Integration of an 88 km 220 kV AC cable into the Victorian Electricity Network in Australia

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ABSTRACT

The Victorian Desalination Plant is connected to Victoria's electricity network via an 88 km 220 kV AC underground transmission line. The cable is the longest of its type in the world. The technical challenges associated with the implementation of long HVAC cable systems have been presented at previous Jicable conferences [1] - [4]. This paper describes how the challenges were addressed for the Victorian Desalination Plant 220 kV cable system.

KEYWORDS

Long underground HVAC cable, 220 kV XLPE

BACKGROUND

The Victorian Desalination Plant was commissioned in 2012 to provide a rainfall independent water supply for Melbourne, Geelong and the surrounding area. The plant is located near Wonthaggi approximately 135 km southeast of Melbourne. It treats seawater to potable standards using reverse osmosis technology. It has a production capacity of 150 GL pa with the capability to expand to 200 GL pa. It is the largest desalination plant in Australia and one of the largest reverse osmosis plants in the world. The plant's electrical consumption is 100 % offset by the purchase of renewable energy credits.

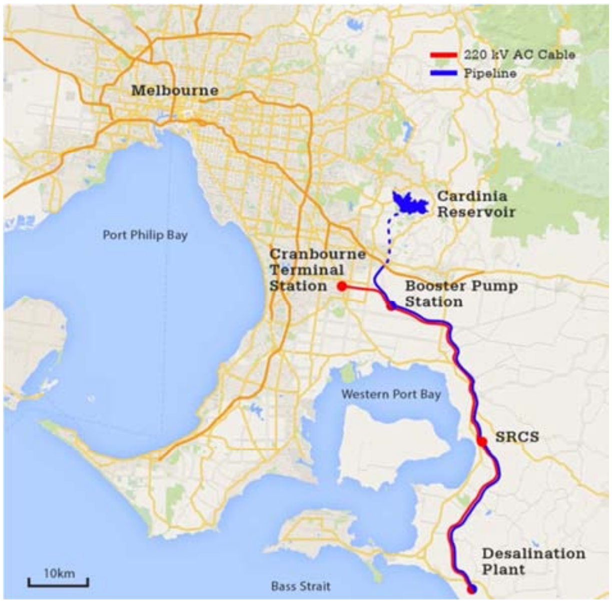

Figure 1: Cable and pipeline routes

The plant is connected to Victoria's water and power networks via an 84 km transfer pipeline and an 88 km underground transmission line. The transfer pipeline and underground transmission line are both rated for the ultimate capacity of the plant and share the same easement for most of their length. The project also included a Booster Pump Station and a shunt reactor station at SRCS.

Figure 2: Victorian Desalination Plant

TRANSMISSION LINE OPTIONS

Many options were considered for the desalination plant electrical supply. A supply via overhead line was long seen as the most appropriate option. The original overhead option was to feed the plant as well as augment the power supply to the surrounding region.

Public concerns for visual amenity and the impact on local landowners later resulted in an underground option becoming the focus of design efforts. The requirements for the link were also changed to a dedicated supply for the desalination plant.

Underground HVDC and HVAC options were considered. An HVAC link was finally selected as it offered a shorter construction period, lower electrical losses and lower cost [5]. The HVAC option also presented operation and maintenance benefits as it utilised equipment and technology used throughout the Victorian electricity network.

PROJECT REQUIREMENTS

The project was delivered as a Public Private Partnership where the overall project scope and requirements were specified by the state of Victoria. The key project requirements related to the 220 kV cable system are listed below.

- The cable system is to be connected to the Victorian 220 kV network at Cranbourne Terminal Station (CBTS)
- The cable system is to be an underground HVAC system located in one trench
- The cable system is to be a dedicated supply for the desalination plant and booster pump station
- The cable system is to provide 165 MW capacity for the desalination plant (145 MW) and booster pump station (20 MW)
- The electrical losses in the 220 kV cable and shunt reactors are not to exceed specified limits

- The cable system is to comply with the automatic access standards specified in Australia's National Electricity Rules. Amongst other requirements, this includes that the power factor at the network connection is to be between unity and 0.95 lagging
- Full redundancy is required for all 220 kV transformers and reactors. The project requirements also included limits on the number of forced outages on 220 kV equipment (other than the cable) and the resulting annual downtime
- Land was allocated at the booster pump station and at the Southern Reactive Compensation Station (SRCS) for the installation of reactive compensation

CABLE SYSTEM DESCRIPTION

The Victorian Desalination Plant 220 kV cable system is illustrated in Figure 3. The cable is split into three sections. The first section runs from the network connection point at CBTS to the Booster Pump Station (BPS). The second section connects BPS to SRCS. Three oil-filled shunt reactors are located at SRCS. The final cable section connects SRCS to the desalination plant.

Substation components

Outdoor air-insulated equipment was selected for CBTS, BPS and SRCS. This configuration minimises the repair time for failures on the 220 kV bus or disconnectors.

Gas insulated switchgear (GIS) was selected for the Desalination Plant Terminal Station (DPTS) due to its reliability and as it is more suited to the marine environment. The smaller footprint of the GIS also allowed it to be more easily integrated with the plant architecture.

Circuit breakers are provided for each of the shunt reactors to facilitate on-load switching for control and maintenance. These circuit breakers also allow reactor faults to be isolated without de-energising the entire cable system. A cable circuit breaker was included at CBTS to comply with network connection requirements.

The cable connections at CBTS, BPS, SRCS and DPTS present a common mode failure point. The cable is connected directly to the DPTS bus to reduce the risk of a failure within the GIS incoming cable module. The following measures were included to assist in minimising repair times:

- Use of air insulated switchgear at CBTS, BPS and SRCS
- Spare breaker provided in case of failure of cable feeder at CBTS
- BPS and SRCS arrangement minimises the point of common mode failure between the cable entry and exit terminations
- GIS at DPTS specified such that each outgoing transformer feeder and the incoming cable module can be isolated from the other parts of the common mode failure point
- A spare incoming cable module with VTs was also included with the GIS at DPTS

The transformers and their respective feeders are sized for the ultimate load and are fully redundant as required by the project requirements. Studies showed a maximum of two shunt reactors were required for the full operational range of the system. The third reactor provides the required redundancy.

Cable specification

The cable was procured via a design and supply contract. The cable supplier was also responsible for supervising the installation, performing all joints and terminations as well as all testing.

The cable size and installation design was based on a performance specification and thermal resistivity measurements taken at 34 locations along the 88 km cable route. The tests showed in-situ, naturally occurring, thermal resistivities were typically less than 1.0 K.m/W. To account for potential reductions in the moisture content, dry out curves were used to determine a design value of 1.9 K.m/W for the native soil thermal resistivity. The design also considered a thermal resistivity of 1.5 K.m/W for the thermally stable backfill material. The key cable design parameters are summarised in Table 1.

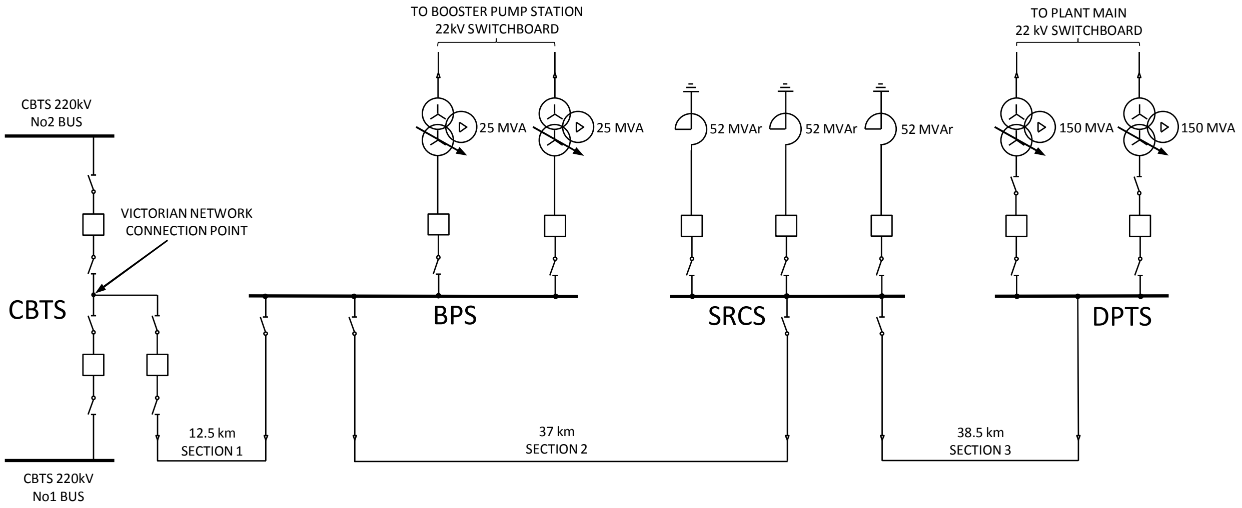

Figure 3: Simplified single line diagram of 220 kV cable system

Capacity	145 MW at DPTS 22 kV 20 MW at BPS 22 kV Both loads 0.95 lagging
Voltage	245 kV
Short circuit withstand	40 kA for 1s
Nominal depth	1200 mm
Remote ground temperature	30 °C
Thermal resistivity	1.9 K.m/W native soil 1.5 K.m/W thermal backfill

Table 1: Cable design parameters

The nominal trench design was modified to maintain the current rating where native soil conditions changed or at crossings. The native soil thermal resistivity was measured at regular intervals during the installation. The thermal properties of the thermal backfill were also monitored through regular testing.

The cable particulars are listed below.

	Section 1	*Section 2*	*Section 3*
Length	12.5 km	37 km	38.5 km
Size	500mm^2 Cu	400mm^2 Cu	400mm^2 Cu
Insulation	XLPE	XLPE	XLPE
Installation	Touching trefoil, direct buried	Touching trefoil, ducted	Touching trefoil, ducted
IEC 60287 current rating	558 A	504 A	504 A
Sheath cross-bonding	Fully cross-bonded		
Phase transpositions	Not required		

Table 2: Cable particulars

The cable also includes a fibre optic Distributed Temperature Sensing (DTS) system. The DTS fibre was installed in a duct on the outer interstice of the trefoil group. This enables the fibre to be repaired or replaced without affecting the operation of the cable.

TECHNICAL CHALLENGES

The technical challenges associated with the implementation of long HVAC cable systems have been presented at previous Jicable conferences [1] - [4]. The following sections describe how the challenges were addressed for the Victorian Desalination Plant 220 kV cable system.

System ratings

At its ultimate capacity of 200 GL pa, the load at the desalination plant and booster pump station will approach 135 MW and 19 MW respectively.

The water system production level is selectable in steps of 25 GL pa. Once the set point is selected, the plant accelerates/decelerates to the required operation point and remains there until a new set point is given. For the purpose of system analysis and specifying primary equipment, the plant and booster pump station loads can be considered as constant and not cyclic.

The steady state performance of the system was analysed to assess:

- Reactive power flow and the ability of the reactors to satisfy the network connection power factor requirements
- Load flow and current and voltage profiles
- Electrical losses
- Ability of transformer tap changers to regulate the 22 kV voltage

The studies determined that these criteria could be met for almost all operation scenarios if two 52 MVAr reactors are switched in at SRCS. The only exception is when the supply voltage approaches its minimum (0.9 pu) at maximum load. In this case, the system is operated with one 52 MVAr reactor switched in.

Voltage and current profiles for the 220 kV cable are provided for two boundary scenarios below. Figure 4 illustrates the no load case where the supply voltage is at its maximum (1.1 pu). Figure 5 depicts the case where the supply voltage is at its minimum (0.9 pu) and the total load is 165 MW ie. 145 MW at the plant and 20 MW at BPS.

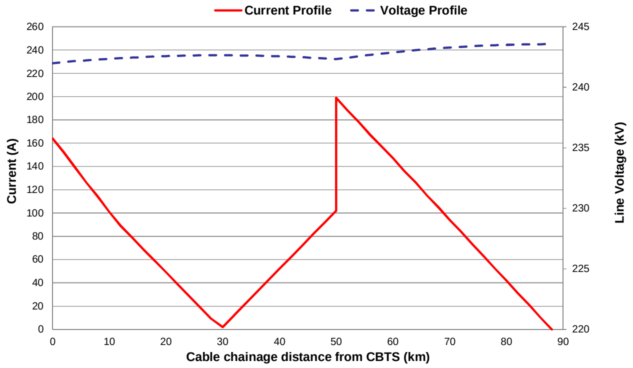

Figure 4: Voltage and current profile (no load)

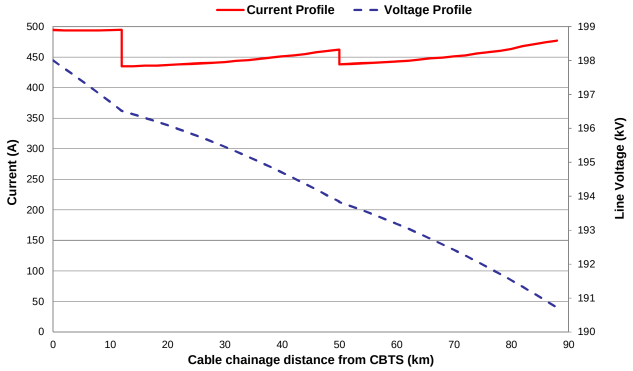

Figure 5: Voltage and current profile (165 MW load)

The steady state studies demonstrated that the design is robust. No reactors are required to keep the load within the continuous current rating of the cable. Only one of three reactors is required to be switched in to maintain the voltage below 245 kV for the worst case condition of no load and maximum supply voltage.

The reactors were specified with off load taps allowing the rating to be varied by ± 5 %. Studies showed that these taps could be used to address variations such as cable parameter tolerances, load power factor and installed cable length.

Dynamic response

Studies were undertaken to assess the dynamic performance of the 220 kV cable system. These included:

- Voltage recovery following a network fault
- Impact of reactor switching on voltage profile
- Impact of sudden rejection of plant load on network voltage and frequency

The dynamic studies did not identify major voltage recovery issues. The impact of reactor switching and load rejection on voltage and frequency is not significant.

Insulation coordination

The effect of lightning events was considered at each substation along the 220 kV cable. Switching surges were also considered however the studies confirmed the transient voltages due to switching are less onerous than those due to lightning.

The studies determined that a statistical Lightning Impulse Withstand Level (LIWL) of 1050 kV and Power Frequency Withstand Voltage (PFWV) of 460 kV are appropriate for the substation 220 kV switchgear. The transformers and reactors were specified with a minimum conventional LIWL / PFWV of 950 / 395 kV. This is consistent with other installations within the Victorian 220 kV network.

The insulation coordination studies were also used to specify the requirements for surge arrestors.

DC aspects of switching

Switching studies identified a DC switching issue. This is the same issue reported in reference [2] as 'Zero Miss Effect'. In the Victorian Desalination Plant 220 kV cable system, the DC switching issue arises due to DC inrush and DC outrush.

DC inrush

When a reactor is energised, the inrush current includes a slowly damped DC component. If the system is operated at low load and the cable reactive power is fully (or near fully) compensated, the inrush current does not have immediate natural current zeros. This may affect the duty of the circuit breaker if it needs to open just after energising. One example is when an earth fault occurs on the cable just after energising a reactor. The current on the healthy phases does not have immediate natural current zeros.

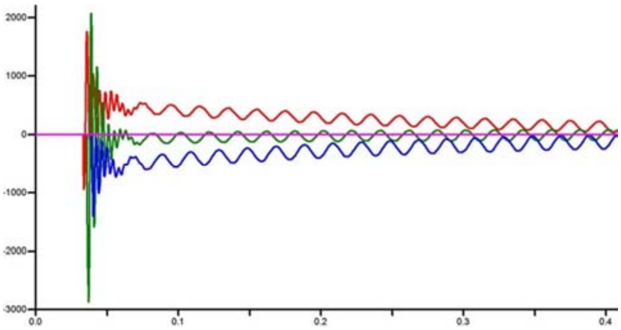

Figure 6: DC inrush during energisation of fully compensated cable at no load

DC outrush

DC outrush occurs when the reactors discharge their energy as a slowly damped DC current during faults. The impact of the DC outrush depends upon the fault location and whether the network contribution to the fault will ensure there are immediate natural current zeros.

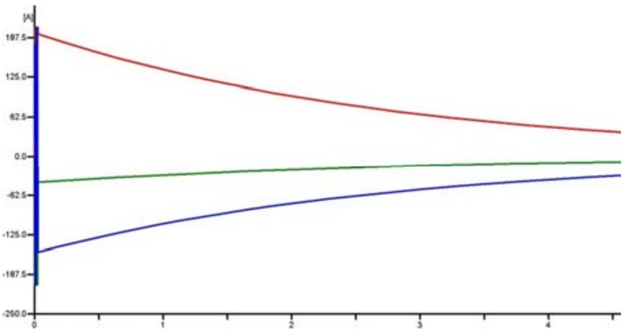

Figure 7: DC outrush from a single reactor following a 3P-G fault on the cable

Options considered for the DC switching issue

A number of options were considered to mitigate the DC switching issue. Some of those are listed below.

- Prevent 100 % compensation of cable
- Pre-insertion resistors on cable feeder and reactor breakers
- Use cable feeder and reactor breakers to switch DC
- Use of different switching sequences
- Point on wave switching

The use of pre-insertion resistors on the cable feeder and reactor breakers would address switching issues due to DC inrush but it would not address the DC outrush issues. The increased size and cost of breakers with pre-insertion resistors meant this was not a preferred solution.

The analysis showed there was no switching sequence that could address switching issues caused by DC inrush on the desalination plant cable system.

Point on wave switching can be used to reduce the effect of DC inrush during energisation and during reactor switching. However, the breakers still need to be capable of switching the transient voltages without relying on the point of wave working correctly.

Solution adopted for the DC switching issue

The solution adopted for the switching issues caused by DC inrush and DC outrush is described below.

DC inrush

Switching issues caused by DC inrush were mitigated by preventing 100 % compensation of the cable. This necessitated a change to the network connection requirements. The automatic access standard requires the power factor at the network connection to be between unity and 0.95 lagging. The project negotiated an allowance to export up to 80 MVAr at the connection point. This allows the cable system to be operated such that there is sufficient AC at low loads so the breakers at CBTS see immediate natural current zeros during the energisation of a single reactor. The two reactors are switched in sequentially so immediate natural current zeros occur during energisation of the cable system.

DC outrush

Switching issues caused by DC outrush were mitigated by using the DC breaking capability of the reactor and cable feeder breakers to interrupt the reactor contribution to faults.

Cable switching

Switching studies together with manufacturer type tests were used to confirm the cable feeder breaker is rated for the required duty. Class C2 circuit breakers, as defined in IEC 62271-100, were specified to reduce the probability of restrike. Note that although the preferred cable charging breaking current listed for 245 kV breakers in IEC 62271-100 is 250 A, manufacturer type tests demonstrated the breaker was rated for the 491 A maximum charging current determined for the desalination plant cable. Surge arrestors were also included at the CBTS cable termination to limit overvoltages in the event that circuit breaker restrike occurs.

A point on wave switching scheme was applied to reduce the impact of inrush currents on the network during cable energisation.

The studies demonstrated that the cable could be energised and de-energised via a single switching point at CBTS. Following de-energisation, the cable is normally discharged through the shunt reactors, transformers and the inductive VT within the GIS at DPTS. The inductive VT is rated to discharge the entire cable in the event the reactors and transformers are not connected.

The studies showed that for the de-energisation of the cable, the voltage on the de-energised cable feeder breaker poles may decay at a frequency near the power system frequency. As shown in Figure 8, this can cause significant Power Frequency Voltages across the circuit breaker poles. This corresponds to the ‘out of phase’ condition defined in IEC 62271-100. Manufacturer type tests were used to confirm the cable feeder breaker is rated for the required duty.

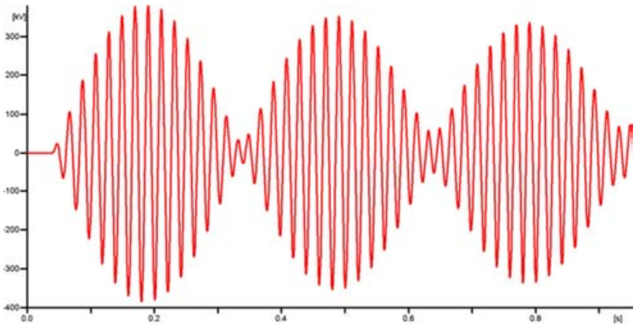

Figure 8: Power Frequency Recovery Voltage at cable feeder breaker following de-energisation

Reactor switching

Switching studies were also undertaken to assess the performance requirements for the reactor breakers. Manufacturer type tests were used to confirm the reactor breakers are rated for the required duty.

A point on wave switching scheme was applied to reduce the probability of re-ignition. The risk of re-ignition is low relative to other shunt reactor installations as the reactor breakers will not be required to operate regularly. Two reactors are switched in for almost all load scenarios. Surge arrestors were included to protect the reactor and associated switchgear should the breaker fail to interrupt the current with more than one re-ignition.

Transformer inrush

Studies analysing the impact of energising the plant transformers indicated a short term voltage dip that is unlikely to have an adverse effect on the operation of the desalination plant.

Additional studies considering possible system resonances that may be induced by the harmonic components of the inrush currents did not suggest 220 kV bus transient overvoltages or voltage ringing.

Harmonics

Harmonic studies were undertaken to analyse the effect of harmonic emissions from the network, plant and BPS on the total 220 kV cable current. It was noted that the cable has series and parallel resonance points within itself. The harmonic source impedance is not significantly affected by the number of shunt reactors due to the high inductive impedance for higher order harmonics.

The studies included considering harmonic levels that may occur in the future. The present network harmonic emission levels were increased until the Total Harmonic Distortion (THD) reached the planning levels specified for the network connection. The results for this future scenario indicated the harmonic currents would increase the cable current by less than 1 % of the cable rating.

The harmonic studies also established the emission limits for BPS and the plant in order to comply with the harmonic voltage and distortion requirements at the network connection at CBTS. These were used to guide the specification of harmonic filters at BPS and the plant.

Secondary systems

Protection

The key components of the cable protection system are listed below.

- All 220 kV plant is protected by duplicate unit protection schemes with full local backup
- The 220 kV cable is protected by duplicate line current differential schemes
- The 220 kV busbars at BPS and SRCS are protected by duplicate high impedance bus protection schemes. The DPTS 220 kV busbar is protected by the transformer and cable current differential schemes
- Local backup protection schemes are included for the failure of any equipment to clear a fault. All 220 kV and incoming 22 kV breakers are protected by breaker failure schemes
- Overvoltage protection is provided throughout the cable system

Communications

Two separate fibre optic cables are used to facilitate protection, supervision and monitoring of the cable system. One of the fibre optic cables is installed in the 220 kV cable trench. The other fibre optic cable is laid alongside the transfer pipeline where the 220 kV cable and transfer pipeline share the same easement. The second fibre optic cable joins the power cable easement for the final section to CBTS. A minimum separation distance is maintained to prevent common mode failure.

Earthing and electromagnetic fields

Earthing

The 220 kV cable is fully cross-bonded. The aluminium cable sheaths are continuous and bonded directly to the earthing systems at each substation and at designated cable joint bays. The sheaths are earthed via sheath voltage limiters at each cross-bond joint bay.

The earthing system design included considering the current distribution during earth faults. The current distribution due to a 220 kV earth fault at DPTS is illustrated in Figure 9. As shown, the return current consists of conductive and inductive components. The conductive component returns to CBTS via the cable sheath and through the general mass of earth. The inductive component is due to mutual coupling between the faulted phase conductor and the cable sheaths.

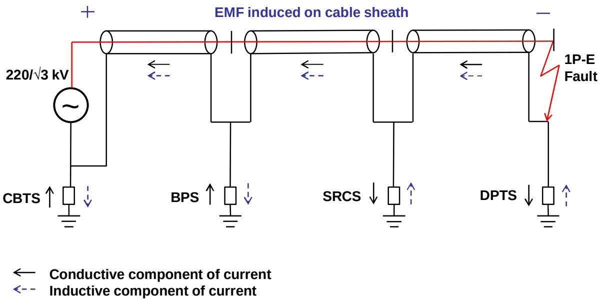

Figure 9: Earth fault current distribution

The inductive component contributes to the current in the cable sheath and reduces the current at each substation and joint bay earth. This reduces the Earth Potential Rise (EPR) and the earthing required to mitigate step, touch and transfer voltages.

In the example shown in Figure 9, although the plant and CBTS earthing systems are large and low impedance, over 99 % of the 9 kA fault current returns via the 88 km long cable sheath. The EPR due to a 220 kV earth fault at DPTS is approximately 15 V.

This is typical of cable fed substations where the strong mutual coupling between the phase conductor and sheaths can result in sheath currents that approach 99.5 % of the fault current [6]. The induced electromotive force (EMF) offsets the voltage drop along the cable sheath. In effect this lowers the apparent impedance of the sheath as seen by the returning fault current.

Electromagnetic fields and AC interference

The cable route is mostly through rural areas however its length brings it near many metallic services. The cable shares an easement with the desalination plant transfer pipeline for over 80 km. It also passes several other pipelines, telecommunication cables and farm fences. In each case, the cable has the potential to cause a hazardous voltage rise on the service via conductive and/or inductive coupling.

Conductive coupling occurs during an earth fault where the EPR is transferred from the power system earth to the service. The EPR can be transferred via a metallic connection or by some other conductive medium eg. the soil.

Inductive coupling occurs during earth faults and also when the cable is carrying load. The touching trefoil arrangement and continuous, fully cross-bonded sheaths reduce the level of inductive coupling however the residual field is still able to cause hazardous voltages where the length of the parallelism is significant.

Mitigation was required at many locations along the transfer pipeline to address hazardous voltages caused by 220 kV earth faults on the cable system as well as earth faults on other power systems along the route. The impact of the 220 kV cable system on other services was found to be within the required limits.

The magnetic field above the cable was also confirmed to be within the required exposure limits.

CONCLUSIONS

The Victorian Desalination Plant and 220 kV cable system were successfully commissioned in December 2012. This paper has described how the technical challenges associated with long HVAC cables were addressed for the 88 km desalination plant cable.

Acknowledgments

The authors would like to acknowledge the efforts of the PB and Beca teams for their work on the 220 kV cable system. In particular we would like to thank Dan Mara and Ian Christmas for their leadership; and Dr. Michael Owen, Sujeewa Vithana and Dr. Wickrama Keerthipala for their valuable contributions to the many system studies.

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GLOSSARY

BPS	Booster Pump Station
CBTS	Cranbourne Terminal Station
DPTS	Desalination Plant Terminal Station
GL pa	Gigalitres per annum
SRCS	Southern Reactive Compensation Station