Chapter 5
Manufacturing and Testing

Contents

5.1 Manufacturing

The manufacturing of land cables is a straight-forward consecutive row of adding layer by layer to the conductor. The short production length (typically a drum length) allows for moving the cable between the different production steps on drums until the final layer has been applied and the cable drums can be put to the final acceptance test.

Submarine power cables on the contrary are often shipped in extreme lengths only limited by the capacity of the cable-laying vessel, which can be several thousand tons of cable. To avoid a large amount of joints, all production steps must be performed on lengths as long as possible. The maximum continuous production length of each production step depends on the cable size and type. Most often

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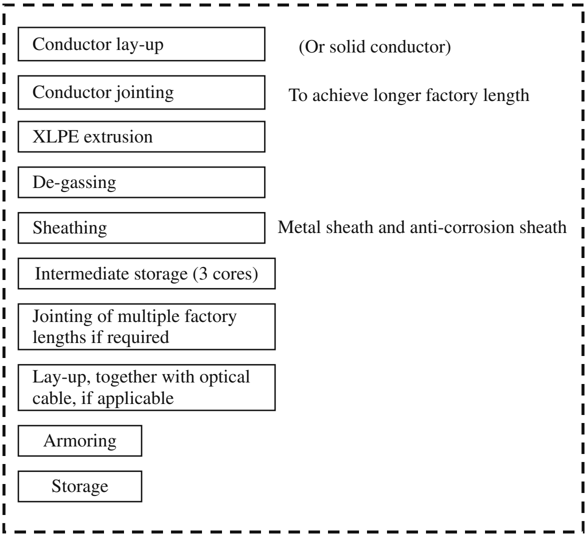

Fig. 5.1 Flow chart for the production of three-core submarine cables with extruded insulation

the production lengths of the different steps cannot be harmonized completely. This results in an intricate planning of the use of production assets. Only a well-orchestrated factory can exploit the advantage of long shipping length.

Figure 5.1 is a flow chart of the manufacturing of a three-core extruded submarine cable.

The core of a cable consists of a conductor, the electric insulation system, and protecting sheathes such as lead and PE sheath. The manufacturing of submarine cable cores is almost identical to the manufacturing of land cable cores and is described here but briefly. More detailed descriptions of cable core manufacturing can be found in [1, 2]. In this chapter the focus is on those manufacturing steps that are characteristic for submarine power cables.

5.1.1 The Conductor

All cable manufacturing starts with the conductor. Conductor making methods are identical to those for underground cables. However, the conductor made from pre-shaped profiled Cu or Al wires is used almost exclusively for submarine HVDC cables where a very compact conductor has a larger advantage than in an a.c. cable. For mass-impregnated cables it is essential that the wires lay closely together not leaving any space for extra impregnation compound [1]. Wire design and manufacturing process must be matched carefully to avoid gaps between the wires, or stepping, which is a misalignment of the profiled wires leading to a saw-teeth like surface on the conductor. A well-adjusted conductor stranding line makes a perfect smooth conductor. Conductor sizes up to around 3000 mm^2 have been achieved.

Some factories can produce conductors in continuous lengths up to 20–30 km but most factories produce the conductor on cable drums in lengths of only a few kilometres. Conductors can be jointed before entering the next production step by a multitude of jointing technologies:

- Solid welding in one piece through the cross section
- Wire-by-wire welding
- Soldering or brazing techniques
- Flush compression sleeve.

Conductor joints for fluid-filled cables (not mass-impregnated) require an oil passage in the centre. All conductor joints must be performed very carefully to provide sufficient mechanical strength and a smooth flush surface. In particular, "cold" soldering must be avoided as the wire ends might snap apart during later bending of the cable and perforate the conductor screen from the inside. The conductor joint must also meet the stringent tensile requirement imposed on submarine cables for larger depths. The area on both sides of the welding is often softer than the weld or the conductor itself on account of the annealing effect of the heat.

A frequent requirement for submarine power cables is longitudinal water tightness in the conductor. This can be achieved by the introduction of various water-blocking agents such as swelling powder, swelling yarns, hydrophobic compounds or gels. They are inserted between the wire layers.

The conductor resistance should be checked on a regular basis according to the quality assessment system of the manufacturer.

The next step in the manufacturing process is the application of the insulation. In modern submarine power cables, only extruded XLPE or lapped paper insulation is being used. These two processes are completely different in material, equipment and production properties.

5.1.2 XLPE Cables

XLPE extrusion is a continuous process. The raw material is a highly sophisticated compound of base polyethylene resin with well-defined distribution of molecular weight, antioxidants and cross-linking agents. The compound is supplied as granules and comes in different purity classes. In general, a higher voltage class requires a higher purity. The properties of the semiconducting compound forming the conductor screen and the insulation screen are tailor-made to fit the insulation compound. There are smooth and ultra-smooth varieties regarding the smoothness of the highly stressed inner semi-conductive surface.

Virtually all modern m.v. or h.v. cable extrusion lines employ a triple-extrusion concept. Three extrusion screws supply the constituent materials to a common extrusion head, which extrudes all three layers concentrically in the same process. Catenary or vertical extrusion lines are used to manufacture the insulation system. While an extrusion length of 2000 m is sufficient to produce underground cables in drum lengths, the long delivery length of submarine cables call for much longer uninterrupted extrusion length in order to reduce the number of joints. Lengths of over 20 km can be extruded in a single run. The long extrusion time requires a faultless supply of resin granules under super-clean conditions. In the best cable extrusion lines there are closed systems for the handling of the granules to avoid any contact with factory air or human hands.

Any interruption in the process causes a cut of the cable rendering shorter cable lengths than anticipated.

Extrusion lengths, whether limited by extruder limitations or by unintended cable cuts, can be jointed together using flexible factory joints to achieve long delivery lengths. Flexible factory joints are provided with a conductor connection of one of the types outlined above. The conductor joint must be flush with the cable conductor. After the conductor connection is made the insulation of the adjacent cable ends are tapered. The gap is filled with lapped XLPE tapes and cured under heat and pressure. The added insulation material melts together with the surface of the tapered cable insulation. Figure 5.2 shows such a flexible factory joint. Some factories produce injection-moulded factory joints. The flexibility of the joint is crucial for the subsequent path of the cable core through the cable gantries of the factory.

Fig. 5.2 Factory joint of an extruded cable core (Courtesy of ABB, Sweden)

Gaseous byproducts that are dissolved in the XLPE matrix must be removed by degassing. If not degassed properly, the cables would emit these gases during operation later on resulting in unwanted gas volumes in the conductor or under the lead sheath. The degassing of long lengths of submarine cable cores requires large heated and ventilated vessels.

The insulation material must be protected against humidity already in the factory. Condensing water can be found on resin pellets cold from the transport. At cable cutting surfaces humidity may enter the conductor and contaminate the insulation from inside. The manufacturer's QA system defines when and where during storage time the cable must be equipped with suitable end caps.

5.1.3 Paper-Insulated Cables

The paper insulation is applied on dedicated paper lapping lines consisting of a row of lapping heads. In each lapping head, typically 12–16 reels with paper tapes revolve around the cable conductor as it passes through.

The paper tapes are applied according to an intricate pattern. Each single paper tape is wrapped around the cable in an open helix (it does not overlap itself in

Fig. 5.3 Lapping of carbon-black paper and insulation paper onto a copper conductor (Courtesy of ABB, Sweden)

subsequent turns). There must be a small gap (1–4 mm) between consecutive turns. This gap is called butt gap. When the cable is bent, the butt gaps in the inner curve accommodate the relative movement of the individual paper tapes.

The paper tension is controlled for each paper tape by brake devices on each reel. The lapping heads rotate in alternate directions to produce a torque-balanced insulation. Figure 5.3 shows the cable core in a lapping head. A layer of semi-conducting carbon-black paper is lapped onto the conductor before the insulating paper is added. High-performance power cables require the use of pre-dried cable paper and a lapping line in a controlled dry atmosphere.

Many cable types use staggered paper thicknesses throughout the insulation, each layer having a well-defined paper tension. The paper thickness ranges between 40 μm and 180 μm.[1] The insulation can have as many as 270 individual paper tapes to be put on the conductor in a single run.

The paper lapping process can be stopped and started at will. Reloading of the paper reels consumes a considerable part of the production time, and it is an appreciable logistic effort to supply sufficient paper reels of the correct type in time. After completion of the insulation including the screen the cable core is guided to the receiving turntable. This can be an intermediate storage turntable, or the cable is being stored directly into the rotating impregnation vessel. In either case the cable must be kept under very dry air.

It is, drawing on sufficient experience, and obeying strict quality standards, possible to produce a firm regular insulation without wrinkles or creases over very long lengths. The process is virtually unlimited as the next conductor length can be welded to the previous one upstream of the lapping line. Only the hold capacity of the receiving turntable limits the uninterrupted lapped cable core length.

While paper in equilibrium with the open air holds a water content of 6–12% the accepted level for paper insulation is only within the range of 1–2%. The

[1] Paper suppliers prefer to specify the paper “thickness” in grams per square metres (g/m^2).

lapped insulation must therefore be dried before impregnation. Today, major cable makers have very large drying vessels to process up to 50 km of cable core in a batch.

Once the lapped cable is in the impregnation vessel the lid is closed and the cable inside is subjected to a heat/vacuum treatment as the final drying step.

So far, the process is identical for mass-impregnated and for LPOF cables. The subsequent impregnation and sheathing processes differ between the two insulation concepts owing to the very different viscosity of the impregnant.

The impregnation compound for mass-impregnated cables (today almost invariably used for HVDC cables) becomes rather liquid at the impregnation temperature of 120°C (Fig. 5.4). The compound is heated and de-gassed in a dedicated oil treatment plant in the cable factory before it is released into the closed impregnation vessel. The vessel is filled completely, and under pressure. Owing to the lower viscosity of the hot compound the impregnation is finished after a few days. However, the cable cannot be processed yet. The cooling of mass-impregnated d.c. cables must be controlled carefully as the contracting compound in the insulation must be completed by new compound from the free vessel volume. As the temperature decreases, the compound viscosity increases, and makes the replenishment more time-consuming. If the cable is taken out to the lead sheathing too early the subsequent cooling would render unwanted voids in the insulation. The cooling time for mass-impregnated cables can sum up to several weeks. Once the cooling criteria have been met the vessel lid can be lifted and the cable can carefully be pulled to the lead sheathing machine. The short-time contact to the free air does not harm the cable insulation since the high viscosity of the compound prevents the diffusion of soluble nitrogen or humidity into the insulation.

LPOF (or SCFF) cables will be impregnated with very low viscosity mineral oil synthetic impregnation fluids. The fluid is degassed and prepared before it is pumped into the vessel to soak the dried cable core. Thanks to the low viscosity the impreg-

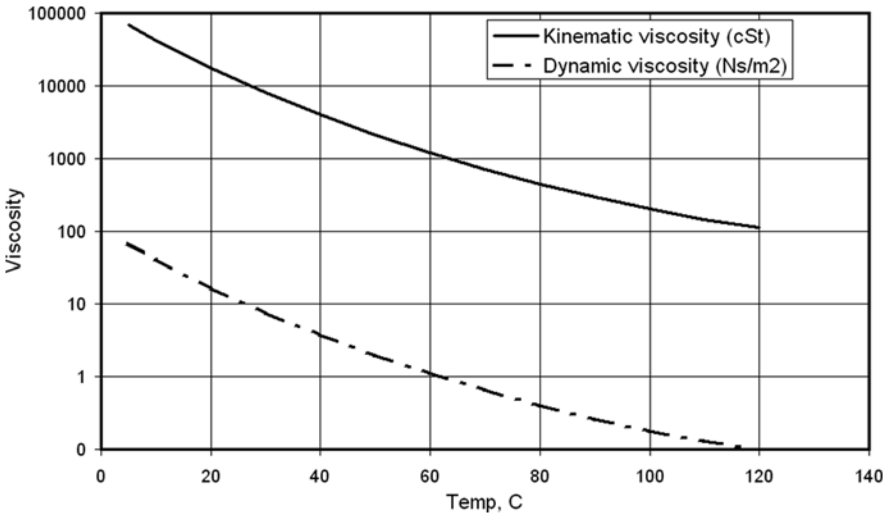

Fig. 5.4 Viscosity vs. temperature of a HVDC cable impregnation mass [3]

nation and cooling process is much faster than for mass-impregnated cables. The impregnated cable core of oil-filled paper-insulated cables cannot be transported from the impregnation vessel to the lead-sheathing machine through open air as the low-viscosity oil would eagerly adsorb air humidity. Instead, an oil-filled tube carries the insulated conductor from under the oil level of the impregnation vessel over the rim and into the lead extruder. The tube is continuously flushed with degassed impregnation oil.

5.1.4 Sheathing

Most submarine power cables have a radial water barrier in form of a metallic sheath.[2] Shorter medium-voltage cables often have an aluminium laminate sheath consisting of aluminium foil coated with a thermoplastic layer. The aluminium laminate is folded longitudinally around the cable core and glued together, sometimes with a Z-fold. The subsequent plastic sheathing provides mechanical support to the laminate.

The lead sheath for submarine power cables is applied in uniform thickness between 2 and 5 mm with a lead press, or an extruder. In the press, also known as ram press, molten lead is being filled into a chamber and cooled down to the correct temperature under the melting point. Then the lead is pressed by hydraulic force through a die forming a seamless tube around the cable, which travels slowly through the press. When the lead chamber is emptied, the process stops and the chamber is being refilled with molten lead. The intermittent process causes change marks in the cable sheath each time the press stops [1]. Another lead sheathing machine is the Hansson-Robertson continuous lead extruder, which was commercialised in 1949. Basically it is a screw extruder fed with lead from a melting pot. Today Hansson-Robertson extruders can deliver 50 km and more of uninterrupted high-quality lead sheath. Continuous extruders have replaced the ram-press as the most common and economical means of producing lead sheathed power cables. Different lead sheathing technologies require different lead alloys for best performance and process stability. The development and properties of different lead alloys in connection with ram press and screw extruder is described in [4].

Long term stability, creep, and extrusion properties can be improved substantially by using lead alloys with alloy elements such as antimony, tin, copper, calcium, cadmium, tellurium, and others. The standard EN 50307 lists a number of lead alloys for cable use (cf. table of lead alloys in Chap. 11).

The lead sheath is vulnerable for mechanical damages and should be protected by additional layers as soon as possible. The use of a continuous lead extruder allows for the extrusion of a rugged plastic oversheath in a tandem process directly after the lead extruder. When the cable has been lead sheathed in a stop-and-go ram press, it must be stored on an intermediate turntable before the plastic oversheath can be applied in the next operation.

[2] In older books on the subject, the word "sheathing" is used for "armouring".

If the cable should be stored temporarily in a bare lead sheath it can be useful to brush the lead sheath with a bituminous solution to prevent the lead sheath from sticking together.

Although it is possible to produce aluminium sheaths by extrusion or strip welding this material is, due to its poor corrosion resistance, hardly ever used for submarine cables. In some cases the sheath is made from copper. A copper strip is folded longitudinally around the cable, and the edges are trimmed and welded continuously. Then the formed copper tube is corrugated to increase the flexibility. So far this process has been used only for shorter cable lengths in the range of a kilometre. As a perfect welding seam is fundamental for a watertight copper sheath, the seam is checked in-line after welding, e.g. by eddy current measurements.

5.1.5 Lay-up

For the production of three-phase cables, the three cable cores must be laid up to form a coherent cable. Just taking three cores in parallel into a common armoring would render a very stiff design without flexibility. Horizontal lay-up machines have three (or more) pay-off drums containing the cable cores, and a take-up drum to receive the laid-up cable. The cable cores travel through a common die where they are put together and secured with a binder tape. The take-up drum is inserted in a drum-twister, which spins the drum axis around the cable axis while the take-up drum rotates and takes up the three-core cable. The lay-up is caused by the drum-twister movement. Also, the pay-off drums rotate in drum-twisters, providing the back-twist that is necessary to keep the three cable cores together. This is the same process as being used when making ropes.

This method is sufficient for short cables to be delivered on drums (probably less than 1000 m per length). For longer submarine cables it would be tedious to manufacture the cable in drum lengths and then joint the cables to achieve delivery lengths of 20–40 km. Such long lengths of three-phase submarine cable can be produced in vertical lay-up machines. The pay-off reels (drums or baskets) are mounted onto a turntable rotating around a vertical axis. The cable cores are fed vertically upward into a collecting die many meters above the turntable centre. The cable cores are pulled through the die, then over a sheave and then placed onto a take-up turntable. Figure 5.5 shows a vertical lay-up machine with rotating baskets as pay-off.

The baskets for the cable cores can accommodate some kilometres of cable core depending on the core diameter and basket size. When the baskets run empty, they are reloaded with the next cable core, which is jointed into the foregoing cable cores by means of flexible factory joints. The turntable carrying the baskets can also carry additional baskets or reels for optical cables and/or filler elements, which would be arranged in the interstices between the cable cores. Vertical cable lay-up machines are the most versatile lay-up machines.

Some of the difficulties caused by the three-phase lay-up topology can be overcome with SZ-lay-up. In this method the lay-up direction (right-handed or left-handed) is altered regularly. This method requires no drum twisters or rotating take-up reels.

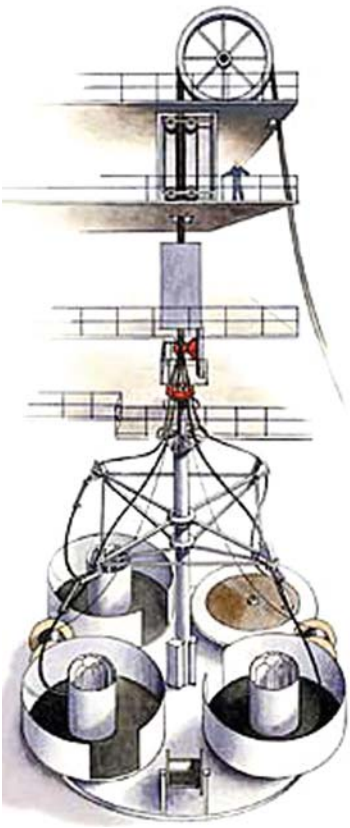

Fig. 5.5 Vertical lay-up machine with three rotating pay-off baskets and a fourth rotating pad for an optical cable. Additional small drums can accommodate filler ropes (Courtesy of ABB, Sweden)

The diameter of the envelope circle of the three-core cable is 2.16 times that of the individual cable cores.

5.1.6 Armoring

The most prominent attribute of submarine power cables is the armoring. Basically, submarine cable armoring is the winding of metal wires around the single core or a multicore cable. The most common wire is galvanized steel wire, but copper, brass, bronze, and aluminium wires sometimes also are used. The beautiful engraving in Fig. 5.6 from 1898 illustrates the working principle of an armoring more clearly than most photographs [5]. Today's armoring machines are very similar except for electronic drives and computerized monitoring equipment. Armoring machines carry a number of wire bobbins arranged on a rotating cage. The cable is travelling through the centre axis of the armoring machine. As the cage rotates the wires are drawn off the bobbins into a collecting bellmouth die at the exit of the armoring machine. In the bellmouth the wires are laid around the cable in the centre. The rotating speed of the machine and the cable travel speed must be synchronized to maintain a correct

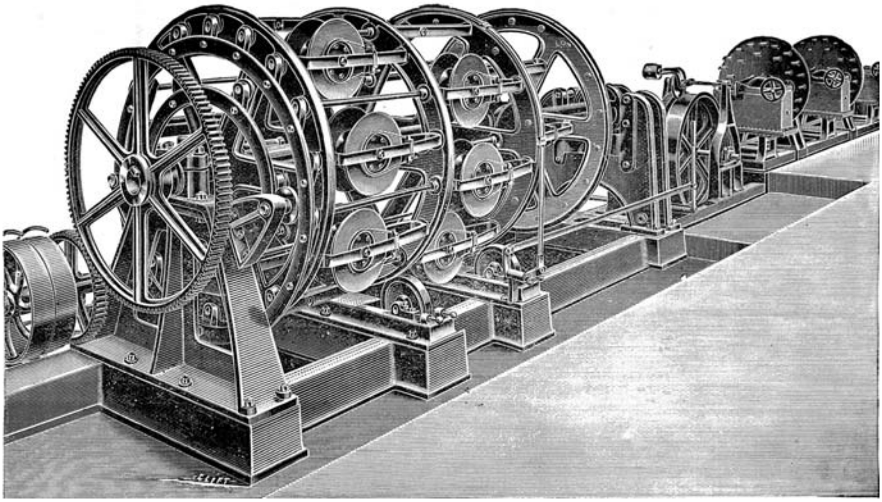

Fig. 5.6 Armoring machine with planetary movement of the wire bobbins. Six bobbins in two groups are visible. The eccentric ring in front of the first rim keeps all bobbins in the same orientation during their rotation (Machine designed and produced by Johnson & Phillips, London)

lay length. Some submarine cable factories have two armoring machines in line to produce submarine cables with double armoring, often with opposite lay direction.

In "rigid" armoring machines the bobbin axles are set up rigidly in the cage frame which means that the axles turn around with the cage. Each wire receives a 360° twist for each rotation of the cage. This can be difficult with heavy wires and a short lay-length. In most large armoring machines the bobbins are guided by a planetary gear, which gives them the same global orientation on their travel around the cable (cf. Fig. 5.6). By this means, the armoring wires will not receive a twist as they are being laid around the cable. However, when flat armoring wires are to be used, the armoring machine must have no planetary movement. There are armoring machines where the planetary movement can be switched on/off at will. Each bobbin has a breaking device that keeps the wires straight, and provides a smooth laying onto the cable core.

Cable caterpillars or other linear cable engines situated downstream pull the cable through the armoring machine. Considerable forces are required to draw off the cable from the armoring machine since a multitude of armoring wires have to be drawn off the bobbins and wound around the cable. For large armored cable the necessary pulling force can be 5 tons or more.

The lay length of the armoring is determined by the ratio of cable speed through the machine and the rotation speed of the cage. The pull-of engine can be coupled mechanically to the rotation drive by means of gearboxes. Modern armoring machines with electronic d.c. drives can achieve any desired lay length with high accuracy.

Large armoring machines for submarine cables have often two rotating cages in a row. Very large submarine power cables can be covered with a complete layer of wires using both cages in tandem operation. The cages are rotated in the same direction with identical lay length, and the wires are combined to a single wire layer. For the production of a double layer uni-directional armoring the cages are rotated at different speeds so that the layers have different lay lengths. Much more common is a double-layer counter-helical armoring using the two cages in opposite rotation direction.

At regular intervals the armoring process must be stopped to swap the empty bobbins for refilled ones. The new wires are butt-welded to the trailing ends of the previous ones. This is a rather quick process, completed by de-burring and zink-coating of the weld. Swapping all bobbins of a machine cage at the same time keeps the downtime shorter. For cables intended for large depth it may be considered to spread the welds over a longer distance.

One or more bobbins can carry optical fibre (OF) cables to be integrated into the power cable. OF cables are more delicate than the rugged steel wires and require more attention, more sophisticated braking units and gentler internal guiding in the armoring machine.

Tape winder units are often situated at the entrance of the armoring machine to apply bedding tapes. Often also metallic tapes are applied under the armoring wires. They provide pressure reinforcement for paper-insulated cables, or a teredo protection where it is required.

The corrosion protection of the armoring is applied in the same process. Most often the corrosion protection is accomplished by flushing the armoring with fluid bitumen. The heated bitumen is showered over the armoring wires right before they are collected into the die, and again after the die. Using this arrangement the wires are covered with bitumen from all sides. The flow of bitumen must be cut off when the armoring machine is halted for wire change or other service, otherwise the cable under the bitumen shower would be overheated.

An outer serving of polypropylene threads (yarns) is finally wound over the armoring wires, one layer right-hand and one left-hand. The rotating stand for the thread spools is shown in Fig. 5.7. The bituminised armored cable can be seen entering into the centre orifice. The serving threads are immersed into the adhesive bitumen. The bitumen under the outermost serving layer, if any, should be applied sparsely, in order to avoid the bleeding of the cable during storage and laying.

Long submarine power cables often consist of a number of factory lengths, which are shorter than the shipping length. When a factory length of unarmored cable core is used up in the armoring process, the next factory length is pulled to a jointing room. The next length is then jointed to the previous one under controlled humidity conditions and high cleanliness requirements. Upon completion the joint is pulled through the armoring machine, and is covered by an uninterrupted wire armoring. The factory joint is only a few millimetres larger in diameter than the cable and is considered an integral part of the cable. Depending on the particular factory jointing technique this may require a 1–5 days break.

It is not possible to combine the cable armoring with the manufacturing of an extruded outer sheath as extrusion lines cannot be stopped easily.

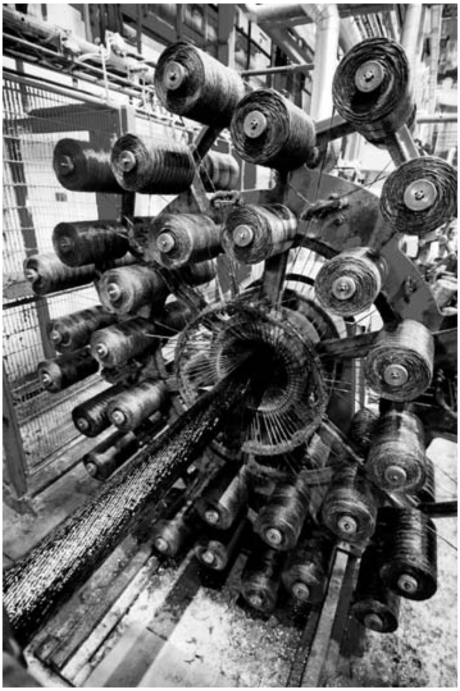

Fig. 5.7 A serving of polypropylene threads is applied on an armored cable covered with hot bitumen (Courtesy of ABB, Sweden)

5.1.7 Storage of Submarine Cables

It can be worthwhile to make some comments on the storage of submarine cables because it may involve the storage of a single product of 7000 tons in weight, without having the means of lifting the entire thing.

Cable drums can carry some hundred meters of armored submarine cables, supersize drums possibly 1–2 km. This storage form is suitable for in-field cables for OWPs, for shorter beach cables and limited water crossings. Cable drums with armored cable can have a weight of 30–50 tons and require suitable lifting and transport gear, and driveways with sufficient stability.

Longer lengths would be stored on turntables or fixed coiling pads. A coiling pad is a flat round or oval surface on the factory premises or in a storing tank on-board of the cable ship. The cable is guided down onto the pad from an elevated position, the guiding mechanism often equipped with a linear cable engine (cf. Fig. 5.8).

Coiling of armored cable can only be done if the armoring is unidirectional. Each turn of the cable around the coiling pad will cause a 360° twist in the cable. Therefore a minimum coiling diameter is required to enable the cable to absorb the twisting generated in each turn. The minimum diameter of the coiling ring should be no less than 60 times the cable diameter [6]. The exact minimum coiling diameter is depending on the armoring lay-length, the bedding under the wires and other design parameters.

Fig. 5.8 Coiling of submarine power cable

A cable with uni-directional (single layer or double layer with the same lay direction) armoring can absorb torsions only in one direction. Coiling is only possible if the cable is twisted in the direction where the armoring is opening up. Coiling in the wrong direction will inevitably lead to kinks and loops in the cable and the entire procedure will fail.

For an S-lay cable the coiling direction must be clockwise. Under clockwise coiling the armoring can open up a little under the influence of the twist in the cable. Choosing the wrong direction of coiling (counterclockwise for a cable with S-laid wires) would provoke a closing-in of the armoring wires. Under these forces the cable would tend to form kinks or loops. However, as an exception to this rule, 3C-cables with single wire armoring and the cable core lay-up in opposite direction can be laid up counterclockwise (cf. Table 5.1).

The coiling pad should be flat. A high fence around the coiling pad provides protection to the coil staff that walks around the coil to direct the cable in position. The cable is fed to the coil from a point some 6–15 m above the coil. It is of advantage to have a caterpillar or wheel engine on the top. A fenced coiling pad with five coilers is shown in Fig. 5.8. The quadrant (roller guide arc) is suspended from a crane and contains a wheel-pair cable engine.

Direct solar radiation on the stored cables can develop high temperatures that easily can unpleasantly bleed out the bitumen.

Cables on coiling pads, outdoor turntables, trailers or cable laying vessels are frequently showered by rain, seawater spray, overflows and similar. In these situations

Table 5.1 Coiling direction depending on armoring lay orientation

	Armoring lay orientation	Coiling
Single core cables with unidirectional armouring	S-lay	Clockwise
Single core cables with counter-helical armouring	S or Z	No coiling
3C cables with core unidirectional armoring, core lay-up in S-orientation	S-lay	Clockwise
3C cables with core unidirectional armoring, core lay-up in Z-orientation	S-lay	Clockwise or counterclockwise

cable ends must always be capped with suitable end caps recommended by the cable supplier. Shrink-on end caps are in most cases not advisable.

5.2 Testing

Submarine power cables are subjected to comprehensive tests during development, qualification, manufacturing and installation. The various tests serve different purposes with the single overall goal – to ascertain a trouble-free operation under specified conditions.

The large variety of cable related tests can be categorised according to their purpose and stage during qualification, manufacturing and installation of the cables.

5.2.1 Development Tests

The development of new cable types, or the extension of existing cable types to new sizes or ratings, may require comprehensive testing of materials, components, and production processes. Many of the new materials and concepts have been developed for underground cables before they were being employed for submarine cables. The reason is simply that possible failures in submarine cables cause much higher repair costs and longer outage time compared to identical failures in underground cables.

The polymeric components of cables are subject to continuous improvement. New polymer formulations proposed by material suppliers need to be evaluated under the specific conditions of submarine power cables. Tests of dielectric strength, loss angle, leakage current, and dielectric response test, are used to characterize and screen insulation materials. These tests can often be performed on samples or model cables avoiding the expensive manufacturing of full-size cables. The ageing performance is being tested under different temperature and ambient conditions. The processing of cross-linked materials can be evaluated with methods determining the cross-linking degree.

Polymeric sheath materials in submarine cables are sometimes tested for their water vapour permeability, stability in salt water, abrasion resistance, carbon-black content, etc. However, in most cases manufacturers use their well-proven sheath materials without the need for change.

Even if most properties of metallic constituent materials are listed in textbooks, some properties need to be evaluated. The fatigue properties of lead sheathing alloys must be assessed by testing very thoroughly, taking the manufacturing method into account. Other metallic sheathing materials are also subjected to fatigue tests to secure trouble-free performance during the cable lifetime.

Another group of development tests addresses the corrosion performance of all metallic materials in submarine cables. Metals are tested separately, but also in relevant combinations to investigate galvanic behaviour.

Mechanical tests on complete submarine cables are designed to demonstrate their ability to withstand all stresses and incidents, which can be encountered during installation and operation of the cable. These tests include tensioning, bending, pinching, impacts, etc. Also the behaviour under the influence of external hydrostatic pressure is important for submarine cables.

Knowing the strong and sensitive points of the cable design, and knowing which tests will be required for a successful qualification, every manufacturer has his own set of tests to be pursued during development programs. For a speedy screening, sometimes short-cut tests are designed that can deliver reasonably reliable results in short time. This is of particular interest for tests for the ageing behaviour of cable materials. The cable maker would subject the newly developed cable design to these pre-tests, before he brings it to the standardised qualifying long-term test.

5.2.2 Type Tests

Once a cable type has been developed or adopted to new applications, it will be subjected to a type test. As many large submarine cable projects require a tailored unique design, many purchase contracts also require the performance of type tests. However, as type tests add considerably to costs and project execution time it should always be considered if the proof that a certain cable design is suitable for the intended project, could be deducted from previous type tests on similar cable types.

The purpose of the type test is to "qualify the design and the manufacturing of the cable system against the conditions of the intended application" [7]. Type-testing of electric equipment is generally regulated by test standards issued by national authorities or professional organisations such as IEEE, AEIC, ANSI, or Cigré. Most power cable testing standards cover underground land cables only, and some standards explicitly exclude submarine power cables from their scope.[3] Therefore test standards for submarine power cables are scarce (Table 5.2).

In practical life, type-tests on submarine power cables are often performed according to test standards applicable to underground cables with the same insulation design and conductor size. These type tests include material tests and electric tests, and in some cases mechanical tests such as bending tests over a cable drum.

[3]Cables for submarine applications are explicitly excluded from the scope of IEC 60502-2. However, it can be considered to use IEC 60502-2 for informational tests in medium voltage submarine cables.

Table 5.2 Type test standards usable for submarine power cables

	Published in	Title or content
Cigré	Electra No. 171 April 1997	Recommendations for Mechanical tests on sub-marine cables Referred to as Electra 171 in the following
Cigré	Electra No. 189 April 2000, pp. 29ff [8]	Recommendations for testing of long a.c. submarine cables with extruded insulation for system voltage above 30 (36) to 150 (170) kV Referred to as Electra 189a in the following
Cigré	Electra No. 189 April 2000, pp. 39ff [7]	Recommendations for tests of power transmission dc cables for rated voltages up to 800 kV (all insulation types excl. extruded) Referred to as Electra 189b in the following
Cigré Technical Brochure TB 219	Cigré Technical Brochure 219, Working group 21.01, February 2003 [9]	Recommendations for testing DC extruded cable systems for power transmission at a rated voltage up to 250 kV (scope includes submarine cables)
IEC 60840		Power cables with extruded insulation and their accessories for rated voltages above 30 kV ($U_m = 36$ kV) up to 150 kV ($U_m = 170$ kV) – Test methods and requirements
IEC 62067		Power cables with extruded insulation and their accessories for rated voltages above 150 kV ($U_m = 170$ kV) up to 500 kV ($U_m = 550$ kV) – Test methods and requirements

The Cigré recommendation published in Electra 171 is the only known test standard describing relevant mechanical tests on submarine power cables. Sometimes the type test specifications include mechanical tests according to the Electra 171 followed by applicable type test elements from IEC standards (for a.c.) or Cigré recommendation (for d.c.). It shall be noted that type tests are normally not mandatory by legal means. The test conditions are sometimes part of the contract negotiations.

Table 5.3 lists the applicable type test standards for the five generic cable types as described in Chap. 2. These standards are adhered to in most European submarine cable projects. Different type test standards may be applicable in other markets.

5.2.2.1 Mechanical Tests

The Cigré test recommendation published in Electra No. 171, April 1997, suggests a few test procedures especially designed for submarine power cables. It is at the discretion of the purchaser to determine which tests to be done.

Table 5.3 Electric type tests for five generic cable types

Cable type No	1	2	3	4	5
Rated voltage U_0	33 kV a.c.	150 kV a.c.	420 kV a.c.	150 kV d.c.	450 kV d.c.
Insulation	XLPE	XLPE	Paper/oil	Polymer	Mass-impregnated
Mechanical tests			Electra 171[4]		
Electrical type test	Electra 189a with reference to IEC 60840	IEC 60840	IEC 62067	Cigré Technical Brochure TB 219	Electra 189b
Test sequence	TB PD Tan δ HC PD LI AC (PD) (same as in IEC 60502)	TB PD Tan δ HC PD LI AC (PD)	TB PD Tan δ HC PD SI (for $U_m \geq 300$ kV) LI AC (PD)	TB LC SI LI & DC DC	TB LC PR LI SI

Abbreviations: TB, Tensile bending test; WP, Water penetration test; PD, Partial discharge test; HC, Heating cycle voltage test; LI, Lightning impulse test; SI, Switching impulse test; LC, Load cycle test; PR, Polarity reversal test; DC, High-voltage test with d.c.; AC, High-voltage test with a.c.

The first suggested test is a coiling test, to be performed only on those cables that are intended to be coiled during manufacturing, loading, or installation. The test confirms the suitability of the cable for coiling according to the parameters encountered in cable handling. The coiling diameter is not specified in Electra 171 but the test shall confirm the value given by the manufacturer. The test cable must be long enough to achieve a sufficient number of turns to exclude end effects.

The tensile bending test according to Electra 171 demonstrates the cable's ability to withstand tensional forces in combination with bending over the laying wheel during installation. The test is to be performed on a piece of cable before the electric tests are performed on the same piece of cable. A flexible joint can be qualified when included in the test cable. The test cable is laid halfway around a large sheave, which represents the laying wheel of the cable-laying vessel. A pulling force is applied to the cable ends while they are moved three times back and forth around the wheel. The wheel diameter is often 6 or 10 m representing typical laying wheel diameters of existing cable ships (cf. Fig. 5.9).

[4] Electra No. 171 is "primarily meant for cables having a rated voltage U_0 higher than 36 kV a.c. or 100 kV d.c.". However, Electra 189a covering 33 kV cables refers to Electra 171.

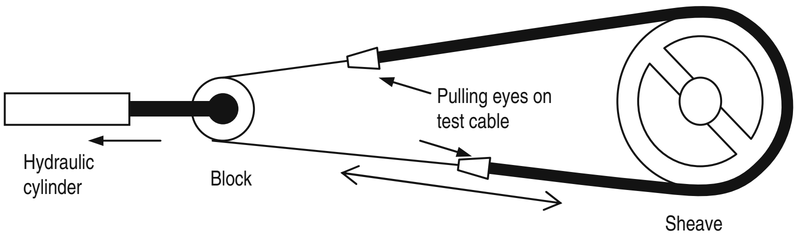

Fig. 5.9 Test arrangement for tensional bending test according Electra No. 171. *Top view*

The test pulling force is given in Electra 171 depending on the cable weight in water and the water depth (cf. Chap. 3). For a depth over 500 m, also the dynamic forces caused by wave movements are included. Experience has shown that actual pulling forces on the laying wheel can considerably exceed the forces given in Electra 171, depending on the weather situation during laying.

For many submarine transmission projects the laying depth is below 100 m, which leads to rather moderate test forces according to the Cigré recommendation. Sometimes the required pulling force is so small that the heavy cable is not even straight but has considerable sag during the test. Tests with the Cigré-recommended forces for laying depth under 100 m often have no practical relevance. Purchaser and manufacturer should consider an agreement to omit the test to save costs.

The tensional bending test confirms the design values of tensional strength and side-wall pressure (SWP), i.e. the uniform lateral force onto the cable side per unit length.[5] Other mechanical stresses might be experienced during installation, such as localized side impact by caterpillar pads or wheeled cable engines, or stresses caused by trenching machinery. Also the transport of cable over curved roller tracks or cable gantries is not covered by the Cigré test recommendations, unless the rollers in the gantry are very close together and the roller diameter is sufficiently large. No type tests have been devised yet for this type of impacts. As installation conditions and gear vary largely between projects, it would not be possible to construct type tests covering all type of impacts. Instead the manufacturer, purchaser and installer should agree on the necessity and character of additional confirming tests.

The Electra No. 171 also recommends an internal pressure test for oil-filled and gas-filled submarine cables.

A very particular test recommended in Electra No. 171 is a sea trial test for cases where laying conditions differ from previously performed operations. For a sea trial test the anticipated laying spread (vessel, on-board equipment and crew if possible) should be established to lay and recover a substantial length of the submarine cable on a seafloor representative for the target area. The tests are very expensive but can reveal possible flaws in cable design and installation equipment. Poor equipment or a cable design that is not appropriate for the installation method can cause immense costs when discovered during the cable installation. In the worst case, the instal-

[5]The established expression “side-wall pressure” actually does not denote a pressure (N/m^2) in a classical sense but a force per unit length. The unit of SWP is kN/m.

lation must be interrupted and the equipment upgraded or refurbished. It is by far less expensive to do this in a well-planned manner after a sea trial test prior to the installation campaign. Acknowledging this, many major submarine power projects have performed sea-trial tests and used the results for the benefit of the project.

5.2.2.2 Load Cycle Test

Load cycle tests are part of the type tests for all submarine power cables. The a.c. cables are usually subjected to electric tests according to the same specifications as underground cables. The load-cycle test procedures for d.c. cables are less well-known and shall be described in the following.

The recommended load cycle test for mass-impregnated HVDC cables is described in Electra 189b. A 24-hours load cycle is combined from an eight-hour period of full cable load, followed by a 16-hours period of natural cooling. The Electra 189b load cycle test comprises ten load cycles with a constant negative voltage of $-1.8 \times U_0$. After this, another ten cycles will be performed with positive voltage of $1.8 \times U_0$. The ambient temperature during the test is subject to agreement between manufacturer and purchaser. Depending on the conditions in the seafloor, the tests may be specified with cold and warm ambient to reflect different thermal conditions and seasons. For a cable installed in the seafloor in moderate waters, the lowest expected ambient is around 6°C when the cable has not been used for a while, and possibly over 30°C after a long uninterrupted period of power transmission. In tropical waters, the ambient temperature would be specified differently. The ambient temperature of the test cable can easily be adjusted if the cable is installed in hoses or pipes with temperature-controlled water. The heating current amplitude should reflect the rated load of the cable and is also subject to agreement.

The limiting factors for the operation of mass-impregnated HVDC cables are the conductor temperature and the temperature drop across the insulation. During type test, only three of the four following parameters can be set independently:

- Conductor temperature
- Temperature drop over the insulation
- Conductor current
- Ambient temperature.

The 8/16 h rhythm of the cycles is widely accepted as it fits well into the working day. As the thermal time constant of this type of cables is 1 to 2 h, a shorter cooling/heating cycle would also achieve appropriate heating of the cable. For development tests, a 4/8 h sequence is an acceptable short-cut.

The test voltage deserves some extra comments. Although the load cycle test for mass-impregnated HVDC cables is described in Electra 189b, its conditions are often altered during contract negotiations. Electra 189b specifies a test voltage of $1.8 \times U_0$, where U_0 is the operating voltage of the HVDC cables. In recent years manufacturers and cable purchasers have often agreed on lower test voltage factors, in particular for the cooling part of the load cycle test. The reason is simply that the dielectric strength during the load phase of the type test (with full current), and in most operational situations is much higher than in the type test cooling phase. It would be uneconomic to oversize an HVDC cable just in order to comply with a single test parameter. For mass-impregnated HVDC cables of the past 15 years a test voltage of $1.55 \times U_0$, $1.6 \times U_0$, or $1.7 \times U_0$ have been specified by purchasers for the cooling phase.

The test cable is terminated with oil-filled pressurized cable terminations. Oil inflow from these terminations into the cable must be prevented during the type test, as this would assist the cable to pass the type test, a situation not available in real life at some distance from the termination. Means to prevent this oil flow must be provided in order to assure relevant type-test conditions. This can be achieved by extra long cable connections between the terminations and the test cable portion, by freezing the cable between the terminations and the test cable portion, or by sealing arrangements inside the terminations.

The next step, after negative and positive voltage load cycles, is the polarity reversal test. The load cycle (8/16 h) is maintained but the voltage is periodically reversed between $+1.4 \times U_0$ and $-1.4 \times U_0$ every 4 h. This is repeated during ten complete load cycles. The recommended reversal speed specified in the Electra 189b is under 2 min, but real tests have been performed with longer reversal times, due to laboratory equipment reasons, or due to transmission system aspects not requiring such short reversal times [10]. After the polarity reversal tests the cable is subjected to impulse testing.

For extruded HVDC cables, which have conquered a reasonable portion of the submarine HVDC cable market, a load cycle test is specified in Cigré Technical Brochure 219 [9]. For cables to be qualified for voltage source converters, i.e. without polarity changes, TB 219 recommends the following load cycle test sequence (Table 5.4):

Table 5.4 Load cycle test sequence for extruded HVDC submarine cables according to Cigré TB 219

Load cycle characteristics	Number of cycles
8/16 h load cycles at $-1.85 \cdot U_0$	12
8/16 h load cycles at $+1.85 \cdot U_0$	12
24/24 h load cycles at $+1.85 \cdot U_0$	3

For extruded HVDC cables to be qualified for line-commutated converters (so called "Classic"), a different suite of load cycles is defined, including polarity reversal tests. Owing to the characteristics of extruded d.c. insulation, a reduction of test voltage in the cooling phase as in the case of mass-impregnated HVDC cables has not been advocated yet.

TB 219 requires the performance of a row of non-electric tests before the load cycle tests. These tests comprise bending tests (depending on submarine or underground application) and water integrity tests, with reference to other IEC or Cigré test standards. After the load cycle tests the cable is subjected to impulse testing.

5.2.2.3 Impulse Tests

Impulse tests are a part of most type test standards. It became clear very early in power engineering that a.c. and d.c. tests alone do not cover all events in the life of a component in the power system. The dielectric strength of any insulation is very much depending on the shape and duration of a voltage wave. Impulse tests are necessary to demonstrate the behaviour of components under temporary overvoltages. The tests are performed according to IEC test standards, which apply in principle to all high-voltage power transmission equipment. As for other high-voltage cables, the test standards specify lightning impulse tests and often also switching impulse tests for submarine cables. Despite their names, the tests do not necessarily resemble real life switching or lightning impulses. The distinction of switching and lightning impulses may be made on the basis of wave shape rather than their origin [11]. The impulse shapes are specified in IEC 60060-1 in terms of front steepness and tail time to half value. The standard lightning impulse (LI) has 1.2 μs front time (t_1) and 50 μs time to half value (t_2) after the crest. For the standard switching impulse (SI) these values are 250 and 2500 μs, resp. IEEE defines 1.4/40 μs as LI wave shape parameters. IEC and IEEE use slightly different formulae as how to determine t_1 and t_2 from the wave shape. Figure 5.10 shows the ideal impulse shape. However, laboratory records usually do not look like this and the evaluation of the test parameters of a specific test (front time, time to half value) is all but easy. Computer-assisted algorithms help to identify parameters from corrupted records with distortions and overlaid ghost oscillations [12, 13].

Impulse test parameters were originally conceived to resemble phenomena in air-insulated power grids and substations. Today, the situation for many submarine cable terminations is different. HVDC cables are connected to converter stations where certain types of overvoltages cannot occur at all, or only with lower amplitude compared to air-insulated a.c. substations. Other modern submarine power cable applications, e.g. in HVDC converters or offshore, have their terminations indoors.

Type tests for a.c. submarine cables comprise impulse tests according to standards for land cables with corresponding rating. For d.c. cables the Cigré recommendations specify impulse tests with superimposed d.c. voltage.

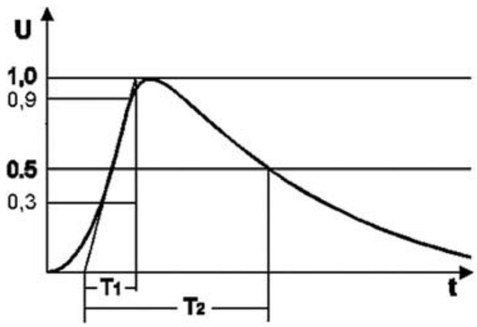

Fig. 5.10 Standard impulse voltage shape

For paper-insulated HVDC cables ten positive lightning impulse shots superimposed over negative d.c. voltage are performed, then ten negative lightning impulse voltage shots superimposed over positive d.c. voltage. The same sequence is done with switching impulses. This concludes the electric type test for paper-insulated HVDC cables.

According to the Cigré TB 219, extruded submarine HVDC cable systems have to undergo a complicated pattern of switching impulse tests with opposite or parallel polarity. Lightning impulse testing may be omitted under certain circumstances.

5.2.3 Routine Tests

Routine tests are performed on all manufacturing lengths and/or delivery lengths. In the various test standards applicable for submarine power cables, different sequences of routine tests are prescribed. Almost all standards require testing of conductor resistance, insulation capacitance, and loss angle tan δ. Resistance and capacitance can be measured either on the complete cable (e.g. on a drum length), or on end pieces cut from a long length of cable. The resistance measurement requires the knowledge of the conductor temperature. For short test pieces, a four-point resistance measurement should be used. The distance between current source contacts to the conductor and the voltage probes should be sufficiently long to allow for a uniform current distribution in the conductor. Should the resistance test for a manufacturing length in a long cable exceed the required value, it should be checked if there are expected hotspots in the cable route sector for which the manufacturing length is destined. If not, the total resistance of the cable route can be adjusted by adding a little to the conductor area of the remaining manufacturing lengths.

The capacitance test is a check that the insulation is not too thin. According to IEC standards the specified value must not be exceeded by more than 8%.

The loss angle tan δ is conveniently measured on a piece of cable cut from a manufacturing length. The IEC standards require the measurements under a.c. voltages corresponding to an electric stress in the insulation of 2 and 8 kV/mm, resp. The measurement can be performed e.g. with a high-voltage Schering bridge. An elaborate description of tan δ measurement methods and their theory can be found in [1]. Limit values are specified both for tan δ at both voltages, and for the difference between both results. The American AEIC standards specify the ionisation factor, IF, being the difference between tan δ at 100 V/mil (=3.9 kV/mm) and 20 V/mil (=0.8 kV/mm). The IF value must not be higher than 0.1% for LPOF cables.

High tan δ values can hint on contaminated insulation, which leads to high ohmic leakage currents through the insulation. The tan δ value can also be increased by partial discharges in the insulation, resulting in an integral current.

5.2.3.1 High-Voltage Routine Tests

Manufacturing lengths are often given a high-voltage routine test either by standard requirement, by agreement, or as an internal test of the manufacturer (Table 5.5). The obvious reason is to exclude faulty cable core from further costly manufacturing

Table 5.5 a.c. test voltages for routine and after-installation tests on a.c. cables

	Rated voltage kV	U_0 kV	Routine test voltage (phase-to-ground), kV	After installation test voltage (phase-to-ground), kV
IEC 60605	30	18	63	30 (5 min) *or* 18 (24 h)
IEC 60840	45–47	25	65	52
	60–69	36	90	72
	110–115	64	160	128
	132–138	76	190	132
	150–161	87	218	150
IEC 62067	220–230	127	318	180
	275–287	160	400	210
	330–345	190	420	250
	380–400	220	440	260
	500	290	580	320

steps. The voltage factors given in standards are different for different cable types, and can also be altered in agreement with the client.

Modern submarine power cable cores can be manufactured in appreciably long length of 20 km or more. Factory testing of these long cable cores with a.c. voltage requires considerable testing power to provide the charging current. In many cases, this is beyond the possibilities of a.c. test voltage generators. More testing power can be achieved with resonance circuits where an inductance is tuned to form a resonance circuit with the test cable capacitance. The testing frequency of resonance systems is between 30 and 300 Hz.

Testing with d.c. voltages (e.g. HVDC cables) requires the charging of the capacitance of the cable up to the specified voltage. The charging current of d.c. test voltage generators is limited and it may take a considerable time to reach the desired voltage. The charged cable capacitance stores a large amount of energy. Strict fencing of the test range should be provided for the case that the energy is released in a breakdown. Should a test termination fail the amount of stored energy can easily explode a porcelain insulator.

5.2.4 Factory Acceptance Tests (FAT)

FAT is the last test program to be performed at delivery. The performance of FAT is often connected to the issuing of client certificates and project milestones. What has been said about testing methods in the routine tests, also applies to the FAT. As delivery lengths can be much longer than the included manufacturing lengths the charging time for d.c. tests are even longer. Also the discharge of the tested cable after the FAT takes considerable time. In case of a.c. FAT on long submarine cables a sizeable set-up of resonance circuit has to be employed (cf. Sect. 5.2.5). Often only specialized submarine power cable makers can provide this type of FAT.

The American standard ICEA No. S-57-401/NEMA Standards Publication No. WC2 recommends a high-voltage a.c. test for armored cables employing 80% of the test voltage for an equivalent un-armored cable.

The FAT for long submarine cables may even include a TDR (Time Domain Reflectometry). The test comprises sending a short voltage impulse into one cable end and recording the echoed impulse. The travelling impulse is partly reflected by changing of Z, the impedance per unit length of the cable. The most prominent change of impedance is of course the far end of the cable where the impulse is being reflected. Also factory joints sometimes constitute a local change in Z causing a faint partial reflection of the travelling impulse. The idea behind the TDR test is to create a reference curve, which can help localising possible future cable faults. There are no pass/fail criteria for the TDR test.

5.2.5 After-Installation Test

A damage-free installation of the submarine cable is confirmed by a successful after-installation test of the entire cable link including joints and terminations (Table 5.6). As in FAT, the tests are performed as high-voltage test with either a.c. or d.c. It is not always easy to bring high-voltage sources to the installation site.

d.c. test voltage generators can be transported quite easy in a truckload. Since the test voltage generators are mostly designed for indoor laboratory use, they must be used only indoors or under dry weather conditions. Fog and dew can degrade the internal insulation of the test equipment. Sometimes temporary shelters can be erected to protect the equipment. Especially with long cable links the testing time can be long due to the cable charging. In one of the recent very long HVDC projects the specified testing time at $1.4 \times U_0$ was only 30 min, but the complete testing took 11 hours due to charging/discharging time. About five hours of this time the voltage was above U_0.

Table 5.6 Test voltages for routine tests and after-installation tests

Cable type No	1	2	3	4	5
Rated voltage U_0 Insulation	33 kV a.c. XLPE	150 kV a.c. XLPE	420 kV a.c. Paper/oil	150 kV d.c. Polymer	450 kV d.c. Mass-impregnated
Applicable standard	Electra 189a with reference to IEC 60840		IEC 62067	Cigré TB 219	Electra 189b
Routine test voltage	–	218 kV	440 kV	$1.85 \times U_0 =$ –278 kV d.c.	$1.8 \times U_0 =$ –810 kV d.c. 15 min
After-installation test voltage	–	150 kV	260 kV	$1.45 \times U_0 =$ –218 kV d.c. 15 min	$1.4 \times U_0 =$ –630 kV d.c. 15 min

Testing long cable links with high-voltage a.c. requires substantial charging currents. The required power for the test circuit is proportional to the cable capacitance and the square of the test voltage. For many cable links, the a.c. testing would require a test power exceeding the capacity of most high-voltage test transformers. Another strategy to test a.c. cables is to connect them to the power grid for 24 h. Obviously, this method is independent on heavy test transformers. The method is also called soak test and is applied frequently to h.v. a.c. cables. The test method has also been recognized in IEC 60840. However, the soak test does not provide testing at elevated voltages. Another strategy is using d.c. voltage also for testing of a.c. cables. This enables the use of simpler test equipment. However, it is not sure that hidden flaws in the cable system can always be detected by d.c. voltage. Even worse, many specialists agree that the d.c. voltage can do more harm than good, and deteriorate the insulation. Today, d.c. testing on a.c. submarine cables is used only to a lesser extend.

Long and very long cable links can be tested at elevated voltages with series resonance circuits. In these test circuits an inductance is connected to the cable capacitance to form a resonance circuit. An exciting transformer supplies the voltage to the resonance circuit in which an a.c. voltage can be maintained by resonance action between the cable capacitance C_{cable} and the external inductance L_{external}. The resonance criterion is:

$$C_{\text{cable}} \cdot L_{\text{external}} = \frac{1}{(2\pi f)^2}$$

where f is the power frequency. In some commercial series resonance circuits the resonance criterion is met by a tunable external inductance at constant frequency, while other systems employ a tunable frequency at constant external inductance. The tunable frequency systems are said to have a better power/weight ratio, a fact that can be very important given the weight of the necessary inductance [14, 15].

The power frequency is in the range of 30–300 Hz. Some commercial resonance testing systems are built modular, i.e. more inductances can be added in order to meet the larger cable capacitance of very long cable links. A wider frequency range is being discussed for future test standards.

The resonance circuit made up of the cable and the external inductance is lossy. In every oscillation of energy between the capacitance and the inductance, a certain amount of energy is dissipated in the ohmic components of the circuit, mainly the cable conductor and screen. This ohmic loss must be replenished by the exciter transformer, and can limit the maximum length of the test cable circuit. A cable length of well above 100 km can be tested, depending of cable capacity, test voltage, system configuration, and desired test duration. Suppliers of test systems can provide exact data in their system specifications.

Depending on the needed a.c. test voltage and the capacitance of the cable, one or more truckloads of equipment must be shipped to the testing site. The method is feasible for submarine cable links where at least one end is accessible easily from a landing site. However, very large submarine cable would require unreasonable amounts of combined inductances to perform the task.

The American standard ICEA No. S-57-401/NEMA Standards Publication No. WC2 recommends a high-voltage after-installation test for armored cables employing 80% of the test voltage used for the test on the armored cable in the factory according to Sect. 5.2.4, i.e. 64% of the factory test voltage for an equivalent un-armored cable.

5.2.6 Non-electrical Tests

The various test standards stipulate, beside the electric tests, also a number of non-electric tests. The tests are performed as sample tests on a defined share of the entire production, as routine tests on the entire production for a certain order, or as a part of the type test. The purpose of these tests is generally to confirm that the physical properties of the produced cable comply with the specifications.

A large spectrum of different non-electric tests is specified in the various test standards, to be performed at very different frequencies and occasions. It is almost impossible to compile a comprehensive summary on this item.

Many non-electrical tests are dimensional checks such as layer thickness or eccentricity. Other test specifications deal with the electric resistivity of semi-conducting materials, or simply the counting of the wires in the conductor. Material properties are checked before and after ageing. Hot-set tests on cross-linked materials check the quality of cross-linking.

Some of these tests are specified in the international test standards, others are specified by utilities, or just common practice in certain countries. The non-electric tests are often in the shadow of the more prominent electric tests. Because of this and the fact that the large number of different test specifications is somewhat confusing, it is recommended to define the bouquet of non-electric tests very clearly in the project contract.

References

1. Bartnikas R (Ed.) (2000). Power and Communication Cables, IEEE Press Series on Power Engineering, ISBN 0-7803-1196-5.
2. McAllister D (1982). Electric Cables Handbook. Granada Technical Books Ltd, 1982, ISBN 0-246-11467-3.
3. Goodwin F E et al. (1994). Recent Technological Developments for Lead Sheathed Cables. Transmission and Distribution Conference, 1994. Proceedings of the 1994 IEEE Power Engineering Society, 10–15 April 1994, pp. 568ff, Chicago, USA.
4. Worzyk T (1996). Keine Gefahr bei Lecks in HGÜ-Seekabeln. Elektrizitätswirtschaft, Vol. 26.
5. Wilkinson H D (1898). Submarine Cable Laying and Repairing, The Electrician Printing and Publishing Company, London.
6. Gilbertson O (2000). Electric Cables for Power and Signal Transmission, John Wiley & Sons, New York.
7. Recommendations for Tests of Power Transmission dc Cables for Rated Voltages up to 800 kV. Electra No. 189, April 2000, pp. 39ff.

8. Recommendations for Testing of Long ac Submarine Cables with Extruded Insulation for System Voltage above 30 (36) to 150 (170) kV. Electra No. 189, April 2000, pp. 29ff.
9. Cigré publication of Working group 21.01 (2003). Recommendations for Testing DC Extruded Cable Systems for Power Transmission at a Rated Voltage up to 250 kV. Cigré Technical Brochure 219, February 2003, Paris, France.
10. Bex S et al. (2006). Basslink HVDC Design Provisions Supporting Ac System Performance. Cigré session 2006, Paper B4-301.
11. Agrawal K C (2001). Industrial Power Engineering and Applications Handbook, Newnes, ISBN 0750673516, 9780750673518.
12. Hällström J and Bergman A et al. (2007). International Comparison of Software for Calculation of Lightning Impulse Parameters Based on a New Processing Algorithm. Proceedings of the XVth International Symposium on High Voltage Engineering, Paper T10-539.
13. Berlijn S et al. (1999). Today's Problems with the Evaluation Methods of Full Lightning Impulse Parameters as Described in IEC 60060-1, 11th International Symposium on High Voltage Engineering, 1999. Conferences Publ. No. 467, Vol. 1, pp. 49–52.
14. Schufft W et al. (2000). Resonant Test System with Variable Frequency for On-site Testing and Diagnostics of Cables, HV Testing, Monitoring and Diagnostics Workshop, Alexandria, VA, USA, 13–14 September 2000.
15. Schikarski P et al. (1999). Two Years of Experience with a Mobile Resonant Test System for Testing of Installed Medium- and High Voltage Power Cables, International Symposium on High-Voltage Engineering, London, UK, August 1999.