Here again the St. Lawrence case (No. 17) is an exception, where a complete set of type tests has been performed, both because of its peculiarity as a short cable section in a long overhead line, and because it is the first 500 kV cable to be installed [11].

# 4. Insulation Capability

## 4.1 Electric Stresses in the Insulation

A summary of factors which influence the electric behaviour of HVDC cables is presented here in order to provide an understanding of the design the solutions, adapted in the existing (or planned) schemes.

When an impulse, or a step voltage is applied, the electrical stress distribution E (in kV/mm) in the cable as a function of radius r is the "capacitive" one, i.e.:

$$E(r) = \frac{U_a}{r \ln r_e/r_i} \qquad (2)$$

$U_a$ = the applied step or impulse voltage (kV)
$r_i, r_e$ = the internal and external radius of insulation (mm)

From equation (2), maximum stress is on the internal radius, $E(r_i)$. It may be noted that stress distribution depends in principle on permittivity , but when the latter is constant, it is not included in the equation.

The most characteristic factor under dc voltage conditions, when the stress is proportional to insulation material resistivity, is the dependence of electric conductivity on both temperature and electric stress. From an experimental and a theoretical point of view, for both mass impregnated and oil filled paper insulation, the most representative expression, for the conductivity σ appears to be [32]:

$$\sigma = \sigma_0 \exp\left(-\frac{a}{T}\right) + b\,|E|) \qquad (3) \quad *)$$

where:

$\sigma_0$ = a constant of conductivity which does not influence stress distribution

a = $1.16\times10^4$ K the temperature coefficient

b = 0.03 mm/kV the electric stress coefficient

T = the absolute temperature (K)

$|E|$ = the absolute value of stress (kV/mm)

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*) From equation (3) the stress distribution can be obtained only numerically. Some approximate expressions [33] are sometimes used, which give an explicit function E = E (r,T).

Thus the conductivity is lower at lower temperatures, and correspondingly the "dc" stress is higher. As a consequence, under dc the well known stress inversion is obtained, that is, when the cable is heavily loaded the maximum stress is not at the conductor but at the outer insulation screen which is colder, and the stress becomes higher, the higher is the temperature difference across the insulation (Fig. 2). For this reason the loading of the cable may be limited by temperature drop across the insulation in addition to the maximum allowable temperature in the insulation.

The stress inversion explains the reduction in breakdown strength given in equation (1). In fact, assuming that breakdown occurs with the same maximum stress both under impulse alone and under impulse superimposed on dc of opposite polarity [34], the following result is obtained (see Appendix 1):

$$\frac{E_{dc}(r_i)}{E_{co}(r_i)} = 1 - K \qquad (4)$$

where:

$E_{co}(r_i)$ = the capacitive stress (at $U_o$) at the internal radius
$E_{dc}(r_i)$ = the resistive stress (at $U_o$) at the internal radius

From equation (4), the coefficient K is computed. It depends on cable design and is of the order of 0.1 for a cold cable (with no load), from 0.4 to 0.6 for a normally loaded cable, and could approach 1 for overload conditions.

Moreover with the same assumption a relationship is obtained between design stresses and voltage ratios:

$$\frac{U_p}{U_o} = \frac{E_p(r_i)}{E_{co}(r_i)} - K \qquad (5)$$

where:

$E_p(r_i) = E_i(r_i)$ = the design stress under impulse with and without a superposition of dc voltage (which is maximum at internal radius)

### 4.2 Overvoltages and Cable Design

In order to correlate overvoltages in HVDC cable systems, impulse test voltages and cable insulation withstand, let assume:

$$U_p = k_s \cdot k_w \cdot U_v \qquad (6)$$

where:

$U_v$ = the expected overvoltages in the cable (of different waveshapes and durations)

$k_w$ = a waveshape factor which correlates withstand for overvoltages of waveshape $U_v$, to lightning impulse $U_p$ (superimposed on dc voltages of opposite polarity)

$k_s \geq 1$ a safety factor

Let now suppose that a cable is designed according to its continuous service requirements. In this case let $\overline{U}_p$ be the impulse test voltage which can be withstood by the insulation. As long as overvoltages are such that, according to equation (6), $U_p > \overline{U}_p$, then a reduction of overvoltage levels would permit a reduction in cable insulation. But there is no advantage in reducing overvoltages below $U_p = \overline{U}_p$, since in this case the cable design would not be changed from that dictated by service requirements.

Equation (5) gives the answer in terms of admissible stresses under transient voltage $E_p$ and service voltage $E_{co}$, and of coefficient K. In order to obtain some very general quantitative values, indicative values of withstand level $\overline{U}_p/U_o$ are given in Table III.

TABLE III – Representative values of design stresses and intrinsic voltage ratios

| $E_p$ (kV/mm) | $E_{co}$ (kV/mm) | K | $\overline{U}_p/U_o$ | Representative cables |
|---|---|---|---|---|
| 80 | 25 | 0.4 | 2.8 | old MI |
| 85 | 30 | 0.4 | 2.4 | new MI |
| 90 | 35 | 0.6 | 2.0 | oil filled – OF |

The first line represents design values of the traditional mass impregnated cables. Now considering for stresses $U_i/U_o = 3$ approximately and hence, from equation (1) with $K = 0.4$, $U_p/U_o = 2.6$ approximately it can be seen from Table III that the capability $\overline{U}_p > U_p$. Therefore the overvoltage level was in general lower than what could be withstood by the cables, designed for their service requirements.

The second line in Table III represents indicative values for new mass impregnated cables, with higher service stress. The result is that test voltage ratios $U_p/U_o$ of the order of 2.4 are required in order that the cables be designed on the basis of their continuous service requirements and not for transient duty requirements. It is too early here to give indications about the factors ks and kw, but, assuming an overall figure $k_s k_w = 1.25$ (e.g. for lightning superimposed on dc $k_s = 1.25$ and $k_w = 1.0$), from equation (6) it would result $U_v/U_o = 1.9$.

The third line in Table III refers to oil filled cables, where, due to higher service stress and temperature capability, a lower value $\overline{U}_p/U_o = 2.0$ applies. Since from equation (1) the required test overvoltage ratio $U_p/U_o$ is 2.4, these cables are presently tested on the basis of overvoltage requirements, and an improvement of cable economy could result if overvoltages are reduced. Considering again a general overall value $k_s.k_w = 1.25$, the overvoltage level should be reduced down to $U_v/U_o = 1.6$.

It may be noted that the values of design impulse stress $E_p$ given in Table III depend on the intrinsic characteristics of the insulation and on manufacturing technology [35]; they are typical of paper insulation and have been kept constant over the years not withstanding the increase in thickness and in overall diameter. Values of $E_{co}$ are defined on the basis of past experience and ageing properties of impregnated paper under dc. Since ageing characteristics result to be very good [36,37], an increase of $E_{co}$ may be envisaged.

## 5. Overvoltages

Insulation coordination of HVDC cables is strongly affected by lightning and internal overvoltages (temporary overvoltages and switching surge type overvoltages). Internal overvoltages will be discussed in chapter 5.1.

Lightning overvoltages can not enter a pure HVDC cable transmission system. Faults on dc cable or faults on the cable side of a smoothing reactor in converter stations can, however, lead to travelling waves with steep front. Amplitude of overvoltages resulting from this case is low, but steep voltage changes, with the amplitude reaching twice the value of the voltage before fault, can occur. These stresses, however, do not represent any major problem for the cable insulation of present dc cable designs.

In mixed dc overhead line/dc cable transmission, however, lightning overvoltages can enter the dc cable and can be decisive for dc cable insulation. The stresses resulting from lightning will be discussed in chapter 5.2.

## 5.1 Internal Overvoltages

### 5.1.1 Overvoltages lower than 1.5 p.u.

Most of internal overvoltages occuring in dc cable transmissions have amplitudes lower than 1.5 p.u. and durations in the range of 100 ms. They do not influence insulation coordination of dc cable and there is no need for their further limitation by overvoltage protection, as the dc cable insulation capability for internal overvoltages at the given operating voltage is higher.

#### 5.1.1.1 Normal Power Changes

During normal power changes, the direct voltage follows the normal voltage control (by means of control angle or converter transformer on–load tap changers), which keeps the transmission voltage substantially constant both when increasing or when decreasing power. The current level is adjusted to obtain the desired power level. (Figure 3a)

If necessary due to cable properties, for power decrease the power regulator can be designed to first decrease the voltage (with the firing angle of the converter combined with action on the tap changer), to achieve the desired value, e.g., 75% of the nominal value. Further decrease of the power is then obtained as normally, through a current reduction.This method is shown in Figure 3b.

At normal power reversal the power is decreased first to zero, in such a way that the tap changers and reactive power compensation switching are able to follow to keep the direct voltage substantially constant. Voltage polarity reversal may occur very quickly (< <1sec) or take a long time depending on other system conditions and control sequences used to achieve the desired final operating mode.

The power reversals as such do not impose higher overvoltages on the cables, but may occur several times within a 24 hour operating period. Figures 4 show how power reversal is normally done.

#### 5.1.1.2 External Disturbances Causing Voltage Variations

Relatively quick variations of the ac system voltage, may occur as a consequence of normal daily ac load, ac line or reactive power compensation equipment switching. These are normally limited to +5% or at worst +10% of the nominal voltage, due to requirements imposed on the ac system voltage quality by ac power consumers.

To achieve an increase of the direct voltage through the ac system voltage, it is however necessary that the ac voltage variation occurs at the VST (Voltage Setting Terminal) of the dc transmission. The ac voltage at current setting terminals will not cause any voltage increase.

Additionally even for ac voltage variations occurring at the VST, the control margins available and the type of control employed, normally do not allow the whole voltage variation to be transferred onto the dc side.

For a substantial voltage disturbance, a control mode shift would occur and the VST would lose the voltage control, which means that it would start to control current, while the terminal previously controlling current would impose its voltage and establish the new system direct voltage. A total response of the voltage, current, power and reactive power controls, in all terminals will give the direct voltage increase. Typically the highest increase is only a few percent of the nominal d.c. voltage. The duration of the imposed overvoltage on the dc side by these events is highly dependent on the speed of the converter transformer tap changers.The normal voltage is expected to be restored after 1 minute of the initial event causing the voltage variation. Figure 5 illustrates this case.

For severe ac network disturbance causing direct voltage rise, all stations contribute to limit the dc side voltage. Therefore to cause a considerable increased direct voltage, both ac sides of the system must be affected for the case of a point-to-point transmission.

The most unfavorable case, is an emergency power change from full to minimum power. This means that the power transmission has almost ceased in both poles of a bipolar scheme imposing a nearly full load rejection on both ac networks as schematicaly shown in Figure 6a. In this situation the amplitude and duration of the overvoltage are initially only dependent on the ac system characteristics. Of particular importance for the determination of the highest amplitude is the strength of the ac power system in relation to the dc power infeed at the particular point of the system, i.e., the short-circuit ratio at the converter station. The highest amplitudes of these overvoltages are 1.3 - 1.4 pu, however these levels are rather an exception than the rule.

The duration is dependent on the ac network voltage regulators and on the reactive power, ac voltage and tap changer controls of the converter stations. A reasonable assumption is that the voltage regulators will act effectively to reduce the overvoltage within the first 200 - 500 ms. The further reduction to nominal values and corresponding compensation for the readjusted load conditions will be achieved by the dc side voltage control (tap changer control) and the reactive power and ac voltage controls at the converter stations. These controls would certainly be carried out within one minute.

Due to flexible design of HVDC controls, it is fully possible, assuming that increased converter equipment costs are justified by decreased cable costs, to achieve an emergency power change by a combined action of voltage and current reduction, which would keep the dc side voltage within a specified range (Figure 6b).

Power reversal combined with overvoltage, could be caused by an emergency power reversal (relatively high speed). In this event the worst situation would certainly occur when full power in one direction should be reversed to minimum power in the opposite direction (Figure 7a): –

a) Power is decreased from maximum to zero by current reduction which causes the direct voltage to increase to a value determined by the short–circuit ratio at the stations.

b) Control mode switch over, required to operate in reverse power direction take place.

c) Start up in the new power direction mode to a condition while the overvoltage is still present.

d) Overvoltage is reduced by the controls and regulators described above and voltage is back to normal values within one minute or less.

It is important to point out that the power reversal sequence can take place very quickly. It is also possible for this case to implement controls to provide a picture as shown in Figure 7b, avoiding dc overvoltages.

#### 5.1.1.3 DC side disturbances

The overvoltages for this type of disturbance are transient to temporary, i.e., from some milliseconds in some of the cases to a couple of seconds in others. The typical decay times are highly dependent on the relative length between cable and overhead line sections. For cable–dominant systems longer decay times are expected as the discharge energy through corona becomes less important.

In transmission systems which consist of overhead line and cable sections, lightning overvoltages and those initiated by earth faults are considered to be the most frequent events which may cause voltage stresses on cable portions and their terminations.

Single commutation failure may occur but in modern thyristor valves using control systems provided with redundancy sustained commutation failures should be considered relatively rare based on the available operating experience of existing schemes.

Similarly other control system failures such as missing control pulses in rectifier or inverter mode, or uncontrolled inverter operation should be considered as very unlikely. In the last named group should also be classed the control failure resulting in starting up of a dc scheme against an open–ended line in all its variations, particularly an uncontrolled rectifier deblocking into such a circuit configuration.

An earth fault causes reflections at the ends of the cable, as the overhead line has a considerably higher surge impedance. The reflected wave has nearly the same amplitude as the direct voltage but with opposite polarity. After reflection at fault location, the voltage at the cable becomes approximately zero. Thus for a short duration of a few milliseconds the cable insulation will experience one or several polarity reversals.

At a restart attempt after a fault on the dc line section of the line/cable transmission overvoltages may occur due to:

a) reflections;

b) load rejection of the faulted pole;

c) reduced reactive power consumption of faulted pole;

d) operation of rectifier at lower than normal firing angle.

If the overhead dc line insulation is not capable of withstanding the re–applied voltage, the attempt is unsuccessful and the whole sequence is repeated a preset number of times. For systems with no overhead line this sequence is not applicable, instead the station design and protections should be selective to distinguish cable faults from switchyard earth faults.

In a normal case the event ceases at a successful reenergization of the line after the first or second deionization interval, restoring the normal pole operation (Figure 8).

At earth faults on one pole of a bipolar transmission having the two pole lines on the same tower, overvoltages will also be induced on the healthy pole with amplitudes varying from 1.1 – 1.5 p.u. and with duration of some milliseconds. The front of waves can be classified as being of switching surge character. The amplitude is dependent on the circuit configuration, i.e., relative length of cable with respect to the length of the overhead line. Overhead line–dominant transmission systems give the highest overvoltages (1.5 p.u.).

For an overhead line–dominant system with a very short cable at the end of the overhead line, the cable overvoltages can however, be higher than 1.5 pu, if no additional measures are taken (Chapter 5.4).

Furthermore, the settings of the control system should be optimized to avoid too fast recovery in order to improve the voltage wave shape at cable sections. This requirement might be in conflict with general expected performance of the dc link for post–fault power recovery. This situation will be applicable in a number of cases described below; it will then be referred to as "Fast Power Recovery Conflict" (FPRC).

In practice, this means that high undamped voltage oscillations at cable locations, should be identified and remedial control measures determined in the dynamic performance study conducted for the hvdc application.

## Single commutation failures

At commutation failures, which are normally caused by disturbances in the inverter ac system, transient power reversals occur due to voltage oscillation between the dc line (including cable) and smoothing reactor (Fig. 9), similarly to what is experienced at earth faults shown in Fig. 8.

At recovery, a transient overvoltage occurs in a similar fashion as described above for the dc earth fault, since the dc voltage is about to be reestablished after a "short" time with zero power transmission, mainly caused by the collapse of the voltage at the inverter.

## Sustained commutation failures and oscillatory disturbances on the dc side.

There are a number of cases which give rise to an alternating voltage to appear on the dc side. The most classical one is obtained with the assumption that a commutation failure causes the dc voltage to collapse, with a possible subsequent polarity change, after which the transmission recovers and a new sequence of these events is initiated (Fig. 10) and repeated with a certain frequency.

The amplitude and period of these oscillations are determined by the parameters of the dc circuit.

This case is theoretical and unlikely to occur in practice, it could be achieved by introducing errors in the control amplifiers deliberately, which would give erroneous reference signals to valve firing control causing the valves to fail to commutate even under normal system conditions. It also should be remembered that many of these classical cases come from the older mercury–arc valve schemes.

Another case corresponds to unsymmetrical ac network faults, e.g., a single phase to earth fault, which imposes a negative sequence voltage to be commutated by the converters and creates a 2nd harmonic voltage on the dc side. The amplitude of the observed oscillation on the dc side is then determined by the 2nd harmonic impedance seen from the converter terminals, as well as the "active impedance" provided by the control dynamics. This type of event may be frequent as single line to ground faults may occur more frequently somewhere in the ac power systems. The severity of these events is also determined by resonances on the dc side, which can be affected by choice of dc smoothing reactors, dc filters and converter station control system dynamics.

### Loss of control pulses to rectifier

At blocking of the rectifier, i.e., removal of all control pulses to the valves, the dc voltage changes polarity, due to the energy stored in the smoothing reactor and the behavior of the inverter, which "follows" the voltage collapse by operating with a rather high extinction angle. The reverse voltage obtained in this situation can be as high as the nominal voltage UdN(+15%) as shown in Fig. 11.

### Loss of control pulses to inverter

Even higher overvoltages can be generated when peak rectification is combined with load rejection (also discussed in Chapter 5.1.2). This case can theoretically be achieved by loss of the control pulses at the inverter.Typically the phenomena is illustrated in Figure 12.

The following sequence would cause considerably high overvoltages:

The first event to start the sequence is an assumed blocking of the inverter with telecommunication channels between stations out of order.

a) Due to the value of the direct current and the strength of the connected a.c. networks, the d.c. current is extinguished in the inverter valves, but not through the rectifier smoothing reactor and line (cable) capacitances.

b) A too fast control action on the rectifier terminal may cause a rapid increase of its voltage to keep ordered current. A consequential reflected wave can contribute to the line overvoltages when inverter end becomes open. Here a FPRC (Fast Power Recovery Conflict) is nearly impossible to avoid.

c) Resonances between cable capacitance and line and smoothing reactors inductance.

The dominant frequency in this case is the power frequency (Fig. 12), since the current extinction combined with removal of control pulses, leaves the last conducting valves continuing to apply only one of the network ac phase voltages onto the dc side.

This classical scenario loses its credibility because in practice several rare contingencies have to be fulfilled simultaneously as follows:

1st – Control or main circuit fault requiring inverter blocking action without possible correct choice of by-pass-pairs with additional failure to execute the complementary actions in a correct protective shut down sequence, or;

inadvertent blocking without by-pass-pairs order being issued by the active control system, without change over to the redundant control system, prior to blocking.

Either of these control mal-operations are very rare by themselves in present-day control systems

2nd – Inverter blocking without firing by-pass-pairs;
Modern enhanced control sequences normally eliminate completely the risk of an uncontrolled blocking.

3rd – No inter-station communications available;
Rectifiers would otherwise be ordered to a forced retard.

4th – Unfavorable combination of:
- ac system strengths and,
- direct current level.

The above is meant to cause the direct current to just touch the zero line in a single point to allow its extinction after the first swing at the fundamental frequency. For many schemes this situation is not possible with realistic parameters. Additionally, this can be significantly counteracted by the converter control damping of fundamental frequency oscillations.

5th – DC side circuit first resonance as close as possible to ac fundamental frequency by means of coincidence of the design parameters, e.g., number of parallel connected cables. This is normally possible to avoid with the proper choice of the lowest resonance frequency range of the d.c. network to lie comfortably below the ac fundamental frequency for all circuit configurations. As mentioned above, the fast action of the converters can then give the damping of fundamental frequency oscillations.

Uncontrolled inverter

If the inverter for some reason would become uncontrolled, i.e., with a firing angle $\alpha = 0$, an immediate voltage polarity change would take place, as if suddenly a "diode bridge" replaced the controlled inverter. Both voltage and power would change sign rapidly (Figure 13).The rectifier would act to limit the current as the voltage would be below a preset abnormal low value.

After a while the dc line fault protection would act to trip the pole with some possible restart attempts. No severe overvoltages would, however, be observed, the main stress would be the sudden voltage polarity reversal.

### 5.1.2 Overvoltages higher than 1.5 pu

Some of the faults described in Chapter 5.1.1 combined with control malfunction can, however, lead to overvoltages higher than 1.5 pu. Depending on the nature of the control failures and the system data - especially if resonance conditions at the fundamental frequency are present in dc circuit - overvoltages exceeding 2 pu can occur. These overvoltages should be limited by overvoltage protection e.g. surge arresters to gain economic advantages in the DC cable insulation. A detailed treatment is needed for each HVDC cable project to determine whether these overvoltages can occur, their amplitude and their probability.

#### 5.1.2.1 Loss of firing pulses in invertor or invertor blocking

To illustrate this severe case calculations have been made on benchmark model suggested by CIGRE WG 14-02 [38], representing a cable transmission scheme. However, some modifications have been made regarding the cable length, cable representation (using PI-sections) and strength of the AC system at the invertor side. The cable length was chosen in such a way that the resonance conditions in the dc circuit were adjustable to different frequency values. The dc current control was in some cases slowed down to show the influence of control parameters on overvoltages.

Results are given in Fig. 14 in the case where all the firing pulses are removed. Oscillograms show currents in the rectifier ($I_{dr}$) and in the invertor ($I_{di}$) and the voltage in the middle of dc cable ($U_{dm}$). Fig. 14a shows the case where current control is slowed down and the dc side is close to the resonance at fundamental frequency. This is the most severe case. An overvoltage of 2.3 pu occurs. With the normal current controller but still with the resonance at 50 Hz on dc side, overvoltage becomes 2.1 pu as shown in Fig. 14b. However, resonance at fundamental frequency should be avoided by adjusting the smoothing reactor. In the case of normal dc current control and resonance frequency of 35 Hz (Fig. 14c), there is no significant overvoltage.

It can be seen that different control parameters and different system data lead to different voltage stresses. It is therefore very important to analyse the conditions in the actual scheme for different operating scenarios using the available control parameters to find the maximum expected overvoltages.

The probability of such a fault is very low, however in most cases it cannot be completely neglected. It is therefore recommended that some overvoltage protection means should be provided on the dc side.

#### 5.1.2.2 Start Against Open End

If the rectifier starts with the invertor terminal open overvoltages can occur on dc cable with amplitudes up to 2.0 pu. The overvoltage can remain on the cable for a longer time. Fig. 15 shows calculations of this case for the same benchmark model as above for resonance conditions at 35 Hz.

The probability that the above case can occur depends on the simultaneous presence of different faults. In the case of recovery after fault, the invertor remains blocked or the dc cable terminal at the invertor side is open due to fault or malfunctioning, and communication between invertor and rectifier is faulty or giving wrong signal. However, in the dc–control additional functions can be implemented, which reduce these overvoltages. The overvoltage can last for longer time as it decays with time constant in the range of about 10 minutes.

In normal dc cable transmissions the rectifier can be used as a peak rectifier to charge the cable for the purpose of testing. In this case if control is faulty an overvoltage of about 1.4 pu can occur. However, this overvoltage is not in the range which could influence the economic design of a dc cable.

#### 5.1.2.3 Fault on dc line in mixed overhead line/cable transmission

In mixed dc line and dc cable bipolar transmission system having a longer section of overhead line, faults on one pole of the line will induce overvoltages on the healthy pole that will be transferred to the cable. The magnitude of these overvoltages is normally below 1.7 pu, but it can reach 2.0 pu in some cases with unfavourable system parameters [39].

Figure 16 shows waveforms of the induced overvoltages obtained from simulation of a monopolar fault on a bipolar two terminal 500 kV system consisting of a long overhead transmission line (1000 km) incorporating a short section of cable (1 km). The magnitude of the overvoltages induced on the healthy pole and the cable depends on the location of the cable as well as on the location of the fault along the line. The case shown in Figure 16 was obtained for a fault close to a cable terminal at the middle of the line and the magnitude of he overvoltage reached 1.65 p.u. on the cable. Increasing the cable length (e.g. to 20 km) will decrease the steepness of the wavefront and reduce the amplitude of the overvoltage on the cable. Moving the cable away from the middle of the line will gradually reduce the overvoltage on the cable to about 1.35 pu for the system shown.

## 5.2 External Overvoltages

External overvoltages are caused by lightning strokes which produce fast front transients with rise times in the order of a few to nearly twenty microseconds and total duration of between 100 and 500 microseconds. Lightning–generated overvoltages on HVDC cables generally arise from two types of events:

1. Shielding failure wherein a lightning stroke terminates directly on the pole conductor of an overhead line close to the cable or a direct stroke occurs to the cable/converter station (the latter is an extremely rare event).
2. A backflashover wherein the lightning stroke terminates on the overhead ground wire or tower of the HVDC overhead line and due to the circuit parameters the overvoltage across the line insulation is sufficient to cause flashover to the pole conductor.

In general, there are two configurations of the transmission system which are of interest relative to lightning overvoltages:

a) DC cable terminating at the substation dc switch yard. No overhead line is connected at the cable terminal.

b) DC systems with a cable terminating on an overhead line section.

For systems of the first configuration, only the very rare event of a stroke terminating directly on the substation is of concern. If such an event is to be taken into account, a detailed representation of the substation bus bar layout and primary components is necessary in order to take into account properly the distance effects between protective devices and the cable insulation.

In mixed dc overhead line/dc cable transmission, both shielding failure events and back flashover events should be taken into account. In general, a detailed modelling of each span of the overhead line and every tower is necessary for the first one to two kilometres close to the cable termination. For shielding failure events, it may also be necessary to consider the impact of multiple strokes in the same stroke channel, with the possibility of a subsequent stroke of higher magnitude than the initial stroke. In addition, the maximum steepness of a lightning current wavefront along with the length of the lightning stroke tail are important parameters in determining the overvoltage at the cable. A detailed discussion of lightning parameters and the statistical approaches which are recommended for calculation of lightning overvoltages due to strokes on overhead lines can be found in [42], [43], [44].

A very important parameter which affects the amplitude of lightning overvotlages impressed on the cable is the cable length. Since the surge impedance of the cable is much lower than that of the overhead line, for long cables the voltage on the cable is reduced and damped before reflections in the cable can lead to high overvoltages. The overvoltages effectively become equivalent to a switching surge and of lower amplitude.

Short cable sections (a few kilometres) connected directly to overhead dc lines can experience multiple wave reflections in the cable due to lightning strokes on the overhead line. These multiple reflections can result in high overvoltages.

To limit these overvoltages it is important to provide measures which prevent direct strokes and backflashovers close to the line/cable junction. Attention to tower footing impulse response and effective shielding are important design considerations in reducing the number of dangerous events occurring close to the cable/line junction. DC cables should be protected against lightning by surge arresters at both ends. For short cables, damping filters or diodes connected in series with surge arresters can serve to reduce the amplitude of reflections and to lower protective levels respectively. For long cables, series reactors can prevent overvoltage from entering the cable. The use of metal oxide arresters with parallel gap can reduce protective levels. The arrester protective level for lightning overvoltages is generally higher than that for internal overvoltages. An example for calculations of cable voltages is shown in Figure 17 [40]. Plotted are voltages every 500 metres along the 4 km long 500 kV dc cable. Calculation was made for a back flashover at the tower closest to the cable terminal.This is the most severe case for polarity reversal. The arrester protective level for lightning was 1130 kV (2.25 p.u.) and for switching surges 960 kV (1.9 p.u.). It can be seen that the maximum lightning type overvoltage in the cable system was limited to 980 kV (1.96 p.u.).

## 6. Means for reduction of overvoltages

In early HVDC schemes protective air gaps have been used for limitation of internal overvoltages. However, this overvoltage protection had disadvantages because of inaccuracy of sparkover voltage and production of a steep transient at the breakdown of the gap. Later conventional gapped surge arresters have been used. However, for these arresters it was difficult to provide equipment with the required energy and reseal capability.

### 6.1 Gapless metal oxide arresters

In recent years overvoltage protection has become easier using gapless metal oxide arresters (Fig. 18a). An important advantage of the metal oxide arresters is the ability to connect units in parallel to achieve the required energy capability.

However, metal oxide arresters have a given physical ratio between the maximum dc operating voltage and the protective level at internal overvoltages. This ratio is about 1.9 pu for internal overvoltage for the present state-of-the-art arresters. It means that overvoltages on dc cables can be limited only to this value if no additional measures are taken. For arresters with this protective level only moderate energy capability is required even at high internal overvoltages (Table IV). This is at present the normally used DC cable overvoltage protection.

### 6.2 Arresters with parallel gap

Metal oxide arresters with parallel gap across part of the arrester (Fig. 18b) make it possible to limit overvoltages to lower values [40]. The idea is to reduce the arrester current at the operating voltage by a larger number of elements. However, when an overvoltage occurs, part of the series connected elements is bridged by the parallel gap to reduce the protective level. Use of this arrester needs careful coordination, considering at which conditions the gap should operate and making sure that it reseals after the operation. It is also possible to trigger the gap using a signal from voltage measurement devices or from dc control.

Fig. 19a shows loss of firing pulses at the invertor for the severe case of resonance conditions at 50 Hz and normal current control. It is the same case as shown in Fig. 14, however surge arresters with protective level 1.7 pu are applied at both terminals of dc cable. It is assumed that, about 60 ms after loss of firing pulse, the protection blocks the rectifier. Plotted are the same values as in Fig. 14 and additionally the energy dissipation in the arrester (E).

TABLE IV - Energy dissipation in kWs/kV of metal oxide arresters depending on the protective level. DC circuit resonance at fundamental frequency 50 Hz, normal current control.

| Arrester protective level | DC cable for ± 250 kV | DC cable for ± 400 kV* |
|---|---|---|
| 1.9 pu | 2.8 | 7.2 |
| 1.7 pu | 6.8 | 17.4 |
| 1.5 pu | 10.0 | 25.6 |

* Extrapolated values

The energy requirement for each of the two arresters is 1700 kWs i.e. 6.8 kWs/kV at ± 250 kV operating voltage. This energy requirement can easily be fulfilled. If this value is extrapolated (according to the square of the voltages) to 400 kV operating voltage, it becomes 17.4 kWs/kV, as shown in Table IV.

Fig. 19b shows calculations for the same case of resonance at 50 Hz and normal current control but taking into account a special arrester device which would limit overvoltages to 1.5 pu. The arrester energy is now 10 kWs/kV at 250 kV and 25.6 kWs/kV at 400 kV, respectively. The value for 400 kV is very high and requires powerful arresters consisting of a large number of parallel connected columns.

### 6.3 Thyristor controlled arrester

An overvoltage limiter could be built using antiparallel connected thyristor valves in series with the metal oxide arrester (Fig. 18c) or using other material as e.g. a metallic resistance. The limiter can be triggered depending on overvoltage conditions or by dc control. Using such equipment even lower protective levels could be reached.

### 6.4 Arrester in Series with Diode

A further overvoltage limiting device is an arrester in series with diodes (fig. 18d) connected in a direction such that an overvoltage of the opposite polarity to the operating voltage is limited to low value because such overvoltages represent the most severe stress of the dc cable insulation. This protective device has an excellent performance for limiting the voltage swing leading to voltage in the opposite polarity (Fig. 20).

## 6.5 DC Damping Circuit

Overvoltages can also be reduced by using damping circuits. The equipment (Fig. 21) consists of a capacitor and resistor in series (RC–circuit), or a capacitor, inductor and resistor in series (RLC–circuit), connected to the dc cable terminal [41].

The parameters of the damping circuit must be adjusted to the dc system data; its task is to detune the resonance conditions and to reduce overvoltages by additional damping.

Lightning overvoltages can be reduced or eliminated by an inductor (L, in Fig. 21) in series with the cable terminal. This inductor will then have the added function of increasing the dc side transmission line impedance which will make dc side filtering easier.

The value of the inductance shall be chosen such that the time constant L/Z (L= inductance, Z = cable surge impedance) is in the range 200 µs to 1 ms, as illustrated in Fig. 21.

The 200 µs value is chosen if it is deemed satisfactory to reduce the lightning transient stress to that of a switching overvoltage type of stress. The 1 ms value is chosen if it is deemed desirable to eliminate the lightning overvoltage stress more completely. The voltage stress across the inductor can be reduced by connecting an arrester in parallel to it. The inductor arrester protective level should then be the same as for the line to ground connected arrester.

## 7.. Withstand Characteristics of HVDC Cables

Table IV gives typical values for the withstand stresses for mass impregnated and oil filled cable insulation. It should be noted that the withstand values depend on the detailed construction of the cable which in turn will depend on such factors as the required mechanical characteristics, e.g. submarine laying conditions, conductor size. Some variation among the values used for particular applications is therefore to be expected. To calculate the withstand voltage of a specific design of cable, reference should be made to the formulae given in Section 4.

Table IV – Withstand characteristics of HVDC cables

| Condition | Mass impregnated | Oil filled |
|---|---|---|
| Continuous dc | 30 kV/mm | 35 kV/mm |
| Nominal 1/50 μs impulse at max. temperature (1) | 95 kV/mm | 95 kV/mm |
| Nominal 250/2500 μs impulse at max. temperature (2) | 80 kV/mm | 85 kV/mm |
| Polarity reversal at max. temperature | 40 kV/mm | 50 kV/mm |
| AC | | |
| 1–3 sec. | 60 kV/mm | 65 kV/mm |
| Continuous | 1 kV/mm | 20 kV/mm |

(1) Representing lightning overvoltage

(2) Representing switching overvoltage

The values given for continous dc operation are those for cables in service rather than values used by new design

Table V gives values used for design of two recent high voltage applications, one involving oil–filled and the other using mass–impregnated, submarine cable.

Table V – Design values used for two recent installations

| | Baltic (1)<br>(Mass-impregnated) | St. Lawrence (2)<br>(Oil filled) |
|---|---|---|
| Continuous dc | 28.5 kV/mm | 28 kV/mm |
| Lightning impulse | 84 kV/mm | 89 kV/mm |
| Switching impulse | 74 kV/mm | 66 kV/mm |
| Polarity reversal | | 37.5 kV/mm |
| AC plus dc | | 40.5 kV/mm (3) |

(1) Installation 21, Table 1
(2) Installation 17, Table 1
(3) 60 Hz

## 8. Insulation coordination

### 8.1 General

Insulation coordination is the choice of the dielectric withstand of the equipment and the tested withstand with consideration of the overvoltage stresses that are expected to occur where the equipment is used. Means to reduce the overvoltage stresses will also provide means for reduction of the withstand level and in this way reduce overall costs. The requirements for economy and for reliability of operations determine how the optimization is done in each individual case.

From the knowledge of the withstand capability for different stresses and the means of reduction of the overvoltage stress the choice of the safety margins is the final step of the insulation coordination procedure and this choice is based on consideration of both reliability and economy. The service experience of existing projects is the foundation upon which these deliberations are based.

In case of long HVDC cables the knowledge of the withstand levels and the means of reduction of the overvoltages is substantial and suggests that the application of means for reduction of overvoltages is justified even if it should require unconventional solutions.

An ambitious choice of a low protection level results in higher energy absorption requirement and a more elaborate overvoltage protection scheme. However, this should not be considered as a hindering factor in the case of HVDC cables. On a comparison note, for station equipment it is normally recommendable to use simple and conventional protection schemes since the economic gains from more elaborate schemes with reduced protective levels are limited. However, in the case of long HVDC cables the large cost of the cable makes it desirable to design and dimension the overvoltage protection means so that only the steady state operating voltage and events associated with it, such as fault transients, are the limiting design stresses.

The choice of the overvoltage protection must be done to fulfill the two requirements:

1. For reasons of overall economy, the choice of the protective level and the safety margins must be made so as to ensure that overvoltages will not become the dimensioning voltage stress.
2. The margins between protective level and the inherent withstand level of the cable must be sufficiently high

## 8.2 Recommended Minimum Margins Between Protective and Withstand Levels

The margin between the protective level and the inherent withstand level of the cable insulation is split into two parts:

1. The margin between the protective level and the test voltage level – the test margin
2. the margin between the test voltage and the expected withstand – the construction margin.

The choice of the test margin is principally the responsibility of the user. The construction margin in solely the responsibility of the producer. In the following only the test margin will be dealt with.

In broad terms, the items under consideration when choosing the test margin can be divided into two groups namely the following:

- Considerations of a general nature that apply to all equipment
- Considerations that apply specially for the HVDC mass impregnated and oil filled cables

General considerations are:

- Experiences from in service operation and indications from model studies
- The frequency of occurrence of the overvoltage
- The characteristics of the overvoltage and the risk of failure
- The consequences in case of failure
- Uncertainties in the determination of the overvoltage stress and the relation to the most relevant test voltage type
- Ageing effects on the equipment and the protection

Considerations that apply specially to HVDC cables are:

- Relation between the tested samples and the purchased item
- Impact for the application of the unconventional means of reduction of the overvoltages that are particular for HVDC cables.

These items will be dealt with in the following treatment of each of the overvoltage types that determines the design of the HVDC cable and the test margins.

### 8.2.1 Lightning Overvoltages

General considerations:

The experience from in service operation is very good. Faults attributable to lightning have not been reported from any of the projects. The test margins used in recent projects has been 20 %. Lightning overvoltages occur only infrequently on cables. In addition, calculations indicate strongly that they can be expected to have a very low level for reasons of the division over the wave impedances at the overhead line–cable junction because of the ratio of their respective surge impedances. The only danger exists from a stroke terminating within the first few spans of an overhead line close to the cable terminal. This, however, would be a very rare event.

The fast transient is relatively quickly damped when propagating into the cable and will therefore have reduced exposure and be of limited hazard to the cable. The only factors that could be in favour of a higher margin are the relative uncertanties of determination of the protective level which depends also on the distance of the protective device from the protected equipment. Another factor is the expected higher withstand of the fast transient in relation to the other overvoltage types for which the protection scheme is also designed. However, nowdays calculation methods are able to take into account such factors with good accuracy. The main reason for recommended margins lies in uncertainties due to aging and other factors mentioned above.

Ageing effects should not be decisive here. A proper test procedure will have tests simulating ageing effects prior to the transient overvoltage tests. In addition, the costs for replacement of an aged arrester is entirely negligable by comparison to all other costs of a long HVDC cable. Thus, if the in–service ageing effects can be determined with acceptable accuracy, the effect can be ignored in the determination of the margin.

Special considerations:

The tested object is a short test specimen intended to represent the very much longer cable that is purchased and put into service. This could lead to the requirements to increase test margin over the minimum test margin.

In the case of the lightning overvoltage, as mentioned in the previous paragraph, the surge – having a fast front – is heavily damped. Therefore, the test of the short specimen can be considered as quite representative for the cable as such.

The effect of any new techniques on the choice of the margins can be dealt with on project by project basis.

For reasons of the limited exposure to lightning transients, it is not justified to use different margins for testing of the cable specimen as compared to the joint specimen.

In summary, the recommended minimum test margins, with regard to the economy and the excellent in–service experience, should be:

| | Cable | Joint |
|---|---|---|
| Recommended minimum margins | 15 % | 15 % |

This is a reduction by 5 % in comparison to recent practice but is justified with due regard to the known good performance of HVDC cable links.

### 8.2.2 Internal Overvoltages

General considerations:

The experience from in service operation is very good. Faults have not been reported to occur in conjunction with switching or from other reasons of internally generated overvoltages.The test margins used in recent projects has been 15 %.

Internally generated overvoltages occur at the same rate as for a.c. links on an approximate basis. This is in the order of 10 per year. The exposure of the overvoltage to the cable is substantial, normally covering the cable in its entire length. The risk of failure is therefore larger as compared to lightning overvoltage exposure. Yet, since the overvoltage can be determined with higher accuracy, the uncertainty factor is in favour of a relatively small margin.

If a cable should fail for reasons of an internal overvoltage, it can be expected that the extended exposure may have caused partial deterioration of the insulation withstand also at locations other than at the fault. This is a factor that requires increased attention to the risks of internal overvoltages as compared to lightning overvoltages.

Special considerations:

The relation between the short test specimens and the purchased item should be accounted for by a relatively high margin for test of the cable. For the joints, this is not a matter of concern, however, since these are only 0.1–1 in percent of the cable.

In summary, the recommended minimum test margins with due regard to the interest in economy and the excellent in–service experiences, should be:

| | Cable | Joint |
|---|---|---|
| Recommended minimum margins | 15 % | 10 % |

For practical testing reasons and for cables with larger number of joints, e.g. land cables, the same test level for cable and joints is reasonable.

### 8.2.3 Long Duration AC Type Overvoltages

In the early years of HVDC cable transmission schemes, there was considerable concern with regard to the risk of ac type overvoltages being fed into the cable and specially so if this fault mode could be expected to last for many seconds in which case the cable would be severely damaged for its entire length. However, in the modern HVDC projects control can mostly avoid the long duration and high amplitude of this type of overvoltages. For this reason an ac voltage test was also used for the early projects. However, experience has shown that the concern for development of this failure mode has been exaggerated. While this is one pertinent reason for an optimistic approach to increasing the operating voltage gradients to higher levels, it should be observed that the risk of ac voltage being fed into the cable should not be completely ignored in the choice of margins.

In dealing with this matter, one option is to take the risk into account by prescribing an adequate margin between the expected overvoltage level, which in a thoroughly studied design will be very moderate, and the calculated withstand level of the cable. In practice, this approach will be the combined responsibility of the producer and the user.

In choosing the margin, due consideration should be taken of the very severe consequences of a fault of this type. It is possible that some deterioration could occur along a substantial portion of cable.To account for this risk, the margin should be high. It is recommended that it should be up to 50 %.

## 9. Conclusions

The work of JWG has led to following results:

- Collection of detailed data and type test information for dc cables in operation or in planning stage
- Analysis of insulation capability of dc cables. Representative values for ratio between test voltage (impulse voltage superposed on the operating dc voltage of opposite polarity) and operating voltage leading to the equivalent design stress have been evaluated. Resulting from this analysis overvoltages should be reduced to 1.9 pu for mass impregnated and to 1.6 pu for oil filled dc cables. If these levels are met than dc cable will be designed based on its operating voltage.
- Analysis of internal and external overvoltages occuring on dc cable schemes. Large majority of overvoltages are low (below 1.5 pu) and do not influence cable insulation. For some faults combined with control malfunction high overvoltages (above 2.0 pu) can occur.
- Overvoltage protection is required because of possible high internal and external overvoltages. Different means for reduction of overvoltages are reported. The desired protective levels (< 1.9 pu) for mass impregnated cables can be achieved by modern metal oxide arresters. Further reduction of overvoltages to the limit required for oil filled cables is not generally achievable without special means for overvoltage protection.
- Typical values for withstand of dc cables for lightning overvoltages, internal overvoltages and long duration overvoltages have been determined.
- Suggestions for safety margins between protective levels and insulation withstand should be 15 % for internal and external (lightning) overvoltage for cables and 10 % and 15 % respectively for joints. For long duration ac overvoltage margins up to 50 % are suggested.

The JWG suggests following future work:

- Discussion of alternatives for dc cable tests. This task will be covered by a special WG of SC 21
- Impact of dc operation on the cable insulation should be analysed. Changes in operation could have consequences on testing requirements of the dc cable
- study of the possibility of increasing the dc operating voltage of existing schemes with consequences on overvoltages

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# Appendix 1

## Electrical Stresses and Breakdown Strength of DC cables

The reduction of breakdown strength when impulse is superposed on a dc voltage of opposite polarity (see equation (1) of chapter 3) is given by:

$$K = \frac{U_i - U_p}{U_o} \qquad \text{A.1)}$$

Consider now electrical stresses, with reference to Fig. 2, and the following symbols.

$r_i$ = internal radius of insulation (mm)

$r_e$ = external radius of insulation (mm)

$h$ = $r_i \ln r_e/r_i$ geometrical factor

$E_{co}$ = $h\ U_o$ capacitive stress at voltage $U_o$ (used as reference) (kV/mm)

$E_i$ = $h\ U_i$ capacitive stress at impulse (kV/mm)

$E_p$ = stress under reverse polarity impulse (not shown in Fig. 2) (kV/mm)

$E_{dc}$ = resistive stress at voltage $U_o$ (kV/mm) depending on temperature drop in the insulation

All stresses being considered here are at the internal radius of the insulation which, as a rule, is the most stressed position. When there is an impulse of reverse polarity $U_p$ (to ground) superimposed to a dc voltage $U_o$, there is a swing of $U_p + U_o$ which produces a capacitive stress. This stress has to be subtracted from the dc pre-existing stress, so that the total stress (at the conductor) results:

$$E_p = h\ (U_p + U_o) - E_{dc} \qquad \text{A.2)}$$

The basic assumption for the behaviour of mass impregnated and oil filled insulation is that breakdown occurs when the maximum stress under conditions of an impulse superimposed on dc equals the value of the maximum stress at breakdown under impulse alone [34].

$$E_p = E_i \qquad \text{A.3)}$$

From eq. A.3) and A.1) it follows:

$$K = 1 - \frac{E_{dc}}{E_{co}} \qquad A.4)$$

which is a definition of coefficient K as a function of stresses and is used in the equation (4) of chapter 4.1.

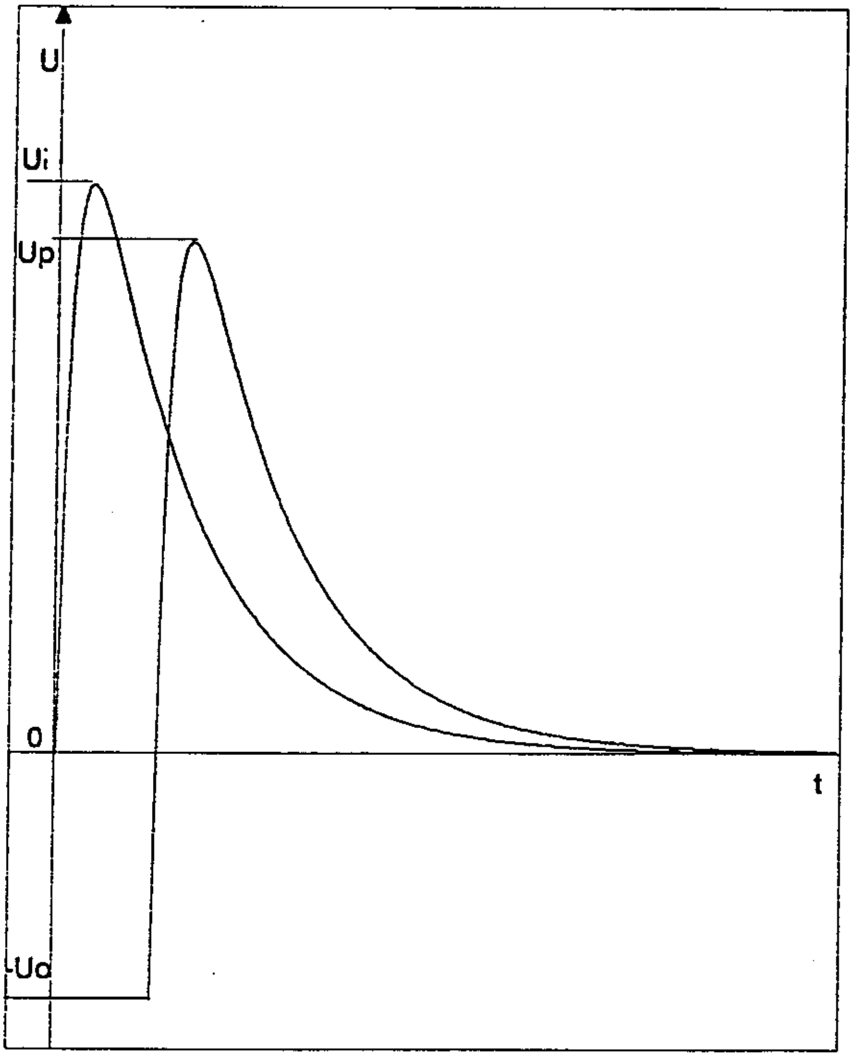


Figure 1: Voltages at breakdown

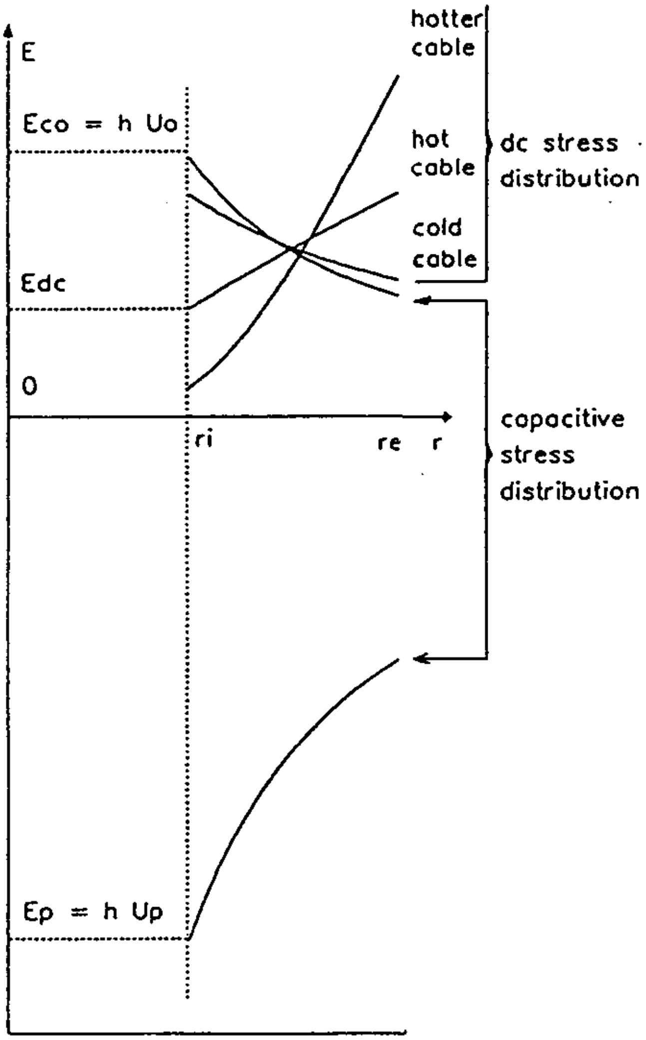
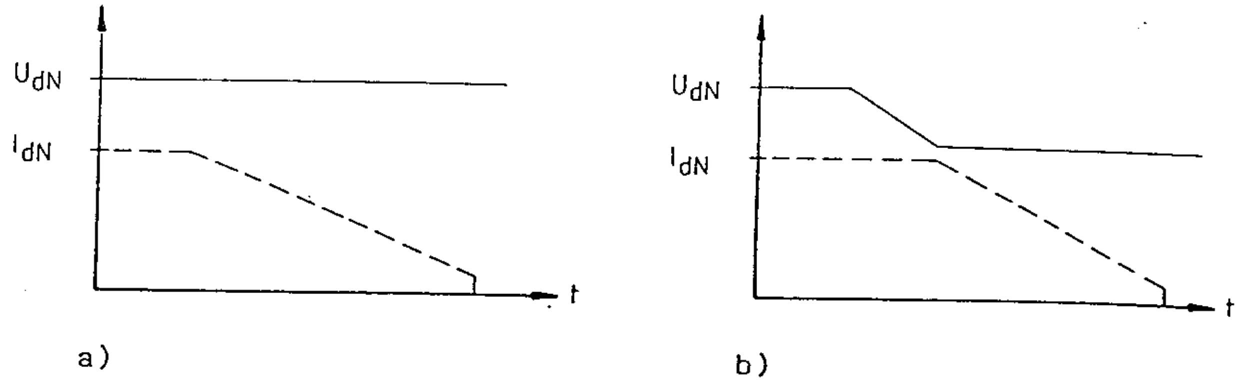


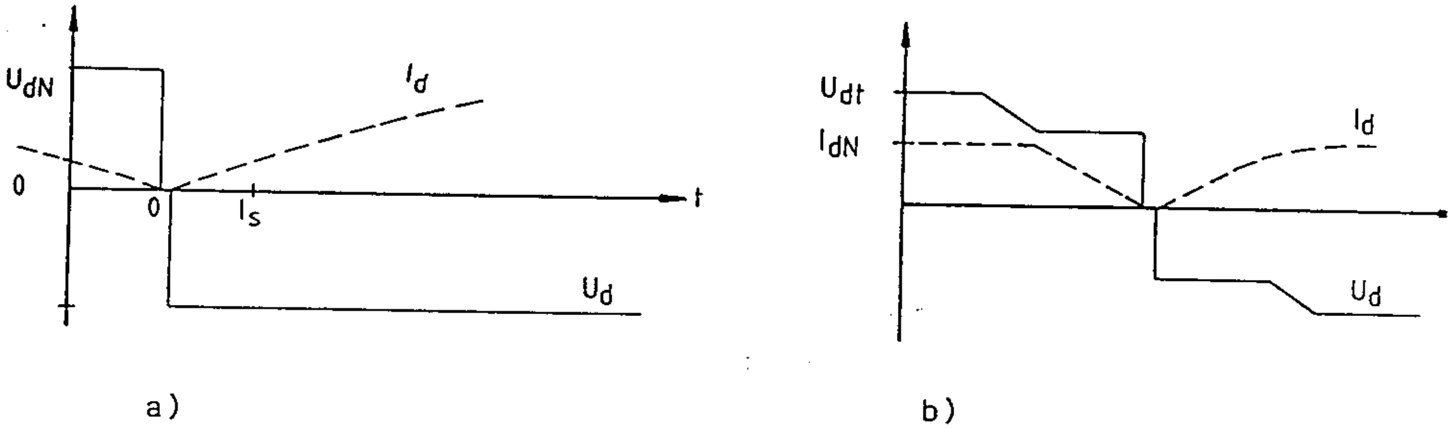
Figure 2: Electric stress distribution



a)

b)

Figure 3: Conditions during normal power change
a) using normal voltage control
b) using control reducing voltage at power reduction



a)

b)

Figure 4: Conditions at power reversal
a) without dc voltage magnitude change
b) with dc voltage magnitude change

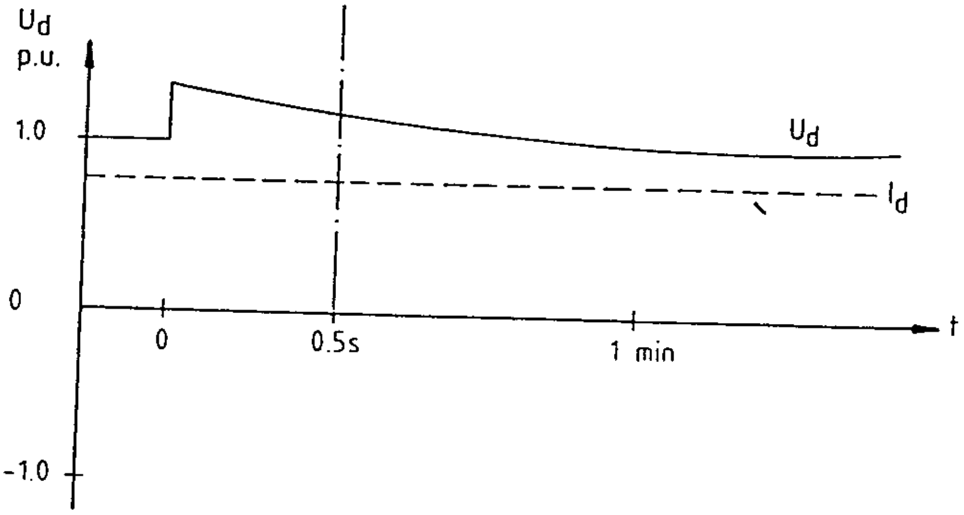


Figure 5: Conditions at larger voltage disturbances in ac system

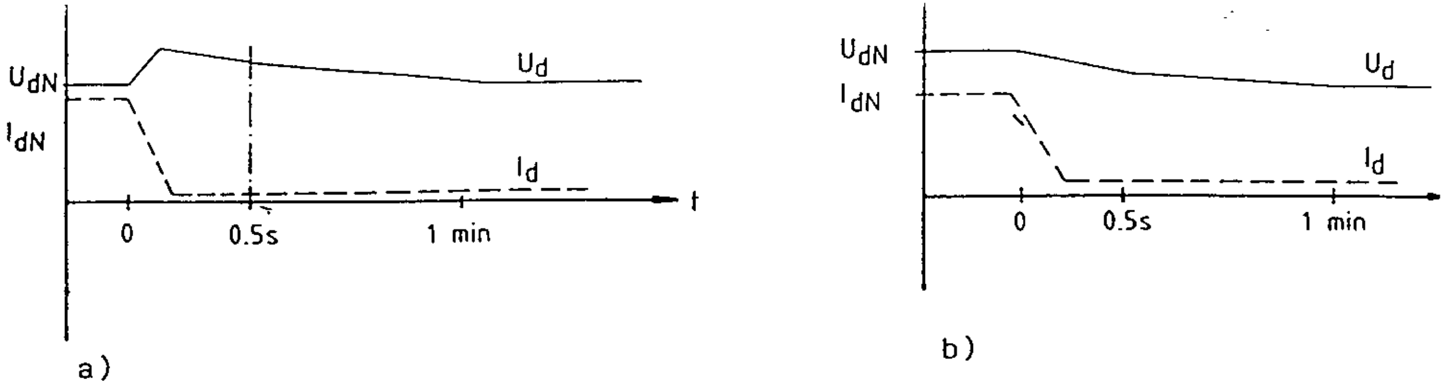


Figure 6: Conditions at emergency power change from full to minimum power

a) without additional voltage control

b) with additional voltage control

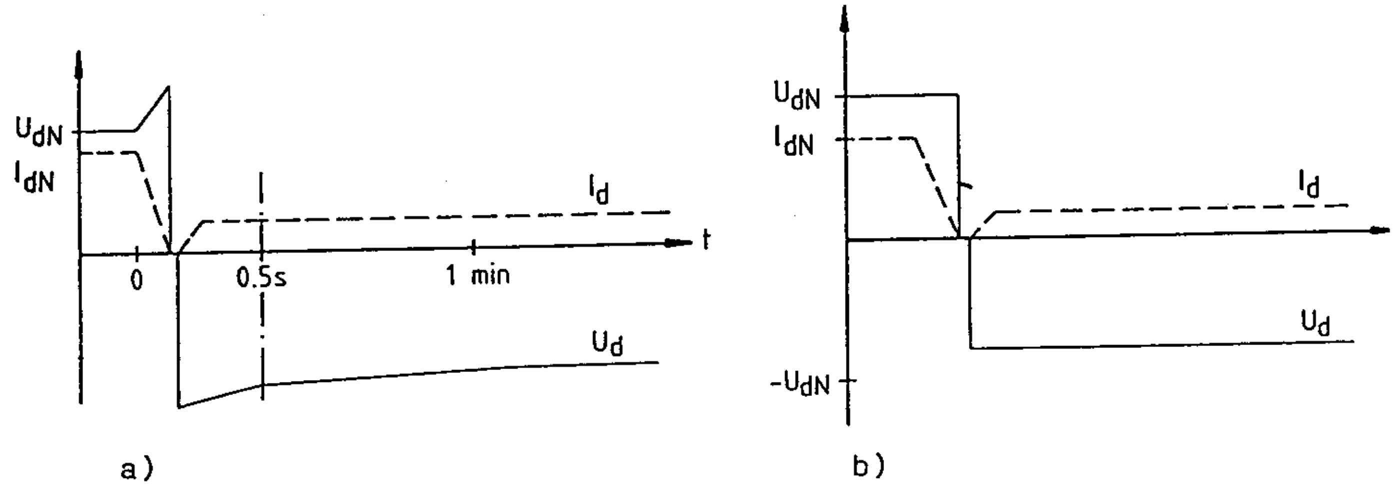


Figure 7: Conditions at emergency power reversal

a) without additional voltage control

b) with additional voltage control

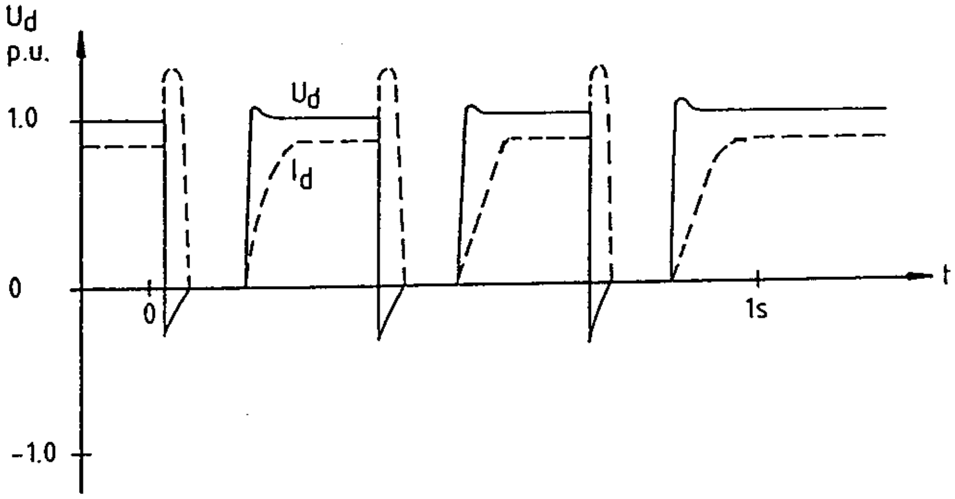


Figure 8: Conditions at earth fault on dc line and reenergization after the third attempt

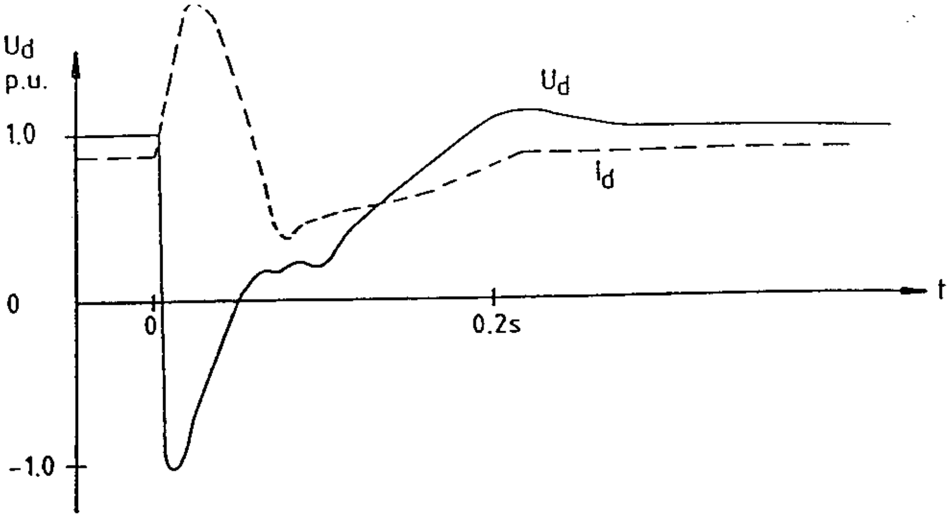


Figure 9: Conditions at single commutation failure

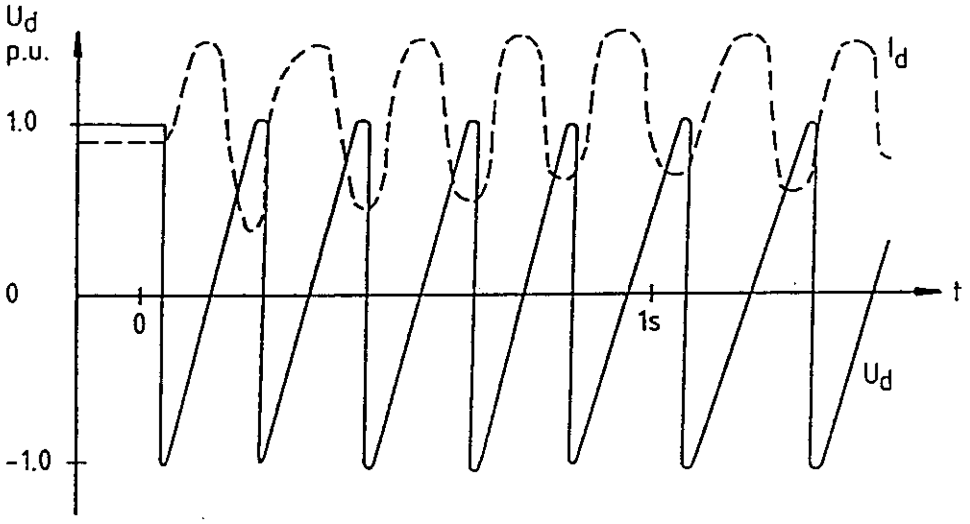


Figure 10: Conditions at sustained commutation failure

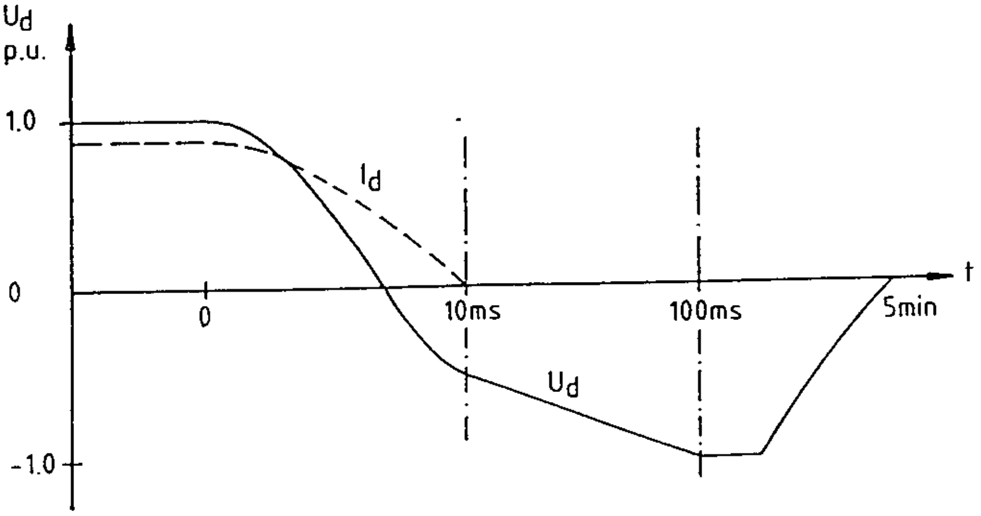


Figure 11: Loss of control pulses at rectifier

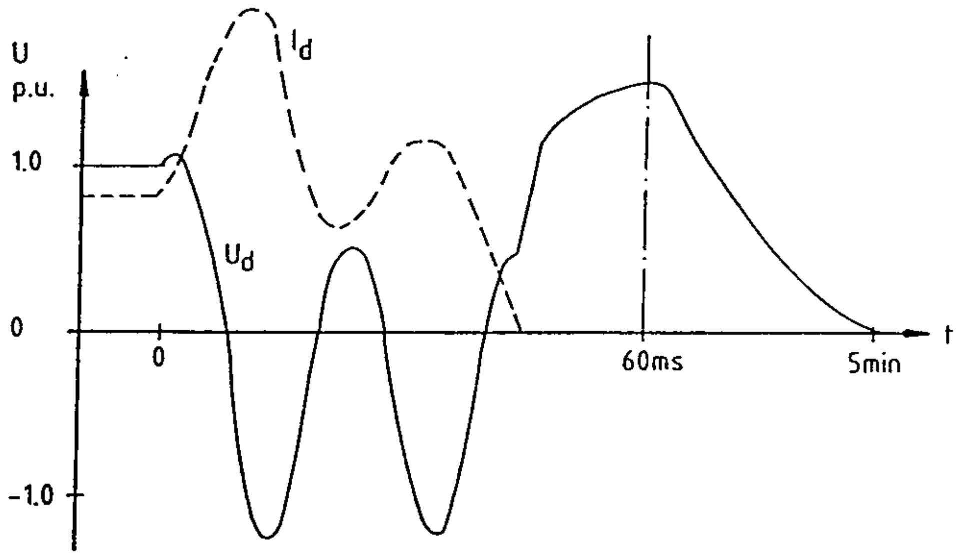


Figure 12: Loss of control pulses at inverter

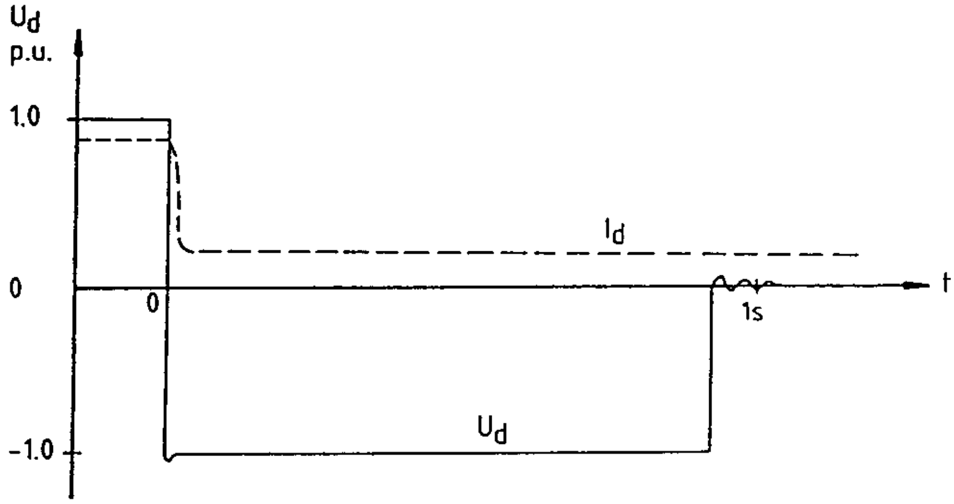


Figure 13: Conditions when inverter becomes uncontrolled

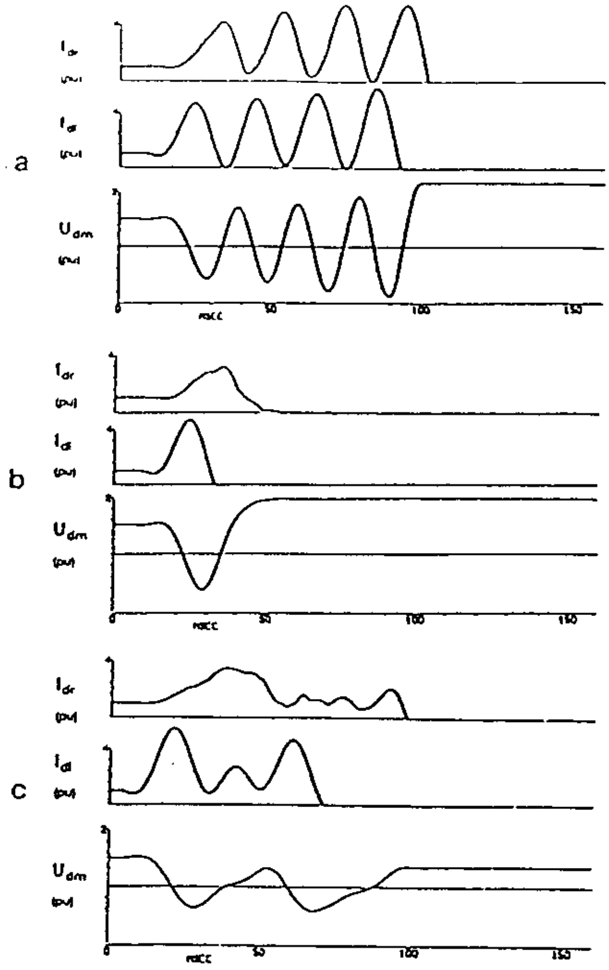


Figure 14: Overvoltage on DC cable when firing pulses are removed in invertor:

a) resonance of DC circuit at the fundamental frequency of 50 Hz, current control slowed down;
b) resonance of DC circuit at the fundamental frequency of 50 Hz, normal current control;
c) resonance of DC circuit at 35 Hz, normal current control.

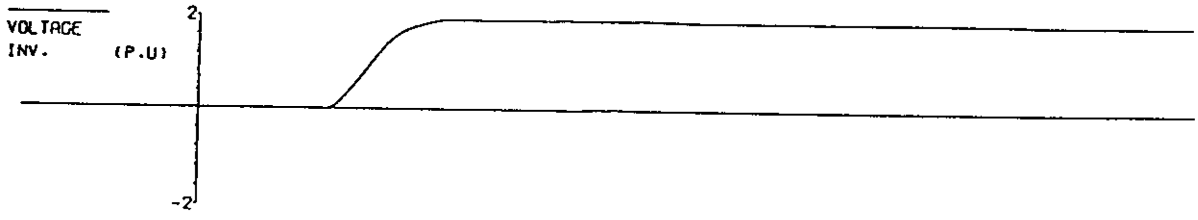


Figure 15: Overvoltage at the start of a rectifier against open end at the inverter

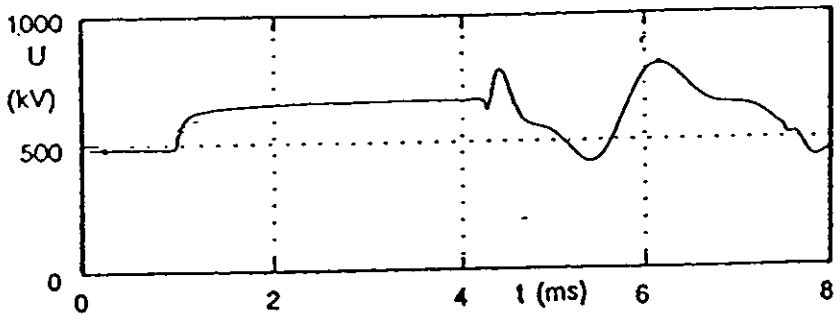


Figure 16: Induced overvoltage on the healthy pole of mixed dc overhead line/dc cable transmission for pole–to–ground fault [40]

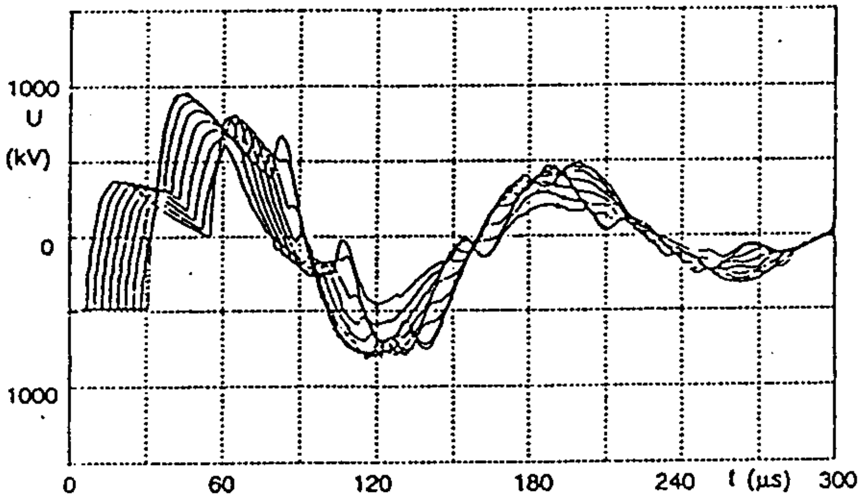


Figure 17: Overvoltages at every 500 m along the cable including both cable terminals. Back flashover at the tower closest to the cable terminal for base case conditions, e.g.:

- cable length = 4 km
- one cable per pole

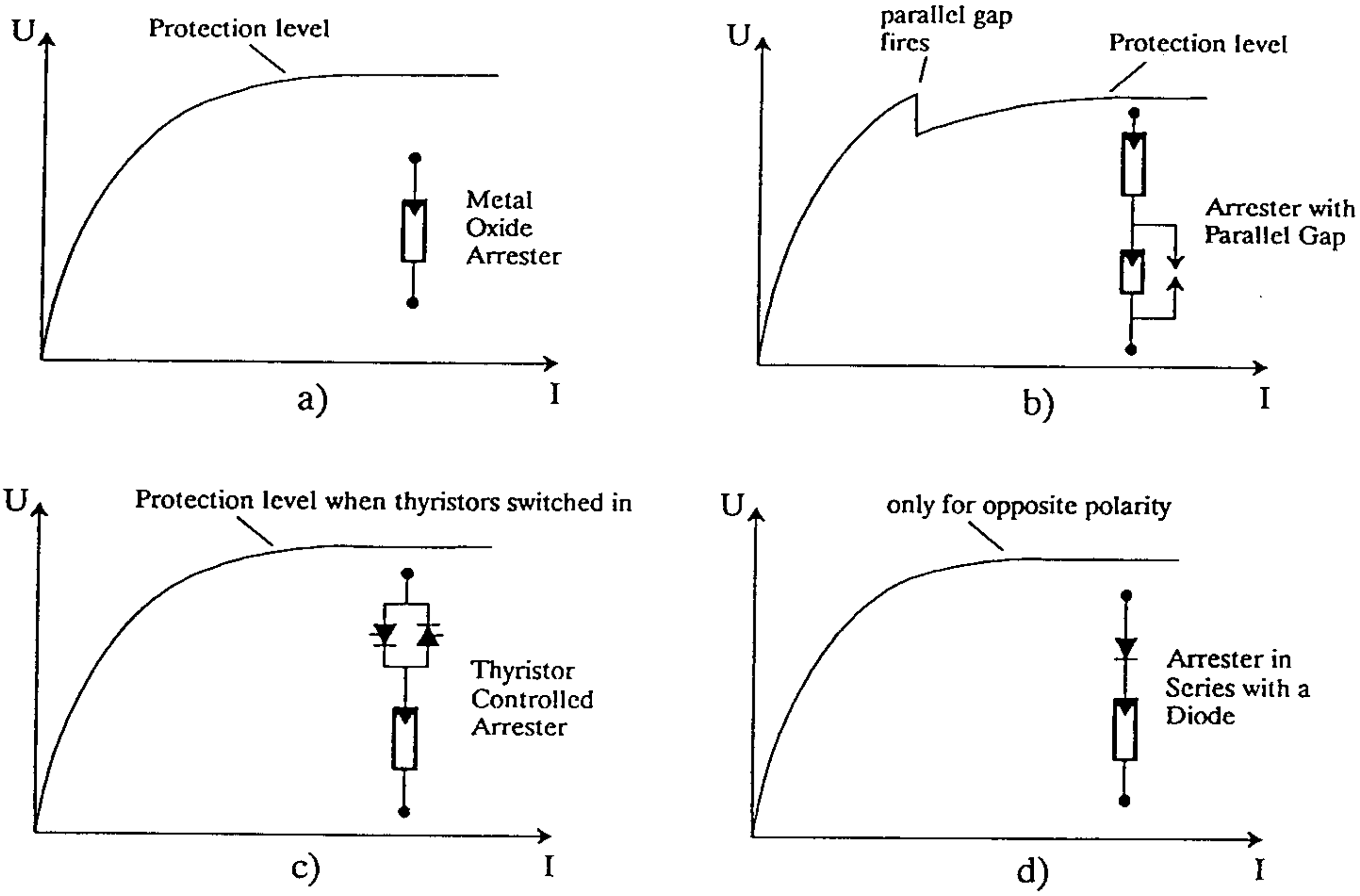


Figure 18: Means for reduction of overvoltages

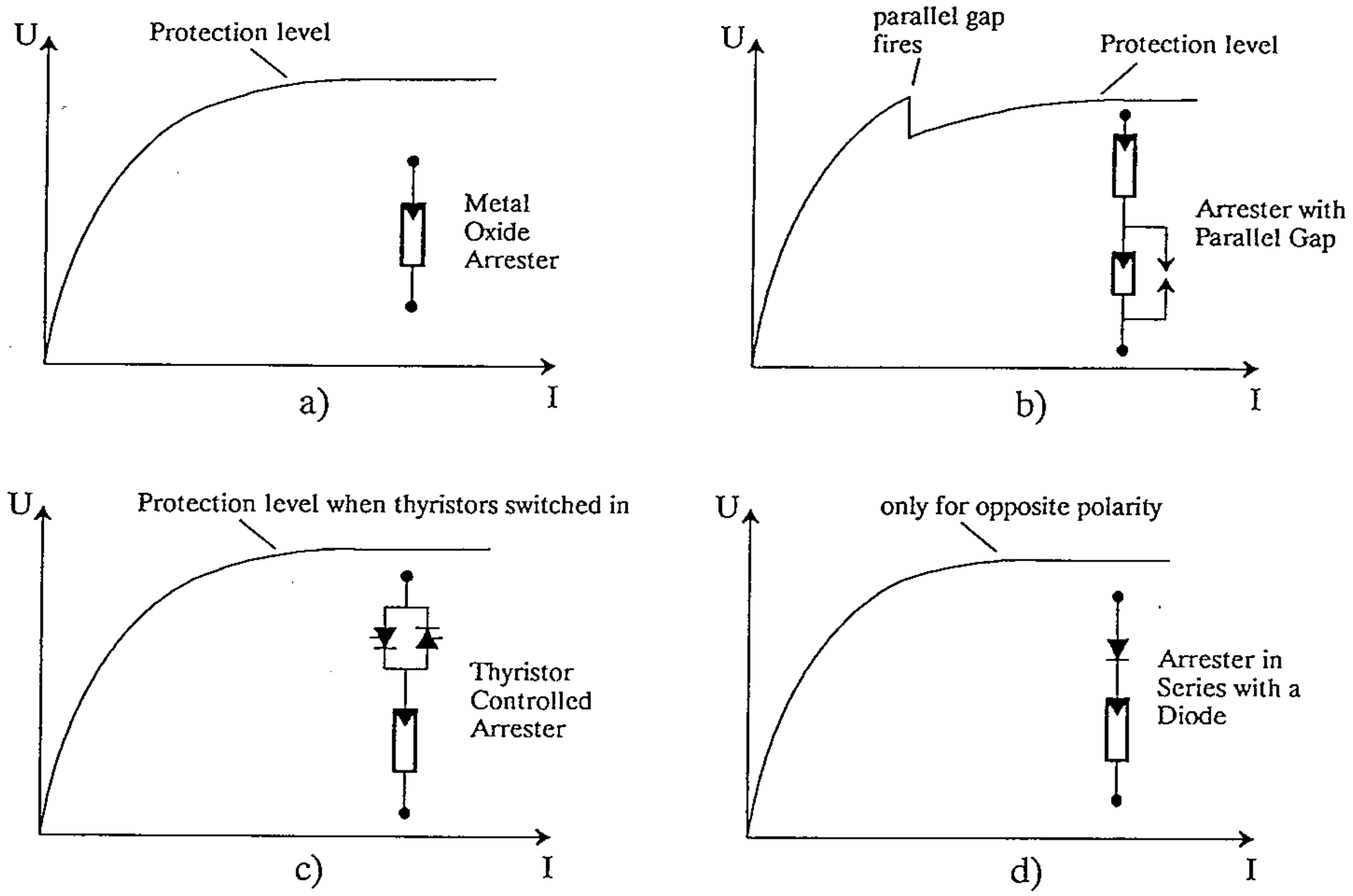


Figure 18: Means for reduction of overvoltages

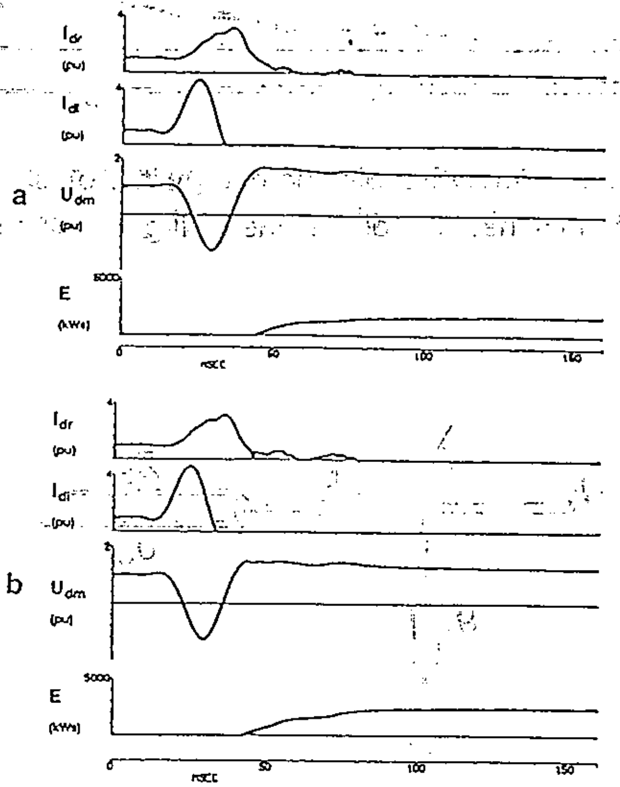


Figure 19: Overvoltage on DC cable and surge arrester energy when firing pulses are removed in the invertor. DC circuit has resonance at the fundamental frequency of 50 Hz, normal current control:

a) surge arrester limitation to 1.7 p.u.

b) surge arrester limitation to 1.5 p.u.

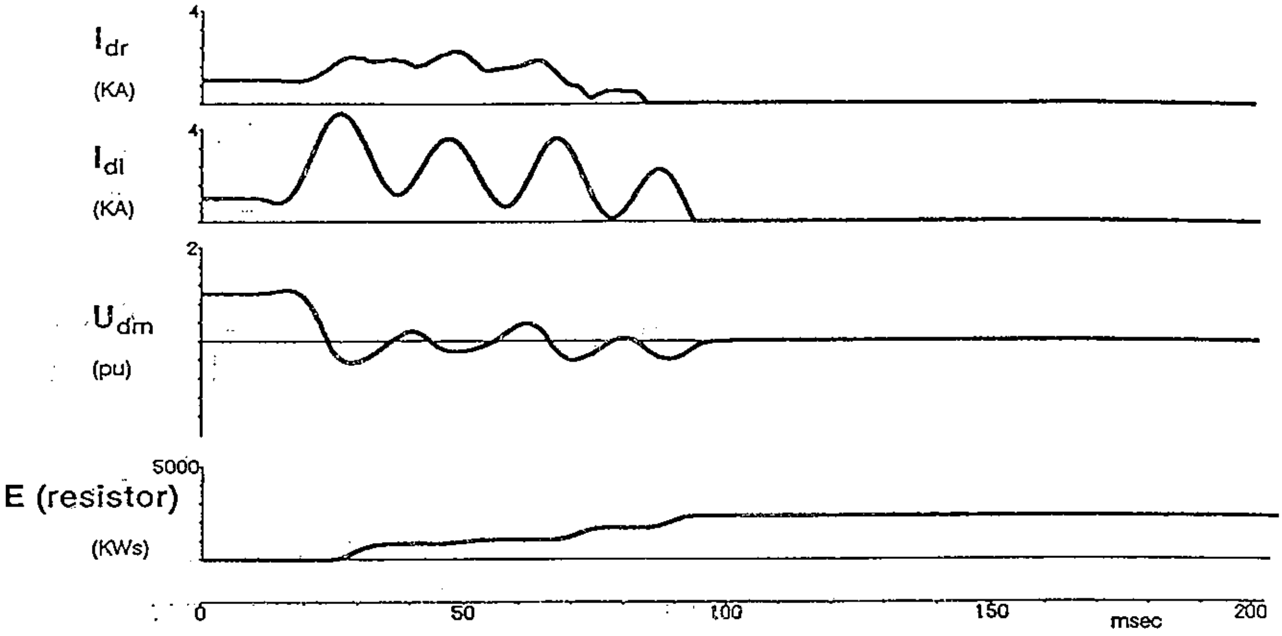
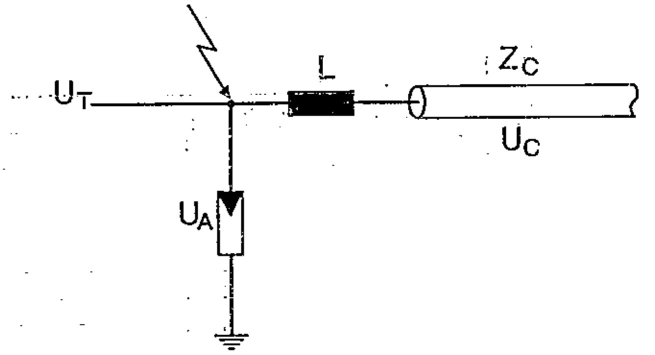


Figure 20: Overvoltage on DC cable and energy in protective device consisting of arrester in series with diode when firing pulses are removed in the inverter



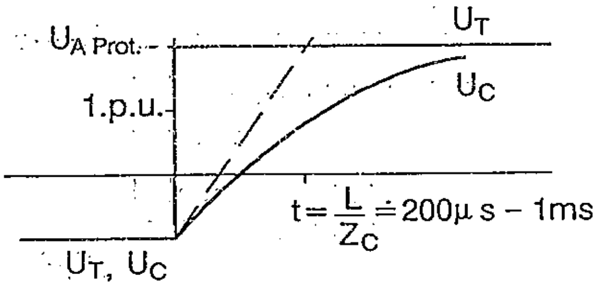


Figure 21: Impact of cable series inductor on the transition of a lightning transient from the transmission line side to the cable

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Publié par le CIGRÉ
21, rue d'Artois
FR-75 008 PARIS
Tél. : +33 1 53 89 12 90
Fax : +33 1 53 89 12 99

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*21, rue d'Artois*
*FR-75 008 PARIS*
*Tel : +33 1 53 89 12 90*
*Fax : +33 1 53 89 12 99*

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