E.S. Cornwall Memorial Scholarship
Final Report

Enhancing the Role of the National Planner

With experience from the California ISO, Electranix and Siemens AG

March 2020

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

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1.0 Executive summary

This report provides an overview of my completed work, lessons learned, and impressions made during my 18 months at the California ISO, Electranix and Siemens AG as part of the E.S Cornwall Memorial Scholarship (Scholarship). In addition, this report will meet the requirements of a quarterly report for my last three months at Siemens AG. The underlying theme of my Scholarship is to identify ways the national transmission planning role can be enhanced. With a focus on my own development, I gained international transmission planning experience, I have a holistic perspective of the application of High Voltage Direct Current (HVDC) transmission solutions and I acquired the necessary skills to conduct studies in weak systems with increasing penetrations from asynchronous sources.

Transmission planning in California and the western North American grid

I began my Scholarship time with six months at the California ISO where I consulted on the Transmission Planning Process (TPP), with most of my time focused on the TPP Reliability Assessment and the Pacific Northwest Informational Special Study. Other areas of learning included an assessment on the integration of large-scale solar generation and a distributed energy resource impact study as part of the Western Electricity Coordinating Council (WECC) Modelling and Validation Work Group (MVWG). See my first and second quarterly reports[1,2] which details my impressions gained and the details of my consultation. My impressions gained are outlined below.

[1] July to September 2018, Christopher du Plessis, October 2018. Available here: http://www.escornwall.com.au/wp-content/uploads/sites/43/2018/11/Q1-report-christopher-duplessis.pdf

[2] October to December 2018, Christopher du Plessis, December 2018. Available here: http://www.escornwall.com.au/wp-content/uploads/sites/43/2019/04/Q2-report-christopher-duplessis.pdf

Impressions

1. **Reliability Assessment: Expanding the scope of contingencies in planning studies improves power system security and transmission network utilisation without significantly increasing cost to consumers.**

The inclusion of non-credible contingencies in transmission planning studies, as is done in North America, will enhance the foresight of the national planner. In addition, the utilisation of the existing transmission network is improved through implementation of non-network options, such as special protection schemes.

AEMO's Power System Frequency Risk Review (PSFRR) provides a platform for studying non-credible events which directly impact frequency. Considering non-credible contingencies which indirectly impact frequency can enhance the foresight of the national transmission planner and improve utilisation of existing network.

2. **Pacific Northwest Informational Special Study: Secure operation of a power system with declining thermal generation will require careful and thorough modelling of interdependencies.**

In order to achieve the ambitious policy goals set in California, it is necessary to understand the capability of neighbouring systems and associated interdependences. California will increasingly require support from neighbouring systems as local base load nuclear and peaking gas retire. An example is the reliance on hydro generation in the Pacific Northwest to support supply adequacy and flexibility requirements in California.

Parallels can be drawn to Hydro Tasmania's Battery of the Nation project, in Australia. The goal of this project is to further interconnect Tasmania, through undersea cables, to mainland Australia and expand the pumped hydro capability in Tasmania to support renewable development in the NEM. Adequate technical and economic analysis is essential to ensure efficient investment.

Working with stakeholders across the power system to better understand interdependencies can enhance the outcomes of modelling conducted by the national transmission planner.

Renewable integration and detailed power system studies

I joined Electranix in Winnipeg, Canada, for six months to work on power system benchmarking studies. I worked on three major dynamic performance benchmarking studies for large inverter connected generation in North America. This report includes an outline of my six-step study methodology for benchmarking PSS/E and PSCAD results which was applied to each of these studies. During this time, I gained experience modelling different power system elements including solar farms, wind farms, High Voltage Direct Current (HVDC) converters, synchronous machines and voltage support elements. In addition, I was able to further develop my PSS/E, PSCAD, E-TRAN, Python and technical communication skills. Note that I have since re-joined the Electranix team, outside of my Scholarship tenure, to continue my development in this area before re-joining AEMO in August 2020. See my Third and fourth quarterly reports[3,4] detailing my impressions gained and the details of my completed work. Through my work I gained the following impressions.

Impressions

3. **AEMO is better positioned to plan and operate a power system with higher penetrations of inverter connected generation.**

For power systems with increasing amounts inverter connected devices, it is necessary for system operators to conduct more detailed studies in order to maintain power system security. This ensures system security now and in the future. It is important for AEMO's engineers to be informed of the issues, nuances and limitations surrounding tools like PSCAD. This is necessary for effective application of the new connection standards.

4. **Increased risk in the connection process.**

The introduction of EMT modeling in the connection process has increased the risk of projects failing to progress through to full operation. Vendors must prioritise model support to reduce the risk of project failure. Publications such as the Integrated System Plan (National Transmission Network Development Plan) or regional annual transmission planning reports can assist in outlining the current and future network limitations. These publications can reduce the risk of project failure through stakeholder education.

5. **Dynamic performance studies are critical to ensure system security**

With my new skills and experience I am better prepared for the system study requirements of a national planner. It is an enhancement to AEMO's national planner role to have the experience I have gained at Electranix, to be able to share this experience with my team and to have developed profession relationships with the excellent study engineers at Electranix.

6. **There are important differences between PSCAD and PSS/E**

PSS/E and PSCAD are both valuable tools in assessing the dynamic performance of network elements. These tools have fewer limitations when used together, than when either is used on its own to run studies. It is important for study engineers to understand the differences between the tools and to be able to identify where these differences propagate in the results. Differences in response can be intrinsic and understanding this is an important enhancement to AEMO's role as the national planner.

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[3] January to March 2019, Christopher du Plessis, April 2019. Available here: http://www.escornwall.com.au/wp-content/uploads/sites/43/2019/06/q3-report-christopher-duplessis.pdf

[4] April to June 2019, Christopher du Plessis, July 2019. Available here: http://www.escornwall.com.au/wp-content/uploads/sites/43/2019/11/2019Q2_Electranix_cduplessis.pdf

HVDC solutions and integration

The remaining six months of my Scholarship time was in the HVDC Sales group at Siemens AG in Erlangen, Germany. I was embedded in the HVDC Sales team, learning about current and past HVDC solutions and refurbishments around the world. In addition, I led a project to develop a process for preparing modelling and connection information required to connect generation systems (including HVDC interconnections) in the National Electricity Market (NEM). During this time, I visited HVDC converter stations in Germany and South Africa, Siemens Nuremberg power transformer factory, Siemens Nuremberg power module factory and Siemens pilot electrolysis assembly line in Erlangen. This report provides an outline what I have learned about Siemens' HVDC technology and how Siemens will prepare modeling information for the NEM connection process. Through my work I gained the following impressions.

Impressions

7. **Contentions with model preparation for NEM connections**

Having worked through the AEMO connection requirements with colleagues at Siemens it is clear there are contentions, particularly those related to source code and detailed modeling information.

Ongoing connection projects which involve both Siemens and AEMO have provided an important learning opportunity for me in terms of how these contentions can be overcome.

8. **HVDC technology is adaptable and capable to support reliability and security**

HVDC technology is incredibly adaptable and capable of meeting a broad range of technical requirements. Simply put, every HVDC transmission solution operating today is completely unique and meet a range of different technical requirements around the world.

Customers who provide specific technical specifications (such as voltage, converter topology) must be aware that these decisions impact the economic competitiveness.

9. Stakeholders which are not market registered will benefit from access to AEMO's MAT testing code

AEMO needs to be clearer about NEM connection study requirements, perhaps releasing their Model Acceptance Testing code to stakeholders who are not only registered in the market. This allows manufacturers and solution providers to prepare model information ahead of time to limit project delays.

10. The success of HVDC solutions outside of Australia

In systems with significant power system and policy constraints, HVDC solutions can provide value. These conditions effectively partially mimic synchronous isolation in that the two systems are limited in their capability to share services.

A good example in the NEM is the mainland system and the Tasmanian system, which already has a HVDC solution with transfer capability. Emerging opportunities for HVDC solutions may include servicing large load centers such as Sydney and Melbourne with HVDC transmission from generation centers. As transmission solutions utilised to supply these centers with power become more expensive, HVDC solutions may become more competitive and capable of providing all the necessary system services required to maintain reliability and security.

With the completion of my scholarship and my return to Australia approaching, my next steps and future focus are as follows:

Next steps

- Apply my new skills, learnings and experience in my new role in AEMO's National Planning group.
- Share my experience with my colleagues inside and outside AEMO.
- Continue developing my international network.
- Promote the E.S Cornwall Memorial Scholarship in Queensland, and the rest of Australia.

2.0 Introduction

This report provides an overview of my completed work, lessons learned, and impressions made during my 18 months at the California ISO, Electranix and Siemens AG as part of the E.S Cornwall Memorial Scholarship (Scholarship). In addition, this report will meet the requirements of a quarterly report for my last three months at Siemens AG. The theme of my Scholarship will be introduced and for each of the quarterly reports already completed, this report will reference them for further reading on the work completed and the impressions gained.

3.0 Scholarship theme

In June, 2017 Dr. Alan Finkel, Australia's Chief Scientist, and an Expert Panel published the Independent Review into the Future Security of the National Electricity Market. The report recommends a way forward to ensure a secure and reliable energy future as the energy industry experiences significant change[5]. Four key outcomes were identified for the National Electricity Market (NEM): increased security, future reliability, rewarding consumers and lower emissions. These outcomes are enabled by three key pillars: Orderly Transition, System Planning and Stronger Governance.

Chapter 5 delivered five key recommendations focused on improving System Planning. The first two recommendations focus on the delivery of an Integrated Grid Plan, conducted by the Australian Energy Market Operator (AEMO), which have since been addressed or are underway. The third recommendation (recommendation 5.3) is now coming into focus and states:

> *The COAG Energy Council, in consultation with the Energy Security Board, should review ways in which the Australian Energy Market Operator's role in national transmission planning can be enhanced.*

AEMO's national transmission planner functions include review and advice on the development of the transmission grid across the NEM; provide a national strategic perspective for transmission planning and coordination; and have regard to the National Electricity Objective. The underlying theme of my Scholarship proposal is to identify ways the national transmission planning role can be enhanced.

In December 2018, the Energy Security Board (ESB) added an Integrated System Plan (ISP) Action Plan which set out twelve recommendations on short, medium- and long-term transmission augmentations. These recommendations are outlined in the ESB's consultation paper[6] staged reform to the transmission frameworks. A major long-term project considered in the 2019-20 Integrated System Plan (ISP) is the Battery of the Nation which includes the development of a new HVDC submarine interconnector ("Marinus Link") between Mainland Australia and Tasmania. This project can be designed to support the ancillary requirements for both systems while assisting to ensure system adequacy, particularly in Victoria where coal retirements are placing pressure on generation reserves.

My time at Siemens has provided me with the opportunity to learn about this technology and understand how it can further contribute to the resilience of the NEM.

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[5]Dr Alan Finkel, Ms Karen Moses, Ms Chloe Munro, Mr Terry Effeney, Professor Mary O'Kane. Independent Review into the Future Security of the National Electricity Market. 2017. Available here: https://www.energy.gov.au/sites/g/files/net3411/f/independent-review-future-nem-blueprint-for-the-future-2017.pdf

[6] Energy Security Board. Converting the Integrated System Plan into Action. May 2019. Available here: http://www.coagenergycouncil.gov.au/sites/prod.energycouncil/files/publications/documents/ESB%20-%20Converting%20the%20ISP%20into%20Action%20-%2020190517.pdf

Siemens is a world leading manufacturer of HVDC solutions and has already contributed to Australia's power system through the delivery of Basslink's two converter stations in Victoria and Tasmania. My time at Siemens has provided me with the opportunity to learn about this technology and understand how it can further contribute to the resilience of the NEM.

4.0 California ISO

This section meets the requirements of a final report by summarizing the impressions gained at California ISO and references the more detailed quarterly report which outline the work completed. I began my Scholarship time with six months at the California ISO where I consulted on the Transmission Planning Process (TPP), with most of my time focused on the TPP Reliability Assessment and the Pacific Northwest Informational Special Study. Other areas of learning included an assessment on the integration of large-scale solar generation and a distributed energy resource impact study as part of the Western Electricity Coordinating Council (WECC) Modelling and Validation Work Group (MVWG). See my first and second quarterly reports[7,8] which details my impressions gained and the details of my consultation. My impressions gained are outlined below.

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6.0 Siemens AG

Siemens is a world leading manufacturer of HVDC solutions and has already contributed to Australia's power system through the delivery of Basslink's two converter stations in Victoria and Tasmania. My time at Siemens has provided me with the opportunity to learn about this technology and understand how it can further contribute to the resilience of the NEM. This section outlines the background behind why Siemens was a good fit for my scholarship theme, the work I completed and the impressions I gained during my last three months. This section meets the requirements of a quarterly report and the final report.

6.1 Background

A secure and reliable supply of low-cost electricity is a highly desirable input into a strong, prosperous and robust economy. The changing generation mix has introduced challenges for system operators to maintain power system security and reliability.

The NEM faces unprecedented changes in supply and demand which can pose a threat to system security and reliability. Conventional synchronous machines which provide majority of the NEM's power and energy are expected to retire over the coming decades. At the same time residential demand is increasingly being met by intermittent sources which increases the reliance on flexible generation to ensure system reliability.

In 2018, AEMO published updated requirements for connecting generation systems in the NEM. These requirements outlined the necessary information needed to process a generation connection. For connecting parties, it is necessary to understand these updated requirements in order to mitigate risk of projects being delayed. In addition, transmission planning studies are being prepared in Australia to assess the feasibility of additional HVDC transfer capability between Victoria and Tasmania.

AEMO has conducted a review of the generation connection process for the National Electricity Market (NEM) as a result of the Australian Energy Market Commissions determinations in September 2017 regarding the Generation System Model Guidelines, Managing the rate of change of power system frequency, and Managing power system fault levels rule changes[11].

AEMO has introduced one of the most stringent requirements for connecting generation systems in the world. Requirements include detailed RMS and EMT models, associated guides for use of these models, data sheets, PSS®E model source code and assessment/benchmarking reports.

In preparation for future Siemens connections in the NEM, I was tasked with preparing a tool which conducts dynamics simulations, in PSS®E, on HVDC converter models. The advantage of having this tool is that models and associated documentation can be prepared and made ready for hand over to AEMO with limited delays.

This experience developed my perception of what stakeholders experience when interpreting technical requirements, what it means for stakeholder risk management and how AEMO's requirements can influence the success of power system solutions.

6.2 Relevant documents

The table below outlines the relevant documents associated with the NEM connection requirements.

Table 1 – Relevant material outlining the AEMO requirements

Reference Number	Publish date	Data Category*	Purpose
[1]	Jul-18	S,D,R	AEMO's requirements concerning the information and models that Generators, NSPs, Network Users, MNSPs, prospective NSCAS tenderers and prospective SRAS Providers (Applicants) must provide to AEMO and NSPs in specified circumstances. AEMO requires this information and models to develop mathematical models for plant, including the impact of their control systems and protection systems on power system security.
[2]	Nov-18	S,D,R	Support the Power System Modelling Guidelines and other studies conducting by TNSP and AEMO.
[3]	Jul-18	S,D	To provide a template for preparation of a RUG.
[4]	Jun-18	S,D,R	To assist in outlining the necessary information to complete a connecting generating system.
[5]	Aug-19	S,D	AEMO has prepared this Guideline to explain how to assess accuracy and robustness of computer models used for power system analysis.
[6]		S,D,R	AEMO's suggested outline of the connection process. This is useful for understanding the inputs and outputs for each stage and the responsibilities of each party.
[7]	Jun-13	R	To provide guidance for preparing testing programs intended to derive R2 models and data.

[8]	Jan-19	S,D,R	These Guidelines explain AEMO's requirements for information from Applicants and NSPs to facilitate the assessment of: • AEMO advisory matters4 for: – New generation connections (NER clause 5.3.4A). – Alteration of existing generating systems (NER clause 5.3.9). – Assessments of compliance of generating systems with agreed performance standards, and proposed amendments to those standards. • Negotiated access standards proposed by Applicants for new generation connections and alterations to existing generating systems connected to the Victorian declared transmission system, for which AEMO also acts as the NSP.
[9]	Jul-12	S	This document describes the technical information requirements for new generator connections and altered generating systems in the NEM (National Electricity Market).
[10]	-	S,D,R	AEMO's outlines the various stages of the connection process on it's website.
[11]	Jul-18	S, D	Provides an overview of the context and the available information available from AEMO.
[12]	2019	D, R	Chapter 5 of the National Electricity Rules which hold ultimate power related to network connection access, planning and expansion of the power system.
[13]	Dec-2011	D, R	These Guidelines are designed to assist Generators and Network Service Providers (NSPs) to understand AEMO's information requirements and the issues AEMO will consider when assessing a Generator's proposed performance standards.

* Data is coded in categories, according to the stage at which it is available in the build-up of data during the process of forming a connection or obtaining access to a network, with data acquired at each stage being carried forward, or enhanced in subsequent stages, eg. by testing. The Power System Model Guidelines, Power System Design Data Sheet and Power System Setting Data Sheet identify for each type of data, its category in

terms of clause S5.5.2. Codes: S = Standard Planning Data; D = Detailed Planning Data; R = Registered Data (R1 pre-connection, R2 post-connection).

6.3 Work completed

During my second three months at Siemens I completed my project to prepare and assess modeling information required (by Siemens) to successfully connect a generation system (converter stations) to the NEM. This involved developing a Model Acceptance Testing Tool which runs PSS®E models through various tests to ensure adequate performance before being given to AEMO as part of the connection information requirements.

This work has advanced my understanding of power electronic solutions in high voltage networks and has prepared me for modeling this technology in transmission planning studies in Australia. My new experience and upskilling can enhance the role of the national planner through the work I conduct in National Planning and how I can support other engineers at AEMO.

This section provides an outline of my work completed during my final three months at Siemens.

6.3.1 Model Acceptance Testing Tool

The Model Acceptance Testing Tool was developed to automate the large number of possible studies outlined in the Test Matrix. This is necessary in preparing final modelling information to AEMO to ensure an efficient connection process.

The Process

The process of preparing models and model information is to be condensed into a six-month period leading up to delivery of this information to AEMO or the network service provider (NSP) for due diligence studies. Key outputs include PSS/E models, PSCAD models, model data sheets, assessment reports and model releasable user guides. A key part of this process is the assessment tool which conducts tests on a small system with the model included and ultimately allows for benchmarking of the PSS/E and PSCAD results.

The Tool

The tool is written in Python 2.7 and works with PSS®E 34. It runs steady state, small disturbance and fault disturbance studies for a range of system conditions (short circuit ratio, X/R ratio, fault severity). Additionally, the post processing tool will be built in MATLAB which assesses the performance of the model to determine whether the model requires further tuning or correction.

Requirements and Test Matrix

The Test Matrix outlines the unique dynamic simulations which may be required according to AEMO and the NSP requirements. The table below is a Test Matrix summary and outlines the unique conditions which are defined as inputs into each study. For certain conditions an indication (in brackets) has been provided to reference the range of tests associated with this condition in the Test Matrix (see sheet **'Test Matrix'** in the '**Work Package 1**' spreadsheet).

Table 1 - Unique simulation conditions

Test Condition	Steady State (T1 to T72)	Small Disturbance (T73 to T172)	Large Disturbance (T173 to T412)
SCR	Minimum to Maximum	Minimum to Maximum	Minimum to Maximum
X/R ratio	Minimum to Maximum	Minimum to Maximum	Minimum to Maximum
Active power (pu)	-1.0 to 1.0	-1.0 to 1.0	-1.0 to 1.0
Reactive power (pu)	-1.0 to 1.0	-1.0 to 1.0	-1.0 to 1.0
Time step (ms)	>20 to 25% of the shortest time constant	>20 to 25% of the shortest time constant	>20 to 25% of the shortest time constant
Acceleratio n factor	Typically, 0.3, 1 or 2 as defined by AEMO	Typically, 0.3, 1 or 2 as defined by AEMO	Typically, 0.3, 1 or 2 as defined by AEMO
Disturbance Type (s)	Not Applicable **(T1 to T72)**	Active Power **(T73 to T102** Angle Step **(T103 to T116)** Frequency Step **(T117 to T128)** PQ limit **(T129 to T138)** Reactive Power **(T139 to T156)** Voltage **(T157 to T172)**	Three-Phase to Ground Fault **(T173 to T412)**
Run Time (s)	Required up to 5 minutes (300 seconds)	Typically, 180-300 seconds (no explicit AEMO requirement)	Typically, 180-300 seconds (no explicit AEMO requirement)
Disturbance Time (s)	Not Applicable	A time after steady state settling (0.1 to 10 seconds)	A time after steady state settling (0.1 to 10 seconds)
Fault Duration (s)	Not Applicable	Not Applicable	Typically, 0.12 or 0.5 seconds as defined by AEMO
Residual voltage (pu)	Not Applicable	Not Applicable	From 0.0 to 1.0 pu

For each test condition in the table above, the AEMO requirement reference is provided below. In the absence of an AEMO requirement a substitute requirement has been provided.
SCR: Table 1 of [5]: AEMO provides a minimum and maximum assessable SCR of 3 and 5, respectively. In the event the SCR values are expected to be lower at the generating systems connection point then the SCR for system normal and the most severe N-1 credible contingency should be used.

X/R ratio: Table 1 of [5]: AEMO provides a minimum and maximum assessable X/R of 3 and 10, respectively. In the event the X/R values are expected to be lower at the generating systems connection point then the X/R for system normal and the most severe N-1 credible contingency should be used.
Active power: Section 3.3 of [5]: The entire range of active power.
Reactive power: Section 3.3 of [5]: The entire range of reactive power/power factor (including limits of reactive power generation and consumptions).
Time step: See page 18 of [1]: (section 4.3.3) numerical integration time step and acceleration factors are 1 ms and 0.2, respectively; (section 4.3.4) transient stability EMT-type models must operate with a time-step greater than or equal to 1 ms, ideally consistent with the switching frequency of the plant.
Acceleration factor: See 'Time step' above.
Run time: Section 6.2.1 (d) of [1]: Taking into account the level at which voltage settles at the connection point, the final active power or reactive power value at which the plant would settle is within the more restrictive of (i) the final value at which the model response settles ±2% of the plant's maximum capacity; or (ii) the final value at which the model response settles ±10% of the total change in the quantity following the Disturbance.
Disturbance time: No requirement from AEMO, chosen arbitrarily as any time after the dynamic simulation has initialized, and is stable, and does not unnecessarily extend the length of the simulation (run time). Typically, between 0.1 and 10 seconds.
Fault duration: Fault clearance times are specified in clause S5.1a.8 of the National Electricity Rules (see [12]) for different voltage ranges. Where no value is provided in the table, 430 milliseconds should be used (see clause S in [12]). For voltages above 250 kV and below 400 kV, the fault clearance times are 100 (Column 2 of Table S5.1a.2), 120 (Column 3 of Table S5.1a.2) and 250 milliseconds (Column 4 of Table S5.1a.2).

- Column 2: short circuit fault – see clause S5.1a.8(b)(3); S5.1a.8(c)
- Column 3: short circuit fault – see clause S5.1a.8(c)
- Column 4: breaker fail protection system – see clause S5.2.5.5(c)(3)(ii); clause S5.1a.8(d)

Residual voltage: AEMO does not provide a specific requirement for residual voltage however does require that 0.8, 0.5, 0.25 and 0.0 pu be considered in the Generating System Model Benchmarking report[11].

Plan
The project spans a six-month period from July to December 2019. General outline of deliverables is below:

- July 2019 [**complete**]
  - Preparation of the plan and outline for deliverables for the coming six months.
  - Collect and consolidate relevant material provided by AEMO.
- August 2019 [**complete**]
  - Preparation of the single machine infinite bus model in PSS/E.

[11] See page 5 of [4].

- Skeleton of the python code.
    - Runs independent of PSS/E.
    - Processes output files into csv’s.
- September 2019 [**complete**]
  - Development of the fault disturbance and steady state simulations are completed by the tool.
- October 2019 [**complete**]
  - Preparation of the tool documentation for use by other engineers.
  - Completion of the small disturbance simulation code.
    - Frequency, voltage, active power, reactive power and angle step simulations.
- November to December 2019 [**complete**]
  - Completion of the python tool, documentation and testing.

Project Completion
The Tool was developed, tested and well documented for use by Siemens engineers for future connection preparation. Throughout this project, some requirements had more than one solution developed as the requirements could be interpreted in various ways. The Angle step test is a good example of a study which has various implementations, each with pros and cons. AEMO needs to be clearer about these study requirements, perhaps releasing their MAT code to stakeholders who are not only registered in the market.

6.3.2 Siemens HVDC technology

Siemens is a world leading company in the area of large transmission projects, particularly in the design and manufacturing of HVDC solutions. Siemens has played a central role in the development of HVDC technology, having delivered 10 GW of line-commutated current-source converters (LCC) (or HVDC Classic) transmission and is also leading in the area of voltage-source converter (VSC) technology (or HVDC Plus).

It is apparent to me, through my experience at Siemens, that HVDC transmission technology leverage unique power system market conditions and can be very successful business ventures. A typical situation where HVDC solutions are successful, from a technical perspective, is when there are two synchronously isolated power systems with a HVDC transfer capability between them. The HVDC solution provides value by accessing the services of one system and providing these services to the other system. In some cases, there is periodic cycling of the benefits of both systems to the other.

The context described above is not the only case where HVDC solutions can provide value. In systems with significant power system and policy constraints, HVDC solutions can provide value. These conditions effectively mimic synchronous isolation in that the two systems are limited in their capability to share services. An example is the trans bay cable in California, constraints on overhead lines, network congestion, seismic requirements and reliability requirements have resulted in a sole HVDC solution being the necessary solution to ensure demand is met in the Bay Area.

6.3.3 CIGRE SC B4 International Colloquium

As part of my time at Siemens, and with the support of AEMO, I was able to attend the B4 International Colloquium in Johannesburg, South Africa in October. This was a valuable networking and learning opportunity. I broadened my perspective on HVDC technology and the current challenges which are being faced around the world. Area of discussions included:

- Network stability
- Renewable energy
- LVDC and MVDC distribution and microgrids, Distributed FACTS devices, synthetic inertia, HVDC insulation
- HVDC reliability, refurbishment and upgrades of HVDC and FACTS installations
- HVDC and FACTS Equipment and technology
- Regional Interconnections

A key area of relevant learning for me, and for my return to AEMO, is ongoing reliability monitoring of operating HVDC systems around the world. It is difficult to come to conclusions on what causes unplanned outages due to limitations in the data being collected. However, ongoing monitoring and adequate data collection is invaluable in the correct and efficient operation of HVDC technology in any power system. This monitoring can be extrapolated into power system planning models to improve supply adequacy projections.

6.3.4 Site visits

During my first three months at Siemens I was fortunate to visit two operating converter station, the transformer factory in Nuremberg and the power module assembly factory in Nuremberg.

The first visit was to the power module assembly factory in Nuremberg following by the transformer factory not far away. Here I witnessed the assembly line which produces the power modules (housing of IGBTs, capacitors and necessary electronics) for FACTS and converter station applications. Following this visit I attended the transformer factory where I witnessed the assembly of various sized power transformers – conductor coiling, assembly and testing.

The second was the BorWin III converter station owned and operated by TenneT in Northern Germany. This converter station receives power from offshore wind systems and injects up to 900 MW into the Northern German power grid at the Emden connection point. I visited the switchyard, switchgear, control room and protection housing.

The third was the +-533 kV Apollo HVDC LCC converter station close to Pretoria, South Africa, which was refurbished from 1977 to 79. This converter station is the southern receiving end of the Cahora Bassa HVDC transmission system and receives power from Songo generation in Mozambique. This station is owned and operated by Eskom, the South African system operator. This source of power is the Cahora Bassa Hydroelectric generation station at the Cahora Bassa Dam on the Zambezi River. The HVDC link is in parallel with relatively lower voltage HVAC and has bus splitting schemes to manage the loss of the HVDC line which is currently operated at 1065 MW.

Eskom has done some interesting pollution monitoring work at the Apollo end of the system. HVDC infrastructure (particularly insulators and switch yard equipment) are much more prone to leakage current than HVAC infrastructure due to the charged nature of the electrical equipment. Eskom’s work provides strong recommendations for composite insulators over glass insulators due to reduced flash over incidence after wet weather.

Finally, I was fortunate to visit Siemens pilot factory for their electrolysers. These systems take water and produce hydrogen and oxygen for consumption in various systems such as the existing gas distribution system and transportation.

6.4 Impressions gained

This section outlines the impressions gained during my time at Siemens from July to September 2019 as reported in my previous quarterly report.

7. **Contentions with model preparation for NEM connections**

Having worked through the AEMO connection requirements with colleagues at Siemens it is clear there are contentions, particularly those related to source code and detailed modeling information.

Ongoing connection projects which involve both Siemens and AEMO have provided an important learning opportunity for me in terms of how these contentions can be overcome.

8. **HVDC technology is adaptable and capable to support reliability and security**

HVDC technology is incredibly adaptable and capable of meeting a broad range of technical requirements. Simply put, every HVDC transmission solution operating today is completely unique and meet a range of different technical requirements around the world.

Customers who provide specific technical specifications (such as voltage, converter topology) must be aware that these

The impressions gained during my time at Siemens from October to December are outlined below:

9. **Stakeholders which are not market registered will benefit from access to AEMO's MAT testing code**

Throughout this project, some requirements had more than one solution developed as the requirements could be interpreted in various ways. The Angle step test is a good example of a study which has various implementations, each with pros and cons. AEMO needs to be clearer about these study requirements, perhaps releasing their MAT code to stakeholders who are not only registered in the market.

10. **The success of HVDC solutions outside of Australia**

In systems with significant power system and policy constraints, HVDC solutions can provide value. These conditions effectively partially mimic synchronous isolation in that the two systems are limited in their capability to share services. A good example in the NEM is the mainland system and the Tasmanian system, which already has a HVDC solution with transfer capability. Emerging opportunities for HVDC solutions may include servicing large load centers such as Sydney and Melbourne with HVDC transmission from generation centers. As transmission solutions utilised to supply these centers with power become more expensive, HVDC solutions may become more competitive and capable of providing all the necessary system services required to maintain reliability and security.

7.0 Next steps

With the completion of my scholarship and my return to Australia approaching, my next steps and future focus are as follows:

- Apply my new skills, learnings and experience in my new role in AEMO's National Planning group.
- Share my experience with my colleagues inside and outside AEMO.
- Continue developing my international network.
- Promote the E.S Cornwall Memorial Scholarship in Queensland, and the rest of Australia.

8.0 Conclusion

This report provides an overview of my completed work, lessons learned, and impressions made during my 18 months at the California ISO, Electranix and Siemens AG as part of the E.S Cornwall Memorial Scholarship (Scholarship). In addition, this report meets the requirements of a quarterly report for my last three months at Siemens AG and my last three months on the Scholarship. The lessons learned across the 18 months and the impressions gained are outlined and underpinned by the theme of my Scholarship, to enhance the role of the national planner.