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Various Cables Used in Practice

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1.1 Introduction

Transmission system operators (TSOs) throughout the world have been seeing growing numbers of transmission line projects in recent years for different reasons including the increase of cross-border trade, renewable energy sources, smart grid projects, the replacement of aging facilities, and in some countries due to growing demand.

Until recently, TSOs have responded to these necessary transmission upgrades mostly by the introduction of overhead lines (OHLs). HVAC underground cable systems have been used, but their applications have been mainly limited to densely populated areas. As such, HVAC underground cable systems are limited both in length and number to date.

This tendency has been changing over the past 10 years as the service experience of HVAC, especially EHV AC, cable systems has become satisfactory [1]. The applications of HVAC cable systems are proposed more often in order to protect the landscape and also public health (e.g., EMF). Hence, HVAC cable systems recently planned or installed are longer than those installed previously.

For example, in Denmark, after receiving public and political pressures to underground its OHLs, Danish TSO, Energinet.dk, published a report on the future expansion and undergrounding of its transmission grid on the 3rd of April 2008 [2]. The report proposed and compared five principles (A–E in Figure 1.1). From the five principles, the Danish government has selected Principle C, as shown in Figure 1.2, in which all new 400 kV lines will basically be undergrounded.

A similar tendency can be observed on HVDC, especially EHV DC, submarine cable systems. The NorNed cable, which connects Norway and the Netherlands, and the BritNed cable, which connects the Netherlands and the UK, are symbolic examples of such a trend. These cable lines, mainly for cross-border trades, have a total length of 580 and 260 km, respectively.

Cable System Transients: Theory, Modeling and Simulation, First Edition.
Akihiro Ametani, Teruo Ohno and Naoto Nagaoka.

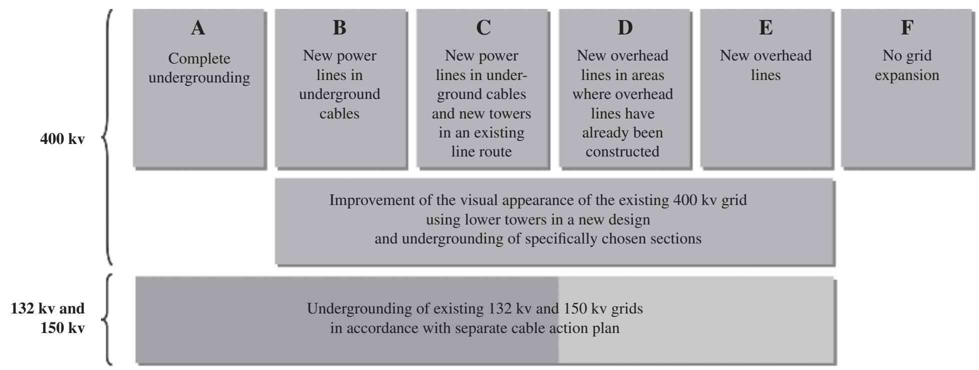


Figure 1.1 Five principles for the future grid expansion (from [2])

The scale of these projects is beyond the level many people expected at the beginning of this century.

As these cable projects increase, there is an increased need to study cable system transients. In particular, the introduction of long cable systems may cause peculiar phenomena, such as resonance overvoltages, which require careful attention. Severe temporary overvoltages in the power system with long cable systems which can be caused in specific network conditions or configurations have been reported [3–9].

Cable modeling for studies on cable system transients, as discussed in Chapter 4, requires the understanding of cable systems. This chapter first discusses the cable itself and then introduces the laying configuration and the sheath bonding, that is, the cable as the cable system. Various cables used in practice are explained in the following two sections – land cables in Section 1.2 and submarine cables in Section 1.3. Section 1.4 discusses the laying configuration including the sheath bonding. The main focus of this chapter is on how these physical characteristics of cable systems affect their electrical characteristics.

Land cables in Section 1.2 cover three major cable types, that is, XLPE (cross-linked polyethylene, PE) cables, SCOF/SCFF (self-contained oil-filled/self-contained fluid-filled) cables and HPOF/HPFF (high-pressure oil-filled/high-pressure fluid-filled) cables. The term “fluid-filled” is used to include both oil-filled cables and gas-filled cables, but most fluid-filled cables are oil-filled cables in actual installations. Even though XLPE cables are increasingly selected for new cable lines in many countries, SCOF cables and HPOF cables are still a popular choice in some countries. HPOF cables are selected, in particular, for the replacement of old HPOF cables since it is often possible to continue using their steel pipes even after the cable replacement.

The laying configuration and the sheath bonding affect cable system transients as the cable itself does. They need to be modeled correctly in order to obtain accurate impedance/admittance of the cable system or reasonable simulation results. Section 1.4 discusses different laying conditions and sheath bonding methods together with their impact on the cable system transients.

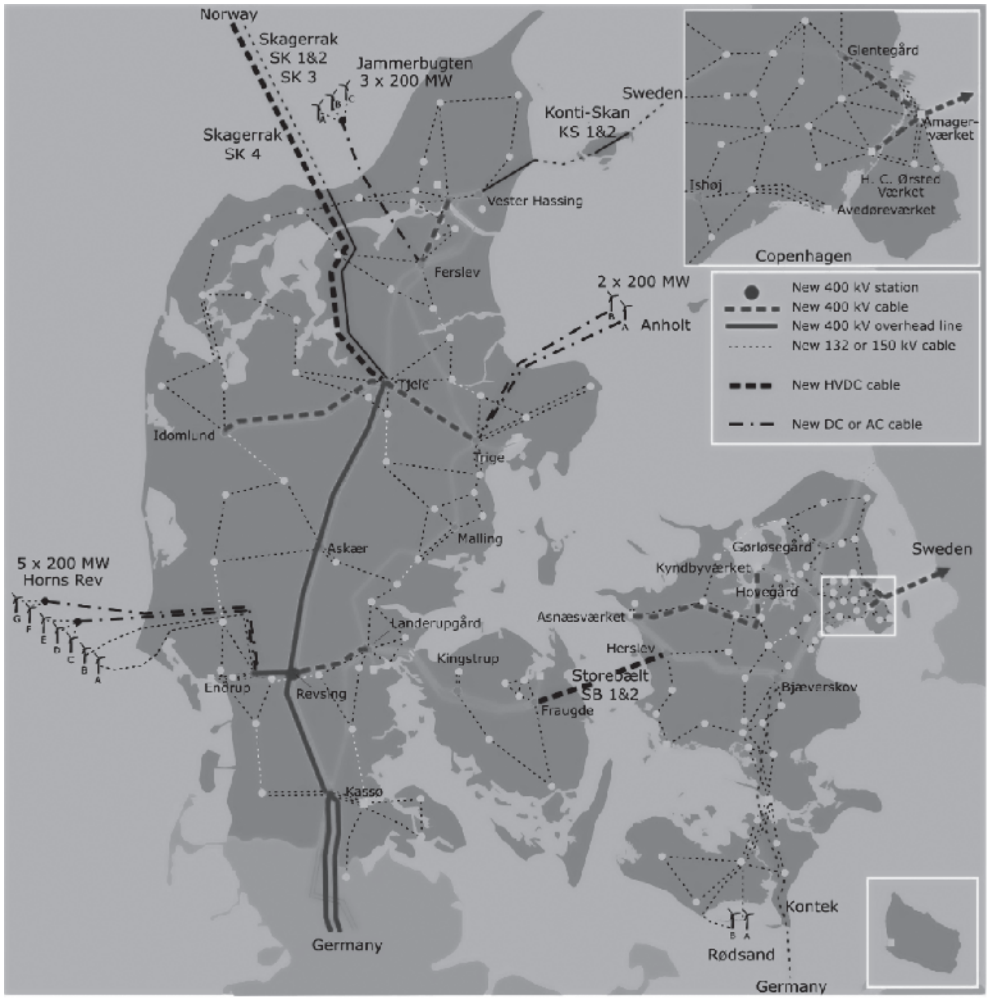


Figure 1.2 Grid expansion plan based on Principle C (from [2])

1.2 Land Cables

1.2.1 Introduction

One obvious difference of a cable from an OHL is that the outer surface of the cable is insulated from the core conductor. This leads to the relatively large admittance of cables compared with OHLs.

The difference in the admittance can be observed not only between cables and OHLs but also between different types of cables. This section explains three types of land cables – XLPE, SCOF and HPOF cables – widely used in practice. These land cables use different insulating materials, and their different relative permittivities lead to different admittances, even with an equal length. The thickness of the insulation layer also affects the admittance of the cable. This section also discusses physical characteristics of land cables together with their electrical characteristics that affect cable system transients.

1.2.2 XLPE Cables

XLPE cables are the newest type of cables among the three major types. The practical application of XLPE cables into the distribution network started in the 1960s. Since then, the applied voltage has been gradually raised and reached the current maximum nominal voltage of 500 kV in 2000 [3], [10].

Until recently, it was more common to select SCOF cables or HPOF cables even for new cable lines. However, in recent years XLPE cables have become the most popular choice for the following reasons:

1. Satisfactory service experience [1]
2. Environmental effect
3. No pressure system
4. No maintenance

For item 2, since XLPE cables use cross-linked PE as the insulating material, flammable oil or greenhouse gases will not leak into the soil or atmosphere even when the cable is damaged. For SCOF and HPOF cables, there is a risk of causing fire or ecological impact when the cable is damaged.

The difference in the insulating material also leads to items 3 and 4. For SCOF and HPOF cables, it is necessary to apply pressure to insulating oil in order to maintain insulation. In contrast, XLPE cables do not require the pressure system including large oil tanks. This can become a major advantage especially when the cable is laid in an urban center and the available space is limited.

Figure 1.3 shows an example of the cross-section of a single-core XLPE cable. The cable is composed of the following layers:

1. Core conductor
2. Inner semiconducting layer
3. Insulation layer
4. Outer semiconducting layer
5. Metallic sheath
6. Outer cover

This configuration of layers is basically identical for single-core XLPE cables with recent technology, regardless of the cross-section size and the adopted material for each layer. The following describes each layer from inside to outside.

1.2.2.1 Core Conductor

The core conductor carries load currents of the cable and is made of copper or aluminum. The copper or aluminum wire is wound to form a stranded conductor as shown in Figure 1.4. Even

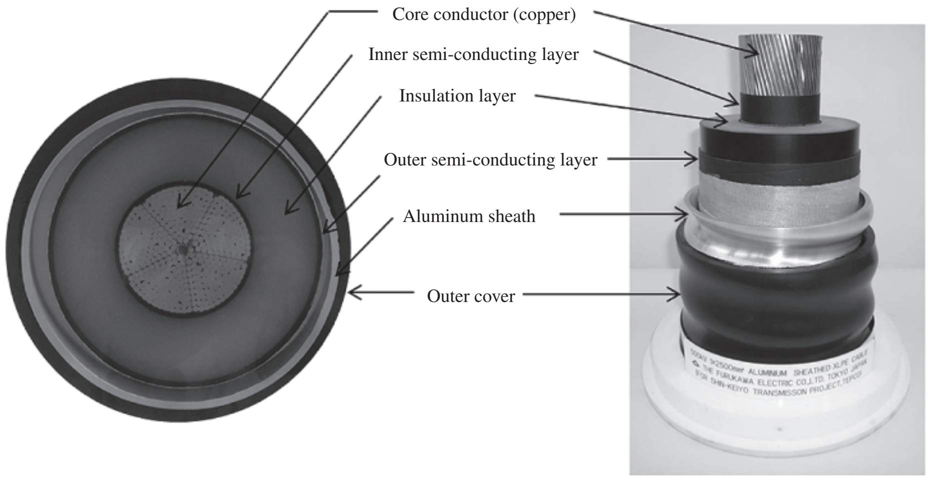


Figure 1.3 Single-core XLPE cable. Courtesy of VISCAS Corporation

Figure 1.4 Stranded conductor. Courtesy of VISCAS Corporation

though it is stranded, the core conductor is considered to be identical to the solid conductor when building a cable model for EMT studies.

The a.c. resistance of a solid conductor is larger than its d.c. resistance due to the skin effect and the proximity effect. The conversion from d.c. resistance to a.c. resistance is made using (1.1) [11].

$$R_{ac} = R_{dc}(1 + y_s + y_p) \tag{1.1}$$

where

R_{ac} = a.c. resistance of a solid conductor
R_{dc} = d.c. resistance of a solid conductor
y_s = skin effect factor
y_p = proximity effect factor

Table 1.1 Resistivity of core conductors

Core conductor	Resistivity at 20 °C (Ωm)
Copper	1.7241×10^{-8}
Aluminum	2.8264×10^{-8}

The d.c. resistance in (1.1) can be calculated from the resistivity of copper and aluminum given in Table 1.1 [11]. The temperature correction is not normally performed since the temperature of the core conductor can be lower than 20 °C for the cable energization. However, it is sometimes necessary to consider the temperature correction when matching simulation results with field measurements, for example for a forensic analysis. It is becoming increasingly popular to choose an aluminum conductor due to recent copper price increases. Since aluminum has higher resistance than copper, a larger cross-section is required in order to provide the same transmission capacity.

Because of the skin effect, the density of an a.c. current is not uniform throughout the cross-section. In fact, the density of an a.c. current is higher at the outer surface of the solid conductor, which reduces the effective area of the cross-section. The formula for calculating the skin effect factor is given in IEC 60287-1-1 [11]. Most EMT-type programs can calculate the skin effect factor, and it is common practice to consider the skin effect when building a cable model for EMT studies.

The proximity effect occurs between conductors of the other phases. Because of the proximity effect, the density of an a.c. current becomes higher at the perimeter close to conductors of the other phases. This also reduces the effective area of the cross-section, but its effect is much smaller than that of the skin effect. The formula for calculating the proximity effect factor is given in IEC 60287-1-1 [11]. Many EMT-type programs cannot calculate the proximity effect factor, and it is common practice not to consider the proximity effect between conductors when building a cable model for EMT studies.

Both the skin effect and the proximity effect are more significant for a cable with a larger cross-section. In order to reduce these effects, a segmental conductor as in Figure 1.5 is normally adopted for a cable with a large cross-section. The segmental conductor is also called the Milliken conductor. In the segmental conductor, each segment is insulated from another by a semiconducting tape or sometimes by an insulating tape. Recently, an enameled conductor has also been considered in order to virtually eliminate the skin effect and the proximity effect.

When EMT-type programs calculate the skin effect factor, they cannot consider a segmental conductor and overestimate the skin effect factor. As a result, they produce higher a.c. resistance than the actual. The same is true for an enameled conductor, which is introduced for the same reason as the segmental conductor. When modeling these types of conductors, it becomes necessary to calculate the skin effect factor outside EMT-type programs depending on the type of study being performed.

1.2.2.2 Inner Semiconducting Layer (Conductor Screen)

The inner semiconducting layer is applied around the core conductor in order to equalize the electric field strength at the outer surface of the core conductor. This layer is also referred to as the conductor screen. Since the resistivity of the semiconducting layer is much larger than the

Figure 1.5 Segmental conductor. Courtesy of VISCAS Corporation

core conductor, the current does not flow through the semiconducting layer. Therefore, it can be considered as a part of the insulation layer for calculating the series inductance of the cable.

In contrast, for calculating the capacitance of the cable, the inner semiconducting layer should be considered as a part of the core conductor. This is because the potential of the inner semiconducting layer becomes equal to the core conductor.

1.2.2.3 Insulation Layer

XLPE cables use cross-linked PE as the insulating material. In the planning stage, the relative permittivity of XLPE is normally set between 2.3 and 2.5 depending on the utility's practice. In the implementation study stage it is given by a cable manufacturer and after the installation it can be calculated from field measurements.

1.2.2.4 Outer Semiconducting Layer (Insulation Screen)

The outer semiconducting layer is applied between the insulation layer and the metallic sheath in order to equalize the electric field strength at the inner surface of the metallic sheath. This layer is also referred to as the insulation screen. Similarly to the inner semiconducting layer, the outer semiconducting layer should be treated as a part of the insulation layer for the inductance calculation and should be treated as a part of the insulation layer for the capacitance calculation.

When building a cable model in EMT-type programs, it is common practice to set the radius of each layer for the accurate calculation of the cable inductance. That is, the inner and outer semiconducting layers are treated as a part of the insulation layer. This treatment of the semiconducting layers makes the cable capacitance smaller than the actual value. In order to compensate for the error in the cable capacitance, the relative permittivity of the main insulation needs to be converted as [12]:

$$\varepsilon_{i1} = \varepsilon_{i0} \frac{\ln\left({}^{R_3}/_{R_2}\right)}{\ln\left({}^{R_{so}}/_{R_{si}}\right)} \tag{1.2}$$

where

ε_{i1} = effective relative permittivity of the main insulation
ε_{i0} = actual relative permittivity of the main insulation
R_2 = outer radius of the core conductor
R_3 = outer radius of the outer semiconducting layer
R_{si} = outer radius of the inner semiconducting layer
R_{so} = outer radius of the insulation layer

1.2.2.5 Metallic Sheath (Metallic Screen)

There are several types of metallic sheath. The most common types are the lead (alloy) sheath, aluminum tape sheath, and copper tape sheath. Figure 1.3 shows the corrugated aluminum sheath, but it is becoming more popular to choose the plain aluminum tape sheath. The lead sheath is manufactured by applying extruded lead alloy on the outer semiconducting layer. The aluminum tape sheath and the copper tape sheath are welded longitudinally to guarantee watertight construction in a radial direction. When water sealing in a longitudinal direction is necessary, the water swelling tape is placed inside these types of metallic sheath.

The lead sheath has a larger resistance than the aluminum tape sheath and the copper tape sheath. In addition, it is expensive, toxic, and heavy. In spite of these unfavorable characteristics, the lead sheath is still adopted due to its high resistance to corrosion especially when a cable is installed in a moist environment.

The copper wire sheath is often formed inside the lead sheath or the aluminum tape sheath in order to carry the required fault current and also to improve the conductivity of the metallic sheath. The copper wire sheath is wound to form a stranded conductor as shown in Figure 1.6. When building a cable model for EMT studies, it is modeled as a solid conductor. The resistivity of copper is modified so that the modeled sheath has identical resistance to the actual copper wire sheath [13]. The resistivity values of lead, copper, and aluminum are shown in Table 1.2.

1.2.2.6 Outer Cover

The outer cover is normally made of PE or polyvinyl chloride (PVC). PVC has better performance than PE in terms of fire resistance. PVC is non-flammable whereas PE is flammable. However, since PVC releases toxic hydrogen chloride gas when burned, PE is the more

Table 1.2 Resistivity of metallic sheaths

Metallic sheath	Resistivity at 20 °C (Ωm)
Lead or lead alloy	21.4×10^{-8}
Copper	1.7241×10^{-8}
Aluminum	2.84×10^{-8}

Figure 1.6 Copper wire sheath. Courtesy of VISCAS Corporation

preferred choice and is increasingly used by many utilities. Even though PVC has much larger permittivity than PE [14], it does not have a noticeable impact on cable system transients.

1.2.3 SCOF Cables

SCOF cables were preferred until recently over XLPE cables because of their reliability. They are less susceptible to a defect that can be introduced during a manufacturing process at a factory or a joint assembly process at a site. In addition, the defect can be found through routine maintenance and can be fixed before causing a cable failure and a subsequent blackout.

Due to the improvement in the manufacturing process of XLPE cables and the joint assembly process, SCOF cables have lost their popularity to XLPE cables. Currently, it is not common to choose SCOF cables for the construction of a new cable line or even for the replacement of an old SCOF cable line. However, SCOF cables are still in the majority in terms of installed cables. Therefore, cable system transients with SCOF cables will be studied for the safe operation of existing cable lines and for forensic studies.

The physical and electrical characteristics of SCOF cables are very similar to those of XLPE cables. Figure 1.7 shows the construction of a SCOF cable.

There are two main differences between SCOF cables and XLPE cables:

1. Hollow conductor

   The hollow conductor is used so that it can serve as an oil duct for insulation. In the setup of the cable model, the inner diameter of the conductor does not become zero for SCOF cables.
2. Insulating material

   The impregnated paper is used as the insulating material. The paper wrapped outside the hollow conductor is impregnated with insulating oil. Kraft paper has been used as the insulating material, but in recent years, it is common to choose PPLP (polypropylene laminated paper) because of its better dielectric characteristic. The relative permittivity and tanδ of the impregnated paper are shown in Table 1.3. Because of the larger relative permittivity, the charging capacity of SCOF cables is normally larger than that of XLPE cables.

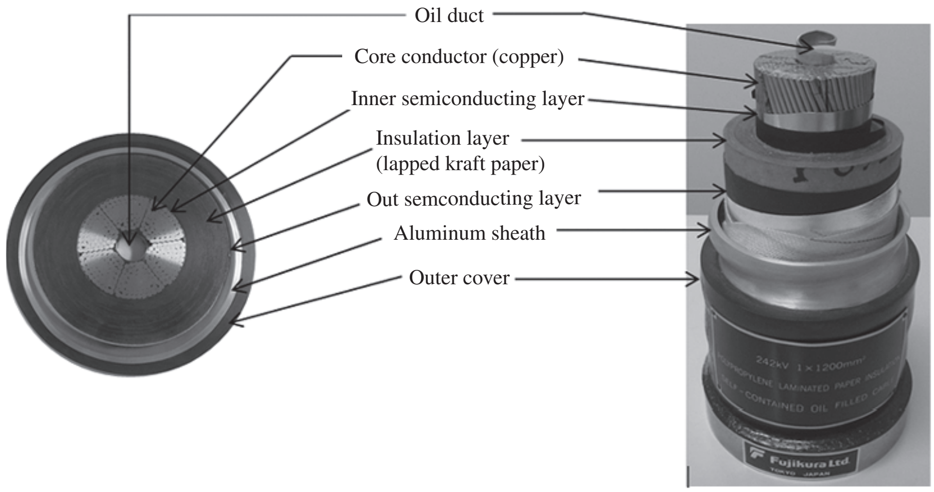


Figure 1.7 SCOF cable. Courtesy of VISCAS Corporation

Table 1.3 Typical values of relative permittivity and tanδ of the impregnated paper

	Relative permittivity	Tanδ (at 80 °C)
Kraft paper	3.2–3.5	0.17–0.2
PPLP	2.7–2.8	0.07–0.08

1.2.4 HPOF Cables

HPOF cables have a significantly different structure compared with XLPE and SCOF cables. Normally, cables of three phases are enclosed in one steel pipe as shown in Figure 1.8.

The cable in the steel pipe has only the conductor and the main insulation. The material and the construction of the conductor and the main insulation are basically the same as those of SCOF cables. One difference is that it is not necessary to use a hollow conductor in HPOF cables as the steel pipe serves as an oil duct.

The steel pipe works as the metallic sheath offering a path for the current return in case of cable faults and shielding for the intrusion of humidity. It is shared by three-phase cables enclosed in it. Because of the larger resistivity and diameter of the steel pipe, compared with the aluminum or copper tape, HPOF cables have a higher zero-sequence impedance (not earth-return, but pipe-return propagation mode), both in resistance and reactance, compared with XLPE or SCOF cables. It is typical for HPOF cables that the zero-sequence impedance is larger than the positive-sequence impedance, which is not the case with XLPE and SCOF cables. The relative permeability of the steel pipe is normally specified as one.

In addition to the proximity effect between conductors of the other phases, the proximity effect occurs between inner conductors and the pipe in the case of HPOF cables. The formula for calculating the impedance and admittance, taking this proximity effect into account, is

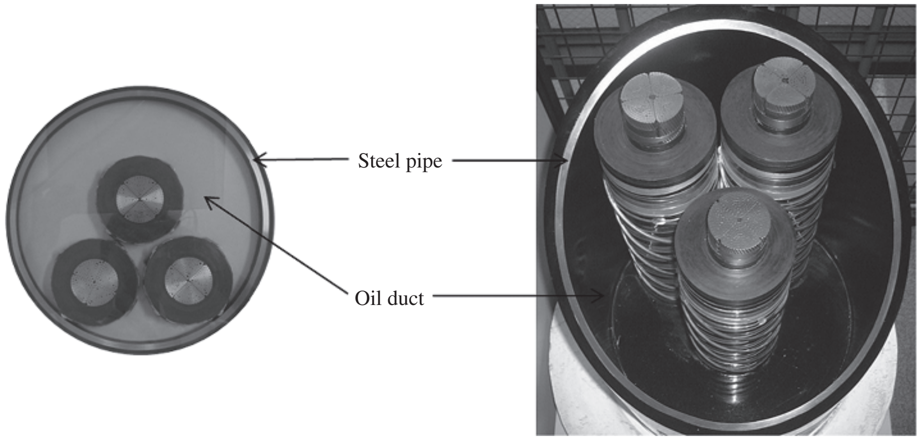


Figure 1.8 HPOF cable. Courtesy of VISCAS Corporation

given in Reference [15]. Many EMT-type programs can consider the proximity effect between inner conductors and the pipe of HPOF cables.

1.3 Submarine Cables

1.3.1 Introduction

Submarine cables are on average longer than land cables since they are often proposed for cross-border trades and for the integration of off-shore wind farms. Long HVAC submarine cables require shunt reactors to compensate for their charging capacity. When the length of a cable line is further increased, it becomes necessary to install shunt reactors at multiple points along the cable length in order to avoid the reduction of transmission capacity for active power or temporary overvoltages. The reactive power compensation incurs an additional cost for the cable project especially when it requires the installation of shunt reactors in the sea. Even though HVDC submarine cables need converter stations, the overall project cost becomes lower for the HVDC option at some cable line length.

1.3.2 HVAC Submarine Cables

XLPE cables are the most preferred option as HVAC submarine cables for the same reasons as land cables. HVAC submarine cables have a layer of armor outside the XLPE land cables as shown in Figure 1.9. The armor helps submarine cables to endure the tensile force they experience during installation. In addition, it can help to avoid a cable failure when a submarine cable is damaged in the sea by a third party.

The most common type of armor is steel wire. As is the case with the copper wire sheath, it is modeled as a solid conductor when building a cable model for EMT studies. The resistivity of steel is modified so that the modeled armor has identical resistance to the actual steel wire armor.

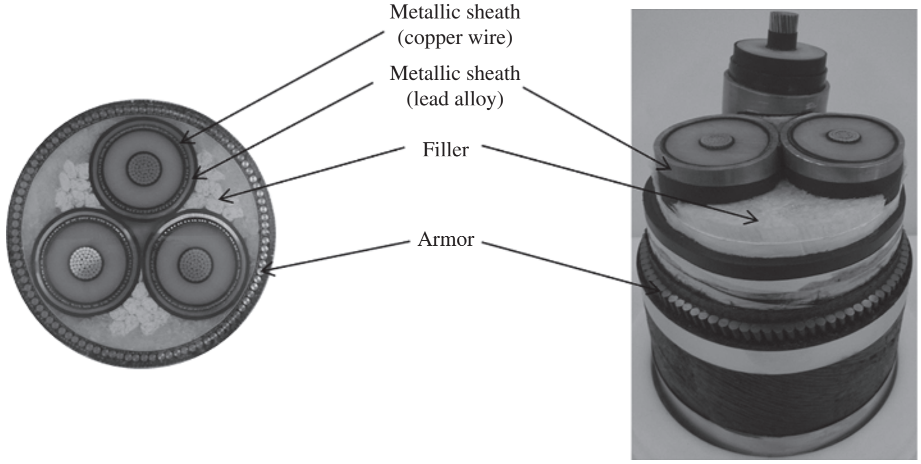


Figure 1.9 HVAC submarine cable. Courtesy of VISCAS Corporation

Some HVAC submarine cable has three-phase cables enclosed together in armor. In this case, the submarine cable is often modeled as a pipe-type cable, considering the armor as a pipe of the pipe-type cable.

1.3.3 HVDC Submarine Cables

Until recently, XLPE cables could not be adopted in a HVDC cable project with LCC–HVDC (line-commutated converter HVDC) technology. The space charge was formed in the main insulation for XLPE cables, and it could lead to an insulation breakdown when the voltage polarity was reversed. The reversal of the voltage polarity occurs with LCC–HVDC when the power flow is reversed. Therefore, SCOF cables have been selected for HVDC cable projects with LCC–HVDC.

The most common type of SCOF cables for HVDC submarine cables is MI (mass impregnated) cables. MI cables are used since the insulating oil cannot be supplied at cable terminations. Figure 1.10 shows the construction of MI cables. Unlike SCOF land cables, it is still common to use Kraft paper as the insulating material. However, it is expected that PPLP will soon become more common because of its better performance as an insulating and dielectric material.

An XLPE cable was first adopted in a HVDC cable project with LCC–HVDC in 2012 for the Hokkaido–Honshu HVDC link in Japan [16, 17]. The 250 kV XLPE cable has overcome the problem caused by the voltage polarity reversal by adding nanoparticles to the insulating material. It is expected that the successful operation of this cable will, in future, lead to the increased application of XLPE cables to HVDC cable projects with LCC–HVDC.

Other than the Hokkaido–Honshu HVDC link, XLPE cables are selected for HVDC cable projects with VSC–HVDC (voltage-source converter HVDC) technology. The VSC–HVDC reverses the power flow by the reversal of the current flow. The reversal of the voltage polarity does not occur with VSC–HVDC, which enables the selection of XLPE cables.

Figure 1.10 MI cable. Courtesy of Nexans

1.4 Laying Configurations

1.4.1 Burial Condition

Cables are, in most cases, buried in the following conditions:

- Directly buried
- Buried in a pipe or a duct
- Buried in a trough
- Buried in a tunnel

When cables are directly buried, they are laid in a flat formation or a trefoil formation as shown in Figure 1.11. The flat formation is often preferred as the required depth of a trench

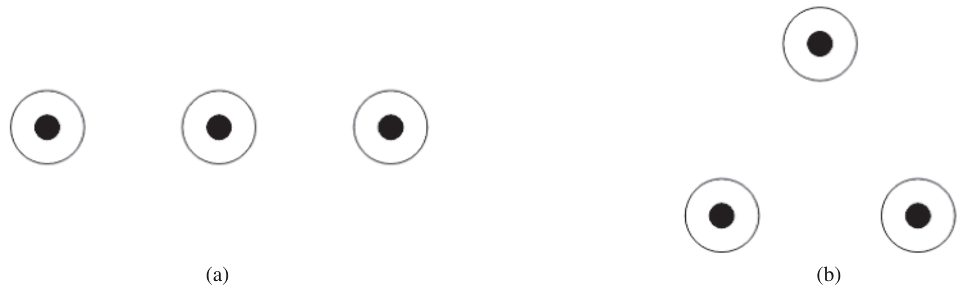


Figure 1.11 Flat formation (a) and trefoil formation (b)

can be shallower compared with the trefoil formation. However, the flat formation requires wider land space, which may prohibit its application when such wide space is not available.

Typical phase spacing for EHV cables ranges from about 300 to 500 mm. Smaller phase spacing may be selected in order to reduce the cost for the digging work as long as the necessary transmission capacity is available.

In relation to cable system transients, this phase spacing affects the inductance of a cable line. In fact, the inductance of a cable line becomes larger for smaller phase spacing if other conditions are equal. This is apparent from the theoretical equation of the impedance of a cable line discussed in Chapter 2. Therefore, larger phase spacing is preferable in terms of both the transmission capacity and the inductance of a cable line.

When a cable is laid in a pipe or a duct, its phase spacing depends on the arrangement of the pipe or the duct. Their arrangement is affected by available land space and the cost for the digging work as in the directly buried cable. Obviously the cable arrangement affects the impedance of the cable line. When surplus pipes or ducts are available for the cable installation, it is recommended to calculate positive-sequence and zero-sequence impedances with different cable arrangements [18].

When a cable is laid in a trough, its phase spacing tends to be small compared with other laying conditions. Since three-phase cables are laid in a trough, phase spacing is limited by the size of the trough. When the trough is made of concrete, the cable is often modeled as a pipe-type cable, considering the trough as a pipe of the pipe-type cable.

When a cable is laid in a tunnel, some utilities decide to choose small phase spacing in order to save space in a tunnel and install more cables in it. Some cables are laid even next to each other with a cable of other phases like a triplex cable. This can be justified considering the high construction cost of a tunnel, especially around big cities where a tunnel needs to accommodate many cables.

Tunnel installed cables are normally modeled as a pipe-type cable considering the tunnel as a pipe of the pipe-type cable. Reinforced concrete is considered electrically conductive because of the steel and concrete.

1.4.2 Sheath Bonding

When considering the sheath bonding, two important factors are the sheath voltage and the sheath current. If only the former factor is considered, the most favorable sheath bonding is solid bonding. However, it causes higher sheath current, leading to a larger sheath circuit loss. Hence, it is only applied to submarine cables, which do not have joints in a cable line.

In contrast, if only the sheath current is considered, the most favorable sheath bonding is single-point bonding. The sheath current in the normal operating condition becomes zero when single-point bonding is adopted. However, it causes higher sheath voltage, which requires the installation of an earth continuity cable (ECC). In fact, single-point bonding is often adopted together with the cross bonding as discussed later in this section.

Cross bonding is applied considering both the sheath voltage and the sheath current. It can suppress the sheath voltage while limiting the sheath current. It is dominantly applied to a cable line with three or more cable sections.

1.4.2.1 Solid Bonding

An example of solid bonding is shown in Figure 1.12 even though this configuration is not applied to land cables due to the large sheath current. As the sheath circuit is grounded at every joint (earthing joint, EJ) and termination, the sheath voltage is suppressed to virtually zero at these points. Only the sheath voltage caused by the grounding resistance remains at joints and terminations. The value of the grounding resistance is normally around 5–10 Ω at joints and 0.1–1 Ω at terminations. The grounding resistance at terminations is lower since the grounding circuit can be connected to the substation grounding grid, except for the termination at the transition point between the underground cable (UGC) and the OHL in the mixed UGC/OHL line.

The solid bonding is applied to submarine cables, which do not have joints in a cable line. The metallic sheath of a submarine cable is grounded every 2–4 km in order to suppress the sheath voltage as shown in Figure 1.13. As a result, the sheath current of a submarine cable becomes larger than that of land cables. The metallic sheath of a submarine cable often has a large cross-section in order to reduce the sheath circuit loss.

1.4.2.2 Single-point Bonding

An example of single-point bonding is illustrated in Figure 1.14. Single-point bonding is applied to a short cable line with one or two cable sections. The sheath circuit on the left

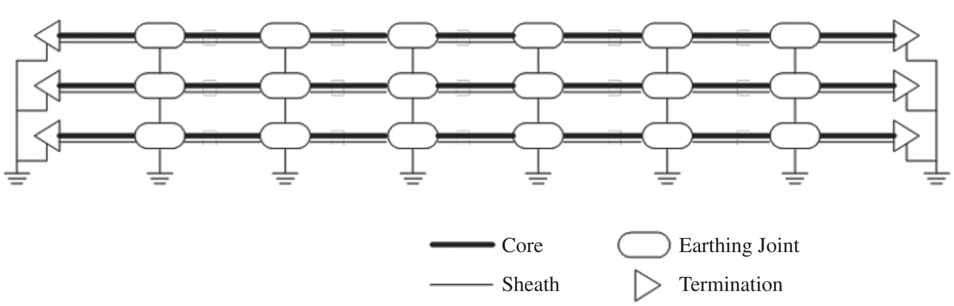


Figure 1.12 Solid bonding

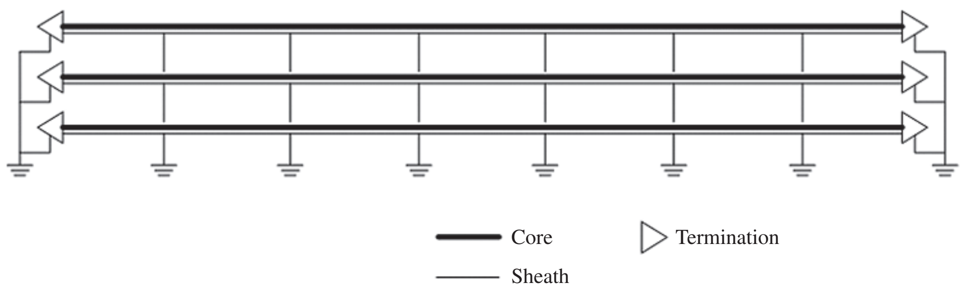


Figure 1.13 Solid bonding of a submarine cable

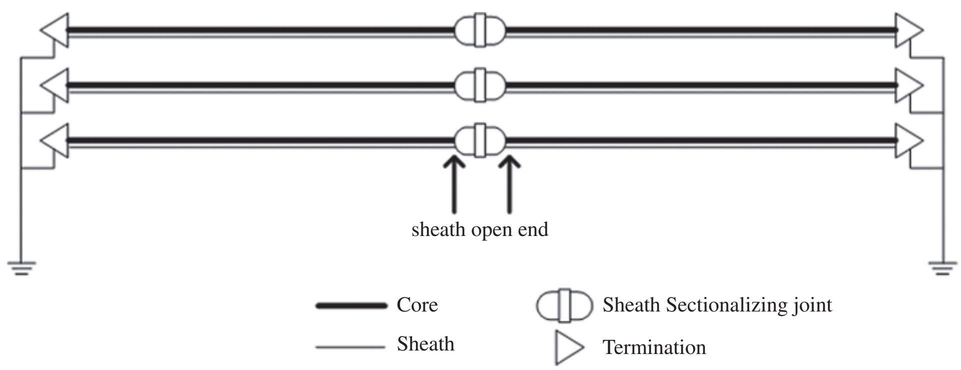


Figure 1.14 Single-point bonding (two sections)

side is insulated from the sheath circuit on the right side by sheath sectionalizing joints (SSJs). This creates open ends in the sheath circuit.

The magnitude of the continuous sheath voltage, which is induced by positive-sequence power flow in a core conductor in normal operating conditions, is equivalent to that in the case of cross bonding. The short-term sheath voltage at the sheath open end becomes an issue in the case of single-point bonding. The short-term sheath voltage under the following conditions is studied, and the earth continuity cable (ECC) and sheath voltage limiters (SVLs) are installed as a countermeasure as shown in Figure 1.15:

- Single-line-to-ground (SLG) faults (external to the targeted major section)
- Three-phase faults (external to the targeted major section)
- Switching surges
- Lightning surges (only for mixed UGC/OHL)

The power-frequency component of the short-term sheath voltage under SLG faults and three-phase faults is calculated using the formulas given in References [19–22]. In addition, it is sometimes necessary to study the transient component of the short-term sheath voltage, especially in order to evaluate the performance of SVLs. The study is performed using EMT-type programs.

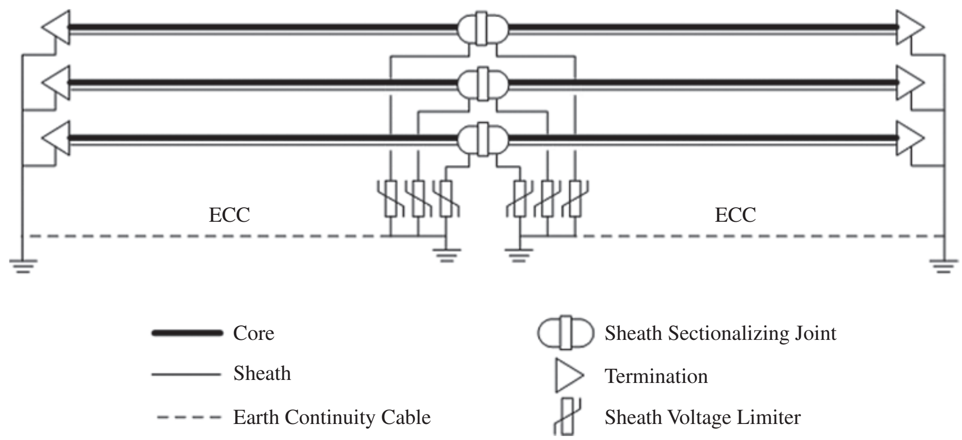


Figure 1.15 Single-point bonding (two sections) with ECC and SVLs

1.4.2.3 Cross Bonding

An example of cross bonding is illustrated in Figure 1.16. The cross bonding is applied to a cable line with three or more cable sections.

As in single-point bonding, the sheath circuit on the left side is insulated from the sheath circuit on the right side by SSJs. In the cross bonding, however, the sheath circuit on the left side is connected to the sheath circuit of a different phase cable on the right side as shown in Figure 1.16. For example, the sheath circuit expressed by the dotted line goes with the phase a cable in the first minor section, with the phase b cable in the second minor section, and with the phase c cable in the third minor section.

Thanks to this connection of the sheath circuit, the cross bonding can suppress the sheath voltage while limiting the sheath current. Assuming the following three conditions, the vector sum of the continuous sheath voltage of three minor sections becomes zero:

- Positive-sequence core current
- Trefoil formation (balanced circuit)
- Equal length of three minor sections

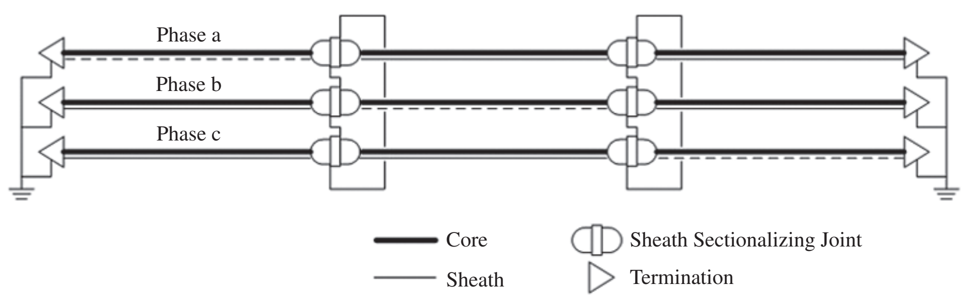
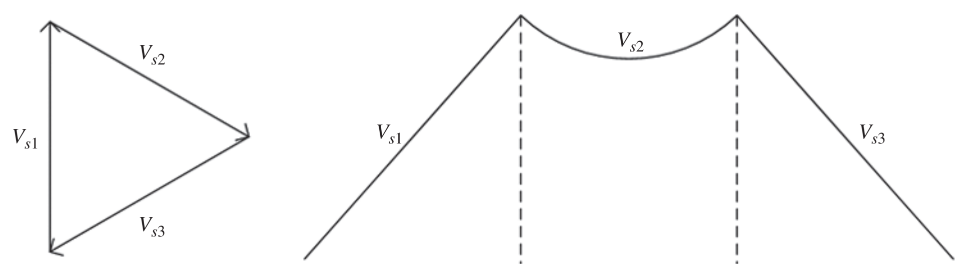


Figure 1.16 Cross bonding (three sections)

The continuous sheath voltage of three minor sections can be illustrated as in Figure 1.17. This means that the sheath current becomes zero if these conditions are satisfied. However, in an actual installation, these conditions are not completely satisfied, which causes an imbalance in the continuous sheath voltage of the three minor sections. The sheath current flows due to this imbalance, but it is much smaller than that in the solid bonding.

Even though the continuous sheath voltage is suppressed by the small sheath current and the balanced sheath voltage, the short-term sheath voltage cannot be suppressed by the cross bonding. As a countermeasure for the short-term sheath voltage, SVLs are installed at sheath sectionalizing joints as shown in Figure 1.18.

SVLs are normally arranged in a star formation, and the neutral point of SVLs is grounded as shown in Figure 1.18. The short-term sheath voltage can exceed the ratings of SVLs when the grounding resistance at a SSJ is high. In this case, ECC can be installed connecting the neutral points of SVLs to grounding wires at terminations and EJs. The installation of ECC



V_{s1}: sheath voltage of the first minor section, V_{s2}: sheath voltage of the second minor section and V_{s3}: sheath voltage of the third minor section

Figure 1.17 Continuous sheath voltage in a major section of a cross-bonded cable

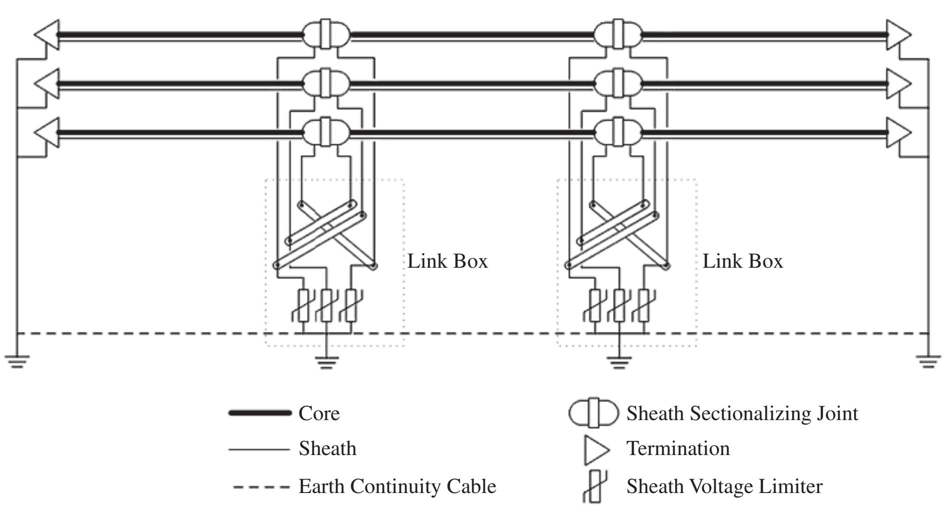


Figure 1.18 Cross bonding (three sections) with ECC and SVLs

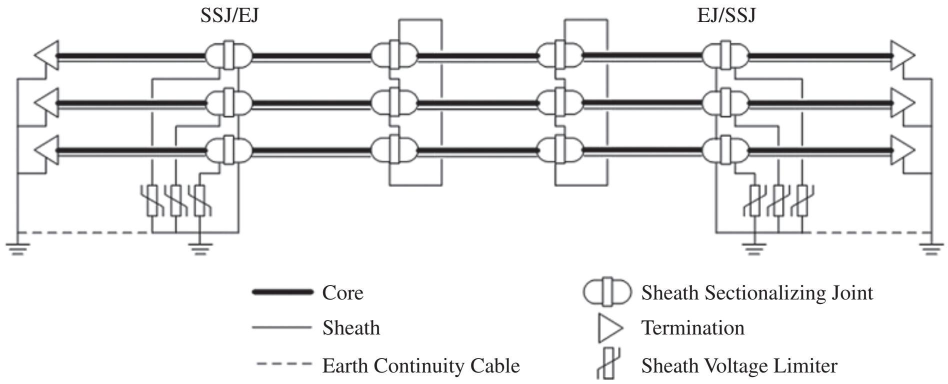


Figure 1.19 Combination of cross bonding and single-point bonding

lowers the effective grounding resistance at the SSJ. Other countermeasures include changing the neutral point from solidly grounded to ungrounded and changing the SVL connection from the star formation to the delta formation [21].

When the number of minor sections is not a multiple of three, one or two minor sections cannot become a part of the cross-bonding configuration. For example, if the number of minor sections is five, two minor sections cannot become a part of the cross-bonding configuration. In such a situation, single-point bonding is applied to the remaining two minor sections as shown in Figure 1.19. In the figure, SSJ/EJ and EJ/SSJ means that:

- The sheath circuit of the left side is insulated from the sheath circuit of the right side as in SSJ.
- The sheath circuit of the left side (EJ/SSJ) or the right side (SSJ/EJ) is grounded as in EJ.

As the single-point bonding is applied to these minor sections, it is important to confirm that the sheath voltage of these minor sections does not exceed the ratings of SVLs, joints, and the sheath.

References

[1] CIGRE WG B1.10 (2009) Update of Service Experience of HV Underground and Cable Systems. *CIGRE Technical Brochure* **379**.

[2] Energinet.dk (2008) Technical Report on the Future Expansion and Undergrounding of the Electricity Transmission Grid. https://selvbetjening.preprod.energinet.dk/NR/rdonlyres/CC966C3A-FE78-41D8-9DC7-6B455210B502/0/TechnicalReportSummary.pdf (accessed 27 November 2013).

[3] Momose, N., Suzuki, H., Tsuchiya, S., and Watanabe, T. (1998) Planning and development of 500 kV underground transmission system in Tokyo metropolitan area. *CIGRE Session*, 37-202.

[4] Colla, L., Lauria, S., and Gatta, F.M. (2007) Temporary overvoltages due to harmonic resonance in long EHV cables. International Conference on Power System Transients (IPST), Lyon, France.

[5] Rebolini, M., Colla, L., and Iliceto, F. (2008) 400 kV AC new submarine cable links between Sicily and the Italian mainland. Outline of project and special electrical studies. *CIGRE Session*, C4-116.

[6] Tokyo Electric Power Company (2009) Assessment of the Technical Issues relating to Significant Amounts of EHV Underground Cable in the All-island Electricity Transmission System. http://www.eirgrid.com/media/Tepco%20Report.pdf (accessed 27 November 2013).

[7] Akhmatov, V. (2006) Excessive over-voltage in long cables of large offshore windfarms. *Wind Engineering*, **30** (5), 375–83.
[8] Ohno, T. (2012) Dynamic study on the 400 kV 60 km Kyndbyværket–Asnæsværket line. PhD thesis. Aalborg University.
[9] CIGRE WG C4.502 (2013) Power System Technical Performance Issues Related to the Application of Long HVAC Cables. *CIGRE Technical Brochure* **556**.
[10] Kawamura, T., Kouno, T., Sasaki, S. *et al.* (2000) Principles and recent practices of insulation coordination in Japan. *CIGRE Session*, 33-109.
[11] IEC 60287-1-1 ed. 1.2 (2001) Electric cables – Calculation of the current rating – Part 1-1: Current rating equations (100 % load factor) and calculation of losses – General.
[12] Gustavsen, B. (2001) Panel session on data for modeling system transients. Insulated cables. Proceedings of the IEEE Power Engineering Society Winter Meeting, Columbus, OH, USA.
[13] CIGRE WG B1.30 (2013) Cable Systems Electrical Characteristics. *CIGRE Technical Brochure* **531**.
[14] Kersting, W.H. (2012) *Distribution System Modeling and Analysis*, CRC Press.
[15] Ametani, A. (1980) General formulation of impedance and admittance of cables. *IEEE Transactions on Apparatus and Systems*, **99** (3), 902–10.
[16] Watanabe, C., Itou, Y., Sasaki, H. *et al.* (2013) Practical application of +/-250 kV DC-XLPE cable for Hokkaido–Honshu HVDC link. *IEEJ Transactions on Power and Energy*, **134** (1), 64–75 (in Japanese).
[17] Murata, Y., Sakamaki, M., Abe, K. *et al.* (2013) Development of high-voltage DC-XLPE cable. *SEI Technical Review*, **182**, 48–55 (in Japanese).
[18] Nakanishi, H., Inoguchi, H., Hashimoto, I. *et al.* (1991) A study of zero-sequence current induced in a cable system. *IEEE Transactions on Power Delivery*, **6** (4), 1352–8.
[19] CIGRE Working Group 07 Study Committee 21 (1973) The design of specially bonded systems. *Electra* No. **28**.
[20] CIGRE Working Group 07 Study Committee 21 (1976) The design of specially bonded systems (part II). *Electra* No. **47**.
[21] CIGRE Working Group 07 Study Committee 21 (1990) Guide to the protection of specially bonded systems against sheath overvoltages. *Electra* No. **128**.
[22] CIGRE WG B1.18 (2005) Special Bonding of High Voltage Power Cables. *CIGRE Technical Brochure* **283**.