Feasibility of Low Voltage Cables for Use at 1500V DC Distribution Networks

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Abstract

A low voltage DC distribution network concept has recently been developed in Finland to challenge the traditional 400 V AC concept. From techno-economical point of view it would be beneficial to use in this system the same cables as nowadays are used in low voltage AC distribution. Nominal voltage of the LVDC system is, anyhow, at the upmost limit of the cable specifications or in some cases no DC specification exists at all. Consequently the suitability of the cables for use in the LVDC system is not clear.

In this paper the basic insulation properties of the typical low voltage cable types used in Finland are studied and discussed. This includes the breakdown voltage levels at AC, DC and lightning impulse voltage as well as aspects of charge accumulation, moisture ingress and partial discharge inception.

1. Introduction to the 1500 V DC concept

Large variety of low-expense low-voltage power electronic components is commercially available as a result of the long history of industrial applications. In addition, the component prices of power electronics have constantly been decreasing over the last decade allowing increase in the number of applications.

The low voltage DC distribution (LVDC) system is one of the emerging SmartGrid technology innovations in electricity distribution and an interesting challenger for the existing network technologies. The European Union (EU) Low Voltage Directive (LVD 2006/95/EC) enables the use of up to 1.5 kV DC voltage in low voltage networks. By combining the benefits of the DC voltage distribution with the opportunities provided by the power electronic converter technology it is possible to significantly improve the performance of electricity distribution.

The main objectives behind the development of the LVDC network have been to; (1) improve the power quality and supply security experienced by the electricity end-users, (2) improve the economy of the electricity distribution, (3) provide flexible and robust coupling point for small scale generation, and (4) develop infrastructure for interactive and intelligent distribution network [1], [2].

The development of the LVDC network was started 2005 in Finland [3] as a continuum to development of the 1 kV intermediate low voltage distribution system. DC network concept with somewhat similar properties and sharing some of the same objectives have been introduced also in [4], [5], [6], [7]. However, in those studies, the perspective has been more application specific, than in the development of the generally applicable LVDC distribution system carried out by LUT and TUT [1]. The principle of LVDC power distribution network concept is presented in Fig. 1.

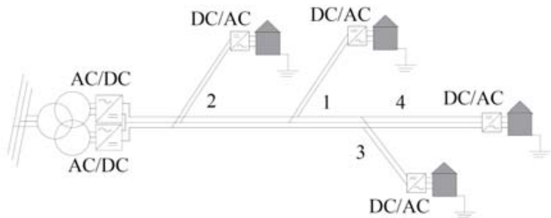

Figure 1 − Principle of bipolar LVDC low voltage electricity distribution system and available customer-end inverter connections [9].

An LVDC distribution network comprises of a centralised rectifier located at the MV/LV distribution substation, a wide-spread bipolar ±750 V DC network between the rectifier substation and customers coupling point and, finally, customer-specific DC/AC inverters responsible for providing 230/400 V AC voltage for the customers' appliances. [3] The LVDC system also includes an ICT system for control and supervision of the system and customer interfaces [1] [8]. The nominal voltage of the system is selected so that it provides as high DC network transmission capacity as possible in the boundaries set by the low voltage directive, the cable standardisation (SFS 4879, SFS 4880) and the acquisition price of the converters. The LVDC system is mainly designed to be constructed as underground cabled system to avoid the possible EMI radiation and in order to respect LV cable standardisation [10][1]. Underground cabling is beneficial also from the system reliability viewpoint. For safety reasons, the LVDC network is operated isolated from ground, when the used earthing scheme is IT. The earthing scheme of customers' AC networks is IT if the customer-end inverter does not include galvanic isolation. If galvanic isolation between the public DC network and customer's AC network is provided, the customer's network can be realised as TN system [9], [11]. The requirement to feed short circuit currents to the customer system has to be taken into account in customer-end inverter design.

The properties of the LVDC system enable achievement of the set objectives (1)-(4). The implementation of LVDC system increases the stabile transmission capacity of low voltage networks [1], [3]. This enables reduction in the length and complexity of the medium voltage networks and reduces losses in LV cables [3]. The converters used for voltage transformation in the LVDC system enable constant active control of power quality and implementation of sophisticated network protection and management functionalities together with the ICT system [1] [8]. In addition, the ICT system gives opportunity to realise versatile services for energy markets, energy efficiency and for the power system control [2].

Reduction in the length and complexity of the MV network bring economical benefits and improve the overall reliability of electricity distribution. The impacts on the reliability of the network are the highest in rural electricity distribution networks. In urban networks, savings can be achieved in the costs of both public and real-estate networks. [1] Principles of using the LVDC system as a part of rural and urban electricity distribution are presented in Fig 2.

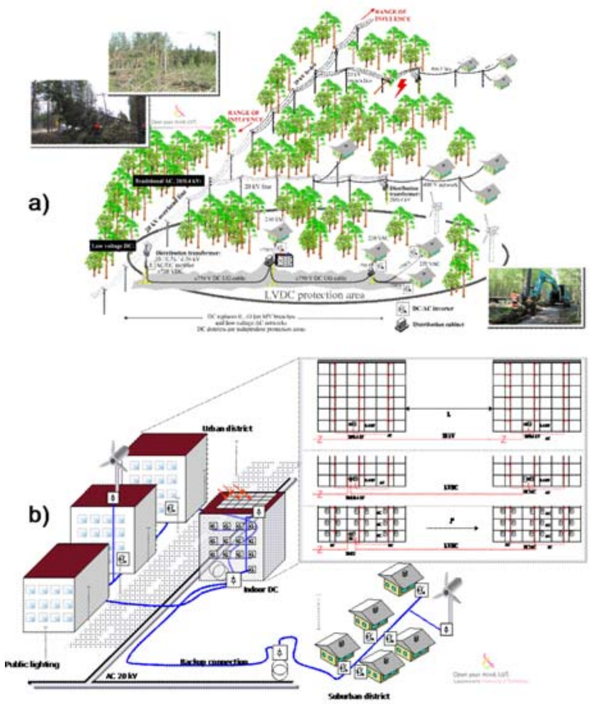

Figure 2 − Concept of a) rural and b) urban LVDC distribution [1].

The drawbacks of the LVDC system are mostly related with the increasing complexity of the low voltage network, and the lifetime and energy efficiency of the power electronics. The expected fault rate of the converters is higher and their expected lifetime is, even in the best case, two thirds shorter when compared with the conventional network components. [1], [12] Furthermore, the achieved reduction in LV cable losses becomes quite rapidly eaten up by the losses due to LVDC system converters and increasing length of LV network. [1]

The need to replace the converters relatively frequently forms a natural cycle for updating to improved and reduced price technology within the utilisation period of other DC network structures. [12] Despite of the disadvantages of currently available converter technology, numerous techno-economically reasonable application sites for the LVDC technology can be found from the public electricity distribution networks. [13] When considering the constant development of power electronics and all the available intelligent functionalities, the LVDC system becomes an attractive solution for developing electricity distribution networks. The more active characteristics are expected from the distribution networks of the future, the higher will be the benefits of the LVDC system. [1]

3. Voltage stresses in the 1500 V DC system

The system is designed to be realized as bipolar system although the cabling of the networks should allow also unipolar realization. Cablings of the system must thus allow a continuous 1500 V stress between conductors.

In addition to the above mentioned continuous stresses also other stresses of shorter durations/higher frequencies will exist in the DC system. These include mainly the different switching transients of the system but also voltages due to system fault situations as well as atmospheric overvoltages. Cablings of the LVDC distribution system shall thus withstand the nominal continuous voltage stress of 1500 V with some recurrent high frequency transients on top. For insulation coordination purposes this maximum recurrent transient voltage caused by converter power switch operations is evaluated to be less than 1500 V.

Direct lightning strikes will be rare in the system even in case of aerial lines because low voltage aerial lines are rather low and are often located close to higher objects like for example in case of forest lines. Atmospheric overvoltages will thus mainly include induced overvoltages of common mode type due to bundle type conductors. Examples of calculated induced overvoltages on a 7.15 m high aerial line are given in Fig. 3.

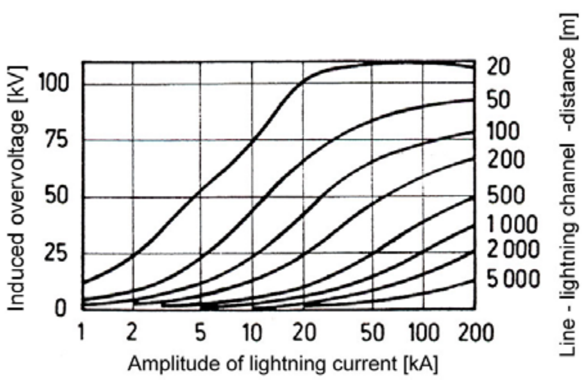

Figure 3 − Induced overvoltages on an aerial line (height 7.15 m) as a function of lightning current amplitude and lightning channel distance from line. [14]

4. Test program and discussion of insulation degradation phenomena

In this phase of the LVDC system development only main considerations of the suitability of typical low voltage AC cablings were studied. This means that no long term ageing phenomena are covered, instead phenomena and properties rapidly degrading insulations are dealt. This study is focused especially on the suitability of cable insulations, although some other aspects are also discussed shortly.

There are no published results available of the withstand voltage levels of low voltage cables. Due to this breakdown tests were decided to be carried out at all typical test voltages, although the withstand voltages of LV cables are supposed to be relatively high due to mechanically needed rather thick insulations.

In DC use space charge formation may decrease breakdown strength of insulation. Although a high field strength is needed for space charge formation (~ 8 – 10 kV/mm (certain XLPE and PE) or more depending on the material and its additives [15]), which is not to be exceeded in LVDC cables, this phenomena was decided to be studied by a test series where test cables were at first prestressed at +65°C, 4 kV_{DC} for 2 days, followed by a lightning impulse (LI) breakdown test of opposite polarity. The LI testing was started at a voltage close to the LI breakdown voltage measured for the cable type in order not to change the possible space charges with the preceding impulses remarkably.

Water treeing is possible in polymeric insulation when moisture and electric field high enough (~2.8 kV/mm_{ACpeak} [19]) are present for a period long enough. Since the field strengths in LVDC cable insulations are most probably not that high and because no problems have raised in 1400 V_{ACpeak} use of the same cables this aspect was decided not to be studied more.

Partial discharge behaviour of AMKA aerial bundle cables have been studied earlier at AC stress in different ambient conditions [16]. These results will be discussed in this paper. Since aerial LVDC lines may also include remarkable recurring voltage peaks due to operation of power electronics the lines may emit EMI. This phenomenon is to be measured and solved later in the pilot lines.

5. Cable types studied

Altogether seven different cable types were studied (Table1). Some of the cables have a DC specification but not all. Cable types AXMK and AMKA are typically used in 400 V and 1000 V AC networks and those are considered as the main choices also for 1500 V DC system.

All the cables types used in the tests are manufactured according to corresponding Finnish national standards which are further based on IEC 60502-1. As defined in the standards the thickness of main insulation varies with the cable size. Cables with thinnest main insulations were chosen for the tests.

Table 1 – Cable types studied and their main parameters. Typical 400 and 1000 V AC network cable types with bold.

Cable type	Main insulation		DC specification	Maximum operating
	material	thickness [mm]	U_0/U [kV]	temp.
AXMK 4×25	XLPE	1.0	0.9 / 1.5	+90°C
AXMK 4×35	XLPE	1.0	0.9 / 1.5	+90°C
AXCMK 4×35+16	XLPE	1.0	0.9 / 1.5	+90°C
AMCMK 3×16+16	PVC	1.0	0.9 / 1.5	+70°C
MCMK 3×16+16	PVC	1.0	0.9 / 1.5	+70°C
AMKA 3×25+35	HD-PE	1.4	–	+70°C
MMJ 3×10	PVC	1.0	–	+70°C

AXMK cable design can be seen in Fig 4. Cables with cross sections of $35mm^2$ and higher have sector-shaped conductors as in Fig. 4 while in smaller cables the conductors are round and there is thus clearly more air space inside the cable. Cables have a PVC sheet and a thin layer of PP band under it.

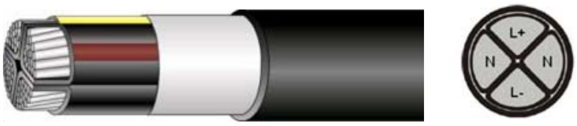

Figure 4 – AXMK cable type and probable connections of conductors in bipolar system.

AMKA is an aerial self supporting bundle cable type (Fig. 5). It has three HD-PE insulated aluminium conductors and a bare steel-aluminium support wire which also acts as a neutral conductor.

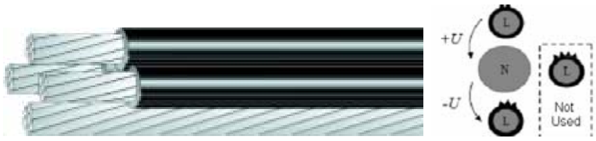

Figure 5 – AMKA aerial bundle cable type and probable connections of conductors in bipolar system.

AXCMK, AMCMK and MCMK are power cables with similar designs with copper wire screen but with different conductor and insulation materials (Fig. 6). MCMK has copper conductors while the two other types have aluminium conductors. Main insulation materials are given in Table 1.

MMJ cable is an indoor installation cable and it is taken into some tests because it may be used in the LVDC system in some sections in indoor conditions.

Figure 6 – AXCMK cable type.

7. Test procedures and results

7.1 AC and DC breakdown strength

Breakdown voltages of the main insulations of most of the studied cable types were measured using the rapid-rise test method with 1 kV/s voltage increase rate both at AC and DC. Since most of the cable types do not have conductive screens or even sheaths and there are thus no terminations available for the cables, normal cable test procedures could not be used. Instead, samples of pure phase conductors with main insulation were immersed in a hollow core porcelain insulator filled with well conducting water. Approx. 9 cm thick layer of transformer oil was poured on top of the water to prevent surface flashovers. Length of the phase conductors immersed in water was approx. 1 m. A schematic drawing of the test vessel is given in Fig. 7. Although the distribution of electric field is not completely even in the interfacial area between water and oil this test setup was decided to be used when the breakdown locations was seen to distribute quite evenly along the length of conductor immersed in water. The test setup was thus considered to be good enough to get breakdown strength results for insulation coordination.

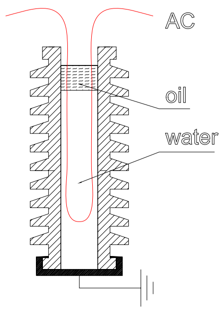

Figure 7 – Test arrangements used in AC and DC breakdown voltage measurements

Results of the AC and DC breakdown measurements are given in Table 2. Standard deviations are quite high, especially in case of round shaped AXMK cable. These deviations are partly due to certain dimensional variations noticed in at least some of the cable samples but also due to small number of parallel test samples (5). In general, the measured U_{50} values are high compared to the service stresses of cables and despite the high deviations the corresponding withstand voltages can be considered to be sufficient for the LVDC system and provide enough margin for insulation coordination.

Table 2 – Measured 50% breakdown voltage estimates (U_{50}) with 95% confidence intervals and corresponding experimental standard deviations (s) at AC and DC [17].

Cable type	AC		DC +	
	$U_{50} \pm CI_{95\%}$	s	$U_{50} \pm CI_{95\%}$	s
AXMK 4×25	25 ≤ **33.5** ≤ 42	11.2	71 ≤ **88.0** ≤ 105	23.0
AXMK 4×35	38 ≤ **43.7** ≤ 49	7.5	89 ≤ **98.6** ≤ 108	13.7
AXCMK 4×35+16	37 ≤ **41.9** ≤ 46	6.4	73 ≤ **78.1** ≤ 84	7.7
AMCMK 3×16+16	29 ≤ **30.6** ≤ 32	2.0	62 ≤ **66.0** ≤ 69	4.8
MCMK 3×16+16	-	-	-	-
AMKA 3×25+35	45 ≤ **49.5** ≤ 54	5.8	96 ≤ **104** ≤ 111	10.2
MMJ 3×10	23 ≤ **25.5** ≤ 28	2.8	37 ≤ **43.3** ≤ 49	8.0

7.2 Lightning impulse breakdown strength without and with a DC prestress

Two lightning impulse test series were performed in order to measure the actual lightning impulse breakdown strength of the main insulations but also to check the effect of possible charging processes on the breakdown strength. In the first test series the impulses were applied across the cables main insulations without any prestress, in the second test series a similar test series was performed after the cable insulations were prestressed at least 48 h with 4 kV DC at +65°C. In both test series a 4 kV DC voltage of opposite polarity than the LI was applied on the cable during LI test. In practice, a 100 nF capacitor was installed between the cable under test and earth to maintain the DC voltage during test because the connection to DC source was disconnected just prior to impulses (Fig. 8). Error in voltage measurement due to capacitive series connection of cable and the capacitor is estimated to be clearly less than 1 %. A piece of copper wire was twisted around the cable main insulation and the impulses were applied on the wire leading to formation of an arc of 1 – 3 m on the surface of cable insulation during tests. Rather long section of the insulation was thus tested. 6 to 8 parallel samples were measured in the tests.

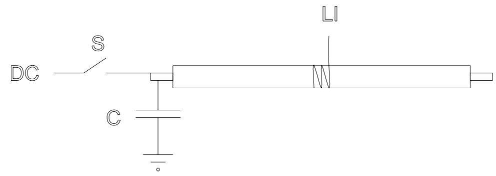

Figure 8 – Arrangements during the LI tests.

Exact values of 50 % breakdown voltage estimates for both test series are given in Table 3. In Fig. 9 the same results are given in graphical form.

Table 3 – 50% breakdown voltage estimates (U_{50}) with 95% confidence intervals and corresponding experimental standard deviations (s) at lightning impulse voltages and without and with a min. 48 h, 4 kV prestress [17].

Cable type	LI		LI after DC prestress	
	$U_{50} \pm CI_{95\%}$	s	$U_{50} \pm CI_{95\%}$	s
AXMK 4×25	85 ≤ **+91** ≤ 97	8.9	93 ≤ **100** ≤ 107	10.0
	-83 ≤ **-90** ≤ -96	9.0	-87 ≤ **-97** ≤ 107	13.7
AXMK 4×35	93 ≤ **+99** ≤ 103	7.0	83 ≤ **94** ≤ 105	14.9
	-79 ≤ **-87** ≤ -94	10.2	-79 ≤ **-84** ≤ -90	7.4
AXCMK 4×35+16	76 ≤ **+87** ≤ 98	14.7	86 ≤ **92** ≤ 98	8.4
	-82 ≤ **-87** ≤ -91	6.7	-81 ≤ **-85** ≤ -90	6.7
AMCMK 3×16+16	70 ≤ **+75** ≤ 80	7.8	69 ≤ **73** ≤ 77	5.3
	-63 ≤ **-70** ≤ -77	9.7	-61 ≤ **-65** ≤ -70	5.9
MCMK 3×16+16	60 ≤ **+65** ≤ 70	6.9	66 ≤ **69** ≤ 73	5.3
	-61 ≤ **-65** ≤ -70	6.3	-54 ≤ **-55** ≤ -57	2.3
AMKA 3×25+35	112≤ **+117** ≤122	7.0	108 ≤ **112** ≤ 116	5.7
	-105≤ **-113** ≤-122	12.0	-112≤ **-119**≤ -127	10.4
MMJ 3×10	56 ≤ **+60** ≤ 64	5.4	64 ≤ **66** ≤ 68	3.0
	-46 ≤ **-49** ≤ -52	4.3	-41 ≤ **-44** ≤ 47	4.3

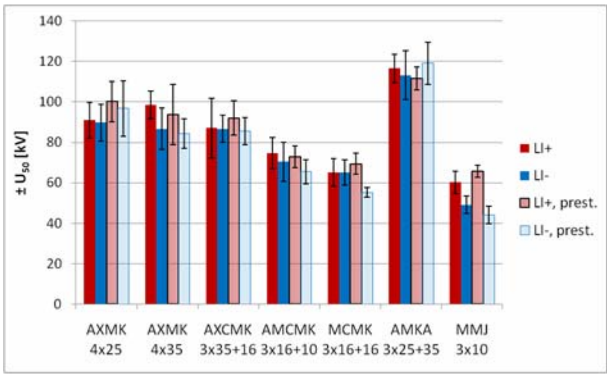

Figure 9 – Absolute U_{50} values of positive and negative LI tests with and without 4 kV prestress at +65°C and corresponding experimental standard deviations.

The experimental standard deviations are in general high as also in the previous tests. Differences between the results of the two test series are typically within the standard deviations and vary in both directions and thus, as expected, no signs of decreased breakdown voltage levels due to DC prestress can be found in the results. Breakdown voltage levels are in general rather high compared to the voltage stresses in the LVDC system, especially in the most typical LV system cable types (AXMK and AMKA).

7.3 Effect of moisture ingress on breakdown strength

Effects of possible moisture ingress on the dielectric strength of the different main insulation was studied by a hot water immersion test conducted on AXMK, AMCMK and AMKA cable types having PEX, PVC and PE main insulations, respectively. The cables were immersed in +70°C water for 7 days after which DC breakdown measurements were conducted as previously described in 7.1.

50% breakdown voltage estimates are given in Table 4 together with the corresponding results of unstressed cables (from Table 2). Breakdown voltage of PEX insulated AXMK cable increased during the immersion. Further crosslinking of main insulation may have taken place due to the heating. Similar effect may be noticed in the LI test results of this cable type with and without +65°C stress. The same result cannot be seen in the LI results of AXMK 4*35 cable. The standard deviations are also close to the values of the differences and this phenomenon cannot thus be verified by these results. In case of the PVC insulated cable a clear decrease of 75 % in the breakdown voltage can be seen. This phenomenon is a character of PVC and cables with PVC insulation are thus not recommended in very moist ambient in LVDC system. Small decrease of breakdown strength was also measured for PE insulated AMKA cable but the change is close to the value of standard deviation.

Table 4 − 50% breakdown voltage estimates (U_{50}) with 95% confidence intervals and corresponding experimental standard deviations (s) at DC after 7 day immersion in +70°C water and the corresponding results without water immersion [17].

Cable type	**After immersion**		**Before immersion**	
	$U_{50} \pm CI_{95\%}$	s	$U_{50} \pm CI_{95\%}$	s
AXMK 4×25	$102 \leq$ **105** ≤ 109	5.3	$71 \leq$ **88.0** ≤ 105	23.0
AMCMK 3×16+16	$16 \leq$ **16.7** ≤ 17	1.1	$62 \leq$ **66.0** ≤ 69	4.8
AMKA 3×25+35	$86 \leq$ **90.2** ≤ 94	5.7	$96 \leq$ **104** ≤ 111	10.2

7.4 Partial discharge inception

As it is well known, continuous partial discharge (pd) activity may rapidly degrade polymeric insulation materials. Due to this possibilities of pd inception need to be evaluated although the continuous voltage stresses in the LVDC are rather low.

In LVDC system the most critical cables in this sense are the cables which are subjected directly to outdoor ambient and which do not have outer sheet (AMKA). These cables will form the aerial sections of LVDC system when such is needed.

No pd measurements have been made for the cables at DC. Pd behaviour of AMKA cables at different weather conditions under AC stress has, anyhow, been studied earlier [16]. Although both pd phenomena and distribution of electric field are different at DC than at AC, the AC results can be used to evaluate the risk of pd inception on AMKA lines at LVDC system. Pd inception voltages of AMKA 3*16+25 cables in different environmental conditions under AC stress are given in Table 5.

Table 5 – AC peak values of pd inception voltages measured for AMKA 3*16+25 cable at different ambient conditions under AC stress [16].

Condition	Ambient air T /RH	Pd inception [kV_{ACpeak}]
Dry conditions	19°C / 35%	3.6 – 3.8
Rain	17°C / 32…94%	2.4 – 2.8
Iced conductor	-6°C … +6°C	1.9 – 2.2
Hoar frost	-6°C … -1°C	1.9 – 2.2

AC_{peak} -values in dry conditions are clearly higher than the DC stresses in LVDC system and most probably there will thus be no pd activity in these conditions although the DC field distribution is different from the AC case. In other weather conditions the pd inception voltages are closer to nominal DC stress between bipolar conductors. In case there are remarkable recurring peaks (transients) in the system the safety margin is even smaller.

Although the pd repetition rate is clearly lower at DC compared to AC and the severity of pd occurrence is thus probably lower some further pd measurements should be conducted under DC excitation. That is also because the DC field distribution varies depending on the weather conditions (since the conductivity of surrounding air/water/etc. varies) and computational studies are thus difficult to make.

8. Discussion and conclusions

DC withstand voltage of all the tested cable types can be concluded to be high enough for the LVDC system. Due to the limited number of parallel breakdown tests and corresponding inaccuracy of standard deviations of breakdown tests no values for, for example, 95% withstand voltages are calculated. It is, anyhow, clear that based either on AC_{peak} or DC breakdown results corresponding withstand voltages of all the cable types are several times higher than LVDC system voltage.

Aerial sections of the LVDC system are subjected to atmospheric, mainly induced, overvoltages and mostly AMKA cables are to be used for these sections. 95% LI withstand voltage of AMKA cables is approx. 100 kV which is enough for the insulations to withstand most of the induced atmospheric overvoltages. These overvoltages will be limited mainly at joints (U_{50}~25 kV [14]) and at surge arresters needed at the terminals of rectifiers and inverters.

No evidence of space charge accumulation and consequent reduction of withstand voltages were measured for the cables. Thus, ambient overvoltages or system polarity reversals do not cause problems in the LVDC system.

Moisture ingress caused a remarkable reduction in the breakdown voltage of the PVC insulated cable. PVC insulation will also attenuate high frequency signals due to higher dielectric losses and thus limit the usability of PLC communication [18]. The use of PVC insulated conductors is thus not recommended in LVDC system.

Based on AC measurements partial discharge inception voltages are high enough in normal conditions but can be close to LVDC system voltage in foul weather conditions. Some further measurements are thus recommended. Possible EMI levels of aerial LVDC lines will be studied later by measurements in pilot lines.

9. References

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