Murraylink Valve Replacement

Project Options Assessment

Amplitude Document Number:
PAU0275-REPT-001

Date of Issue:
17 June 2022

Revision:
Rev 0

Revision History

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Executive Summary

Murraylink is a 180 km ±150 kV 220 MW HVDC transmission system connecting the electricity networks of Victoria and South Australia. APA Group (APA) manages and operates the regulated Murraylink on behalf of Energy Infrastructure Investments (EII).

Murraylink is an important interconnection between the transmission networks of South Australia and Victoria. With an original design life of 40 years, it is anticipated that the link will remain in operation for at least the next 25 years. Murraylink uses ABB's (now Hitachi) Generation 2 Insulated Gate Bipolar Transistors (IGBTs) in a three-level Voltage Source Converter (VSC) technology, with approximately 3,000 IGBTs in each converter station.

In December 2020, the sole provider (Hitachi) advised APA that the Generation 2 IGBT positions used for Murraylink would no longer be produced, and that Murraylink would only have access to a portion of the IGBT positions required for continued operation.

Amplitude Consultants Pty Ltd (Amplitude) were engaged to undertake the necessary preliminary investigations into the feasibility of options for continued operation of Murraylink. In doing so, Amplitude have considered the reliability of the existing units, the costs to replace the valves and associated equipment and the benefits of upgrading to the newer modular multi-level converter (MMC) VSC technology.

Options for replacing a single phase with a newer generation of IGBT positions to free up spares to be used elsewhere were considered, however the expected increase in operational life gained is dependent on the IGBT position failure rate and the remaining life of the used component.

The MMC VSC solution is expected to be more expensive, with this being shown in the estimates developed, however the difference may not be as great as expected if pricing can be obtained on a competitive basis, compared to other options considered, as these are dependent of contracting with the current OEM. Upgrading to MMC VSC technology is expected to:

- Reduce losses by approximately 2% at maximum power transfer;
- Improve the reliability of the converter stations; and
- Improve the thermal performance of the converter stations.

A summary of the assessment of options is presented below:

	Replace Gen 2 IGBT Positions with Newer IGBT Positions	MMC Upgrade (one converter station)	MMC Upgrade (both converter stations)
Losses	• As per existing system.	• Expected reduction of 1% at peak transfer capacity.	• Expected reduction of 2% at peak at peak transfer capacity.
Thermal Performance	• As per existing system. • Derated at higher temperature.	• Thermal performance limited by remaining converter station • Derating at higher ambient temperatures. • Potentially some improved performance at replaced converter.	• Improved thermal performance due to lower switching frequency. • Existing cooling system likely oversized. • Potential for better performance at higher ambient temperature.
Service Life	• Operational life of existing IGBT units as spares unknown.	• Operational life of existing IGBT units as spares unknown.	• Operational life extended to 40 at least existing design life. • Potential to extend operational life.
Suppliers	• Locked into one supplier. • No Competitive pressure on pricing.	• Multiple vendors available. • Competitive pressure on pricing. • Potential for smaller MMC vendors (e.g. Japan) to provide competitive pricing • Potential interfacing issues – different vendors/technology at each end.	• Multiple vendors available. • Competitive pressure on pricing. • Potential for smaller MMC vendors (e.g. Japan) to provide competitive pricing.
Outage Requirements	70 days for one phase	5 months	5 months
Cost Estimate	$17.8m per phase	$36.7m	$71.8m

In order to finalise the replacement strategy adopted, our recommendation on the next steps would be to:

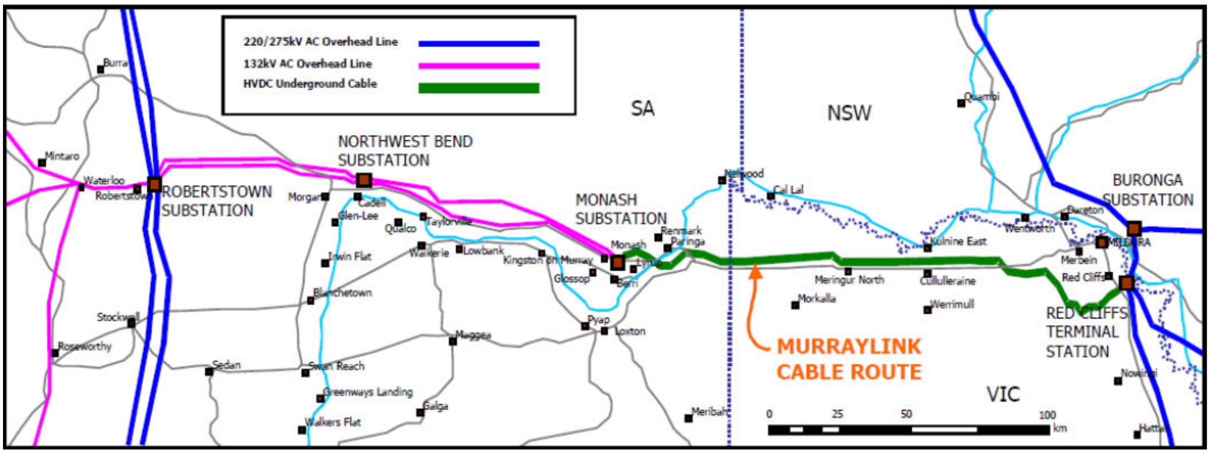
- Consult with other impacted Generation 2 IGBT operators to ascertain if they have firm replacement strategies and if any synergies can be found; and
- Develop functional MMC specifications to obtain pricing, basic design and project schedule information from prospective suppliers.

1. Introduction

Murraylink is a 180 km ±150 kV 220 MW HVDC transmission system connecting the electricity networks of Victoria and South Australia. APA Group (APA) manages and operates the regulated Murraylink on behalf of Energy Infrastructure Investments (EII).

The Murraylink facility includes converter stations at Red Cliffs, Victoria and Berri, South Australia, connected by a pair of underground DC cables, approximately 180km in length, as shown in Figure 1. The converter stations, DC cables and associated control and protection systems, were commissioned in 2002, with an upgrade of the whole control system completed in 2020 to address technical obsolescence.

Figure 1 – Murraylink Asset Location and DC Cable Route [1]



Murraylink is an important interconnection between the transmission networks of South Australia and Victoria. With an original design life of 40 years, it is anticipated that the link will remain in operation for at least the next 25 years. However, integral to this is the timely replacement of Insulated Gate Bipolar Transistors (IGBT).

An IGBT is a three-terminal power semiconductor device primarily used as an electronic switch for high-voltage, high-current applications. IGBTs are an integral part of the operation of the Murraylink converter stations. Each IGBT is comprised of the IGBT power electronic part and a gate control unit. Collectively these are referred to as IGBT “positions”. The gate control unit includes electronics required for the switching and monitoring of the IGBT and for communications to and from the valve control unit via fibre optic connections.

In December 2020, the sole provider of the IGBT positions (Hitachi) advised that the relevant units are no longer in production, and that Murraylink would have access to circa 115 new units. Murraylink forecast that, based on current failure rates, to remain serviceable through to the end of the next regulatory control period (RCP), approximately 200 spare IGBT positions would be required.

This paper assesses the scope and high-level cost estimates for options for the replacement of these IGBT positions to provide continued operation of Murraylink.

1.1. Consultant's Scope and Contributing Authors

Amplitude Consultants Pty Ltd (Amplitude) were engaged to undertake the necessary preliminary investigations into the options for the upgrade of the IGBTs, development of available options and to perform a comparative assessment of these options.

Amplitude's scope can be summarised as:

- Review existing technical information on the converter systems to establish a picture of the likely performance of the Murraylink HVDC system.
- Determine the extent of upgrade required at all levels within the converter systems for each option.
- Develop a conceptual scope of work for the replacement of both converter systems, as this represents the most onerous option.
- Develop "ballpark" budgetary cost estimates for the converter system upgrade.
- Document the need and options assessment to support the investment required.

The contributing authors to this paper are identified below along with relevant skills and experience.

<u>Les Brand, Managing Director, Amplitude Consultants</u>

Les Brand (FIEAust, CPEng, RPEQ) is an experienced electrical engineer with over 28 years of experience in the transmission and distribution industry in Australia, Asia and the USA. He has held senior and executive roles within the power transmission and distribution sectors, including utilities, consultancies and private companies. He has held senior technical roles for a number of HVDC projects including Directlink (Australia), Murraylink (Australia), Basslink (Australia) and Trans Bay Cable (California, USA).

For Murraylink, Les was the Project Manager for the design and construction of the project, Commissioning Manager for the final completion and the original Operations Manager including setting up O&M operating procedures and training operational staff. Les was responsible for the overall management and witnessing of the Factory System Tests (FST) of the existing Mach II systems in Sweden during both the Directlink and Murraylink projects, and later for the Trans Bay Cable project in San Francisco, USA. Les was the project manager and owner's engineer for the replacement of the Directlink and Murraylink control and protections systems, completed in 2019 and 2020 respectively.

Les was the convenor of the Cigre Australian Panel for HVDC and Power Electronics (B4) between 2013 and 2019 and was the convenor of the international working group B4.63 "Commissioning of VSC HVDC Systems", which published its technical brochure on VSC commissioning in 2017. Les was also an active member of Cigre working group B4.54 "Life Extension of Existing HVDC Systems" and a contributing author to the technical brochure 649 "Guidelines for life extension of existing HVDC systems", which also covers the lifecycle, upgrade and replacement of power electronics and HVDC valves. Les is also currently serving as an Australian representative of IEC TC 99/JMT 7, responsible for the revision of IEC/TS 61936-2, the international standard for the design and the erection of DC facilities greater than 1.5kV.

Alastair Pinkard, Principal Consultant

Alastair Pinkard (MIEAust, CPEng, RPEQ) is an experienced electrical engineer with over 20 years of experience working in transmission and distribution in Australia. He has held leadership and senior technical roles in system planning and operations working for Powerlink and Energex in Queensland and provided and overseen the development of parts of the Integrated System Plan at the Australian Energy Market Operator.

Alastair has extensive experience in the development of the Regulatory Investment Test for Transmission (RIT-T), including development of network need and options assessment documentation. He was selected as a subject matter expert for augmentation expenditure on a Revenue Determination and provided key supporting documentation for several other Regulatory Determinations.

Thavenesen Govender, Principal Consultant

Thavenesen (Thavi) Govender (MIEAust, CPEng, RPEQ) is an experienced engineer with over 17 years of experience covering project engineering, commercial and procurement functions as well as research, testing and development in high voltage power transmission. His experience covers a balance between experience in the electrical industry and academia with nine years of experience in the electrical transmission utility environment and five years as a research fellow and lecturer.

Thavi has significant experience in the development of equipment specifications for HVDC converter stations, SVC, STATCOM and AC filter equipment and facilities and also in the operations and maintenance, lifecycle management, asset health appraisals and root cause analysis of such equipment. He is also experienced in the technical support and input into commercial and procurement activities including development of tender documentation, undertaking tender evaluations, leading technical aspects of supplier negotiations. Immediately prior to joining Amplitude, Thavi held the role of Chief Engineer – HVDC and FACTS Devices for Eskom in South Africa.

Since joining Amplitude in late 2019, Thavi has been heavily involved in the third-party assessment of the factory system testing and subsequent factory acceptance testing for the control and protection systems for a large HVDC project under development in Canada as well as the development of concept designs and cost estimates for proposed HVDC projects. Thavi was the site lead for the installation, testing and commissioning of the new control and protection systems for the Murraylink HVDC system between Victoria and South Australia and has been involved in various HVDC interference engagements.

Thavi is active in international engineering bodies, having participated in various capacities with SANS-IEC, CIGRE, SAIEE (South African Institute of Electrical Engineers) and the IET as well as providing support to university programs in Electrical Engineering.

1.2. Key HVDC Terminology and Abbreviations

Key terminology relating to this report is summarised in Table 1.

Table 1 – Terms and Abbreviations

Term / Abbreviation	Definition
AC	Alternating Current
Arm	One side (positive or negative) of leg of a VSC station.
DC	Direct Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistors
Leg	One phase, comprising both the positive and negative arms, of a VSC station.
MMC	Modular Multi-Level Converter
NER	National Electricity Rules
OEM	Original Equipment Manufacturer
C&P	Control and Protection
PWM	Pulse Width Modulation
VSC	Voltage Source Converter

2. Background

2.1. Murraylink

Murraylink is a HVDC transmission line that connects the power transmission networks at Red Cliffs (in Victoria) and Berri (in South Australia) via HVDC cables. The facility consists of the converter stations at Red Cliffs and Berri, the DC cables connecting the two converter stations and the AC cables connecting each converter station to the nearby AC substation (Red Cliffs Terminal Station in Victoria and Monash Substation in South Australia). Murraylink utilises three-level voltage source converter (VSC) technology. The DC cables are buried underground and are approximately 180 km in length. [1]

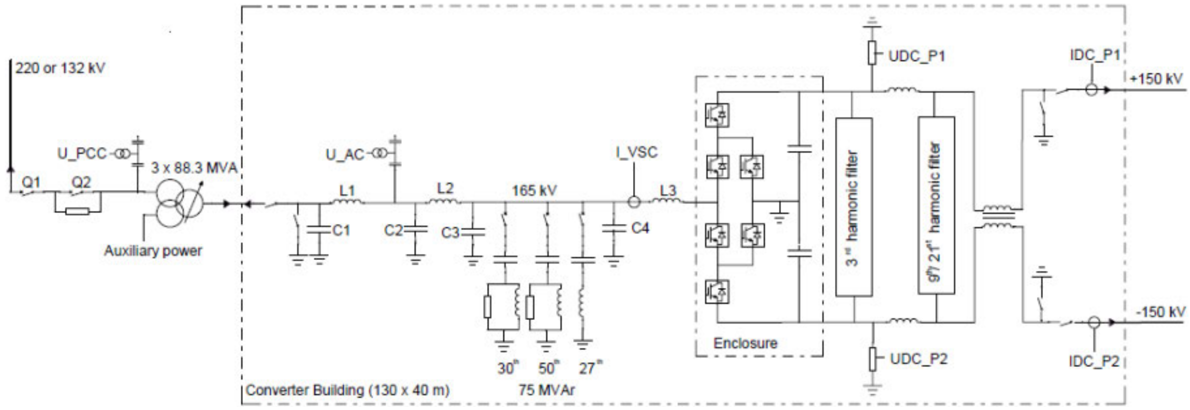
The Australian Energy Market Operator (AEMO) determines the power transmission through Murraylink as a part of their central dispatch process considering the limitations on the power systems in South Australia and Victoria.

To summarise the key parameters of Murraylink:

- Bi-directional, with maximum power flow of 220 MW;
- Maximum reactive power generation between +140 MVAr and -150 MVAr at each end;
- AC connection voltage of 220 kV at Red Cliffs and 132 kV at Berri; and
- DC voltage of ±150 kV.

Figure 2 shows the circuit diagram of one phase leg of one of the converter stations. Within each converter station there are three phase legs connected to the AC network by three single phase transformers.

Figure 2 – Murraylink Converter Station Diagram [1]



Murraylink also includes a substantial spare parts holding which are stored in spare parts buildings located at both the Red Cliffs and Berri converter stations. Those spare parts requiring controlled temperature/environments are stored in a dedicated air-conditioned room at each of the converter station sites.

2.2. IGBT Failure Rates

Murraylink is constructed using three level voltage source converter (VSC) technology, with one positive and one negative arm per phase. Each arm contains nine valve stacks of 18 IGBT positions, totalling 972 IGBT positions per phase and 2,916 IGBT positions per converter station.

Failure of any components within the gate control unit can result in the IGBT reporting as failed, or potentially can lead to the failure of the IGBT power electronics itself. Within each valve, up to five IGBT positions can fail before performance is impacted, with the failed IGBT positions bypassed upon failure. This provides a degree of built-in redundancy in each valve.

In December 2020, the sole provider of the IGBT positions (Hitachi) advised that there are currently circa 115 of the Generation 2 IGBT positions available to Murraylink for purchase as future replacements. However, as the IGBT positions are presently failing at a rate of 24 per year [2], this allocation, combined with existing spares holding, is expected to exhaust these available IGBT positions within approximately six years, assuming constant failure rates.

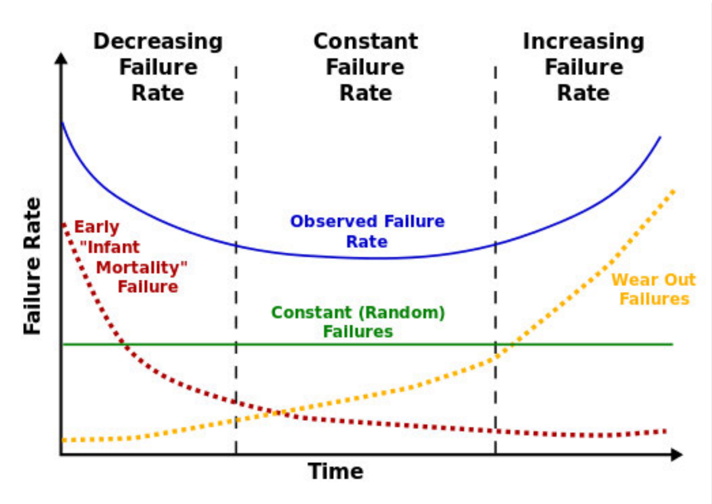
The failure rate of IGBTs is unlikely to remain linear. For electrical equipment such as IGBT positions, a more common expectation of failures will follow the "bathtub curve". The bathtub curve is so named in that there are three modes of failure, namely:

- Failure of units early in life, also known as "infant mortality". These failures are predominantly caused by manufacturing defects, with the early failure rates decreasing over time.

- Intrinsic failure of units, remaining largely constant for the life of the components.
- Wear-out failure caused by aging of components. As the components approach their design life, the failures due to wear-out increase.

Overlaying these, the observed failure rate as shown in Figure 3 can be seen to represent the shape of a bathtub.

Figure 3 – Bathtub Curve [3]



Given the present IGBT position failure rates and the potential for this failure rate to increase due to the ageing of the components within these IGBT positions, it will not be possible to maintain reliable operation of the Murraylink converter stations without intervention.

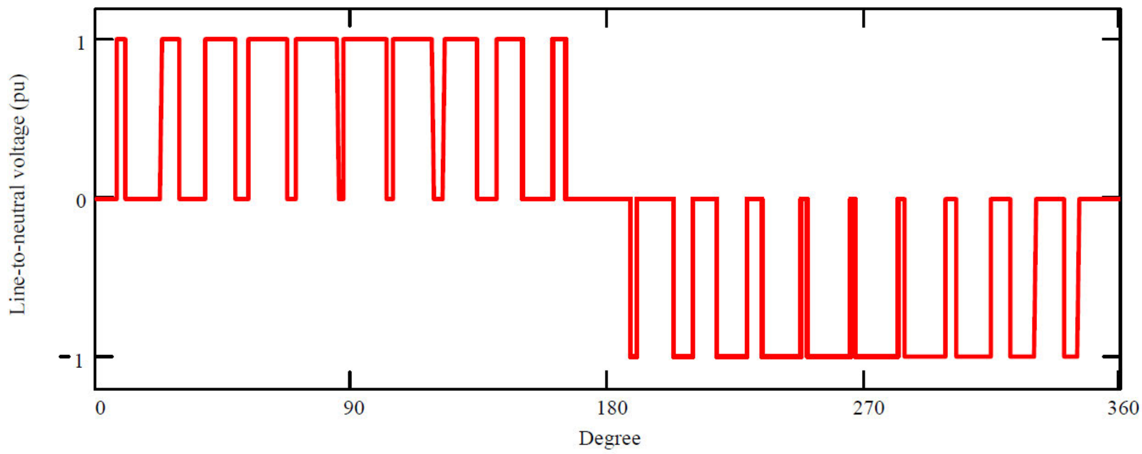
Murraylink was one of the first VSC converters to implement the Generation 2 IGBT positions, of which there are few other installations in service globally. Therefore, there is no real data available from other operational projects that can be used to assess the proven asset life of these IGBT positions beyond the current age of the Murraylink IGBT positions.

2.3. VSC Converter Technology

Murraylink presently uses three-level voltage source converter (VSC) technology, which was new technology at the time of installation. Three-level VSC converters use pulse width modulation (PWM), switching between two DC voltages (±150 kV in the case of Murraylink) at a frequency of 1,350 Hz [4]. A phase reactor is used as a flow-pass filter to create a sinusoidal AC voltage waveform from the high frequency PWM voltage waveform. Three-level VSC requires harmonic filters to smooth the sinusoidal AC voltage waveform from the high frequency PWM voltage and filter out higher order harmonics. Figure 4 Shows the DC voltage switching for a three-level VSC converter.

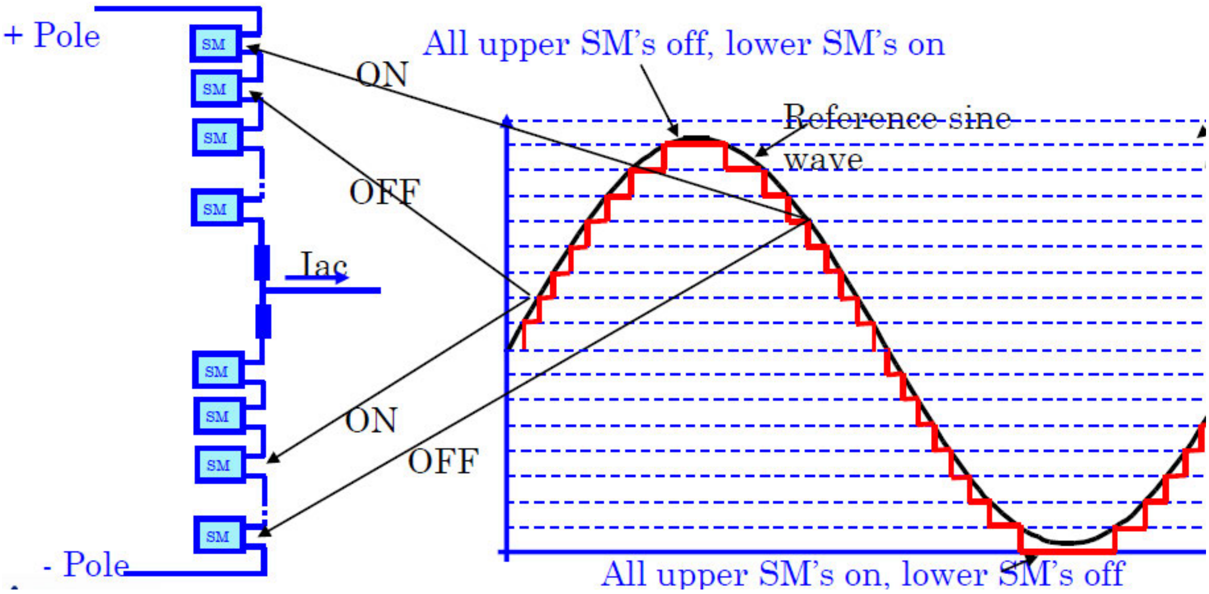
On the DC side, a DC voltage waveform is created by the summation of the three voltage waveforms on both the positive and negative sides to create the steady DC voltage.

Figure 4 – Three-Level VSC Switching [5]



Typically, VSC HVDC links like Murraylink installed today would use modular multi-level converter (MMC) technology. The MMC operates by switching in and out "sub-modules", comprising of a capacitor bank switched by a number of IGBTs. The switching, combined with the profile of the capacitors at various states of charge, is used to build the AC and DC voltage waveform. Figure 5 shows an example of an MMC VSC switching profile. Typically minimal, if any, filtering of the AC voltage waveform will be required. As the switching frequency of MMC VSC is lower than three-level VSC, the losses and cooling requirements of MMC VSC are significantly lower.

Figure 5 – MMC VSC Switching [6]



2.4. Murraylink Operation

Murraylink, as a regulated link between Victoria and South Australia, is dispatched by AEMO to ensure that the required energy is available to consumers considering the availability, constraints and price across all regions in the NEM. When Murraylink is out of service, there are additional constraints applied to ensure that the network is able to operate securely. These constraints can not only impact the transfers between South Australia and Victoria, but also generation in North West Victoria and South West NSW and transfers between Victoria and NSW.

Murraylink provides a significant amount of the energy transfer between South Australia and Victoria. In Q1 (March to January, inclusive) 2022, Murraylink carried its highest ever level of average quarterly net flow from Victoria into South Australia (86 MW), accounting for nearly half the net flow between these regions [7].

Removal of Murraylink would significantly constrain generation and transfers between South Australia, Victoria and New South Wales, impacting the NEM.

2.4.1. Murraylink Operation post Project EnergyConnect

Project EnergyConnect (PEC) is a major interconnector between South Australia and New South Wales to be completed by 2025, as shown in Figure 6. It includes a new double circuit 330 kV to be constructed from near Robertstown in South Australia to Buronga, Dinawan and Wagga in New South Wales. It also includes duplication of the existing 220 kV circuit between Buronga and Red Cliffs as well as supporting dynamic and static reactive plant.

Murraylink is expected to provide significant benefits to the network post PEC, given the length of PEC and the significant amount of renewable generation connected around Murraylink. The ability of Murraylink to provide significant flexibility, and the ability to ramp and control flow will be critical to the stability of the South Australian grid. [2]

Figure 6 – Project EnergyConnect

3. Valve Replacement Options Considered

It was stated in Section 2.2 that Murraylink it will not be possible to maintain reliable operation of the Murraylink converter stations without intervention. The intervention required here is to perform a replacement of the IGBT positions or valves so that the facility can utilise other IGBT position generations or types that are to be supported over the coming years or decades.

In addition, the determination of options could consider how the removed Generation 2 IGBT positions during the required valve replacement work could be re-purposed as spare parts for other parts of Murraylink that continue to use this generation of IGBT position.

The valve replacement options are listed below, and described in the following sections:

- Continued operation with existing valves (i.e., do nothing);
- Replace existing IGBT positions with newer generation of IGBT position; or
- Replace one converter with VSC MMC valves; or
- Replace both converters with VSC MMC valves.

3.1. Continued Operation with Existing Valves

The option for continued operation with the existing valves is presented as the base case. Under this option, the procurement of all available IGBT positions is undertaken and operation of the link continued as long as possible. Unplanned outages would have significant market impacts, and it is likely that Murraylink would incur penalties from failing to meet service obligations. Based on the current stock of IGBT positions available, both held by APA and offered by the supplier, we estimate that there will be only 6-7 years of operation assuming the current rate of failure of IGBT positions remains steady. If the failure rate were to increase, this will shorten the operational life to even less.

Once the available stock of IGBT positions is exhausted, it would be necessary to proceed to the replacement of one or more phases with newer generation IGBT positions, or conversion to MMC VSC valves, which are described as other options in this section.

A sub-option of this would be to consider engagement with the owners and operators of other HVDC systems that use the Generation 2 IGBT positions, of which there are a few globally, including one in the US and potentially others in Europe. Assuming that these systems are seeing similar constraints around accessibility to IGBT position spares, it may be possible to approach these owners and operators to develop a shared strategy in relation to access to spare parts. This may particularly be the case if other systems choose to undertake a replacement and offer their existing IGBT positions for use by other systems.

3.2. Replace Existing IGBT Positions with Newer Generation of IGBT Positions

This option would entail replacement of the existing Generation 2 IGBT positions with a newer generation of IGBT positions from the same supplier (Hitachi). These IGBT positions will not be compatible, from a physical and electrical perspective, with the Generation 2 IGBT positions, and as such the minimum that can be replaced is expected to be a single phase at one converter station. From an overall switching perspective, it is expected that the replacement of one phase should not impact the overall operation of the converter station, nor would the AC and DC waveforms generated be expected to be any different from those being created by the current Generation 2 IGBT positions.

It is expected that the existing cooling system, protection and control systems and AC and DC filtering would be retained. The recently replaced control and protection system is the latest system offered by Hitachi, and should require only relatively minor modifications, if any, to account for the later generation IGBT positions.

In this option, the balance of serviceable IGBT positions from the replaced phase would be recovered, retained and stored as spare parts to be used on the remaining (not upgraded) valves, and therefore will be used to extend the operation of the remaining valves and the other converter station. Should failure rates remain constant, the circa 900 IGBT positions recovered from the replacement of one phase is expected to extend the operation of Murraylink by more than 20 years before subsequent action is required. In practice, increasing IGBT failure rates would mean that this is likely an optimistic timeframe, and a subsequent replacement of another phase (or more) would likely be required at a later date.

There are further options to replace more than one phase, potentially at more than one converter. These will have a higher cost and will "free up" more IGBT positions. However, this assessment has been based on the replacement of a single phase, as this represents the minimum scope that can be practically replaced, which is also the lowest capital cost option.

3.3. Replace One Converter with VSC MMC Valves

The replacement of the existing valves with VSC modular multi-level converter (MMC) technology would address the IGBT obsolescence issues.

Due to the completely different switching configuration and topology, MMC valves cannot be installed in containers as the Murraylink ones are. They need to be installed in levels, usually in a clean-room valve hall, which has humidity and environment controls. The way in which the MMC valves "create" the AC and DC waveforms is also significantly different, and this means that it is not practical to replace a single phase in a converter with MMC valves. As a minimum, the valves in an entire converter station (i.e. all three phases) will need to be replaced. It is technically possible for a HVDC system to have an MMC at one end and a PWM three-level converter at the other.

The existing AC filters are typically not required with MMC VSC technology – except in cases where there are significant or tight harmonic requirements. This is not expected to be the case for Murraylink, and therefore it is expected that the existing AC filters in the large AC filter room can be removed and the space repurposed as a valve hall for the three phases of VSC IGBT sub-modules. VSC MMC technology is currently being offered by a number of HVDC vendors, including three suppliers from Europe and a few emerging suppliers in Japan. It is likely that the installation of MMC VSC from other suppliers will also require a replacement of the control and protection system to be compatible.

The main benefit of conversion will be access to spare IGBT sub-modules. With MMC being relatively new and recent technology, it is likely that the types of sub-modules to be used will be supported by the suppliers for many years or decades. Other benefits of conversion to MMC technology include a reduction in losses in the converter station, an expected improved reliability of the newer IGBT sub-modules (fewer failures, fewer outages), improved thermal performance (due to the lower switching frequency) and the option to have multiple suppliers provide quotes and pricing for this technology.

The benefits of replacing only one converter are limited. Losses would only be reduced for the one converter, and the thermal performance and reliability of the link improvements would only be realised at that one converter. However, the in-service IGBT positions removed at the replaced converter (just under 3,000 positions) could then be used to support the other converter to extend its life, with the same outcomes and risks as the option discussed in Section 3.1.

The replacement of the valves is expected to require at least a five-month outage. Ideally, this would be undertaken shortly after commissioning of Project EnergyConnect is complete to minimise the impact on the NEM.

It may be possible to engage with the owners and operators of other HVDC systems that still use the Generation 2 IGBT positions about the potential to supply them the recovered IGBT positions and components.

3.4. Replace Both Converters with VSC MMC valves

This is the option as described in Section 3.3, however with both converter stations replaced. This will have a much higher capital cost, although the replacement of both converter stations could be done in parallel to minimise the overall impact on the outage of Murraylink – and therefore the expected outage would be about the same as for the single-converter replacement option.

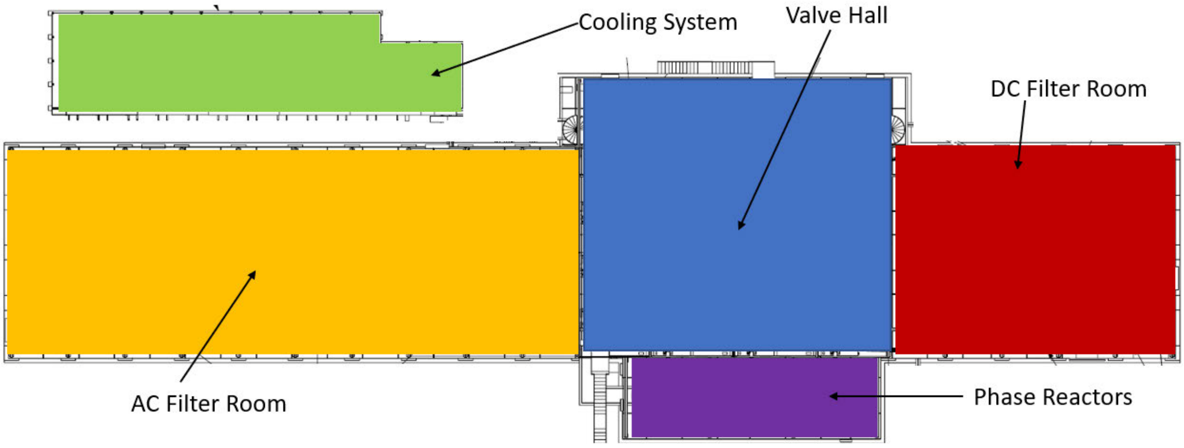
For this option, the overall benefits described in Section 3.3, would be fully realised for the whole HVDC link. The reduction in losses and improvements in reliability and thermal performance, would be realised at both converters – effectively doubling the benefits. In addition, the option will result in the future-proofing on the entire HVDC system, without any need to retain and use existing Generation 2 IGBT positions.

It may be possible to engage with the owners and operators of other HVDC systems that still use the Generation 2 IGBT positions about the potential to supply them the recovered IGBT positions and components.

4. MMC VSC Option - Layout Considerations

To assess the different options, it is necessary to consider the feasibility of the prospective spatial arrangements within the constraints imposed by the existing plant and site layout. The layout the Red Cliffs Converter Station building is shown in Figure 7. The Berri Converter Station layout, within the building, is the same with key differences being the relative location of the cooling plant and cooling rooms.

Figure 7 – Red Cliffs Converter Station Layout



The operation of the converter in rectifier mode (i.e., exporting power) is such that power flows from the incoming AC feeder connection through the power transformers (not shown) into the AC filter room, highlighted in yellow. From the AC filter room, the power passes through the phase reactors (purple) and into the valve containers (blue). There are six valve "arms" producing a positive and negative DC voltage for each phase, which are cooled by the cooling system, highlighted in green. From the valve halls, the power flows through the DC filter room (red highlight) and into the two DC cables (also not shown). The power flow for inverter mode (i.e., importing power) is in the reverse direction.

Considering the options presented, the replacement of the converter station with MMC converters would require changes to the converter station buildings and site layout.

4.1. Concept MMC Layouts

For the MMC upgrade options considered, most of the equipment in the AC filter room is expected to become redundant. The voltage waveform produced by the MMC conversion process tends to demonstrate excellent harmonic performance and therefore AC filtering is not required to address harmonics generated by the conversion process itself. Therefore, the expectation is that the majority of the existing AC filtering equipment can be removed from this area and the objective would be to fit as much as possible of the MMC valves and associated equipment within this area, limiting the scope of modifications needed to the rest of the building and site.

For the existing AC filter room to be able to house the new MMC equipment, it would have to be converted into a "clean room" environment and the following modifications are anticipated, as a minimum:

- Installation of dust seals, air handling and filtration plant.
- Thermal cladding of the walls and roof.
- Humidity control.
- Cable tray systems.
- Arc flash detection and associated protection.

- CCTV.
- Vermin proofing.
- Painting of the floors and wall to effectively seal the surfaces.

It is assumed that the load bearing capacity of the existing floor is adequate, though this needs to be confirmed at the appropriate stage.

The assumptions for the equipment dimensions and possible configurations of the MMC plant is discussed in the following sections, together with options for laying out the new MMC equipment in the available space at the Red Cliffs and Berri Converter Stations.

4.1.1. Component Dimension Assumptions

For the purpose of assessing whether conversion of Murraylink to an MMC valve within the existing building and site is possible, the estimated MMC converter arms and arm reactor dimensions have been based primarily on the Trans Bay Cable Project and taken from publicly available information [8] [9], together with Google Earth images [10]. Trans Bay Cable is rated at 400MW with a ±200kV DC voltage and is currently one of the smallest MMC converters in service. The system has been in service since 2010 and the technology applied has been proven technically sound and reliable.

The centre to centre rack spacing has been estimated to be 6 m from the satellite imagery of the exiting wall bushings. Assuming a rack width of 1.75 m, the clearance between racks has been estimated to be in the order of 4.25 m. The estimated dimensions and assumptions applied are listed in Table 2.

Table 2 – MMC Plant Dimension Estimations and Assumptions

Parameter	Dimension Assumption
Sub-module dimensions	**Module width:** 0.4 m including electrical connection to adjacent unit **Module height**: 0.65 m **Module depth:** 1.5 m **Number of sub-modules per rack**: 6 **Rack width**: 2.5 m **Inter rack spacing (vertical):** 1.25 m
Working clearance between the valve stacks	4.0 m to 4.5 m
Valve stack width	1.75 m
Reactor	**Body diameter:** 2 m **Body height:** 2.5 m **Height of reactor base above ground**:2.5 m

Parameter	Dimension Assumption
Estimated number of modules	The Trans Bay Cable Project has 216 modules per phase arm for the ±200 kV system which includes circa 7% redundancy. Assuming the use of similar rated IGBT sub-modules, an estimated number of 160 modules has been used based on the ±150 kV DC voltage at Murraylink.

There are several options for configuring the prospective MMC equipment (valves/sub-modules and reactors) at both sites. In all cases, modifications to the building, below ground infrastructure and site equipment is needed to achieve an acceptable engineering solution. At this stage, the assessment focused on determining the viability of an MMC based conversion and did not consider the range of all possible solutions. The optimum configuration or layout would need to be assessed in greater detail during the feasibility stage.

Due to the relatively narrow width of the Murraylink converter stations and available space, a valve stack length of between 10 m to 11 m could be accommodated, either perpendicularly or in parallel to the building walls, whilst retaining reasonable horizontal clearances for maintenance and access during outages. The available height within the AC filter room is estimated at 10 m excluding any required electrical clearances.

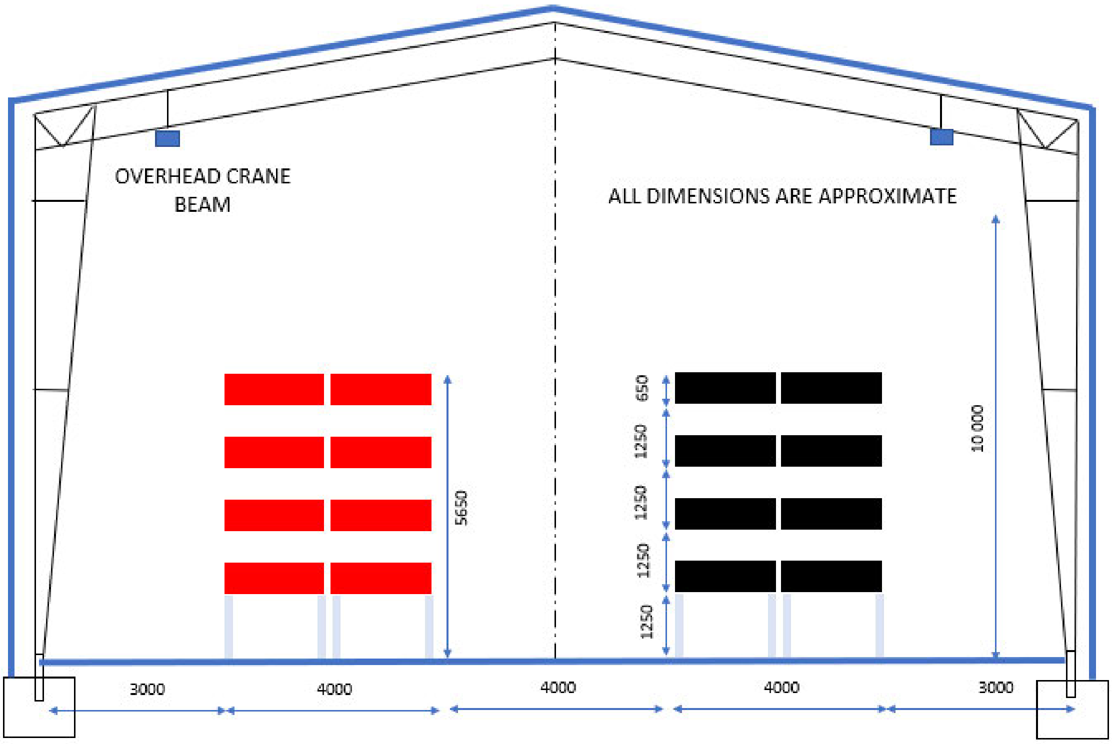
During operation, the MMC valve hall will need appropriate interlocks to prevent personnel access and to ensure safety. The existing Castell Key system will likely be suitable with minimal modification.

Our current preference in terms of valve and reactor layout is for parallel aligned valve stacks, due to the reduced complexity for connecting the valve stacks from the indoor DC yard and through the existing outgoing cable ducts to the outdoor plant areas. The use of cables will be required due to the space constraints. To avoid cutting into the concrete floor, surface mounted cable trays will be needed in sections of the new valve room and potentially other areas. The existing cable pit will be re-used to the maximum extent possible.

To accommodate 160 modules of 0.4 m width with a phase arm length in the order of 10 m, requires a four level stack layout using a double stack arrangement. With optimisation this could potentially be realised as a three level stack depending on the actual component dimensions.

Using a 1.25 m height above ground assumption for the first MMC level and the same for the inter-level spacing, yields a valve stack height in the region of 6 m for a four level MMC arrangement. The concept MMC valve arrangement and maintenance clearance are shown in Figure 8. The electrical clearance to roof and wall is considered adequate for the 150 kV peak voltage stress.

Figure 8 - Concept MMC Valve Arrangement



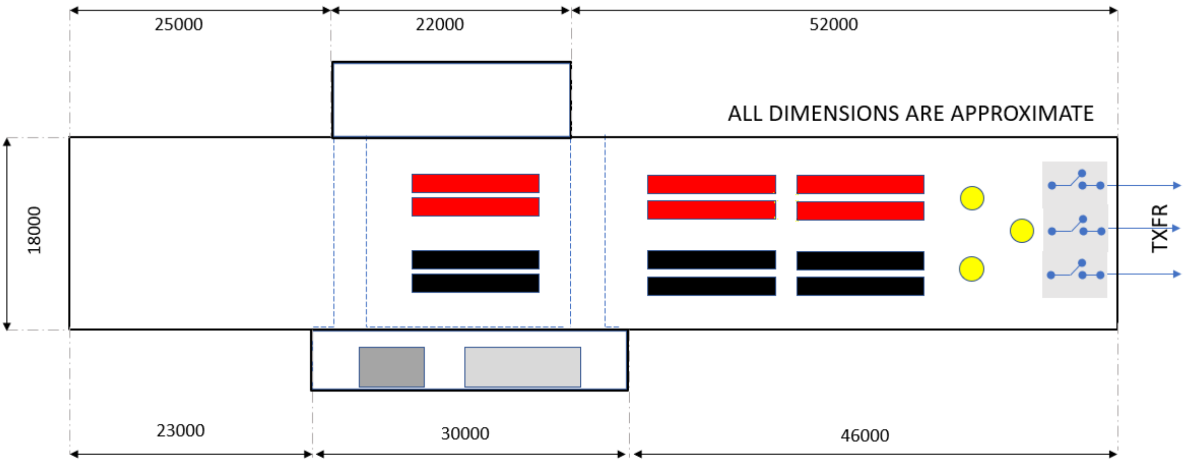
An important consideration is the location for the six new converter arm reactors. Optimising the layout to fit the valve stacks and to accommodate the reactors narrowed the assessment to two scenarios:

1. Scenario 1 - Installing the valve reactors within the existing AC filter room footprint; or
2. Scenario 2- Installing the reactors outdoors with additional cabling works for the connection.

Considering required electrical and maintenance clearances, there is insufficient space in the existing AC filter room alone to install all six converter arms together with the converter arm reactors for scenario 1. Figure 9 demonstrates one layout concept for scenario 1. The concept would involve removing the existing valve enclosures in order to install two of the converter arms. The reactors will need to be vertically stacked to fit within the space. It may be possible to re-use the existing isolators in the AC filter room. A disadvantage of stacked reactors is that a catastrophic failure of single reactor could result in the loss of both units in the arrangement. To reduce this risk, conservative ratings of the reactors should be considered.

A minor benefit of this scenario is that it limits outdoor cable laying works, however the cooling of these reactors and the impact of them being within the sealed building will need to be assessed. It is envisaged that this option will only be used if no suitable alternative is available.

Figure 9 – Scenario 1 - Converter Arm Reactors Installed Within Existing Building Footprint



To achieve scenario 2, both the Berri and Red Cliff Converter Stations are observed to have a portion of available space adjacent to the transformer bays that could potentially be used for the siting of the converter arm reactors. The land area appears adequate, however as a backup, vertically stacked reactor arrangements could also be used if space is deemed to be tight during the design phase. This scenario will involve the construction of additional cable duct segments outdoors, together with outdoor isolators installations and is preferred to the concept proposed for scenario 1 due to the reduced scope of building modifications needed. Figure 10 and Figure 11 show diagrammatically the proposed layouts to achieve scenario 2 for the Red Cliffs and Berri Converter Stations respectively. The magnetic clearance requirements for the converter arm reactors will have to be assessed at the design stage and this could impact on the reactor location and positioning of equipment and cable circuits in their vicinity.

Figure 10 – Scenario 2- Red Cliffs Converter Station

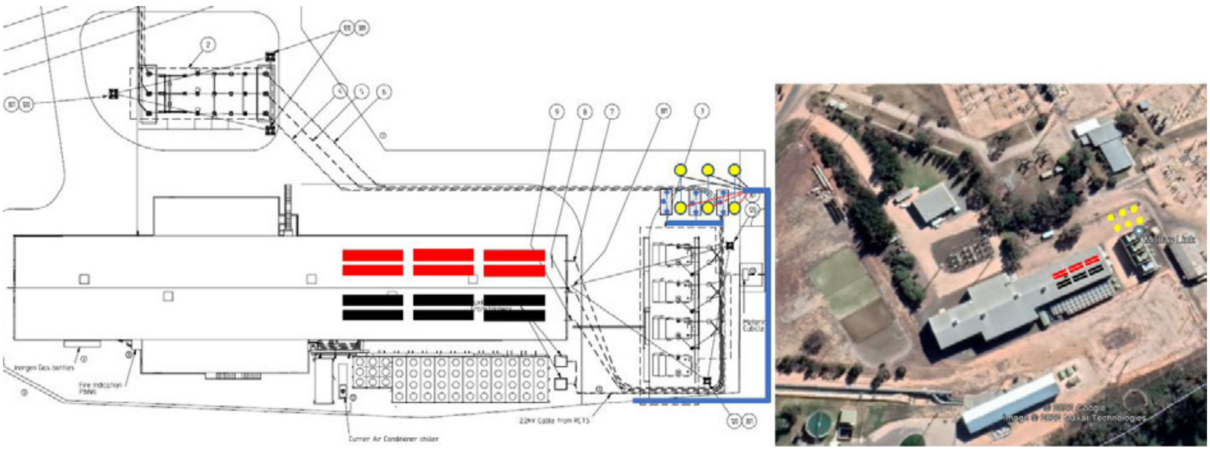
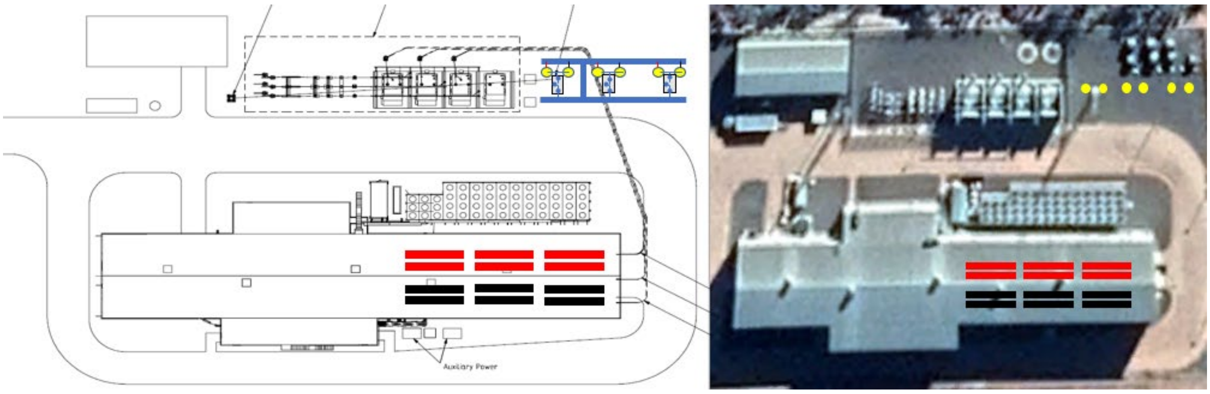


Figure 11 – Scenario 2 - Berri Converter Station



Using higher rated e.g., 3.3 kV IGBT sub-modules was considered. Being double the voltage rating used in the Trans Bay Cable Project, the design would require half the number IGBT sub-modules (80 sub-modules per converter arm) and could be achievable as a single stack 4-level arrangement with a slight increase in height. The disadvantage of this option is that power quality and refinement of the output AC waveform could suffer. A reduction on the number of sub-modules needed could overcome potential space constraints; however, deeper analysis would be required to confirm acceptability during the feasibility stages and following engagement with potential HVDC suppliers.

5. Comparison of Options

In this chapter, we provide a comparative assessment of the four options presented in Section 3. The outcomes of the comparative assessment are summarised in Table 3. Further narrative for each category is provided in the subsequent sections.

Table 3 – Comparison of Murraylink Valve Replacement Options

	Like for like replacement	MMC Upgrade (one converter station)	MMC Upgrade (both converter stations)
Losses	• As per existing system.	• Expected reduction of 1% at peak transfer capacity.	• Expected reduction of 2% at peak at peak transfer capacity.
Thermal Performance	• As per existing system. • Derated at higher temperature.	• Thermal performance limited by remaining converter station • Derating at higher ambient temperatures. • Potentially some improved performance at replaced converter.	• Improved thermal performance due to lower switching frequency. • Existing cooling system likely oversized. • Potential for better performance at higher ambient temperature.
Service Life	• Operational life of existing IGBT units as spares unknown.	• Operational life of existing IGBT units as spares unknown.	• Operational life extended to 40 at least existing design life. • Potential to extend operational life.
Suppliers	• Locked into one supplier. • No Competitive pressure on pricing.	• Multiple vendors available. • Competitive pressure on pricing. • Potential for smaller MMC vendors (e.g., Japan) to provide competitive pricing • Potential interfacing issues – different vendors/technology at each end.	• Multiple vendors available. • Competitive pressure on pricing. • Potential for smaller MMC vendors (e.g., Japan) to provide competitive pricing.
Outage Requirements	• 70 days for one phase	• 5 months	• 5 months

5.1. Losses

Losses on Murraylink, as determined by calculation during the design phase, are specified in the Murraylink Main Circuit Parameters Technical Report [11]. [redacted].

Whilst specific loss calculations will depend on the final design, information available in the public domain indicate that the converter losses for three-level VSC converters are around 2% per converter, but with MMC technology this can be reduced by at least 1% per converter [12]. From this, the losses for each converter can be reduced by approximately 1%, with total system losses reduced from ~8.5% to ~6.5%. Some publications are showing that MMC valve losses can get close to 0.8% per converter.

Replacement of only one converter station is expected to reduce the total system losses from ~8.5% to 7.5%.

The replacement of one phase with a newer generation of IGBT positions is not expected to decrease losses and, based on recent experiences with the proposed valve upgrade at Directlink, may actually marginally increase losses on that phase. Any increase is not expected to be material.

5.2. Thermal Performance

Both converter stations at Berri and Red Cliffs are designed to be derated during high ambient temperatures. [redacted]

APA have identified that, during the next RCP it will be necessary to upgrade the cooling at a cost of $3.21 M [2], and it is expected that this upgrade will deliver a positive market benefit to consumers.

The MMC valves will have a significantly lower switching frequency (per IGBT) than for the three-level converter design. This switching frequency could be of the order of three to four times less. The reduced switching requirement will mean less cooling is needed to maintain the required water temperatures in the cooling circuit. It is anticipated that for the options involving replacement of the Murraylink valves with MMC sub-modules, the existing cooling system could remain, and that this cooling system will become over-designed for its purpose. We expect this to result in a capability of the new valves to operate at higher ambient temperatures. The actual new design point for the new valves will need to be determined during the design phase, and may be limited by other equipment, such as the transformers and retained reactors. For the MMC upgrade options, it is likely that the additional investment in the cooling system identified in the Revenue Proposal [2] can be avoided at the upgraded converter stations.

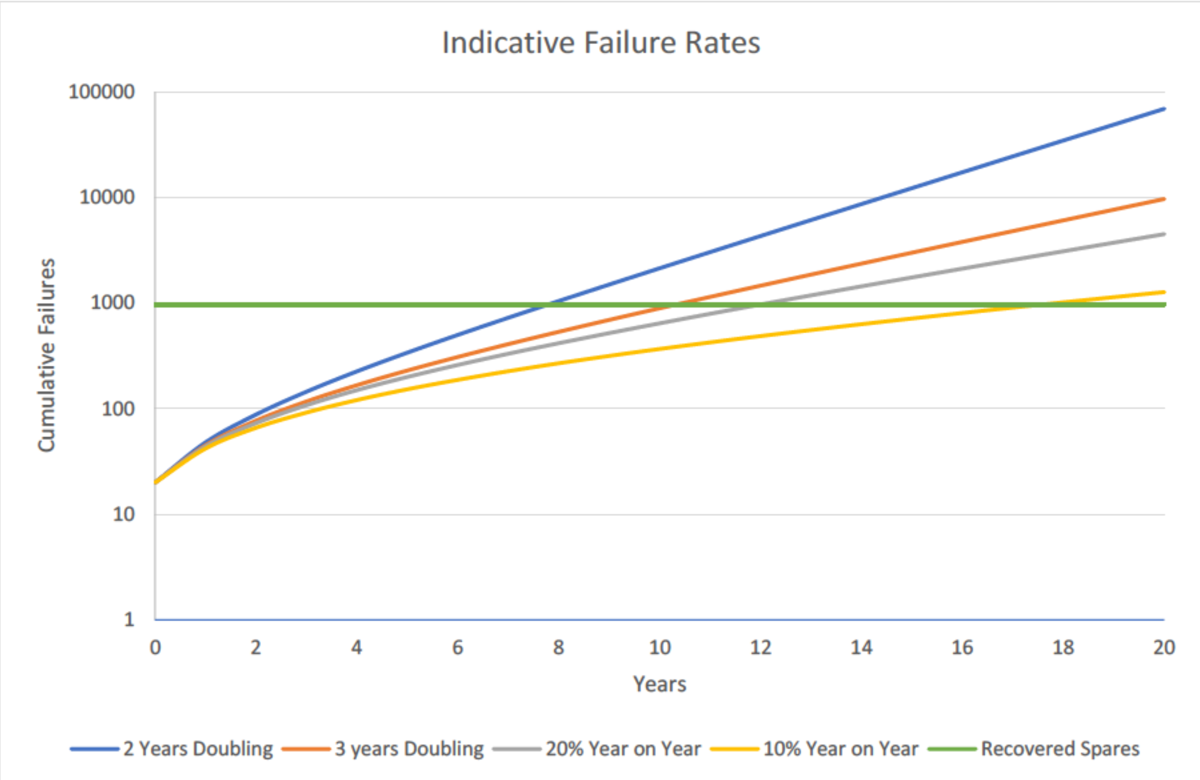
The replacement of one phase with a newer generation of IGBT positions may require additional cooling upgrades to improve the thermal performance of the IGBT positions as anticipated in the RCP.

5.3. Valve Service Life

Murraylink was commissioned in 2002, with an expected design life of 40 years. In 2020, an upgrade of the protection and control system was completed to ensure ongoing reliable operation and to extend the life of these assets.

The option to replace a single phase of the Generation 2 IGBT positions with a newer generation of IGBT positions will recover circa 900 Generation 2 IGBT positions. As failure rates are likely to increase due to the "bathtub curve" effect, Figure 12 considers the expected time that it would take for the recovered spares to be exhausted, assuming cumulative failures on a logarithmic scale. The most aggressive increase in failure rate shown in Figure 12 assumes that there is a doubling of failures every two years, in which case the recovered IGBT positions would be exhausted in approximately seven years. At the other end of the scale, a 10% year on year increase in failure rates would mean the recovered units would last approximately 17 years. It is expected that to achieve a 40-year life out of the assets, a further replacement of another phase of the valves will be required before the end of the operational life.

Figure 12 – Indicative IGBT Failure Rates



The option to replace both converter stations with MMC technology is expected to extend the life of the converter stations. Some assets, such as the control and protection systems and AC filters, would have residual value when removed from service, but it is expected that the balance of the assets on the AC and DC side would be suitable for continued operation at least until the end of the asset's design life of 40 years and most likely significantly beyond.

The option to replace a single converter station with MMC technology would significantly extend the life of that converter station, and allow the removed Generation 2 IGBT positions to be used only for the other converter station, however unless remedial action is taken, the other converter station would reach end of life in the early 2040s. The replacement of one of the converter stations would allow for recovery of approximately 3,000 IGBT positions for the remaining converter station, however Figure 12 indicates that these could be exhausted within 20 years for all but the most conservative failure rate projections.

The major concern for options that rely on the re-use of Generation 2 IGBT positions removed from service is that the condition and life expectancy of these units is unknown. Most of these IGBT positions will have seen almost 20 years of operational life, and it may be that the IGBTs themselves or the electronics within the gate control units may be close the end of their operational life (i.e., the "increasing failure rate" part of the bathtub curve referred to in Section 2.2. With Murraylink being one of the early facilities to install these Generation 2 IGBT positions, there is no operational data to support the future expected life of these assets, even after refurbishment. Therefore, it is difficult to say whether the available spare IGBT positions could be used to keep Murraylink reliably operating to the end of its 40-design life.

5.4. Suppliers

The original supplier of the Generation 2 IGBT positions is currently the only supplier of two- and three-level converter technology and the only supplier that uses the "press pack" IGBT positions of the type needed to replace the Generation 2 IGBT positions on a "like-for-like" basis. All other suppliers who have commercialised their VSC solution utilise the MMC valve technology.

For options involving the replacement of a single phase of a converter with newer generation IGBT positions, APA would be locked into using the existing Generation 2 suppliers. A key benefit to this fact is that the control and protection system, which was replaced in 2020, is supplied from this same supplier and therefore likely to be able to be re-used, requiring no new or replacement control and protection system.

The replacement of one or both converter stations with MMC technology would open up the opportunity for a broader range of suppliers to provide the new valves. While there is a significant demand for VSC MMC links at the present time, these new projects tend to be of the higher capacity or rating, meaning that there is still expected to be a relatively small demand for the smaller IGBT sub-module units. There are also some relatively new entrants in the MMC market who may be targeting this smaller rating market. In our view, the smaller size of Murraylink, both in terms of voltage and capacity, could open the door to suppliers who may not to date have the capability to deliver the larger scale projects being built presently around the globe. It is however expected that the replacement of the valves by these alternative suppliers will require significant if not wholesale additions or replacements to the converter control and protection system, increasing the cost to undertake such works.

In essence, selecting an MMC technology solution is expected to be more expensive, however the difference may not be as great as expected if pricing can be obtained on a competitive basis, compared to the "like for like" options where pricing cannot be obtained on a competitive basis.

5.5. Outage Requirements

In order to deliver each of the options described in Section 3, extensive outages will be required to facilitate construction.

To replace the Generation 2 with a newer generation of IGBT positions , an outage of up to 10 weeks is assumed. This includes removal of the existing valve stacks, install of the new IGBT valve stacks, testing and commissioning.

To replace one or both converter stations with VSC MMC, an outage of up to 5 months will be required. This encompasses removal of the existing IGBT positions, construction and building modifications, installation of the new MMC sub-modules, replacement of the control and protection systems, and testing and commissioning.

6. Option Cost Estimates

Cost estimates have been developed using a bottom-up approach for the options to replace the Generation 2 IGBT positions with a newer generation of IGBT positions and to upgrade one or both converter stations to VSC MMC valve technology. These are provided in Table 4 below.

Table 4 - Option Cost Estimates

Option	Cost
Replace Gen 2 IGBT positions with newer generation IGBT positions	$17.8m per phase
Upgrade one converter station to VSC MMC	$36.7m
Upgrade both converter stations to VSC MMC	$71.8m

At this stage of the assessment, these cost estimates are to be considered ballpark only. The pricing for individual IGBT positions and IGBT sub-modules is closely guarded by the vendors, and our ballpark costs have applied rules of thumb to costing of other projects based on publicly available sources.

Some key assumptions and qualifications applied in determining these estimates are:

- That inflationary adjustments, as applied to available costing data, are weighted towards and track Australian CPI over the longer term, noting that price spikes and demand being experienced by the electronic manufacturing sector currently, could influence pricing received.
- The current demand for HVDC equipment could limit supplier participation and pricing received.
- Assumptions applied to pricing data and estimating cost element breakdown, particularly for brownfield HVDC projects could negatively influence the estimate.
- Detailed engineering studies and calculations have not been performed, and inaccuracies in scaling, component estimates and equipment ratings could change the scope of work anticipated and consequently pricing.

Whilst we have done our best to estimate the cost of the replacement works, especially when considering replacement of the Generation 2 IGBT positions with a newer generation of IGBT positions, the reality is that there is very little, recent information on the costing of non-MMC VSC projects, and it is difficult to factor in costing factors due to lack of economy of scale (i.e. replacing one phase instead of the entire converter) and the lack of competitive pressure on the pricing of the work. It is possible that the cost estimate for this option may be under-stated, and these need to be checked against any quotes received from the supplier to complete the works.

7. Replacement Using MMC Technology

Replacing the existing three-level VSC converter valves with modular multi-level converter (MMC) technology, as presented in Chapter 1, could realise a reduction in electrical losses, improvement in reliability, improvement in thermal capability (operating at higher ambient temperatures), potential for competitive pressures during the pricing of the work and an expected improvement in overall reliability of the asset (or at the very least, avoiding anticipated future "end of life" failures of the existing valves). Further analysis and impact of this option is discussed below.

7.1. Impact of Replacement using MMC Technology

Amplitude has considered further the impact (or non-impact) of replacing the existing three-level valves with MMC valves, on other parts of the Murraylink facility. These impacts are summarised in Table 5.

Table 5 – Equipment Impacts for MMC Technology Adoption

Equipment	Anticipated Impact
AC circuit Breakers, Disconnectors and Earth Switches	Whilst the disconnectors and earth switches are suitable for ongoing use, they will need to be removed or relocated from their existing location within the AC filter room. No change is expected to the balance of AC plant.
Power Transformers	It is expected that the existing transformers will be suitable for the application. This will be confirmed at the detailed design phase.
Phase Reactors and AC Filters	The existing phase reactors, filter reactors, filter resistors and filter capacitors on the AC side of the converter will not be required for the MMC conversion, and therefore can be removed and disposed of. Six new converter arm reactors will be installed, one on the AC side of each of the six new converter arms.
DC Smoothing Filters	The DC smoothing filters can be retained. Confirmation of the suitability for the MMC converters will be carried out at the detailed design stage.
Surge Arresters	Dependent on position in the circuit, some surge arresters could require replacement or relocation, with specifications to be confirmed at the detailed design phase. This will require a detailed insulation coordination study to be done

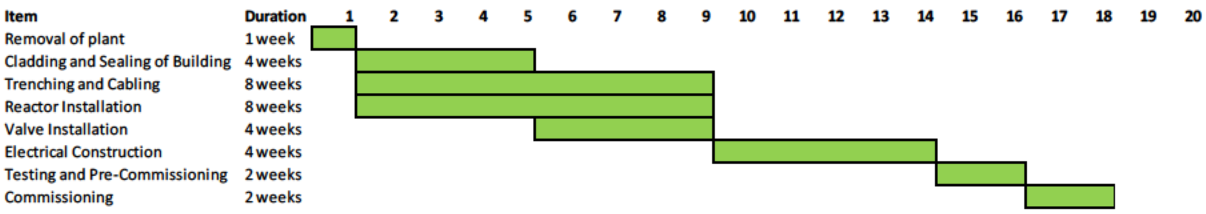
Equipment	Anticipated Impact
	to confirm the required ratings and locations of surge arresters throughout the facility.
Current and Voltage Transformers	The current and voltage transformers are expected to be retained, except those to be removed as part of the AC filtering or phase reactor circuits. Confirmation of the suitability of these for the MMC converters will be carried out at the detailed design stage.
Wall Bushings	The existing wall bushings from the valve containers to the phase reactor room will be disposed of. Depending on the selected layout installation, new wall bushings, including any required supporting structures, could be required e.g., to facilitate connection from the new converter arm reactors to the converter arms inside the valve hall.
IGBT Positions and Valve Enclosures	The key driver for this project is the lack of IGBT spares. New MMC sub-modules will be installed, with the existing IGBT positions to be removed. The existing valve enclosures (containers) can be stripped out and left as is, for possible conversion for other purposes. Opportunities may exist to convert some of these to storage rooms, workshops, battery rooms and/or to hold new control and protection equipment.
HVDC Cable	The HVDC cable is rated to match the specifications of the existing converter stations. It is not expected there will be any impact on the HVDC cable due to the conversion.
Land and Easements	These works are not expected to require any additional land or easements, subject to detailed design confirmation. Works outside of the building are expected to be limited to cable works and the new phase reactors with respective isolators.
Control and Protection System	If the MMC valves are provided by anyone other than the current supplier (i.e., Hitachi), the control and protection system will most likely require replacement to suit the new MMC valves.
Fire System Equipment	The fire system has recently undergone replacement and is expected to remain serviceable. The water sprinkler system in the AC filter room (i.e., the new valve hall) will need to be removed. Arc flash detectors that trip the converter on detection will need to be installed inside the new valve hall. It is expected that the new valve hall could be too large for a gaseous fire protection system.
HVAC, Valve and Reactor Cooling Systems	The new (converted) valve hall will require additional air handling and humidity control systems. With the removal of the phase reactors, the current reactor cooling system, including the pump room and all external fans can be removed and disposed of. It is expected that the current valve cooling system can be retained, although it will be oversized for the expected duty of an MMC converter valve. This could mean that the valves may be readily designed to operate at higher ambient temperatures, improving the thermal performance of the overall converter station.

Equipment	Anticipated Impact
Auxiliary Power Supply	It is expected that the conversion will not require much, if any, additional auxiliary power. The auxiliary power requirement may reduce with the removal of the reactor cooling system, although the additional power requirement of the new air handling system will counter that reduction. Confirmation of the suitability for the MMC conversion will be carried out at the detailed design stage.
Buildings and Structures	It is expected that any works to address the need will be carried out within the shell of the existing buildings, however modifications to the building may be required subject to detailed design confirmation. The AC filter room will need to be converted to become the new valve hall. This will require, as a minimum, the sealing and painting of the room to "clean room" conditions, the installation of air handling and humidity control systems and the installation of arc-flash detectors and CCTV cameras.

7.2. Outage Schedule

It is expected that the replacement of the existing valves with MMC VSC technology will require an outage of up to five months to complete. Figure 13 provides the indicative schedule for replacement of the plant, including commissioning.

Figure 13 – Indicative MMC Installation Schedule



Note that project development and design is excluded from this project schedule. These activities can be performed while Murraylink is running and in operation.

7.3. Cost Estimate

A breakdown of the cost estimate is shown in Table 6.

At this stage of the assessment, these cost estimates are to be considered ballpark only. The pricing for individual IGBT sub-modules is closely guarded by the vendors, and our ballpark costs have applied rules of thumb to costing of other projects based on publicly available sources.

Table 6 –Cost Estimate Breakdown

Item	Qty	Units	Unit Cost	Cost
Electrical Plant				
MMC Sub Modules	1920	ea	$20,000	$38,400,000

Item	Qty	Units	Unit Cost	Cost
HVAC Cable	2000	m	$1,500	$3,000,000
HVDC Cable	1200	m	$1,500	$1,800,000
Control System	2	ea	$10,000,000	$20,000,000
Phase Reactors	12		$200,000	$2,400,000
Building Modifications				
Cladding	4800	m²	$50	$240,000
HVAC and Filtration	2	ea	$300,000	$600,000
Project Costs				
Development	600	hr	$350	$210,000
Design	1730	hr	$350	$600,000
Installation	6400	hr	$200	$1,280,000
Testing	2240	hr	$350	$780,000
Commissioning	1350	hr	$350	$470,000
Site Works	60	days	$20,000	$1,200,000
Overheads	1900	/person / day	$350	$670,000
Travel	20	per person	$8,000	$160,000
Spares				
MMC Sub Modules	40	ea	$20,000	$800,000
Total Cost				$71,810,000
Note: The option of upgrading only one of the converter stations to VSC MMC technology is estimated at $36.7m				

8. Conclusion

There are few known VSC converters to employ the Generation 2 IGBT positions as used in Murraylink. Consequently, limited data is available from other operational projects to assess the proven asset life of these IGBT positions beyond their current age. Given the present IGBT position failure rates and the potential for this failure rate to increase, it will not be possible to maintain reliable operation of the Murraylink converter stations without intervention.

For the base case option of purchasing all IGBT positions made available, we estimate that there will be an additional 6-7 years of operational capability, assuming the failure rate of IGBT positions remains steady. The potential for the failure rate to increase is not discounted and this will shorten the operational life further. A possible approach would be to partner with other owners and operators in order to develop a shared strategy in relation to access to spare parts, though the success of this is viewed as more of an opportunity and other decisive options should be developed.

The option for the replacement of the existing Generation 2 IGBT positions in one phase with a newer generation of IGBT positions from Hitachi is expected to release sufficient spares to extend the operation of Murraylink between seven and 17 years depending on the failure rate assumptions. The replacement of one phase with a newer generation of IGBT positions is not expected to decrease losses and a major concern is that the condition and life expectancy of the recovered units are unknown. Replacing more than one phase will "free up" more IGBT positions but the higher cost is likely to be uneconomical when compared to upgrading to MMC technology and the additional benefits that this unlocks.

The replacement of the existing valves with MMC technology would address the IGBT obsolescence issues and initial concepts layouts indicates that this is feasible with the physical space available. Building and site modifications are required, however, upgrading both converter stations to MMC VSC is expected to:

- Reduce losses by approximately 2% at maximum power transfer;
- Improve the reliability of converter stations; and
- Improve the thermal performance of the converter stations.

The benefits of replacing only one converter are limited as losses would only be reduced for the one converter, and the thermal performance and reliability of the link improvements would only be realised at that converter. However, the in-service IGBT positions released could then be used to support the other converter to extend its life. The replacement of the valves with MMC equipment is projected to require a five-month outage with little difference if one or both are replaced as this would be done in parallel.

The cost to replace one phase in converter station with a newer generation of IGBT positions is estimated at $17.8m per phase and the option of upgrading one or both converter stations to VSC MMC technology is estimated at $36.7m and $71.8m respectively.

Pursuing the MMC upgrade solution is expected to be more expensive, this being shown in the estimated developed, however the difference may not be as great as expected if pricing can be obtained on a competitive basis, compared to other options considered where this is not possible, and the OEM has to be retained.

In order to finalise the replacement strategy adopted, our recommendation on the next steps would be to:

- Consult with other impacted Generation 2 IGBT operators to ascertain if they have firm replacement strategies and if any synergies can be found; and
- Develop functional MMC specifications to obtain pricing, basic design and project schedule information from prospective suppliers.

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