Energy
Infrastructure
Investments

Directlink Joint Venture

Directlink
Revised Revenue Proposal

Attachment 5.3

PSC - *Directlink DC Cable Replacement Strategy*

Effective
July 2015 to June 2020

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Directlink - Opinion Paper on Directlink DC Cable Replacement Strategy

1 Introduction

Directlink is a High Voltage Direct Current (HVDC) transmission system that connects the power networks at Mullumbimby (NSW) and Bungalora (NSW) via HVDC cables. The transmission system consists of the converter stations at Mullumbimby and Bungalora, the 59km long HVDC cables connecting them and the AC cables, switchgear and converter transformers connecting each converter station to the nearby AC substation. Directlink utilizes Voltage Source Converter (VSC) technology, and comprises three independent, 60MW VSC “links” operating in parallel. Each of the three links is labelled as System 1, System 2 and System 3, each with a positive 80kV and a negative 80kV DC cable connecting the converter station sites. This means there are six, 59km, DC cables installed between Mullumbimby and Bungalora.

The Directlink facility commenced commercial operation in December 2000 and the Directlink Joint Venture (DJV) was acquired by Energy Infrastructure Investments (EII) in 2006. APA Group (APA), a part owner of EII, operates and maintains the facility on EII’s behalf.

Directlink utilises HVDC polymeric insulated cable technology for its DC cables. Since its commissioning in 2000, the Directlink facility has experienced a significant number of DC cable failures. The nature and frequency of these cable faults has changed over the year as described in this paper. Each cable failure results in a shutdown of that particular Directlink “system” until it is repaired. Repairs can be time consuming, requiring the location of the fault, excavation and then cutting out of the failed cable section and replacement with a new piece of cable, which is jointed at each end to the remainder (healthy) section of cable. A high level of cable faults typically means high costs, a drain on resources and reduced availability on the Directlink system. In response to this, and following investigation on the potential causes of the cable failures, APA has been applying a trial process where they take the opportunity to replace sections of cable that experience or have experienced a high number of faults, and replace these with much longer lengths of new cable (of the order of 125m each side of the fault) than typically replaced for a cable repair. APA proposes to also implement a proactive replacement of cable sections that have been known trouble spots.

PSC was requested to review the information available in relation to the instances of DC cable faults for Directlink and, based on publicly available information and the experience of the authors, provide an opinion on:

1. The prudency of the opportunistic and proactive cable repair strategy that has been implemented by APA in the past and proposed to be implemented in the coming years; and
2. The anticipated short-, medium- and long-term reliability benefits of the proposed proactive repair strategy.

The authors of this opinion paper and a summary of their experience relevant to this engagement, are detailed below:

- **Bradley D. Railing, P.E.** - Brad is an experienced Principal HVDC Consultant based with PSC on the east coast of the USA, responsible for all HVDC activities for PSC North America. He holds a Bachelor of Science in Electrical Engineering and a Master of

Engineering degree in Electric Power Engineering, is a licensed professional electrical engineer in Massachusetts and has over 30 years of electricity utility experience which includes direct involvement with regulated and merchant transmission projects around the world. His extensive experience encompasses technical feasibility studies, conceptual design, technical specifications, field commissioning, fault tracing, root cause analysis, project management, operations and maintenance with a specialization in HVDC transmission systems.

As Vice President of Projects for TransÉnergie US Ltd, Brad was responsible for project implementation, EPC contract administration, commissioning, operations and maintenance for all TransÉnergie projects, which were all ABB HVDC Light®, VSC based projects. These projects included Directlink and Murraylink as well as the Cross Sound Cable project in the US (330 MW). Prior to joining PSC, Brad held various operational roles on the Cross Sound Cable and Trans Bay Cable HVDC facilities, with over a decade of responsibility for the operation and maintenance of a facility which utilises the same insulation and cable technology as Directlink.

- **Leslie N. Brand –** Les is a Brisbane based Chartered Engineer (Fellow) with over 20 years of experience in the electricity industry and the last 15 years mostly on HVDC projects. Les held key project and operational roles on the Directlink and Murraylink HVDC projects and was the Technical Advisor to the Project Inspector for the Basslink HVDC project and the Operations Manager of the Trans Bay Cable HVDC project in San Francisco, USA. As a consultant, Les continues to provide specialist advice to clients on HVDC projects in countries throughout the world, including Canada, USA and Ireland. Les has written and presented Cigre papers on the topic of the operation and maintenance of HVDC facilities, is a member of Cigre working group B4.54 “Life Extension of Existing HVDC Systems” and is the convenor of Cigre working group B4.63 “Commissioning of VSC HVDC Facilities”. Les is also the convenor of CIGRE Australian Panel B4 “HVDC and Power Electronics”.

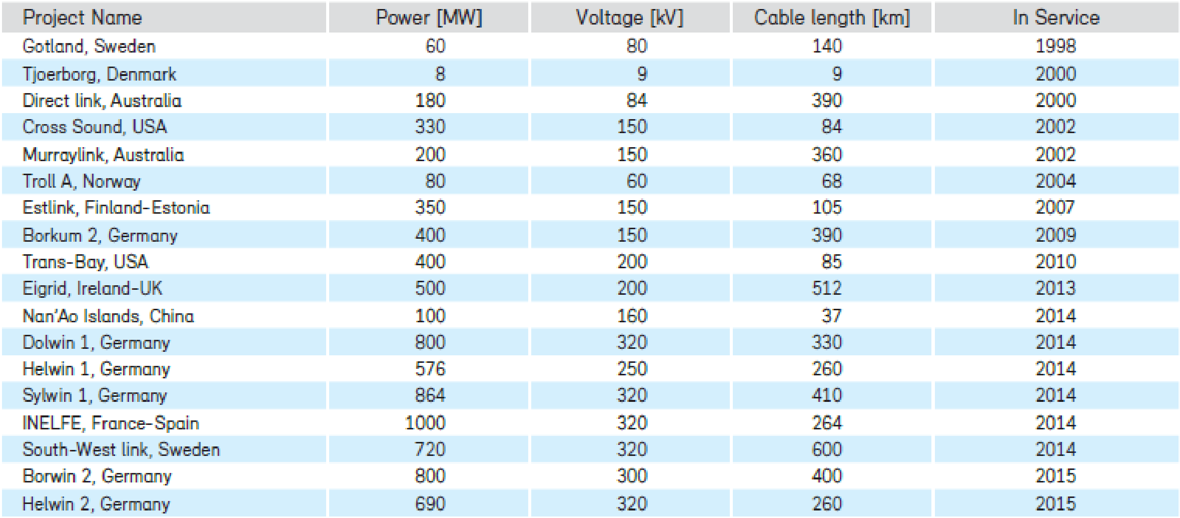
The HVDC cable technology utilised by Directlink is relatively new as described in this paper. There is much less operational experience (in terms of km-years) with this cable technology than in other DC and AC cable technologies and to date publically available information on the operational performance of the HVDC technologies have been scarce. Combined, the authors have held key installation, commissioning and/or operational roles in almost 30% of in-service HVDC projects globally that utilise this cable technology and continue to provide technical advice to similar products under development. Where reliable publicly available information is not available, the authors have drawn on this experience in the development of their opinion.

2 Operational Experience of HVDC Polymer Cables

Polymeric solid dielectric insulation for HVDC cables was largely experimental prior to the mid-1990s. The main challenges prior to the mid-1990s were (1) tendency to have trapped charges in the insulation, (2) the polymeric material was not designed specifically for HVDC and (3) polymeric insulation often failed when exposed to voltage polarity reversal. ABB was the first manufacturer to develop, during the mid-1990s, an HVDC transmission technology, HVDC Light®, that utilized voltage source converters (VSC). An HVDC transmission system based on VSC converters will not be exposed to voltage reversals. ABB was also the first high voltage cable manufacturer to utilize a newly developed polymeric insulation that was specially formulated for HVDC voltage stress. This new HVDC polymeric insulation was designed to be applied via a triple extrusion process to apply the conductor shield, the polymeric insulation and the insulation shield. The combination of the new HVDC polymeric insulation material and the triple extrusion process significantly reduced the risk of failure due to trapped charges, and was suitable for the DC voltage stress across the insulation. ABB utilized VSC converters together with HVDC polymeric insulated cables on the Gotland Project in 1999 (Sweden, 50 MW, 70km, ±80kV) followed closely by Directlink in 2000.

The Borealis Company's BorLink™ has been the majority supplier of the polymeric insulation for HVDC cables since the mid-1990s. BorLink is now used by the major manufacturers of HVDC polymeric insulated cables as shown in Table 1.

Table 1 - HVDC VSC-based Transmission Projects using BorLink insulation [Borealis]



Project Name	Power [MW]	Voltage [kV]	Cable length [km]	In Service
Gotland, Sweden	60	80	140	1998
Tjoerborg, Denmark	8	9	9	2000
Direct link, Australia	180	84	390	2000
Cross Sound, USA	330	150	84	2002
Murraylink, Australia	200	150	360	2002
Troll A, Norway	80	60	68	2004
Estlink, Finland-Estonia	350	150	105	2007
Borkum 2, Germany	400	150	390	2009
Trans-Bay, USA	400	200	85	2010
Eigrid, Ireland-UK	500	200	512	2013
Nan'Ao Islands, China	100	160	37	2014
Dolwin 1, Germany	800	320	330	2014
Helwin 1, Germany	576	250	260	2014
Sylwin 1, Germany	864	320	410	2014
INELFE, France-Spain	1000	320	264	2014
South-West link, Sweden	720	320	600	2014
Borwin 2, Germany	800	300	400	2015
Helwin 2, Germany	690	320	260	2015

Table 1 shows that the operating voltage of the HVDC polymeric insulated cables has increased from 9kV to 320 kV between 1998 and 2014, which is to be expected at the early stages of life for such new technology. ABB announced in August 2014 that they have successfully designed, built and tested an HVDC polymeric insulated cable for operation at ±525kV. Since its introduction in 1998, the adoption of HVDC polymeric insulated cables has significantly increased and their use is considered good practice for underground or subsea DC transmission when using VSC converters.

HVDC polymeric insulated cables have been used in commercial operation since the Gotland project began commercial operation in 1999. Table 1 provides a list of the HVDC polymeric cable projects where some are underground cables, some are submarine and some have a combination of both. There were ten HVDC projects that were installed between 1998 and 2013, with a total of 17,371 km-years of operating experience. Of those ten projects, three are underground cable projects with a total of 12,020 km-years of operating experience; Gotland (Sweden), Directlink (Australia) and Murraylink (Australia).

Table 2 provides a comparison between the Gotland, Directlink and Murraylink transmission systems regarding operating km-years, internal cable faults and external cable faults[1]. Information

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[1] An external fault is a fault that has been caused by a third party and/or external action, such as digging up or excavating close to the cables. An internal fault is a fault caused by a factor associated with the

was requested from Gotland regarding their cable fault data, but this data was not provided and is not available publically. Directlink has experienced 87 cable faults compared to two at Murraylink.

Table 2- Gotland, Directlink and Murraylink Operating Experience through 2014

Project	Installation Year	Operating km-years	Cable Fault Internal	Cable Fault External
Gotland	1998	2,240	n/a	n/a
Directlink	2000	5,460	87	0
Murraylink	2002	4,320	2	0

Directlink and Murraylink were installed within two years of each other, and both projects were manufactured and supplied by ABB via the same cable factory in Karlskrona, Sweden. Some significant differences in the Directlink and Murraylink DC cable installations are listed in Table 3.

Table 3 - Key Differences Between Directlink and Murraylink HVDC Cable Installations

	Directlink	Murraylink
Site Installation, management and quality assurance	Performed by parties other than the cable manufacturer which had no previous experience with the installation of HVDC polymeric cables.	Performed by ABB, the cable manufacturer, who did have significantly more experience installing HVDC polymeric cables and HVDC cable systems in general.
Installation conditions, terrain, site access	Rain and wet ground conditions were frequent, the terrain was hilly and dense in some areas. Some areas of the cable route is installed above ground in Galvanized Steel Troughs (GST) which require transitions between direct buried and the GST (See Figure 1).	Conditions during installation were generally dry and the terrain was generally flat. The cables were direct buried the entire route and jointed under controlled atmosphere conditions.
Cable joints	ABB supplied Gotland and Directlink with a type SOJ cable joint that was a modified AC joint. These SOJ joints were successfully installed at Gotland however the Directlink cables had a larger outer diameter than Gotland's cable. Numerous SOJ joint body tubes split at Directlink possibly due to this larger cable diameter. An SOJ split joint body will eventually fail electrically, which can puncture the joint and allow water to enter the joint and cable. A joint repair requires excavation crews to uncover the joint bay, which exposes all six joints and cables to potential damage. ABB replaced the SOJ joint with the type JDC-A joint, which was developed specifically for HVDC polymeric cables. APA has been using the type JDC-A joints for all cable repairs since 2008. There have been no failures of the type JDC-A joints.	ABB used the type JDC-A joints on Murraylink. There have been no joint failures and only two cable faults, so the exposure of the cable and joints to excavation and repair crews has been insignificant compared to Directlink.

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cable's insulation system not a result of an external action, such as defects in the insulation material and key cable layers, water ingress, high temperatures etc.

Figure 1 - Typical Directlink GST and Transition

Table 3 summarises the key differences between Directlink and Murraylink in relation to the DC cable installation. The Directlink cables were not installed by the manufacturer (ABB) as it was for Murraylink. Compared to Murraylink, Directlink's terrain is hilly, often wet, has difficult access and includes underground to above ground GST transitions as shown in Figure 1. Finally, Directlink experienced numerous cable joint body failures which exposed the joints and cables to construction activity and water ingress, compared to zero cable joint failures at Murraylink.

From the comparison between Directlink and Murraylink shown here, and the authors' experiences in other HVDC projects that utilise similar HVDC polymeric insulated cables, the rate of failure of the Directlink DC cables is not typical of other installations that utilise the same technology. Technical organizations such as CIGRE Working Group B1.10 and their latest report #379, "Update of Service Experience of HV Underground and Submarine Cable Systems", April 2009, have reported on over 250,000 km-years of experience with AC, polymeric insulated high voltage cables through to 2005. Unfortunately, the 17,371 km-years of experience with HVDC polymeric cables does not have the same pool of experience and associated good industry practice as can be expected for AC polymeric cables. Owners and operators of the initial HVDC polymeric cable projects such as Directlink will need to take the responsibility to investigate and resolve problems such as the unusually high number of cable faults.

3 Summary of Directlink Cable Failure Experience

Directlink initially had problems with cable joint faults due to the type SOJ joint bodies mechanically splitting followed by electrical failure. Cable joint failures began to taper off in early 2008. Cable faults (Figure 2) started to show up in 2003 largely near the GST transitions and then showing up in the buried sections in 2008 between the joint bays. Figure 2 excludes faults caused by joint failures.

Figure 2 - Directlink Cable Faults - Jan 2001 to Nov 2014 – Excluding Joint Failures

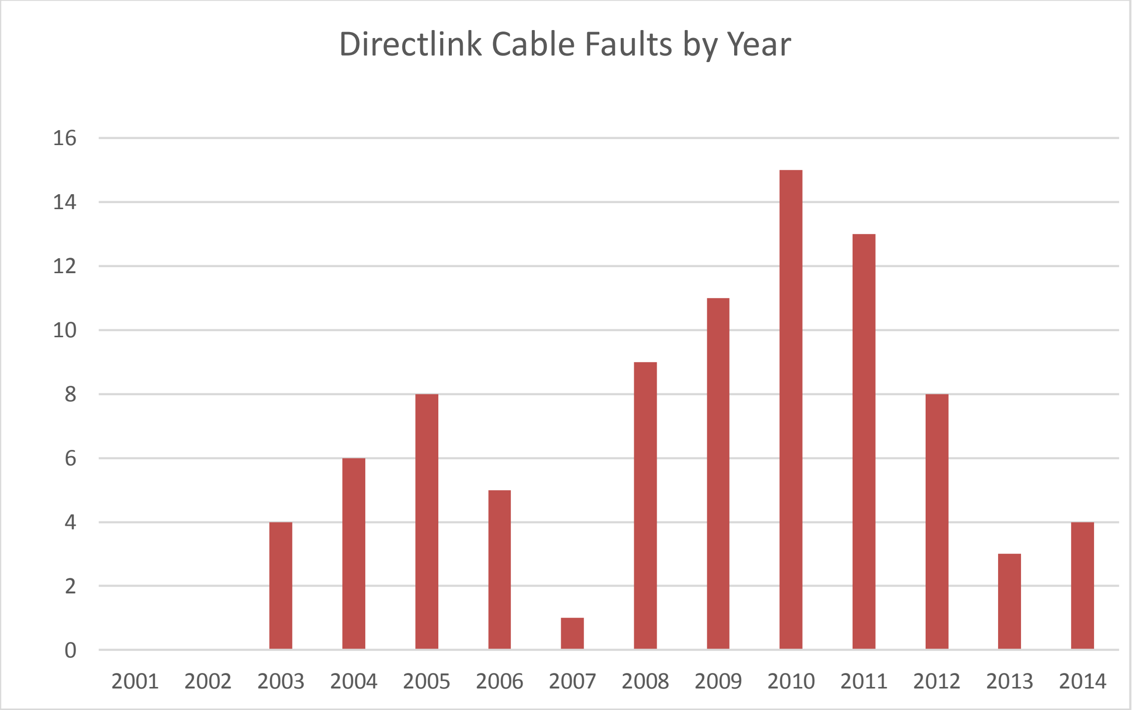
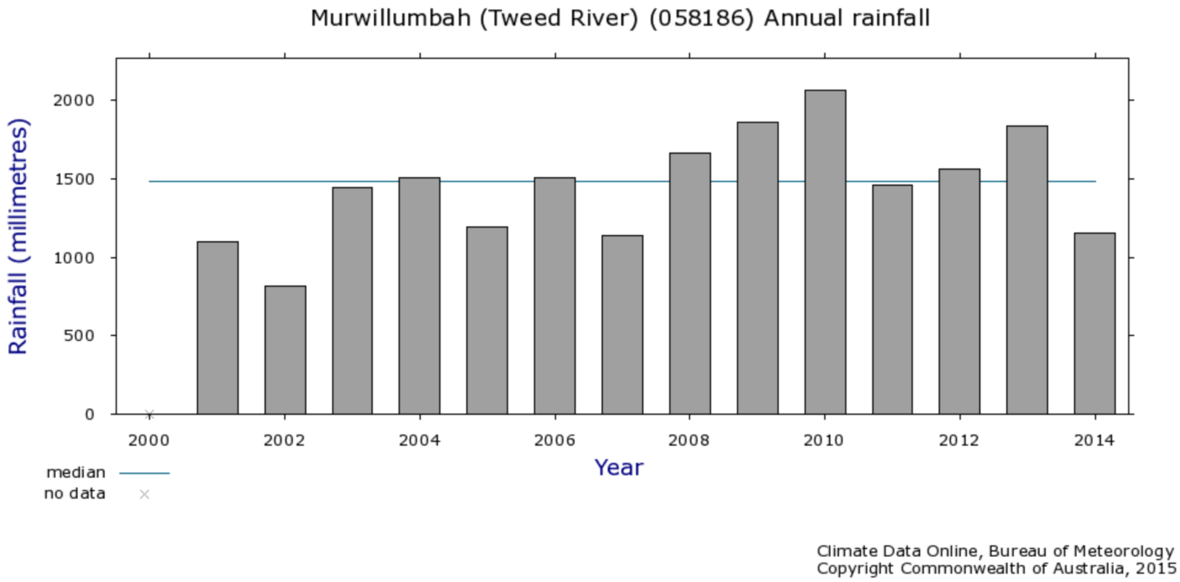


Figure 2 illustrates that the number of cable faults per year increased significantly between 2007 and 2010. One of the concerns due to the original installation and numerous repairs to the Directlink cables, is the ingress of water. A cable is very dry inside and will absorb water readily when the cable jacket or a joint is punctured. Figure 3 shows the annual rainfall in the Murwillumbah (Tweed River) area. The increase in annual rainfall from 2007 to 2010 correlates well with the dramatic increase in the cable faults between 2007 and 2010.

Figure 3 - Annual Rainfall – Murwillumbah (Tweed River)



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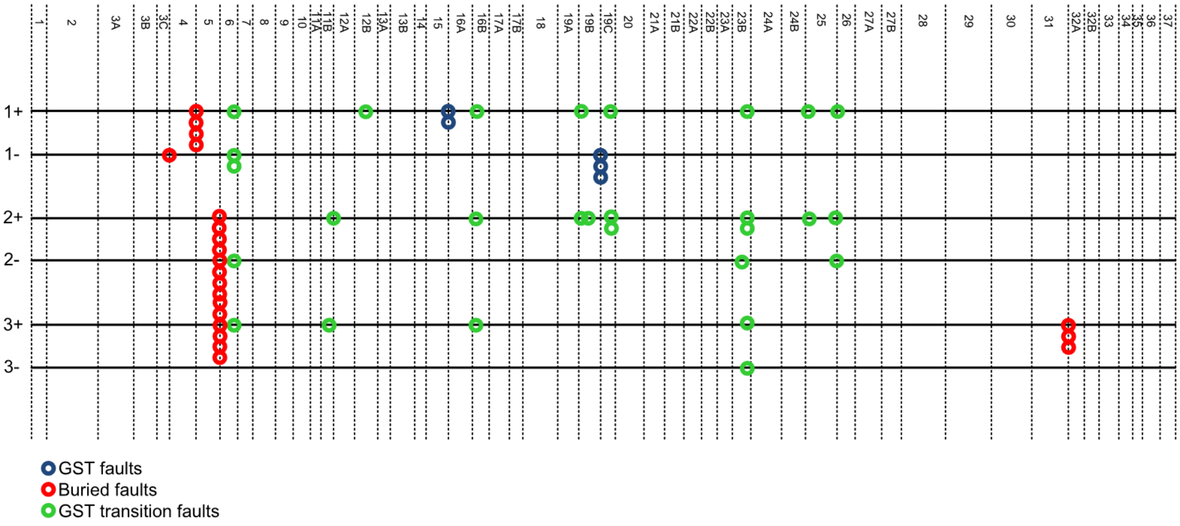
APA retained ABB High Voltage Cables in November 2010 to perform an investigation to determine the root cause of the cable faults. ABB performed a desktop study of the Directlink cable failure data and a field investigation in January 2011 and provided a report in May 2011. One of the more interesting observations by ABB was a “map” showing the 59 Directlink cable faults that occurred between May 2003 and April 2011, in terms of their location on the cable route as shown in Figure 4.

Figure 4 - ABB Mapping of Directlink’s Cable Faults



The numbers at the top of Figure 4 are the joint bay locations with #1 starting at Mullumbimby and #37 ending at Bungalora. The numbers on the left side of the figure identify which cable faulted (i.e. the positive (+) and negative (-) cable of System 1, System 2 or System 3). There were cable fault clusters identified in the cable route sections as listed in Table 4, which also shows the length of the cable route section. The entire route length is not targeted for replacement, but Figure 4 shows that there are sections of the cable within these route sections that have been exposed to multiple failures on either System 1, System 2 or System 3.

Table 4 - Cable Route Sections with Fault Clusters Identified in ABB Report

Cable Route Sections With Fault Clusters (Start and Finish Joint Bay Numbers)	Section Route Length (m)
3C-4	1,268
5-6	2,197
11B-12B	3,001
15-16B	3,696
19A-19C	3,292
23A-23B	982
25-26	2,341
32A-32B	639
Total	**17,416**

Based on a route length of 59km, the sections of cable affected by cable faults to date represent just under 30% of the whole cable route.

The information presented in Figure 4 and Table 4 indicates that there are certain parts of the cable route more susceptible to cable faults than others, and hints at a failure mechanism related to the cable location rather than the design and construction of the cable itself. In our opinion though, using historical analysis on the basis that the same behaviours will continue into the future is not a reasonable assumption without engineering analysis to support it.

ABB performed an analysis of the cable fault samples from the fault cluster areas and their analysis concluded:

1. The presence of water in the faulty cables as the reason for all cable failures in the buried sections and the GST sections (i.e. red and blue circles in Figure 4).
2. Mechanical exposure of the cables is considered another contributing factor (in addition to the presence of water in many instances) to the cable faults at the GST transitions (i.e. green circles in Figure 4).

The water is suspected of entering the cables either during installation, through the hole created when a cable has faulted or during the repair of cables, including during the repair of those initial cable faults caused by joint failure. The possible effects of cable location on faults caused by the mechanisms concluded by ABB is clear – it could be the case that areas of cable close to where previous repairs had taken place (particularly during wet or rainy periods) and which is more susceptible to water (exposure to heavy rain and/or the pooling or flooding of water) would be more likely to fail. The authors do not have any more detail to conclusively prove why certain clusters fail more than others, but based on the evidence have the opinion that the failures could reasonably be location dependent.

It should also be noted that the ABB report states that as of the time of the report, there are no suitable diagnostic techniques for detecting and locating the presence of water on very long high voltage cables.

4 Evaluation of APA's Proactive Cable Repair Strategy

In ABB's report, they recommended the following mitigation strategies:

1. Short term repair strategy - Replace approximately ±100m of cable in cable sections where cable faults have occurred within close proximity to each other.
2. Medium term repair strategy – Replace the cables on all sections were faults have occurred. Repair, modify and/or replace the GST transitions were cable failures have occurred.
3. Long term repair strategy – Replace any remaining cable sections where water is suspected to have migrated into the cable.

APA amended its reactive repair strategy starting in July 2011 (shortly after receipt of the ABB report), with an opportunistic strategy which involved repairing cable faults by replacing longer sections of cable to remove cable sections that were prone to multiple failures or were suspected of being exposed to water ingress. APA has completed 19 of these long section repairs replacing a total of 1.6km of new cable between July 2011 and August 2013. With a total cable length for Directlink of approximately 354km, this represents less than 0.5% of the installed cable and just above 1.5% of the total maximum area affected within the cable fault clusters.

APA have developed a business case to expand the reactive strategy with an opportunistic and proactive cable repair strategy with the following key elements:

1. When there is an internal fault (i.e. not an external fault, for example a fault caused by digging or excavation), take the opportunity to replace 125m of the DC cable either side of the fault (a total of 250m per repair).
2. Immediately undertake the necessary analysis and investigation (including and specifically parts of the cable routes that have experienced prior joint failures and/or where water ingress into the cables is likely to have occurred) to identify sections for strategic proactive replacement, replacing a 250m length each time.
3. Target an average replacement of 3km (combination of opportunistic and proactive) per year for 5 years.

Referring to Table 4, a maximum of 17.4km route length was identified as cable fault clusters. As there are six cables, 17.4km route length equates to 104.4km cable length. The replacement of 3km per year for 5 years (i.e. 15km per year) represents the replacement of only 14% of the total maximum area affected within the cable fault clusters. However within each cable route section identified in Table 4, working out which cable (of the six cables) and which 250m section of cable route section length should be replaced requires detailed record keeping, investigation and analysis. With the assignment of the right resources to undertake this analysis, this strategy could seek to ensure that the trouble areas within each cable fault cluster length are replaced as priority.

In the authors' view, this strategy is very closely aligned with the short-term and medium-term strategies recommended by ABB after they had performed a detailed investigation. ABB are the manufacturers of the cable. As explained earlier, the rate of failure of the Directlink DC cables is not typical of other installations that utilise the same technology and therefore there will not be a "pool" of experience that demonstrates the good industry practice approach to dealing with them. It is the authors' opinion that in this case, seeking advice and implementing the recommendations of the cable manufacturer is good industry practice.

Further, it is both the authors' and ABB's opinion that there are presently no suitable diagnostic techniques for detecting and locating the presence of water on very long high voltage cables. Without these techniques, it is the authors' opinion that a strategy of careful analysis of past cable faults to identify areas that have and are likely to experience clusters of failures, and the replacement of these cables, is a cost effective and prudent approach to improve the reliability of the DC cables.

5 Conclusion

There have been 87 cable faults on the Directlink polymeric insulated DC cables between January 2001 and November 2014, all due to internal failures within the cables. The comparable Murraylink HVDC transmission system, also owned and operated by APA, was built two years after Directlink, utilising the same technology and manufacturer, and has experienced only two cable faults due to internal failures of the cables. Key differences in the DC cable installation of the two projects point to the Directlink HVDC cables being exposed to conditions where water is likely to have entered the cables during installation, from fault punctures through the cable joint body or cable or during the cable of failed cable joints and cable sections.

Directlink experienced a significant increase in cable faults from 2007 – 2010. APA retained ABB High Voltage Cable in November 2010 to perform a site investigation, determine a root cause of the cable faults and provide recommendations. ABB's investigation concluded that the presence of water in the faulty cables is the reason for all cable failures in the buried and GST sections. A review of the historical cable fault data highlighted areas where there are clusters of cable faults. ABB noted there are no suitable diagnostic techniques to test the cable sections for water ingress on long lengths of cable. ABB recommended mitigation strategies to use longer cable repair lengths in the fault cluster areas and to replace sections of the cable where water ingress is suspected.

APA implemented a trial of an opportunistic repair strategy starting in July 2011 to use longer repair sections in a percentage of the areas recommended by ABB. A total of 19 cable repairs were completed between July 2011 and August 2013 in this manner, with a total cable length of 1.6km being replaced. The fault cluster route lengths are approximately 17.4km, so with a total of six transmission cables, the total possible exposure is 104.4km. To date, APA has replaced only 1.5% of the total possible exposure of cable in the fault clusters.

APA have developed a business case to expand the reactive strategy with an opportunistic and proactive cable repair strategy with the following key elements:

1. When there is an internal fault (i.e. not an external fault, for example a fault caused by digging or excavation), take the opportunity to replace 125m of the DC cable either side of the fault (a total of 250m per repair).
2. Immediately undertake the necessary analysis and investigation (including and specifically parts of the cable routes that have experienced prior joint failures and/or where water ingress into the cables is likely to have occurred) to identify sections for strategic proactive replacement, replacing a 250m length each time.
3. Target an average replacement of 3km (combination of opportunistic and proactive) per year for 5 years.

The APA business case to apply opportunistic and proactive cable replacement is supported by the mitigation recommendations by the ABB investigation. There are no suitable diagnostic tests that can be performed to detect the cable sections that have been impacted by water ingress. Without these techniques, it is the authors' opinion that a strategy of careful analysis of past cable faults to identify areas that have and are likely to experience clusters of failures, and the replacement of these cables, is a prudent approach to improve the reliability of the DC cables.

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Revision: 0

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