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Increased voltage for the HVDC Light® product range – a complete solution

Marc JEROENSE, ABB Power Systems, (Sweden), marc.jeroense@se.abb.com
Mikael BERGKVIST, ABB Power Systems, (Sweden), mikael.bergkvist@se.abb.com
Anders GUSTAFSSON, ABB Power Systems, (Sweden), anders.h.gustafsson@se.abb.com
Hans RAPP, ABB Power Products, (Sweden), hans.rapp@se.abb.com
Torbjörn SÖRQVIST, ABB Power Products, (Sweden), torbjorn.sorqvist@se.abb.com
Jörgen SVAHN, ABB Power Products, (Sweden), jorgen.svahn@se.abb.com

ABSTRACT

A new voltage level – 320 kV – has been introduced for HVDC Light® cable systems. The design principles of this system are the same as for the previous 80 and 150 kV levels. A total power window of several tens of MW to at least 1000 MW is now covered. The 320 kV cable system has been type tested according to the applicable CIGRÉ Recommendation. The diameter and weight of polymer HVDC submarine cables is about half the weight of three-phase HVAC submarine cables. Longer lengths of polymer HVDC land cable can be wound on a drum due to the lower weight and dimensions. This results in fewer joints per circuit length and less transportation costs.

KEYWORDS

HVDC, polymer, cable, system, installation

INTRODUCTION

The electricity networks of today increasingly need control and stability at high levels of loading. Increasing the stability through adding more lines is not always an option due to restrictions in right-of-way or limits to acceptable short circuit currents. Here, HVDC transmission solutions using undergrounding through extruded cables systems offer unique advantages.

Other reasons for introducing HVDC Light® cable systems in the network are the bulk transport of power both at land and sea, the interconnection of different parts of network for stability or control reasons and the connection of remote loads as for example oil-platforms.

Both underground and submarine projects have been realised using the HVDC Light® converter and the HVDC Light® polymer cable technology [1, 2]. The installed systems, so far, work on voltages of 80 and 150 kV. The installed powers have increased from the first project (Gotland) at 50 MW to the latest installed (Estlink) at 350 MW. At the moment of writing a total of 1566 km of HVDC Light® cables has been installed.

A gradual increase in both power and voltage is foreseen. For the larger powers, that is more than ca. 400 MW, it is more suitable to use a higher transmission voltage. The next DC voltage that complies with AC system levels through the use of HVDC Light® converters we see is 320 kV. For that reason the gradual cable system development has focused on this voltage. This new voltage level opens a window of power transmission between roughly 400 and 1000 MW – see Figure 1 [3].

HVDC connections need cable systems and converter stations. The development of the cable systems has so far focused on the Voltage Source Converter type. In order to keep down delivery time of stations these are more and more standardised around fixed voltages and power blocks. The standardized voltages are 80, 150 and 320 kV.

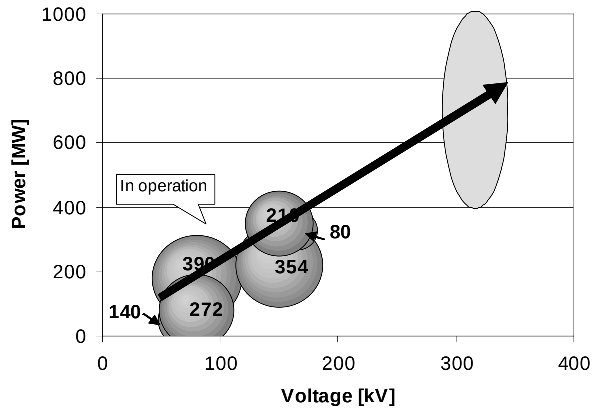

Figure 1. Foreseen increase in power and voltage for polymer HVDC. Every bubble represents an existing commercial project. The size of the bubble refers to the amount of cable delivered. The numbers denote the number of cable kilometers of the projects.

DEVELOPMENT OF 320 KV SYSTEM

The development of the 320 kV polymer cable system started from the earlier experience of the 80 and 150 kV experience. Virtually the same design concept was used for the development of the 320 kV system. This ensured a safe and solid basis for the development and future operation of this next voltage level.

Differences and similarities

A difference with the lower voltage classes is introduced though. The insulation thickness was chosen such that the mean electrical field strength was increased. The reason for this is the same as for the increasing field strengths of HVAC cables. That is, the outer diameters of cables become unrealistically large for higher voltages if the design field stresses are kept too low. The insulation thickness d of 150 kV HVDC Light®™ cables is standardized to 12 mm whereas the insulation thickness of the first 320 kV cables were set to 18 mm. This means an increase of the mean electrical field strength $E_m = U/d$ of 42%.

The electrical design of the termination is such that the heart of the termination is still based on the 80 and 150 kV designs. That is, a combination of non-linear field controlling adapters and a stress cone.

The prefabricated joint is based on the same principles as for the 150 kV design. The joint consists of an EPDM insulated body, where a layer with non-linear dielectric properties controls the electric field under stable DC as well as transient conditions. Over this layer, the insulating EPDM takes over the electric field from the cables. The last layer is a conducting layer of EPDM rubber that confines the field to the inside of the joint. A deflector of conducting rubber at high potential shields the field from the sharp edges of the conductor connection. See Figure 2.

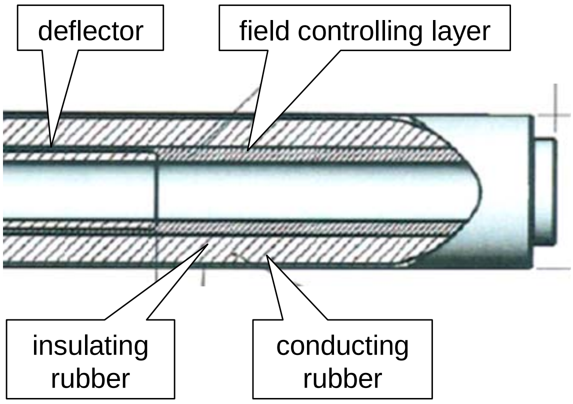

Figure 2. One half of a 320 kV HVDC Light®™ prefabricated joint.

The design has been optimized compared to the 150 kV design such that the highest field strength is increased by only 15%.

Testing

A type test based on the relevant CIGRÉ Recommendations [4] has been performed on a test loop consisting out of 19 meters of unarmoured, 320 kV dc 1200 mm2 aluminum cable with 18 mm of insulation, two terminations and a prefabricated joint. AC-transformers inducing current in order to heat the conductor were used. See Figure 3.
The circuit was wrapped in a layer of thermally insulating foam in order to reach a maximum conductor temperature of at least 70°C while keeping the temperature across the insulation at 17°C. Without foam and using a heating-current in order to reach a conductor temperature of 70°C would have resulted in unrealistically high temperature drops that would never occur in service.

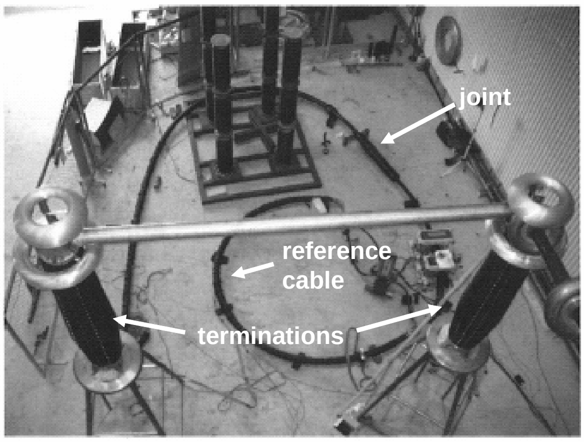

Figure 3. Type test set-up of the 320 kV cable system.

The type test was executed as follows:

- Load Cycle Test
  - 12 cycles -592 kV, 8/16 hours heating/cooling
  - 12 cycles +592 kV, 8/16 hours heating/cooling
  - 3 cycles +592 kV, 24/24 hours heating/cooling
- Superimposed Surge Voltage Test
  - Udc = +320 kV, U_{p2s} = +665 kV, 10 times
  - Udc = +320 kV, U_{p2o} = -375 kV, 10 times
  - Udc = -320 kV, U_{p2s} = -665 kV, 10 times
  - Udc = -320 kV, U_{p2o} = +375 kV, 10 times
- Subsequent DC test
  - Udc = -592 kV, 2 hours

The test factor for the load cycle test was 1.85 (1.85 x 320 = 592 kV). For more details we refer to the CIGRÉ document. The object passed the type test successfully.
In order to learn about the margins a shortened type test on a higher voltage level was made on the same circuit, continuing after the first type test. A nominal voltage U_0 of 350 kV was assumed. The test factor was increased from 1.85 to 2.0 in order to compensate for the lower number of cycles. This test was executed according to the following program:

- Load Cycle Test
  - 5 cycles -700 kV, 8/16 hours heating/cooling
  - 5 cycles +700 kV, 8/16 hours heating/cooling
- Superimposed Surge Voltage Test
  - Udc = +350 kV, U_{p2s} = +727 kV, 10 times
  - Udc = +350 kV, U_{p2o} = -410 kV, 10 times
  - Udc = -350 kV, U_{p2s} = -727 kV, 10 times
  - Udc = -350 kV, U_{p2o} = +410 kV, 10 times
- Subsequent DC test
  - Udc = -648 kV, 2 hours

Again the cable circuit passed without remarks proving the robustness of the 320 kV design of cable, termination and joint.

PRODUCT MAP

Now with the introduction of the 320 kV level extruded HVDC cables of the HVDC Light® type cover power levels from below 50 MW up to levels as high as 1000 MW. The maximum transmission power P using a bipolar VSC scheme is given by equation 1:

$$P = 2U_0 I_{dc} \qquad [1]$$

in which I_{dc} stands for the rated current of the conductor. This rated current depends on the burial conditions. For DC cables this current I_{dc} is given by equation 2:

$$I_{dc} = \sqrt{\frac{\theta_c - \theta_a}{R(T_1 + T_2 + T_3 + T_4)}} \qquad [2]$$

in which θ_c stands for the conductor temperature, θ_a denotes the ambient temperature, R stands for the conductor resistance at the relevant temperature and T_i stands for the thermal resistance of the different layers [5]. The thermal resistance of the surrounding medium T_4 is given by equation 3 and depends on the thermal resistance of the soil ρ, the burial depth H, the distance between the two plus and minus cables d as well as the outer diameter D_e of the cable.

$$T_4 = \frac{\rho}{2\pi}\ln\left(\frac{4H^2}{D_e}\right) + \frac{\rho}{2\pi}\ln\left(\frac{\sqrt{4H^2+d^2}}{d}\right) \qquad [3]$$

This means that if one wants to present a figure or table relating power to conductor area and cable voltage, the laying conditions have to be specified. Figures 5 and 6 are an attempt to do so covering an area of maximum and minimum power for a given cable design, but relating to two extreme but realistic laying conditions. Condition 1 results in a minimum power and condition 2 in a maximum power.

- Condition 1: soil temperature 28°C, burial depth 1.0 meter, thermal resistivity 1.2 KW/m, close laying (touching)
- Condition 2: soil temperature 15°C, burial depth 1.0 meter, thermal resistivity 1.0 KW/m, spaced laying

The graph, both for copper and aluminium conductors represent a product map for polymer DC cables. Although the graph is specific for HVDC Light® cable systems, other polymer HVDC systems would probable result in quite similar graphs.

Product features

The product map for copper HVDC cable systems is shown in Figure 4, whereas Figure 5 shows the map for aluminium cable systems. The fact that the shaded areas stop after a certain conductor area is not as strict as in the picture; both larger and smaller conductor areas are possible. It was chosen such that a natural overlap occurs from the maximum power from one voltage class to the minimum power from the next voltage class. As expected, higher powers can be transmitted with copper conductors compared to aluminium conductors given a certain conductor area. Especially for the 320 kV cables it is seen that the laying conditions have a large impact on the transmission
power.

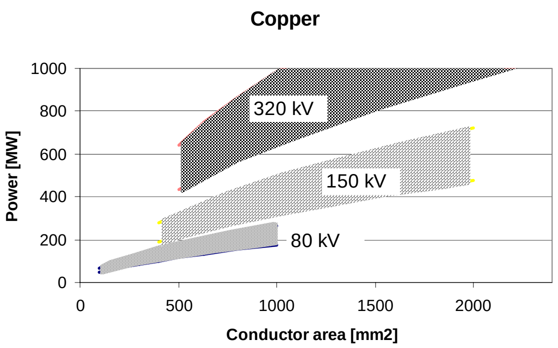

Figure 4. Power versus conductor area for the different voltage levels for cables with copper conductor.

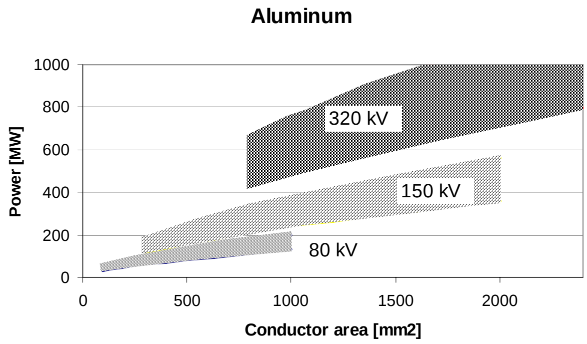

Figure 5. Power versus conductor area for the different voltage levels for cables with aluminium conductor.

In the next sections the dimensions in terms of outer diameter and weight of the cables as a function of power are discussed.

Diameter versus transmitted power

The diameter and weight of cables are important parameters dictating important installation details. In the case of submarine cables the maximum batch that can be loaded on a vessel depends of course on these parameters. For a given circuit length a larger cable needs more batches, vessel loadings and last but not least more joints compared to a smaller cable.

In the case of land cables with smaller dimensions more cable can be loaded on one drum decreasing the amount of joints, cable transport and right of way. Conclusively one can say that outer diameter and weight are important parameters for installation issues.

Figure 6 shows the relation between the outer diameter of the cable as a function of the transmitted power. Cables with copper and aluminium conductors are considered. The upper borders of the shaded areas denote more severe laying conditions (Condition 1 in Section “Product Map”), whereas the lower borders of the shaded areas represent better laying conditions (Condition 2). In the case of the copper cables one layer of tensile steel armouring and a lead sheath was added. So in the following graphs, the copper cables are submarine cables, whereas the aluminium cables were land cables. This means not that aluminium conductors are disqualified for submarine cables.

The diameter of the cables is increasing less and less as the power increases. This is expected as the diameter increases with the square root of the conductor area, which in its turn is approximately linear with the current and the power. Another reason is the increased mean field strength for the 320 kV cables resulting in slimmer cables.

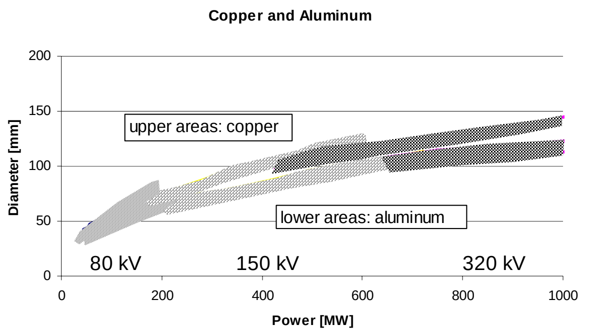

Figure 6. Cable diameter as a function of power. Both for copper and aluminum conductors.

Weight versus transmitted power

The same graph was made considering the weight of the cables as a function of power. Again both cables with copper and aluminium conductors are presented (Figure 7). Also here the copper cables are of the submarine design having one layer of steel armouring and a lead sheath.

Due to this and the higher specific weight of copper, the submarine cables are heavier than the land cables with aluminium conductor.

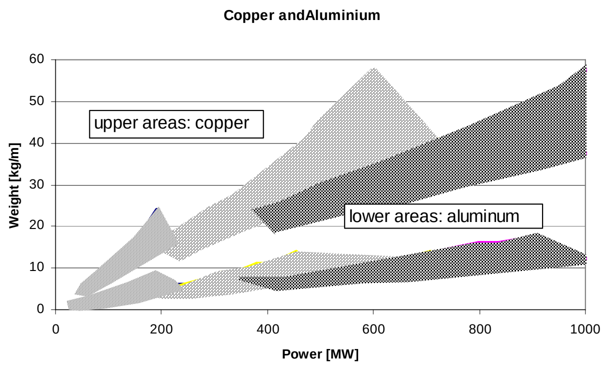

Figure 7. Cable weight as a function of power. Both for copper based submarine cables and aluminium based land cables.

INSTALLATION ASPECTS

Having stated that diameter and weight are important parameters concerning installation of these cables, polymer three-phase HVAC cables with polymer HVDC cables are compared.

Submarine installation

Weight and outer diameter of HVDC and three-phase HVAC cables are compared. The laying conditions were: one meter burial depth, thermal resistance 1.0 KW/m, sea soil temperature 15°C. In the case of the bipolar HVDC cables the poles were closely layed (touching).

The HVAC cables that were used for the calculations are shown in Table 1. The real power that can be transmitted using the HVAC cables depends strongly on the length of the circuit due to charging currents. This maximum length can be stretched using shunt reactors, static var compensators or other means. Anyhow, the power values stated in Table 1 has to be looked upon as maximum numbers. The HVDC cables are also shown in Table 1. Two cables are needed (bipolar system).

	HVAC		HVDC	
P [MW]	U [kV]	A [mm2]	U [kV]	A [mm2]
80	115	240	80	185
100	115	380	80	300
140	115	800	80	500
200	220	400	150	300
260	220	800	150	500
450			300	400
530			300	500
700			300	800
1000			300	1600

Table 1. HVAC three-phase submarine cables and HVDC submarine cables. For the latter, two cables are needed. The powers were approximated to the nearest whole number.

The weight of these cables are shown in Figure 8, whereas the outer diameters of the cables are shown in Figure 9. In order to compare the outer diameter of one single three-phase HVAC cable with two HVDC cables (plus and minus) an equivalent outer diameter $D_{e,eq}$ for the HVDC cables was used according to equation 4.

$$A_{eq} = 2A_{single}, \quad D_{e,eq} = \sqrt{2} D_{e,single} \qquad [4]$$

where A stands for the area of the cables and $D_{e,single}$ denotes the outer diameter of one single pole. The weight of the HVDC cables denotes two poles.

One can see that polymer HVDC cable are in the advantage concerning both weight and diameter.

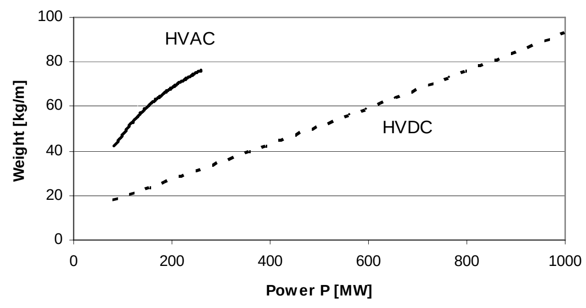

Figure 8. Weight of HVAC three phase and HVDC submarine cables as a function of power.

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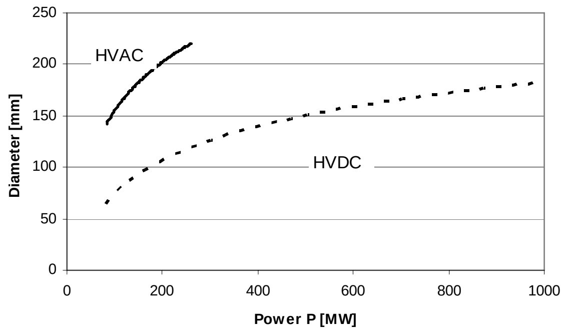

Figure 9. Diameter of HVAC three phase and HVDC submarine cables as a function of power.

Now with this knowledge one can deduce the maximum length of cable that can be loaded, transported and layed in one batch. Several specialised cable vessels can handle huge amounts of cable such as the Oceanteam 102&103 (under completion), Skagerrak and the Gulio Verne to mention some. The maximum lengths that can be loaded has been calculated using the vessel properties of the Oceanteam 103 and using the cable data of Tables 1 and 2. Both maximum allowed weight and turntable dimensions have been considered. Figure 10 shows the maximum lengths that can be handled. It has been taken into account that two poles are needed for the HVDC cases. Please observe that no attention has been paid in this analysis whether it is technically feasible to bridge more than 100 kilometers with HVAC systems. This study concentrated on weights and dimensions only.

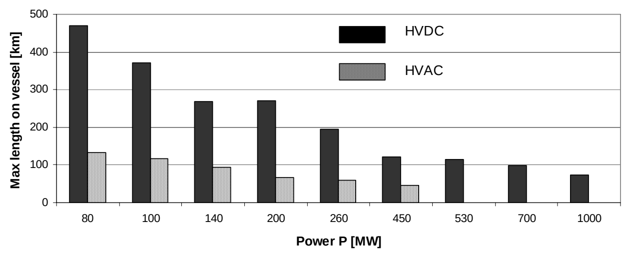

Figure 10. Maximum length loaded on large vessel as a function of transmitted power.

From the perspective of vessel loading no field joints are needed in the HVDC case. HVAC cables need joints in order to come up at longer circuit lengths in those cases that it is technically feasible to use HVAC at all.

Land installation

Cables with lower weight and diameter can also be an advantage in the case of land installation. Lower weight and diameter means in general that longer lengths can be loaded on one single cable drum. This means in its turn that less joints are needed for a given circuit length. For the purpose of comparison a number of suitable land cables were compared with the following laying conditions: one meter burial depth, thermal resistance 1.0 KW/m, soil temperature 20°C. To make a fair and yet simple comparison possible the laying was in three-foil for the HVAC cables and touching for the HVDC cables. Cross bonding has been assumed in the AC case. In both cases the maximum design temperatures have been decisive, that is 90°C for the AC cables and 70°C for the polymer DC cables.

The HVAC and HVDC land cables that were used for the calculations are shown in Table 2. All cables have aluminium conductors.

	HVAC		HVDC	
P [MW]	U [kV]	A [mm2]	U [kV]	A [mm2]
40	45	400	80	120
60	60	400	80	185
140	110	630	80	800
160	132	630	150	400
250	150	1200	150	800
400	220	1600	300	630
500	275	1600	300	800
700	330	2000	300	1400
800	380	2000	300	1800
1000	500	2000	300	2800

Table 2. HVAC and HVDC land cables with aluminium conductors. The powers were approximated to the nearest whole number.

Using these cable designs the weight per circuit meter of cable and the diameter of each single core was calculated and is presented in Figures 11 and 12. The weight per circuit meter denotes then the weight of three times one meter HVAC cable and two times one meter HVDC cable.

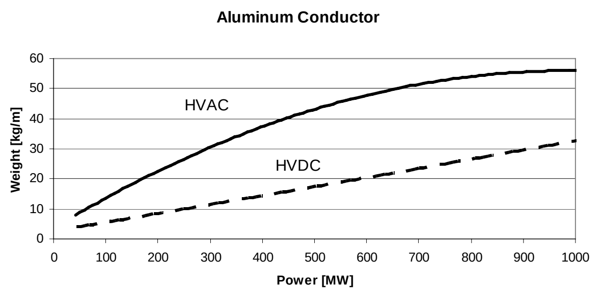

Figure 11. Weight per circuit meter length of three HVAC single core cables and two HVDC cables as a function of power.

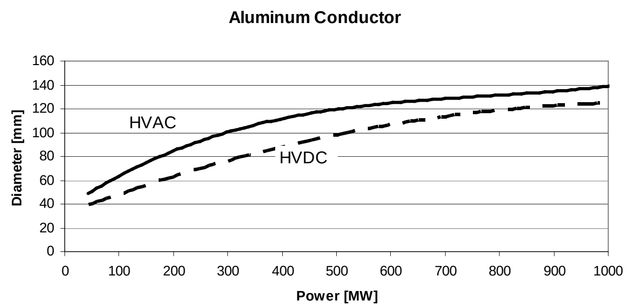

Figure 12. Diameter of one HVAC single core cable and one HVDC cable as a function of power.

As can be seen the HVDC polymer cables are in the advantage concerning both weight and diameter. This has of course an impact on the maximum length that can be wound on a cable drum. Given the dimensions of a large steel cable drum one can calculate the maximum length for the given cable designs (Figure 13). A steel drum with the following dimensions has been used: diameter 3,93 meters, width 2,40 meters and suitable barrel diameters taking into account the minimum bending radia of the cables. The drum dimensions were chosen such that no special transporting issues had to be considered such as police escort.

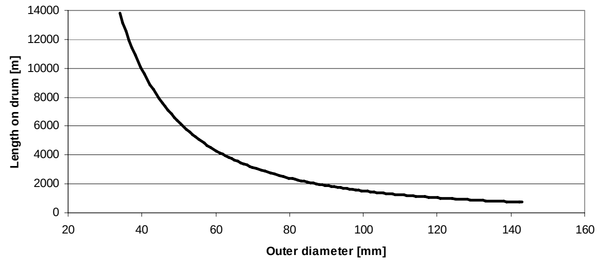

Figure 13. Maximum cable length on drum

From this it can be understood that depending on the outer diameter of the cable one or more joints are needed to bridge a certain distance. The number of joints needed per ten kilometer of circuit length as a function of transmitted power is shown in Figure 14 (cable designs from Table 2). It follows that in general more joints are needed for HVAC land cables compared to HVDC land cables.

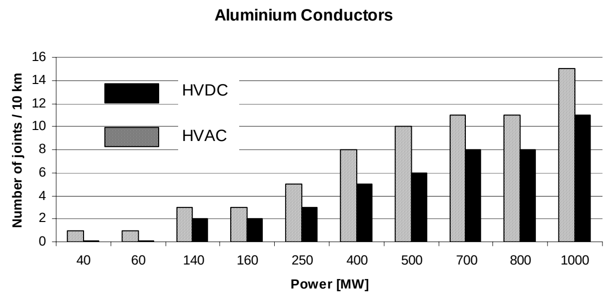

Figure 14. Number of joints needed per 10 km of circuit length as a function of transmitted power. The powers were rounded to the nearest whole number.

CONCLUSIONS

The total installed length of polymer HVDC cable system has reached 1566 kilometers. Both land and submarine polymer HVDC cables are in commercial operation now. This means that the polymer HVDC cables have become a more and more mature product.

Recently a 320 kV polymer HVDC cable system has been type tested according to the CIGRÉ Recommendations for polymer HVDC cable systems. The development of this new voltage level was built on the solid knowledge base of the previous voltage levels of 80 and 150 kV. The same design principles as for the lower levels can be distinguished. The mean electrical field for the 320 kV level was increased in order not to increase the outer diameter of the cable of this and future voltage levels too much.

The polymer HVDC product map covers now the whole area of 80 to 320 kV and from a couple of tens of MW to at least a 1000 MW.

When installing submarine and land cables outer dimensions and weight are important. The weight and diameter of three-phase HVAC submarine cables and submarine bipolar HVDC cables were compared for several designs. Over a broad power range the submarine HVDC alternative is about half the weight and equivalent diameter of the polymer HVAC alternative.

For the same reasons more polymer HVDC land cable can be wound on a drum resulting in less joints per circuit length and lower transportation costs.

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