UNDERGROUND CABLES

In the this article a short overview is given of paper-insulated and extruded high voltage (*HV*) underground cables and gas-insulated transmission lines.

Basic investigations of insulated conductors were carried out in the second half of the nineteenth century. One of the first underground cables was laid in 1880 in Berlin in Germany. This was the worldwide beginning of HV electric cables (1). In subsequent years a variety of different insulating materials were developed, culminating in the impregnated paper technology. With impregnated paper, it became possible to manufacture cables that were resistant to increased conductor temperatures and could withstand the stresses of the electric field.

A basic innovation in 1880 was dielectric insulation, made with paper lapped around the conductor. With this idea due to Ferranti, the risk of failure is distributed over the different layers and therefore minimized for the whole insulation. Table 1 shows the development of voltage ratings for HV cables starting from 1880.

The development of the multilayer paper-insulated cable improved over the decades, allowing higher voltages to be employed. This type of cable has high reliability for HV transmission systems, and many kilometers of such cables were built worldwide. On-site experience showed that for ac applications it is of great importance to achieve freedom from partial discharge after commissioning.

A second important criterion for reliability of HV cable over its lifetime (in today's terms this is 50 years) is thermal stability. The solid insulation must be free of hot spots to avoid accelerated thermal aging.

Along with multilayer paper insulated cable, investigations had also been carried out on gas pressure pipe cables and oil-filled cables to meet the requirements under service conditions. Service load changes continually cause mechanical forces within the cable due to contraction and expansion of the core. These thermal and pressure changes, may cause small voids, which, in turn, may cause partial discharges in the insulation. Suitable remedies for paper-insulated cables, taking advantage of various measures such as increased gas and oil pressures, have been developed.

It is obvious that additional equipment for service is needed for these cable installations, such as oil tanks or pumping stations. This equipment needs to be maintained, which inevitably results in personnel and energy costs over its lifetime. Customer requirements have thus forced the development of maintenance-free and easy-to-lay cables. The answer of the cable industry was the development of an extruded cable. These dry cables do not need fluids for insulation and thus do not need additional equipment for maintenance.

Table 1. Increase in Voltage Ratings of High Voltage Cables Since 1880 (1)

Year of First Use	Voltage Rating (kV)
1880	10
1924	100
1930	120
1950	400
1974	500

Table 2. Increase in Voltage Ratings of High Voltage Extruded Cables (2)

Year of First Use	Voltage Rating (kV)
1944	3
1960	138
1970	220
1986	400
1988	500

The first extruded cables were made in 1940 out of polyvinyl chloride (*PVC*), but it was realized at a very early stage that the loss factor tan δ of this material is too high for HV applications, so that thermoplastic polyethylene (*PE*) was utilized in further development. The first PE cables were produced in 1944 in the United States. After that their worldwide development started, with the main dates of ratings improvement shown in Table 2. The next step in the development of PE cables was to use cross-linked polyethylene (XLPE) to increase the in-service temperature from 70° to 90°C. After 1960 further development improved the technique steadily to a point when 500 kV cables were commissioned in 1988 (see Table 2).

At the beginning of cable development the energy transmission capacity was raised basically by increasing the applied voltage. With test setups in France for 750 kV and Italy for 1100 kV between 1960 and 1980, it was found that the effort to increase the voltage leads to problems and makes large investments necessary. An alternative approach, beginning in 1960, was to increase the current-carrying capacity. For such systems the heat transfer owing to the losses was the central problem to be solved, and it was found that one could do so by simply increasing the cross section of the conductor as well as by lowering the ac losses by means of improved conductor design. The difficulty was to keep the cable flexible enough to wind it onto a coil. Success allowed an increase in the power transmission capacity of buried cable systems (depending on the ground resistivity) to ratings of 600 MVA to 800 MVA at voltages of 400 kV or 500 kV.

To achieve power transmission ratings of 1100 MVA to 1500 MVA per system, forced cooling of the cable installation is required. This cooling is usually done by circulating water through pipes laid parallel to the cable (lateral cooling) or integrated with it (direct forced cooling). This requires more engineering effort and makes higher initial investment necessary. Additionally the maintenance costs are increased.

BASIC ELEMENTS

To connect point *A* to *B* with a HV underground cable, three basic elements are needed:

- The cable
- The accessories (joints and terminals)
- System components

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The cable itself is only one functional element of an underground energy transmission system. For HV applications today mainly oil-filled paper- or PPLP-insulated cables, gas pressure pipe cables, and solid insulated EPR or XLPE cables are used.

A cable terminal is needed to connect the cable at the end with an overhead line or a substation. A cable joint is needed to connect cable sections to each other. The cable terminals and joints are considered critical components of the system because they undergo increased electric stresses within their insulation and at their interfaces. Issues for concern are:

1. To keep overall dimensions of the components small, high electric stresses have to be considered when designing the accessories.
2. The need to perform the cable installation by hand has led to intensive development of prefabricated and pretested joints and stress cones.

From the foregoing, it is apparent that cables and accessories have to be developed, manufactured, and tested very carefully.

Different system components are needed to operate the HV cable system. Some typical components are:

- Pressure control—to maintain the oil or pressure gas pressure (for oil-filled or gas pressure pipe cables)
- Corrosion protection—active and passive
- Optional temperature control—equipment for the measurement of cable temperature along the transmission line or at special points (to monitor hot spots)
- Partial discharge measurement—equipment to measure partial discharges in cables or joints, mainly during commissioning (for extrahigh voltage XLPE cables)

There is now equipment available, developed with modern computers, par monitoring cable transmission systems, as well as new sensors for pressure, temperature, or partial discharges to improve reliability and to detect failures during laying and installation.

CABLE CONSTRUCTION

In this section, the construction elements of cables are explained. For the electrical and thermal behavior of the cable, the basic elements are the conductor, the insulation, and the metallic enclosure.

All HV cables are designed as radial field cables. The long concentrical cylinder is formed by means of a conductor and a shield, separated by the insulation. The outer metallic enclosure is connected to the ground, so that the electric field outside of the cable is zero.

The conductor of the cables is designed to carry service as well as short circuit currents. In case of a single-phase breakdown the shield of a cable must be designed to transport the necessary short circuit current ratings during the switching time of the HV circuit breaker (less than 100 ms).

The shield of the cable is not designed to carry the current of the conductor, so that outside the cable the magnetic field of the inner conductor can be measured.

Insulation Material

Under normal service it is desirable to keep the reverse current in the screen to almost zero in order to minimize losses. This is ensured in large cable installations by making use of a *cross-bonding system*. Outside the cable a resulting magnetic field is present.

For HV cables, two groups of dielectrics are used as insulation material: impregnated paper or PPLP, and extruded polyethylene. In some areas of the world ethylene propylene rubber (*EPR*) cables are also used.

Impregnated Paper Cables. Oil is used to fill the air gaps in multilayer impregnated paper cable. Typically, for impregnated cable one uses multilayer dielectrics employing different types of oil, depending upon the manufacturer. In some designs, plastic foils have replaced part or all of the paper insulation, and this has resulted in lower dielectric loss and higher electrical resistivity and breakdown voltage.

Instead of fluid oil, mass-impregnated cables are also used in the lower voltage ranges.

Oil-filled paper-insulated cables have been proved and tested over many decades. Hardly any problems with this type of insulation material have been reported, and a even nowadays paper-insulated extrahigh voltage cable, for example in the voltage range 400 kV, requires a smaller insulation thickness than the newly developed cross-linked polyethylene cables.

Extruded Cables. In order to minimize the maintenance work for cable systems, solid extruded insulation materials made out of PE, XLPE, and EPR have been developed for HV applications worldwide. Polyethylene-insulated HV cables were introduced into the market in the 1960s. Most of the new cables today use XLPE insulating materials, which offer a higher transmission capacity than PE cables. A cross section of such a HV XLPE cable is shown in Fig. 1. A voltage range of up to 500 kV is covered today by XLPE cables and accessories. Most recently, in 1998, two bulk power XLPE cable installations in Copenhagen and Berlin were commissioned.

The cross section of a polyethylene cable is similar to that of a paper-insulated cable. The conductor (1) at the center is designed without a hollow channel, because no oil circulation is necessary. The cable core is then manufactured in a triple extrusion process, making the inner semiconducting layers (2 and 3), the XLPE insulation (4), and the outer semiconducting layer (5) in one manufacturing step. The insulation (4) is protected by different foil layers (5–7, and 8) and is watertight, covered by a metallic enclosure (9), and mechanically protected by a polyethylene sheath (10).

The elevated electric stresses make necessary superclean insulating compounds, production under clean room conditions, and highly sophisticated design of cable and accessories. The cables are designed to last up to 40 years.

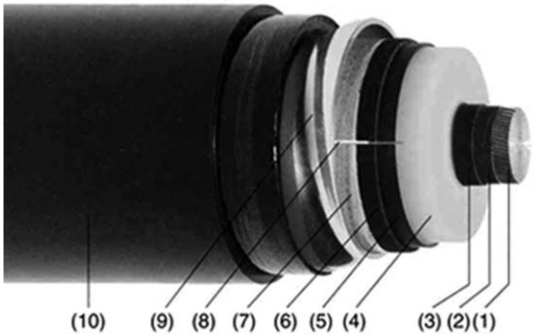

Figure 1. Cross section of a cross-linked polyethylene cable: (1) Milliken conductor, (2) semiconducting plastic fabric tape, (3) conductor shield, (4) XLPE insulation, (5) insulation shield, (6) semiconductive cushion layer, (7) textile tape with interwoven copper wires, (8) integrated optical fiber, (9) corrugated aluminum sheath, (10) PE outer sheath.

Special conductive sheets are used in HV cables to limit the maximum field strength and the cross sections between the conductor and the insulating material and between the metallic enclosure and the insulating material. The main task of these conductive sheets is to equalize and to reduce the electric field strength, to eliminate inhomogeneities in the cylindrical field of the cable, to reduce the maximum strength of the electric field between the single conductor wires, and to eliminate partial discharges within gaps or voids in the insulating material. For extruded cable the inner and outer semiconducting layers may be also extruded in order to ensure a cylindrically symmetrical electric field. These layers are also called the conductor and insulation screens.

Conductor

The materials used for the conductor are aluminum (Al) and copper (Cu). The conductivity of aluminum is lower than that of copper, which means that the cross section of aluminum conductors must be larger for the same transmission power. The choice of copper or aluminum for a cable system is dictated by economic considerations. Some customers require copper conductors because the connecting accessories are then simplified (no Al–Cu transitions are needed). Copper also has better rigidity than aluminum and thus is more resistant to mechanical impact.

Cross sections of HV cables are standardized, with values for copper conductors in the range of 240 mm^2 up to 2500 mm^2. The upper limit of the cross section is fixed by the manufacturing capability of the machinery, the overall bending radius, and the transport length and weight limits of the delivery drums.

The type and cross section of the conductor are determined by the rated current, the cable design, and laying conditions. Oil-filled cables contain a hollow conductor through which oil is forced during thermal load changes. A variety of conductor designs for HV cables are shown in Fig. 2. The selection of an appropriate conductor construction is governed by various parameters. Ac losses with regard to skin and proximity effects are to be taken into consideration.

For XLPE, cables of large cross section ($>$1200 mm^2), e.g., the low loss Miliken conductor shown in Fig. 2(a) and 2(b). have advantages over the compact designs shown in Fig. 2(c)., 2(d)., and 2(e). In this example the Miliken conductor achieves 10% to 20% increase in transmission power over the compact design. Single wire insulation applied to the Miliken conductor reduces the ac losses further by several percent. Compared to the single cross sections of Fig. 2(f), 2(g)., and 2(h)., the Miliken conductor achieves higher transmitted power.

Metallic Sheath

The metallic sheath can be designed in various ways. The tasks of the sheath are:

- To carry the capacitive load current
- To carry the ground fault current until the system is switched off
- To avoid an electric field outside the cable
- To protect the cable core mechanically during laying and in service
- To avoid ingress of moisture or other solvents present in the soil

For a flexible and therefore bendable mechanical enclosure, copper wires with laminated aluminum sheaths or with corrugated aluminum, copper, steel, or lead sheaths are used. Gas pressure pipe cables are enclosed in solid steel tubes, which are jointed together on site. Three cable cores are arranged in trefoil formation at the center of the tube.

CORROSION PROTECTION

The outer sheath serves as corrosion and mechanical protection, especially during the laying process. Mechanical protection and watertightness can be achieved by means of high density polyethylene (*HDPE*). Except for PVC, it is today the most utilized material for corrosion protection.

To protect the outer sheath against corrosion and thus avoid longitudinal water spreading in case of sheath damage, it is also important to have good bonding between the HDPE and the metallic enclosure. The corrosion protection can be checked after 1 or 2 years in service by the proven test method of measuring the ohmic resistance between the metallic enclosure and the soil with a dc voltage. If in dry areas the resistivity of the soil is too high, the outer polyethylene sheath may be coated with graphite, r example, to enable the measurement. New developments also allow the online measurement of corrosion protection by means of water sensors, integrated in the screening area of the cable. If water enters the screening area after mechanical impact on the cable sheath, a computer system triggers an alarm and prints out phase and location in which the fault occurred, so that repair personnel can react immediately to avoid further damage to the cable installation.

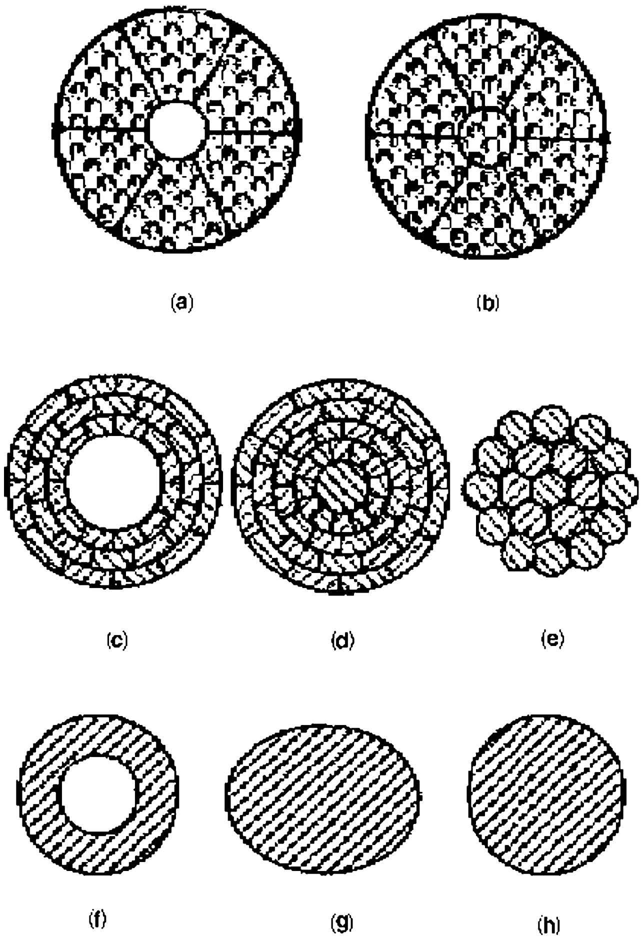

Figure 2. Typical conductor cross sections.

CABLE ACCESSORIES

High voltage cables can be produced in long lengths, limited by the manufacturing and transportation capabilities. The sizes of trucks or railroad trailers and the maximum weight of the drums are decisive factors. In general extrahigh voltage cables in the voltage range 400 kV are produced to a maximum delivery length around 1 km. Some Japanese manufacturers can today deliver lengths of up to 2.5 km, but the resulting very large drums have to be shipped by barge, rather than by truck as usual. Ordinarily, then, cables need to be jointed together to cover the complete system length.

At the end of the cable installation the cables need to be connected to a transformer, a circuit breaker, or a disconnector within a substation, or to an overhead line. Therefore, cable terminals are needed. Cable terminals have to be designed very carefully because of the high electric stresses in them and the need to install them on site.

The overall service record of HV cable installations is excellent. Most failures in cable installations are related to accessories, as shown in Table 3. The basis for these data is a three-phase HV circuit of 3 km length with two sets of terminals, one set of stop joints, and auxiliary equipment; in the case of oil-filled cables, there are five sets of joints in total.

Table 3. Relative System Failures in a 3 km Circuit of Insulated High Voltage Cable (3)

Insulation	Oil	XLPE
System Failure Rate per Year	0.033	0.0048–0.0102
Proportion Due to Cable (%)	14	54–62
Proportion Due to Accessories (%)	86	38–46

Cable Terminals

A cable terminal is used to connect a cable to another system such as an overhead line, circuit breaker, transformer, or disconnector within a substation.

In Fig. 3, the main components of an outdoor type cable terminal with sealed end are shown schematically for a 400 kV XLPE cable. At the support base (1), the cable is fixed to the copper entrance bell. The slip-on stress cone (2) ensures homogeneous stress grading by means of capacitive field control within the terminal in the area where the outer semiconductor of the cable core has been removed. The porcelain (4) is filled with the liquid filling compound (5). The conductor of the cable is connected to the copper busbar (3) on top of the porcelain.

Cable Joints

A cable joint is used to connect two cable sections. In the following a typical 400 kV prefabricated slip-on joint for

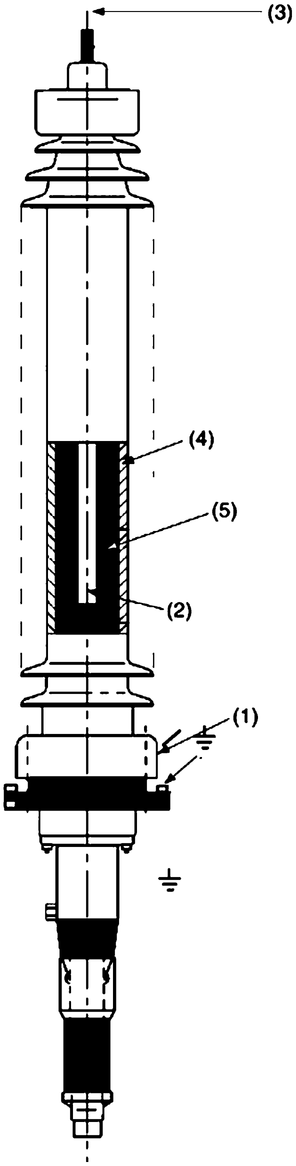

Figure 3. Cable terminal of outdoor type with sealed end: (1) support base, (2) slip-on stress cone, (3) conductor, (4) porcelain, (5) filling compound.

XLPE cables is described.

The cable ends are prepared by removing the sheath and the outer semiconducting layer to a certain length. The conductor connection is made, for example, with mechanical pressing, the prefabricated joint is moved into position, and the outer screening and housing of the joint are prepared as a final step. Such a joint may be designed as a *straight* joint, having the screens of the two cable ends connected to each other, or, as can be seen in Fig. 4, as an *insulated* joint, enabling the user to install a cross-bonding system in order to minimize sheath losses of the installation.

SYSTEM COMPONENTS

To use the cable for power transmission, various other components are needed. Depending on the type of insulation, monitoring or maintenance systems may be required. Oil-filled cable systems need service equipment to ensure continuous oil pressure in the cable installation. For high power transmission it may also be necessary to install oil pumps that ensure steady oil flow through the conductor, thus avoiding hot spots or thermal bottlenecks in joints. Mass-impregnated gas pressure pipe cables require equipment to monitor the gas pressure.

Extruded cables do not need maintenance equipment during service, because the insulation is solid. To control the temperature along the cable, fiber optic cables may be inserted into the sheath. With a laser impulse the temperature along the cable transmission can be measured to look for hot spots and provide an opportunity for controlling the transmission power. After installation and commissioning, tests with hv-ac and partial discharge measurement systems permit checking of the proper assembly of all system components on site. Although further measurement is not necessary, a monitoring system may be operated in parallel for the lifetime of the cable in order to monitor possible aging of the installation.

TESTING

Numerous short and long term electrical and mechanical tests have to be carried out on cables and accessories in the HV range in order to meet performance requirements:

- Development tests, where aging processes at increased temperatures and voltages are to be checked for up to 2 years
- Type tests, whose requirements are defined in specifications
- Prequalification and qualification tests, to provide information about the performance of new developed cable installations under realistic field conditions (these tests involve laying cable in the soil, tunnels, or ducts with lengths up to 100 m)
- Routine tests carried out in the factory after manufacture of cable, slip-on stress cones, and joints
- Commissioning tests performed after installation in order to check the quality of the jointers' work on site

As can be seen from Fig. 5, development tests in the extrahigh voltage range require great effort. The picture in Fig. 5. shows the test of two outdoor terminals (1), the cable (2), and two back-to-back gas insulated substation (*GIS*) sealing ends (3). On the right side the heating transformers (4) can be seen. The cables are connected by a copper bar (5) between the two outdoor sealing ends (1). In the test arrangement shown the long term reliability of a 400 kV XLPE cable installation has been checked for one year at elevated temperatures and voltages.

Type testing, routine testing, and on-site testing are well covered by international standards such as IEC 60141,

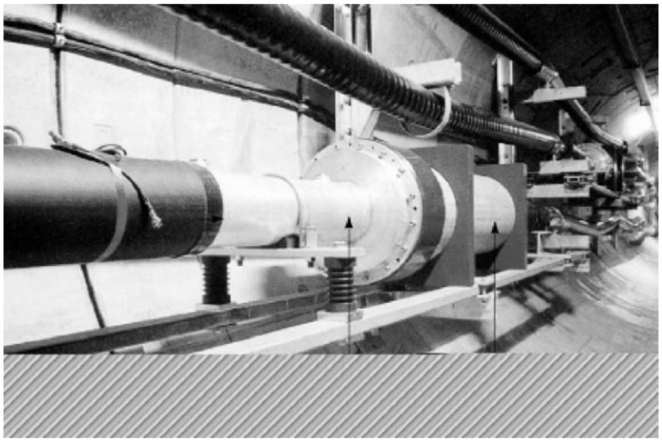

Figure 4. Single-core straight cable joint: (1) Al housing, (2) cable ends.

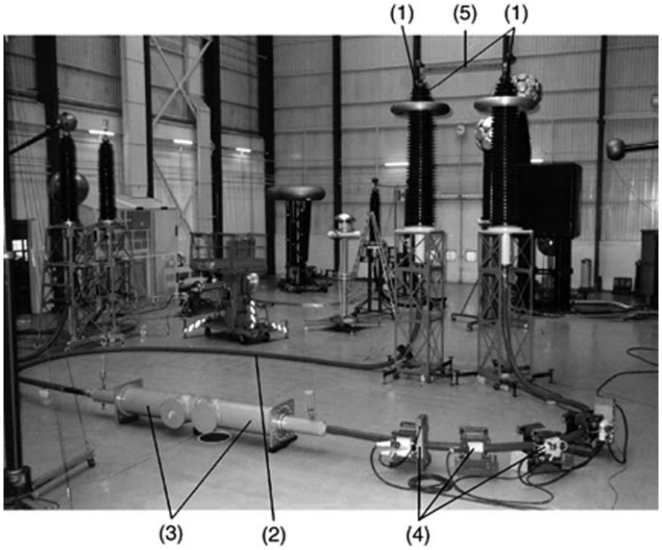

Figure 5. Long duration high voltage test of a 400 kV XLPE cable: (1) outdoor termination, (2) cable, (3) back to back GIS reality ends, (4) heating transformer, (5) copper bar.

Table 4. Typical Type Test Values for XLPE Insulated High Voltage Cables

System Voltage (kV)	Ac Test Voltage (kV)[a]	Lightning Impulse Withstand Voltage (kV)[b]
110	130	640
132	155	640
275	324	1050
400	460	1425
500	590	1550

[a] At 95° to 100°C, heating cycle voltage test, $2U_0$.
[b] At 100° to 105°C.

60840, 60287, 60228 and for North and South America AEIC-CS1-31 and AEIC-G1-7, to mention only the most relevant.

Some data for type testing are given in Table 4.

Some typical requirements for type testing of XLPE cable installations (4) are:

- The bending test is carried out in order to check the mechanical stability of the cable in bending the cable three times in both directions prior to electrical testing.
- The heating cycle voltage test with elevated voltages, typically at $2U_0$, is typically performed with 8 h of heating up to a conductor temperature of 90° to 95°C and followed by 16 h of cooling. This test has to be done for 20 days, which means 480 h.
- Partial discharge measurements are carried out with polymeric cables at $1.5U_0$ of the rated voltage.
- Measurement of the loss factor and capacitance at elevated cable temperatures up to 95°C is performed.
- An impulse voltage test with 10 positive and negative shots at BIL and 100° to 105°C has to be performed.
- Finally, an ac test at $2U_0$ or $2.5U_0$ (room temperature) checks that the cable dielectric suffered no damage during the whole test procedure.

The routine test finalizes the manufacture of cables and accessories. This test has to be done in order to ensure constant quality of cable lengths and accessories such as prefabricated slip-on stress cones and joints.

For commissioning tests of extruded cable installations, dc voltage has been found to be questionable because of the formation of undesirable space charges in the dielectric. For this reason an ac test method that uses the same frequency (50 Hz or 60 Hz) but elevated voltages is more

Figure 6. On-site voltage test of a 400 kV XLPE cable.

Table 5. Technical Data on a GIL through a Mountain

Rated voltage	420 kV
Rated impulse withstand voltage	1640 kV
Rated current	2500 A
Rated short-time current	53 kA

frequently required. A mobile testing station mounted on a truck is shown in Fig. 6. The experience with and service record of this new method are excellent.

GAS-INSULATED TRANSMISSION LINES

The application of gas-insulated transmission lines (*GILs*) yields the largest benefit if high power transmission capability (up to 3000 MVA) is needed and/or if the energy is to be transported underground over a long distance without electrical compensation. The GIL—because of the gas insulation and the large cross section of the conductor—offers the advantages of low capacitive load and low resistive losses.

For the dielectric insulation, gas mixture of N_2 and SF_6 is used (5). The conductor is held in position by epoxy resin insulators.

By allowing a reverse current flowing in the outer enclosure to act as a sheath, the electromagnetic field outside the GIL is made negligibly small. The installations can be either directly buried or installed in a tunnel or above ground, either horizontally or vertically.

History

In 1975, in the southern part of Germany, one of the first GILs was commissioned with a total tube length of about 4 km. This GIL connects two hydroturbine generators placed in a cavern in the mountain through a tunnel about 700 m long with the substation placed at top of the mountain (6). Hydrogenerated electric energy is transformed to a voltage of 400 kV and then transmitted through the tunnel at a rated current of 2500 A to the top of the mountain. See Fig. 7. and, for technical data, Table 5.

The second typical example shows gas-insulated transmission lines within a substation in Bowmanville, Canada, with a total tube length of 2.5 km. See Fig. 8. and, for technical data, Table 6. The GIL was commissioned in three stages between 1985 and 1987 and connects gas-insulated substations with overhead lines at a rated voltage of 550 kV. In this substation, a very high power rating with rated currents of up to 8000 A was required. Because of the interconnection of several 550 kV overhead lines entering the substation, rated short time currents of 100 kA must be handled by the GIL. This gives this application one of the highest current ratings in the world.

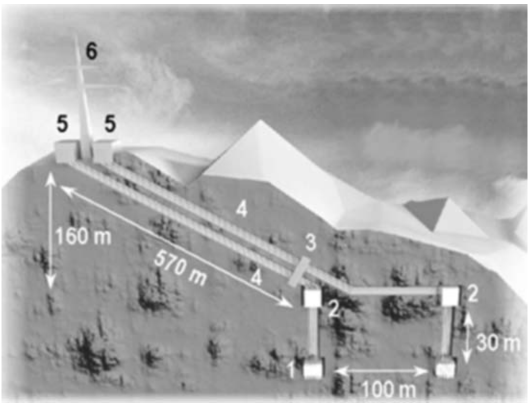

Figure 7. GIL in a tunnel through a mountain: (1) 600 MVA transformer, (2) encapsulated surge arrestors, (3) transfer switching units, (4) GIL connection, (5) open air surge arrestor, (6) overhead line.

Table 6. Technical Data on a GIL in a Substation

Rated voltage	550 kV
Rated impulse withstand voltage	1550 kV
Rated current	4000, 6300, 8000 A[a]
Rated short-time current	100 kA

[a] In different sections of the installation.

Applications

Typical applications for GILs are in urban areas to bring large amounts of electric energy underground into a city or into other load centers. The GIL can be connected directly

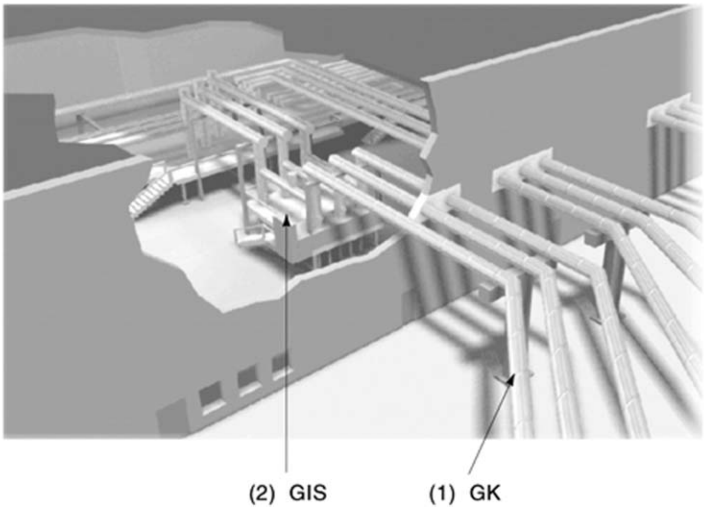

Figure 8. GIL in a substation: (1) GIL and (2) GIS.

Table 7. Performance Range of GIL (9)

Rated voltage	Up to 800 kV
Rated normal current I_N	2000–4600 A
Transmission capacity	1000–4000 MVA
Short circuit current	63 kA for 0.5 s
Impulse withstand voltage	Up to 2100 kV
Overload capacity (typical)	2.2 I_N for 10 min 1.9 I_N for 1 h
Capacitance	≈60 nF/km
Typical length	1–100 km
Gas mixture $SF_6 : N_2$	10% : 90% to 25% : 75%
Laying options	Directly buried In tunnel On gallery

to an overhead line that carries the energy from the generation point into the vicinity of a metropolitan area. Here the GIL goes underground into the urban or load center with the same energy transmission capability as the overhead line (7).

In areas where the expense for overhead lines increases significantly, the GIL can be the solution. Because the GIL can be laid underground, there is no influence of ice load or dust on the electrical insulation, as is the case with overhead lines (8).

The performance range of the GIL is given in Table 7.

With a high power transmission capability of 1000 MVA to 4000 MVA and a low capacitive load of approximately 60 nF/km, the GIL is the only technical system available today capable of transmitting the total power of an overhead line underground over a long distance. This can be done as a direct buried system or in a tunnel.

Construction

For the GIL, two different basic construction types are known: three-phase and single-phase encapsulation. For three-phase encapsulation, three conductors are within one enclosure of the same gas compartment. Single-phase systems use one enclosure for each conductor. A typical arrangement of a single-phase GIL in a tunnel is shown in Fig. 9.

Figure 9. View into the tunnel with a double system of single-phase GIL.

Basic Elements. To build a gas-insulated transmission line, three basic elements are needed: straight sections, elbows, and connection housings.

One straight GIL segment is shown schematically in Fig. 10. The single phase encapsulated GIL is made using aluminum pipes. Within the outer enclosure (1) the conductor (2) is centered by support insulators (4). These support insulators can move in an axial direction so that the extension due to the thermal heating of the system can be adjusted for. The conductor is able to move in a sliding contact system (5a) and (5b). The nongastight insulator (3) is also a conductor fixture point and fixes the conductor with respect to the enclosure (1).

A GIL for long distances is separated into gas compartments of approximately 1 km length. The gas compart-

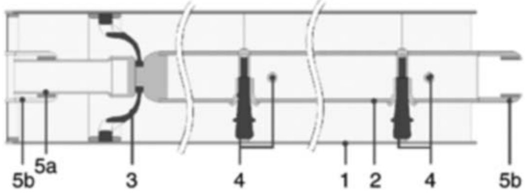

Figure 10. Straight segment of GIL: (1) enclosure, (2) inner conductor, (3) conical insulator, (4) support insulator, (5a) male sliding contact, (5b) female sliding contact.

ments are separated by gastight conical insulators. Each gas compartment is separated into sections of approximately 100 m with nongastight insulators, which fix the conductor to the enclosure. In between the fixing points, the conductor is able to move in the axial direction to take care of thermal expansion.

The gas compartments are connected by the connection housings, which are also used to connect HV test bushings.

In Fig. 11. such a connection housing is shown as a computer graphic. The main elements are the gastight insulators (4), which form a gas compartment in the connection housing (1) and thus in the straight GIL segment connected to it. The conductor (2) can be separated at the center to connect the HV test equipment. The sliding contact (3) covers the thermal expansion of the conductor during service.

The main task of the disconnector housing is to separate the gas compartments and provide a connecting point for the on-site commissioning test. Further on, the decentralized monitoring units are connected to this housing.

Elbow elements allow changes of direction, if the GIL cannot follow the route by simple bending of the straight tubes.

Orbital Welding. To ensure high welding quality, the welding process must be highly automated by using an orbital welding machine; this gives high productivity with uniform quality. The time taken to complete the welding is directly related to the speed of laying. The quality of the welding process is controlled by an integrated computerized quality assurance system. Quality criteria are porosity, surface roughness, and tube ovalization. Figure 12 shows the orbital welding machine, with the welding head, where the arc is initiated and the drive, which is guided by a ring.

Figure 12. Orbital welding machine.

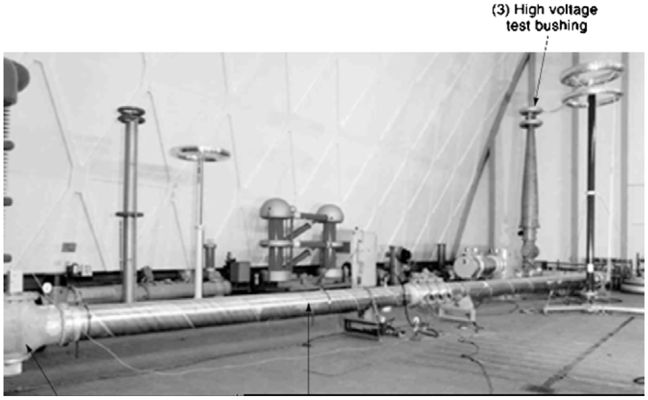

Figure 13. Test setup: (1) disconnector housing, (2) straight segment of GIL, and (3) high voltage test bushing.

Test Setup

In Fig. 13 a test setup is shown to evaluate the electrical and mechanical properties of such a system. The setup includes all basic elements and is approximately 30 m long. The ratings for the test voltages have been applied for power frequency, switching, and lightning impulse, and the results have proven the reliability of the system (4,10,11).

LAYING DIRECTLY BURIED

For the cross country application outside of dense populated areas the best way to lay a GIL is to bury it directly into the ground. A typical use is to connect a city to a high

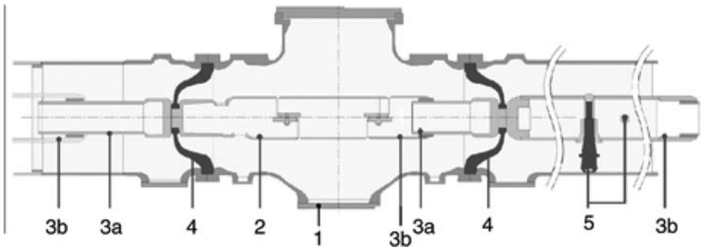

Figure 11. Disconnector housing to connect the high voltage bushing, including gastight insulators: (1) enclosure, (2) inner conductor, (3a) male sliding contact, (3b) female sliding contact, (4) gastight insulator, (5) support insulator.

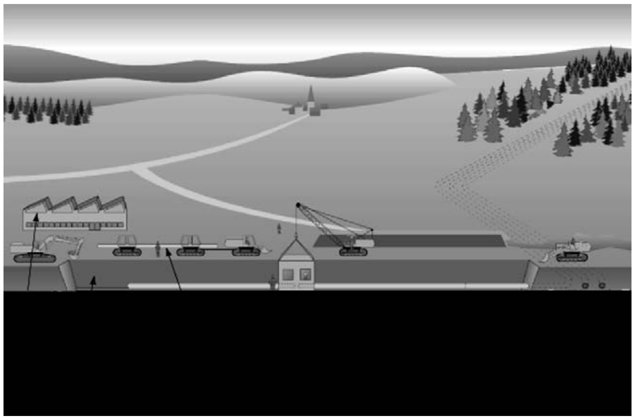

Figure 14. Laying technique of direct buried GIL.

voltage transmission line or a power plant. The different landscapes need in detail different technical solutions (12). In this chapter the basic technique of laying will be explained, which is shown in Fig. 14.

For the single phase encapsulated GILs a trench (1) will be built so that a minimum of soil covering of 1.5 m is guaranteed. In distances of approximately 1 km concrete underground shafts are made to take the disconnect housing for the separation of the single gas compartments. These concrete underground constructions are integrated into the landscape.

For directional changes, which cannot be followed by the elastic bending of the GIL, housings are used which are directly buried in the ground. The trench follows the landscape with a minimum radius of 400 m to 500 m in vertical and horizontal direction.

The laying process is shown in Fig. 14. To connect the system segments (straight GIL segment or elbows) during the laying process a tent for jointing (2) the pipes is used. The tent makes sure that the conditions of cleanliness for high voltage systems are fulfilled. Close to the trench a preassembly side (3) is erected. On this preassembly side GIL segments of up to 100 m length are getting preassembled. Special trailers (4) bring the preassembled segments to the trench. The lengths of the preassembled segments very much depend on the on site condition for transportation and local obstacles.

After the GIL is jointed, welded and protected against corrosion the backfill of the trench starts. Basically, the soil which has been dug out will be backfilled. Only under certain thermal conditions and direct at the GIL is a special backfill material used to increase the heat transfer conductivity. The GIL is fixed in the ground by friction caused by the weight of the soil above. The concrete underground constructions are accessible for high voltage testing and for monitoring devices as temperature, gas pressure or partial discharge measurements.

Corrosion protection uses passive and active systems. Active corrosion protection system uses protection potential of an electrode (e.g., zinc anode) or the protection potential can be made by a dc current. The GIL is a solid grounded system, therefore it is necessary to decouple the grounding and the corrosion protection, which can be done by polarity cells or diodes. Passive corrosion protection is made by polypropylene (*PP*) or polyethylene (*PE*) coating of the aluminum pipe, similar to the outer polyethylene sheath shown in Fig. 1 (10).

After commissioning, the site can be used for agriculture. Huge trees with large roots should not be located directly above the GIL.

LAYING IN A TUNNEL

In dense populated areas like city centers sometimes tunnels are used to lay a cable or GIL because it is the lowest cost, effective solution. The higher the density of buildings, streets, industrial, public, and private buildings with obstacles like rivers, subways, and all the various types of underground cables for communication or power distribution and underground pipes for waste water, the higher the cost of a directly buried system. The accuracy and drilling speed of tunnel drilling technologies improved during the last few years. This brought lower prices for drilled tunnels to the user. The application of electric power transmission systems in a tunnel has its most advantages for extra high voltage systems (13) of 420 kV in Europe and 550 kV in America and Asia.

In a tunnel of 3 m diameter, power ratings of up to 1000 MVA for a cable and 2000 MVA for GIL per system are possible. This gives the opportunity to deliver electric energy into the centers of big cities and metropolitan areas and is an alternative solution to the today widely used ring system, where an extra high voltage ring of overhead lines is laid around cities. The energy from that ring is brought into the center at lower high voltage levels (about 100 kV). This increases the cross section of the conductor and the use of material (copper).

Two drilling methods are used today: directional drilling and accessible tunnels.

Directional Drilling

Directional drilling, also called microtunnel, is used usually to bypass obstacles like streets, rivers, railroads, which cannot be derouted during the time of the GIL erection. Typical lengths for such microtunnels are some hundred meters, with possible lengths up to 1 km. The diameter of a microtunnel is between 0.5 m and 1.0 m and single phase cables or GIL systems are pulled in.

Accessible Tunnel

Accessible tunnels can be built for several kilometer lengths and with diameters of several meters. To be accessible the minimum diameter of the tunnel is about 3 m. In Fig. 15 the cross section of such a tunnel is shown with two GIL systems. The tunnel can take two 3 phase cables or GIL systems. They are fixed on support structures in the tunnel.

These tunnels are usually built at a large depth of 20 m to 40 m under ground level. The advantage is that the shortest way can be choosen, which saves costs on transmission length (13).

Figure 15. Cross section of an accessible tunnel with two 3 phase GIL systems.

GIL USE IN TRAFFIC TUNNELS

The combination of traffic tunnel and electrical transmission system is today available with GIL.

Traffic tunnels are large investments to solve traffic congestion of railroad and road traffic, mainly needed in large metropolitan areas. These so called MegaCities of today like New York, Paris, London, or Tokyo and those of the near future like Shanghai, Mumbai, Sao Paulo, or Laos need also strong electrical energy supply into their centers. Both tasks can be managed by a combined use of tunnels for traffic and electricity.

One basic requirement—the need of safety—when such combinations of traffic and electric power transmission is chosen, is fulfilled by Gas Insulated Transmission Lines (GIL). The GIL offers a safe surrounding even if an internal failure occurs. The GIL, because of its solid metallic encapsulation does meet this requirement in normal operation.

The metallic enclosure is strong enough to withstand an internal arc of 63 kA and the pressure increase of the N_2/SF_6 gas mixture is low because of the large gas compartments of the GIL with lengths up to 1 km (14).

The investment for such long distance GIL needs systems which are reliable and long living. The GIL has proven high reliability with more than 25 years of service worldwide with this technology. No major failure of any installed GIL is reported until today of the about 200 km of installed length for voltages up to 550 kV.

Long living product: The GIL is filled with a non-ageing insulating gas while solid insulated cables do have thermal and electrical ageing. The experience of GIL installed world-wide is that, once they are in operation no maintenance is needed and no limitation of life time is seen today.

Gas mixture with N_2/SF_6 is a well proven insulation gas in high voltage systems in operation since more than 30 years. The GIL is connected by welding joints which are proven gas tight, so that no gas losses are expected and the gas filling is for life time. The handling of the gas mixture is automated in a closed cycle, so that the gas taken out of the GIL for any reason will be in compartments under high pressure and filled into the GIL for operation again.

To prove the reliability of the GIL long term tests have been carried out to simulate 50 years of life time with successful results (15–18).

Typical traffic tunnels are shown in Fig. 16 and 17.

Traffic Tunnels

The underground laying of a GIL in traffic tunnels is one alternative solution to bring high electrical energy connections into the load centres and industrial areas on the one side and to enforce the cross border connection in Europe. The crossing of the Alps with the train tunnel, the “Brenner Basis Tunnel”, is one example using the double railroad tunnel with a separate pilot tunnel as shown in Fig. 16 in the centre. The pilot tunnel of such tunnel types is usually used to explore the mountain before the two big tunnels for the trains are bored. The pilot tunnel also serves as a transportation tunnel during erection time. When the tunnel for the railroad is finished it is not used anymore, and can be used for electrical transmission of power ratings (e.g. 2000–3000 MW) with GIL.

The double track railroad tunnel on the right hand side in Fig. 16 is another possibility of railroad tunnels in the mountains with the possibility to install the GIL in the roof areas.

Railroad tunnels are usually more narrow than car and truck traffic tunnels because of the exhaust of the vehicles and the need of ventilation. This gives a limitation in available space. In a railroad tunnel temperature limits are given because of maximum allowed temperatures for the air conditioning systems and the electrical motors of the trains.

Any installation in a railroad tunnel has therefore limited value to add any heat, e. g. because of thermal transmission losses. This often limits the power transmission possibility of the GIL.

In road traffic tunnels as shown in fig. 16 and 17 the space and volume of the tunnel is much larger because of the exhaust of the traffic and the ventilation of the tunnel. This additional space can be used to insert one or two GIL systems under roof or below the street level.

The technology of tunnel boring has been further developed in the last years with the result of higher accuracy and lower erection cost. Tunnels in boring technology are used to cross water straits like Eurotunnel from France to the United Kingdom or to pass under a city like in Berlin or London.

Such tunnels do have a round shape, see fig. 17. In this round shape space is naturally available in the lower part of the tunnel. In this free space one or two GIL systems can be built in.

Railroad or street traffic tunnels are large investments and need long planning times. Financing is often a big question to solve, also the ownership and purpose of use. In this very complex project planning it is from great impor-

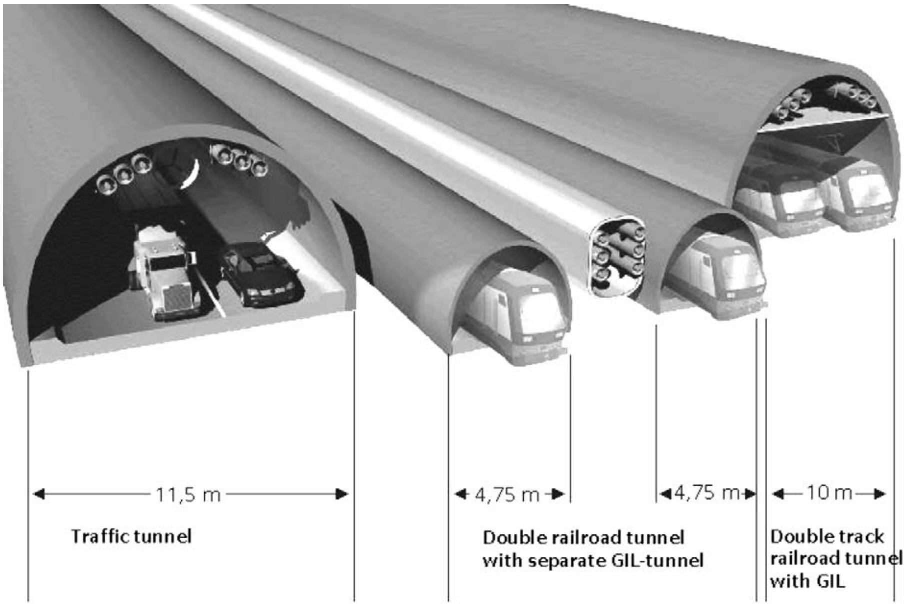

Figure 16. Railroad and traffic tunnels in mountains

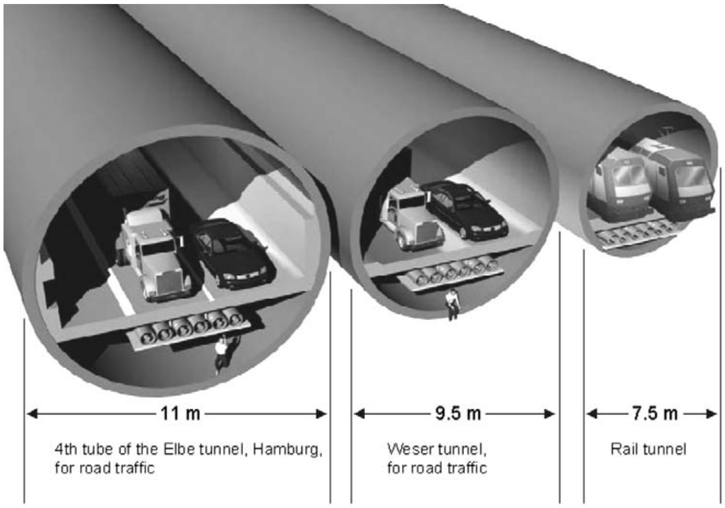

Figure 17. Railroad and traffic tunnels in boring technique

tance to be early enough to bring in the idea of combined use of tunnels for traffic and electrical power transmission.

In cases when the tunnel is used for both traffic and electricity the investment cost can be shared between the users. This helps to make projects profitable.

The early planning is needed to find the right tunnel concept which covers all requirements of the traffic tunnel and the electric power transmission. This is a fundamental decision for the design and layout of the tunnel and often cannot be changed later at all or may cause high additional cost.

Outlook Traffic Tunnel

The electrical power transmission requirements of the future are leading to high power underground transmission lines also for long distance of some tenth of kilometres. The deregulated electric energy market will bring more electric energy trade and therefore requirements for new high power transmission lines. The load increase in the large cities and metropolitan areas like New York, London, Paris, or Tokyo and new high power infeeds to guarantee reliable and safe energy supply will be required in the near future.

In the same time the street and rail traffic is increasing for the transport of persons and cargo alike. This will lead to new traffic tunnels crossing country borders and leading into or crossing large cities or metropolitan areas.

The GIL offers now an opportunity to combine traffic with electrical energy transmission in the same tunnel system and is therefore one alternative. The very good experiences with GIL over the last 25 years in high voltage transmission, its high reliability and its very long life time with almost no ageing make the GIL to the solution of energy transmission of today.

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