Electra 306
Reference Paper

Overhead transmission lines, gas insulated lines and underground cables

By M. MARELLI, P. ARGAUT, SC B1, H. LUGSCHITZ, SC B2, K. KAWAKITA, SC B3

Introduction

There is a considerable amount of highly technical information, specifications and guides available on the transmission of bulk electrical power from one area to another. This information is available from bodies such as CIGRE, IEC (International Electrotechnical Commission), and many National-based organizations. There is, however, very little information that would explain the fundamentals of the technologies in such a manner that it could be understood by a non-technical person or a person not involved on a day-to-day basis in that industry. This paper will attempt to fulfil that need by providing basic information in hopefully a readily understandable manner.

This paper refers to transmission lines exceeding 170kV alternating current (AC). Direct current (DC) connections and subsea cables are not a part of the scope of this paper (for those, other criteria apply to compare).

Technical Basics

Some of the fundamentals of power transmission are the voltage and current levels used to transmit the power from one area to another. Roughly speaking the voltage multiplied by the current is equal to the power. If one thinks of electricity in terms of water flow then voltage is like pressure i.e. it drives the current through the conductor in the same that pressure drives water through a pipe. Current is the flow of electricity through the conductor.

In AC transmission the power is transmitted utilizing a three phase system with three metallic conductors; the size of the conductors govern their thermal capability to carry current i.e. the larger the conductor the more current it can carry. The conductors must be insulated from the ground and from each other in order to be able to withstand the voltage applied; again, the more insulation the higher the voltage that can be used in the transmission circuit.

The three conductors may be assembled in an overhead line circuit (OHL), an underground cable circuit (UGC) or a gas insulated lines (GIL) circuit. Each one will be described below.

One basic technical aspect to be considered is related to routing a transmission line, including:

- **route availability**: it must be possible to construct the line
- **urbanisation:** if the line is to be routed through an urban area, then future developments may have an impact on the route and design of the line.
- **route topography**: if the terrain is very uneven or hilly, the technical challenges and costs increase

OHL: Overhead Lines

An overhead line circuit is typically composed of lattice steel towers which support the three conductors that make up the circuit. In some lines, tubular poles (pylons) are used instead of lattice structures. The conductors are insulated from the structures by means of insulators, which are made of toughened glass, porcelain or of composite materials.

Typical examples of OHL designs in current use are shown in several Cigre technical brochures and the Cigre Green Book “Overhead Lines”.
Depending on voltage and terrain, towers are typically 200 - 500m apart from each other.
Many OHL designs are fitted with one or several earth wires at the top of the tower. These earth wires have two functions, firstly to protect the conductors from a lightning strike which might cause an outage and secondly in the event of a fault: the fault current will be mainly contained within the conductor/ earth wire loop and returned to earth. Earth wires are often fitted with fiber optic elements for communication purpose.

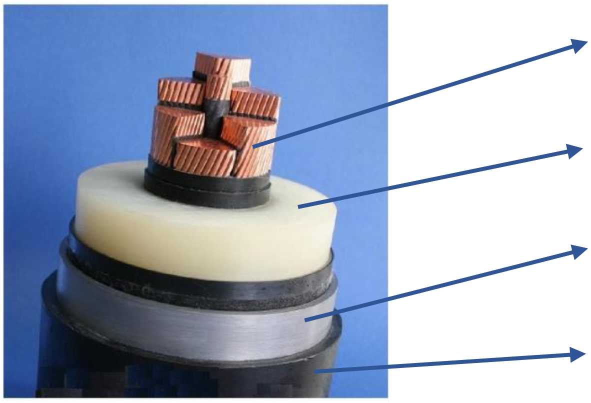
It should be noted that in many cases OHLs have two electric circuits or more on the same tower. Each circuit may have 1-4 conductors in a bundle for each phase (and even more at Ultra High Voltage Lines). These OHLs can carry many times the power of a single circuit line with single conductors.

The design of an OHL depends on many factors including:

- **conductor size**: the size of the conductor is dependent on the current to be carried. Of course, the size of the conductor also has an impact on the weight the tower must support – currently the standard maximum conductor size used is about 800 mm^2.
- **ground clearance**: the conductor must have a safe clearance from the ground and any buildings that may be located underneath it i.e. there must be no possibility of flashover from the conductors to the ground, persons or obstacles.
- **impact of weather**: very strong winds may exert considerable mechanical loadings on the conductors and the towers; in addition, large ice loadings on conductors can impact on the towers. Of course, the worst loading is the potential combination of wind and ice. The lines are designed for such loadings.
- **electrostatic/charging effects**: the impacts on metal structures in the proximity of the OHL are eliminated by earthing of such metallic facilities. In some countries, national regulations may apply in addition to ICNIRP values (International Committee for Non-Ionising Radiation Protection).
- **magnetic effects**: The current in the conductor produces a magnetic field, and the voltage produces an electric field, both must be considered during the design of the line. There are non-binding, but recommended limit values provided by ICNIRP 1998/2010. The ICNIRP recommendation must be considered taking into account of the costs and benefits and where the time of exposure is significant.

UGC: Underground Cables

An underground cable circuit is composed of three power cables (three phases) and normally one communication cable installed in the ground to form one electric circuit. A typical design of a power cable is shown in figure below:



Conductor - made from Copper or Aluminium

Insulation – typically Cross-linked polyethylene (XLPE)

Screen - copper wires, aluminium foil or lead sheath (acting as water barrier when needed)

Outer covering - of PVC or PE (polyethylene)

If the power to be transmitted is beyond the capability of one circuit, more parallel cable circuits (or more cables per phase) must be installed. The larger the conductor the more current it can carry and the thicker the insulation the more voltage it can withstand. The cables are manufactured in highly specialised factories and they are normally delivered in drum lengths varying from 500 - 1000m. In some cases, delivery cuts can be longer (2000m and above).

Such a circuit of 10km route length with drums of 1000m would have 10x3 i.e. 30 drums in total. It would require 27 joints to join the cables together and there would be 3 terminations or sealing ends at each end (Substation, Transition Compound or Equipment installed on towers).

The cables are typically installed in one of the following arrangements:

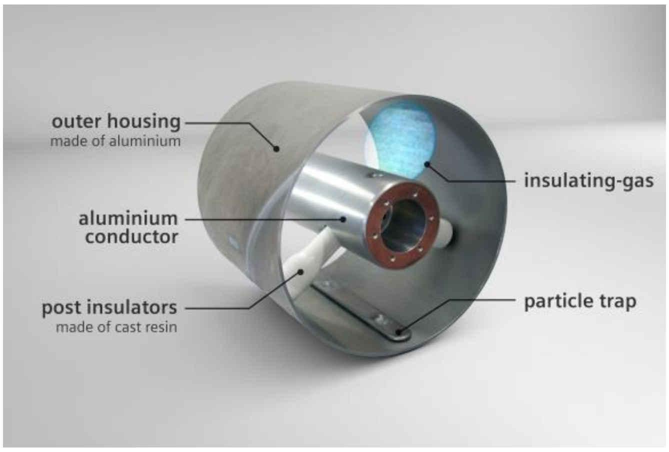
- directly in the ground (trench)
- in ducts installed in the ground
- in concrete troughs
- in a tunnel
- in a pipe or pipes drilled into the ground to pass under some obstacle or encumbrance
- on a cable tray attached to a bridge

The design of an underground cable circuit depends on many factors including:

- **conductor size**: the size of the conductor is dependent on the current to be carried and the increase of temperature (due to the current flowing through the cable) of the surroundings as allowed by regulations. Of course, the size of the conductor also has an impact on the weight and size of the cable drum being delivered – currently the maximum standard conductor size used is 2500mm^2.
- **soil thermal conductivity**: the conductor size has an impact on the ability of the cable to dissipate the heat, which is created by the current flowing through the cable when it is delivering power. In the case of a cable installed in the ground this heat must travel through the soil surrounding the cable. Therefore the ground thermal conductivity and temperature also have an impact on the cable sizing.
- **presence and possible impact** of other services in the soil which may conflict with the cable route either now or in the future (e.g. other cables, heating or cooling pipes, water supply and waste water).
- **urbanisation**: if the cable is to be routed through an urban area future building or road developments may impact on the circuit
- **possibility of flooding**: flooding may undermine the installed cable circuit.
- **cable pulling**: the route and drum lengths and route topography must be such that the cables can be pulled into the selected installation arrangement i.e. trench, duct, tunnel, etc.
- **electrostatic effects**: underground cables have no electrostatic effects initiated by the cable as the electric field is contained inside the cable and shielded by the screen. Electrostatic effect may come from equipment installed above ground (terminations)
- **magnetic effects**: the current sets up a magnetic field which must be considered during the design of the underground circuit. As for OHL, the ICNIRP recommendation must be considered taking into account of the costs and benefits and where the time of exposure is significant. It should be noted that underground cables have higher magnetic fields than overhead lines at close distance, but the fields fall off more rapidly with distance.

GIL: Gas Insulated Lines

GIL are generally composed of three parallel aluminium tubes for one three phase circuit. The aluminium tubes are in sections (typically 12-18 m long and 500 mm enclosure diameter). They are bolted together with flanges (sealed with O- rings) or welded together on site to be gas tight (automated welding process including 100% weld quality control by ultra-sonic test). Inside each enclosure pipe a smaller cylindrical aluminium conductor pipe is supported by cast resin post insulators. The GIL enclosure pipe is filled with a gas mixture of 20% sulphur hexafluoride (SF_6) and 80% nitrogen at 0.8 MPa pressure to reduce the greenhouse impact from SF_6.



GIL may have approximately the same transmission capacity as an overhead line and about double the capacity of a XLPE cable system, depending on actual situations. GIL systems are mostly used to EHV voltages (>245 kV) up to 1000 kV. GIL installation is adapted to pipe line laying technologies and is carried out at local assembly and installation on site. All parts are delivered to the construction site and the laying follows a continuing process. The cost efficiency for this on-site laying process increases with the length of the transmission line to be above 1 km. For shorter length the factory orientated laying process may be more cost effective. This on-site laying process has been verified in many projects world-wide and offers a reliable and safe installation of the GIL. When the outer diameter of the enclosure is enlarged to about 750 mm also a clean air solution of GIL can be offered using Nitrogen and Oxygen only with a GWP (Global Warming Potential) of zero.

GIL are typically installed above ground, in tunnels (phases in vertical or horizontal arrangement) or in underground galleries. Direct buried installations are uncommon today, as it requires additional coatings for passive corrosion protection and cathode corrosion. Experiences with GIL worldwide is constantly increasing with ever larger project sizes (10-20 km route length), higher rated voltages (mainly 400, 500 and 1000 kV) and current ratings (3000, 4000 and 5000 A). The longest installation is the Tokai Line of Chubu Electric in Japan with two three phase systems of 275 kV and 5000 A of 3.3 km transmission route length in a tunnel.

The design of a GIL circuit depends on many special factors including:

- **presence and possible impact** of other services which may conflict with the GIL route either now or in the future (e.g. cables, heating or cooling pipes, water supply and waste water).
- **route considerations** the given bending radius can be a limiting factor for a route.
- **urbanisation**: if the line is to be routed through an urban area, future building or road development may impact on the circuit, that’s why separate tunnels for electric transmission lines may be the best solution.
- **Electromagnetic effects**: GIL circuits have negligible electromagnetic effects as the electric field is earthed through the metallic enclosure. The magnetic field is mostly superposed by the induced current into the solid grounded enclosure pipe.

Advantages and disadvantages of various technologies

It is very difficult to compare the three technologies as each circuit installation is different with respect to location, importance of the circuit, reputational and financial impact if there is an outage, method of installation, operational and maintenance aspects, environmental impact, planning/licensing, etc. In view of this no general conclusions can be drawn, and each installation must be treated on a case by case basis. For the comparison of GIL and UGC see CIGRE TB 639.

In Table 1 we endeavor to compare the three technologies under the listed heading:

Table 1 - Comparison of Technologies

	UGC	**OHL**	**GIL**
Investment Costs	High	Not so high	High
	There are no general rules for the comparison, as the cost of each technology will depend on how that technology deals with the specific factors that apply on each specific project		
Installation Difficulty	Yes	No	Yes
Experience	Yes	Yes	Yes
Mature Technology	Yes	Yes	Yes, for short lengths above ground
Competitive Tendering	Yes	Yes	Yes, some cases with short length
Reliability	Yes	Yes	Yes
Repair Time	High (*)	Low	High (*)
Lifetime	>40 years	>80 years	>50 years
Installation time	Depending on local site conditions and requirements	Faster than UGC or GIL	Depending on local site conditions and requirements
(*) highly dependent on the availability of spare parts and thus on maintenance policy			

The operational and environmental aspects are considered in sections 4 and 5 below.
Each of the above factors needs to be considered specifically for the project being investigated taking the potential installation methodologies into account, which is for UGC and GIL e.g. direct burial, ducting, horizontal directional drilling, tunnelling. Lifetime-costs may give other factors than investment costs. They also depend strongly on the project and must be calculated case by case.
In order to rank the different possibilities, a scoring system could be developed for each of the above factors. Notwithstanding any scoring system experience and mature technology will always be important in any project as the Line owner will not wish to use unproven technology, as that would constitute a high and unacceptable risk.

Operational Aspects

In the table below the various technologies are compared from an operational point of view.

Table 2 - Comparison of Operational Issues

	UGC	**OHL**	**GIL**
Length limitation	Yes (60-100 km depending on voltage)	No	No theoretical technical limitation
Need for electric compensation	Yes, if longer than above	No	No
Extreme weather effects e.g. mechanical overloading due to ice/snow/wind	No	Possible	No
Can be re-energized if temporary fault	No, as faults that occur are not temporary	Yes	Yes, auto reclosure is possible
	Experience exist of reclosure for combined OHL-UGC lines		
Ease of fault finding	No	Yes	Yes
Ease of fault repair	No	Yes	No
High Level of expertise required for repair	Yes	No	Yes
Difficult to store repair material	No	No	No
Limited shelf life time of repair material	Yes	No	Yes
Outage time required after fault	Long	Short	Long
Haul road required for access	Yes, if installed in cross country	No	No

Each of the above factors needs to be considered specifically for the project being investigated taking the potential installation methodologies into account e.g. direct burial, ducting, horizontal directional drilling, tunnelling, etc.

Due to the very different electrical parameters of the UGC, the application of UGC introduces a series of technical challenges that must be addressed during planning, design and operation stages of the UGC system. In AC networks there normally is an offset between the current and voltage. This is due to the different components and loads in the network. The current will fill up the conductor to a certain degree, but only a part of the current can be used as “real power” because of this offset. The rest is “reactive power”. This reactive power shall be compensated to reduce the losses in the network and to control the voltage.

The exchange of reactive power between the UGC and the power system is significantly higher compared to an equivalent OHL. This reactive power must be compensated and therefore a number of additional components are introduced. This adds complexity to the system both in term of operation and maintenance.

Another complication that must be addressed is the shift in system resonance frequencies introduced by the application of UGC. Experience from several countries shows that amplification of background harmonics (electrical noise) occurs due to interaction between the UGC and the power system. Furthermore, the risk of temporary overvoltages is also increased for the same reasons. Both diminished power quality (due to electrical noise) and temporary overvoltages are serious challenges for which mitigation methods are expensive. A further complication is that study and design for the mentioned issues are still comparable immature and little practical experience exist worldwide. Hence, it can be difficult to quantify the risk to the system when a longer UGC is added.

The capacitive load of GIL is much lower (factor 4-5) than for solid insulated cables. Therefore, a phase angle compensation is only needed with GIL transmission length of 100-200 km length. This is depending on the network conditions and needs to be calculated. In principle the GIL can be operated like an OHL including the auto-reclosure function for short time interruption without any danger to the surrounding.

Environmental Issues

In the table below the various technologies are compared from an environmental impact point-of-view.

Table 3 - Comparison of Environmental Issues

	UGC	**OHL**	**GIL**
Landscape and visual	Maybe, if going across open landscape and need construction access roads	Yes	Limited impact, as the construction site for GIL can be kept short (some 100 m)
Electric Field Effects (voltage)	No	Yes	No
Magnetic Field Effect (current)	Yes, limited	Yes	No, because of induced return current.
Noise effects	Yes during construction, No during operation	Yes during construction, Can be during operation at certain weather conditions (corona)	Yes during construction, No during operation
Restricted use of land	If UGC going across fields, the area over the cable may be used for ordinary crops but not for trees. No excavation or deep ploughing is allowed. Restrictions depends on local regulations.	Limited to tower footing area and possible restrictions regarding trees and buildings under the conductors	If GIL going across fields restrictions similar to those for UGC are expected – dependent on installation method
Geology and Soils	Possible impact during construction	Possible Limited impact at tower areas	Possible impact during construction
Water Resources	Possible impact during construction	Possible Limited impact at tower areas	Possible impact during construction
Ecology and Nature	Possible impact during construction	Possible Limited impact at tower areas	Possible impact during construction
Cultural Resources	Possible impact on archeological important areas	Possible impact on archeological important areas at tower areas	Possible impact on archeological important areas
Recreation and Tourism.	Limited impact	Maybe some impact depending on location	Limited impact
Air Quality	Possible impact during construction	Possible impact during construction	Possible impact during construction
Traffic and Noise	Possible impact during construction	Possible impact during construction	Possible impact during construction
Requirement for dumping material off site	Maybe, during construction	Limited	Maybe during construction
Acceptance by landowners	Yes	Limited acceptance	Yes
Acceptance by public	Yes	Limited acceptance	Yes

Behaviour under large disturbances

The following table compares the technologies when subject to large disturbances:

Table 4 - Comparison of behaviour under large disturbances

Heading	**UGC**	**OHL**	**GIL**
Earthquake	Major damage can occur, but flexible mitigation methods can limit damage.	Limited damage to structures can occur.	Major damage can occur, but flexible designs important.
Tsunami	Damage to exposed ends only.	Major damage.	Damage to exposed ends only.
Storms, Hurricanes, Tornadoes, Typhoons etc.	Minimum damage, only to exposed ends.	Extensive damage to lines, if not designed for such events. Falling and blown down trees will be an issue.	Minimum damage, only to exposed ends.
Flood	No damage except in wash-out areas. De-energise circuit for safety reasons.	Structures can be taken out in wash-out areas, but otherwise minimum damage.	No damage except in wash-out areas. De-energise circuit for safety reasons.
Wild Fire and Bushfire	Minimum damage to cable route, damage to exposed ends. Burial depth important.	Extensive damage during heavy fires	Minimum damage to cable route, damage to exposed ends. Burial depth important.
Landslide	Scouring damage only. Otherwise no damage.	Damage to concerned structures	Scouring damage only. Otherwise no damage

New Technologies

OHL, UGC and GIL continue to evolve with improvements in the manufacturing and in the installation equipment and technologies.

As far as the technology aspect is concerned for OHL, the adoption of composite insulators has been widely adopted. In addition, the use of high temperature conductors and real-time rating applications has become standard use.

For UGC there have been some developments in polymeric materials for insulation other than the currently used XLPE, but it is not yet clear when they will become commercially used. In addition, sensors are often embedded in UGC thus improving the use of real time monitoring and management systems.

There is little further development in the GIL technology, except maybe the routes can become longer. Insulating gases others than N_2 / SF_6 gas mixtures are under development for clean air (N_2 / O_2).

Better use of existing lines

One of the areas of interest is about the “better use of existing lines” i.e. the possibility to get more power through the existing lines as this might replace or postpone the need for a new development.

In the case of existing OHL it is possible to replace existing conductors with high temperature conductors or to use real time rating applications or to increase the voltage. Existing AC OHL can be converted to DC, if the design of the line allows this. A remarkable increase of transport capacity can be achieved.

In the case of both UGC and GIL the preferred method to increase the power capacity on existing lines consists in the possible use of real time rating applications and the mitigation of hot spots. For buried systems (typically for UGC) this is associated with the longer thermal transients that may allow for cables overloads.

Conclusions

The fundamentals of UGC, OHL and GIL technologies have been outlined in Section 2. It is very difficult to compare the three technologies as each installation is different with respect to location, importance of the circuit, costs, reputational and financial impact if there is an outage, method of installation, operational and maintenance aspects, environmental impact, planning/licensing, lifetime, etc. In view of this no general conclusions can be drawn and each installation must be treated on a case by case basis using the headings outlined in Sections 3, 4 and 5.

In order to rank the different development possibilities a scoring system could be used for each of the headings. Notwithstanding any scoring system, some headings will always be important in any project as the Project Engineer will not wish to propose an installation that would be unacceptable to the planners or to proceed with a development that may appear too costly or where the technology is not suitable for the proposed end-use.

Literature and Glossary

CIGRE published lot of documents and Technical Brochures (TB) that can help to further understand the technologies available for power transmission. Most relevant are:

TB 194: Construction, laying and installation techniques for extruded and SCFF cable systems.
TB 218: GAS INSULATED TRANSMISSION LINES (GIL)
TB 250: Technical and Environmental issues regarding the integration of a new HV underground cable system in the network.
TB 351 APPLICATION OF LONG HIGH CAPACITY GAS-INSULATED LINES IN STRUCTURES
TB 498: Guide for application of direct Real-Time monitoring systems
TB 583: Guide to the conversion of existing AC lines to DC operation
TB 601: Guide for thermal rating calculations of overhead lines
TB 606: Upgrading and uprating of existing cable systems.
TB 639: Factors for investment decision GIL vs Cables for AC transmission.
TB 680: Implementation of Long AC HV and EHV cable systems.
TB 695: Experience with the mechanical performance of non-conventional conductors
TB 748: Environmental issues of high voltage transmission lines in urban and rural areas.
TB 756: Thermal monitoring of cable circuits and grid operator’s use of dynamic rating systems.
CIGRE Green Book “Overhead Lines”
CIGRE Green Book “Substations”

The following acronyms are used in the text:

AC	Alternating Current
DC	Direct Current
EHV	Extra High Voltage
GIL	Gas Insulated Line
GWP	Global Warming Potential
ICNIRP	International Committee for Non-Ionizing Radiation Protection
OHL	Overhead Line
PE	Polyethylene, insulating material
PVC	Polyvinyl Chloride, insulating material
UGC	Underground Cable
XLPE	Cross-linked Polyethylene, insulating material