Transmission Lines

High Level Electrical Design Criteria - Guideline

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1. Introduction

1.1 Purpose

This document provides a general introduction to the basis of electrical design and typical design parameter considerations for HV and EHV overhead transmission lines and underground transmission cable assets forming part of:

- The regulated transmission network for Powerlink Queensland.
- Identified user shared assets (IUSA) consisting of overhead transmission lines and underground cables forming part of a shared transmission network.

In the context of this guideline, IUSA's generally consist of an overhead line or underground cable, or a hybrid mixture of both, and that may be:

- Designed and constructed by the owner of the third party IUSA, as a non-regulated transmission service.
- Functionally specified, cut-in, operated, maintained and controlled by Powerlink Queensland as a negotiated transmission service.

1.2 Scope

This document introduces:

- General electrical design expectations relating to the asset functional specifications.
- General electrical design expectations relating to cut-in and line construction works.
- Typical electrical design aspects that influence asset operational considerations over the nominated asset design lifetime.
- Typical electrical design aspects that influence asset maintenance considerations over the nominated asset design lifetime.

This document covers transmission lines as overhead or underground construction, or configured as hybrid mixture of both.

1.3 References

Document reference	Document title
ARPANSA	Australian Radiation Protection and Nuclear Safety Agency
AS/NZS 7000	Standards Australia (2016) *Overhead Line Design*
Electrical safety code of practice - Works	Electrical safety code of practice (2010) *Works*
EMF Handbook	Energy Networks Australia (2016) *EMF Management Handbook*
ENA EG-0	Power System earthing guide Part 1:management principles, version 1
IEC Standards 60287	International Electrotechnical Commission (2006) *Electrical Cables - Calculation of the current rating*
IEC Standards 60853	International Electrotechnical Commission (2002) *Calculation of the cyclic and emergency current rating of cables*
Technical Brochure 640	Cigrè (2015) *A Guide for Rating Calculations of Insulated Cables*
Transmission Line Ratings	TNSP Operational Line Ratings (2009) *v.2*

1.4 Defined terms and abbreviations

Terms	Definition
BIL	Basic Insulation Level
CASA	Civil Aviation Safety Authority
DTS	Distributed Temperature Sensing
EHV	Extra High Voltage
EMF	Electromagnetic Field
EWP	Elevating Work Platform
HV	High Voltage
IUSA	Identified User Shared Asset
OHEW	Overhead Earth Wire
OPGW	Optical Fibre Groundwire
SVG	Surface Voltage Gradient
TNSP	Transmission Network Service Provider

1.5 Monitoring and compliance

This document provides a number of functions as follows:

- Defines typical electrical design considerations, and high level design criteria typically addressed as part of the detailed design process for overhead or underground transmission line connections forming part of regulated or shared transmission networks.
- Defines the typical asset requirements required to facilitate a connection to a transmission network.
- Publishes clear and concise high level design guidelines and technical considerations to assist connection applicants and independent engineers to understand typical TNSP design considerations for a safe, reliable, secure, efficient and compliant transmission connection.
- Strengthens the understanding of key design principles to underpin negotiations between connecting parties and the TNSP.

1.6 Risk management

This document has been developed to introduce and discuss electrical design considerations for typical situations and scenarios encountered in Powerlink Queensland. Particular site conditions, specific project requirements or location specific considerations may require additional design considerations that are not specifically introduced in this document.

All design work, and associated supply of materials and equipment, must be undertaken in accordance with and consideration of relevant legislative and regulatory requirements, and in accordance with the latest revision of Powerlink's functional specifications, Australian and International Standards.

2. General Design and Operational Deliverables for Overhead Lines– Electrical Design Aspects

2.1 Electrical Design for Common Mode Failure Considerations

From an electrical line design perspective, there are a number of design considerations that can result in a single event on a shared user asset causing the failure or interruption to multiple transmission circuits. Typical considerations should include:

- Multiple circuits (power, telecommunications and protection signalling) on a single structure.
- Electrical and mechanical clearances (eg. between an upper and lower circuit of the same or different voltage) including consideration of the crossing location in-span for unattached electrical crossings.
- Transmission line hardware or insulated termination arrangements supporting multiple circuits for power, telecommunication or protection signalling circuits.
- Double or multiple circuit outages from lightning strike incidents to transmission lines.

2.2 Electrical Design for Shared Asset Reliability

Reliability of a transmission line asset is generally determined by the frequency of an outage event, and the duration to rectify the event and return the asset to service. There are many design decisions that can impact on the shared asset reliability. Table 1 summarises the impact of electrical design issues as factors affecting shared asset reliability.

Table 1

Reliability Impact Factors	Electrical Transmission Line Design Considerations
Bushfire – *Conductor Damage or Flashover to Ground*	Ground clearance criteria and fire risk assessment Conductor selection criteria
Flooding – *reduced ground clearance across watercourses, navigable waterways and flood backwater*	Ground clearance criteria
Flooding – *structure damage or collapse from floodwater/debris*	Watercourse considerations in line layout Deflection mechanisms
Clearance above ground – *safety criteria and exclusion zones*	Ground clearance criteria. Development of safety margins, constructability tolerances, conductor long-term metallurgical creep assumptions for 10 year creep assumptions
Clearances – *other objects, buildings, vegetation, railway assets*	Development of clearance criteria including negotiated requirements for other infrastructure owners Electrostatic and Electro-magnetic induction Easement width criteria
Corrosion – *earthing and bonding equipment or line hardware failure*	Galvanic corrosion & dissimilar metals Ground line corrosion of transmission structure earthing Poor quality line materials and electrical hardware Mitigation of insulator pin corrosion

Reliability Impact Factors	Electrical Transmission Line Design Considerations
Thermal Load – *loss of tensile strength of conductor*	Optimised conductor size and correct selection of conductor type to address resulting sustained operating temperatures across localised weather seasons and projected short-term overload during network contingency events
Maintainability	Design for maintainability by declaring the applicable methods to be incorporated into the electrical design: • De-energised only and compacted clearances • Climbing and Inspection access only • Live maintenance clearances when working from structure, bare hand or EWP • Provision of clearances for working from a helicopter platform
Pollution – *Insulator Flashover*	Insulator selection • Creepage and Pollution Category • Insulator type (glass, porcelain, polymer) • Shed profile (normal, fog, aerodynamic)
Failure and Damage Restoration	Improved restoration times by designing based on TNSP standard designs and associated transmission line materials including conductors, earthwires and optical fibre ground wire
Storms – *Conductor damage*	Conductor selection and minimum sizing to account for impact damage from flying debris
Storms – *Lightning damage to shieldwires*	Selection of minimum OPGW strand sizing, outer diameter, earthwire and OPGW material type in high lightning areas
Storms – *Lightning Performance*	Insulation co-ordination with substation BIL Insulation parameter selection based on nominated outage reliability target Footing resistance criteria
Storms and Extreme Weather – *Wind induced Flashover and Outages*	Design for limit state wind pressures, insulator swing and conductor intra-span clearances in accordance with AS7000
Vandalism and Theft	Insulator selection avoids use of glass type in high risk areas Anti-theft or theft-resistant designs adopted for buried earthing systems to minimise risks associated with copper theft Anti-tamper solutions for transmission structures
Aircraft Impact	Marking of structures and/or wires in accordance with CASA and Australian Standard requirements for aircraft, including low-altitude agricultural operations in accordance with identified and negotiated stakeholder engagement.
Sub-Conductor Spacing & Vibration Control	Provision of damping system on conductors, OPGW and OHEW Spacing of sub-conductor bundles to minimise conductor damage from clashing

Reliability Impact Factors	Electrical Transmission Line Design Considerations
Touch and Step Voltage Hazards	Earthing system design to AS/NZS 7000 Earthing system commissioning and compliance testing
Wildlife Interaction	Insulation selection to control risk of bird damage to polymer line insulators

2.3 Electrical Design Considerations for Shared Asset Power Quality

In terms of power quality consideration, design of shared transmission line assets should consider:

- Voltage unbalance code compliance requirements to determine the transmission line transposition requirements.
- The effect of transient and sustained outages based on the lightning outage performance targets set in the design process.

2.4 Electrical Design Considerations for Shared Asset Electrical Losses

In the transmission electrical design process, conductor selection plays a vital role in optimising losses associated with shared asset transmission line operation and generally considers:

- I^2R losses associated with total circuit length and the load (current) trends for the circuit.
- Power losses associated with the prevalence of corona discharge involving ionisation of air at the conductor surface as a function of the conductor surface voltage gradient, and the annual proportion of time of fair vs foul weather (including rain).

2.5 Electrical Design Considerations for Shared Asset Voltage Regulation

It is normal operating practice to operate the transmission network at higher than nominal voltage to optimise losses for long transmission connections. Electrical design aspects should assume higher than nominal voltage operation in the design, and calculation elements that utilise an operating voltage assumption, including but not limited to insulation design and selection, electrical clearance development, electric field calculations and lightning performance.

2.6 Lightning Performance of Shared User Assets

The design of the transmission line generally considers a number of factors to predict the long term average outage rate for single, or multiple circuits on the common structure due to lightning strikes to the structure or in-span to the phase or earth conductors. Factors that influence the long term outage performance statistics for user shared transmission network are influenced by:

- The number of earthwires, and their geometric arrangement in relation to the phase conductors both on the structure and in-span.
- Heights of structures and the in-span conductor and OHEW separation.
- Mutual coupling factors between phases, circuits and overhead earthwires.
- Insulation co-ordination between transmission line and substation plant.
- The statistical distribution of structure footing resistances and annual variation for structures along the user shared asset.

Overhead earthwires, including OPGW are specified to shield and minimise the risk of direct strikes to phase conductors. OHEW and OPGW's are typically designed to remain intact mechanically and electrically from lightning strikes over their nominated design lifetime. OPGW's should also continue to function reliably for optical transmission during incident lightning strike conditions.

2.7 Overhead Line Thermal Ratings

Overhead transmission line ratings are calculated in accordance with the defined procedure and standardised TNSP calculation approach as outlined by TNSP Operational Line Ratings version 2.

The design approach should ensure that the minimum legislated ground clearances are maintained under the maximum operating temperature of the conductor that includes:

- Provision for the statistically applicable range of seasonal weather conditions for the line locality. Typically this is used to determine a seasonal workbook rating for the asset, for seasonal definitions, and for day and night.
- Proponents may also consider the applicability of the real time rating system to dynamically rate and dispatch the transmission line asset and nominated time intervals. Design for such a system will need to interface with the applicable communication protocols for the TNSP energy management systems.

As highlighted in Table 1, selection of conductor size and conductor type shall need to address the operating temperature trend for the range of asset operating conditions to manage the risks for loss of conductor strength due to annealing and increase in maximum sag due to conductor permanent elongation (temperature related creep).

2.8 Electrical Design Considerations for Shared Asset Fault Current Management

The electrical design and specification for shared asset transmission line equipment should generally consider the nominated maximum network connection point fault level, including future fault level projections for revised network connectivity and/or changes in generation configurations. Fault levels are generally advised by the TNSP for the shared transmission network, periodically revised and published.

For overhead transmission lines, overhead earthwires are typically sized and installed to provide a low impedance aerial return path from the location of the fault to the fault current source. The impedance of the footing system of the support structure in combination with the impedance of the overhead earthwire path is generally low enough to ensure the adequate flow of fault current allowing fast detection of earth fault current and clearance by secondary protection systems.

Overhead earthwires can also include Optical Fibre Groundwire (OPGW) that provides dual functionality both as an overhead earthing conductor, as well as a dedicated communication path using optical transmission. The flow of earth fault current in the OPGW should not be detrimental to the optical performance properties of this optical connection during a transient earth fault condition.

Earth fault current flows into substation earth mats and transmission structure footings result in step and touch voltage at these locations. Transmission line earthing is generally undertaken to provide reliable operation of the protection systems, controlling the step and touch voltages around structures, and providing acceptable long term average lightning performance.

Earthing of transmission lines is generally in accordance with AS/NZS 7000 Overhead Line Design, and underpinned by the risk based approach informed by ENA EG-0 Power system earthing guide Part 1: management principles.

2.9 Electrical Design Considerations for Environmental Performance

The selection of conductor size for transmission assets generally considers the resulting electric field on the surface of the conductor, and the resulting corona onset and extinguishing characteristics, as well as the audible noise emitted from sources consisting of the conductor, insulation and line hardware.

The gradient of the electric field on the surface of the conductor is a design parameter considered in the conductor selection, and is referred to as the Surface Voltage Gradient (SVG). Guidelines for SVG design are generally considered in accordance with the informative requirements of AS/NZS 7000 Overhead Line Design.

Grading of electric fields on the conductor, line hardware and insulator assemblies are typically considered in the electrical design process to ensure the effects of audible noise, radio and TV interference are addressed in accordance with the relevant industry standards, guidelines and communication regulatory bodies.

Electrical design factors also influence the required easement width to address issues including electric and magnetic fields and audible noise both underneath the asset, and at the easement boundary.

Electric and magnetic fields are generally considered in the design process in accordance with sound industry design principles from Energy Networks Australia EMF Handbook, and underlined by the occupation and general public guideline limits outlined by the Australian Radiation and Nuclear Science Agency (ARPANSA).

3. General Design and Operational Deliverables for Underground Cables– Electrical Design Aspects

3.1 Electrical Design for Common Mode Failure Considerations

From an electrical line design perspective, there are a number of design considerations that can result in a single event on a shared user asset causing the failure or interruption to multiple underground transmission circuits. Typical considerations could include:

- Accommodating multiple circuits (power, telecommunications and protection signalling cabling) installed in a single trench or common duct bank, and the consequence of external damage mechanisms (e.g. dig-ins, heaping of spoil on top of cable route etc.). Consideration should be given to the ease of access for one service type for inspection or repair, whilst minimising risk to other circuits in-service and personnel safety (e.g. repair or splicing of fibre optic cables installed in proximity to an adjacent power cable circuit)
- Soil dry-out, consideration of soil temperature isotherms, seasonal moisture content and the variation in native soil thermal parameters that can result in thermal runaway phenomena associated with accommodating multiple circuits in shared cable backfill.
- Multiple underground circuits sharing a common joint bay buried vault structure and the consequence of external damage mechanisms.
- Cable installations where fire may cause damage to multiple cable circuits (e.g. tunnels and basements)
- Insulation co-ordination and surge protection design controlling the risk of double or multiple circuit outages (with non-restoring insulation damage) from lightning strikes and power system switching surges incident to adjacent overhead transmission infrastructure. Note that this phenomenon is exacerbated by the surge impedance for underground cable assets generally being an order of magnitude lower than for the interconnected overhead transmission line asset.

3.2 Electrical Design for Shared Asset Reliability

Reliability of an underground transmission asset is generally determined by the frequency of an outage event, and the duration to rectify the event and return the asset to service. There are many design decisions that can impact on the shared asset reliability. Table 2 summarises the impact of electrical design issues as factors affecting shared underground asset reliability.

Table 2

Reliability Impact Factors	Underground Transmission Electrical Design Considerations
Bushfire – *Cable and Accessory Damage*	Vegetation and ground cover clearance around above ground cable accessories (terminations) and ancillaries (kiosks, bonding leads, link boxes etc.)
Other Fires	Consider the use of fire retardant jacket materials that are low smoke, zero halogen to retard the spread of fire and smoke where applicable (tunnels, cables in air etc.)
Flooding – *accessory mounting heights/ control of moisture*	Ancillaries are designed with the required IP rating to control moisture ingress from regular flooding or rainwater events filling pits or circuit

Reliability Impact Factors	Underground Transmission Electrical Design Considerations
ingress in flooded joint vaults and below ground link box pits)	maintenance access points. Accessory mounting structures account for clearance above flood level to ensure no inundation of cable terminations. Drainage design for joint bay vaults
Insects & Vermin	Cable jackets, bonding lead and buried communication cable resilience to damage from termites, ants and rodents
Vegetation	No plantings of vegetation with extensive route systems that shall mechanically degrade the cable, or significantly alter the moisture content thus increasing the thermal resistivity of the native soil adjacent to the installed cable system. Easement width
Mechanical Damage – *dig-ins and inadvertent excavation*	Cable selection with an applicable type of metallic water barrier to account for the risk exposure along the cable route. Use of radial and longitudinal water-blocking to limit the internal transfer of moisture should the water barrier be breached. Use of mechanical protection by cover plates, or concrete slabs of nominated strength where applicable
Corrosion – *conductor or metallic sheath integrity*	Provision of cable designs with effective water barriers and water blocking designs Selection of conductor type, type of metallic sheath and outer jacket material for the required installation conditions (direct buried, ducts, tunnels, directional bores, submarine cables, acidic soils, swamps and contaminated land)
Thermal Load – *accelerated aging of insulation from elevated temperature operation* *forces on terminations from cable elongation and contraction* *soil dry-out and thermal runaway of the cable operation temperature*	Sizing of the cable cross-section area and selection of conductor type for the nominated thermal loading conditions. Consideration of the loss load factor to look at the operating temperature profile of the cable. Snaking and cleating systems to control expansion, contraction and anchoring of the cables where these enter jointing and termination locations. Design and selection of thermally stable backfills with controlled moisture content under a wide range of seasonal variation and operational loading variations. Thermal route surveys to establish native soil thermal resistivity for the correct selection of cable cross-section area
Maintainability	Adequate mechanical separation between joint bay vaults to ensure that incorrect joints are not inadvertently exposed during emergency repair or excavation operations. Design that mitigates and nominates the magnitude of standing voltages that appear on the metallic sheath during normal and fault current conditions where these may be accessed for in-service sheath insulation

Reliability Impact Factors	Underground Transmission Electrical Design Considerations
	testing. Clear and concise signage identifying link boxes, complete with circuit id and phase id that each link corresponds to. Clear signage identifying the route of the buried takes, especially at bend points and crossing of other infrastructure, and where risk of dig-in is increased Use of conduit systems Easement width and maintenance access criteria
Workmanship – *Cable System Manufacturing*	Selection of prequalified (where applicable) and type tested cable systems (consisting of cable and accessory range of applicability).
Workmanship – *Quality and repeatability of jointing and termination works*	Jointer training records and qualifications for the relevant manufacturer and the respective cable and accessory combination. Nomination of additional commissioning tests to verify workmanship
Pollution – *Termination Flashover*	Termination bushing insulator selection • Creepage and Pollution Category • Bushing type (porcelain, polymer) • Stand-off insulator type
Reliability of Cable Ancillary Systems – *SVL selection, operation and maintenance*	Routine maintenance and inspection regimes for cable surge voltage limiters (SVL's) Earthing design and testing for cable sheath and bonding systems
Failure Restoration	Improved restoration times by designing based on TNSP standard designs for associated underground transmission cable standard sizing, and interchangeability of termination and joint types for typical cable cross-section sizing. Selection of accessories to suit the training regime of available jointers.
Vandalism and Theft	Anti-theft or theft-resistant designs adopted for buried earthing systems to minimise risks associated with copper theft Security of kiosks, buried pits and link boxes to ensure that these are anti-tamper design.

3.3 Electrical Design Considerations for Shared Asset Power Quality

In terms of power quality consideration, design of shared underground transmission line assets should consider voltage unbalance code compliance requirements to determine the transmission line transposition requirements.

3.4 Electrical Design Considerations for Shared Asset Electrical Losses

In the underground transmission electrical design process, conductor cross-sectional area and the required insulation type and thickness plays a vital role in optimising losses associated with shared asset transmission line operation and generally considers:

- I^2R losses associated with total circuit length and the load (current) trends for the circuit

- Dielectric losses and associated thermal losses for the cable, generally of most importance where the operating voltage is 220 kV or greater.

3.5 Electrical Design Considerations for Shared Asset Voltage Regulation

It is normal operating practice to operate the transmission network at higher than nominal voltage to optimise losses for long transmission connections. Electrical design aspects should assume higher than nominal voltage operation in the design, and calculation elements that utilise an operating voltage assumption (e.g. cable insulation dielectric losses)

3.6 Underground Cable Thermal Ratings

Underground transmission cable ratings are calculated in accordance with international best practice including documented approaches from IEC Standards 60287 and 60853, and supported by additional guidelines from Technical Brochure 640 published by Cigrè.

The design approach should ensure that ratings are calculated for steady state (100% load factor), cyclic and emergency operational scenarios. De-rating factors for multiple circuits in service, sharing common cable routes should also be considered.

Cable rating calculations are generally performed:

- With provision for the statistically applicable range of seasonal ambient temperatures for both air and soil. Ratings for summer and winter are generally determined as a minimum.
- Nominating the required cable sheath bonding arrangement, and allowance for the de-rating effects of metallic sheath circulating currents.
- Developing site specific soil thermal parameters and moisture content assessment from thermal route measurement surveys. The effects from variation of soil and backfill thermal resistivity and moisture content should be catered for in the design process.
- Specifying the required thermally stable backfill thermal resistivity.
- Proponents may also consider the applicability of the real time rating system to dynamically rate and dispatch an underground transmission line asset. This is typically undertaken with the addition of a DTS system, requiring the installation on optical fibre cabling close-to, on or within the cable to determine cable temperature. Design for such a system also needs to interface with the applicable communication protocols for the TNSP energy management systems.

3.7 Underground Cable Typical Installation Arrangements

Trench design and associated nominal cable arrangements are typically designed on a project specific basis to optimise the selection of the required cable cross-sectional area. Trench cross-section design and dimensioning is primarily related to achieving the nominated thermal rating. In addition to aspects highlighted in Section 3.6, trench dimensioning, cable arrangement including cable to cable separation and circuit to circuit separation will typically consider:

- Nominal depth of cover for the cable or conduit.
- Required conduit size to facilitate cable pulling arrangements, whilst limiting associated derating effects.
- Increased depth of cover and deep installations resulting from other controlling authority requirements at crossings (road reserves, carriage ways, pipelines and railway corridors).
- Thermal resistivity and dry-out properties for thermally stable cable backfills and the surrounding native soil.
- Method of cable sheath bonding and consideration of sheath standing voltage limits at accessible locations (link boxes and kiosks).

- Positioning and mechanical offset of other associated non-electrical circuits for protection, communication and temperature sensing requirements.
- Determination of magnetic field on easement, and on the easement boundary.

Consideration of these elements will generally determine whether a cable trench can accommodate:

- A trefoil arrangement (with or without cables/conduits touching) conceptually shown in Figure 1.
- A flat arrangement (with or without cables/conduits touching) conceptually shown in Figure 2.

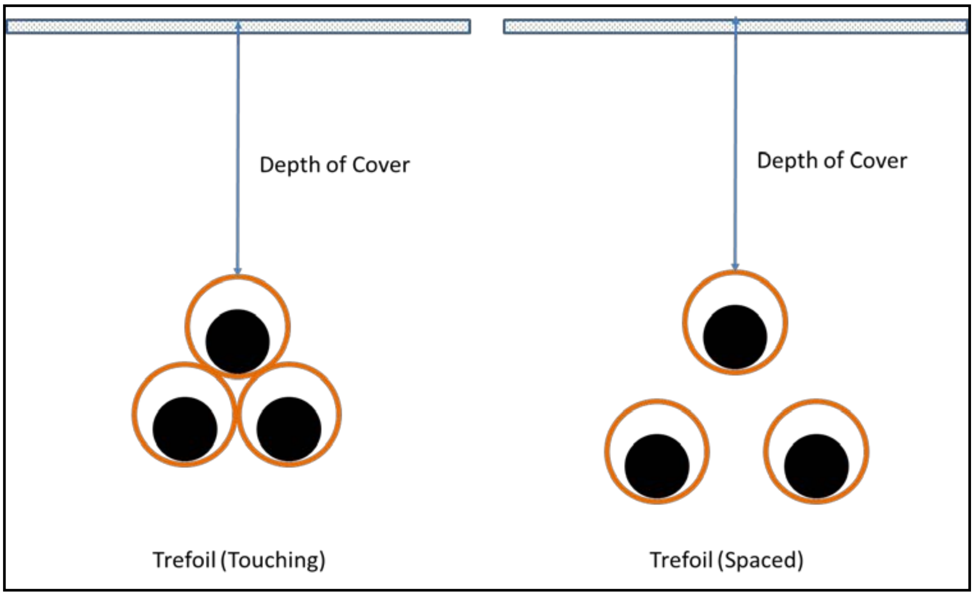

Figure 1

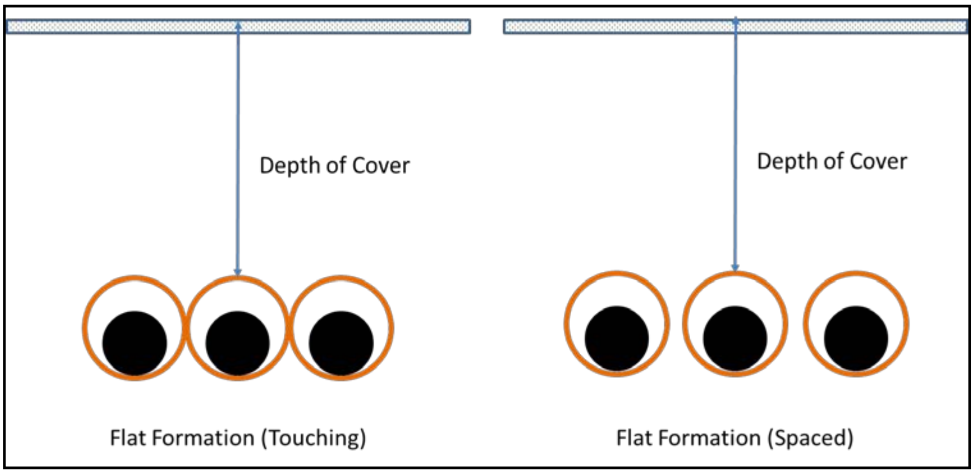

Figure 2

Cable installations are generally in conduit for most transmission applications.

For standard easements, nominal depth of cover is a minimum of 900mm. Requirements for the crossing and service separation distances to other infrastructure operated by other parties shall generally be in accordance with negotiated requirements, wayleave agreements, recognised industry practices and the relevant Australian Standards and guidelines where applicable.

For cables installed with less than 900 mm depth of cover, generally associated with short defined sections for crossing of obstructions, additional precautions for route identification, trench marking and mechanical protection is required in accordance with the Electrical safety code of Practice 2010 – Works and the project specific design specification.

Regardless of the degree and extent of mechanical protection employed, transmission cables are generally not installed with less than 600 mm depth of cover for typical installations on easement and where crossing other route obstacles.

3.8 Electrical Design Considerations for Shared Asset Fault Current Management

The electrical design and specification for shared asset transmission line equipment should generally consider the nominated maximum network connection point fault level, including future fault level projections for revised network connectivity and/or changes in generation configurations. Fault levels are generally advised by the TNSP for the shared transmission network, periodically revised and published.

For underground transmission lines, the metallic cable sheath, earth continuity conductor system (where applicable), and design of the sheath bonding system topology are typically sized and installed to provide a low impedance fault current return path from the location of the fault to the fault current source. The impedance of the earthing system is generally low enough to ensure the adequate flow of fault current allowing fast detection of earth fault current and clearance by secondary protection systems.

Earth fault current flows into substation and joint bay earth mats, resulting in step and touch voltage at these locations. Transmission line earthing is generally undertaken to provide reliable operation of the protection systems, whilst controlling the step and touch voltages around accessible locations occupationally and by the general public.

Earthing of underground transmission lines are generally in accordance with the risk based approach informed by ENA EG-0 Power system earthing guide Part 1: management principles.

3.9 Electrical Design Considerations for Environmental Performance

Magnetic fields are generally considered in the design process in accordance with sound industry design principles from Energy Networks Australia EMF Handbook, and underlined by the occupation and general public guideline limits outlined by the Australian Radiation and Nuclear Science Agency (ARPANSA).

