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to the Electricity Industry

Network Extensions to Remote Areas

Part 2 – Innamincka Case Study

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Disclaimer

Selection of Innamincka for this case study does not imply that either Power Systems Consultants (PSC), or the Australian Energy Market Operator (AEMO) has formed a view about the generation capacity at Innamincka, or the economic viability of this site, or the economic viability of network extensions to it. The conclusions in this report are based on the technical characteristics of the various options and exclude any cost/benefit analysis. More detailed technical and cost/benefit investigations could identify more favourable options.

Also, PSC and AEMO have not developed the transmission options in this report with a view for them to be classified as a Scale Efficient Network Extension (SENE). The options have been developed only to identify some possible transmission solutions for connecting generation at Innamincka to the shared transmission grid.

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Executive Summary

This report forms Part 2 of a study into ‘Network Extensions to Remote Areas’ and provides a hypothetical case study of the application of planning considerations for connecting remote geothermal generation at Innamincka in South Australia to the shared grid.

This high level study investigated various network extension options to connect staged Innamincka generation of 500MW, 2000MW, and 5000MW.

Table E1 shows the six transmission development options that were studied to connect Innamincka to Adelaide, Melbourne, Sydney, and Western Downs using either AC transmission at 500kV and 765kV, or HVDC transmission at +/-500kV and +/-800kV. The table includes an indicative cumulative capital cost as each stage is added.

The development options were selected to explore possibilities for the application of AC and HVDC technologies, and to show how each technology could be staged to match growth in generation. Each development option was partially optimized so as to provide a reasonable indicative comparison of likely capital costs (however detailed technical and cost benefit investigations have not been performed).

The design for the different development options took into account a number of the planning considerations discussed in Part 1 of this study. These included selecting a transmission route, AC or HVDC transmission, transmission voltage and losses, security, staging, and choice of connection points on the shared grid.

The results of the study suggest that the capital costs of HVDC transmission connections to Innamincka are about 70% of the capital costs of AC transmission connections, for similar levels of capacity. However the AC connections have an advantage in that they also facilitate the connection of other generation and demand along the route.

It is possible that a mixed AC and HVDC transmission connection could be more beneficial than an all AC or all HVDC solution as proposed here. For example AC transmission to Adelaide and Melbourne would facilitate the connection of generation and demand along the route, whilst HVDC transmission to Sydney or Western Downs would be the preferred lower cost option if there are no future connections anticipated along that route.

Table E1. Transmission Development Options and Indicative Cumulative Capital Costs

Innamincka Generation	**Option 1** **AC** **INN-ADL-MEL-SYD**	**Option 2** **AC** **INN-MEL-SYD**	**Option 3** **AC** **INN-WSD-SYD**	**Option 4** **HVDC** **INN-ADL-MEL-SYD**	**Option 5** **HVDC** **INN-MEL-SYD**	**Option 6** **HVDC** **INN-WSD-SYD**
Stage 1 **500MW**	950km 500kV double circuit line to Adelaide via Broken Hill switching station	1250km 500kV double circuit line (strung one circuit) to Melbourne	1000km 500kV double circuit line (strung one circuit) to Western Downs	850km 500MW, +/- 500kV bipole to Adelaide	1250km 600MW, - 500 kV monopole to Melbourne	1000km 600MW, - 500 kV monopole to Western Downs
	A$0.9 – 1.4 Billion	A$1.0 – 1.5 Billion	A$0.8 – 1.2 Billion	A$0.3 – 0.5 Billion	A$0.7 – 1.0 Billion	A$0.6 – 0.9 Billion
Stage 2 **2000MW**	Extend 500kV double circuit line 750km from Broken Hill switching station to Melbourne plus series compensation	Upgrade by stringing 2nd 500kV circuit plus series compensation	Upgrade by stringing 2nd 500kV circuit plus series compensation	1250km 2400MW +/- 500kV bipole to Melbourne	Upgrade by adding 600MW -500kV half pole in parallel and 1200MW +500kV pole (making a 2400MW bipole)	Upgrade by adding 600MW -500kV half pole in parallel and 1200MW +500kV pole (making a 2400MW bipole)
	A$2.1 – 3.2 Billion	A$1.7 – 2.7 Billion	A$1.4 – 2.2 Billion	A$1.5 – 2.2 Billion	A$1.2 – 1.7 Billion	A$1.0 – 1.5 Billion
Stage 3 **5000MW**	1100km 765kV double circuit line to Sydney with series compensation.	1100km 765kV double circuit line to Sydney with series compensation.	1100km 765kV double circuit line to Sydney with series compensation.	1100km 4000MW, +/- 800kV bipole to Sydney	1100km 4000 MW, +/- 800 kV bipole to Sydney	1100km 4000 MW, +/- 800 kV bipole to Sydney
	A$3.9 – 6.1 Billion	A$3.6 – 5.6 Billion	A$3.3 – 5.1 Billion	A$2.8 – 4.0 Billion	A$2.5 – 3.5 Billion	A$2.3 – 3.3 Billion

1. Introduction

This report is Part 2 of a study into ‘Network Extensions to Remote Areas’ which discusses planning for electrical transmission schemes required to connect remote generation to the existing shared grid in Australia. Part 1 of the study discussed planning considerations. Now, by way of example, Part 2 of the study applies the planning considerations to a hypothetical case study investigating options for connection of large scale geothermal base load generation at Innamincka in South Australia to the existing shared transmission grid.

Innamincka is a very large known geothermal reserve which has had significant public exposure. Innamincka is in the northeast of South Australia, in the Cooper Basin, near the border with Queensland, and is approximately 1200 km due west of Brisbane. It is also approximately 1200 km from Sydney and Melbourne, and 800 km from Adelaide.

A pilot plant is currently being developed on behalf of Brisbane based company Geodynamics Limited. Innamincka has been selected for this case study as it represents a potentially very high capacity renewable generation source at significant distance from the shared transmission network. Selection of this site for the case study does not imply that Power Systems Consultants (PSC), or the Australian Energy Market Operator (AEMO), has formed a view about the generation capacity at Innamincka, or the economic viability of this site, or the economic viability of network extensions to it.

The case study considers AC and HVDC network extension options to connect the following total generation at Innamincka :

Stage 1	500MW
Stage 2	2000MW
Stage 3	5000MW

The development options were selected to explore possibilities for the application of AC and HVDC technologies, and to show how each technology could be staged to match growth in generation. Each development option was partially optimized so as to provide a reasonable comparison of indicative capital costs (however detailed technical and cost benefit investigations have not been performed).

2. Planning Considerations for Innamincka Study

Part 1 of this study discussed a range of considerations to be taken into account when planning transmission connections to remote generation. This section describes how specific planning considerations were applied to this case study.

2.1. Transmission Routes

In this case study the transmission route was generally ‘as the crow flies’ so as to minimize the cost, but avoiding sensitive areas such as nature reserves (with the exception of the Innamincka Regional Reserve itself). The exception was the AC line from Innamincka to Adelaide which was routed through Broken Hill so as to facilitate the connection of potential wind generation near Broken Hill.

In all options double circuit lines were built instead of parallel single circuit lines over diverse routes in order to reduce the costs associated with easements.

Note that this study has not taken into account the following routing considerations which could add to the cost of the transmission options :

a) Excessive wind and ice loading (the study assumed moderate winds with no allowance for cyclonic conditions and no ice loading)
b) Minimization of visual impact
c) Complexity of terrain

2.2. AC Transmission and HVDC Transmission Options

Both AC transmission and HVDC transmission options were considered. The modelled development options were based on either AC transmission exclusively or HVDC transmission exclusively, however the most optimal development could potentially involve a mixture of the two technologies.

The HVDC transmission was based on ‘classical’ current source converters which are well proven but do not facilitate the connection of other generation along the route. Voltage source converter (VSC) DC transmission was not considered in this study because VSC converters are currently significantly more expensive than classical converters and the potential for VSC converters to facilitate the connection of other generation is yet to be proven.

Note that this study has not investigated issues associated with DC earth current which may cause problems such as corrosion on pipelines or DC current flow through the earthed neutrals of transformers, causing magnetic saturation. Detailed studies will be required to determine whether a long electrode line is required to locate the earth electrode in a low resistivity area far from pipelines or transformers.

2.3. Transmission Voltage and Losses

The development options in this case study include AC transmission at 500kV and 765kV, and HVDC transmission at +/-500kV and +/-800kV. Transmission at these high voltages will help to minimize losses, which is likely to be an important consideration, especially given the long distances involved. AC transmission at 500kV is already established in Australia and AC transmission at 765kV is well established elsewhere in the world. There are several HVDC transmission schemes operating at +/-500kV elsewhere in the world, and +/-800kV schemes are under construction and expected to be commissioned within a few years.

An economic trade-off between capital cost and the cost of losses is beyond the scope of this study. However, as a proxy for this economic trade-off, the conductor sizes were selected so as to limit losses to less than 10% of the transmitted power. As a consequence of this the thermal rating of the circuits is significantly higher than the intended power transfer.

In order to reduce corona effects, 4 conductor bundles were selected for 500kV AC and +/-500kV HVDC transmission, whilst 6 conductor bundles were selected for 765kV AC and +/800kV HVDC transmission [1].

2.4. Project Costs

There can be wide variations in published costs for transmission projects, often because it is unclear as to which aspects of the project are included in the cost (such as allowances for contingencies) and also many of the considerations in Part 1 of this work add cost uncertainty. Also the international economy is presently experiencing some large fluctuations which could result in widely varying costs for transmission project components.

For any specific project, up-to-date budgetary costs for components are best sourced directly from manufacturers, and these costs are often treated as being confidential. For the purpose of this high level case study the indicative estimates for capital costs were based on information published from 1996 to 2009. The published costs were converted to US dollars in the year of publication, inflated at 2.5% per annum, and then converted to Australian dollars at the 2008 average exchange rate of US$1.00 to A$1.20.

2.4.1. Costs for AC Substation Equipment

Indicative costs for AC substation equipment are based on cost estimates prepared for the US Department of Energy in 1997 [2], and a 2005 study into the economics of AC and HVDC transmission to windfarms [4]. A range of +/-20% was applied to the cost of AC substation equipment.

As these cost estimates have been acquired from relatively old sources, some comparisons were made with more recent sources to check for consistency.

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[1] It is also possible that 4 conductor bundles could be used for 765kV AC and +/-800kV DC transmission in sparsely populated areas which can tolerate higher levels of audible noise and radio interference.

[2] J.E. Dagle, D.R. Brown, 'Electric Power Substation Capital Costs', Pacific Northwest National Laboratory, December 1997.

For example the *Victorian APR 2009* indicates that a 1000MVA 500/330kV transformer at South Morang is estimated to cost about A$47million. This is consistent with the cost estimation methodology used in this study which would place the cost at A$35-53million (including switchgear).

2.4.2. Costs for HVDC Converters

Indicative costs for HVDC converter stations are based on ranges given in an IEEE paper summarizing HVDC technology in 1996 [3], and the previously mentioned 2005 study into the economics of AC and HVDC transmission to windfarms [4].

As a check for consistency, a comparison was made with a Powerlink / Transgrid report on upgrading the 330kV Queensland/New South Wales Interconnector (QNI) which indicates that a 1500MW Back-to-Back HVDC connection is estimated to cost about A$470million [5]. This is consistent with the cost estimation methodology used in this study which would place the cost at A$400-550million [6].

2.4.3. Costs for Overhead Transmission Lines

Indicative costs for overhead transmission lines are based on an approximate cost estimation methodology applicable to lines in Europe published in 2003 [7]. The costs assume that the line is built over flat or gently rolling terrain. These costs were reduced by 25% to account for the European lines being designed to handle ice loading which was assumed to be an insignificant factor for the routes selected in this study. A range of +/-20% was applied to the cost of overhead lines.

Again these cost estimates have been acquired from relatively old sources, therefore some comparisons were made with more recent sources to check for consistency. For example a 2009 study into connecting Cooper Basin generation to the grid estimates that a double circuit 500kV line strung in quad ‘Orange’ ACSR/GZ conductor would cost about A$1.1million/km (based on TNSP estimates for supply and erection only, without easement costs) [8]. This is consistent with the cost estimation methodology used in this study which would place the cost at A$1.0-1.5million/km for a line with similar rating.

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[3] N.G. Hingorani, ‘High Voltage DC Transmission : A Power Electronics Workhorse’, IEEE Spectrum, April 1996.

[4] L.P. Lazaridis, ‘Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under Special Consideration of Reliability’, Master’s Thesis X-ETS/ESS-0505, Royal Institute of Technology, Department of Electrical Engineering, Stockholm, 2005.

[5] ‘Potential Upgrade of Queensland/New South Wales Interconnector (QNI) – Assessment of Optimal Timing and Net Market Benefits’, TransGrid & Powerlink, Final Report 13 October 2008.

[6] This study assumes that the Back-to-Back HVDC connection provides a 1500MW overload capacity following a pole trip.

[7] F. Kiessling, P. Nefzger, J.F. Nolasco, U. Kaintzyk, ‘Overhead Power Lines – Planning, Design, Construction’, 2003.

[8] ‘How to Connect Cooper Basin Generation to the Grid – Phase 1 Route Selection’, WorleyParsons, 21 August 2009.

As another example a 2009 study into connecting the NEM grid to Mt Isa estimates that a +/-500kV bipole line strung in triple ‘Sulphur’ AAAC conductor would cost about A$0.6million/km [9]. This is at the upper end of the cost estimation methodology used in this study which would place the cost at A$0.4-0.6million/km. (It is possible that the difference is due to allowances for difficult terrain, easements, or project contingencies which are excluded in the PSC estimate).

Note that the thermal ratings and estimated per km costs of the 500kV AC overhead lines in this study are significantly less than the thermal ratings and per km costs of many other existing 500kV AC lines in the shared grid. The 500kV conductor size in this study was selected to reduce costs, but also limit losses to < 10%. This criteria has lead to selection of conductor with higher thermal capacity than the intended power transfer, but less thermal capacity than many heavier 500kV lines existing in the shared grid, and comparatively less cost.

2.4.4. Cost of Easements

This high level case study did not include a detailed investigation into the cost of land along the line routes. An indicative cost for easements was obtained by averaging land valuations published by the New South Wales Government in 2009 [10] , and assuming that these valuations were also applicable in Queensland, Victoria, and South Australia. A range of +/-50% was applied to averaged land valuations for :

- ‘Western Grazing Land’ (A$40/ha)
- ‘Wheat Properties’ (A$1,200/ha)
- ‘Hobby Farms’ (A$14,000/ha).

The easement widths were assumed to be :

500kV AC	70m
765kV AC	110m
+/-500kV DC	50m
+/-800kV DC	80m

The last 200km of line leading into Adelaide, Melbourne, Western Downs, or Sydney were assumed to be over land of the same value as ‘Hobby Farms’, whilst the remaining line was assumed to be 50% over land of the same value as ‘Wheat Properties’, and 50% over land of the same value as ‘Western Grazing Land’.

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[9] ‘North West Queensland Energy Delivery Options – Economic Assessment Report’, ROAM Consulting, 10 February 2009.

[10] Land Valuations from New South Wales Government Land and Property Management Authority, November 2009.

2.4.5. *Excluded Costs*

The indicative costs in this report exclude :

a) Allowance for difficult terrain such as forested, hilly ,or mountainous
b) Costs for access roads
c) Statutory compliance costs
d) Consenting costs
e) Allowance for project scope accuracy
f) Price contingency for exchange rate variation, manufacturing market pressures, and price of materials
g) Interest During Construction
h) Operating and maintenance costs
i) Cost of losses

2.5. Security and Reliability

2.5.1. *Credible Contingency Events*

The transmission connection to Innamincka represents a significant security risk to the system due to the large quantity of power being transferred. Further investigation would be required to ensure that AEMO will be able to manage system security following various contingencies associated with such a large generation connection. This detailed analysis would need to consider issues such as the availability of FCAS reserves, thermal loading on lines and transformers, bus voltages, and stability.

For the purpose of simplifying this high level case study, it has been assumed that there will be no loss of supply for N-1 credible contingency events if :

a) The loss of power to a region due to the new generation connection is limited to the rating of the largest existing generator in the region [11] .

b) The post-contingent load flow voltage phase angle difference between Innamincka and the receiving terminal substations does not exceed 30 deg for AC transmission [12] .

c) Post-contingent bus voltages remain within 0.9 – 1.1 pu.

The various options within this report have been designed to ensure these conditions are met. This is likely to lead to a conservative set of options which

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[11] This is a conservative assumption because AEMO may be able to dispatch reserves to cover the loss of significantly more capacity than the largest generator in a region.

[12] Limiting the post-contingent load flow voltage phase angle difference to 30 deg is a rudimentary ‘rule-of-thumb’ for preserving stability for long distance AC transmission schemes. The method is typically conservative and is based on the power transfer being approximately proportional to the sine of the angle difference, consequently operation at 30 deg results in about half the maximum possible transfer at 90 deg, at which point there is a loss of synchronous stability. Note that this method does not apply to systems where there is generation or shunt dynamic voltage support distributed along the line (in which case operation at much larger angles is possible), and is also not a substitute for stability analysis during detailed investigations.

potentially overbuild the transmission connection, although reduce uncertainty regarding the manageable risk to system security.

2.5.2. Non-Credible Multiple Contingency Events

The National Electricity Rules also require AEMO to manage the system to arrest the impacts of multiple contingency events affecting up to 60% of the total power system load [13]. In this study the relevant multiple contingency events would be the loss of a double circuit AC line or an HVDC bipole.

For the purpose of this high level study this requirement is applied in a conservative manner by limiting the amount of power transferred on a double circuit AC line or an HVDC bipole line to no more than 60% of the minimum load in a region. It is possible that more detailed investigations could show that a higher transfer is possible.

In general the studied options may be regarded as being expensive on the grounds of the simplified criteria assumed to limit the loss of power due to single credible contingencies and multiple contingencies. It is possible that some regions may cater for larger contingencies and subsequently costs could be reduced through reductions in link capacity.

2.5.3. Substation Reliability

A high level of substation and switching station reliability was incorporated into the transmission designs :

a) Single phase transformers were installed at substations with one spare single phase bank at each substation.

b) Breaker-and-a-half switching schemes were used at substations, and switching stations (a double breaker scheme was used if there was no through connection).

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[13] National Electricity Rules Version 31, Chapter 4 'Power System Security', 4.3.1 'Responsibility of AEMO for Power System Security', (k) states that AEMO has a responsibility to "assess the availability and adequacy, including the dynamic response, of *contingency capacity reserves* and *reactive power reserves* in accordance with the *power system security and reliability standards* and to ensure that appropriate levels of *contingency capacity reserves* and *reactive power reserves* are available:

> (1) to ensure the *power system* is, and is maintained, in a *satisfactory operating state*; and
> (2) to arrest the impacts of a range of significant multiple *contingency events* (affecting up to 60% of the total *power system load*) to allow a prompt restoration or recovery of *power system security*, taking into account under-*frequency* initiated *load shedding* capability provided under *connection agreements* or otherwise;

2.6. Staging Transmission Capacity

If there is a high confidence that the geothermal generation at Innamincka will be gradually developed over an extended time, then there may be economic benefits in overbuilding transmission capacity or staging transmission capacity such that one high capacity connection is built rather than multiple smaller capacity connections.

This case study includes examples of staging transmission capacity for AC transmission and for HVDC transmission. The staging methodology is based on building a transmission connection that initially has a lower capacity but is designed and consented to be eventually upgraded to a higher capacity connection. This allows some capital costs to be deferred until the generation is further developed.

If the development of Innamincka generation was completely uncertain in terms of both capacity and timing, then the transmission staging strategy could be very different. It is possible that this would lead to a very limited transmission development with no flexibility to easily upgrade transmission capacity.

2.7. Potential Connection Points

The location of the connection point(s) to the shared network needs to be considered given the scale of generation, increments in generation capacity, distance to the shared transmission network, and ‘knock on’ effects on transmission congestion.

Each state is discussed in the following sections in very high level and simplified terms of its demand and transmission capacity to absorb the Innamincka generation.

2.7.1. Queensland

From *Powerlink APR 2009* the forecast load growth is from 8,330MW in the 2008/09 summer peak to 12,047MW [14] in 2018/19 – a total 10 year increase of 3717MW. Existing light load periods range between 4,200 – 4,800MW [15] . The simplified assumptions of this study require the loss of power for an N-1 credible contingency of the transmission connection to be limited to about 750MW, the rating of the largest generator in the region (Kogan Creek). Also the loss of power for a multiple contingency should be limited to about 2,500MW (60% of the regional light load).

The closest connection point in Queensland to Innamincka is in the Surat Basin, an area with large scale potential for renewable generation. Powerlink recently completed the required regulatory consultation for transmission development in this area. The regulatory consultation sought approval to construct a 275kV double circuit line from the Surat Basin (from a new substation referred to as Western Downs) to Halys with further development from Halys to Blackwall at 500kV (but initially operating at 275kV). The

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[14] Based on medium economic forecast growth rate and 10%POE.

[15] Based on summer, winter, and mid season high/low load flows provided by AEMO.

development plan for the area also foreshadowed two future 500kV double circuit lines from Western Downs and Halys (the first, circa 2016) [16] to connect to Blackwall and Greenbank. Powerlink note that the first of these new lines will initially operate at 275kV prior to being upgraded to 500kV as increased capacity is required.

Western Downs is approximately 1000km east of Innamincka. Powerlink has indicated to AEMO that there is potential to connect about 6000MW at the new Western Downs 500kV Substation. This can be from additional local generating capacity at Western Downs and/or from remote geothermal generation at Innamincka. Either way the knock on congestion in the network is similar. Dominant new generation capacity injecting at Western Downs, relative to other Queensland zones, will change flow patterns on the Powerlink network. The impact will also be very dependent on the location and size of any displaced and/or retired generation.

Significant dominant new generation capacity injection at Western Downs may also change the inter-regional flows between Queensland and the southern states depending again on the location and size of displaced and/or retired generation across the NEM. Furthermore, if the N-1 credible contingency on the Innamincka connection increases above 750MW, this could result in lower northerly transfer capability across the QNI resulting from voltage instability limitations. Under these conditions there may be net market benefits to increase the transfer capability of QNI in accordance with the AER Regulatory Test. One such option to increase the transfer capability is the installation of series compensation[17] , at a cost of about A$120 million.

2.7.2. New South Wales

From *Transgrid APR 2009* the forecast load growth is from 14,514MW in 2008/09 summer peak to 18,692MW [18] in 2018/19 – a total 10 year increase of 4178MW. Existing light load periods range between 5700 – 7800 MW [19]. The simplified assumptions of this study require the loss of power for an N-1 credible contingency of the transmission connection to be limited to about 700MW, the rating of the largest generator in the region (Mt Piper) [20]. Also the loss of power for a multiple contingency should be limited to about 3,400MW (60% of the regional light load).

The majority of the state’s electricity usage occurs in the Newcastle-Sydney-Wollongong area and at peak demand load in this area accounts for over 75% of state power demand . An attractive connection point in New South Wales which would be capable of absorbing and distributing a large quantity of Innamincka generation is the western 500kV network,– nominally at or near Mt Piper (about 1100km from Innamincka).Connection at this location would

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[16] ‘Planning a 500 kV network to meet growth in South East Queensland’, Powerlink, October 2008.

[17] ‘Potential Upgrade of Queensland/New South Wales Interconnector (QNI) – Assessment of Optimal Timing and Net Market Benefits’, TransGrid & Powerlink, Final Report 13 October 2008.

[18] Based on medium economic forecast growth rate and 10%POE.

[19] Based on summer, winter, and mid season high/low load flows provided by AEMO.

[20] Discussions with TransGrid suggested it may be possible to handle a loss of up to 1000MW for a single contingency.

limit augmentations required to the existing transmission system to support the new generation, however, there are likely to be significant knock on effects on network utilisation within NSW and between neighbouring regions.

TransGrid has published a Strategic Network Development Plan for New South Wales [21], which includes development of a 500kV ring around the Newcastle-Sydney-Wollongong area. The sections of this ring which are yet to be constructed include the Southern link between Bannaby and Sydney, and the Northern link between the Hunter Valley and the Coast. Development and timing of these sections is dependent on future generation planting and load growth. These developments would strengthen the ability to connect large scale generation into the 500kV ring, supporting NSW demand and inter-regional transfers.

Large scale generation connection north of the 500kV ring would require significant additional transmission reinforcement. Development opportunities exist west of the 500kV ring, at the Wellington 330kV Substation (about 960km from Innamincka) but capacity would be limited to 1100 – 1300MW (limited by the rating of the two 330kV circuits supplying Wellington plus the load off-take at Wellington).

There is a proposal for a large wind farm (Silverton) with 1000MW capacity to connect into the network between Red Cliffs and Broken Hill. A transmission connection from Innamincka through this area would facilitate the connection of the Silverton generation and also support the growing South West New South Wales load.

2.7.3. Victoria

From *Victorian APR 2009* the forecast load growth is from 10,623MW in 2008/09 summer peak to 12,500MW [22] in 2018/19 – a total 10 year increase of 1877MW. Existing light load periods range between 3500 – 5400MW [23]. The simplified assumptions of this study require the loss of power for an N-1 credible contingency of the transmission connection to be limited to about 600MW, the rating of the Basslink monopole which is the largest single contingency in Victoria. Also the loss of power for a multiple contingency should be limited to about 2,100MW (60% of the regional light load).

An attractive connection point would be the 500kV network at or between Moorabool or Sydenham substations. There are large load off-takes in this area which would minimize congestion and limit the need to augment the existing network. However, future generation connection into the 500 kV network in the south west corridor may require additional 500 kV lines in the Melbourne area to cater for Innamincka injection.

In country Victoria there would be limited opportunities to connect without significant additional reinforcement. Red Cliffs presents some opportunity given its access to Murraylink, country Victoria and South West New South Wales loads. VENCorp's 2030 Vision update document [24] lists a number of

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[21] TransGrid Strategic Network Development Plan, 2008.
[22] Based on medium economic forecast growth rate and 10%POE.
[23] Based on summer, winter, and mid season high/low load flows provided by AEMO.
[24] VENCorp 2030 Vision Update, 1 May 2009.

220kV line upgrades in country Victoria between Moorabool and Red Cliffs as being required before 2019, with replacement of existing 220kV line with 500kV lines after 2019 – all depending on the generation development scenarios. 500kV development would provide a significantly increased capacity between Red Cliffs and Moorabool and provide another attractive connection point for Innamincka generation.

2.7.4. South Australia

From *Electranet APR 2009 and ESIPC APR 2009* the forecast load growth is from 3413MW in 2008/09 summer peak to 4,190MW [25] in 2018/19 – a total 10 year increase of 677MW. Existing light load periods range between 930 – 1300MW [26]. The simplified assumptions of this study require the loss of power for an N-1 credible contingency of the transmission connection to be limited to about 260MW, the rating of the largest generator in the region (Northern). Also the loss of power for a multiple contingency should be limited to about 560MW (60% of the regional light load).

Some attractive connection points in South Australia for Innamincka generation would be :

- Olympic Dam 275kV Substation
- Davenport 275kV Substation (near Port Augusta)
- Tungkillo 275kV Substation (near Adelaide).
- Tepko, which is near Tungkillo. A potential future new 275kV connection point at this location would represent a site which is electrically very similar to generation injection Tungkillo, although has more favourable foundations and topography. It is also in close proximity to the SEA Gas pipeline, which would facilitate connection of gas fired generation [27].

A previous study for the Australian Geothermal Association [28] has suggested that a 275kV AC connection from Innamincka to Olympic Dam would be attractive if the Olympic Dam load increases by some 400MW to about 550MW over 10 years, as per Electranet's high growth forecast.

As an alternative, this case study considers a scenario with less load growth at Olympic Dam and the Innamincka generation is connected to a possible new connection point at Tepko (near Tungkillo). Tepko represents an attractive site given the close proximity to Tungkillo where reasonably large load off-takes minimise the need for augmentation of the existing shared network.

At present under conditions of light load with high wind farm generation in South Australia, there can be considerable congestion exporting power from South Australia to Victoria on the Heywood interconnector. Large scale

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[25] Based on medium economic forecast growth rate and 10%POE.

[26] Based on summer, winter, and mid season high/low load flows provided by AEMO.

[27] Information regarding Tepko was provided to AEMO by ElectraNet.

[28] "Preliminary Assessment of the Value of a New 275kV Transmission Line to Connect Geothermal Resources to the NEM in South Australia", MMA, 1 Sept 2009, for Australian Geothermal Association.

renewable generation injection into South Australia is likely to cause significant additional congestion under these conditions, dependent on future plant retirements in the region. There may be net market benefits for increasing the capacity of interconnection between South Australia and Victoria, which would improve reserve sharing between the regions and facilitate increased Victorian access to renewable generation sources.

3. Transmission Development Options

3.1. Overview of Transmission Development Options

For the purpose of this case study, six different transmission development options were investigated, three based on AC transmission and three based on HVDC transmission. Table 1 in Appendix 1 summarizes the transmission development options and their respective cumulative capital costs. The capital costs are made up from the ‘building blocks’ given in Table 2A for the AC transmission options and Table 2B for the HVDC transmission options.

1. AC INN-ADL-MEL-SYD (AC transmission from Innamincka to Adelaide, Melbourne, and Sydney)
2. AC INN-MEL-SYD (AC transmission from Innamincka to Melbourne and Sydney)
3. AC INN-WSD-SYD (AC transmission from Innamincka to Western Downs and Sydney)
4. HVDC INN-ADL-MEL-SYD (HVDC transmission from Innamincka to Adelaide, Melbourne, and Sydney)
5. HVDC INN-MEL-SYD (HVDC transmission from Innamincka to Melbourne and Sydney)
6. HVDC INN-WSD-SYD (HVDC transmission from Innamincka to Western Downs and Sydney)

While this report provides indicative estimates of capital costs, no economic justification has been carried out for these options. It is possible that a mixed AC and HVDC transmission option could be more beneficial than an all AC or all DC solution as proposed here. For example AC transmission to Adelaide and Melbourne would facilitate the connection of generation and demand along the route, whilst HVDC transmission to Western Downs or Sydney would be the preferred lower cost option if there are no future connections anticipated along the route.

3.2. Load Flow Analysis

The steady state feasibility of each stage of each option was demonstrated through load flow analysis to check operation in the intact N system and for N-1 contingencies on the Innamincka transmission connection. (Note that the AC and HVDC connections to Western Downs were not specifically studied in the load flow analysis as they are similar to the connections to Melbourne, and were assumed to have similar load flow characteristics).

The scope of this study did not include load flow analysis of contingencies and congestion in the existing shared network. Discussion with TNSP's suggested that injection of Innamincka generation into the shared grid is likely to materially increase network congestion, although the selected connection points were attractive in terms of minimizing this congestion and the need for deep network augmentation.

The load flow analysis confirmed that circuits were operating within thermal capacity and that bus voltages remained within acceptable limits. In addition a rudimentary stability assessment was made by checking that the N-1 voltage angles across the AC transmission connections were limited to about 30 deg (corresponding to the 'stable transmission capacity').

All of the transmission options will require more detailed load flow and stability analysis to confirm the feasibility of each solution. A subsynchronous resonance analysis will also be required due to the heavy series capacitor compensation on AC lines, or large HVDC converters, connecting to areas with large thermal generators.

3.3. AC to Adelaide, Melbourne, and Sydney

Figure 1 in Appendix 1 shows the staged AC development option connecting Innamincka generation to Adelaide, Melbourne, and Sydney. Technical details and indicative costs for the building blocks of each stage are provided in Table 2A.

3.3.1. Stage 1 AC INN-ADL-MEL-SYD

In Stage 1 the 500MW generation at Innamincka is connected to Adelaide at Tepko with a 500kV double circuit line, via an intermediate switching station at Broken Hill.

If a 500kV circuit is tripped as a credible contingency then the stable transmission capacity of the remaining connection is about 500MW, therefore the loss of power is zero and within the assumed 260MW N-1 credible contingency limit for South Australia. The power loss associated with the multiple contingency tripping of both 500kV circuits is 500MW and is within the assumed 560MW limit.

Note in Table 2A that the line from Innamincka to Broken Hill is strung with a heavy conductor (4 x Phosphorous) providing a thermal capacity that is significantly higher than the stable capacity. This design reduces the line resistance in anticipation of the need to reduce losses in the Stage 2 high capacity connection to Melbourne. The line from Broken Hill to Adelaide is strung with a lighter conductor (4 x Krypton) because it is assumed that this line will typically carry less power and have less losses.

3.3.2. Stage 2 AC INN-ADL-MEL-SYD

In Stage 2 a 500kV double circuit line connects Broken Hill to the 500kV network near Melbourne at Moorabool. The Innamincka-Broken Hill-Melbourne line is 70% series compensated and bussed at 4 intermediate switching stations (including Broken Hill) to provide N-1 stability.

If a 500kV circuit is tripped as a credible contingency then the stable transmission capacity of the remaining connection is about 2000MW. Therefore, assuming all of Stage 1 and Stage 2 Innamincka generation (2000MW) is being transferred across these circuits, the loss of power is zero and within the assumed 600MW N-1 credible contingency limit for Victoria. The power loss associated with the multiple contingency tripping of both 500kV circuits is 2000MW and is within the assumed 2100MW limit.

The line from Broken Hill to Melbourne is strung with a heavy conductor (4 x Phosphorous), the same as the line from Innamincka to Broken Hill so as to limit losses and handle a potential transfer of 2000MW.

3.3.3. Stage 3 AC INN-ADL-MEL-SYD

In Stage 3 a 765kV double circuit line is capable of transmitting all 3000MW from Stage 3 Innamincka generation to the 500kV network near Sydney at Mt Piper. The 765kV transmission voltage was selected because the Stage 2 500kV connection to Melbourne suggested that stability was barely achievable for a 2000MW transfer over a similar distance. (It is possible that detailed investigation could show that a transmission connection at 500 kV might be achievable under some 500 kV network configurations in New South Wales.)

The 765kV line is strung with a 6 x Nitrogen conductor bundle to reduce the effects of corona (compared with the quad bundles used for 500kV lines). It is possible that 4 conductor bundles could be used in sparsely populated areas which can tolerate higher levels of audible noise and radio interference.

The line is 70% series compensated and bussed at 3 intermediate switching stations to provide N-1 stability. The Stage 3 Innamincka generation supplying Sydney is isolated from the generation supplying Adelaide and Melbourne. This provides for improved control of power flow on the three connections from Innamincka to the major load centres. [29].

If a 765kV circuit is tripped as a credible contingency then the stable transmission capacity of the remaining connection is about 3000MW. Therefore the loss of power is zero and within the assumed 700MW N-1 credible contingency limit for New South Wales. The power loss associated with the multiple contingency tripping of both 765kV circuits is 3000MW and is within the assumed 3400MW limit.

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[29] Connecting the generation buses at Innamincka is likely to improve system stability, however power flows on each of the three connections may be difficult to control and fault levels may be an issue. Phase shifting transformers may be considered for power flow control if it was necessary to connect all generation at Innamincka and power flow control was problematic. Note that connection of all generation at Innamincka would form an interconnection between South Australia, Victoria, and New South Wales, which may be beneficial.

3.4. AC to Melbourne and Sydney

Figure 2 in Appendix 1 shows the staged development option connecting Innamincka generation to Melbourne and Sydney. In this development option there is no connection to Adelaide. Technical details and indicative costs for the building blocks of each stage are provided in Table 2A.

3.4.1. Stage 1 AC INN-MEL-SYD

In this development option a 500kV double circuit line connects Innamincka to the 500kV network at Moorabool near Melbourne via Broken Hill. In Stage 1 only one 500kV circuit is strung, the cost of the second circuit being deferred to Stage 2. The line is strung with a 4 x Phosphorous conductor bundle which provides sufficient thermal capacity to handle the anticipated power flow and reduce losses in Stage 2.

The stable transmission capacity of the single circuit is about 500MW, which is able to support Stage 1 Innamincka generation.

If a the single 500kV circuit is tripped as a credible contingency then Innamincka will be disconnected from the shared grid and the loss of power will be 500MW, which is within the assumed 600MW N-1 credible contingency limit for Victoria. There is no applicable multiple contingency event.

3.4.2. Stage 2 AC INN-MEL-SYD

In Stage 2 the second 500kV circuit is strung and the line is 70% series compensated and bussed at 4 intermediate switching stations (including Broken Hill) to provide N-1 stability.

If a 500kV circuit is tripped as a credible contingency then the stable transmission capacity of the remaining connection is about 2000MW, therefore the loss of power is zero and within the assumed 600MW N-1 credible contingency limit for Victoria. The power loss associated with the multiple contingency tripping of both 500kV circuits is 2000MW and is within the assumed 2100MW limit.

3.4.3. Stage 3 AC INN-MEL-SYD

Similarly to the other AC development options, in Stage 3 a 765kV double circuit line transmits 3000MW from Innamincka to the 500kV network near Sydney at Mt Piper.

3.5. AC to Western Downs and Sydney

Figure 3 in Appendix 1 shows the staged development option connecting Innamincka generation to Western Downs and Sydney. This study assumes that Powerlink's planned 500kV network at Western Downs is in place and that the system has sufficient electrical strength to support the remote connection from Innamincka. Connections to Western Downs were assumed to have similar characteristics as connections to Melbourne and were not studied explicitly in load flow.

Technical details and indicative costs for the building blocks of each stage are provided in Table 2A.

3.5.1. Stage 1 AC INN-WSD-SYD

In this development option a 500kV double circuit line connects Innamincka to the future 500kV network planned at Western Downs. In Stage 1 only one 500kV circuit is strung, the cost of the second circuit being deferred to Stage 2. The line is strung with a 4 x Phosphorous conductor bundle which provides sufficient thermal capacity to handle the anticipated power flow and reduce losses in Stage 2.

The stable transmission capacity of the single circuit is about 500MW, which is able to support Stage 1 Innamincka generation.

If a the single 500kV circuit is tripped as a credible contingency then Innamincka will be disconnected from the shared grid and the loss of power will be 500MW, which is within the assumed 750MW N-1 credible contingency limit for Queensland. There is no applicable multiple contingency event.

3.5.2. Stage 2 AC INN-WSD-SYD

In Stage 2 the second 500kV circuit is strung and the line is 70% series compensated and bussed at 3 intermediate switching stations to provide N-1 stability.

If a 500kV circuit is tripped as a credible contingency then the stable transmission capacity of the remaining connection is about 2000MW, therefore the loss of power is zero and within the assumed 750MW N-1 credible contingency limit for Queensland. The power loss associated with the multiple contingency tripping of both 500kV circuits is 2000MW and is within the assumed 2500MW limit.

3.5.3. Stage 3 AC INN-WSD-SYD

Similarly to the other AC development options, in Stage 3 a 765kV double circuit line transmits 3000MW from Innamincka to the 500kV network near Sydney at Mt Piper.

3.6. HVDC to Adelaide, Melbourne, and Sydney

Figure 4 in Appendix 1 shows the staged HVDC development option connecting Innamincka generation to Adelaide, Melbourne, and Sydney. Technical details and indicative costs for the building blocks of each stage are provided in Table 2B.

This all HVDC option is expected to improve system stability and power flow control as these are inherent characteristics of HVDC transmission.

3.6.1. Stage 1 HVDC INN-ADL-MEL-SYD

In Stage 1 the 500MW generation at Innamincka is connected to Adelaide at Tepko with a +/-500kV 500MW HVDC bipole. Each pole is rated at 250MW with an overload of 300MW. Each pole is strung with 4 x Krypton conductor in order to reduce losses (which also results in a thermal capacity of 920MW, well in excess of the required thermal capacity).

The overload capability limits the loss of power associated with a credible contingency pole trip to 200MW which is within the assumed 260MW limit for South Australia. The loss of power associated with a multiple contingency bipole trip is 500MW and is within the assumed 560MW limit.

3.6.2. Stage 2 HVDC INN-ADL-MEL-SYD

In Stage 2 a +/-500kV 2400MW HVDC bipole connects Innamincka to Melbourne at Moorabool. Each pole is rated at 1200MW with an overload of 1500MW. Each pole is strung with 4 x Sulphur conductor in order to reduce losses (which also results in a thermal capacity of 2250MW, well in excess of the required thermal capacity).

If the power transfer to Melbourne is 1500MW (with 500MW also going to Adelaide) then the overload capability limits the loss of power associated with a credible contingency pole trip to zero. If all Stage 1 and Stage 2 Innamincka generation is being transferred to Melbourne (2000MW) then the power loss associated with a pole trip is 500MW, which is within the assumed 600MW credible contingency limit for Victoria. The bipole transfer may be limited to 2100MW [30] which is the assumed multiple contingency limit for Victoria.

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[30] Under light load conditions.

3.6.3. Stage 3 HVDC INN-ADL-MEL-SYD

In Stage 3 a +/-800kV 4000MW HVDC bipole connects Innamincka to Sydney at Mt Piper. Each pole is rated at 2000MW with an overload of 2500MW.

The +/-800kV line is strung with a 6 x Nitrogen conductor bundle to reduce the effects of corona (compared with the quad bundles used for +/-500kV lines).

If the power transfer to Sydney is 3000MW (with 2000MW also going to Adelaide and Melbourne) then the overload capability limits the loss of power associated with a credible contingency pole trip to 500MW, which is within the assumed 700MW limit for New South Wales. The loss of power associated with a multiple contingency bipole trip is 3000MW, within the assumed 3400MW limit for New South Wales.

3.7. HVDC to Melbourne and Sydney

Figure 5 in Appendix 1 shows the staged HVDC development option connecting Innamincka generation to Melbourne and Sydney. In this development option there is no connection to Adelaide. Technical details and indicative costs for the building blocks of each stage are provided in Table 2B.

3.7.1. Stage 1 HVDC INN- MEL-SYD

In this development option Stage 1 consists of a -500kV HVDC monopole line connecting Innamincka to the 500kV network at Moorabool near Melbourne. The cost of the second pole is deferred to Stage 2. The monopole is rated at 600MW with an overload of 750MW. This rating is in anticipation of further generation expansion at Innamincka. The pole is strung with 4 x Sulphur conductor in anticipation of the need to reduce losses in Stage 2.

The loss of power associated with a single credible contingency pole trip is all of Stage 1 Innamincka generation at 500MW, which is within the assumed 600MW limit for Victoria. There is no applicable multiple contingency event.

3.7.2. Stage 2 HVDC INN- MEL-SYD

In Stage 2 a second 600MW half-pole is added in parallel with the Stage 1 600MW half-pole. Also a 1200MW pole is added and the second pole is strung to complete the 2400MW bipole. Each pole is rated at 1200MW with an overload of 1500MW.

The overload capability limits the loss of power associated with a credible contingency pole trip to 500MW, within the assumed 600MW credible contingency limit for Victoria. The bipole transfer of 2000MW is within the assumed 2100MW multiple contingency limit for Victoria.

3.7.3. Stage 3 HVDC INN-MEL-SYD

Similarly to the other HVDC development options, in Stage 3 a +/-800kV 4000MW HVDC bipole connects Innamincka to Sydney at Mt Piper.

3.8. HVDC to Western Downs and Sydney

Figure 6 in Appendix 1 shows the staged HVDC development option connecting Innamincka generation to Western Downs and Sydney. This study assumes that Powerlink's planned 500kV network at Western Downs is in place and that the system has sufficient electrical strength to support the remote connection from Innamincka. Connections to Western Downs were assumed to have similar characteristics as connections to Melbourne and were not studied explicitly in load flow.

Technical details and indicative costs for the building blocks of each stage are provided in Table 2B.

3.8.1. Stage 1 HVDC INN-WSD-SYD

In this development option Stage 1 consists of a -500kV HVDC monopole line connecting Innamincka to the future 500kV network planned at Western Downs. The cost of the second pole is deferred to Stage 2. The monopole is rated at 600MW with an overload of 750MW. This rating is in anticipation of further generation expansion at Innamincka. The pole is strung with 4 x Sulphur conductor in anticipation of the need to reduce losses in Stage 2.

The loss of power associated with a single credible contingency pole trip is all of Stage 1 Innamincka generation at 500MW, which is within the assumed 750MW limit for Queensland. There is no applicable multiple contingency event.

3.8.2. Stage 2 HVDC INN-WSD-SYD

In Stage 2 a second 600MW half-pole is added in parallel with the Stage 1 600MW half-pole. Also a 1200MW pole is added and the second pole is strung to complete the 2400MW bipole. Each pole is rated at 1200MW with an overload of 1500MW.

The overload capability limits the loss of power associated with a credible contingency pole trip to 500MW, within the assumed 750MW credible contingency limit for Queensland. The bipole transfer of 2000MW is within the assumed 2500MW multiple contingency limit for Queensland.

3.8.3. Stage 3 HVDC INN- WSD-SYD

Similarly to the other HVDC development options, in Stage 3 a +/-800kV 4000MW HVDC bipole connects Innamincka to Sydney at Mt Piper.

Appendix 1. Tables and Figures for Transmission Development Options

Table 1. Transmission Development Options and Indicative Cumulative Capital Costs

Innamincka Generation	**Option 1** **AC** **INN-ADL-MEL-SYD**	**Option 2** **AC** **INN-MEL-SYD**	**Option 3** **AC** **INN-WSD-SYD**	**Option 4** **HVDC** **INN-ADL-MEL-SYD**	**Option 5** **HVDC** **INN-MEL-SYD**	**Option 6** **HVDC** **INN-WSD-SYD**
Stage 1 **500MW**	950km 500kV double circuit line to Adelaide via Broken Hill switching station	1250km 500kV double circuit line (strung one circuit) to Melbourne	1000km 500kV double circuit line (strung one circuit) to Western Downs	850km 500MW, +/- 500kV bipole to Adelaide	1250km 600MW, -500 kV monopole to Melbourne	1000km 600MW, -500 kV monopole to Western Downs
	Building Block A+B	Building Block E	Building Block G	Building Block J	Building Block K	Building Block M
	A$0.9 – 1.4 Billion	A$1.0 – 1.5 Billion	A$0.8 – 1.2 Billion	A$0.3 – 0.5 Billion	A$0.7 – 1.0 Billion	A$0.6 – 0.9 Billion
Stage 2 **2000MW**	Extend 500kV double circuit line 750km from Broken Hill switching station to Melbourne plus series compensation	Upgrade by stringing 2nd 500kV circuit plus series compensation	Upgrade by stringing 2nd 500kV circuit plus series compensation	1250km 2400MW +/- 500kV bipole to Melbourne	Upgrade by adding 600MW -500kV half pole in parallel and 1200MW +500kV pole (making a 2400MW bipole)	Upgrade by adding 600MW -500kV half pole in parallel and 1200MW +500kV pole (making a 2400MW bipole)
	Building Block B+C+D	Building Block F	Building Block H	Building Block J+L	Building Block L	Building Block N
	A$2.1 – 3.2 Billion	A$1.7 – 2.7 Billion	A$1.4 – 2.2 Billion	A$1.5 – 2.2 Billion	A$1.2 – 1.7 Billion	A$1.0 – 1.5 Billion
Stage 3 **5000MW**	1100km 765kV double circuit line to Sydney with series compensation.	1100km 765kV double circuit line to Sydney with series compensation.	1100km 765kV double circuit line to Sydney with series compensation.	1100km 4000MW, +/- 800kV bipole to Sydney	1100km 4000 MW, +/- 800 kV bipole to Sydney	1100km 4000 MW, +/- 800 kV bipole to Sydney
	Building Block B+C+D+I	Building Block F+I	Building Block H+I	Building Block J+L+O	Building Block L+O	Building Block N+O
	A$3.9 – 6.1 Billion	A$3.6 – 5.6 Billion	A$3.3 – 5.1 Billion	A$2.8 – 4.0 Billion	A$2.5 – 3.5 Billion	A$2.3 – 3.3 Billion

Note : ‘Building Blocks’ for indicative costs are taken from Table 2A and Table 2B

Table 2A. Indicative AC Transmission Costs – Building Blocks

Building Block	**A**		**B**		**C**		**D**		**E**		**F**	
Description (DC = Double Circuit)	New DC line build		New DC line build		Block A plus series comp		New DC line build with series comp		New DC line build ½ strung		Block E plus 2nd circuit and series compensation	
Stage	1		1		2		2		1		2	
From	Innamincka		Broken Hill		Innamincka		Broken Hill		Innamincka		Innamincka	
To	Broken Hill		Adelaide		Broken Hill		Melbourne		Melbourne		Melbourne	
Line length (km)	500		450		500		750		1250		1250	
Voltage (kV)	500		500		500		500		500		500	
Number of circuits	2		2		2		2		1/2 strung		2	
Easement width (m)	70		70		70		70		70		70	
Conductor (AAAC)	Phosphorous		Krypton		Phosphorous		Phosphorous		Phosphorous		Phosphorous	
Sub-conductors per bundle	4		4		4		4		4		4	
Thermal capacity per cct (MVA)	2900		1600		2900		2900		2900		2900	
Stable capacity per cct (MW)	500		500		2000		2000		500		2000	
Normal load per cct (MW)	250		250		1000		750		500		1000	
Shunt reactors per cct (MVAR)	480		360		480		720		1200		1200	
Series comp (%)	-		-		70		70		-		70	
Series comp per circuit (MVAR)	-		-		1500		2300		-		3800	
Intermediate stations	-		-		1		2		-		4	
From terminal transformers (MVA)	2x1000		-		3x1000		-		1x1000		3x1000	
To terminal transformers (MVA)	-		2x500		-		-		-		-	
Typical losses (%)	1.0		2.0		3.4		4.8		4.8		9.6	
Capital costs	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Line cost (A$M/km)	1.0	1.4	0.5	0.7	1.0	1.4	1.0	1.4	0.7	1.1	1.0	1.4
Line cost (A$M)	480	720	220	340	480	720	720	1100	900	1300	1200	1800
Easement cost (A$M)	1	3	10	31	1	3	11	33	12	36	12	36
Shunt reactor cost (A$M)	34	51	25	38	34	51	51	76	42	63	84	126
Series compensation cost (A$M)	0	0	0	0	110	180	160	270	0	0	270	450
Intermediate station cost (A$M)	0	0	0	0	14	20	27	40	0	0	54	80
From terminal cost (A$M)	82	120	0	0	100	150	0	0	39	58	100	150
To terminal cost (A$M)	14	20	49	74	20	30	14	20	9	13	14	20
Total capital cost (A$M)	611	914	304	483	759	1154	983	1539	1002	1470	1734	2662

Table 2A. Indicative AC Transmission Costs – Building Blocks (cont.)

Building Block	**G**		**H**		**I**	
Description (DC = Double Circuit)	New DC line build ½ strung		Block G plus 2nd circuit and series compensation		New DC line build plus series compensation	
Stage	1		2		3	
From	Innamincka		Innamincka		Innamincka	
To	W. Downs		W. Downs		Sydney	
Line length (km)	1000		1000		1100	
Voltage (kV)	500		500		765	
Number of circuits	1/2 strung		2		2	
Easement width (m)	70		70		110	
Conductor (AAAC)	Phosphorous		Phosphorous		Nitrogen	
Sub-conductors per bundle	4		4		6	
Thermal capacity per cct (MVA)	2900		2900		5000	
Stable capacity per cct (MW)	500		2000		3000	
Normal load per cct (MW)	500		1000		1500	
Shunt reactors per cct (MVAR)	960		960		2800	
Series comp (%)	-		70		70	
Series comp per circuit (MVAR)	-		3000		3200	
Intermediate stations	-		3		3	
From terminal transformers (MVA)	1x1000		3x1000		3x1500	
To terminal transformers (MVA)	-		-		3x1500	
Typical losses (%)	3.8		7.7		5.3	
Capital costs	Low	High	Low	High	Low	High
Line cost (A$M/km)	0.7	1.1	1.0	1.4	1.1	1.6
Line cost (A$M)	720	1080	960	1440	1200	1800
Easement cost (A$M)	12	35	12	35	18	55
Shunt reactor cost (A$M)	34	51	67	101	109	163
Series compensation cost (A$M)	0	0	220	360	230	390
Intermediate station cost (A$M)	0	0	41	60	49	73
From terminal cost (A$M)	39	58	100	150	140	210
To terminal cost (A$M)	9	13	14	20	140	220
Total capital cost (A$M)	814	1237	1414	2166	1886	2911

Table 2B. Indicative HVDC Transmission Costs – Building Blocks

Building Block	**J**		**K**		**L**		**M**		**N**		**O**	
Description (BP = Bipole)	New BP line build		New BP line build ½ strung		New BP line build OR Add second pole to Block K		New BP line build ½ strung		New BP line build OR Add second pole to Block M		New BP line build	
Stage	1		1		2		1		2		3	
From	Innamincka		Innamincka		Innamincka		Innamincka		Innamincka		Innamincka	
To	Adelaide		Melbourne		Melbourne		W. Downs		W. Downs		Sydney	
Line length (km)	850		1250		1250		1000		1000		1100	
Pole voltage (kV)	+/-500		-500		+/-500		-500		+/-500		+/-800	
Number of poles	2		1/2 strung		2		1/2 strung		2		2	
Easement width (m)	50		50		50		50		50		80	
Conductor (AAAC)	Krypton		Sulphur		Sulphur		Sulphur		Sulphur		Nitrogen	
Sub-conductors per bundle	4		4		4		4		4		6	
Rated pole power (MW)	250		600		1200		600		1200		2000	
Overload pole power (MW)	300		750		1500		750		1500		2500	
Normal load per pole (MW)	250		500		1000		500		1000		1500	
Current rating of pole conductor (kA)	1.84		4.504		4.504		4.504		4.504		3.78	
Losses at normal load (%)	6.2		4.4		7.9		3.7		6.5		6.7	
Capital costs	Low	High	Low	High	Low	High	Low	High	Low	High	Low	High
Line cost (A$M/km)	0.19	0.28	0.39	0.58	0.52	0.78	0.39	0.58	0.52	0.78	0.41	0.61
Line cost (A$M)	160	240	480	730	650	970	390	580	520	780	450	670
Easement cost (A$M)	8	24	9	26	9	26	8	25	8	25	13	40
From terminal cost (A$M)	85	120	97	140	250	340	97	140	250	340	420	570
To terminal cost (A$M)	85	120	97	140	250	340	97	140	250	340	420	570
Total capital cost (A$M)	338	504	683	1036	1159	1676	592	885	1028	1485	1303	1850

Figure 1. AC to Adelaide, Melbourne, and Sydney

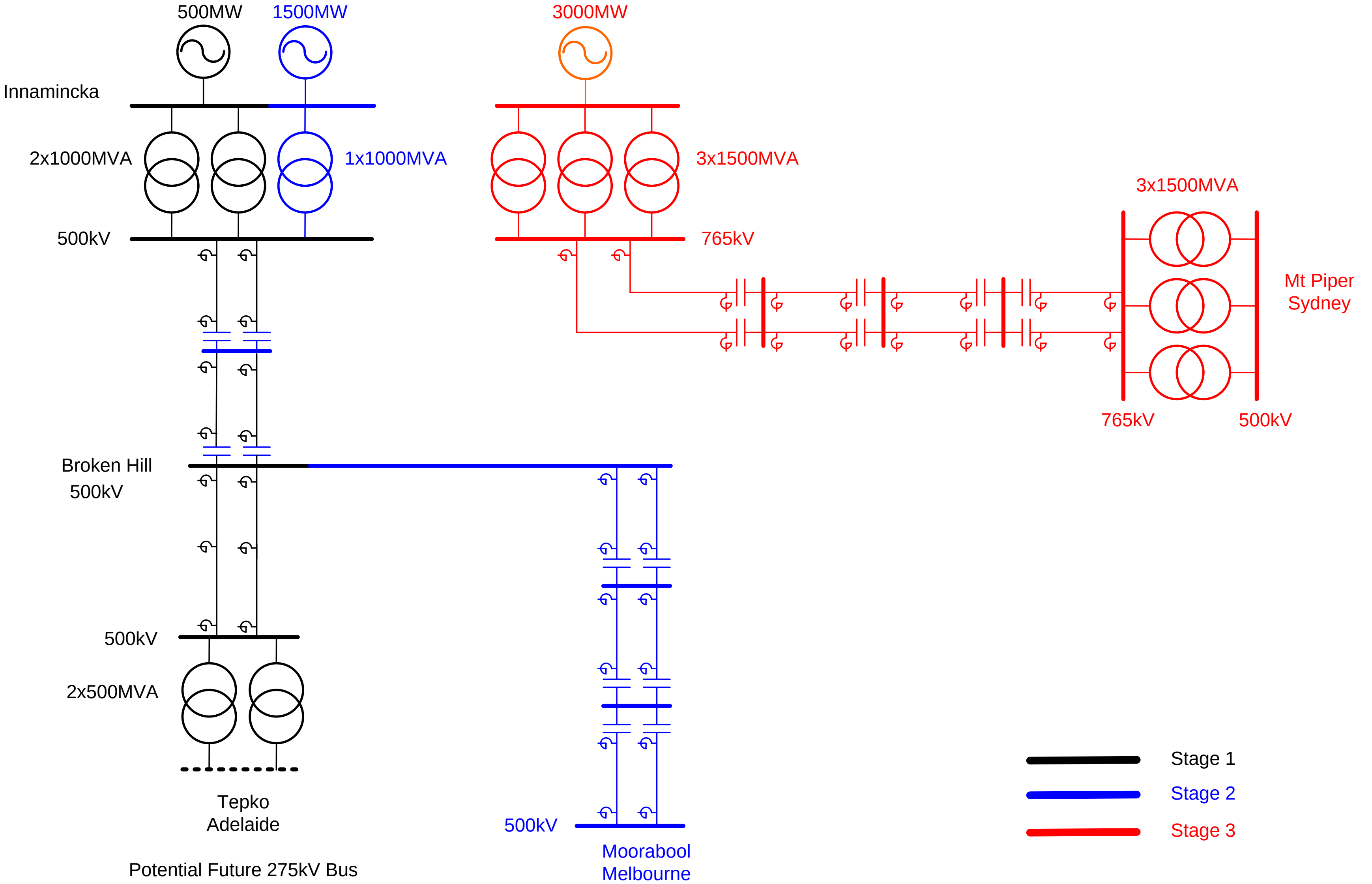

Figure 2. AC to Melbourne and Sydney

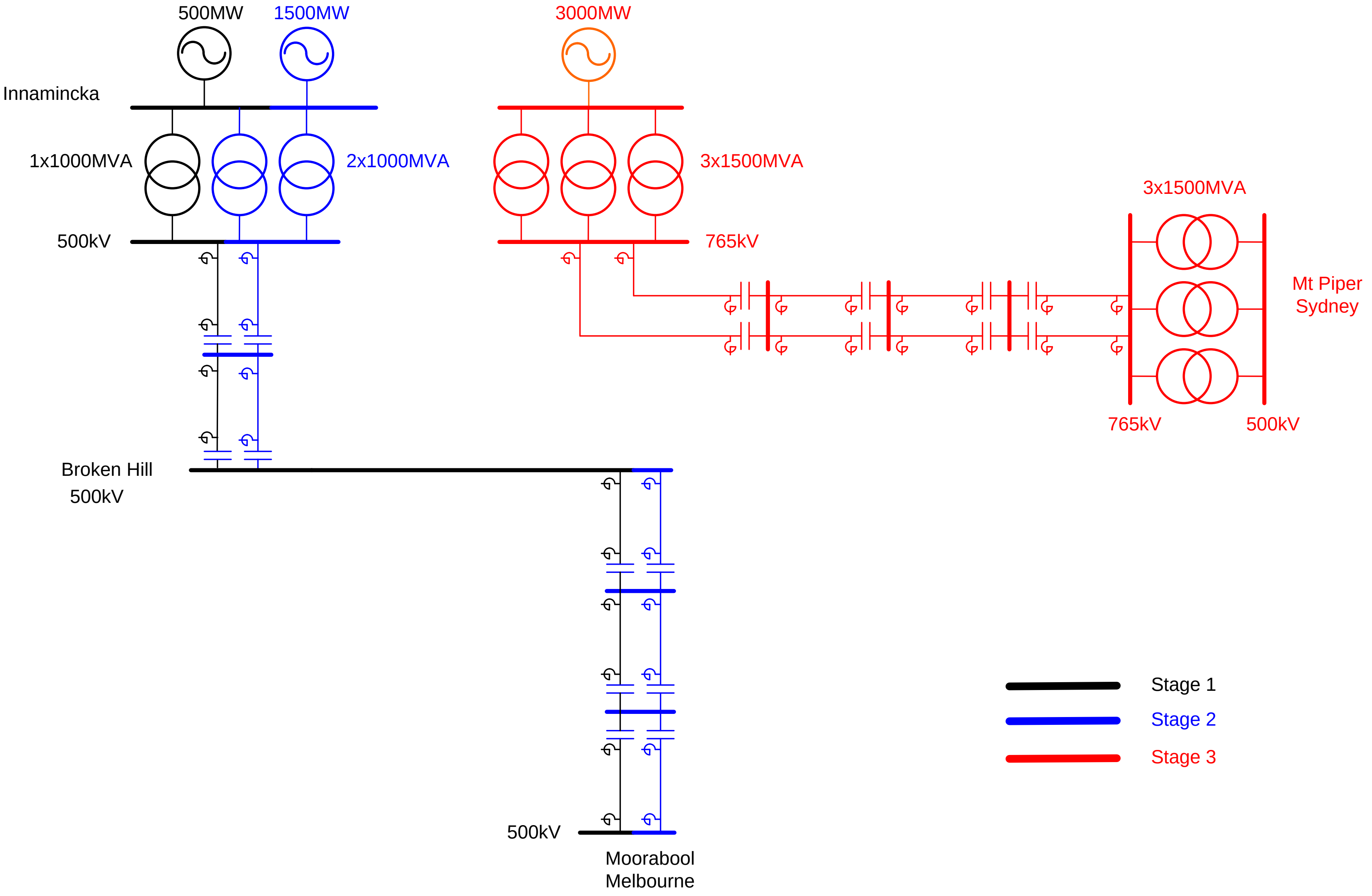

Figure 3. AC to Western Downs and Sydney

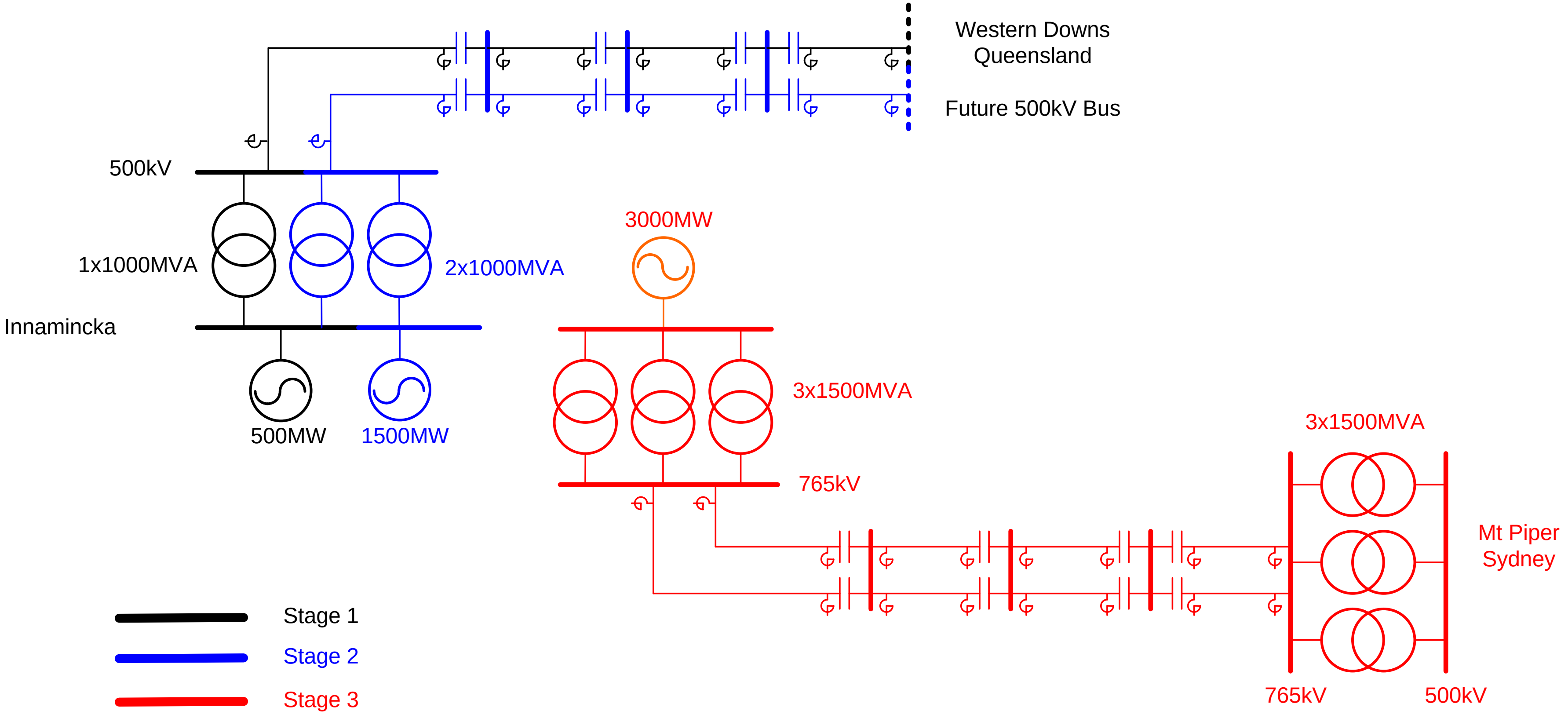

Figure 4. HVDC to Adelaide, Melbourne, and Sydney

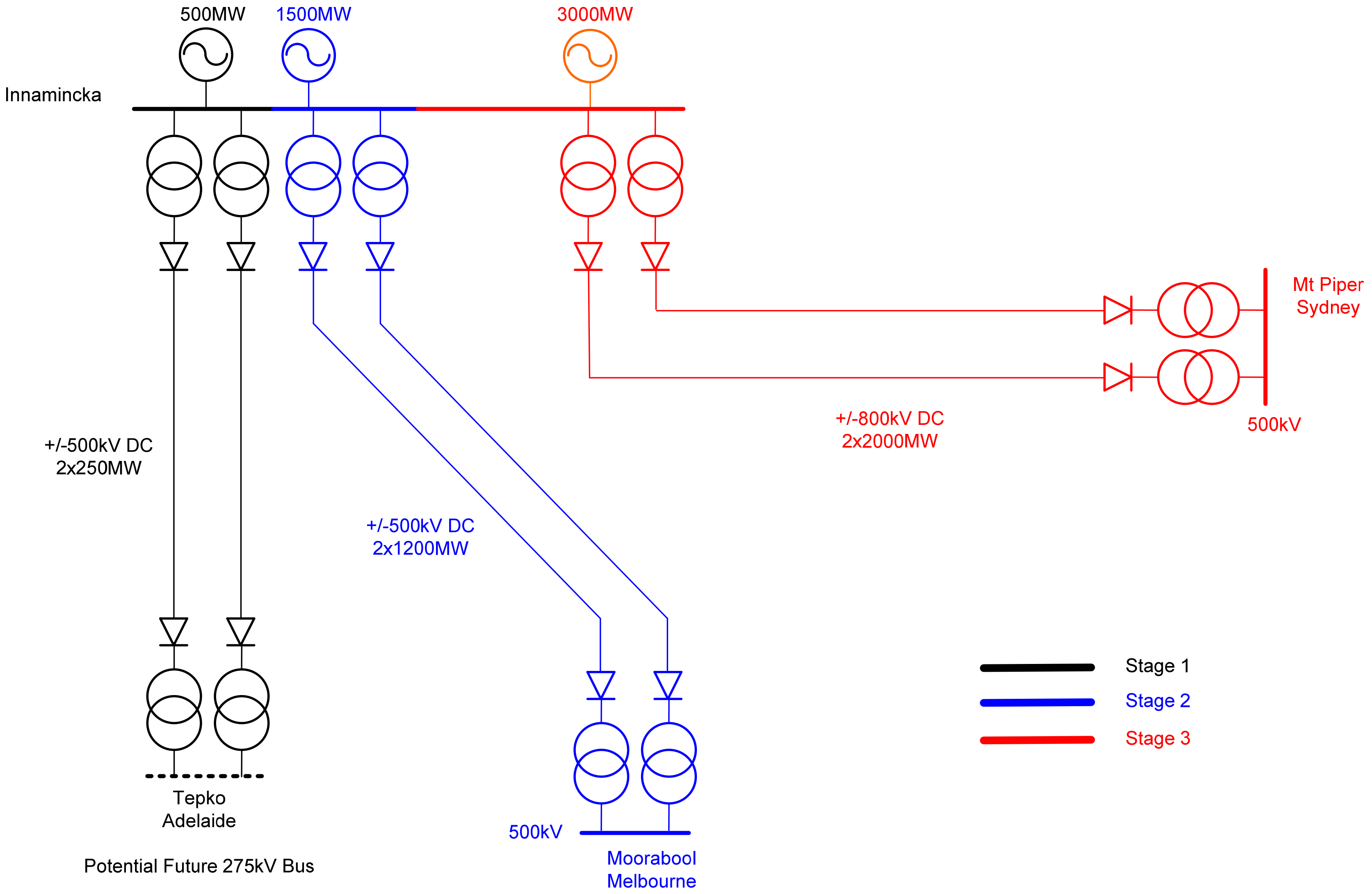

Figure 5. HVDC to Melbourne and Sydney

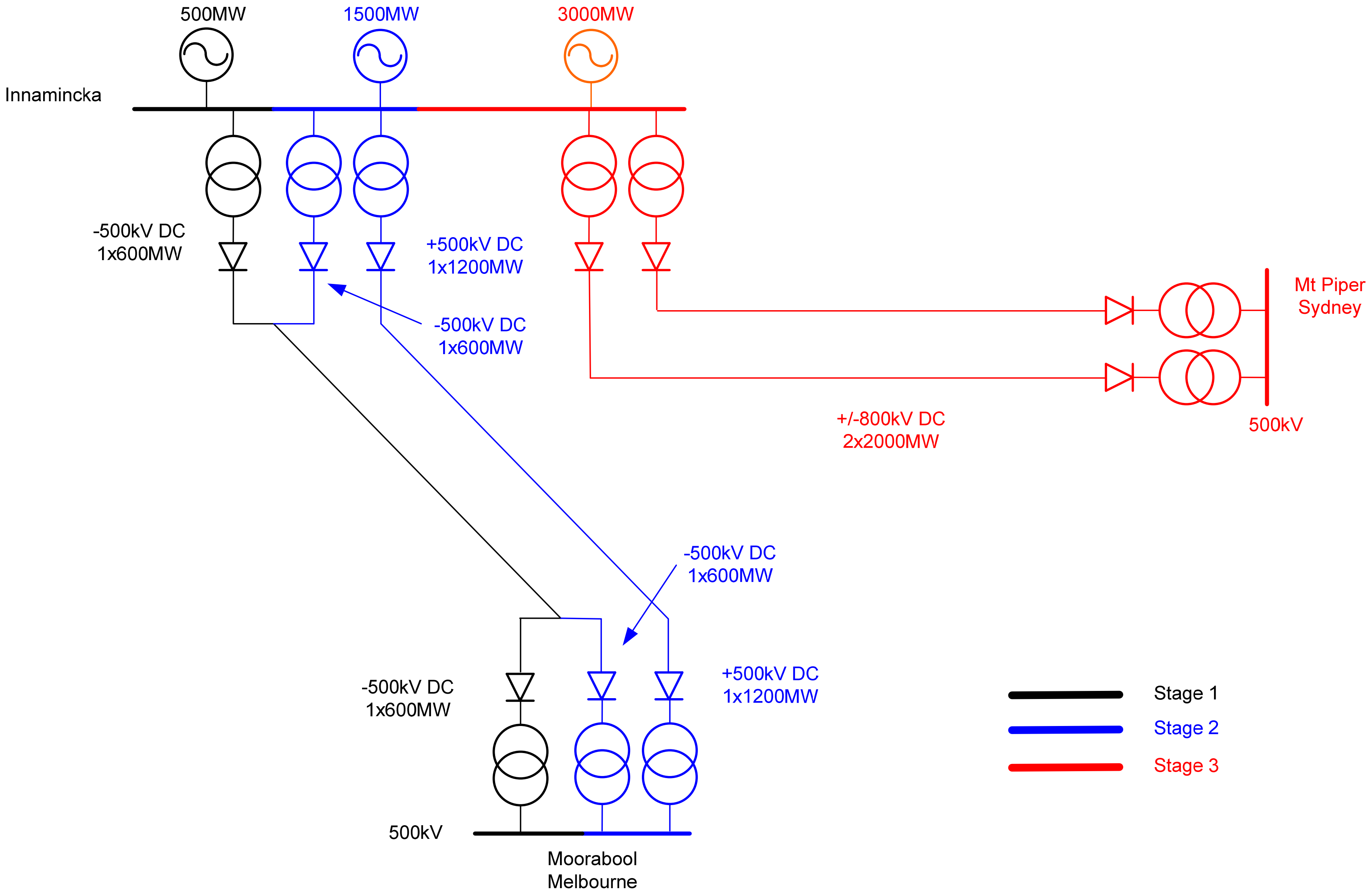

Figure 6. HVDC to Western Downs and Sydney