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3.

Technical Aspects

Comparing high voltage overhead and underground transmission infrastructure (up to 500 kV)

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Abbreviations and Acronyms

Abbreviation	Description
AC	Alternating Current
ACSR	Aluminium conductor steel-reinforced cable (or conductor)
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
AER	Australian Energy Regulator
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AVP	AEMO Victorian Planning
CBA	Cost Benefit Analysis
CIGRE	International Council on Large Energy Systems
DC	Direct Current
EHV	Extra High Voltage—consensus for AC Transmission lines is 345kV and above
EIS	Environmental Impact Assessment
EIR	Environmental Impact Review
EIS	Environmental Impact Statement
ELF	Extremely low frequency
EMF	Electromagnetic Fields
ENA	Electricity Networks Australia
EPR	Ethylene propylene cable
EPRI	Electrical Power Research Institute
GIL	Gas Insulated Line
GC	Gas cable
HDD	Horizontal Directional Drilling
HPOF	High-pressure oil-filled cable

Abbreviation	Description
HTLS	High Temperature Low Sag Conductors
HV	High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
ICNIRP	International Commission on Non-Ionizing Radiation Protection
ISP	AEMO's Integrated System Plan
NEM	National Electricity Market
OH	Overhead
OHTL	Overhead transmission line
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
REZ	Renewable Energy Zone
RIT-T	Regulatory Investment Test—Transmission
ROW	Right of Way (e.g. easement)
SCOF	Self-contained oil-filled cable
SLO	Social Licence to Operate
UG	Underground
UGC	Underground cable
UGTL	Underground transmission line
XLPE	Cross-linked polyethylene

Glossary

Term	Description
Impedance	The impedance in an AC electrical circuit or transmission line are a combination of characteristics which oppose current flow and result in voltage drop or rise and losses in the line. Impedance comprises of two components a) resistive, and b) reactive. The reactive component is a combination of inductance and capacitance.
micro-Teslas (µT)	A measurement unit for magnetic field strength (1µT = 10mG)
milli Gauss (mG)	A measurement unit for magnetic field strength (1µT = 10mG)
Right of Way	The general term used for a corridor secured for a transmission line. An easement provided a legal right of way on a property which may be privately or publicly owned. Transmission lines may also be installed on wider public road corridors.
Trefoil	Trefoil refers to a method of laying and arranging 3 single core cables in a triangular formation to form a 3-phase circuit.

1.

Introduction

This study aims to investigate the benefits and trade-offs between overhead and underground transmission line infrastructure, specifically focusing on issues associated with undergrounding new transmission infrastructure. It seeks to establish a clear and consistent approach to the evaluation of overhead lines and underground cable transmission, including the consideration of community concerns around the need for new transmission infrastructure to connect large renewable energy generation projects. It does this through systematic reviews of the literature as well as incorporating experiences of Transmission Network Service Providers (TNSPs) in Australia and overseas. The study has a particular focus on 500kV infrastructure which is expected to be the system voltage for high-capacity transmission lines in Australia going forward.

Historically, transmission networks in Australia developed from the need to transfer large amounts of power from large coal fired power stations, typically co-located near coal reserves, over long distances to major cities and industrial load centres. In contrast, the proposed large scale renewable generation facilities, mainly solar and wind farms, require greater land areas and are largely being located in greenfield areas with little or no existing transmission network infrastructure. These new developments are naturally creating community interest and concerns around a range of potential impacts, including but not limited to: visual amenity; environment; Traditional Owner lands; agricultural land use; and social licence to operate concerns. This has led to questions surrounding when it is appropriate to underground transmission infrastructure and the likely implications of doing so.

This chapter focuses on the technical aspects of overhead and underground transmission lines. To ensure the most up to date and objective information was used to form the basis of any comparisons, the research included both systematic literature reviews of published papers using the PRISMA methodology. The literature review focused on the technical and economic aspects of HV transmission infrastructure. The technical and economic literature review is contained in Appendix A of this chapter report. A purposeful search of additional published materials included: i) reference books and major reports from the leading electrical engineering research organisations of CIGRE and EPRI[1]; and ii) standards, reports, and reference material from electrical industry sources; Australian and international Transmission System Operators; the Australian Energy Market Operator (AEMO); the Australian Energy Market Commission (AEMC); and other federal, state, and local government reports.

[1] CIGRE Green Books Overhead Lines International Council on Large Electric Systems (CIGRE) Study Committee B2: Overhead Lines. Springer Reference.
CIGRE TB 680—Implementation of Long AC HV and EHV Cable System. CIGRE, 2017. EPRI Underground Transmission Systems Reference Book. Electric Power Research Institute, 2015.
EPRI AC Transmission Line Reference Book 200kV and above, 2014 Edition.
EPRI Underground Transmission Systems Reference Book: 2015.

2.

Comparison Factors—Overhead and Underground Cable Transmission Lines

There are several areas in which a technical comparison can be made between overhead and underground cable transmission lines. The main areas relate to the design and life cycle phases and include:

- System Design
- Construction and Installation
- Operation and Maintenance
- End of Life and Decommissioning

The main technical factors to be considered in the design of transmission line systems can be summarised as follows:

(a) Factors common to overhead and underground line design:
  - Power transfer requirement
  - Performance requirements – reliability, quality of supply, power system stability
  - Redundancy e.g. single or double circuit
  - Transmission voltage e.g. 132, 220, 275, 330, 400 and 500kV
  - Electromagnetic fields
  - Future requirements for additional circuits or upgrades.
  - Corridor, right of way and easements requirements
  - Life span requirement
  - Environment, topography, and ground geology
  - Land use e.g. urban, rural etc
  - Vehicle access and traffic conditions

(b) Overhead lines:
  - Overhead line structure types e.g. steel lattice towers, steel monopoles, single or double circuit per structure
  - Structure heights and conductor span length
  - Conductor size and number of conductors per phase
  - Climatic conditions—seasonal temperatures, wind speed and direction, lightning and severe weather exposure

(c) Underground cables:
  - Cable type e.g. conductor size, insulation, outer protective sheath
  - Number of cables per phase
  - Distance between cable joints and cable drum lengths
  - Direct buried, ducts or tunnel installation
  - Cable installation configuration—flat or trefoil formation, spacing and depth.
  - Ground geology
  - Ground temperature

Extra high voltage (EHV) is generally defined as transmission network operating at voltage levels greater than 345kV. In Australia, there is only a small network of 500kV transmission lines located mainly in Victoria and NSW. However, transmission voltages of 400kV or greater have been common in many countries and regions, since around the 1960s, including the regions of North and South America, Europe, and Asia. Based on this growing trend for higher voltage new transmission lines the comparison which follows, focuses on the 400 to 500kV range. However, where relevant, there are some references to lower voltage transmission lines. An overview of HVDC transmission lines will be provided in this section also.

3.

Transmission Lines in Australia

Most Transmission lines in Australia are rated at either 110, 132, 275, 330 or 500kV. The 110 to 132kV transmission lines are mainly operated by the larger Distribution Network Providers (DNSPs), while the 275 to 500kV transmission lines are operated by the Transmission Network Providers (TNSPs).

The first overhead 500kV transmission line in Australia was constructed in 1970 connecting Hazelwood Power Station to Melbourne. The 500kV network was later extended to Portland. The first 500kV line in NSW was constructed in the 1980s from Eraring Power Station to Kemps Creek. A network of 500kV lines has since been built in the central parts of NSW linking the major power stations in the Hunter Valley with the major load centres.

In contrast the installation of HV underground transmission lines of greater than 132kV in Australia has generally been limited to relatively short route lengths, mainly in higher density urban and CBD areas, where the lines are normally installed in road corridors. Some examples are listed in Table 1.

Table 1. Significant HV Transmission Cable Installations in Australia

Location	Voltage (kV)	Transfer Capacity (MW)	Length (km)	Year Completed	Route
Sydney South	330	750	28	2003	Urban area, 24.5 km in road corridor and 3.5 km in tunnel
Potts Hill-Alexandria	330	750	20	2023	Urban area, cable in conduits in road corridor
Cranborne Victoria	220	165	88	2012	Fringe urban in trenches and conduits (Connects desalination Plant)

4.

Characteristics of HVAC Overhead Transmission Lines

This section details the main system design characteristics and life cycle requirements for overhead transmission lines.

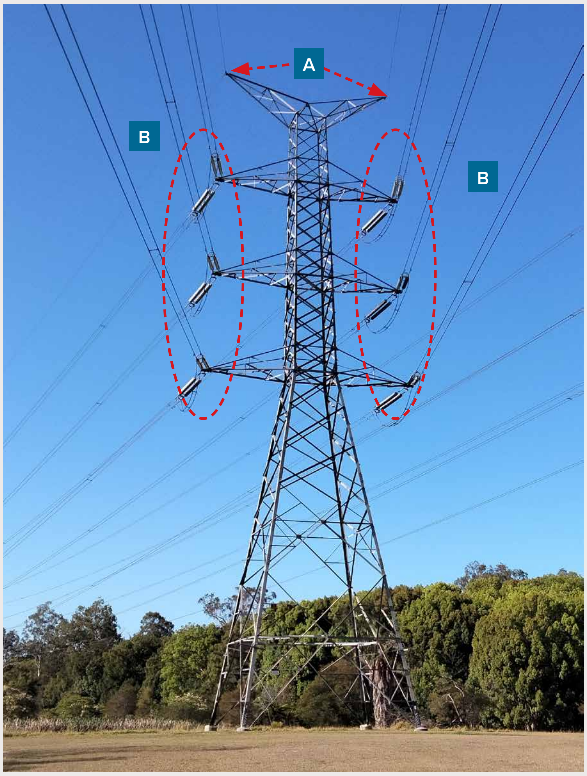
4.1 System Design – Overhead Transmission Lines

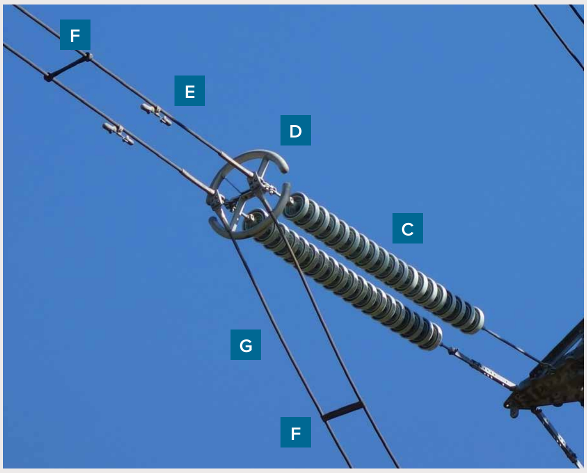
Transmission lines can be constructed as either a **single** or **double circuit** line. Each circuit will comprise of a 3-phase set of insulators and conductors. A typical transmission line tower is shown in Figure 1.

Tower structures – the most common and cost-effective structures are the steel lattice structure. The structures are constructed using prefabricated galvanised steel components which are assembled on-site and mounted on concrete **foundations** or footings.

There are two main types of tower constructions: (1) **Suspension towers** –with vertical insulator strings supporting conductors with no change in direction of the line, and (2) **Tension tower**s – with horizontal insulators strings in both directions of the line from the tower. Tension towers are placed at the ends of long sections of conductors or at change in directions of the line. Tension towers need to have higher strength steel construction and concrete foundations to support the higher tensile loads.

Structure Heights in Australia are determined by: (a) the clearances to ground requirements in State Regulation and Standards (AS/NZS7000); (b) the phase to phase and phase to earth wire clearance requirements in Standards (AS/NZS7000); (c) requirements to meet the





A Earth wires
B Phase conductor bundles
C Insulator strings
D Corona rings (aka grading rings)
E Vibartion dampers
F Spacers
G Bridging conductors (aka jumpers)

Figure 1. Transmission line components (275kV double circuit tension tower)

ICNIRP Electromagnetic field reference levels. At most transmission voltages the height is not affected by the 5kV/m ICNIRP electric field reference limit, but at 500kV, the limit becomes a factor and transmission designers typically increase the height of structures to comply with this limit. The typical height for a 500kV structure is 60 to 80m, whereas a 275kV structure[2] is around 40m to 50m.

Conductors used on overhead transmission lines are predominantly Aluminium Conductor Steel Reinforced (ACSR) which use a galvanised steel core with standard grade aluminium on the outer layers. An alternative is All-Aluminium Alloyed conductors (AAAC) which comprise alloyed aluminium (typically 1120-type) for the conductor strands. The strength to mass ratios for ACSR and AAAC are similar and result in similar spanning and sagging capabilities[3].

The maximum temperature for operating transmission conductors is typically in the range or 75°C to 90°C. The reason for this is to limit the effects of annealing which causes loss of strength of the conductors (see Figure 8 for annealing curves). However, some utilities have uprated their ACSR conductors to operate up to 120°C. This was based on better annealing performance of the ACSR with a steel core and a greater understanding of the operating characteristics of ACSR at elevated temperatures.

There have been a small number (around five) of transmission lines in Australia constructed with a high temperature low sag (HTLS) ACSR conductor. This type of conductor uses special high strength low sag steel cores with thermal resistant aluminium outer strands. The high temperature conductors can operate up to 200°C, which effectively can double the rating out of a transmission line. The high temperature conductors are very expensive (typically 1.5 to 5 times the cost of conventional ACSR—reference [1]) and require special fittings and connectors for the higher temperature.

Conductor Bundles When designing overhead powerlines, the designer is required to address corona discharge and will aim to keep the surface voltage gradient (SVG) on the conductor to below 16kV/cm. To achieve the SVG limit, it is common for there to be a bundle of 2 conductors for 275/330kV and 4 conductors for 500kV (See Figure 2). Each of the conductors in the bundles are limited by their thermal capacity. As an example, a quad bundle conductor with ACSR Drake conductor (26/4.44 Aluminium and 7/3.45 Steel) has been calculated to have a rating around 2200 MVA per circuit. **Spacers** holding bundled conductors in place are installed at approximately 75 m intervals) to avoid conductors clashing during high winds and fault conditions.

Figure 2. Transmission Line Quad Bundled Conductor with Spacer (Marcus Wong)

Conductors are susceptible to fatigue damage from aeolian vibration[4] and **vibration dampers** are required to address aeolian vibration effects and ensure a long life for the conductors. Aeolian vibration occurs during light laminar winds and the effects are more predominant in flat rural countryside or over waterways. The vibration dampers are installed close to conductor attachment positions.

The configuration of the phase conductors is determined by (a) the phase to phase clearance and climbing clearance requirements in AS/NZS7000; (b) the requirement to keep the SVG on the conductor to below 16 kV/cm; (c) the justification due to prudent avoidance for compacting the conductors and reduce magnetic fields.

Earth Wires and Cross-member Widths effectively shield conductors to provide protection against damage from lightning strikes and are required on transmission lines to achieve an acceptable level of reliability. In general, there are two earth wires per structure with the earth wires generally directly above or close to being directly above the top conductor. A 500kV line

2 https://www.powerlink.com.au/reports/our-transmission-network
https://www.transgrid.com.au/media/3tkdd5lr/easement-guidelines.pdf.
3 AS/NZS 7000:2016 Overhead Line Design.
SA/SNZ HB 331:2020 Overhead line design handbook.
4 Aeolian vibration is a type of motion caused by wind on conductors and overhead shield wires of transmission and distribution lines. Aeolian vibration is characterised by low amplitude (conductor diameter) high frequency (5 to 150 Hz).

Tension tower followed by suspension towers (Marcus Wong)

V string suspension towers (Irby Construction)

Figure 3. 500kV Double and Single Circuit Overhead Lines

is expected to be designed for a lightning outage rate similar to a 275kV line which would be of less than 0.3 outages per 100 km per year[5]. Fibre optic cables can be integrated into special types of earth wires – Optical Ground Wire (**OPGW**) to provide a telecommunication channel.

Corona rings at the ends of insulator strings help provide a smooth surface to mitigate against an electrical phenomenon called corona discharge which can cause noise and electrical losses.

Images of double circuit 500 kV lines are shown in Figure 3.

Insulators used on transmission lines are predominantly ceramic discs (porcelain or glass) with high strength capability (160 and 220kN tensile strength). The insulators are required to support: (a) conductor loads on suspension type structures; (b) tensile loads on angle and termination structures; (c) cascade longitudinal loads [2]. Given the high mechanical tensions in the transmission conductors, there are often multiple insulator strings (particularly for the termination structures).

Transmission Line Electrical Characteristics—A key characteristic of a transmission line is its surge impedance loading (SIL). The impedance in an AC electrical circuit (e.g., a transmission line) are characteristics of the circuit which oppose current flow and result in voltage drop or rise and losses in the line. The Impedance comprises of two main components a) resistive, and b) reactive. The reactive components are a combination of inductance and capacitance. The SIL for a lossless transmission line is where at the given power transfer, the reactive capacitance and inductance on the line are equivalent.

Figure 4. Live Insulator Change-out (North-western Energy UK)

[5] Data sourced from Powerlink Queensland.

Table 2. Typical Surge Impedance Loading for Transmission Line Voltages

Line Voltage	132kV	220kV	275kV	400kV	500kV
Surge Impedance Z0 (Ohms)	400	375	370	320	312
SIL (MW)	44	129	204	500	801

$$SIL = V_{LL}^2/Z_0;$$

Where V_{LL} is line to line voltage, and Z_0 is the characteristic impedance of the line.

Loaded below its SIL, a line supplies capacitive reactive power to the system, tending to raise system voltages. Above it, the line absorbs reactive power, tending to depress the voltage. The *Ferranti effect* describes the voltage rise towards the remote end of a very lightly loaded (or open circuit) transmission line. Typical SILs are given in the Table 2. This shows that doubling of voltage, results in approximately a quadrupling of the SIL.

Reactive compensation plant such as shunt reactors and static var compensators (SVCs) are installed at transmission line terminal substations to extend the critical lengths due to voltage limit effects described above.

Thermal and stability limits—Overhead transmission lines are limited by thermal, voltage and stability limits.

The thermal limit is the maximum temperature (under steady state and short circuit conditions) for operating the conductor and this is described in more detail in a later section on Power Transfer Capability.

There are 2 types of stability limits on transmission lines; (1) voltage stability and (2) transmission angle stability. Voltage stability is associated with the load on the system and is dependent on the power factor of the load, the power transfer and the impedance of the network. Voltage stability can occur on long radial transmission networks and is not usually encountered on highly meshed transmission networks. If the power transfer voltage stability limit is exceeded, there is potential for voltage collapse and generation plant disconnecting from the grid, resulting in widespread customer supply outages.

Transmission angle stability is associated with generation and can arise during disturbances such as faults on the transmission network. In normal operation the load angle (or rotor angle) on the transmission network is low and is much less than the 900 limit. In the event of a faults which can disconnect transmission lines, the load angle) will increase and if it exceeds the 900 limit, the system can become unstable and cause loss of generation.

4.2 Right of Way Corridor Requirements—Overhead Transmission Lines

'Right of Way' is the general term used for a corridor secured for a transmission line. An **Easement** provides a legal right of way on a property which may be privately or publicly owned. Transmission lines may also be installed on wider public road corridors.

The typical easement width for a 500kV line (single or double circuit) is 70m but could be up to 100 m depending upon other design factors. By comparison, a typical easement width for a 275kV line (single or double circuit) is 60m. However, the determination of the right of way or easement corridor width will depend on several factors. These can vary depending on local regulations, environmental considerations, and technical requirements. Some of the common factors that influence the width of the corridor include:

(a) Voltage and Line Configuration: The voltage level and configuration of the transmission line play a significant role in determining the corridor width. Higher voltage lines often require wider corridors to maintain safety clearances and reduce the risk of electrical arcing or interference.

(b) Safety Clearances: Safety regulations dictate the minimum distance that must be maintained between the transmission line and surrounding objects or structures. This includes considerations for the height of the towers, sag and sway of conductors, and any potential hazards in the vicinity, such as roads, railways, buildings, or water bodies. The corridor width is determined by adding appropriate safety clearances on either side of the transmission line.

(c) Electro Magnetic Field (EMF): Consideration is needed of prudent avoidance and recommended

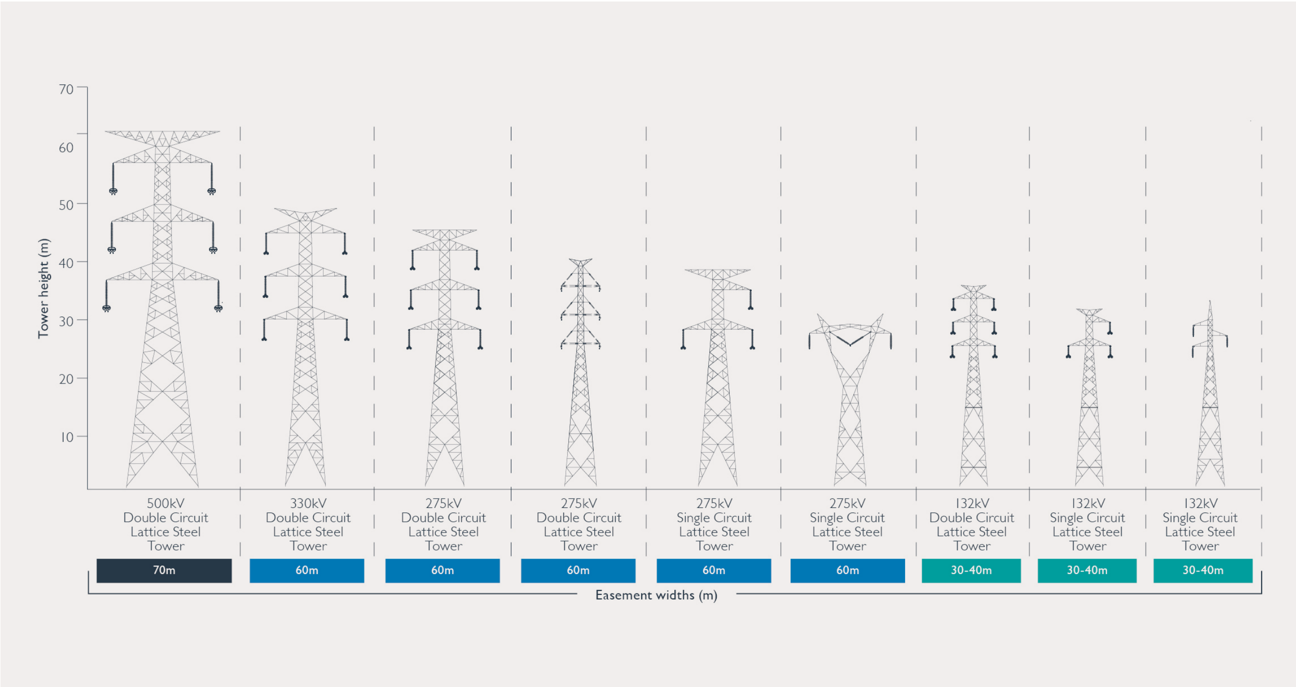


Figure 5. Typical OHTL Structure Types – Height and Easement Widths (Powerlink Queensland[6].)

guidelines from lead organisations—ENA, ICNIRP and ARPANSA (Refer section 7 Electromagnetic Fields).

(d) Environmental Considerations: Environmental factors, including protected areas, sensitive habitats, and ecological considerations, may influence the width of the corridor. In some cases, wider corridors are required to minimize the impact on wildlife migration, vegetation, or protected areas.

(e) Maintenance and Construction Access: Sufficient space is required to allow for maintenance and construction activities along the transmission line. The corridor width should accommodate the safe movement of personnel, vehicles, and equipment necessary for inspection, repair, and construction purposes.

(f) Future Expansion and Upgrades: When planning new transmission lines, the potential for future expansion or the need to upgrade the line capacity also needs to be considered. Providing a wider corridor can facilitate easier expansion or modification of the transmission line infrastructure in the future.

(g) Local Regulations and Standards: Different countries, states, or regions may have specific regulations and standards that dictate the required corridor width for transmission lines. Compliance with these regulations is essential and can influence the final determination of the corridor width.

The determination of the corridor width is often a collaborative process involving various stakeholders, including utility companies, landowners, government agencies, and environmental groups. Factors such as cost, public opinion, and specific project requirements can also influence the decision-making process. Typical corridor widths for various line voltages are shown in Figure 5.

[6] https://www.powerlink.com.au/reports/our-transmission-network

Figure 6. 275kV Double Circuit Compact Steel Pole

4.3 Aesthetic Overhead Transmission Structures

Over many years there have been developments by transmission line engineers and designers to improve the visual impact of transmission line support structures in the environment to gain more public acceptance (CIGRE [2]). Traditionally, transmission lines are constructed using lattice steel towers which are fabricated from galvanised angle structural steel. The need to develop more aesthetic structures emerged in the late 1960s when the demand for transmission line infrastructure resulted in more visual exposure to the general population.

General measures used to improve the aesthetics of transmission line structures include the following:

(a) Adopt compact pole top design—by utilising insulated crossarms (horizontal vee assembly or line post insulators) in place of steel crossarms and insulators strings which results in a lower tower height.

(b) Change the lattice steel structure to monopole steel or concrete—refer to Figure 6 showing typical double circuit 275 kV compact steel pole.

(c) Paint the structures—typically green in a treed environment, or a brown, rust colour in arid or desert areas.

(d) Dull the gloss of the galvanised steel structures and glossy aluminium conductors by sandblasting the structures and conductors prior to erection. The sandblasting of the conductors has an additional benefit—it reduces the hydrophobicity (water repelling property) of the conductors and minimises the risk of the water droplets on the surface of the conductors causing corona discharge resulting in audible noise.

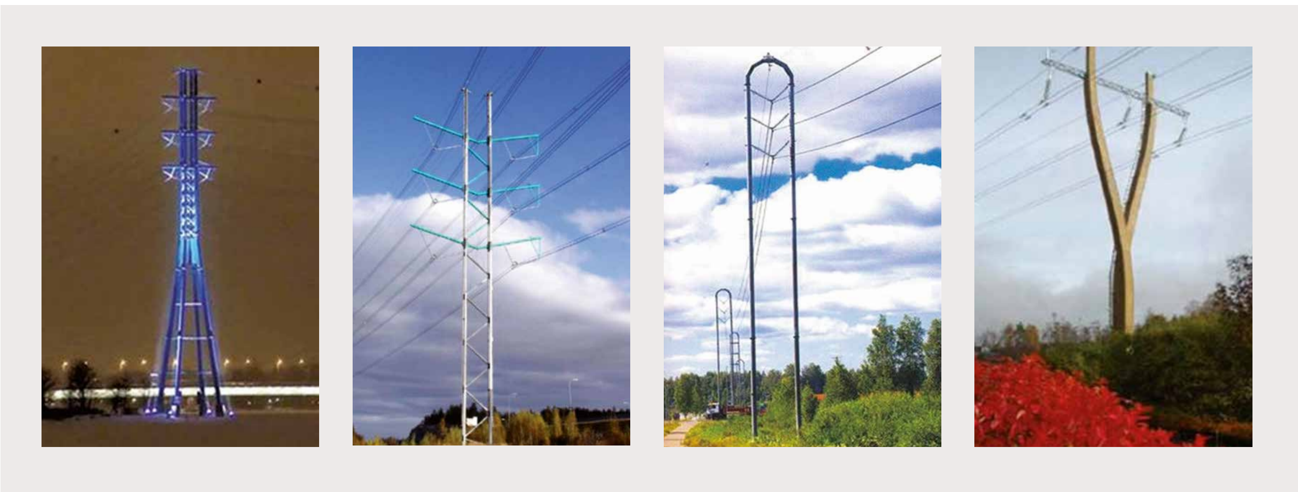


Figure 7. Examples of Aesthetic Design Transmission Line Structures (CIGRE 2017 [2, pp. 905–908])

Aesthetic Transmission Line Structures—CIGRE 2017 [2, pp. 905–908] have reported on a number of examples of innovative and artistic transmission line structures aimed at improving public acceptance. Most of the aesthetic structures are single circuit, utilising single or double pole steel with round or curvy shapes. The crossarms are a variety of different shapes and are often coloured to blend in with the environment. Blue is a colour regularly used to match the colour of the background sky. Poles are often left the galvanised steel colour—which matches the colour of clouds. Development of aesthetic structures involves additional time and cost for a project, so only tends to be used where the need is justified. Some examples are shown in the photos below.

Besides adding time and cost to the project the other major trade-offs with using aesthetic structures or using lower height structures are as follows:

1. Compacting of the phase conductors with the use of aesthetic/innovative structures may not meet the clearance requirements of AS/NZS7000 [3] and restrict climbing access and maintenance.
2. There will be a trade-off with reducing the height of the structure and compliance with the ARPANSA electric field reference levels.
3. There will be a trade-off with reducing the height of structure and reduced span length with reduced span lengths resulting in more structures on the line route.
4. There will be a trade-off in easement requirements when using a wider delta configuration as opposed to the standard vertical formation on a double circuit transmission line. A standard 500kV double circuit line will typically have an overall width of 20 metres, whereas the delta configuration will be 48 metres. This will lead to an additional 30 metres in easement widths.

4.4 Power Transfer Capability

One of the most significant advantages of overhead transmission lines compared to underground transmission cables is the line power transfer capability or rating and the short-term overload capability.

The line power transfer capability is mainly dependent on the resistance of the conductor/cable (material and size), the assumed ambient temperature, the maximum allowable temperature of the conductor above ambient, assumed wind speed and direction.

For example, if we assume a conductor with a maximum allowable temperature of 75°C, for a summer day at noon when the assumed ambient temperature is 40°C, the allowable temperature rise for the conductor is 35°C. For a winter evening, if the assumed ambient temperature is 10°C, the allowable temperature rise increases to 65°C. This has a significant increase on the line rating as illustrated in the examples below.

When calculating ratings, the transmission utilities tend to apply a conservative approach and for normal summer noon ratings, assume the maximum summer temperature, in range of 35°C to 40°C, with a corresponding low wind speed, typically in the range of 0.5 to 1.0m/sec. For emergencies, some transmission utilities assume a higher wind speed for example up to 2.0m/sec.

Dynamic ratings can be determined and applied by use of real time measurements of temperature, wind speed, and conductor sag. (This is described below also).

Typical Power Transfer Rating—Examples

The power transfer capability or rating on a powerline is proportional to the square of voltage. If the voltage doubles, the power transfer goes up four times.
The typical MW ratings across a range of overhead transmission voltages are:

- 132 kV—100 to 300MVA
- 275 kV—300 to 1000MVA (twin conductors)
- 500 kV—2000 to 3000MVA (quad conductors)

The factors which influence the line ratings are: (inputs to the Heat Balance Equation)

- Current flow and resistance of conductor (I2.R)
- Solar radiation (typically 1100W/m^2)
- Ambient temperature and maximum conductor temperature
- Wind speed (m/sec)
- Emissivity and absorption values (typically 0.5 for rural weathering and 0.85 urban weathering – where more pollution on conductors is expected)

Line rating calculations have been calculated by the authors for typical 275kV conductors: sulphur and twin phosphorus and shown in Table 3. The assumed parameters for the rating calculations are:

- Solar radiation = 1100 W/m^2
- Emissivity and absorption = 0.5 (assumed rural)
- Maximum temperature of conductors = 75 0C
- Summer noon ambient temperature—35°C, wind speed—0.7m/sec
- Summer noon ambient temperature—35°C, wind speed—2.0m/sec
- Winter evening ambient temperature—10°C, wind speed—0.7m/sec
- Winter evening ambient temperature—10°C, wind speed—2.0m/sec

Table 3. Typical 275kV Overhead Transmission Line Power Transfer Ratings

Conductor (code name)	Summer Noon Normal (MW)[1]	Summer Noon Emergency (MW)[2]	Winter Evening Normal (MW)[3]	Winter Evening Emergency (MW)[4]
Single Sulphur	500	680	670	920
Twin Phosphorus	735	980	990	1300

1. Summer noon ambient temperature—35°C, wind speed—0.7m/sec
2. Summer noon ambient temperature—35°C, wind speed—2.0m/sec
3. Winter evening ambient temperature—10°C, wind speed—0.7m/sec
4. Winter evening ambient temperature—10°C, wind speed—2.0m/sec

To limit the effects of long-term annealing[7], the maximum temperature for a conductor is set. Annealing is dependent on both the operating temperature and the duration of time at the operating temperature (see Figure 8 for typical annealing loss for aluminium conductor). Conductors which are operated at 80°C or less will generally lose 2 to 3% of strength with time. However, if operated under short time emergencies above 100°C, may lose 5% of their original mechanical strength.

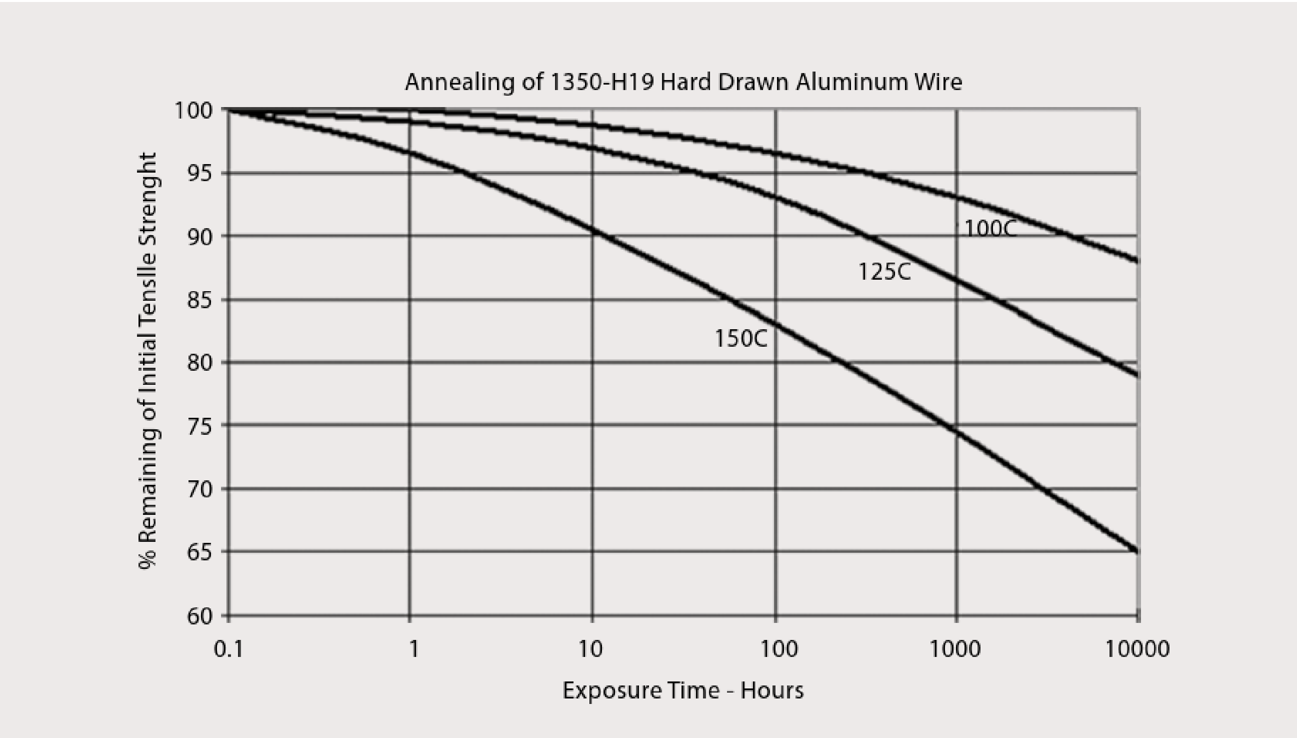


Figure 8. Typical Annealing Curves for Aluminium Wires, Drawn from "Rolled" Rod, of a Diameter Typically Used in Transmission Conductors (The Aluminium Association 1982)

[7] The loss in mechanical strength of the conductor.

Table 4. Example of Overhead Transmission Line Dynamic Ratings

Conductor	Summer Noon Normal (MW)[1]	Summer Noon Dynamic Ambient Change (MW)[2]	Summer Noon Dynamic Ambient and Wind Change (MW)[3]
Single Sulphur	500	570	1046

1. Ambient temperature—35°C, wind speed—0.7m/sec
2. Actual temperature—25°C, wind speed—0.7m/sec
3. Actual temperature—25°C, wind speed—4m/sec

Dynamic Ratings

Transmission utilities have been introducing dynamic line ratings for overhead transmission lines where actual conductor temperatures and wind speeds are measured, or conductor sags are monitored.

To evaluate the impact of using dynamic ratings, additional calculations were performed for a summer noon day but with a reduced actual temperature of 25°C and the wind speed in the range of 0.7m/sec to 4m/sec (see Table 4).

Summary

Overhead transmission lines can be uprated by increasing the maximum operating temperature, varying the assumptions for ambient temperature and wind speeds based on location, season and environment. There is a significant variability in line ratings between the summer and winter seasons (around 30%), but the largest variability is caused by wind. It is practicable to achieve higher ratings with overhead transmission lines using dynamic rating capability. Ratings of two times or more are practicable.

The Literature Review (Appendix A) also found that power transfer capability of existing overhead infrastructure could be increased in cost-effective ways by upgrading/uprating as follows:

(a) Expand current overhead transmission line into multi-circuits, multi-voltage lines.

(b) Replace ACSR conductors with HTLS conductors.

(c) Convert existing AC line into a hybrid AC/DC line.

It should be noted that an underground transmission line cannot be upgraded/uprated like an overhead transmission line.

4.5 Reliability Performance

Most of the overhead transmission lines in Australia, perform to a high level of reliability—typically forced outages are less than 1.0 incident per annum per 100km per year. In general, a higher system voltage line has better reliability performance – this is mainly due to measures to address lightning performance (e.g use of two earthwires, longer insulation and lower footing resistances). For example, using the above design measures, it is possible to design a 500kV overhead line to achieve a forced outage performance rate not greater than 0.5 outages per 100km per year.

In Victoria, the electricity system code [4] outlines the performance standard of forced outage rate due to primary failure and lightning/storms for overhead transmission lines. The requirement is less than 1.0 incident per annum per 100 circuit km. For a double circuit line of 100km length, the requirement is 2.0 incidents per annum. There is also a requirement for a secondary failure to be less than 0.5 incidents per annum per 100 circuit km [7].

Structural Failures—More recently, there have been 2 incidents of structural failures to overhead transmission lines. These occurred in Victoria and South Australia. The first was the six tower failures on the 500kV double circuit line in Southwest Victoria on 31 January 2020 that supplied power to the Portland aluminium smelter. In this instance, it was reported that the wind speeds were more than 160km/hr. The second was on the 28 September 2016, with one single circuit and one double circuit tower failure on the Victoria to South Australian inter-connector. It was reported that there were tornadoes with wind speeds in the range of 190–260km/hr.

In the 1990s, in Queensland, there were several double circuit 275kV transmission tower failures in the Esk ranges. One of the incidences resulted in a cascading failure of 6 towers, after one tower failed mainly due to severe uplift wind conditions. The section of transmission line had been built on the ranges and the towers were reported to have experienced a 1 in 80-year wind on a cold day (where tensions on the conductors were higher than normal). The tension on the conductors is dependent on the temperature. Under hot conditions, the conductors elongate, and conductor tensions reduce, whereas under cold conditions, the conductors contract and conductor tensions increase.

Figure 9. Fallen 500kV Double Circuit Tower, Victoria (Zinfra Pty Ltd.) and 275kV tower, South Australia (ABC News: Dean Faulkner)

While transmission structure failures have occurred in recent times, these failures are considered rare and the failure rate of transmission structures in Australia is in the order of 0.85 in 175,000 per annum [5] or 0.0012 per 100 km per annum (based on 70,000 km of overhead transmission lines in Australia).

Repair times for overhead transmission lines will in general, be of shorter duration compared to underground cable transmission. Even in the cases illustrated above, where towers have fallen, temporary line diversions can usually be constructed within a week, thereby allowing permanent repairs to be subsequently completed without causing continued disruption.

The literature review (Appendix A) highlighted a study which reviewed the Estonian transmission system has compared the reliability (in terms of outage rate) for different voltages (110kV, 330kV) and for steel and concrete structures:

- The concrete structures have tended to have a better performance than steel (There was however no explanation given for this trend).
- Outage times for the higher system voltage lines tended to be longer.
- Outage times tended to be longer where access to the line was further from public roads.

4.6 Construction Phase

An Environment Management Plan (EMP) will generally be implemented for transmission line projects. Requirements for this plan will have been identified in the overall Environmental Impact Study during the planning phase of the project. In general, the key activities and sequence for construction of an overhead transmission line are:

1. Construction surveys
2. Corridor clearing and site access tracks.
3. Excavation and construction of structure foundations
4. Structure assembly
5. Conductor stringing
6. Fitting of insulators hardware and fittings
7. Final inspections
8. Testing and commissioning

Time frames for the construction phase of an overhead line will of course vary depending upon factors such as route length, geography, environment, and packaging of segments of the project for concurrent work. A typical overhead transmission line construction of 100 km will generally take from 1 to 2 years to complete.

4.7 Operation and Maintenance

Policies, plans, and strategies for operation and maintenance of transmission lines form a major part of a utility's overall life-cycle asset management regime. The basic categories of maintenance activities for overhead transmission lines are [2]:

(a) Periodic inspections and condition-based assessments may include ground based or aerial based inspections, detailed inspections of structures, and assessment of vegetation growth near the lines.

(b) Periodic maintenance includes activities such as vegetation management, painting of steel strictures, and insulator washing.

(c) Preventative maintenance or defect repairs usually involves repairs or replacement of defective or damaged components identified from inspections, e.g., insulators, clamps, spacers, excessive conductor sag.

(d) Emergency restoration or repairs are done after a failure

Maintenance tasks are carried out by highly trained personnel. Application of modern technologies such as drones and robotics are being introduced and trialled in some areas [6].

4.8 Increasing the Utilization of Existing Overhead Transmission Lines

An advantage of overhead transmission lines compared to underground cables is that there are options to increase the utilization of the transmission line during its lifespan. CIGRE publication 353 “Guidelines for Increased Utilization of Existing Overhead Transmission Lines” [7] identified 4 main categories of areas for the utilisation of existing overhead transmission lines as follows:

1. Uprating is defined as increasing the electrical characteristics of a line due to, for example, a requirement for: higher electrical capacity or larger electrical clearances.
2. Upgrading is defined as increasing the original mechanical strength and or electrical for increased applied loads such as wind, ice and any load case combination or increasing electrical performance such as pollution or lightning performance.
3. Refurbishment is defined as being the extensive renovation or repair of an item to restore the intended design working life. Life extension is an option of refurbishment which does not result in the complete restoration of the original design working life.
4. Asset Expansion is defined as increasing the functionality of transmission line, e.g. utilising structures for 3rd party assets such as mobile phone antennas and fibre optic cables.

Table 5. Categorisation of CIGRE 353 Case Studies and Cost Impact

Utilisation Description	Uprating	Upgrading	Refurbishment	Asset Expansion
Painting of steel towers			Minor cost	
Attaching conductors at higher location on tower	Minor cost			
Line voltage uprating	Moderate cost			
Increasing temperature of conductor	Minor cost			
Raising height of structures	Moderate to High cost			
Upgrade towers to higher wind speed (change steel members)		Minor cost		
Reinforcement of wood pole K-frame			Minor cost	
Reinforcement of concrete foundations			Moderate costs	
Upgrading of insulators		Moderate cost		
Increasing capacity of line (changing conductors)		Moderate to high cost		
Installation of optic fibre to line				Minor cost
Installation of mobile antennas to towers				Minor cost

The CIGRE publication also considers the economics of the various categories of increasing utilisation and identifies 2 key points in asset lifespan:

1. Technical end of life—where the line fails to perform within the normal operating requirements without abnormal maintenance or when the line is no longer fit for the original purpose) and
2. Optimal time for renewal where the cumulative net present value of future annual costs of the transmission line, (including maintenance, losses and risk costs, per years of service of is equal to the minimum long run average costs of a renewal project.

The optimum time for renewal and the technical end of life are intrinsically linked as the optimum time for renewal. This is influenced by factors such as the original design, construction and workmanship of the asset, operating environment (e.g. degradation due to ultra violet radiation, extreme ambient temperature, lightning, wind and ice exposure), maintenance quality and subsequent requirements to comply with new safety or design standards and codes.

There were a number of case studies for each of the asset renewal options, with some being low cost (e.g. painting of towers), some having moderate costs (replacement of insulators and tower members) and some having high costs (upgrading of line by replacing the conductors with higher capacity high temperature conductors). Table 5 summarises and categorises the case studies and identifies the likely cost of the changes.

The majority of the case studies involving minor costs only achieve an incremental increase in electrical or structural ratings or life extension of the transmission line.

Where moderate or high costs are expended, such as (a) changing of conductor to a higher capacity high temperature conductor or (b) adding extensions to height of the structures, or (c) change voltage on the line, will generally result in a significant up-rating of the line.

Feasibility of uprating HVAC lines to a higher voltage

A case study from Brazil had the highest benefit to cost ratio and involved uprating line by re-insulating from 69kV to 138kV to achieve a 100% increase in line capacity at a cost of 20% of a new line.

Given the age when the up-rating of the transmission line is being considered (around 50 years) and the up-rating is not likely to increase the expected life of the transmission line (being in the range of 70 to 80 years), an economic study will need to be performed to determine if the benefits are greater than the costs.

In the past, some utilities in Australia have considered up-rating conductors on aged transmission lines to high temperature conductors and found the economics did not support the up-rating option. It was more economic to pull down the existing line and build a new line with the high temperature conductors.

Some of the cases which involve either (a) attaching conductors at a higher location on the crossarm/tower or (b) increasing temperature of conductor are generally incurred at a minor cost and would tend to show a positive benefit to cost ratio.

In general, uprating existing HVAC lines to a higher voltage, e.g. 275kV to 500kV, will not be economically feasible if significant modifications to the existing structures are required such as:

- Increasing reach of earthwire cross-arms for effective lightning protection
- Increasing strength of structures, conductor cross-arms to support additional bundled conductors (from double to quad bundled
- Increasing height to meet ground clearance requirements for the higher voltage.

HVAC transmission line conversion to a HVDC Line

There is also an option of converting existing HVAC transmission circuits to HVDC to achieve a higher rating, typically between 50% and 100%. One such approach is being undertaken on the UltraNet project by Amprion and TransnetBW in Germany, where an existing 380kV AC line is being converted to a ±-380kV line with a metallic return—refer to Figure 10. This new HVDC line has a 2GW capacity.

4.9 End of Life and Decommissioning

CIGRE's Green Book (2017) [2] suggest an estimated lifetime of 60 to 120 years, for overhead transmission lines if well maintained. This assumes that major components such as conductor fittings, insulators and corrosion protection are replaced or addressed during that time. Maintenance policies and practices including inspection and testing are key factors that influence the lifetime of transmission lines.

Decommissioning of overhead transmission lines requires a comprehensive approach that considers a range of factors to ensure the process is conducted in a responsible and efficient manner to minimise any negative impacts on the environment and surrounding communities. Key factors include:

(a) Safety and Environmental Impact: Measures must be taken to ensure the safe removal of equipment, structures, and conductors. These need to be carried out in compliance with

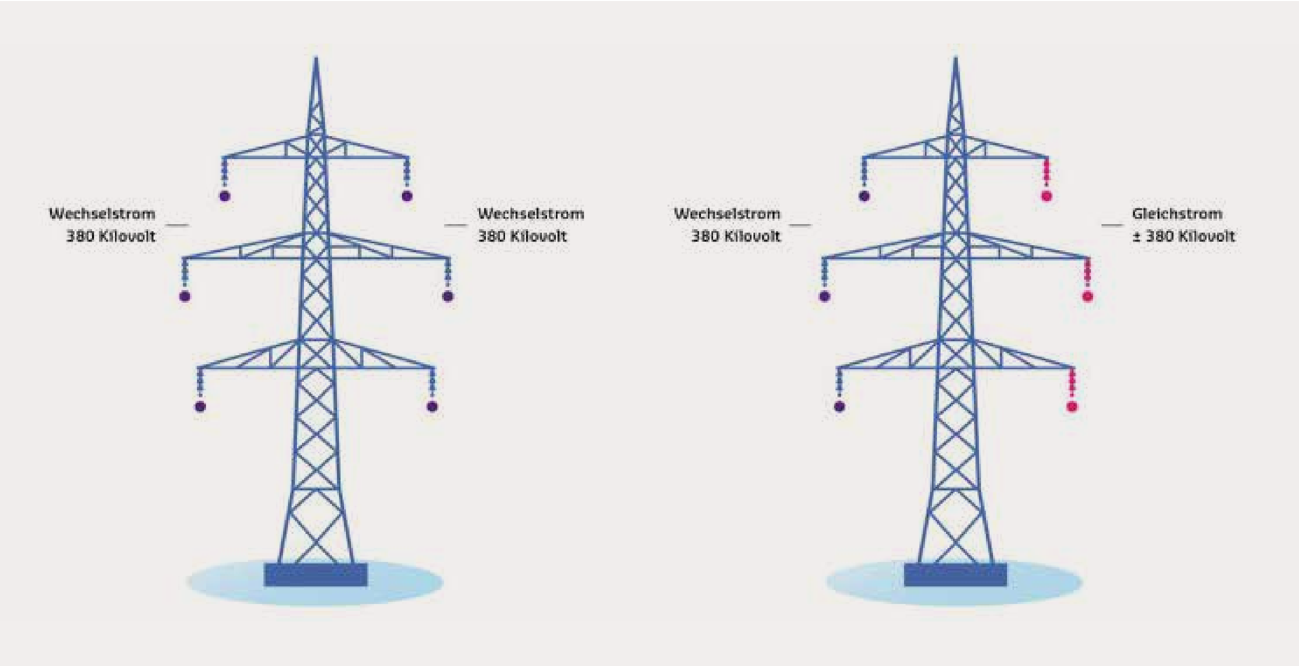


Figure 10. Ultranet Project—HVAC to HVDC Conversion (Amprion[8])

environmental regulations to prevent any harm to human health or the environment.

(b) Removal and Disposal of Equipment: Towers, conductors, insulators, and other equipment need to be carefully dismantled and transported to designated facilities for recycling, reuse, or proper disposal. Maximisation of the recovery of valuable materials and minimisation of waste are also important.

(c) Site Remediation: Site remediation may be necessary to restore the land to its original condition or repurpose it for other uses. This may involve activities such as grading, erosion control, vegetation restoration, or land reclamation. Environmental assessments may be required to ensure compliance with local regulations and mitigate any potential impacts.

(d) Stakeholder Engagement: Stakeholder engagement is crucial throughout the decommissioning process. Communication with local communities, landowners, regulatory agencies, and other relevant stakeholders needs to be established to provide adequate information about the works to address any concerns that might arise. This can include notifying residents about the decommissioning activities, coordinating road closures or traffic diversions, to minimise any potential disruption or inconvenience caused by the process.

(e) Transmission System Reliability: Decommissioning of overhead transmission lines should be carefully planned to minimise any impact on the reliability of the overall transmission system.

(f) Regulatory Compliance: Compliance with applicable regulations and permits is essential during the decommissioning process.

(g) Cost and Financial Planning: Decommissioning overhead transmission lines can involve significant costs, including equipment removal, site restoration, and any required environmental assessments.

[8] https://www.amprion.net/Grid-expansion/Our-Projects/Ultranet/

05.

Characteristics of HVAC Underground Transmission Lines

This section details the main system design characteristics and life cycle requirements for underground transmission cables.

5.1 Types of Transmission Cables

Fluid-Filled Cables were the first underground transmission cables developed around 100 years ago. Comprised of a conductor with layered paper tape insulation which was impregnated with an insulating oil and kept under positive pressure by a hydraulic system including tanks located along the cable route to suit the route profile. Gas-filled pressurised cables were another a common fluid-filled cable design but was found to be only suitable for lower transmission voltages. The last two decades have seen most fluid-filled cable systems decommissioned and replaced.

Cross Linked Polyethylene (XLPE) Insulated Cables have become the dominant technology for high voltage cables. A typical HV cable construction in shown in Figure 11.

XLPE insulated cables have many advantages over previous cable types which include:

- not containing fluids that could leak and cause environmental harm;
- requiring less maintenance compared to fluid-filled cables;

Figure 11. Typical Underground Transmission Cable Construction (Wuxi Lonheo International Trade Co., Ltd.)

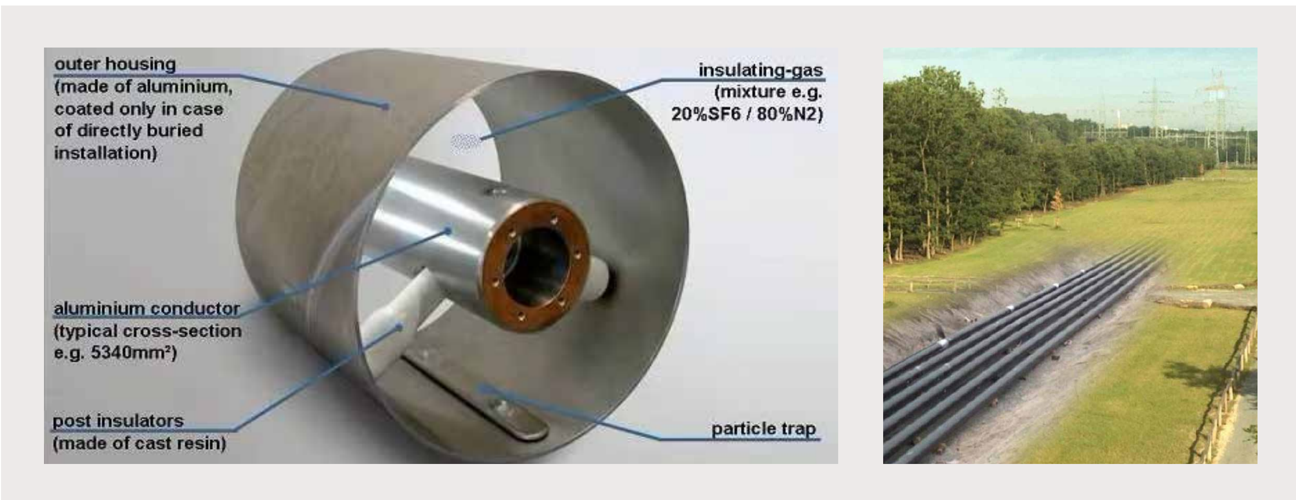


Figure 12. HV Gas Insulated Transmission Line (Siemens)

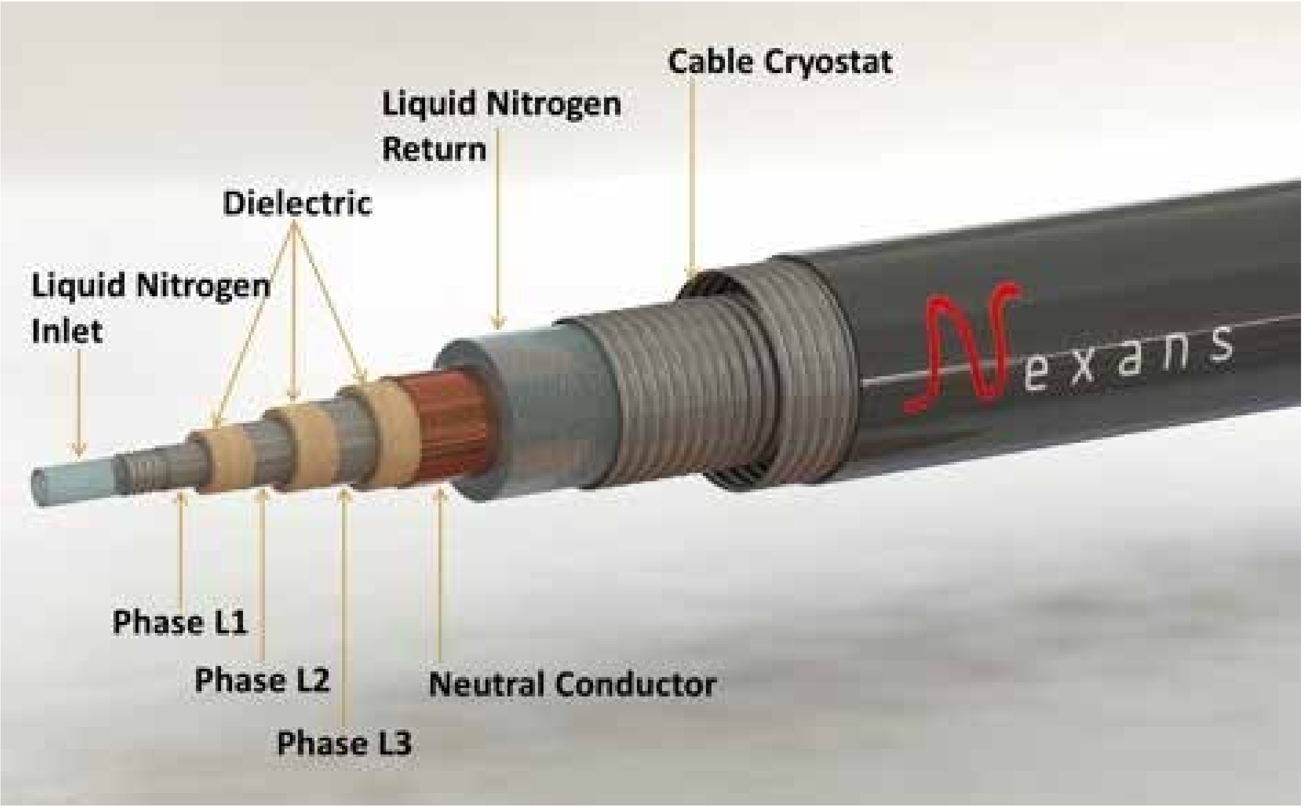


Figure 13. Design of a High Temperature Superconducting (HTS) Cable for AC Operation with 3 Phases Cooled by Liquid Nitrogen (Nexans)

- having improved fire resilience and performance;
- having lower dielectric losses and are therefore cheaper to operate;
- being more economical to manufacture compared to other designs.

The world's first 500kV XLPE system was commissioned in Japan by Hitachi in 1988 [8]. XLPE cable technology has considerably matured since that time and has become the dominant and most economical technology for EHV cables.

Gas Insulated Lines (GILs) were invented in the early 1970's with the objective of providing a high-capacity transmission system with maximum safety for equipment and personnel in energy tunnel systems. This target was reached by replacing flammable insulation materials (e.g. XLPE and fluid-filled cables) with non-flammable and non-toxic insulating gas such as nitrogen (Energinet [9]). These systems have been used in Europe in special limited applications. Disadvantages of the system are the additional installation and maintenance requirements associated with the gas-filled system. The construction of this systems is illustrated in Figure 12.

Super-Conducting Transmission Lines (SCTLs) are currently a developmental technology that offers lower losses, higher power transfer, compact size requiring much reduced corridor width and low electromagnetic field emissions [10]. An example of a superconducting cable is shown in Figure 13. There are several short route length (100 to 2500m) trial installations around the world in USA, China, Japan, Russia, Korea and Germany [11]. Superconductors are materials that, when cooled below a certain critical temperature, can conduct electric current without any resistance, resulting in extremely efficient electrical transmission, and significant increases in thermal rating and transfer capability. This technology however is not yet considered to be viable at this point in time for transmission line projects.

For this report only XLPE cable systems have been considered for the comparison with overhead transmission because this is now the dominant HV cable technology used by transmission utilities around the world and in Australia.

5.2 Long HV Underground Cable Transmission Installations

There are many significant underground transmission cable projects from around the world that have been reported in various publications including by CIGRE TB680 2017 [12]. A summary of these is provided in Table 6.

Table 6. Long HV Underground Cable Installations-Onshore, 275kV or Greater (adapted from CIGRE 2017 [12])

Ref	Country	Tear	Name	No. of Circuits	Voltage (U0 0	Power	System Length (Total)	Conductor Size	Conductor Material	Insulation type	Cable type
1	United Kingdom	1967	New Cross	2	275 kV	800 MVA	22 km	1613 mm^2	Copper	SCFF	3 x1 core
2	United Kingdom	1967	Wimbledon	1	275 kV	760 MVA	21 km	1613 mm^2	Copper	SCFF	3 x1 core
3	USA	1967	NYC-1967	1	345 kV	650 MVA	21 km	1267 mm^2	Copper	HPFF	3 x1 core
4	USA	1968	NYC-1968	1	345 kV	650 MVA	21 km	1267 mm^2	Copper	HPFF	3 x1 core
7	USA	1974	NYC-1974-1	1	345 kV	650 MVA	28 km	1267 mm^2	Copper	HPFF	3 x1 core
8	USA	1974	NYC-1974-2	1	345 kV	650 MVA	28 km	1267 mm^2	Copper	HPFF	3 x1 core
9	USA	1978	NYC-1978	1	345 kV	650 MVA	29 km	1267 mm^2	Copper	HPFF	3 x1 core
11	Canada	1984	BC Hydro - Vancouver	2	525 kV	1200 MVA	38 km	1600 mm^2	Copper	SCFF	3 x1 core
12	Denmark	1997	Copenhagen; Southern Cable Route	1	400 kV	975 MVA	22 km	1600 mm^2	Copper	XLPE	3 x1 core
13	Spain -Marocco	1997	Spain-Morocco Interconnection	1	400 kV	700 MVA	28 km	1600 mm^2	Copper	SCFF	3 x1 core
14	Australia	2000	NSW - Transgrid	1	330 kV	750 MVA	28 km	1600 mm^2	Copper	SCFF PPLP	3 x1 core
15	Japan	2000	Shin - Toyosu Line	2	500 kV	1800 MVA	40 km	2500 mm^2	Copper	XLPE	3 x1 core
19	Japan	2005	Nishi Osaka - Ozone Line	1	275 kV	322 MVA	19 km	1500 mm^2	Copper	XLPE	3x1 core
22	United Kingdom	2005	St Johns Wood	1	400 kV	1600 MVA	26 km	2500 mm^2	Copper	XLPE	3x1 core
23	Saudi Arabia / Bahrain	2006	GCCIA Interconnection	2	400 kV	1200 MVA	51 km	2000 mm^2	Copper	SCFF	3x1 core
24	Spain -Morocco	2006	Spain-Morocco Interconnection	1	400 kV	700 MVA	33 km	1600mm^2/ 800 mm^2	Copper	SCFF	3x1 core
28	USA	2008	Middletown – Norwalk	2	345 kV	600 MVA	38 km	1500 mm^2	Copper	XLPE	3x1 core
29	China	2009	Hainan - Guangdong	1	525 kV	740 MVA	32 km	800 mm^2	Copper	SCFF	3x1 core
55	Japan	2014	Chiba -Katsunan Line	2	275 kV	860 MVA	30 km	2000 mm^2/ 2500 mm^2	Copper	XLPE	3x1 core

Ref	Country	Tear	Name	No. of Circuits	Voltage (U0 0	Power	System Length (Total)	Conductor Size	Conductor Material	Insulation type	Cable type
61	Italy	2015	Sorgente-Rizziconi	2	380 kV	2000 MVA	47 km	2500 mm²/ 1500 mm²	Copper / Aluminum	XLPE / SCFF PPLP	3x1 core
62	Netherlands	2015	Randstad	2	380 kV	5280 MVA	20 km	2500 mm²	Copper	XLPE	3x1 core
68	Japan	2016	Kawasaki - Toyosu Line	3	275 kV	1710 MVA	22 km	2500 mm²	Copper	XLPE	tri-core cable
71	Norway	2017	Kollsnes - Mongstad	1	420 kV	300 MVA	30 km	1200 mm²	Copper	XLPE	3x1 core
75	Japan	1995	Katsunan -Setagaya Line	3	275 kV	1380 MVA	33 km	1200 mm²/ 1400 mm²/ 1600 mm²	Copper	XLPE	tri-core cable
76	Japan	1995	Yokohama - Kohoku Line	3	275 kV	2220 MVA	20 km	2000 mm²/ 2500 mm²	Copper	XLPE	3x1 core
77	Japan	1993	South Route by CEPCO (Chubu)	2	275 kV	1180 MVA	28 km	2500 mm²	Copper	XLPE	3x1 core
78	Japan	1999	West Route by CEPCO	2	275 kV	1280 MVA	23 km	2500 mm²	Copper	XLPE	3x1 core
79	Korea	T.B.A.	Nam Pusan - Buk Pusan	3	345 kV	520 MVA	22 km	2000 mm²	Copper	SCOF	3x1 core
80	USA	T.B.A.	Yonkers - East Garden City	1	345 kV	693 MVA	42 km	1267 mm²	Copper	HPFF / SCFF	3x1 core

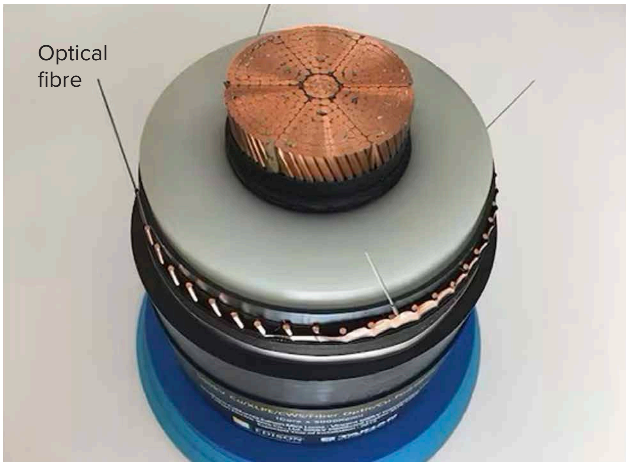


Figure 14. 500kV 2500mm Copper Conductor XLPE Cable with Laminated Copper Sheath and Embedded Optical Fibre Cable (T&D World[9])

5.3 XLPE Cable and Accessories—Design Factors

Conductors used on underground transmission cables are predominantly copper because of its higher conductivity to aluminium and small cross-section for the equivalent rating. Copper is also considered more corrosion resistant compared to aluminium and has a longer life. The early 500kV transmission cables had a cross sectional area of 800mm^2 but in recent times conductor sizes up to 2500mm^2 are common. A typical 500kV UGTL cable is shown in Figure 14.

This cable can achieve a rating or around 600MW single circuit and 1200MW double circuit. If power transfers of over 2000MW are required, there may need to be two sets of cables per phase per circuit. The embedded fibre optical cable is used for distributed temperature sensing (DTS) along the cable route to identify sites of overheating which can lead to electrical failure of the cable. The fibre optical cable can be installed on the conductor core (to directly measure the core temperature) or on the surface of the cable (to indirectly measure the core temperature). DTS monitoring equipment is normally installed at the substations which the cables terminate.

XLPE Insulation—In the early years of manufacture using XLPE, there was poor quality control in the manufacturing process. This caused (a) protrusions on the conductor shield; (b) contaminants in the insulation, including conductive and insulating particles, which have a significant effect on conductivity of insulation; (c) voids in the insulation, which permit electrical discharges. When put into service in environments subject to moisture, if there were ingress of water (via the joints/conductors or diffusion in the insulation), there was initial “water treeing”, which led to electrical treeing and finally breakdown of the insulation. These issues have been addressed by design and manufacturing improvements. The maximum operating temperature of the XLPE is in the range of 80°C to 90°C. Insulation thickness for cables rated at 400/500kV tend to be in the range of 27 to 32mm [13] .

Electrical Operating Stress (kV/mm) on a cable’s insulating shields is a major influence on the cable design and its service life. The design of HV cables in the 400 to 500kV range generally results in higher electrical stresses, but the installation thickness and overall diameter of the cables have to be designed to accommodate flexibility and practical installation. Data sourced from EPRI [8] shows that the electrical stresses with XLPE insulation shields increase with voltage levels—refer Figure 15. The electrical stresses on a 500kV nearly double compared to the values for 220kV

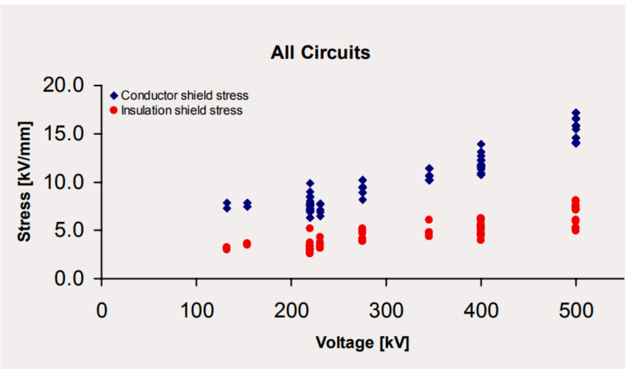


Figure 15. Conductor and Insulation Shield (Screen) Stresses Increase with Voltage (EPRI -2002 [8])

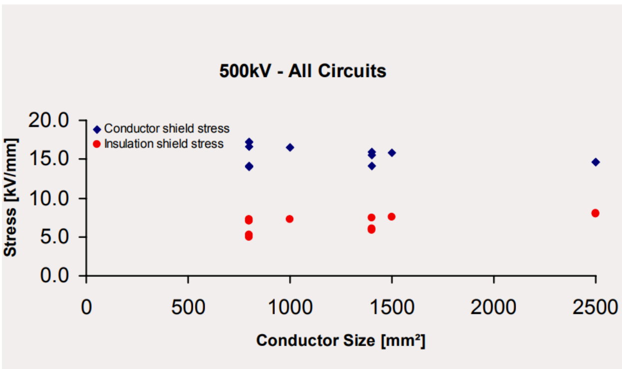


Figure 16. Variation in Conductor and Insulation Shield Stresses with Conductor Size at 500kV (EPRI 2002 [8])

[9] Engineering a 500-kV Underground System | T&D World (tdworld.com).

at around 15 kV/mm for the conductor and 8kV/mm for the insulation shield.

Smaller conductor sizes can be seen to have higher conductor shield stresses, while insulation shield stresses remain similar [8] as shown in Figure 16.

The breakdown voltage of XLPE varies significantly with temperature. It has an electrical breakdown voltage of around 50 kV/mm at room temperature but will reduce by 25% at 90°C and if increased from 90°C to 130°C will reduce by another 40% [13]. These factors influence the selection of cable conductor size and installation design to achieve the desired normal and emergency power transfer rating.

Cable Joints and terminations are essential components in a transmission cable system. Joints are required as cable is typically manufactured in continuous lengths of 500m to 1000m for transport logistics and also to suit site project specific requirements for joint bay location. Maximum lengths can be up to 1000m for transmission cables. This length range allows for transport of cable from factory to site on large drums or reels, so joints are required at regular intervals along the route.

Cable joints and terminations are required to meet the same electrical performance as the cable and an ideal joint would result in no mechanical, thermal or electrical discontinuity in the cable. In practice, joints have a larger radial dimension compared to the cable, and this leads to longitudinal components of stress in the joint component. Joints can also be a point for moisture ingress which can accelerate electrical breakdown and failure of the cable insulation.

Today's HV transmission cable accessories are manufactured using high quality materials, sophisticated production equipment and quality control. Prefabricated or pre-moulded joints and stress cones for terminations are now used extensively with HV transmission cables including at voltages of 400 to 500kV. A systems approach is required with accessories being purpose designed to match the cable. A diagram of typical XLPE cable joint is shown in Figure 17.

Cable terminations are required at the termination points of the cable usually in a substation or at overhead to underground transition points in a hybrid transmission line. Terminations for outdoor locations are air insulated of porcelain or composite insulator construction as shown in Figure 18. Gas insulated terminations are used where cables are required to connect directly to a transformer or gas insulated switchgear (GIS)—see Figure 19.

Joints and terminations are assembled on site by highly trained and qualified personnel. The environment for this work must be protected from the weather, clean and dust-free.

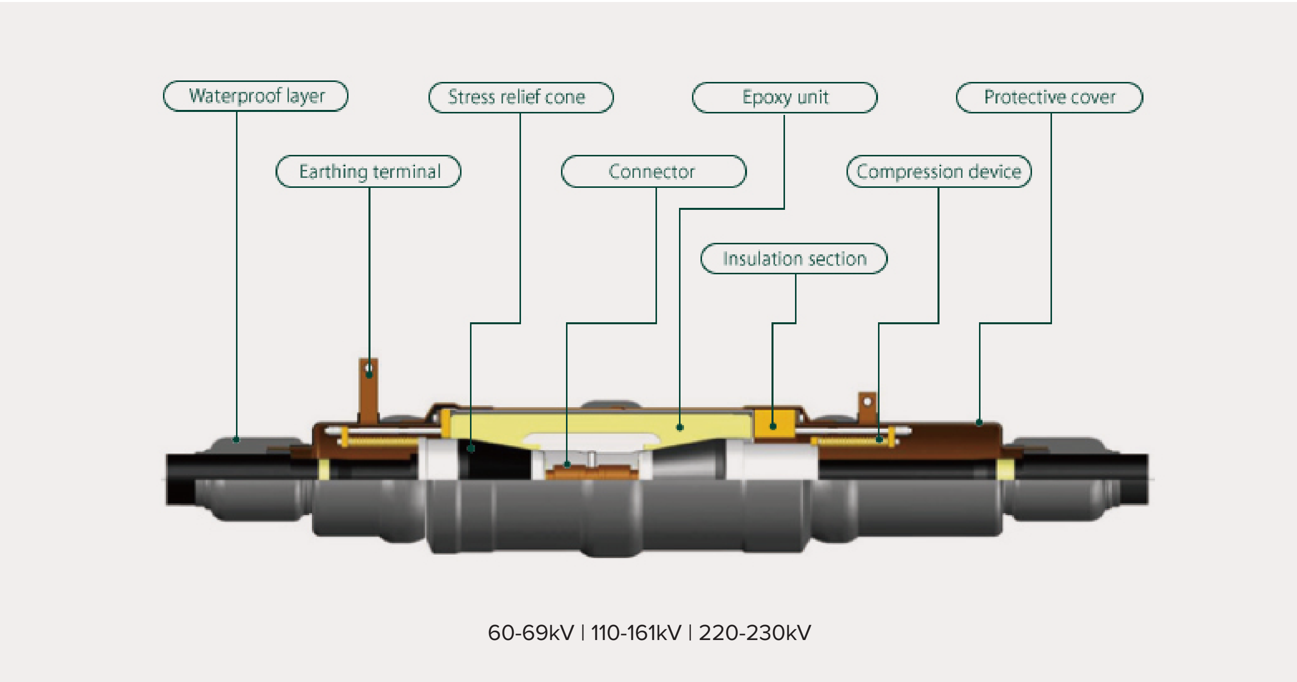


Figure 17. Prefabricated XLPE Straight Cable Joints (SWCC Corporation[10])

[10] https://www.swcc.co.jp/eng/products/siconex/cable_joint.html.

5.4 Transmission Cable System Design and Implementation

Critical Length—In contrast to overhead lines the impedance of an underground transmission cable is highly capacitive in nature—across the insulation, which is between the conductor and the external metallic sheath. The maximum length of AC transmission cable is limited by the capacitive charging current since charging current increases proportionally with length. As the length of cable is increased, a point is reached where the total charging current equals the cable rating. This point is known as the "Critical Length". The Critical Length can be calculated by equation below from EPRI 2015 [13]

$$Critical\ Length = I / Ic$$

Where:
I = normal rating, in amps
Ic= charging current, amps/m

The maximum feasible cable length must be significantly less than the Critical Length to transmit a reasonable amount of power. EPRI 2015 [13] provides examples. The values for XLPE cable from this reference are provided in Table 7.

Table 7. Critical Length for XLPE Underground Cables at Different Voltages (EPRI—2015)

Voltage (kV)	Critical Length (km)
138	193
230	130
345-400	85
500	76

Note: assumes 1600 mm^2 cable with XLPE insulation

Reactive Compensation Plant—Transmission cable capacitance causes voltage rise from the sending end to the receiving end. If the transmission cable capacitance is not compensated by inductance, the voltage at the receiving end would be higher than the voltage at the sending end. The effect can be most noticeable at times of low system load.

Reactive compensation is provided by supplying inductive power, which acts in the opposite way to capacitive power and consequently cancels it

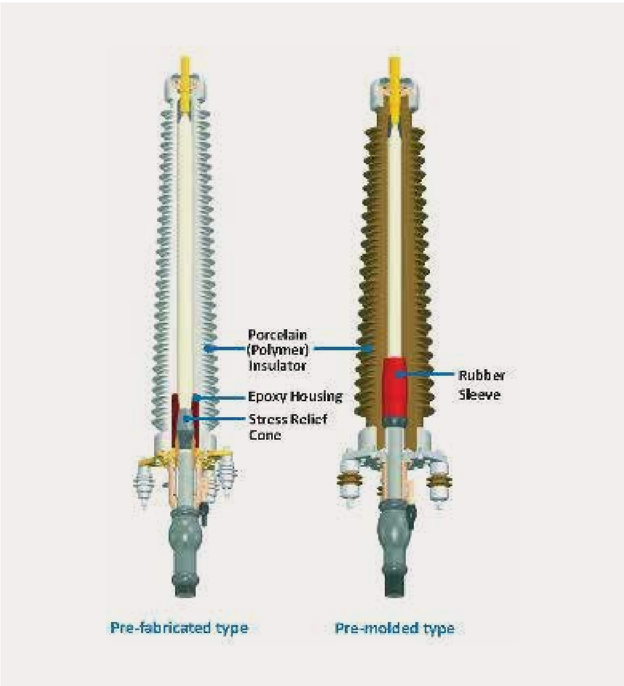


Figure 18. Outdoor XLPE Cable Termination
(LS Vina Cable & System[11])

Figure 19. Typical HV Gas Insulated Switchgear (GIS) with cable terminations Installed in Horizontal Position (Nexans / Frederic Lesur)

[11] https://lsvinacns.vn/outdoor-terminations.

out. Small amounts of capacitive reactance, say, in a short route length of cable of a few kilometres, can in most cases be compensated by the inherent inductance of generators and overhead lines in the system nearby. However, for longer route lengths, reactive power compensation plant in the form of passive compensation plant such as shunt reactors or active compensation plant such as static Var compensator (SVC) or STATCOM is required. The reactive compensation plant is normally installed at the terminal substations, but for long cable routes reactive compensation may be required points along the route to avoid unacceptable voltage rise at times of low load.

CIGRE -2017 [12] provides a guide for the amount of reactive compensation required per km cable route transmission cable. Reactive power compensation quantity is normally expressed in Mega Volt-Amperes Reactive (MVAr). From the CIGRE 2017 reference, as an example for a 400kV 2000mm^2 conductor cable, reactive compensation of 9.5MVAr/km would be required. The actual amount of reactive power compensation required would be determined in the planning phase of the project based on the system specific studies.

In comparison with an equivalent overhead line, an underground transmission cable line is estimated to produce 8 to 10 times more reactive capacitive power (Energinet [9]). This is therefore a significant cost in an underground transmission system.

Harmonic Filters and Resonance Mitigation Techniques—CIGRE 2017 [12] reports that low levels of harmonic distortion are present in the electricity supply voltage wave form mainly from: a) power electronic equipment by end users; b) HVDC connections; c) solar and wind farms. The addition of a long EHV transmission cable to a network can amplify the effect of exiting harmonics present in the supply systems. This is due to the high levels of capacitance in EHV transmission cables that can cause resonance with the inductance of the external system in power grid at a particular frequency. Inter-harmonics could also be from switching actions, especially transformers and cables.

Resonance can cause damage to components of the grid and must be avoided. This is mainly done by passive filters or in special cases by means of active filters.

The requirement for harmonic filters for the transmission line would be assessed in the planning phase of the project.

Cable Sheath Bonding—The effect of induced voltages in the outer metallic sheath of a cable must be considered in the cable system design. Induced sheath voltages are a function of the route length, phase currents, mean diameter of the metallic sheath, spacing between phase cables, supply frequency, and laying configuration of cable (e.g. flat, tre-foil etc.). Sheath bonding arrangements are required: 1) to protect people working on the cables from un-safe voltages; 2) to protect the cable from damage due to transient over-voltages that may occur during system disturbances or faults.

There are 3 main types of bonding arrangements for transmission cables. These are described below and illustrated in Figure 20, Figure 21 and Figure 22.

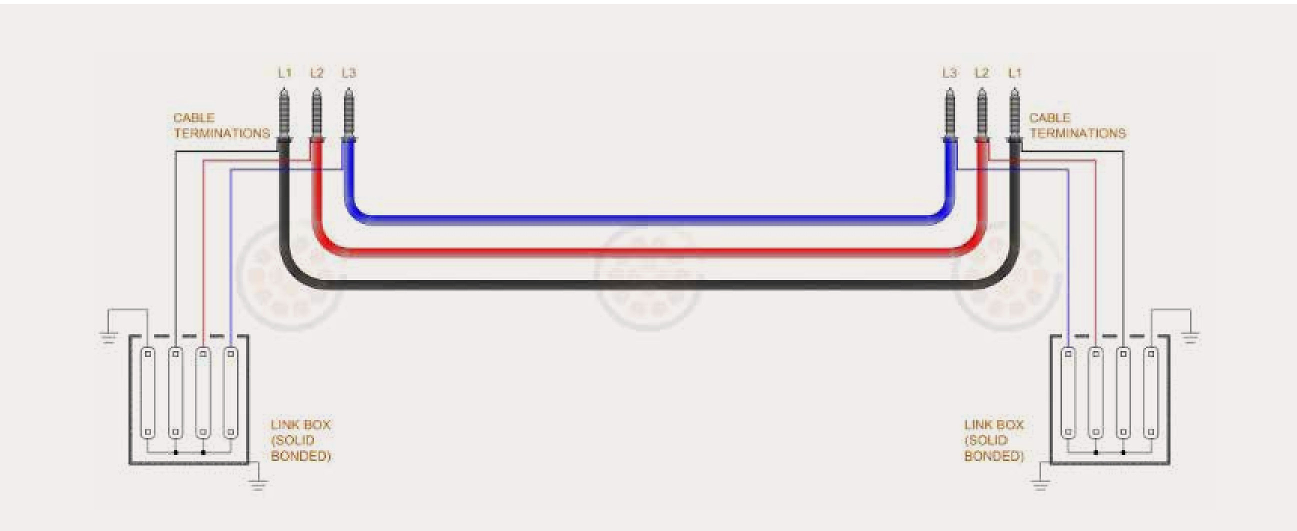


Figure 20. Solid Bonded Cable System (Electrotechnik[12])

[12] https://elek.com.au/articles/sheath-bonding-design-guide-for-hv-cables/

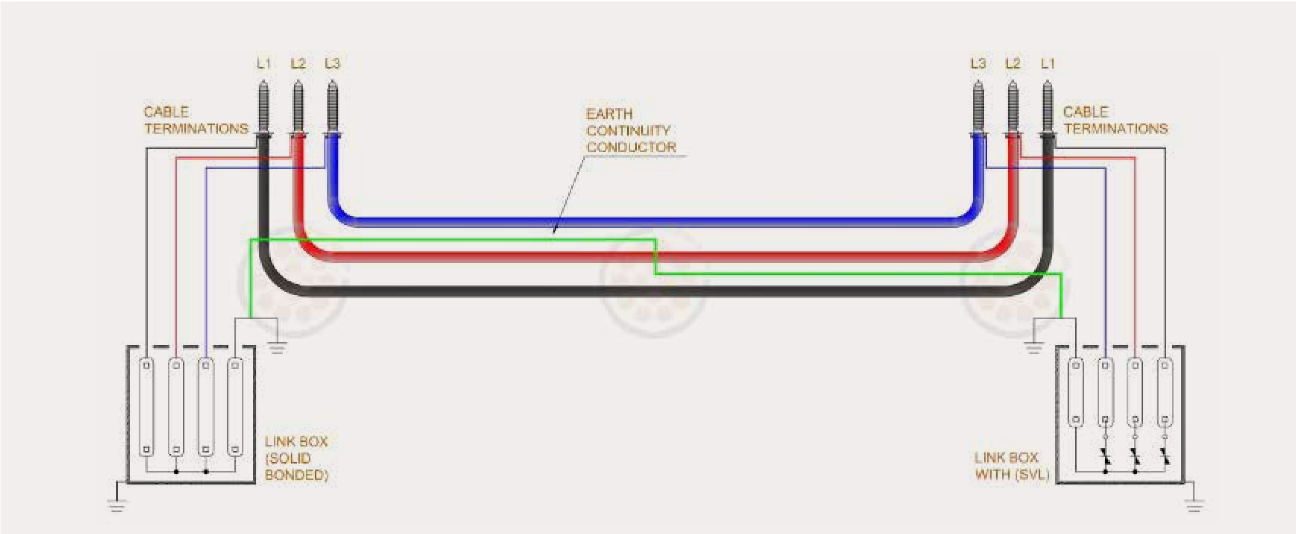


Figure 21. Single-point Bonded System (Electrotechnik[12])

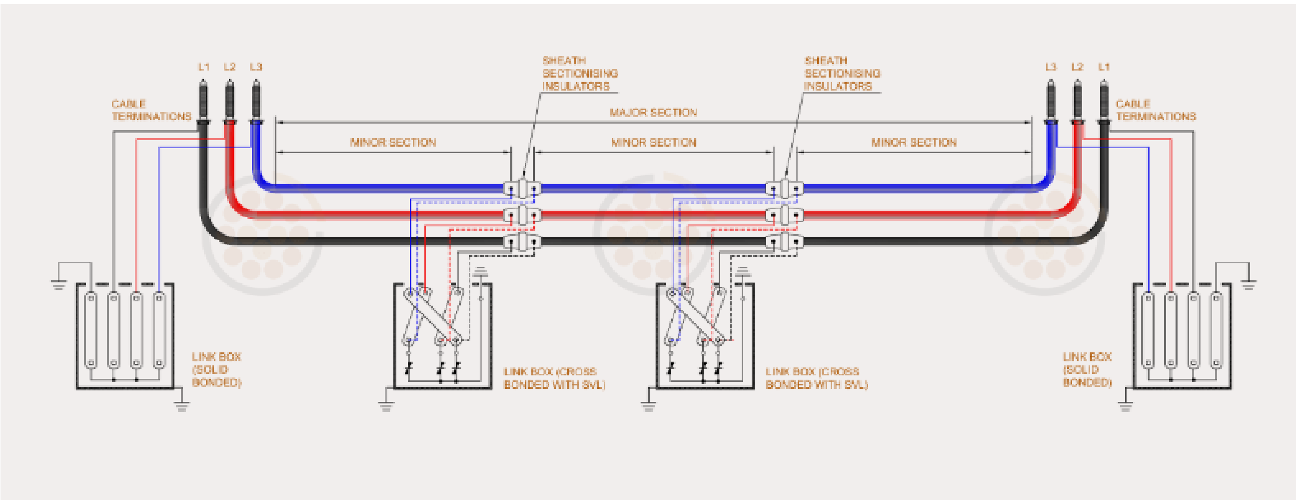


Figure 22. Cross-bonded System (Electrotechnik[12])

a) Solid bonding—with solid bonding there will be a continuous induced current flowing in the sheath, and this can be quite high (due to the close mutual coupling) with the phase conductors. This will significantly reduce the power transfer rating of the cable and result in additional losses. Therefore, this method is only used for very short lengths of underground cable.

b) Single point bonding—typically used for relatively short cable lengths, otherwise electromagnetic induction will produce a significant un-safe voltage on the cable sheath under steady state conditions. Transmission cables typically have a sheath voltage limit of 65V. Additional earthing points in the middle of a cable route may be required if this limit is exceeded.

c) Cross-bonding—transmission cables of reasonable lengths will generally utilise cross-bonding in the installation. With cross-bonding, the cable length is broken up into thirds and the sheath bonding rotates from, say, A phase to B phase to C phase at each third section. With cross-bonding, the electromagnetic induced voltages are cancelled in the cable. Circulating currents in the sheaths are also minimised reducing losses compared to solidly bonded systems. There are some variations with cross-bonded systems. Physically transposing the phase cables at the cross-bonding points will provide additional reduction in induced voltages and currents further.

To protect cables sheaths from phase to earth faults, surge protection devices, Sheath Voltage limiters (SVLs) are used in the link boxes and at termination structures.

Induced Voltages on Nearby Services—As with overhead transmission lines, underground transmission cables can induce voltages in nearby metallic services such as pipelines and other cables that run parallel. This can result in un-safe voltages on the services and damage such as corrosion of the metallic services. Bonding systems as described above can be employed to limit the induced voltages.

On-line Monitoring of Cable Temperature Performance—Modern XLPE transmission cable systems are designed with means of monitoring performance including cable temperatures. Temperature monitoring can be implemented by either:

(a) Discrete temperature sensors placed at hot spots or locations where the calculated thermal rating of the cable is known to be a limiting factor.

(b) Continuously along the cable—known as Distributed Temperature Sensing (DTS). This is normally achieved via a system using an optical fibre cable along the cable. The optical fibre can be integrated into the cable construction (see Figure 14).

Temperature data can be logged and analysed in real time for grid operations or used to review assumptions and parameters for installation and environmental conditions.

Matching overhead and underground transmission line ratings in a hybrid system based on continuous ratings can be economically unattractive, due to the larger cross sections or numbers of cables per phase for underground cables that is needed [12]. Consideration of the thermal inertia of underground cable and application of cyclic or short-term emergency ratings can result in a more optimal economic solution considering number of cables per circuit, conductor sizes, cable installation configuration.

5.5 Underground Cable Installation Methods

Transmission cable routes can comprise one or more different installation methods depending upon different factors and requirements along the route. The main installation methods are detailed below.

Cable Tunnel Installation is the most expensive option and is usually only justified in highly congested areas such as CBD areas or a section of a cable route into a major substation, that is shared by multiple circuits. Tunnels require extensive planning, design, and construction work as well as coordination with local authorities and other utilities. However, there are some advantages of tunnelling such as the opportunity to improve power transfer capability and providing a ready corridor for future cables.

Figure 23. Cable Tunnel Installation (Nexans / CIGRE 2017 [12])

Direct Buried Cable Installation is usually the least cost option and common in Europe and the UK, particularly in areas where cables are not under public roads. Direct buried sections require that the cable trench should remain open for the complete section between joint bays until all cables are installed, which can take up to 4 weeks or more. Depending on the project the length of these trenches may be up to 1000 metres or more. On completion of excavation works the trench is backfilled with special backfill materials and protective slabs are placed above the cables in the trench. Direct buried cables can offer improved power transfer capability compared buried duct installation with equivalent cable as thermal transfer from the cable is not reduced by air spaces around a cable within a duct.

The main disadvantages of direct buried systems include the fact that the trench must remain open for the cable installation work, which can be an inconvenience and safety hazard for pedestrians and vehicle drivers in the area. It also requires that the local council and/or road authorities agree to the installation and timeframes. As well, any installation of replacement or additional cables in the future requires complete re-excavation of the trench.

Buried Conduit or Duct Installation involves the use of ducts or conduits made from PVC or heavy-duty polyethylene (HDPE) and is the most common method for installation of underground cables. While buried duct cable installation is more expensive than direct buried cables it does have several advantages. For example, the trenching and duct installation for a section of cable between 2 joint bays, can be carried out progressively along the route, including re-instatement, thereby not requiring the total route section trench to be left open for long periods of time. Spare ducts can also be installed in the trench to allow for future network upgrades in an economic staged approach without having to re-excavate the whole route again.

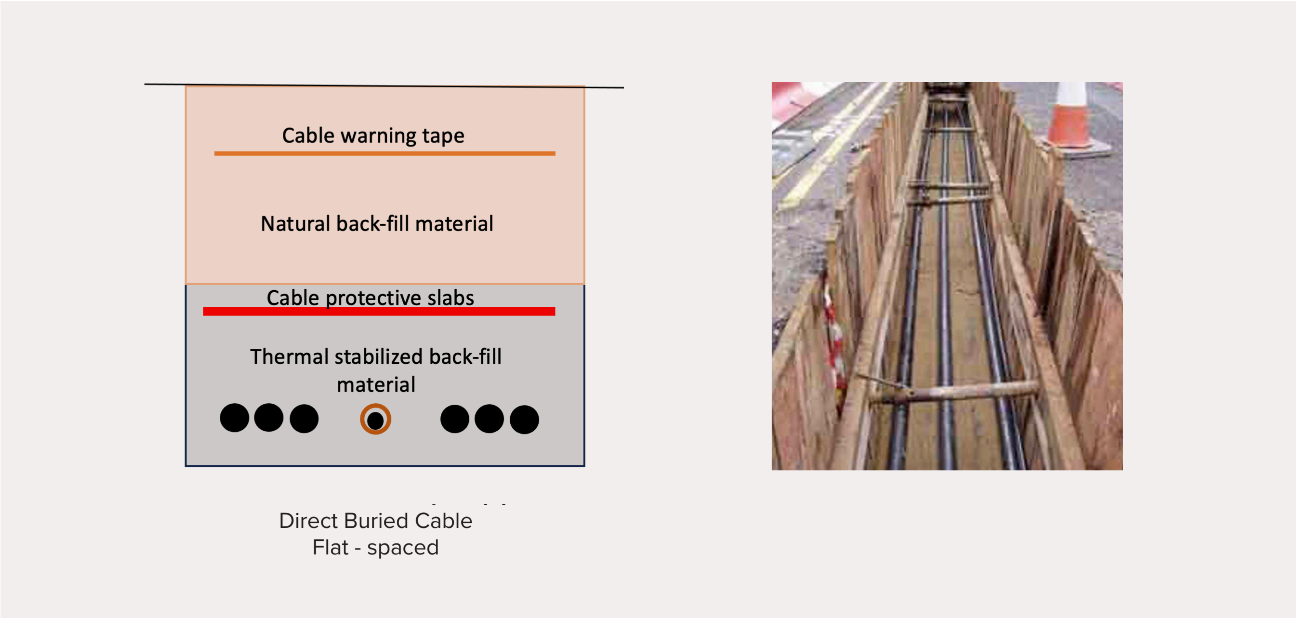


Figure 24. Diagram and Photograph of Direct Buried Cables and Trench (emfs.info[13])

Horizontal Directional Drilling (HDD) [12], is a steerable trenchless method of installing underground conduits and cables in a shallow arc along a prescribed bore path by using a surface-launched drilling rig, see Figure 26. A key benefit of this method is that is has minimal impact on the surrounding area. HDD is used when trenching or excavating is not practical. It is suitable for a variety of soil conditions and jobs including road, landscape, and water way crossings, with different types of heads used in the pilot-hole process depending on soil conditions. The bore profile can be designed to avoid other services and obstacles.

The elevations of the bore vary from a shallow open pit level and are then guided to the required depths across the crossing and finished at the ground level at the other end. A directional drilling machine drills the bore, and the cable conduit is drawn back through the bore. The depth of the bore can be monitored and adjusted accordingly as per the bore profile drawing during the drilling process.

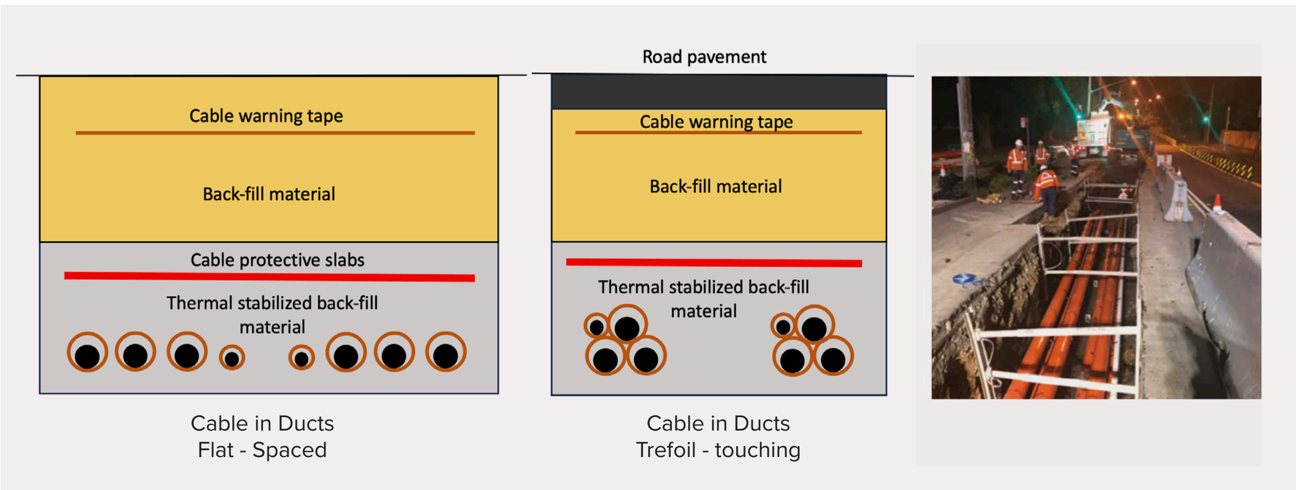
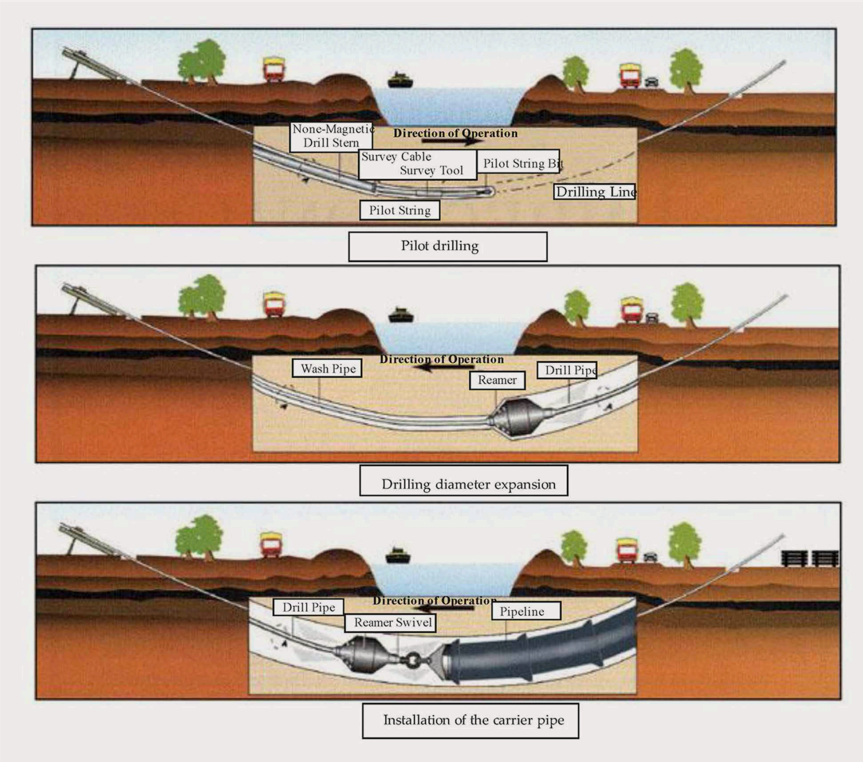


Figure 25. Diagram and Photograph[14] of Cable Duct / Conduit Installation (Photograph: TransGrid)

[13] https://www.emfs.info/sources/underground/types/.
[14] april-2021-project-update-newsletter-inner-west.pdf (transgrid.com.au).



Pilot Drilling:
Installing a pilot hole drilled from the surface at a pre-determined angle and along a prescribed path. During the pilot bore, a sonde (transmitter) and a tracking (receiver) device are utilized to be able to precisely locate and steer the drill string underneath the surface.

Reaming
Enlarges the pilot hole to achieve the required size. Reaming is usually performed in stages until the final desired diameter of hole is reached.

Pipe pullback
The pipe is connected to the drill string and then pulled from the exit pit side towards the entry pit side on the same pre-reamed path.

Figure 26. Horizontal Directional Drilling (HD DRILLING CONTRACTORS[15])

Sleeve bore or micro-tunnelling is like HDD. In most micro-tunnelling operations, the machine is launched through an entry eye and cable conduits are pushed behind the machine. This is a process that is often called pipe jacking. As the machine advances, more tunnel liner or conduit is pushed from the starting shaft, through the entry eye. Voids between the sleeve & conduits are filled with grout.

One disadvantage with HDD is that the cable profile will result in a greater burial depth which will de-rate the power transfer capacity. This can be mitigated by using special flowable fill material with low thermal resistivity to fill voids between the cable and constraining conduits.

Management of Thermo Mechanical Forces—Power cables, joints, and terminations are subject to thermo-mechanical forces due to the nature of cyclic loading that occur in a power grid over a daily and weekly basis. The design of a cable installation needs to analyse the thrust forces that apply in the different parts of the installation so that suitable construction methods to control and mitigate the risk of cable failures due to mechanical forces can then be applied in the design.

Installing cables in a wave formation often known as “snaking” (see Figure 23) is one way of mitigating thermo-mechanical forces. Constrained clamping of cables at points most exposed to thermo-mechanical thrust forces risk, is another method used.

Locations where snaking and clamping of cables are employed include the 15 to 25m sections at the entries of joint bays, inside cable tunnels, bridge structures, substations, and at cable termination points in substations or overhead to underground transitions.

Underground to Overhead Transition Structures

Hybrid overhead and underground transmission lines require overhead to underground transition structures at either end of an underground route segment. The size of these structures increases as the system voltage increase. The designs can be aesthetically improved depending on the locations. Examples of different overhead to underground transitions stations are shown in Figure 27.

To improve the aesthetics of the transition structure, there are designs where the underground cables are installed directly on the transmission tower or pole and

[15] https://www.hddrilling.co.za/what-is-horizontal-directional-trenchless-drilling.

1. T&D World (~220kV)
2. Public Service Commission of Wisconsin (~345kV)
3. IOP Today (~132kV)
4. HVDC example (Structurae / Harald Lutz)

Figure 27. Examples of Overhead to Underground Transmission Line Transitions

the surge arresters are also mounted on the structure. This may be suitable for transmission voltages of 132kV and below, but is generally restricted at 275/330kV and above for the following technical reasons:

- There is a generally a maximum height for making off the cables for safe working (for the cable jointers).
- The cables add significant weight and larger wind area for the structure (and may overload the capability of the structure).
- The UGTL cable termination will restrict access to the tower for maintenance.

5.6 Right of Way and Corridor Requirements

Transmission cable routes can vary and may be under public roadways, as well as on public or private lands. Underground cables can also be installed within an existing overhead line corridor or easements. Determining the right of way or easement corridor width for underground transmission cable lines involves considering a range of factors. Because underground cable systems are buried this immediately affects the corridor width. Factors influencing the determination of the corridor width include:

(a) Traffic Management, Safety and Security: All the logistics associated with the construction works need to be fully assessed for route options. Cable joint locations are also critical as those locations remain active worksites for the longest durations during the works - covering cable hauling in and jointing.

(b) Safety and Clearance Requirements: Clearances and safety considerations are essential to avoid physical and electrical interference with other utilities or potential hazards. The corridor width should accommodate required clearances from existing infrastructure such as water pipelines, gas lines, sewer systems, and other underground utilities. It should also ensure safe distances from structures, roads, railways, or other sensitive areas.

(c) Ground and geological conditions: The soil and ground conditions along the route influence excavation requirements, safety and environmental measures that may be required for the installation. These factors also influence the overall cost and feasibility of undergrounding.

(d) Cable Installation Arrangement and Method: The type and configuration of the underground cable system plays a crucial role in determining the corridor width. Factors such as the number of cables, their diameter, and the arrangement (single or double circuits) and power transfer capability, impact the space and the width of corridor required for installation, maintenance, and future expansion.

(e) Cable Protection and Depth: Underground cables require appropriate protection to ensure their integrity and prevent damage. The trench and corridor width needs to accommodate protective measures such trench shoring during construction and protective slabs above cables or ducts.

(f) EMF: EMF levels for underground cables tend to reduce more rapidly with distance from the line compared to overhead lines. However, consideration of prudent avoidance and recommended guidelines from lead organisations—ENA, ICNIRP and ARPANSA are important factors for influencing required corridor widths (Refer separate section on EMF in this report)

(g) Access and Maintenance Requirements: Adequate space is necessary to ensure access to the underground cable system for ongoing maintenance, repair, and monitoring purposes. The corridor width should allow for safe and convenient movement of personnel, equipment, and vehicles required for these activities. This includes considerations for vertical access points such as manholes or vaults.

(h) Environmental and Land Use Factors: Environmental considerations such as protected areas, environmentally sensitive regions, cultural heritage, and ecological requirements may influence the corridor width. Additionally, the specific land use and land ownership conditions can impact the determination of the corridor width, including considerations of private property boundaries or public access requirements.

(i) Future Expansion and Flexibility: Planning for future expansion or upgrades is crucial when determining the corridor width for underground transmission cable lines. Providing additional space within the corridor allows for potential cable system expansion, accommodating increased capacity or incorporating future technological advancements.

(j) Regulatory and Industry Standards: Compliance with local regulations, codes, and industry standards is essential in determining the corridor width for underground cable lines. These standards may specify minimum clearances, separation distances, or recommended practices that influence the width of the corridor.

The determination of the corridor width for underground transmission cable lines involves coordination among various stakeholders, including utility companies, landowners, regulatory agencies, and engineering professionals. It aims to balance technical requirements, safety considerations, environmental impacts, and future needs while adhering to applicable regulations and industry best practices.

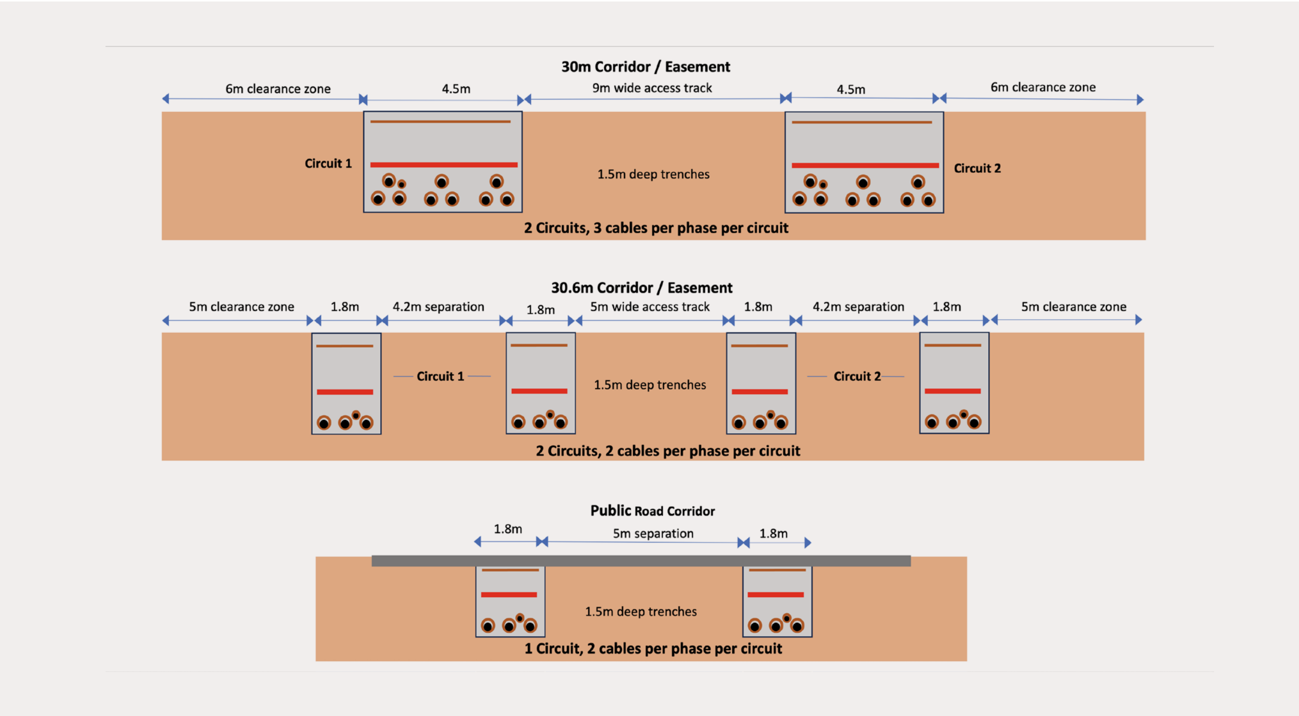


Figure 28. Indicative Installations and Corridors for 500kV Underground Cables

400kV and 500kV Underground Cable Corridor Examples

Examples of corridor requirements for 400kV and 500kV underground cable projects are found in some of the references for this report:

- 400kV double circuit (2 x 2200MVA) arrangement comprising 4 trenches occupying a total corridor width of 21m (CIGRE 2017 [2])
- 400kV AC Interconnector, Idomlund Denmark to German border [9, p. 40] - a total corridor width of 36m was required to accommodate construction and a 30m wide right of way for ongoing operation for a 2500MVA double circuit underground transmission line.
- Western Renewable Link Underground Construction Summary [14] identified a requirement for a nominal 30m wide easement for a double circuit underground installation.

Indicative 500kV double circuit underground line corridors are shown in Figure 28. The general requirements for a 2 x 2500MVA line are:

- Trench, cable laying configurations (flat or tre-foil) and separation between cable groups are determined based on power transfer requirements and spatial constraints.
- A vehicle access track is needed for construction and maintenance.
- A buffer zone of 5–6m at each side of the corridor is needed for work access and EMF prudent avoidance. This can be varied based on estimated EMF levels and future access requirements.
- Trenches separated by 5 to 6m to allow for access, construction shoring, and separation of circuits to meet the power transfer rating requirements.
- Additional width for temporary work zones may be required during construction, e.g., for large volumes of stockpiling and installation of drainage.

In some locations where under boring or HDD is required, the easement width may need to be increased to accommodate the drilling equipment and greater separation of the trenches to meet power transfer rating requirements.

5.7 Power Transfer Capability

The transfer capability of underground cables is a function of several factors:

- conductor type (copper or aluminium);
- conductor cross-sectional area (mm^2);
- conductor resistance (Ohms/m);
- installation method—direct buried, ducts or open air (e.g., tunnel);
- maximum operating temperature (typically 900C for XLPE insulation);
- laying configuration (flat or tre-foil);
- cable burial depth;
- metallic sheath material (copper or aluminium) and method of bonding (single point or cross-bonding);
- backfill and ground thermal resistivity;
- the ground and ambient temperatures;
- spacing between adjacent cable circuits.

The maximum operating temperature of the conductor in the cable is limited by the temperature performance limits of the insulating materials. There are 2 types of cable temperature limits that are referred to in the industry. For XLPE cables these limits are as follows: (reference EPRI 2017 [13]):

1) maximum normal (continuous) temperature—90°C
2) maximum emergency temperature—105°C

Transmission system operators apply the higher operating temperature of 105°C for short term emergency rating purposes. This allows the cable to have higher power transfer rating in an emergency such as an outage of another circuit in the network. The emergency rating can be applied for a short period, typically 2 hours, to allow operators time to take controlled actions to restore the network, followed by a period of loading at 50% of the maximum continuous rating.

The power transfer capability for the underground transmission cable is specified by the utility and the cable and installation is then designed to meet that requirement.

Most of the above factors are considered in the design with the main variable factors which influence dynamic ratings of underground cables are the maximum operating temperature, the ground temperature, and the ambient air temperature. Because underground cables are buried at depths of 1 to 2 metres below ground, the ground temperatures are relatively constant at these depths.

Underground cable ratings are not affected by annealing (conductors are already annealed) but limited by the maximum temperature for operating the XLPE insulation.

The XLPE key properties remain relatively stable at temperatures below 80°C. If this temperature is exceeded, it can cause accelerated ageing of the insulation and significantly reduce its life. The insulation may go through irreversible chemical changes which effect electrical breakdown strength and make it susceptible to electrical failure.

XLPE has an electrical breakdown voltage of around 50kV/mm at room temperature, but will reduce by 25% at 90°C and if increased from 90°C to 130°C will reduce by another 40% [13].

Utilities have typically restricted overload capability to a maximum temperature of 105°C. A temperature rise from 80°C to 105°C will only produce an additional 30% of extra cable rating.

A list of EHV underground cable projects is provided by CIGRE, 2017 [12, p. 170]. The list indicates that for 400–500kV cable projects utilising 2500mm^2 copper conductor XLPE cable, normal continuous power transfer capacity are in the range of 1600 to 1800MW per circuit. [12] The list indicates that for 400 – 500 kV cable projects utilising 2500mm^2 copper conductor XLPE cable, normal continuous power transfer capacity are in the range of 1600 MW to 1800 MW per circuit.

5.8 Reliability Performance

The CIGRE publication –Technical Brochure 815—Update of Service Experience of HV Underground and Submarine Cable Systems (2020) [15] provides a recent and comprehensive analysis of underground transmission cable reliability performance. The reporting period was for 10 years ending December 2015. The report covers both fluid-filled cables (GC, SCOF, and HPOF) and extruded cables (XLPE, PE, EPR). Because XLPE cable, installed on land, is the most used around the world and likely to be used in Australian projects the results and analysis of XLPE cables are detailed below only. The CIGRE report did report higher failure rates for fluid-filled cables compared to extruded cables, partly attributable to greater age of the fluid-filled cable grouping.

Cable failures can be categorised as:

(a) internal failures of cable, joints or terminations involving conductor, insulation, screen, over-sheath, moisture barrier, with potential causes being:
- lightning, transient or switching surges—which are higher than the rating of the surge protection;
- water ingress—generally at joints, which can lead to a reduction of sheath resistivity and electrical breakdown on the cable;
- manufacturing defects;
- localised hot spots leading to thermal or electrical failure;

(b) external failures including:
- third party mechanical damage e.g., dig-ins, vibration from machinery;
- corrosion;
- environmental impacts such assoil erosion or tree roots;
- wildlife impacts from burrowing animals and termites.

Cable Failure Rates reported by CIGRE in 2020 for XLPE transmission cable installed on land are summarised in Table 8. These failure rates are only for the cable component of the system, failure rate of the accessory components is reported separately. Note that no failures were reported for 500kV cables, largely attributable to the relatively small amount of this cable in service, i.e. 291kms out of 227,554kms in this CIGRE survey.

The report also concluded that for internal faults in XLPE cables, insulation system failures are the major cause (64 %), followed by over-sheath failures (18 %).

Table 8. Failure Rates of HV XLPE Land Cables—Faults/100km-year (Adapted from CIGRE—2020)

	All voltages	60–109kV	110–219kV	220–314kV	315–499kV	500kV and above[1]
Internal failures	0.0686	0.0702	0.0199	0.229	0.0511	0
External failures	0.0368	0.0211	0.0717	0.0403	0.0511	0
Unknown origin failures	0.0055	0.0026	0.0139	0	0	0
All failures	**0.111**	**0.0939**	**0.108**	**0.269**	**0.102**	**0**

1. The 500kV failure rates are based on a relatively small quantity (171km) of installed cable reported in the CIGRE 2020 report.

Table 9. Number of External Faults Reported for XLPE Land Cables (Adapted from CIGRE—2020)

Failure Type	Installation Mode	
	Direct Buried	Ducts
External—Total	31	30
External—Abnormal System Conditions	1	0
External—Other Physical External Parameters	3	3
External—Third Party Mechanical Damage	27	27
External—Corrosion	0	0

Table 10. Failure Rates of Accessories for Extruded Cables (XLPE, EPR, PE) on Land—Faults /100 Units—Year (adapted from CIGRE—2020)

Component	All voltages	60–109kV	110–219kV	220–314kV	315–499kV	500kv and above[1]
Joint	0.0047	0.0021	0.0160	0.0266	0.113	0
AIS Termination Fluid Filled Porcelain	0.0107	0.0018	0.0111	0.570	0	0
AIS Termination Fluid Filled Composite	0.132	0.0362	0.0307	0.344	0.833	0
AIS Termination Dry Porcelain	0.0036	0.0040	0	0	0	0
AIS Termination Dry Composite	0.0880	0.111	0	0	0	0
GIS or Transformer Termination Fluid Filled	0.0127	0	0.0265	0.0347	1.00	0
GIS or Transformer Termination Dry	0.0068	0.0039	0.0114	0.155	0	0
Other Components	0	0	0	0	0	0

1. The 500kV failure rates are based on a relatively small quantity (171km) of installed cable reported in the CIGRE 2020 report.

The results summarised in Table 9 from the CIGRE 2020 report show that 3rd-party damage is the most common cause of external failures for XLPE cable installations. The report did note, however, that the external failure rate has decreased around 40% for XLPE cables since previous CIGRE report (TB379) on this topic was published. This indicates better positioning and Geographic Information System (GIS) mapping of cable systems today than before. However, better protection of the cables via the use of ducts and/or warning tapes can also be a possible explanation for the reduction in the external failure rate. “Dial before you dig” programs have also improved over that period with messaging in media and improved on-line information access.

Cable Accessory Failure Rates from the CIGRE 2020 report in Table 10 show the failure rate for internal faults involving the cable accessories. The results show that cable terminations tend to be more prone to failure than joints with fluid filled terminations being most prone, particularly at the higher voltages. As with cable failures, due to the relatively limited quantity of 500kV cables in service, there were no failures reported.

The report also commented that most faults in XLPE cable systems occur within the first 10 years of operation, with a very large number of faults occurring during the first two to three years of operation. Most failures in XLPE cable systems during the first 10 years of operation are found in accessories, whereas failures in the latter years of operation occur in the cable.

Outage and Repair Times data from the CIGRE 2020 report shows that the outage times in days for repairs for extruded cables (XLPE, EPR, PE) on land ranged from 9.3 to 33.9 days. The longer outage and repair times for underground transmission cable compared to overhead transmission lines is a disadvantage from a reliability perspective.

5.9 Construction Phase

Underground installation methods were described in section 5.5 Underground Cable Installation Methods.

An Environment Management Plan (EMP) needs to be implemented for any underground transmission line project. Requirements for this plan will have been identified in the overall Environmental Impact Study in the planning phase of the project.

Open cut trenching is the most common method of constructing an underground transmission cable system. Excavation equipment is used to remove any asphalt road surface, concrete, topsoil, and normal soil to the required depth of the cable (typically 1m to 2 m). This will lead to large stockpiles of material which will have to be removed to an appropriate dump site.

Trenches are dug in sections along the line route (typically the cable drum lengths are between 500—1000m), and after the trench is dug, there is the need to shore up the trench—to maintain the trench sides and provide safety to the workers. There is also often a need to install steel covers (for driveway access and worker crossings) along the trench sections. Trenches will need to be left open for long periods and will suffer from rain and water ingress. Any such water needs to be pumped out and treated before disposal.

The steps in a typical underground cable transmission installation after trenching are:

1. installing a layer of bedding sand;
2. installing the conduits on the bedding sand (if using ducts);
3. installing a backfill material (typically weak mixed concrete) with good thermal properties (for much of the trench volume);
4. positioning cable pulling equipment and cable drums at the ends of the trench section;
5. installing the cables in the conduits;
6. reinstating the ground surface to the condition it was originally in or better;
7. making off the joints in the joint bays.

There are likely to be major obstacles along the cable route, such as waterways, major highways/motorways, railroads where under boring or horizontal directional drilling is required to minimise impact on the service corridor.

Construction Timeframes for an underground transmission cable line will vary depending upon factors such as route length, geography, environment, and packaging of segments of the project for concurrent work.

ENTSOE and Europecable reported [16]:

“The average installation time per km (direct buried in urban area) is 1.5 months/km for opening the trench per circuit, cable laying and closing the trench. For the cable laying alone, 1–2 days per km and per phase is required. Installation times indicated here refer to working with one civil work team only. By increasing the number of teams, installation times can be reduced. Also, if there are more systems in the same trench timing will only increase by approximately 10–20%.”

The case studies found in the Chapter 7 report of this study of this report also provide a comparison of construction timeframes for various projects of relatively short lengths (5.6 to 26km), which are in the range of 2 to 4 years.

5.10 Operation and Maintenance

Policies, plans, and strategies for operation and maintenance of transmission lines form a major part of a utility’s overall life-cycle asset management regime.

The basic categories of maintenance activities for underground transmission lines include:

(a) periodic line route patrols and visual inspections to identify risks such as:
    - construction activities involving excavation near cables;
    - changes in environmental conditions—waterways, soil erosion, vegetation;
    - terminations;
    - easement / corridor clearances;
- cable tunnels, bridge structures etc.;

(b) periodic testing and maintenance: this includes components such as:
    - outer sheath tests;
    - cross-bonding system—link boxes, surge voltage limiters (svls);

(c) preventative maintenance or defect repairs:
    - repair or replacement of defects identified from patrols, inspection, or testing;
    - locating and repairing sheath faults or damage;

(d) emergency restoration or repairs after a failure:
    - cable dig-ins;
    - sheath faults;
    - joint or termination failures.

Table 11. Typical Duration of Repair Works for Cable Joint Failure under a Road (adapted from CIGRE 2017)

No.	Task	Duration (Days)
1	Fault location	1
2	Road traffic management	1
3	Excavate to confirm fault location	1
4	Excavation of joint bay	1
5	Remove faulty joint	1
6	Excavate joint bays	2
7	Lay new cable	1
8	Install new joints (2)	4–14
9	Reinstate road	1
10	Test and put into service	1–2
	Total	**14-25**

One of the major disadvantages of underground cable transmission lines compared to overhead lines is that repair times for major failures involving joints or terminations are significantly longer. For example, the work typically required to replace a failed joint involves a number of activities [12] that can take up to 25 days as shown in Table 11. By comparison with overhead transmission, as stated in 4.5 Reliability Performance, most repairs, including fallen structures can be restored within one week.

The literature review (Appendix A) reported that asset management is a crucial part of operations and maintenance of underground cable system. In numerous instances, it is challenging to assess the physical conditions of underground cable assets due to their installation locations that are either hard to reach or inaccessible [17]. Also, existing tests used to determine the remaining lifespan of an underground cable circuit necessitate obtaining an actual cable sample from the field and conducting laboratory testing. However, acquiring samples from an existing underground cable circuit is typically difficult and usually only possible after a cable fault has taken place [17]. Non-destructive in-situ testing of cable insulation can also be undertaken.

5.11 End of Life and Decommissioning

Expected Lifetime of HV Transmission Cables

Most references [12] [2] support an estimate of on average of at least 40 years for XLPE cables based on tests and operating experience. XLPE transmission cables have been in service since the mid 1970s. The reasons for end of life of a cable system are typically:

- Network planning analysis determines that continued operation of the underground cable circuit is not the most economic option to meet network demand forecasts.
- Service condition result poor reliability or reduced transfer capacity.

Maintenance policies and practices including inspection and testing are also a key factor. Replacement of cables in tunnel systems or ducts is a practical economic option compared to direct buried cable systems which cannot be replaced without extensive excavation works.

End of Life Works

Decommissioning an underground cable transmission line involves several requirements and activities to ensure the safe and efficient removal of the infrastructure. Some common requirements and activities associated with the decommissioning process include:

(a) Planning and Coordination: A comprehensive decommissioning plan needs to be developed, outlining the objectives, timeline, resources, and stakeholders involved in the process.

(b) Safety Assessments: This involves assessing risks such as electrical hazards, hazardous materials, structural integrity, and ensuring compliance with safety regulations.

(c) Equipment Removal: Where it is necessary to remove cables, the physical removal of underground cable infrastructure is a key activity. In most cases the redundant cables can be removed from ducts, allowing the ducts to be reused. In other cases, such as direct buried cables it is often not economically feasible to remove all of the cable unless there are specific environmental factors.

(d) Cable Disposal: Proper disposal of the decommissioned cables is essential. Recycling or proper disposal methods should be followed to minimize environmental impact. This may involve separating cables into different material types, such as copper or aluminium conductors, for recycling. Compliance with environmental regulations regarding waste management and hazardous materials is also crucial. With cables, in some cases it may be feasible to obtain scrap value, e.g. copper and aluminium conductors.

(e) Site Restoration: The decommissioned site should be restored to its original condition or repurposed appropriately. This may include backfilling the excavated trenches, re-establishing the land contours, restoring vegetation, and implementing erosion control measures. Site restoration activities should adhere to environmental regulations and any specific requirements set by local authorities.

(f) Documentation and Reporting: Comprehensive documentation of the decommissioning process is important. This includes recording project details, safety procedures, equipment removed, disposal methods, and any environmental monitoring carried out during the process. Reporting to relevant regulatory bodies, utility companies, or stakeholders may also be required.

(g) Stakeholder Communication: Effective communication with stakeholders throughout the decommissioning process is vital. This includes notifying affected parties, such as landowners, local communities, and regulatory agencies, about the decommissioning activities, timelines, and any potential impacts. Providing regular updates and addressing concerns helps maintain transparency and foster positive relationships throughout the process.

(h) Regulatory Compliance: Compliance with applicable regulations and permits is essential throughout the decommissioning process. This may include obtaining permits for excavation, waste disposal, environmental monitoring, or any other specific requirements set by local authorities.

(i) Safety and Environmental Monitoring: Monitoring activities during the decommissioning process are important to ensure compliance with safety and environmental standards. This may involve monitoring air quality, water quality, noise levels, or other environmental parameters. Safety monitoring should also be conducted to ensure the well-being of workers and to prevent any accidents or incidents.

It is important to note that the specific requirements and activities for decommissioning an underground cable transmission line may vary depending on local regulations, project specifications, and environmental considerations.

6.

HVDC Transmission Lines (Overhead and Underground)

This section provides an overview of HVDC overhead and underground transmission infrastructure.

6.1 Overview of HVDC Transmission Technologies

High-Voltage Direct Current (HVDC) transmission systems are a proven alternative technology to AC systems for transmitting large amounts of electrical power over long distances. To date the application of HVDC transmission has mainly been with submarine cables or transmission system interconnectors that have no requirement for other circuit connections along the route.

The main components of a HVDC transmission system include:

(a) Converter Stations: These stations are located at the endpoints of the transmission line and are responsible for converting AC power to DC power (rectification) at the sending end and converting DC power back to AC power (inversion) at the receiving end.

(b) Transmission Line: HVDC transmission lines are typically made of overhead lines, underground cables, or a combination of both. They carry the DC power between the converter stations.

Figure 29. Single Circuit Guyed HVDC Overhead Transmission Line (Left) and Self-Supporting HVAC Transmission Line (Right) (AlternativeUniversity.net[16])

Some of the key characteristics and advantages of HVDC transmission systems compared to AC transmission systems are as follows:

(a) Lower Transmission Line Losses: HVDC systems have lower line losses compared to AC systems, especially over long distances. This is because the conductors for HVDC tend to be larger cross-sectional area with lower resistance compared to equivalent rated AC lines and also there is no reactive power losses. However, energy losses in the converter stations may be significant, depending on the size and type of technology.

(b) More compact overhead line structure or towers normally requiring 2 conductors (or bundles) per circuit. An example is shown in Figure 29. Note that only 2 main conductors are required on the DC line compared to 3 phases on the AC line. The AC tower structure is consequently much larger.

(c) More compact underground cable trench profiles due to the reduced number of cables and conductors for the same power transfer rating. An example is shown in Figure 30.

(d) Interconnection of Asynchronous AC Systems: HVDC allows the interconnection of AC systems that operate at different frequencies or have different characteristics. It enables power transfer between systems that would otherwise be incompatible, facilitating the integration of renewable energy sources or the interconnection of grids between different regions.

(e) Controllability and Stability: HVDC systems offer better controllability and stability compared to AC systems. The ability to regulate power flow and control voltage helps in managing power grids and improving system reliability.

(f) Lower Environmental Impact: HVDC transmission lines have a smaller footprint and emit lower electromagnetic fields compared to long-distance AC lines. Additionally, the use of underground cables reduces visual impact and environmental concerns.

16 https://alternativeuniversity.net/aec/electricity/hvdc/.

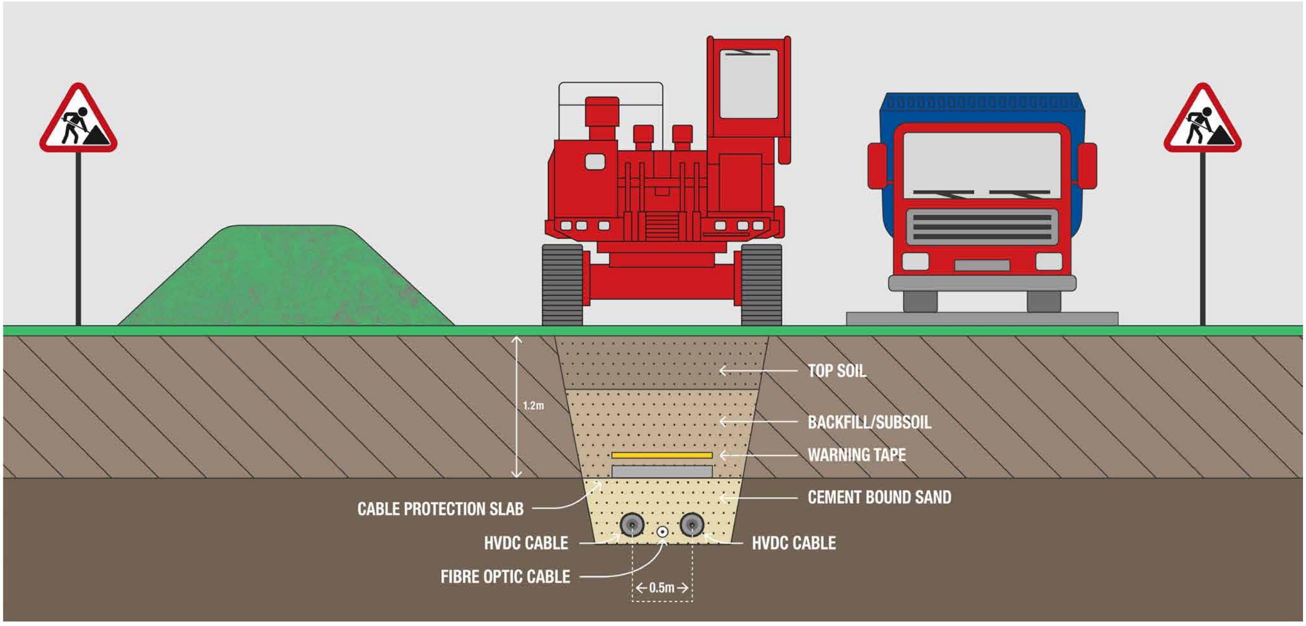


Figure 30. Example of HVDC Single Circuit Underground Cable Installation (gridlinkinterconnector.com David Barber)

(g) EMF for HVDC systems is discussed in the section 7 Electromagnetic Fields of this report. EMF from HVDC are static fields and generally lower than similar voltage AC transmission lines.

(h) Efficient for Long-Distance Transmission: HVDC is particularly suitable for transmitting electricity over long distances, such as across continents or seas (using submarine cables). It can transmit power over thousands of kilometres without significant losses. DC conductors and cables can carry significantly more current for the same conductor or cable size.

However, there are some disadvantages with HVDC when compared to HVAC transmission in Australia:

(a) HVDC systems are generally more expensive to build compared to AC systems due to the requirement for large AC/DC converter stations and specialized equipment contribute to higher initial costs (The economics and break-even distance for HVDC compared to HVAC is discussed later in this report).

(b) Intermediate connections for loads or generation along a line route will require additional converter stations, increasing the cost of project.

(c) There is limited experience with the design and operation of HVDC transmission in Australia.

(d) Design related impacts such as longer insulator strings compared to AC, measures required to mitigate increased corrosion risk, and noise levels from the lines and equipment at converter stations [18] must all be considered.

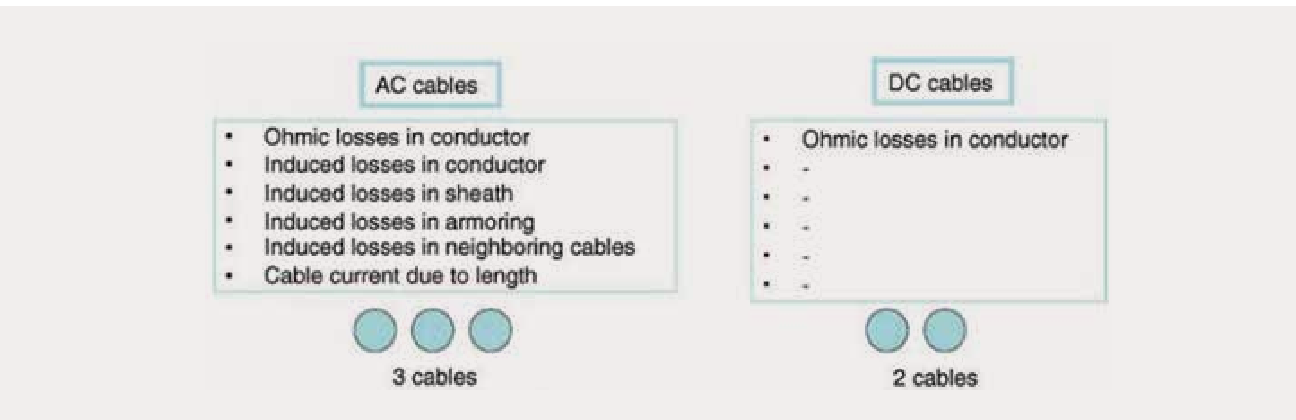


Figure 31. Comparison of HVDC and HVDC Cable (Extruded Cables for High-Voltage Direct-Current Transmission [19])

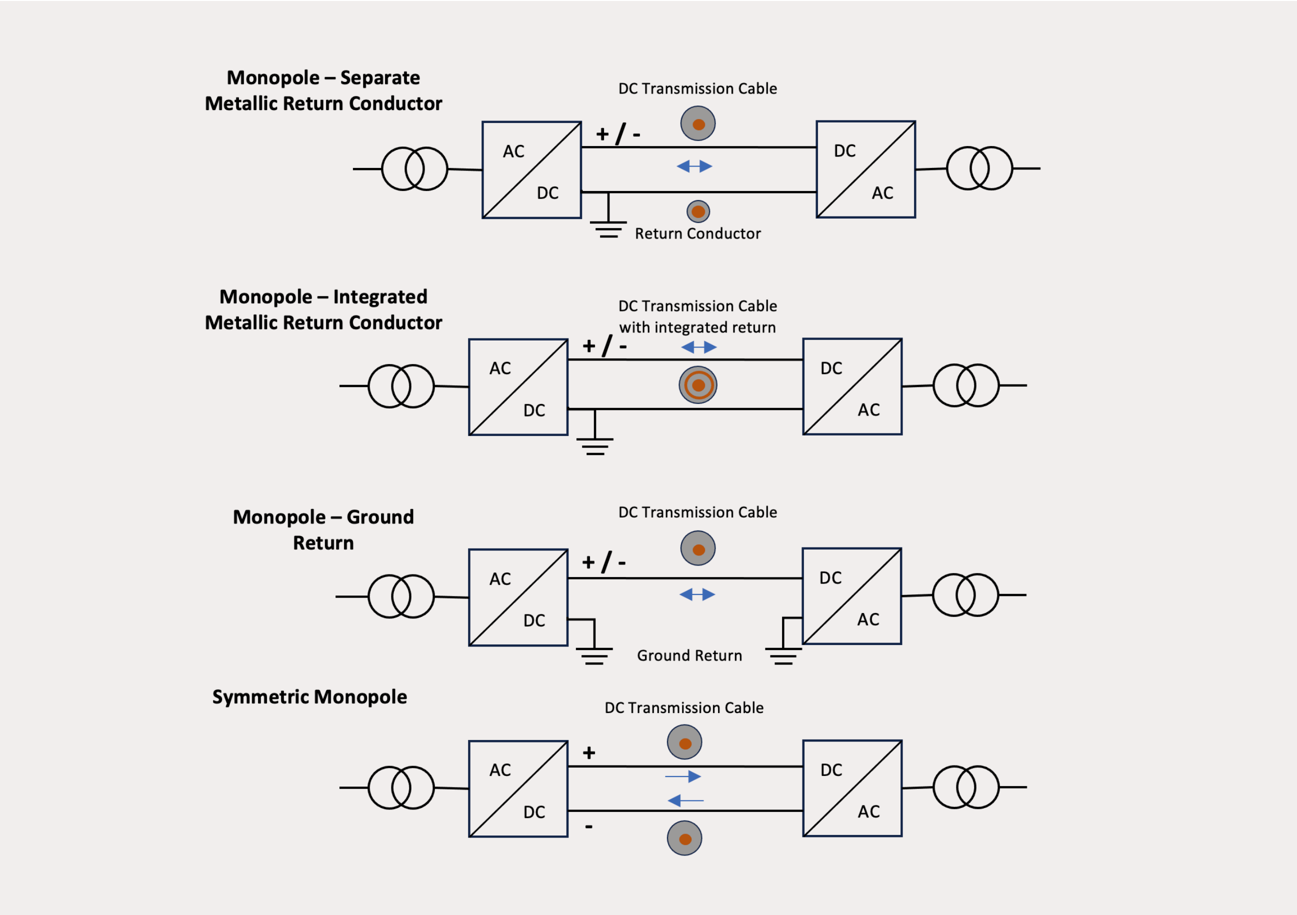


Figure 32. Monopole HVDC Configurations

Both AC and HVDC transmission systems have their own applications and are used based on factors such as distance, power capacity, grid interconnections, and cost considerations. The choice between AC and HVDC depends on the specific requirements and constraints of the power transmission project.

The Literature Review (Appendix A) reported that advantages of HVDC cable over HVAC cable are shown through Figure 31 [19]. A very thorough comparison between the HVAC and HVDC system is presented in [20]. The results show the additional sources of losses in HVAC cables compared to HVDC.

6.2 HVDC Transmission Systems Topologies

There are several types of HVDC systems and topologies, each having advantages and disadvantages depending upon the application requirements.

Monopolar HVDC Systems

Monopole DC links are most applicable to power transmission over long distances, with submarine cables. An example is the Basslink interconnector between Victoria and Tasmania, which is approximately 300km long with a capacity of 500MW at 400kV DC. Examples of network topologies for monopole systems using cables are shown in Figure 32.

With a Monopole HVDC system, there are important design considerations for the ground electrodes as follows [21]:

1. Current—both DC and harmonic currents flow in the ground electrodes.
2. Ground potential rise (GPR)—current flow across a ground resistance generates a voltage on the structures. These need to be electrically safe.
3. Electrical resistance—needs to be low to ensure low voltage to remote earth.
4. Potential gradient—gradients in ground need to be electrically safe.
5. Long life—components need to be selected for long life.
6. Reliability—ground electrodes are generally sectionalised into discrete parts to facilitate maintenance.

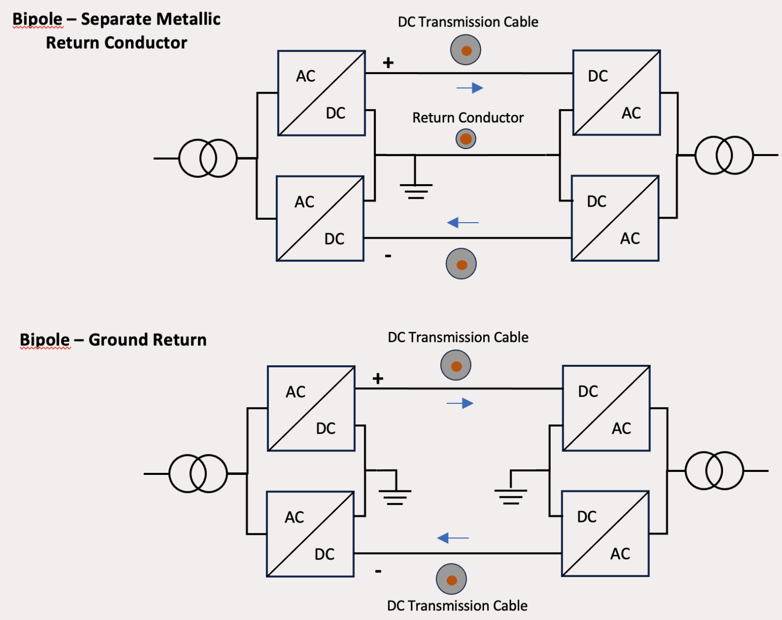


Figure 33. Bipole HVDC Configurations

Bipolar HVDC Systems

A bipolar DC link caries DC current via separate positive and negative cables with a return conductor carrying any imbalance which should ideally be zero. This configuration is applicable for higher transfer capacities and provides additional security of supply. Typical configurations are shown in Figure 33.

Homopolar HVDC System

Homopolar DC links are like bipolar links but have the same polarity in each cable. The configuration is simpler and lower cost with reduced insulation in the cables [22]. However, the disadvantages with the homopolar arrangement are reduced power transfer capacity and power flow control capability. An example of this configuration is shown in Figure 34

Induced Voltages and currents from HVDC Lines

Both AC and DC power lines can cause induced voltages and currents in nearby metallic structures which can create a hazard with un-safe touch voltages or cause damage by corrosion. The Canadian Association of Petroleum Producers, 'GUIDE - Influence of High Voltage DC Power Lines on Metallic Pipelines [23] reports that induced voltages can occur by three modes: (1) capacitive coupling, (2) inductive coupling, and (3) conductive coupling.

Steady state induced voltages from capacitive and inductive coupling effects from HVDC lines are static (i.e. not alternating current) and less than equivalent rated HVAC lines. During fault conditions there can be momentarily high induced voltages.

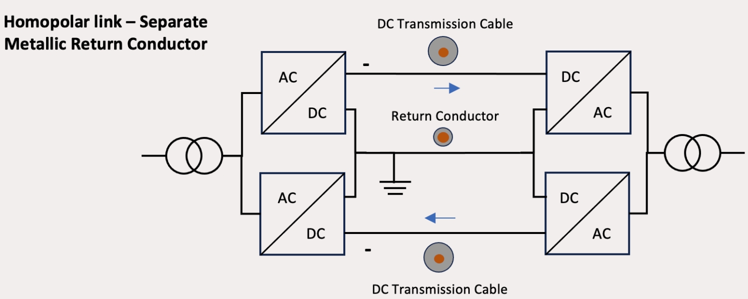


Figure 34. Homopolar HVDC Configurations

Conductive coupling effects can occur through discharge of current through grounding electrodes, leading to ground potential rises.

Although the levels and effects of HVDC induced voltages are generally less than equivalent HVAC rated lines, induced voltage in nearby metallic objects must be addressed in the design of a HVDC overhead or underground transmission line.

Figure 35. HVDC Converter Station (ABB[17])

6.3 HVDC Converter Technologies

There are several converter technologies used in HVDC transmission systems. The choice of converter technology depends on project requirements considering factors such as power transfer, system requirements, associated HVDC configuration and cost considerations. The main types of converters used in HVDC transmission are:

(a) Line-Commutated Converter (LCC): LCC is the most established and widely used converter technology in HVDC systems. It utilizes thyristor-based converters that operate on line-commutation principles. LCC converters provide robust and reliable operation and are suitable for high-power, long-distance transmission applications.

(b) Voltage-Sourced Converter (VSC): VSC-based converters have become the most used technology in recent years, particularly for applications such as offshore wind farm connections and grid interconnections. VSC converters use insulated-gate bipolar transistors (IGBTs) or integrated gate-commutated thyristors (IGCTs) to generate the desired voltage waveform. VSC technology provides benefits, such as better controllability, reactive power support and the ability to independently control active and reactive power flow.

(c) Modular Multilevel Converter (MMC): MMC is a specific type of VSC technology. It utilizes a modular structure with multiple sub-modules connected in series to form a high-voltage waveform. MMC offers advantages such as scalability, fault tolerance, reduced harmonics and improved control flexibility.

(d) Current-Source Converter (CSC): CSC-based converters were commonly used in early HVDC systems but have been largely replaced by LCC and VSC technologies. CSC converters utilise current-source inverters and require external capacitors to provide the required voltage waveform. While CSC technology offers certain benefits, such as inherent short-circuit protection, it has limitations in terms of control and reactive power capabilities.

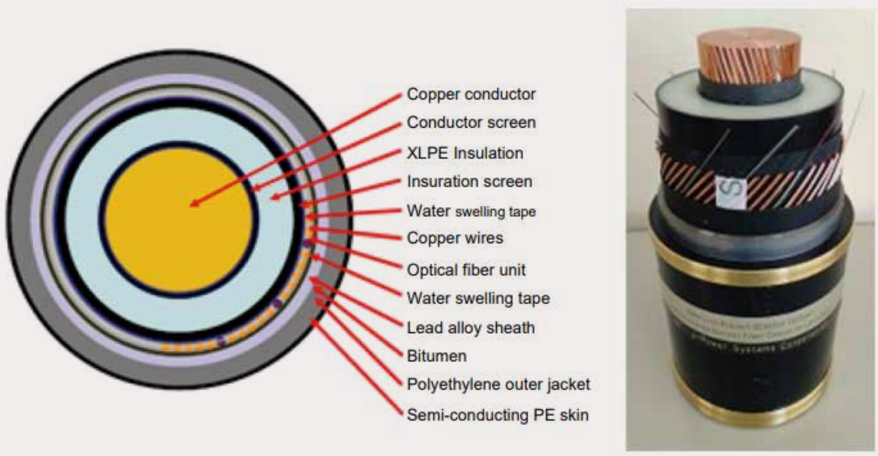


Figure 36. HVDC Land Cable (Sumitomo)

[17] https://new.abb.com/news/detail/45972/abb-completes-upgrade-of-first-major-hvdc-link-in-us-transmission-history

Table 12. HVDC Transmission Lines in Australia

Name	Route Length	Voltage	Power Rating	Year	Type	Other Details
Directlink (NSW)	59km	80kV	180MW	2000	VSC / IGBT	Underground and above ground polymeric cables
Murraylink (Vic—SA)	176km	150kV	200MW	2002	VSC / IGBT	Underground XLPE cable
Basslink (Vic—Tas)	370km	400kV	500MW	2006	LCC /Thry	Monopolar system, Submarine cable

An example of a HVDC converter station is provided in Figure 35. The converter stations have a large land requirement, for example the converter stations for the Suedlink project will occupy around 7 hectares (Tennet [24])

6.4 Design

The design of HVDC cables has many similarities to HVAC cables. The key differences are [13]:

- Mechanical design for submarine cables
- Insulation design for DC electrical stresses
- Special requirements for accessories i.e., joints and terminations
- Design issues relating to DC ground return current.

The two main types of cables are characterised by the insulation medium i.e.

- Mass impregnated (MI)—insulation material is layered paper tape impregnated with a high viscosity fluid.
- Polymeric insulated cable includes XLPE.

HVDC XLPE cable is now the most used for onshore or land projects. A typical HVDC XLPE cable is shown in Figure 36.

The literature review (Appendix A) provided a finding that HVDC cables may show better reliability than their AC counterpart due to their better performance at elevated temperatures and fields, minimal space charge retention, favourable material compatibility, and reliable and robust accessories.

6.5 HVDC Transmission Line Projects

Basslink submarine cable, and the relatively small capacity Directlink and Murraylink transmission lines are the only completed HVDC transmission projects in Australia (refer Table 12). In other parts of the world, such as Europe, America, and Asia, HVDC has been used extensively for inter-regional transmission connectors, offshore and onshore renewable zone interconnections. In Europe, regulatory drivers for HVDC are also promoting the adoption of HVDC underground transmission. The Changji-Guquan project [25] in China was the world's first UHV DC (ultra-high voltage DC) at +1100kV, 12GW capacity over 3324km, completed in 2016. The Suedlink HVDC 4000 MW 700km project in Germany is significant because it is all underground cable.

The literature review (Appendix A) provided a list of recent international large HVDC transmission projects with year, voltage, power, distance, type, and supplier is provided in Table 13.

Table 13. International HVDC Projects [26]

Name of the Project	Country	Year	Voltage (kV)	Power (MW)	Distance (km)	Type	Supplier
Three Gorges-Shanghai	China	2006	500	3000	1060	Thy	ABB
Estiink	Estonia-Finland	2006	150	350	105	IGB	ABB
NorNed	Netherland -Norway	2008	450	700	580	Thy	ABB
Yunnan-Guangdong	China	2010	800	5000	1418	Thy	Siemens
SAPEI	Italy	2011	500	1000	435	Thy	ABB
BorWin1	Germany	2012	150	400	200	IGB	ABB
Mundra-Haryana	India	2012	500	2500	960	Thy	Siemens
Zhoushan	China	2014	200	400	134	IGB	NA
AL-link	Aland-Finland	2015	80	10	158	IGB	ABB
Western Alberta TL	Canada	2015	500	1000	350	Thy	NA
Nord: Balt	Sweden Lithuania	2015	300	700	450	IGB	ABB
Skagerrak 4	Denmark Norway	2015	300	700	244	IGB	Nexans, ABB
Jinsha River II-East China	China	2016	800	6400	NA	Thy	NA
DolWin2	Germany	2016	320	900	135	IGB	ABB
SydVastlanken	Sweden	2016	300	720	260	IGB	Alstom
Western HVDC Link	UK	2017	600	2200	422	Thy	Prysmain Group, Siemens
Xinjiang-Anhui	China	2017	1100	10000	3333	Thy	NA

6.6 The Future of HVDC Transmission in Australia

There are many HVDC transmission lines currently in the planning or construction phase around the world. The Marinus Link 1500MW, 250kM undersea cable from Victoria to Tasmania is currently in planning and approval phase and is the only large HVDC transmission project in Australia.

The relatively small number of HVDC transmission projects in Australia compared to other parts of the world historically indicates that the Australian industry will need to increase the knowledge, skills and experience base in grid planning, design, construction, operation, and maintenance of HVDC transmission if this technology is to be utilised on a larger scale.

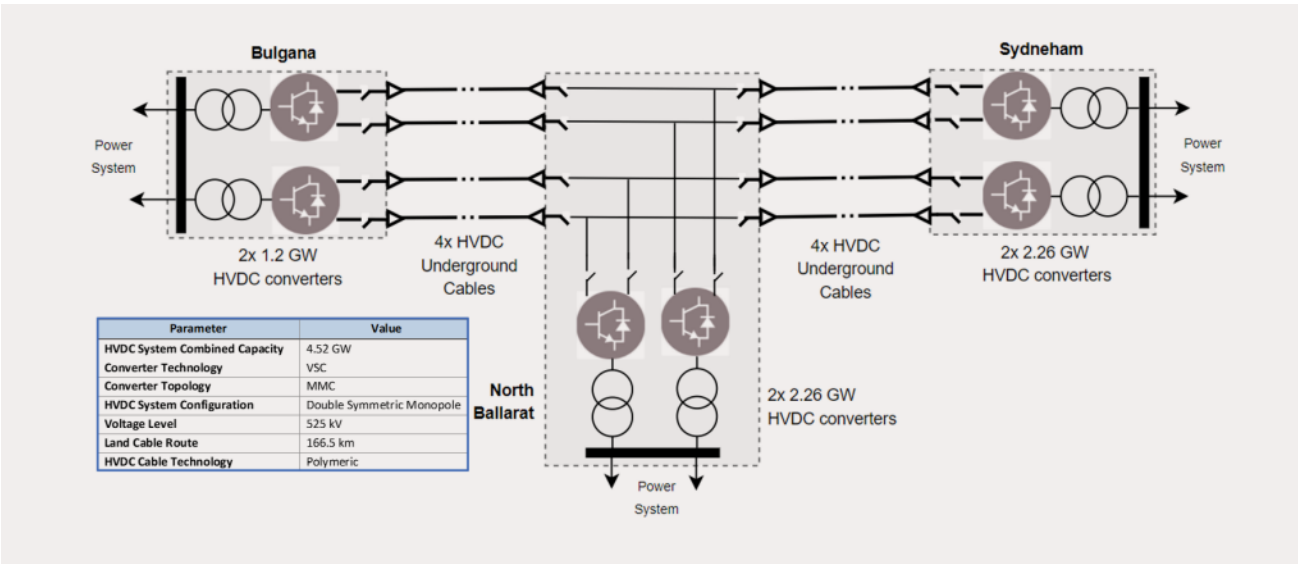
A recent report on HVDC systems titled "Western Victorian Transmission Network Project—High Level HVDC Alternative Scoping Report" [27] was commissioned by Moorabool Shire Council and authored by Amplitude Consultants. This report provides an example of how HVDC could be an option in a current project. The consultants were engaged to investigate an alternative HVDC option utilising underground cable to the AEMO preferred Western Victoria Transmission Network Project (WVTNP) Option C2, which includes the erection of new 220 kV and 500 kV overhead transmission lines refer Figure 37.

The features of the HVDC proposal were:

- 78km of underground cable in a three metre wide trench
- Three converter stations, located at Bulgana, Sydneham and North Ballarat
- Base case for N-1 Reliability planning criteria
- Rating of around 2700 MVA, voltage of 525kV dc

The key findings and commentary on this report are summarised as follows:

- High level base case cost estimate circa $2.7 billion, which was 5.7 times the cost of AEMO preferred AC OHTL WVTNP option C2. Converter stations range from $536 to $710M each. Prior cost ratios of HVDC to HVAC OHTL had been in the range of 10:1.
- Lowering the N-1 planning capability can significantly lower capital costs (particularly with sizing of cables and cost of converter stations).
- HVDC can facilitate a staged approach to renewable development. For example, if a double circuit HVDC is required for the long term, and only half the capacity is required for the medium term, the initial converter stations installed can be rated for this lower capacity (which equates to one circuit of the double circuit). It would still be prudent to install the double circuit cables (or have conduits installed for the second circuit).
- The staged approach may be prudent, because the total output from a renewable zone is not certain and the expected capacity factors (of around 30%) for wind turbine may not be realised.
- The reduced underground trench (3-metre width) and corridor/easement requirements for HVDC have significant benefits compared to underground AC and overhead AC transmission. It is possible to locate the HVDC cables on existing overhead easements and on road reserves.



Parameter	Value
HVDC System Combined Capacity	4.52 GW
Converter Technology	VSC
Converter Topology	MMC
HVDC System Configuration	Double Symmetric Monopole
Voltage Level	525 kV
Land Cable Route	166.5 km
HVDC Cable Technology	Polymeric

Figure 37. Option of using HVDC technology (Amplitude Consultants [27])

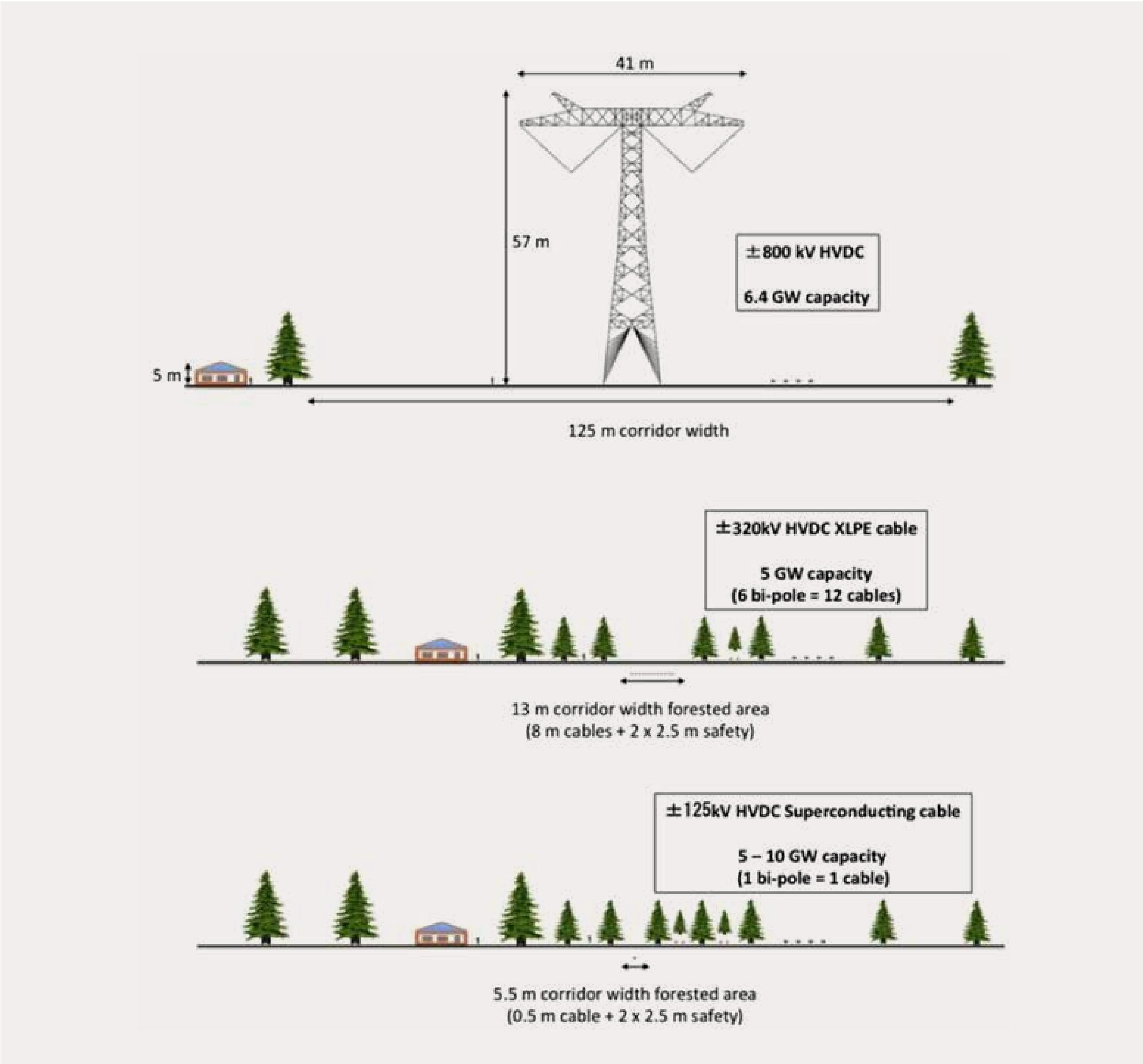


Figure 38. ROW and Power Transfer Capacity Comparison between Different Power Transmission Lines (Thomas et al [11])

6.7 HV Superconducting Cables

Super-Conducting Transmission Lines (SCTL) are currently a developmental technology that offers many advantages compared to existing overhead transmission and underground transmission cables, including: lower losses, higher power transfer, compact size requiring very reduced corridor width and low electromagnetic field emissions [10]. SCTL require a circulating cooling medium of liquid nitrogen within the cable. At this stage the technology is not considered to be at a mature stage of development necessary for commercial application.

The literature review (Appendix A) reported several advantages of superconducting power lines compared to the most modern underground standard HVDC cables (320 kV XLPE HVDC) [11]. The most notable is the compact size and reduced ROW corridor requirements and significantly reduced losses for long route lengths compared to HVAC and DC cables. A corridor comparison is shown in Figure 38.

6.8 Summary and Conclusions – Technical Aspects of HVAC and HVDC Transmission

A summary and comparison of the technical aspects of HVAC and HVDC overhead and underground transmission lines presented in this section is provided Table 14. Comparison of HV Overhead and Underground Cable Transmission Lines.

7.

Electromagnetic Fields

7.1 Introduction

Electromagnetic fields (EMF) is the term used to describe the combination of electric and magnetic fields that are generated by electrically energised or charged objects, including power lines, cables, appliances, and electronic devices. These fields are present everywhere in our environment, including the Earth's natural magnetic field. There is much information available on EMF from many sources. Scientific research on the health effects of EMF from powerlines has occurred since the 1970s.

There are several key organisations and authorities that provide guidance for industry.

Energy Networks Association (ENA)—is the peak national body representing electricity transmission and distribution businesses in Australia. ENA published its EMF management handbook in 2016 [28]. The purpose on the EMF Management Handbook is to provide, industry-wide information for guidance to the Australian Electricity Distribution and Transmission Industry and public on EMF. The ENA states in the handbook [28, p. 3]:

> *"Based on the findings of credible public health authorities, the body of scientific research on EMF does not establish that exposure to EMF at levels below the recognised guidelines cause or contribute to any adverse health effects. Some scientists however believe there is a need for further scientific research, although the World Health Organization has found that the body of research on EMF already is extensive."*

Australian Radiation Protection and Nuclear Safety Agency (ARPANSA)—is the Australian government's primary organisation responsible for protecting people and the environment from the harmful effects of radiation. ARPANSA operates under the Australian Radiation Protection and Nuclear Safety Act 1998. ARPANSA advises on its website[18] that:

> *"The scientific evidence does not establish that exposure to extremely low frequency (ELF) EMF found around the home, the office or near powerlines and other electrical sources is a hazard to human health".*

> *"There is no established evidence that ELF EMF is associated with long term health effects. There is some epidemiological research indicating an association between prolonged exposure to higher than normal ELF magnetic fields (which can be associated with residential proximity to transmission lines or other electrical supply infrastructure, or by unusual domestic electrical wiring), and increased rates of childhood leukaemia. However, the epidemiological evidence is weakened by various methodological problems such as potential selection bias and confounding. Furthermore, this association is not supported by laboratory or animal studies and no credible theoretical mechanism has been proposed."*

International Commission on Non-Ionizing Radiation Protection (ICNIRP)—is an independent scientific organisation that provides guidelines and recommendations on the protection against non-ionizing radiation. This includes EMF from various sources such as power lines, radiofrequency fields (RF) from wireless devices, and optical radiation (e.g., from lasers). The primary role of ICNIRP is to develop and promote guidelines for limiting exposure to non-ionizing radiation to protect human health and ensure the safety of the public and workers. ICNIRP advises that [29, p. 824]:

> *"It is the view of ICNIRP that the currently existing scientific evidence that prolonged exposure to low frequency magnetic fields is causally related with an increased risk of childhood leukemia is too weak to form the basis for exposure guidelines. In particular, if the relationship is not causal, then no benefit to health will accrue from reducing exposure."*

World Health Organization (WHO)—undertakes and sponsors research on the health impacts of radiation including EMF. Considerable information and technical resources are available on their website[19].

[18] Source: ARPANSA Electricity and Health, ARPANSA Extremely Low Frequency Electric and Magnetic Fields www.arpansa.gov.au.
[19] https://www.who.int/.

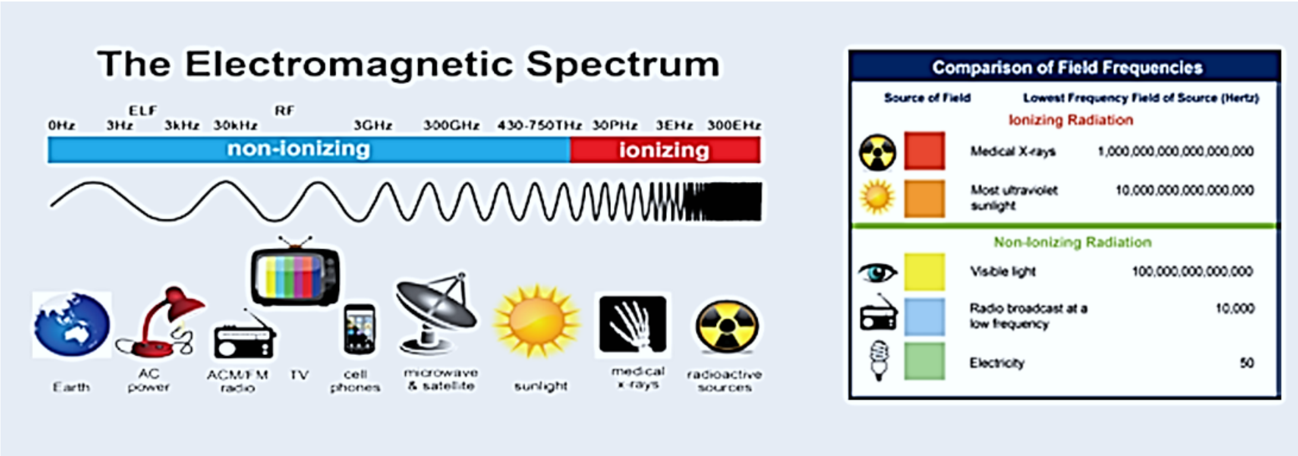


Figure 39 . The Electromagnetic Spectrum (ENA [28, p. 5])

7.2 How the Australian Electricity Network Operators approach EMF

Australian network operators including TNSPs broadly adopt the approach recommended by ENA as outlined in their handbook. The ENA's position on EMF has been adopted in the light of authoritative reviews having concluded that no adverse health effects have been established from exposure to EMF below the recognised international guidelines.

ENA recognizes that even, so some members of the public continue to have concerns about the issue. The ENA position on EMF includes [28, p. 3]:

- *"...recommending to its members that they design and operate their electricity generation, transmission and distribution systems in compliance with recognised international EMF exposure guidelines and to continue following an approach consistent with the concept of prudent avoidance,*
- *monitoring engineering and scientific research, including reviews by scientific panels, policy and exposure guideline developments, and overseas policy development, especially with regard to the precautionary approach,*
- *communicating with all stakeholders including assisting its members in conducting community and employee education programs, distributing information material including newsletters, brochures, booklets and the like, liaising with the media and responding to enquiries from members of the public, and*
- *cooperating with bodies established by governments in Australia to investigate and report about power frequency electric and magnetic fields."*

ENA's policy includes designing and operating electricity generation, transmission and distribution systems in compliance with relevant Australian guidelines and in an approach consistent with prudent avoidance i.e. no cost and very low cost measures that reduce exposure while not unduly compromising other issues should be adopted.

7.3 EMF—The Science, Health and Safety

Electromagnetic fields can be classified into two types:

(a) Non-ionizing radiation: This is electromagnetic fields (**EMF**) with frequencies below the ionizing radiation range, and includes, visible light, radio waves, and microwaves. Examples of non-ionizing radiation sources include power-lines, household electrical wiring, cell phones, and Wi-Fi routers.

(b) Ionizing radiation: This is higher-energy electromagnetic radiation (**EMR**) that can remove tightly bound electrons from atoms and molecules, leading to ionization. Ionizing radiation includes X-rays and gamma rays. Unlike non-ionizing radiation, ionizing radiation has sufficient energy to cause damage to biological tissues and DNA, and prolonged exposure to high levels of ionizing radiation can increase the risk of cancer and other health effects.

EMF is sometimes confused with **EMR**. The differences are illustrated in Figure 39.

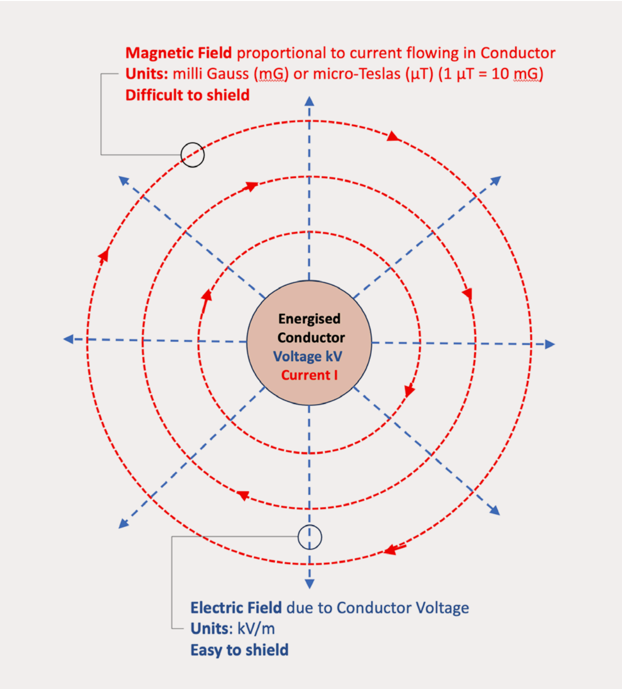


Figure 40. Simple Representation of Electric and Magnetic Fields from a Conductor

TABLE 5-1 BASIC RESTRICTIONS AT 50HZ FOR IEEE AND ICNIRP.

	IEEE 2002	ICNIRP2010
GENERAL PUBLIC		
Exposure to head	0.0147 V/m	0.02 V/m
Exposure elsewhere	0.943 V/m (heart) 2.10 V/m (hands, wrists, feet) 0.701 V/m (other tissue)	0.4 V/m (rest of body)
OCCUPATIONAL		
Exposure to head	0.0443 V/m	0.1 V/m
Exposure to rest of body	0.943 V/m (heart) 2.10 V/m (hands, wrists, feet, other tissue)	0.8 V/m (rest of body)

Figure 41. EMF—Basic Restrictions at 50Hz from IEEE and ICNIRP (ENA [28, p. 15])

EMF refers to two types of fields — Electric and Magnetic as illustrated in a simplified representation in Figure 40.

EMF Guidelines and Exposure Limits

The two international recognised exposure guidelines are ICNIRP:2010 and International Committee on Electromagnetic Safety, Institute of Electrical and Electronics Engineers (IEEE): 2002

ARPANSA's advice is [28, p. 14] "The ICNIRP ELF guidelines are consistent with ARPANSA's understanding of the scientific basis for the protection of people from exposure to ELF EMF."

ARPANSA directly references ICNIRP 2010 as a guideline for exposure and indicates the IEEE:2002 guideline provides an alternate set of guideline limits applicable to electric and magnetic field exposure.

Electric Fields are produced by the voltage in the powerline and magnetic fields by the current flowing in the powerline. The higher the voltage is, the higher is the electric field. Electric fields can be shielded by most objects, including trees and buildings. Electric fields tend to drop off quickly with distance. The units commonly used for electric field strength are volts per metre (V/m) of kilovolts per metre (kV/m).

Underground cables with metallic outer sheaths (i.e. transmission cables) bonded to earth will have no external electric fields.

Magnetic Fields are proportional to the current in the powerline, the higher the current the higher the magnetic field. When there is no current flow, there is no magnetic fields. Magnetic fields also drop quickly with distance. In general, the magnetic fields will decrease as follows:

- Single current—1/n
- Double circuit un-transposed—$1/n^2$
- Double circuit transposed or coil (e.g., transformer)—$1/n^3$

The units of magnetic field are commonly in milli Gauss (mG) or micro-Teslas (µT) with 1µT = 10mG.

Basic restrictions are the fundamental limits on exposure and are based on the internal electric currents or fields that cause established biological effects. The basic restrictions are given in terms of the electric fields and currents induced in the body by the external fields. If basic restrictions are not exceeded, there will be protection against the established biological effects. The basic restrictions include safety factors to ensure that, even in extreme circumstances, the thresholds for these health effects are not reached.

These safety factors also allow for uncertainties as to where these thresholds lie. The physical quantity used to specify the basic restrictions is the tissue induced electric field. The Basic Restrictions relating to 50Hz are shown in a Table 5-1 from the ENA EMF Management Handbook (see Figure 41).

TABLE 5-2 MAGNETIC FIELD REFERENCE LEVELS AT 50HZ FOR IEEE AND ICNIRP.

	IEEE 2002	ICNIRP 2010
GENERAL PUBLIC		
Exposure general	Not specified	200 μT*
Exposure to head and torso	904 μT	Not specified
Exposure to arms and legs	75,800 μT	Not specified
OCCUPATIONAL		
Exposure general	Not specified	1,000 uT*
Exposure to head and torso	2,710 μT	Not specified
Exposure to arms and legs	75,800 μT	Not specified

TABLE 5-3 ELECTRIC FIELD REFERENCE LEVELS AT 50HZ FOR IEEE AND ICNIRP

	IEEE 2002	ICNIRP 2010
GENERAL PUBLIC		
Exposure	5 kV/m 10kV /m (within right of way)	5 kV/m
OCCUPATIONAL		
Exposure	10 kV/m 20kV /m (within right of way)	10 kV/m

Figure 42. EMF Reference Levels from IEEE & ICNIRP (ENA [28, pp. 15–16])

Reference Levels—The basic restrictions in the ICNIRP and IEEE Guidelines are specified through quantities that are often difficult and, in many cases, impractical to measure. Therefore, reference levels of exposure to the external fields, which are simpler to measure, are provided as an alternative means of showing compliance with the basic restrictions. The reference levels have been conservatively formulated such that compliance with the levels will ensure compliance with the basic restrictions. If measured exposures are higher than reference levels, then a more detailed analysis would be necessary to demonstrate compliance with the basic restrictions. The ENA handbook specifies the reference levels for exposure to magnetic fields and electric fields respectively at 50Hz in Tables 5.2 and 5.3 and are shown in Figure 42.

7.4 Prudent Avoidance Principles

The prudent avoidance principle, also known as the precautionary principle, is a guiding principle used in the management and mitigation of EMF near power lines. It emphasises taking proactive measures to reduce exposure to EMF, even in the absence of conclusive scientific evidence of harm. The principle recognises the potential for health risks and aims to minimise exposure as a precautionary measure. The prudent avoidance policy adopted by TNSP's involves implementing no cost and very low-cost measures that reduce exposure while not unduly compromising other issues. In most cases the application of prudent avoidance can be implemented on a project or incorporated into network standards without the need for a specific assessment.

These general guidelines which follow assumes there will be compliance with the exposure limits (see above).

Potential locations of interest—from a practical perspective, the focus of public attention to EMF issues and therefore areas considered more relevant in a precautionary context would include schools, childcare centres, and other places where children congregate, homes and residential areas.

Exposure assessment—the focus of an exposure assessment in the context of prudent avoidance is on determining magnetic field exposure sufficient to be able to determine whether there are no cost and very low cost measures that reduce exposure while not unduly compromising other issues. This can often be achieved without the need for complex calculations and, in many cases, without calculations at all.

Loading conditions for prudent avoidance calculations—where specific calculations are required the following guidance is provided.

With prudent avoidance assessments, which address the ability to reduce fields with no cost or very low cost measures, the reduction in exposure arising from potential measures is more relevant than the highest predicted magnetic fields (as would be the case for exposure limit assessments).

While loads of substations and powerlines will generally increase over time after commissioning, a conservative approach which considers daily and seasonal variations would be to calculate the time-weighted-average (TWA) over a complete year using loads shortly after commissioning and also in the year representing the maximum foreseeable projected TWA.

Ground clearance for overhead lines—where specific calculations are required the following guidance is provided. A conservative estimate of ground clearance (or average conductor height) for prudent avoidance assessments would be to assume 2/3 of the calculated sag for a typical span under typical ambient conditions for the year representing the maximum foreseeable projected loads. There may be specific circumstances that justify alternative methods.

Prudent avoidance assessment reference points—when undertaking a prudent avoidance assessment, the primary reference points for calculations should be those areas where people, especially children, spend prolonged periods of time. As the epidemiological studies typically use exposure within the home (often a child's bedroom), and in the absence of data suggesting otherwise, a conservative approach for residential areas is to select the reference point as being the nearest part of any habitable room from the source. There may be specific circumstances that justify alternative methods.

The exception to this is noncompliance with exposure limits If the average exposure is less than or equal to typical background magnetic field levels, and no further assessment is required.

Possible ways to reduce exposure—exposure reduction can involve siting measures, which result in increased separation from sources and/or field reduction measures.

Consideration of other issues—Measures to reduce magnetic field exposure must be considered against numerous other objectives and constraints of the project including:

- worker safety,
- the location of the power source and the load to be supplied,
- availability of suitable sites,
- ease of construction and access,
- reliability,
- cost (prudent avoidance / precautionary measures should be no cost / very low cost),
- conductor heating,
- the nature of the terrain,
- maintenance requirements,
- visual amenity,
- provision for future development,
- legal requirements, and
- environmental impacts.

The goal of any project is to achieve the best balance of all the project's objectives, considering relevant social, technical, financial and environmental considerations.

Cost–benefit analysis

In Australia, there have also been some "benchmark" inquiries into the health impacts associated with EMF initiated by governments, most notably those lead by Sir Harry Gibbs[20] and Professor Hedley Peach[21].

Sir Harry Gibbs and Professor Peach recommended a policy of prudence or prudent avoidance, which Sir Harry Gibbs described in the following terms:

> *"…. [doing] whatever can be done without undue inconvenience and at modest expense to avert the possible risk …"*

The WHO, in its document Extremely Low Frequency [ELF] Fields—Environmental Health Criteria Monograph No. 238 [30, p. 13], advise that:

> *"Provided that the health, social and economic benefits are not compromised, implementing very low cost precautionary procedures to reduce exposure is reasonable and warranted' [WHO 2007]."*

If the available mitigation measures cannot be implemented at no cost or very low cost then no further action is required.

Undergrounding is not consistent with prudent avoidance.

Because undergrounding is usually far more expensive than overhead construction, it is normally outside the scope of prudent avoidance / precaution in the context of an overhead powerline. On the issue of undergrounding, the Gibbs Report specifically stated that,

> *"…because of its additional cost, undergrounding solely for the purpose of avoiding a possible risk to health should not be adopted".*

[20] Gibbs, Sir Harry (1991). Inquiry into community needs and high voltage transmission line development. Report to the NSW Minister for Minerals and Energy. Sydney, NSW: Department of Minerals and Energy, February 1991.

[21] Peach H.G., Bonwick W.J. and Wyse T. (1992). Report of the Panel on Electromagnetic Fields and Health to the Victorian Government (Peach Panel Report). Melbourne, Victoria: September 1992

7.5 Measures to Mitigate EMF from Overhead and Underground Powerlines

Further to the prudent avoidance guidelines outlined above, the ENA's EMF Reference Management Handbook (2016) [28] recommends the following measures to mitigate EMF levels for designs and consideration of prudent avoidance.

1. Increasing the distance from source.
2. Modifying the physical arrangement of the source:
   - reducing the conductor spacing,
   - rearranging equipment layout and equipment orientation, and
   - for low voltage, bundling the neutral conductor with other phases.
3. Modifying the load:
   - optimally phasing and balancing circuits,
   - optimally configuring downstream loads,
   - applying demand management, and
   - for low voltage, balancing phases and minimise residual currents.

Additional measures which are less likely to satisfy the cost and convenience criteria which apply to precautionary measures but may be considered include:

4. incorporating a suitable shielding barrier between the source and the receiver;
5. active and passive compensation.

Examples of Mitigation of EMF on Overhead Lines by optimising phase conductor positions

The following diagrams in Figure 43 and Figure 44 below show the effect of re-arranging the phase conductors (A, B and C) on a 3 phase power line.

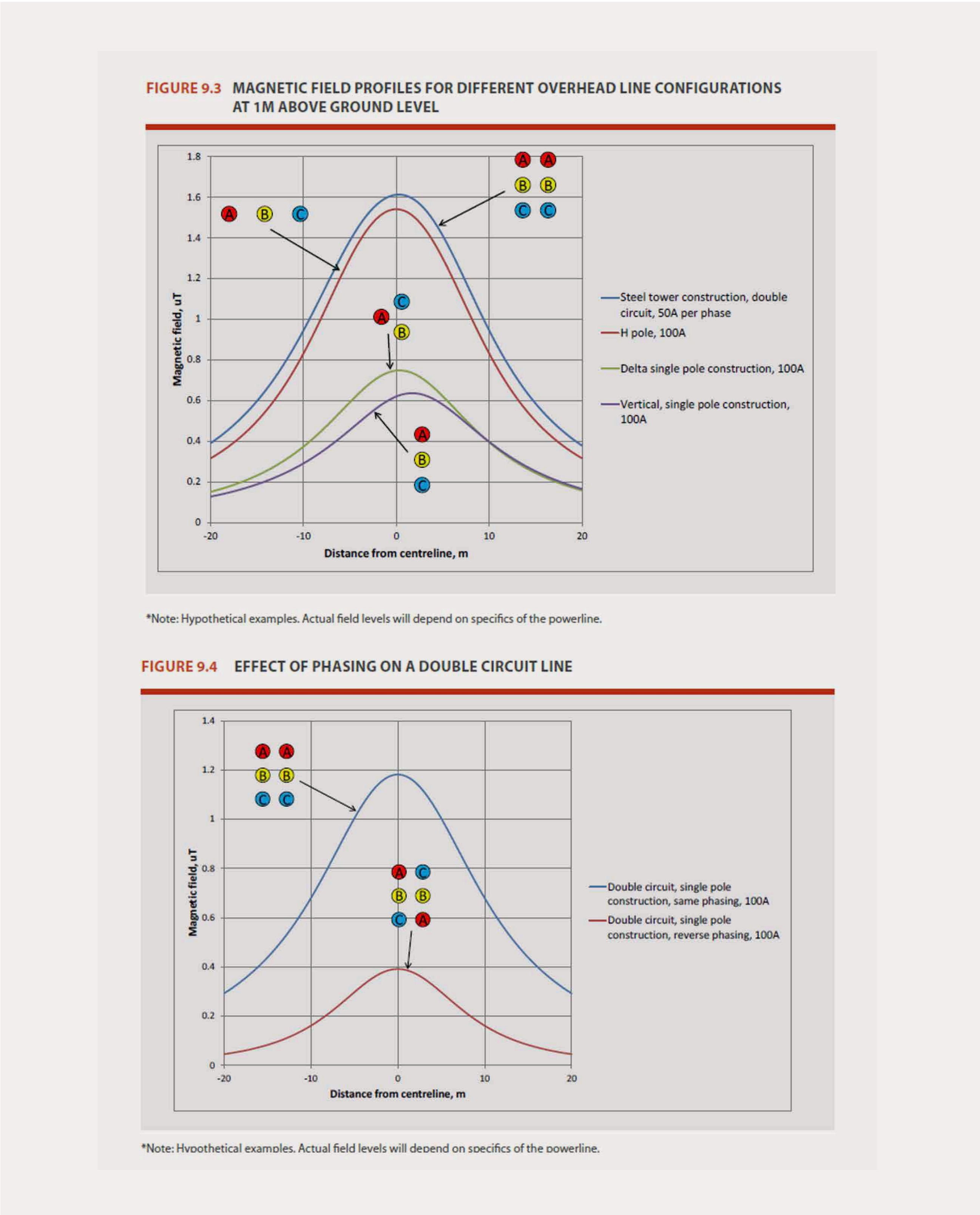


Figure 43. Effect of Phasing on EMF for Overhead Lines (ENA [28])

Examples of Mitigation of EMF on Underground Lines by Optimising Phase Positions (Flat Vs Tre-foil)

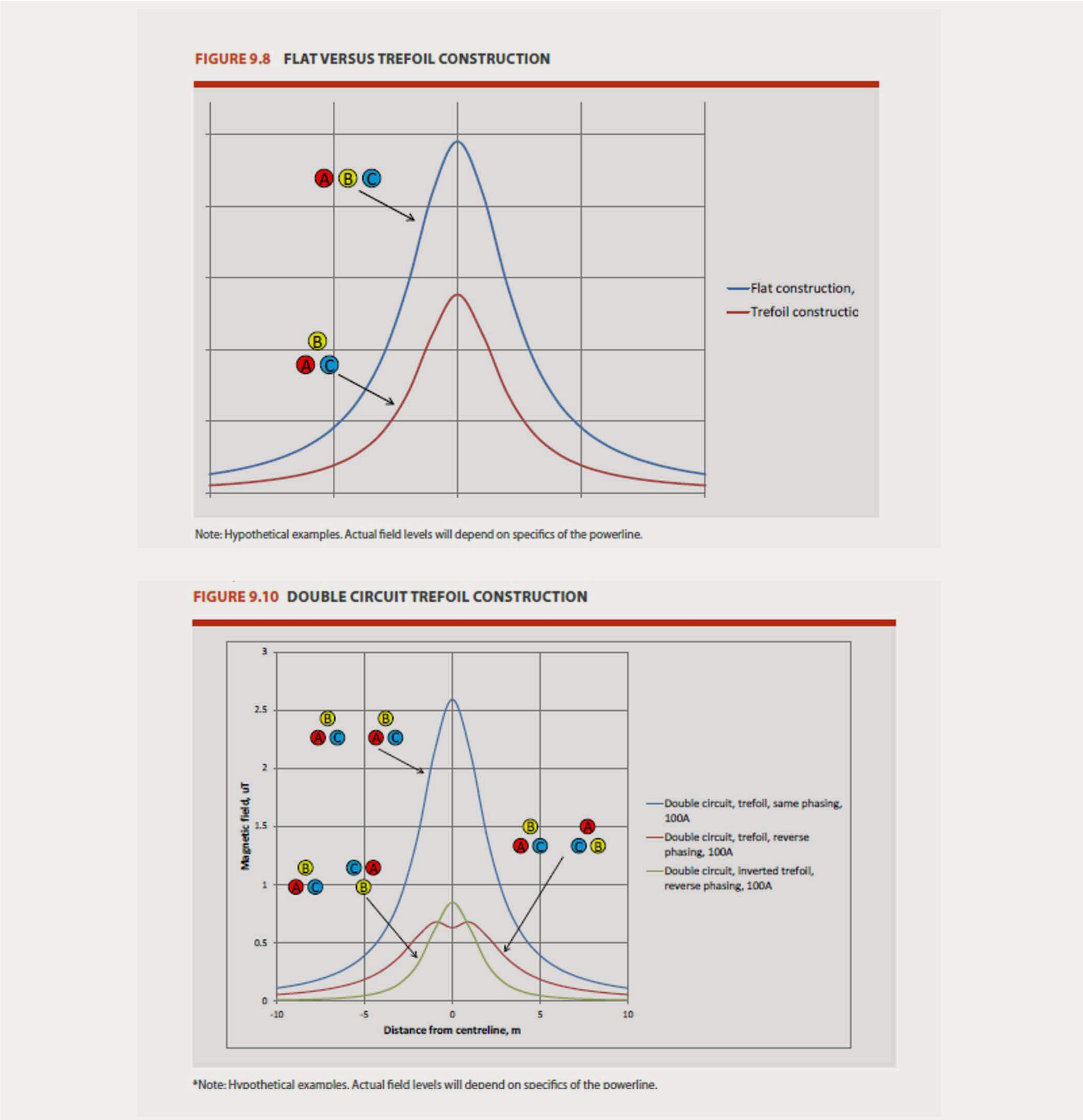


Figure 44. Effect of Laying Configuration and Phasing on EMF for Underground Cables (ENA [28])

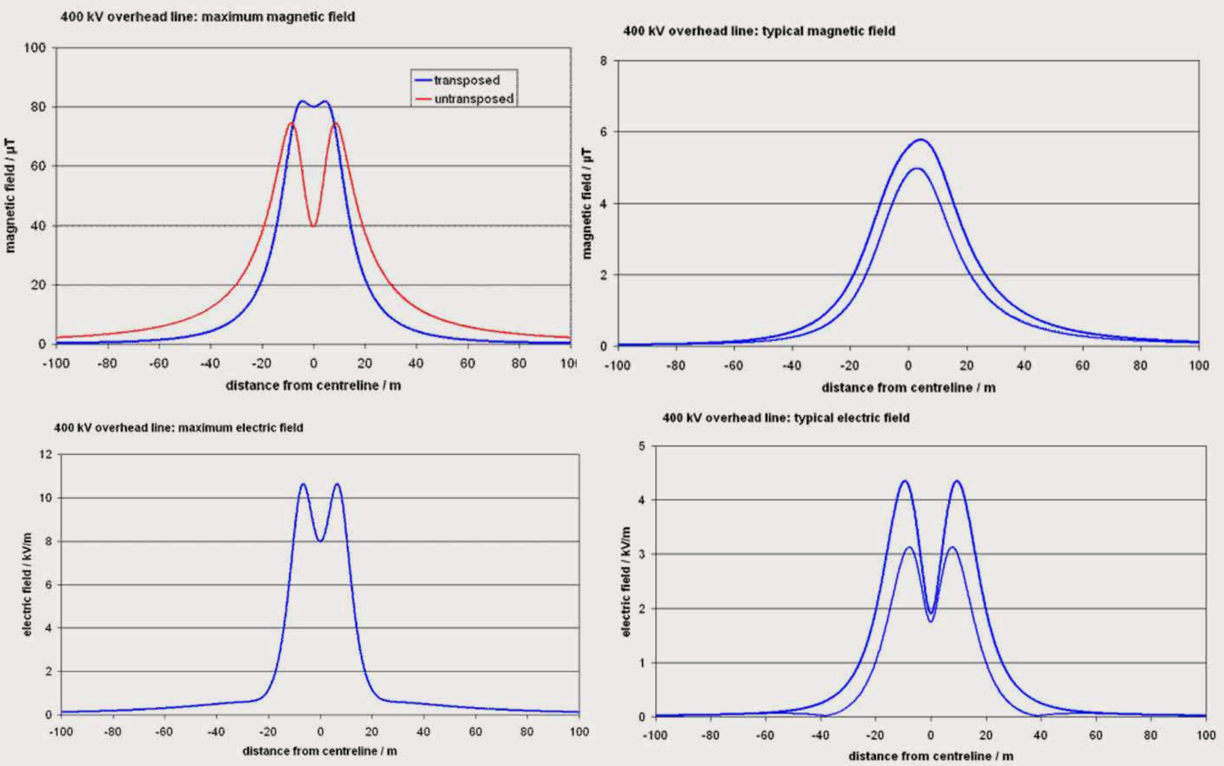
7.6 Typical EMF Profiles near Overhead and Underground Transmission Lines

7.6.1 EMF Profiles for 400KV Overhead and Underground Transmission Lines

The following EMF profiles for 400kV Overhead and Underground have been sourced from the UK's National Grid website emfs.info[22]. The website is operated by the UK company—National Grid which is responsible for transmission networks in England and Wales. The website also serves a purpose of providing information on EMF for the whole of the UK electricity industry. These profiles are likely to be similar on a comparative basis to 500kV Overhead and Underground.

[22] https://www.emfs.info/.

400kV Overhead Transmission Lines



Magnetic Field Graphs

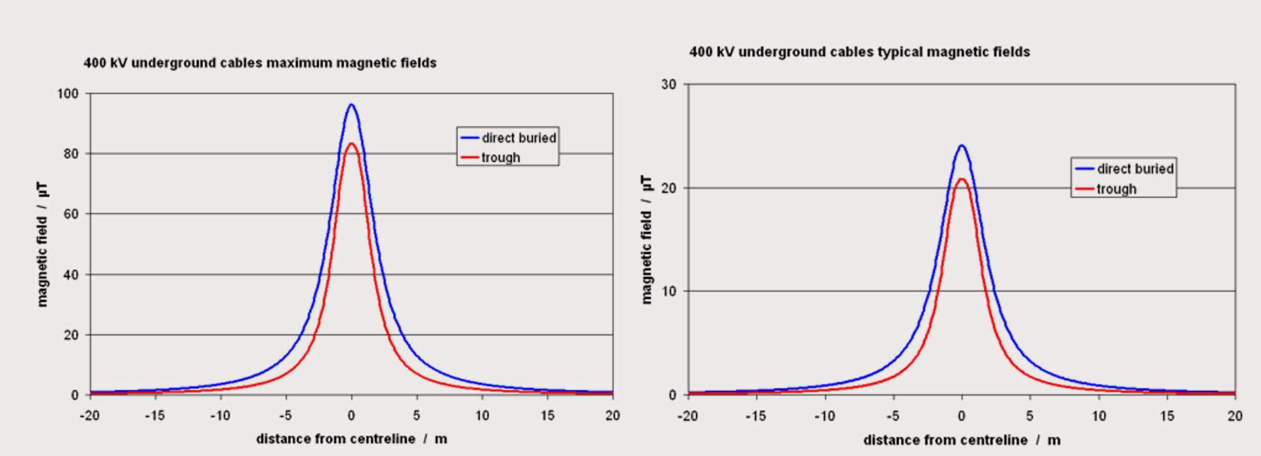
1. All fields calculated at 1 m above ground level.
2. All fields are given to the same resolution for simplicity of presentation (1 nT = 0.001 µT) but are not accurate to better than a few percent.
3. Calculations ignore zero-sequence current. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent and less close to the line.
4. The “maximum field under the line” is the largest field, which is not necessarily on the route centreline; it is often under one of the conductor bundles.
5. Calculated fields agree well with measured fields.

Electric Field Graphs

1. All fields calculated at 1 m above ground level.
2. All electric fields are calculated for the nominal voltage. In practice, voltages (and hence fields) may rise by a few percent.
3. All electric fields calculated here are unperturbed values.
4 All fields are given to the same resolution for simplicity of presentation (1 V/m) but are not accurate to better than a few percent.
5. Calculations ignore zero-sequence voltages. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent and less closer to the line.
6. The “maximum field under the line” is the largest field, which is not necessarily on the route centreline; it is often under one of the conductor bundles.
7. In efforts to reduce aerodynamic problems, a small number of 400 kV lines with quad bundles have had expanded bundles fitted, e.g. 500 mm horizontally. This produces slightly higher electric fields but is not included in these tables.”

Figure 45. Maximum and Typical EMF Profiles for 400kV Overhead Line (emfs.info)

400kV Underground Transmission Cables



1. All fields calculated at 1 m above ground level.
2. All fields are given to the same resolution for simplicity of presentation (0.01 µT = 10 nT) but are not accurate to better than a few percent.
3. Calculations ignore zero-sequence current. This means values at larger distances are probably underestimates, but this is unlikely to amount to more than a few percent.
4. Cable designs are not standardised to the same extent as overhead lines and the examples given here are representative.
5. The trough calculation is for a double circuit and the direct buried is for a single circuit, but in practice there may be other nearby circuits which affect the field.

There is no external electric field from metallic sheath underground cables.

Figure 46. Maximum and Typical EMF Profiles for 400kV Underground Line (emfs.info)

The typical and maximum magnetic field levels at 1 m above ground level at the centre of the line will be greater for an underground line compared to the equivalent overhead line.

However, the magnetic field levels for an underground cable drop off more rapidly compared to an overhead line, due the conductors being closely spaced. This results in corridor widths for underground transmission cables being less than overhead lines to meet reference levels.

7.6.2 Comparison of EMF from Power Lines and Typical Household appliances

ARPANSA provides a comparison of magnetic fields from typical household appliances and transmission and distribution lines. This information is presented in the Figure 47.

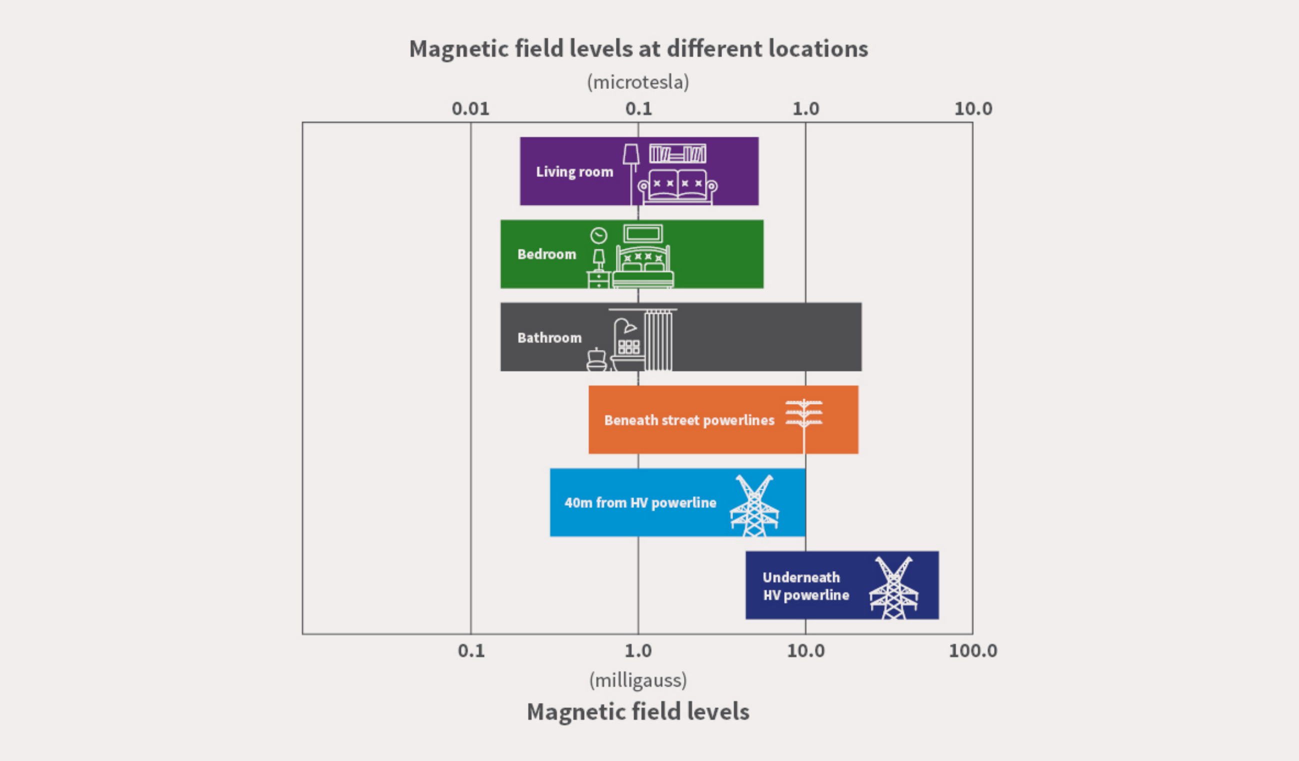


Figure 47. Comparison of Magnetic Fields from Household Appliances and Power Lines (ARPANSA[23])

7.7 HVDC Power Lines and EMF

Whilst AC transmission lines are characterised by low frequency (50Hz in Australia) electric and magnetic fields, HVDC is characterised by static electric and magnetic fields.

Characteristics and effects of static electric fields

On static electric fields, the INCIRP advises on its website[24]:

The strength of a static electric field is expressed in volts per meter (V/m). The strength of the natural electric field in the atmosphere varies from about 100 V/m in fair weather to several thousand V/m under thunderclouds. Other sources of static electric fields are charge separation because of friction or static electric currents from varied technologies.

Static electric fields do not penetrate the human body because of the body's high conductivity. The electric field induces a surface electric charge, which, if sufficiently large, may be perceived through its interaction with body hair and through other phenomena such as spark discharges (microshocks). The perception threshold in people depends on various factors and can range between 10–45 kV/ m. Furthermore, very high electric fields, such as from HVDC lines, can charge particles in the air, including polluted particles. There was a hypothesis that charged particles might be better absorbed by the lung than uncharged ones and so, raise people's exposure to air pollution. Current knowledge, however, suggests that an increased health risk from such charging of particles is very unlikely. Overall, the limited number of animal and human laboratory studies that have investigated the effects of exposure to static electric fields, have not provided evidence of adverse health effects.

[23] https://www.arpansa.gov.au/understanding-radiation/radiation-sources/more-radiation-sources/electricity
[24] https://www.icnirp.org/en/frequencies/static-electric-fields-0-hz/index.html

Effects of Static Magnetic Fields on the Body and Health Implications

On static magnetic fields the ICNIRP advises on its website[25]:

There are several known mechanisms by which magnetic fields can influence biological systems. Magnetic fields not only exert physical forces on metallic objects but also on moving electric charges. With respect to biological functioning, exposure to static magnetic fields will affect the electrically charged particles and cells in the blood, especially when moving through the magnetic field. The magnetic force can accelerate or reduce the movement of charged particles. An example is a reduction in the velocity of blood cells flowing through blood vessels. A further mechanism is via complex electronic interactions that may affect the rate of specific chemical reactions.

The ICNIRP in 2009 [31] reported a number of findings as follows. There is no evidence for adverse effects of exposure to fields up to 8 Teslas (T) except for limited information on minor effects such as on hand-eye coordination and visual contrast. Magnetic fields of 2-3T or higher (such as those generated by equipment in some industrial and medical settings or in some specialist research facilities—i.e., MRI) can evoke transient sensations such as vertigo and nausea. These occur as the result of the generation of small electrical currents in the ear's balance organ. The currents generate signals to the brain that provide different information to that obtained through vision, resulting in the sensations of vertigo and nausea. These effects are not adverse health effects in themselves, but they can be annoying, and they may impair normal functioning. Overall research has not shown to date that exposure to low-level static electric and magnetic fields have detrimental effects on health.

Sources of Exposure from HVDC Lines

The natural static magnetic field of the Earth is around 50µT, depending on the geographic location, and varies from between 30 to 70µT. Magnetic flux densities of the order of 20µT are produced under HVDC transmission lines.

ICNIRP Exposure Limits

The static electric field exposures according to ICNIRP are:

- occupational exposure: 10kV/m
- public exposure: 5kV/m.

The static magnetic field exposures according to ICNIRP are given in the table from ICNIRP presented in Figure 48.

Table 2. Limits of exposure[a] to static magnetic fields.

Exposure characteristics	Magnetic flux density
Occupational[b]	
Exposure of head and of trunk	2 T
Exposure of limbs[c]	8 T
General public[d]	
Exposure of any part of the body	400 mT

[a] ICNIRP recommends that these limits should be viewed operationally as spatial peak exposure limits.
[b] For specific work applications, exposure up to 8 T can be justified, if the environment is controlled and appropriate work practices are implemented to control movement-induced effects.
[c] Not enough information is available on which to base exposure limits beyond 8 T.
[d] Because of potential indirect adverse effects, ICNIRP recognizes that practical policies need to be implemented to prevent inadvertent harmful exposure of persons with implanted electronic medical devices and implants containing ferromagnetic material, and dangers from flying objects, which can lead to much lower restriction levels such as 0.5 mT.

Figure 48. ICNIRP Limits of Exposure to Static e.g. HVDC Magnetic Fields (ICNIRP [31, p. 511])

[25] https://www.icnirp.org/en/frequencies/static-magnetic-fields-0-hz/index.html

8.

Conclusions

8.1 Key findings

1.

High voltage alternating current (HVAC) overhead line technology, has been the dominant form of transmission infrastructure worldwide since the early twentieth century. This is because it has provided the most cost- effective and technically feasible system for constructing, operating, and maintaining a grid that meet high standards of safety and reliability. Overhead transmission lines have a service life of around 60 to 80 years with appropriate maintenance.

2.

HVAC underground cable transmission is feasible only for relatively short route lengths e.g around 50km for 500kV. This is due to the high electrical capacitance of transmission cables which requires expensive reactive power compensation plant (e.g. shunt reactors) to counteract the resulting transmission losses from this phenomenon.

3.

HVDC can be a feasible alternative to HVAC transmission for specific applications requiring high power transfer capacity over very long route lengths (i.e. several hundred kms depending on power transfer) that are point to point without intermediate connections. The economic feasibility for application of HVDC compared to HVAC, ultimately depends on project specific requirements, factors and constraints which determine whether HVDC should be considered. Regulatory investment test requirements also need to be satisfied.

8.2 Comparison Table – Technical Factors of HV Transmission Infrastructure

A summary comparing the technical factors of overhead and underground infrastructure is presented in Table 14 below.

Table 14. Comparison of HV Overhead and Underground Cable Transmission Lines

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
	Technical Factors - System Design, Installation and Performance				
1	**Power transfer capacity (typical):**	500kV: AC Single Circuit Quad Bundle ~3000 MW. 330kV: AC Single Circuit ~ 1000 MW. 275kV: AC Single Circuit Twin bundle – 800 to 1000 MW. 132kV: AC Single Circuit Single bundle ~ 200 MW.	500kV AC: 2000MW 330kV AC: 800MW 275kV AC: 800MW 132kV AC: 150MW	+/- 525kV: 2000MW +/1 320kV: 750MW	+/- 525kV: 2000MW +/1 320kV: 750MW
2	**Feasible maximum line route lengths**	Overhead transmission lines can traverse long routes up to 1000km. Overhead lines require less reactive compensation plant (per km) compared to underground cables.	40 to 60km based on critical length (length where cable capacitance equals the rating on cable, typically around 85km for 330 kV and 76km for 500 kV; practical lengths will be around half of these values). Reactive compensation plant such as shunt reactors or static var compensators at termination points are required for underground transmission to counteract the more significant capacitive effects of cables compared to an overhead line.	Feasible route length for comparable power transfers to HVAC lines is currently **up to around 750 to 1000km**. Route lengths greater than 1000km are feasible.	
3	**Conductors, Insulators and Cables**	Typically, aluminium and aluminium with steel core, with 2 conductor bundles at 275/330kV and quad bundles at 500kV. Insulator strings can be glass, porcelain or composite.	XLPE insulated cable is the most common technology. The first installation at 500kV was in 1988, so the technology is now mature.	Conductors similar to HVAC. Longer insulator strings generally required due to higher voltage across insulators compared to 3 phase AC.	XLPE cables similar to HVAC. However cable design provides for insulation subject to greater electrical stresses compared to HVAC.
4	**Reactive compensation equipment requirement**	Reactive compensation is required for longer line routes but is much less than the requirements for an equivalent rated UGTL.	Significant reactive compensation is required for circuit lengths at 50% to 100% of the critical length (around 50km to 70 km for EHV cables).	Not applicable.	Not applicable.
5	**Power conversion equipment requirement**	Not Applicable.	Not Applicable.	AC/DC power conversion equipment required at each end of the transmission line. This is a major cost factor for HVDC systems.	

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
			Technical Factors - System Design, Installation and Performance		
6	**Above ground impacts and construction requirements**	Typical lattice tower height and conductor span lengths for double circuit: 500kV : 60 to 80m high, spans 300 to 500 m 330kV : 50 to 60m high, spans 300 to 400 m 275kV : 40 to 50m high, spans 300 to 400 m 132kV : 30 to 40m high, spans 200 to 300 m Alternative pole or aesthetic designs may have lower heights. Aesthetic structures such as steel poles, T-pylons (UK) and lower height structures can be used in specific applications. However, there may be significant trade-offs such as cost, access and maintenance, additional structures and increased easement width.	Transition structures and fenced ground terminations required for connection to OHTL or at terminal substation.	Structure heights depend on DC voltage but will typically be less than the equivalent rated HVAC OHTL Structures will be more compact as less conductors will be needed. HVAC lines can be converted to HVDC application.	Transition structures required for connection to OHTL or at terminal substation.
7	**Below ground impacts and construction requirements**	Tower foundations and earthing conductors.	Depending upon design, voltage and power transfer rating: Cable trenching to lay conduits or cables - typically 1 to 2 m deep. Trench widths varying depending on number of cables and power transfer rating e.g. 500kV : 4 to 5m wide per circuit 330kV : 1.5 to 2m wide per circuit 275kV : 1.5 to 2m wide per circuit 132kV: 1 to 1.5m wide per circuit Horizontal direction drilling or micro-tunnelling required at some locations e.g., under waterway, rail corridors or busy roads. Cable tunnels will generally be required in high density urban areas for EHV cables.	Tower foundations and earthing conductors. Special earthing design required for ground electrodes.	Similar to HVAC UGTL, however trench widths will be less as a lesser number of cables will generally be required for same power transfer capacity.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
8	**Induced voltages**	OHTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines. Earthing and mitigation measures, such as phase conductor arrangements need to be considered in the design of an OHTL to ensure that the hazard is mitigated, and the design complies with standards.	UGTL's can induce voltages in nearby metallic objects such as fences, rail tracks and pipelines, however the earthed metallic screen significantly mitigates the induced voltages. Earthing arrangements of UGTL's that have metallic outer sheaths must also be considered as the induced voltages can cause current flows in the sheath that result in heat losses. Arrangements such as cross-bonding cancel the induced voltages in a 3-phase cable installation.	Induced voltages from HVDC lines into nearby metallic objects are static and tend to be lower than HVAC lines. Both steady state and fault currents in the HVDC line must be considered. Ground potential rise due to discharge currents via earth electrodes in HVDC systems must be considered in the design.	
9	**Vehicle access tracks**	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.	Access tracks required for construction (heavy vehicle) and on-going maintenance (light vehicle). Primary requirement is access to structure location for construction lay down areas and where there is an ongoing requirement for vegetation management along the route.	Apart from where installation is under a formed public road, access tracks along the cable route are normally required for construction and on-going routine inspection and maintenance. The impact will vary depending upon the route, terrain, and installation methods.
10	**Future connection capability**	HVAC OHTL's provide the most economic and flexible capability for future connections to the line.	HVAC UGTL's provide economic and flexible capability for future connections to the line. Cost will be greater than OHTL's however with more expensive underground works to extend, joint and terminate cables.	HVDC lines provide the least economic and flexible capability for future connections due to the requirement for additional converter stations. HVDC is more suited to applications for direct power transfer between two distant locations.	
11	**Reliability**	Reliability of performance (typical forced outage rate of 0.5 to 1.0 per 100 km/year). Structural failures (for Australia, failure rate is around 1 in 150,000 per annum). Overhead lines are exposed to severe weather including lightning strikes. Repair time for faults is much shorter duration compared to underground.	For XLPE cables outage rates are typically less than 1 outage/100km/year and lower than equivalent overhead lines. Repair time for underground cable faults is a much longer duration than overhead lines due to excavation, cable jointing and electrical testing work required e.g., up to 4 weeks.	Limited data is available; however, outage rates are expected to be like HVAC OHTLs. The lesser number of conductors in a HVDC line would result is less exposure to faults compared to HVAC.	Limited data is available; however, outage rates are expected to be like HVAC UGTLs. The lesser number of conductors, joints and terminations in a HVDC line would result is less exposure to faults compared to HVAC.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
12	**IElectro Magnetic Fields (EMF)**	Magnetic field levels are maximum under the centreline of the transmission line and decrease less gradually with distance from the line compared to an underground line. Transmission lines are designed to meet industry compliance limits within the corridor. Electric fields are emitted from overhead lines, but lines are designed to be within compliance limits. Magnetic field levels at 40m from overhead transmission line are similar to levels from typical appliances found within a home. The electric fields from transmission lines rated at 330 kV and below will generally produce electric fields less than the reference levels or industry guidelines. Design measures need to address electric fields from 500 kV transmission lines.	Magnetic field levels are above the centreline of the underground transmission line and decrease more rapidly with distance from the line compared to an overhead line. Electric field are contained within a cable with outer earth bonded metallic sheath. EMF levels at 4m from underground transmission line are similar to levels from typical appliances found within a home.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. DC electric fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied.	DC magnetic fields are static and subject to higher reference limits (i.e., less onerous) compared to AC. Design measures to ensure compliance with standard limits are applied. Electric fields are contained within the cable system.
13	**Audible Noise**	Audible noise can occur due to: • corona discharge on the transmission line conductors • dirt or pollution build-up on insulators • wind effects on structure and fittings These effects need to be considered in the design and maintenance measures employed to ensure noise is within compliance limits.	No audible noise from underground cables.	Audible noise – similar to HVAC OHTLs, but is dependent on voltage and size of conductors. Design measures are applied to ensure noise levels are within compliance limits. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.	No audible noise from underground cables. Audible noise from HVDC converter stations will occur. This needs to be considered in the design and location of converter stations in order to minimise impact.
14	**Corridor and easement requirements:**	For double circuit: 500kV AC – 70m wide 330kV AC – 60m wide 275kV AC – 60m wide 132kV AC – 20 to 40m wide Adjoining public roads may form part of a corridor.	For double circuit, rural: 500kV AC – 30 to 40m 330kV AC – 10m to 20m 275kV AC – 10m to 20m 132kV AC – 5m to 10m Urban installation corridor width depends on availability of suitable public road corridors or there is a requirement for a tunnel. Land is also required for underground to overhead transitions.	Corridor widths for HVDC OHTLs of equivalent power transfer ratings are similar to HVAC OHTLs. Buffer zones required for EMF reduction or prudent avoidance would be less.	Corridor widths for HVDC UGTLs of equivalent power transfer rating will be generally less than HVAC UGTLs. This is due to a lesser number of cables and reduced width trench widths required for an installation. Road corridors may be more readily used for cable routes. Land is also required for underground to overhead transitions.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
15	**Lifespan (Typical)**	60 to 80 years.	Greater than 40 years.	60 to 80 years (OHTL) Converters to be considered also.	Greater than 40 years (UGTL cable) Converters to be considered also.
16	**Project timeframes**	e.g. for a 500kV double circuit for 100km route length: Planning and approvals: 3-5 years. Construction: 2 years.	e.g. for a 500kV double circuit for 50km route length: Planning and approvals: 3 years. Construction: 4-6 years.	Construction: 2 years.	Construction: 4 – 6 years.
			Risk Management Aspects		
17	**WH&S – construction**	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works.	General construction industry risks. Excavation machinery risks Electrical safety risks – HV switching, testing. Overall risks considered lower for UGTLs compared to OHTLs.	General construction industry risks. Working at heights risks for erection of towers and conductor stringing. May involve helicopter work. Electrical safety risks – HV switching, testing, live line works also at converter stations.	General construction industry risks. Excavation machinery risks. Electrical safety risks – HV switching, testing including converter stations. Overall risks considered lower for UGTLs compared to OHTLs.
18	**Severe weather**	OHTL are exposed to severe weather damage from high winds, flooding, and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL.	OHTL are exposed to severe weather damage from high winds, flooding and lightning strikes.	UGTL have limited exposure risk to severe weather. Lightning strikes to the overhead network can cause damage to UGTL lines.
19	**Bushfire risk and exposure**	OHTL can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.	OHTLs can cause bushfires (releasing molten particles from conductor clashing or conductor contact with vegetation or ground). OHTL's may be exposed to bushfire damage risk (high bushfire risk areas).	UGTLs have limited exposure to bushfire damage risks. Above ground equipment including cable terminations at overhead to underground transitions would be exposed.
20	**Climate change**	Long term climate change effects could increase risks associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need to consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.	Long term climate change effects could increase risk associated with severe weather, wind loads and bushfires on OHTL's. OHTL's line designs will need consider these impacts which may result in increased project costs.	UGTL's will be less exposed to long term climate change risks. There is exposure to damage in flooding events where erosion of ground can expose cables.
21	**Damage by other parties**	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.	OHTL's may be exposed to malicious and accidental damage. Accidental damage can be by vehicles, construction machinery or aircraft.	UGTL's may be exposed to risk of third-party damage by other excavation machinery including drilling.

	Factor	HVAC Overhead	HVAC Underground	HVDC Overhead	HVDC Underground
22	**Earthquake**	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.	Earthquakes have potential to cause damage to overhead infrastructure. However, repair times will be less than for underground cables.	Earthquakes have potential to cause damage to underground cables, joints, and terminations. Repair time in such situations would be considerably longer than for overhead infrastructure.

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