The status and future of HVDC Light cable systems

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SUMMARY

With the introduction of VSC converter stations and extruded polymeric HVDC cables the traditional market for HVDC cable interconnections, i.e. long submarine links, is expanded and new market driven opportunities are realised. These include off-shore applications, e. g. oil platforms and wind farms. But also the opportunity for undergrounding, with substantially shorter project realisation times due to the simplified permission schemes made possible with the HVDC Light concept. The small dimensions of the cable system and the simplified installation procedure all help to reduce the installation cost.

Today's experience with HVDC Light cable systems is summarized by some key figures. That is 1482 installed kilometres and another 400 kilometres on the way under 2009, 8800 km x years service experience at the moment of writing and a maximum qualified voltage of 320 kV.

Future demands for transport of higher powers by land and strengthening the land-based networks will push the development of the HVDC Light concept to even higher powers and voltages. Today's maximum transmission capacity equals around 1 GW for HVDC Light® cable systems with aluminium conductors. Future voltages may go for 500 or 600 kV and thus increasing the transmittable power with one aluminium cable pair to 1.5 or 2 GW.

A pair of HVDC-Light submarine cables weighs about two times less than a 3-phase ac alternative. This means that HVDC Light cables are suitable for installation at larger depths compared to their ac counterparts. A type test showed the suitability of the concept for installation at depths beyond 1 kilometre.

The oil and gas industry faces the fact that new reserves have to be exploited at larger depths. Their platforms will be more and more of the floating type. Floating wind mills may be another future trend. Power from shore or power to shore means the necessity of so-called dynamic cables. Such cables are suitable to connect to floating devices. In 2009 the world's first dynamic 3-phase ac 115 kV power cable is installed. The technology that is introduced in this cable is applicable to dynamic extruded dc cables as well.

KEYWORDS

HVDC, cables, dynamic, submarine, land, voltage, power

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INTRODUCTION

This article aims to describe today's technical status of the HVDC Light cable system. From there on some possible future technology trends will be described. These are increased voltage, increased installation depth for submarine cables and the introduction of dynamic power cables.

TECHNICAL STATUS TODAY

Early research on extruded cables for dc has been started already in the nineteen sixties. The results were sometimes very promising and sometimes very discouraging. The early extrusion technology was unreliable and quite simply not yet ready for the challenges of HVDC at that time. From that point in time and onwards the extrusion technology experienced a major increase in quality and understanding. Also, in the nineteen eighties special non-destructive measurement technologies based on the family of electro-acoustic principles were introduced in the high voltage engineering. This helped the understanding of charging mechanisms in extruded dc cables. Renewed and intensive research was restarted in the nineteen nineties. It resulted in the commercial available extruded HVDC cable systems known under the name of HVDC Light.

Currently three standardized voltage levels exist, namely 80, 150 and 320 kV. However there exists no principal objection against intermediate voltage levels. The Troll-A platform for instance is connected to the mainland by an HVDC Light cable that is energized at 60 kV dc.

The current amount of installed HVDC Light cable is 1482 km. Under 2009 this amount will increase to 1888 km after the installation of the NORD E.ON 1 project [1, 2] connecting the sea based wind park to the German mainland. The amount of experience expressed in the product kilometres times years goes up to 8800 km x years at the moment of writing and is steadily increasing.

On the qualification side a considerable amount of type tests have been performed since the 1990's. More than 20 type tests have been performed on the 80, 150 and 320 kV levels on cable systems with different conductor sizes. Long term tests on 80, 150 and 320 kV levels have also been conducted. Today the extruded cable system HVDC Light relies on a solid base of laboratory and commercial experience.

Qualification of 320 kV

The qualification of the HVDC Light cable system on the 320 kV level is highlighted especially. No commercial installation exists yet, however two extended type tests and a long term test have been conducted successfully.

Both type tests have been performed on a 1200 mm^2 aluminium conductor cable with 18 mm insulation thickness and accessories. The test was conducted according to the CIGRÉ recommendations [3]. The first type test was conducted for a nominal voltage of U_0=300 kV whereas the second type test was performed for a U_0=320 kV. The nominal voltage was increased to 320 kV in a later stage of the development after consultation of the supplier of the converter stations (ABB).

Type test 1

The type test was performed in two stages. The first stage qualified the system for a VSC converter type. The second stage qualified for a LCC converter type, that is, polarity reversals were applied during heat cycling. Stage one would have been enough to qualify the cable system for VSC. The cable system passed the tests successfully. See Table 1.

STAGE ONE	STAGE TWO including polarity reversals
• Load Cycle Test o 12 cycles -555 kV, 8/16 hours h/c* o 12 cycles +555 kV, 8/16 hours h/c o 3 cycles +555 kV, 24/24 hours h/c • Superimposed Surge Voltage Test o U_{dc} = +300 kV, U_{p2s}= +630 kV, 10** o U_{dc} = +300 kV, U_{p2o}= -350 kV, 10 o U_{dc} = -300 kV, U_{p2s}= -630 kV, 10 o U_{dc} = -300 kV, U_{p2o}= +350 kV, 10 • Subsequent DC test o U_{dc} = -555 kV, 2 hours * - h/c means heating/cooling ** - 10 means 10 surges	• Load Cycle Test o 8 cycles ±-435 kV, 8/16 hours h/c polarity reversal every 8th hour • Superimposed Surge Voltage Test o U_{dc} = +300 kV, U_{p2s}= -660 kV, 10 o U_{dc} = -300 kV, U_{p2o}= +660 kV, 10 • Subsequent DC test o U_{dc} = -555 kV, 2 hours

Table 1. 300 kV type test.

Type test 2

The type test was performed in two stages. The first stage was a test exactly according to the CIGRÉ recommendations. In order to prove the robustness of the design a second stage was added. The testing during the second stage was continued on the same circuit, after completion of stage one and was performed while assuming the cable system had a nominal voltage U_0 of 350 kV instead of 320 kV. The test factor of 1.85 during cycling was increased to a factor 2.0 to compensate for the shortened test time. The circuit passed the two stages without breakdown or any other problem [4]. See Table 2.

STAGE ONE	STAGE TWO
• Load Cycle Test o 12 cycles -592 kV, 8/16 hours h/c* o 12 cycles +592 kV, 8/16 hours h/c o 3 cycles +592 kV, 24/24 hours h/c • Superimposed Surge Voltage Test o U_{dc} = +320 kV, U_{p2s}= +665 kV, 10** o U_{dc} = +320 kV, U_{p2o}= -375 kV, 10 o U_{dc} = -320 kV, U_{p2s}= -665 kV, 10 o U_{dc} = -320 kV, U_{p2o}= +375 kV, 10 • Subsequent DC test o U_{dc} = -592 kV, 2 hours * - h/c means heating/cooling ** - 10 means 10 surges	• Load Cycle Test o 5 cycles -700 kV, 8/16 hours h/c o 5 cycles +700 kV, 8/16 hours h/c • Superimposed Surge Voltage Test o U_{dc} = +350 kV, U_{p2s}= +727 kV, 10 o U_{dc} = +350 kV, U_{p2o}= -410 kV, 10 o U_{dc} = -350 kV, U_{p2s}= -727 kV, 10 o U_{dc} = -350 kV, U_{p2o}= +410 kV, 10 • Subsequent DC test o U_{dc} = -648 kV, 2 hours

Table 2. 320 kV type test.

Long term test

According to the CIGRÉ Recommendations a prequalification test, also called long term test, is to be performed if "*there is a substantial change in the cable system with respect to materials, manufacturing processes, construction or design parameters*". As the field stress has been increased, it was judged that a new prequalification test on a full-scale 320 kV cable system was necessary. The test consists of a one year voltage test at 1.45 U_0 and different time sections containing heat cycles, cold and warm periods. The test ended with superimposed switching surges on the one year tested circuit. The test has been completed successfully [4].

Transmittable power

The power that can be transported in an HVDC cable system, which consists of a plus and a minus pole, is at first approximation independent of the length and is given by $2U_0I$, in which I is the current in the conductors. The maximum current that can be conducted before reaching the maximum temperature, depends apart from conductor size also on installation conditions. These are for instance, installation depth, distance between the two cables, ground temperature and soil thermal resistivity. A cable pair that is installed in a warm country, deeply buried in a soil with a high thermal resistivity and the cable pairs close to each other transports less power than a cable pair buried less deep, well separated from each other in a soil with a low thermal resistivity in a cold country. So, the power that a given cable can transport depends significantly on external factors.

The powers that can be transported using 80 kV, 150 kV and 320 kV cables with different conductor sizes are given in Figure 1. The areas denote an approximate minimum and maximum power as follows from different installation conditions.

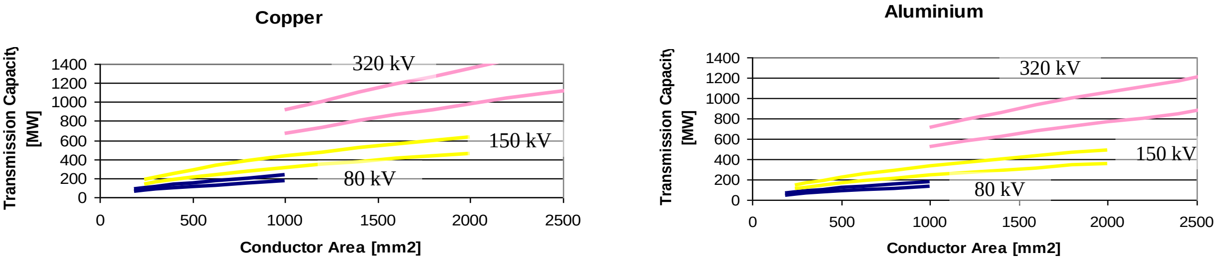


Figure 1. ***Power maps for HVDC Light cables with copper (left) and aluminium (right) conductors.***

HVDC LIGHT CABLE SYSTEMS – FUTURE

Looking into the future we note at least three trends. At first, extruded dc cable systems will be developed for higher power and for that reason for higher voltages. At second, submarine extruded dc cable systems will reach for increasingly larger depths. And at third, we foresee that extruded dc cable systems will be used for floating marine devices as floating platforms, FPSO’s and floating wind-mills. These three areas will be focused upon in the next sub-sections.

Land cable systems – towards higher voltages

The earth’s resources are becoming more and more limited. Building the infrastructure to satisfy growing population demands is fast becoming a critical issue. Energy companies amongst others are now, more than ever, compelled to find ways of providing increased services using, in many cases, the same infrastructure in a more compact, effective and environmentally friendly way. The energy sector, for example, has been investigating ways of increasing power transmission in the already existing power corridors. Not only this but in the framework set by the European Commission in 2003 [5], electrical trade between member countries must be increased. Because this is currently underdeveloped compared with other sectors of the economy, a larger number of inter-connectors must be built, either on land or at sea.

Concerning dc land cable transmission we see currently a dramatic increase in the number of studied projects where considerable amounts of power are to be transmitted. Many projects demand a transmission power of 1 GW or more. If several GWs of power is to be transported by land parallel circuits are needed with the current status of the technology. Of course one can use cables with copper conductors, but this increases the cost. If we foresee the use of aluminium as conductor material we can either increase the conductor area or increase the voltage. The right-hand side of Figure 1 shows already quite large conductor areas. We cannot expect to increase conductor areas much more, quite probably not beyond 3000 mm^2. That leaves us with increasing the voltage. The left hand side of Figure 2 shows a power map for aluminium conductor dc cables for three different voltages, 320, 400 and 600 kV. The reason for leaving out 500 kV is just to avoid too many curves in the graph. The same logic as in Figure 1 is used, that is, a lower curve for less favourable installation conditions and an upper curve for more favourable installation conditions. The right-hand side of Figure 2 shows the particular transmittable power for a 2000 mm^2 aluminium conductor for different voltages. The interesting area around 1.5 GW of power can be reached with voltages around 500 kV. To crush the 2

GW border with one pair of cables with 2000 mm^2 aluminium conductors we have to increase the voltage to more than 600 kV.

Extruded cable systems at these voltages are judged to be feasible in the future. To increase the voltage to 800 kV or more might need technologies beyond standard extrusion.

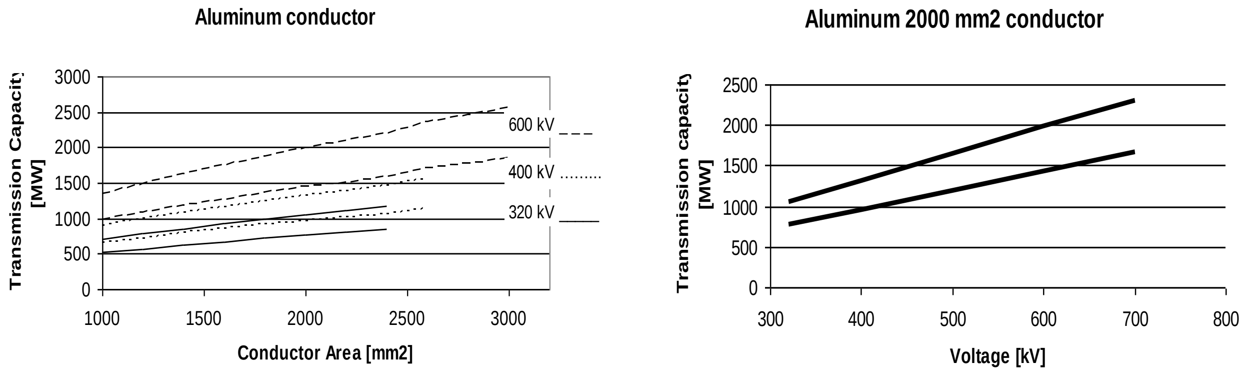


Figure 2. Left : Transmittable power for different voltages and conductor areas. Right: transmittable power for a 2000 mm^2 aluminium conductor as a function of voltage.

Submarine cable systems – increasing depths

As mentioned under the previous section a larger number of inter-connectors must be built, either on land or at sea. Concerning submarine inter-connectors this means in some cases increased depth. The next section that deals with dynamic cables, also mentions increased depths. In Europe especially around the Mediterranean and the North Sea (see Figure 3).

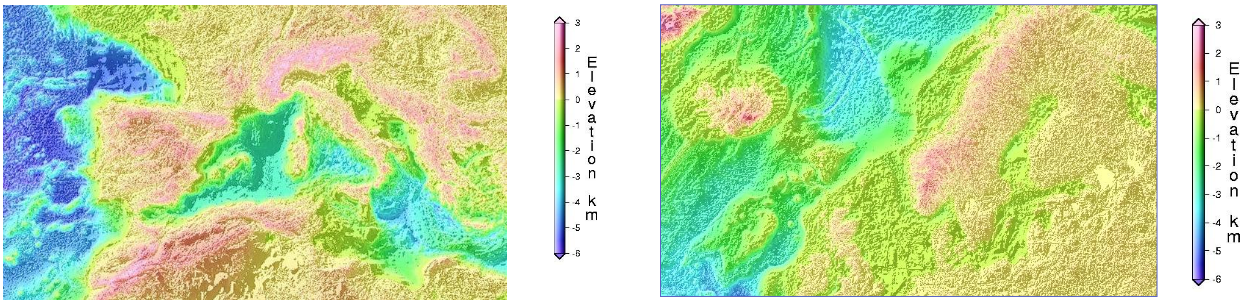
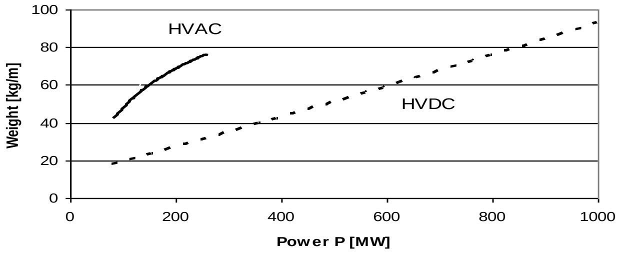


Figure 3. Depth map of the Mediterranean and the North Sea.

HVDC Light cables are particularly suitable for installation at larger depths due to the low weight per kilogram of cable as compared to 3-phase ac cables. Of course, only depth is not enough as a driving force to choose direct current as the transmission alternative. However, if dc is chosen as the alternative, extruded dc cables will show to be capable of being installed at large depths.

Three-phase ac submarine cables have approximately double the weight compared to a pair of submarine HVDC Light cables (see Figure 4). The armour has to carry this weight during installation or recovery. For this reason HVDC Light cables can more easily be used for installation at larger depths than 3-phase ac cables. Moreover, stiff joints for HVDC Light cables are less complex and have lower weight and dimensions compared to the 3-phase ac alternatives.



	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

Figure 4. Approximate weight of 3-phase submarine cables and a pair of HVDC Light submarine cables as a function of power. The exact numbers depend on installation conditions and cable design. Copper conductors have been used.

In order to prove that HVDC Light cables are suitable for installation at large depths the following test has been conducted. A 300 mm^2 Cu, 8 mm insulation, double steel armoured HVDC Light cable including a submarine flexible joint was subjected to a tensile bending test according to Electra No.171. A force of 380 kN was used. The test corresponded to a laying depth of more than 2000 meters. An electrical type test according to IEC60840 based on an AC voltage U_0 = 52 kV was performed after the tensile bending test. An AC type test was chosen as it was assumed that an AC cycle test would be a harsher test to detect eventual mechanical distortions in the insulation system.

- PD test at 39 kV, Tan δ test at 26 kV
- 20 days of heat cycling at 52 kV (4 hours heating, 8 hours cooling, maximum conductor temperature >95°C)
- Hot impulse test at 250 kV (10 positive and 10 negative impulses)
- Power frequency voltage test at 65 kV followed by a PD test at increased voltage (65 kV)

The test was performed with shorter temperature cycle duration to include more cycles within 20 days. However, it was ensured that steady state temperatures for conductor and sheath were reached in each cycle. The objects passed all the tests without any problem. A local permanent maximal decrease in diameter of less than 3% was measured after the test. Demonstrably this had no effect on the functionality of the cable and joint [6].

Submarine cable systems – Dynamic cables

At least three applications need a type of power cable that has not been written so much about up to now. These applications are floating oil and gas platforms (semi-submersibles – SEMI, Tension Leg and Spar types), Floating Production, Storage and Offloading vessels (FPSO’s) and floating wind mills. The common factor is that these devices are floating and are apt to movements induced by wind, current and waves.

The use of these floating oil and gas platforms and FPSO’s is expected to increase in the future as the exploitation of oil and gas fields will be at locations of increasing depth (see Figure 5).

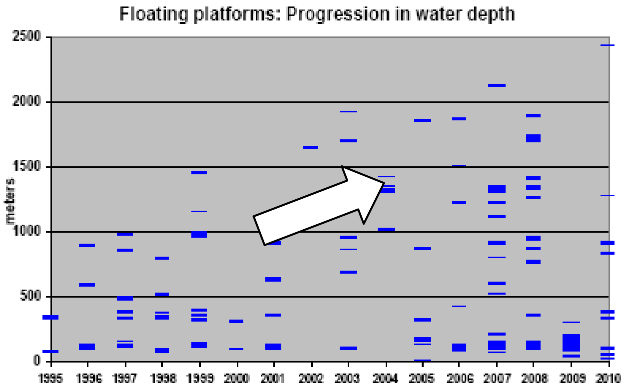


Figure 5. Increase of the depth at which floating devices were and are to be installed.

Static platforms that stand solidly on the sea bottom become too expensive. Floating devices are not new. What is new is the fact that we now face the challenge to connect these platforms to land by means of a power cable. Because in more and more cases it becomes economically interesting to avoid local generation and to import power from shore, thus reducing the generation of CO_2. Now the cable has to be connected to a platform that floats around in a circle with a certain radius. And the cable itself will be prey to the currents and waves. The cable will be apt to recurrent bending, axial and torsional forces with frequencies induced by the currents and waves.
An FPSO has an additional degree of freedom and may turn around its axis. The connection of the power cable has to be performed by means of a so-called swivel.
A floating wind-mill may be compared to a SEMI, but of course much, much smaller.
The fact that the floating device may move in a circle with a radius of at least several tens of meters means that the cable needs some kind of extra length that might stretch when the device floats away or that takes up cable when the device moves towards land. This is achieved by a so-called configuration like there is Lazy Wave, Lazy S, Pliant Wave, etc. A picture of a Lazy Wave configuration is shown in Figure 6. The configuration is achieved by applying buoyancy units to the cable. Most of the cable may be of the static type, but the last part close to the floating device is a so-called dynamic cable. These two types are connected by means of a transition joint.

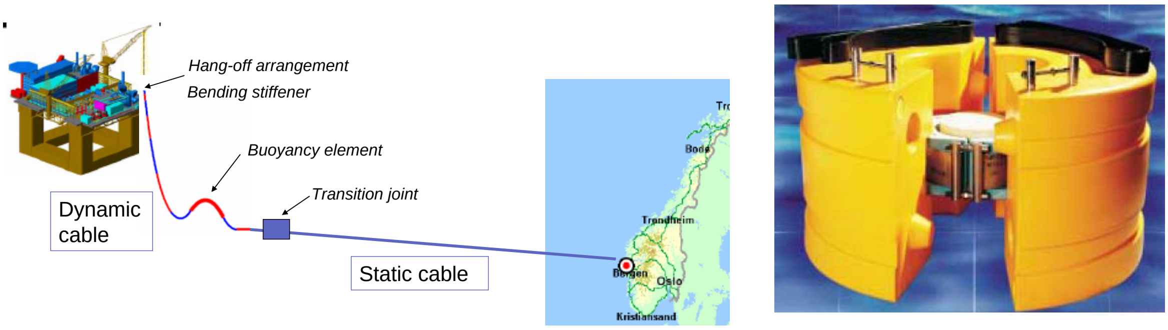


Figure 6. Left : Lazy Wave configuration of the dynamic cable. Right: one buoyancy unit.

As the dynamic cable is subject to recurrent movements the cable must be able to withstand this mechanical fatigue. The most fatigue prone element in an ac or dc high voltage cable is the metal sheath which is commonly made of lead. Lead can withstand only low mechanical loads and will crack after a low amount of wave induced movements. Then the water tightness cannot be guaranteed anymore. Instead metal sheaths that can withstand these recurrent movements have to be used. One such a solution is a so-called corrugated welded copper sheath. This solution is currently being used in the realisation of a project named Gjøa [7, 8]. A 100 km long connection of which the last 1.5 km is of the dynamic type will connect a SEMI with the Norwegian main land. The cable is a 3-phase 115 kV ac cable with welded corrugated copper sheaths. A picture is shown in Figure 7 (left-hand side). The mechanical fatigue properties of the welded corrugated cable cores have been measured in a specially designed test rig that simulates the relevant forces (Figure 7 – right-hand side).
However not realised yet, a dynamic dc cable could look like the picture in the middle in Figure 7. A dynamic dc cable is a simpler construction than its 3-phase ac counterpart.

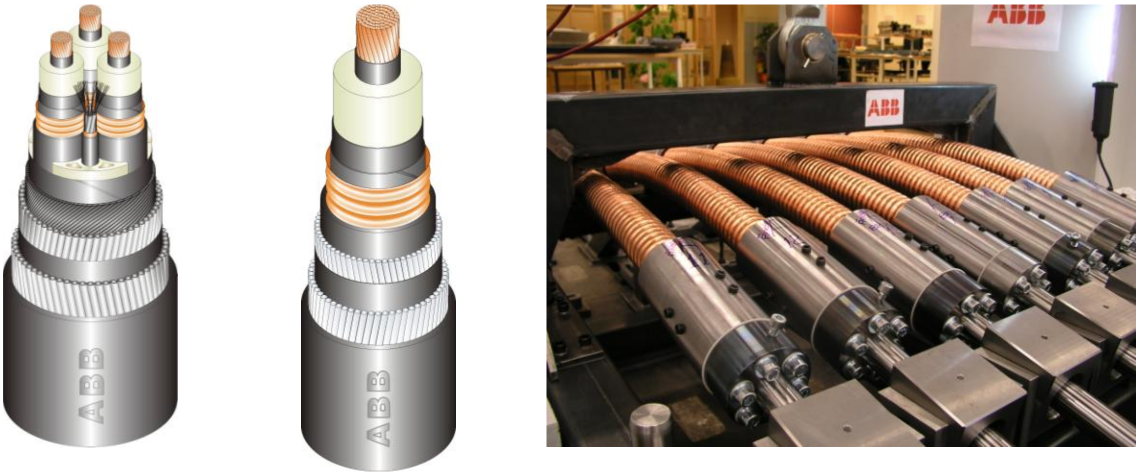


Figure 7. Left: dynamic 3-phase ac cable. Middle: dynamic dc cable. Right: test rig for corrugated welded cable cores.

CONCLUSIONS

Extruded dc cable systems have been installed and are in service since the late nineties. Since then 1482 km of cable have been installed and are in service with another 400 km on the way. At the moment of writing these cable systems have 8800 km x years service experience. HVDC Light cable systems are commercially available up to 320 kV and cover a power up to about 1 GW with aluminium conductors and higher with copper conductors.

The future trends for extruded dc cable systems that we see are higher powers and for that reason higher voltages, larger depths and dynamic cables.

Concerning higher voltages we will probably see a trend towards 500 or 600 kV and as such covering powers towards 1.5 and 2 GW for land cables with aluminium conductors.

HVDC Light cables are even more suitable for installation at larger depths due to their relative lower weight as compared to the 3-phase ac alternatives. Also the stiff field and repair joints are less complex and weigh less.

Another future trend we will see is cable connections from land to floating devices such as floating platforms for the oil and gas industry and floating wind mills. The introduction and installation of the world’s first 3-phase ac dynamic power cable opens the possibility to use this technology even for extruded dc cables.

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