THE UNIVERSITY OF QUEENSLAND
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ES Cornwall Memorial Scholarship

First Quarter Report

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KEMA Labs, Arnhem, The Netherlands

The KEMA Labs campus in Arnhem, The Netherlands.

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I would also like to thank Energy Queensland and in particular my managers Alan Louis and Michelle Taylor for their support in allowing me to undertake this opportunity. I am looking forward to my return to the Intelligent Grid New Technology team and using the experiences I have gained to help during what is shaping up to be an exciting time as Queensland and Australia pursues a highly renewable future.

Finally, thank you to the ES Cornwall Memorial Scholarship and its Board for this fantastic opportunity. I have no doubt that this chance to gain international experience will help me to become a more well-rounded engineer and I endeavour to bring this experience back to Australia to hopefully share and contribute to the ongoing development of the Australian electricity supply industry.

DISCLAIMER

This report provides a summary of the experiences and work undertaken by the author during the period of September – December 2022 as part of an overseas ES Cornwall Memorial Scholarship placement. Statements and material contained within this report are the opinion of the author and do not reflect the opinion or positions of any other person or organisation. Reproduction or referencing of this report should also reflect this.

EXECUTIVE SUMMARY

The Australian electricity supply industry is in the midst of a rapid transition to an electricity network with a high penetration of renewable generation reliant on inverter-based resources to connect these to the grid. Many obstacles to facilitate this future have already been overcome, however there are still significant challenges associated with moving away from the traditional synchronous generation that has reliably powered the electricity industry for a number of decades.

During my time as an ES Cornwall Scholarship holder I hope to explore a number of these challenges and learn from some of the leading European organisations in this field to help grow my capabilities and understanding of how Europe intends to complete this transition. I am hoping to return to Australia with this knowledge that will not only help me in my day-to-day nominal role, but also I am hoping to share my experiences more broadly to express gratitude for this opportunity that has been afforded me.

This quarterly report is the first of four reports I will submit during my time as an ES Cornwall Scholarship holder and covers my first three months with KEMA Labs. During this period I was also fortunate enough to attend the 2022 CIGRE Paris Session therefore I have also included my takeaways from this session in the report.

In these three months, I have been involved in a number of projects at KEMA Labs relating to the development and performance of testing on inverter-based devices such as battery chargers and solar inverters. This testing has involved a combination of simulation/modelling and physical testing and hardware-in-the-loop testing has been implemented on occasion. A summary of the lessons learned during these projects is as follows:

1. Silicon controlled rectifier (SCR) thyristors provide different advantages to the more common insulated-gate bipolar transistor (IGBT) transistors in terms of their performance in a rectifier bridge. While SCRs can be cheaper and possibly more efficient than IGBTs for high power applications, they often require a stronger incoming reference signal and therefore may struggle in weaker networks.
2. Testing of inverter-based devices may require a sufficiently strong source, such as a diesel generator, which may make power amplifier based testing (and therefore common power-hardware-in-the-loop setups) not possible. This is a result of inverter-based equipment distorting the incoming AC signal and introducing transients that may cause instabilities in the system.
3. The differences between two common real-time simulators, RTDS and OPAL-RT, and how these can both be used for in-the-loop testing.
4. Best practices for power-hardware-in-the-loop testing including recommended protection, restrictions on model and controller timesteps and the typical test execution procedure.

I will remain in my role at KEMA Labs until the 24th of March during which time I will continue working in similar areas with the testing of a battery storage system currently planned for January. Following this, I will be moving across to the United Kingdom to undertake a role with National Grid ESO.

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GLOSSARY

Table 1: List of acronyms and terms with their meaning.

Acronym/Term	Meaning
AEMC	Australian Energy Market Commission
AEMO	Australian Energy Market Operator
BESS	Battery Energy Storage System
CHIL	Controller Hardware-in-the-Loop
DER	Distributed Energy Resource
EMC	Electromagnetic Compatibility
ESO	Electricity System Operator
FPGL	Flex Power Grid Laboratory
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
HPL	High Power Laboratory
HVL	High Voltage Laboratory
IBR	Inverter Based Resource
IGBT	Insulated-Gate Bipolar Transistor
PHIL	Power Hardware-in-the-Loop
RoCoF	Rate-of-Change-of-Frequency
RTDS	Real-Time Digital Simulator
SIPS	System Integrity Protection Schemes

1 SCHOLARSHIP PLAN / OVERVIEW

The problem statement that I will be addressing during my time as an ES Cornwall Scholarship holder is:

"Maintaining Stability in an Electricity Network with a High Penetration of Distributed Energy and Inverter Based Resources"

This motivation is driven by the challenges currently being experienced in Australia regarding the energy transition. The Australian energy industry is continuing to face unprecedented growth in renewable energy technology and distributed energy resources (DERs). A result of this is that the industry of today looks very different from ten years ago, and this change will only continue to accelerate as Australia transitions to the network of the future. To ensure this transition takes place as smoothly as possible, with both consumers and industry in mind, there are several key areas of complexity that must be addressed. One of these is the need to ensure that the electricity network maintains an adequate level of network stability and resilience in the face of significant change to the fundamentals that the network was built upon – namely one-way energy flow from centralised large synchronous generators.

Network stability is a multi-faceted problem, with two of the main aspects being system strength and inertia. System strength is defined by the Australian Energy Market Commission (AEMC) as a "characteristic of an electrical power system that relates to the size of the change in voltage following a fault or disturbance on the power system[1]". The system strength at any given location is proportional to the fault level at that location. Similarly, frequency stability is linked to system inertia and the ability of the network to resist high rates of change of frequency (RoCoF) in the event of significant active power changes.

Networks with low system strength and low inertia are susceptible to several issues including wider area undamped voltage oscillations, prolonged voltage recovery after disturbance, instability of generator and dynamic plant voltage control systems, mal-operation of protection equipment and increased harmonic distortion[2]. In the past, synchronous machines have traditionally provided system strength. Meanwhile, inverter-based resources (IBRs) are reliant on adequate system strength to operate reliably but do not necessarily contribute positively to overall system strength. This is because the fault level contribution from synchronous generators is high, whereas system strength is inversely proportional to grid-following IBR penetration since the fault level contribution of IBRs is low[3]. With the growing penetration of IBRs causing the make-up of Australia's energy generation to swing more towards IBRs, synchronous generators are slowly being phased out. This is therefore leading to decreasing system strength which then has the flow-on effect of limiting the amount of IBRs that can be added to the network. The key question is therefore how the Australian energy industry can increase renewable energy production from IBRs whilst also ensuring an adequate level of system strength.

The challenges being brought on by increasing levels of DERs are not likely to slow down. Connected rooftop solar capacity in Queensland is already estimated to be over 3,346 MW with approximately one-

[1] AEMC. (2017). *National Electricity Amendment (Managing power system fault levels) Rule 2017*. Australian Energy Market Commission.
[2] AEMO. (2020). *System Strength in the NEM Explained*. Australian Energy Market Operator.
[3] Keller, J., & Kroposki, B. (2010). *Understanding Fault Characteristics of Inverter-Based Distributed Energy Resources*. NREL.

in-three households having rooftop solar installed[4]. The further development and cost reduction of other DER technologies, such as battery storage and electric vehicles, will also serve to increase the level of DER penetration on the distribution network. The best time to act and plan for a high DER future with significant contribution from IBRs is therefore the present and implementing effective management plans will help smoothen the transition from the grid of the past to the grid of the future.

In my role as a Technology Innovation Engineer at Energy Queensland I am fortunate enough to be able to work in an area that I am passionate about; helping to enable new technologies in the distribution network and aiding the transition to an energy network with a higher penetration of DERs. While I have had some exposure to the challenges relating to network stability in a highly inverter-based network, I would love the opportunity to gain more of an understanding about how the energy industry as a whole can tackle this problem by observing what is being done overseas. My aim would be to then bring these learnings back to Australia to help the Australian energy industry best transition to a higher DER future.

To fulfil my proposed problem statement and target the challenges outlined above, I will be looking to achieve the following key aims while undertaking work placement overseas;

- Learn from leading network operators on what they are currently doing and plan to do to help modernise their energy network and allow for a high penetration of DERs;
- Undertake work with manufacturers of products that are providing solutions to network stability problems to gain a better understanding of the technology and how it can be best integrated in a distribution network;
- Improve my overall understanding of network stability challenges and how these can be collaboratively managed by all stakeholders of the electricity supply industry;
- Learn how international countries are enabling customers to make the most of new technologies such as solar, wind, energy storage and electric vehicles; and
- Use my time overseas to attend international conferences, workshops and company site visits outside of what I have been exposed to in Australia.

Table 2 shows the schedule I have currently planned for my time as an ES Cornwall Memorial Scholarship holder.

Table 2: Planned placement and conference schedule.

Dates	Activity
28/08/2022 – 02/09/2022	2022 CIGRE Paris Session
September 2022 – April 2023	KEMA Labs – Test Engineer
April 2023 – October 2023	National Grid ESO
12/06/2023 – 15/06/2023	CIRED 2023 Rome
October 2023	Return to Australia

[4] RenewEconomy. (2020). *Rooftop Solar's Stunning Surge to New Records, As Australia Installs Reach 2.5 Million.*

2 PLACEMENT 1 – KEMA LABS

2.1 KEMA INTRODUCTION/BACKGROUND

KEMA Labs is a world-renowned testing, inspection and certification organisation with a long history of providing quality high voltage and high power testing services to the electricity supply industry. Acquired by CESI in 2019, KEMA Labs has now joined the broader CESI group to form a network of testing facilities with laboratories located in Arnhem, Berlin, Chalfont, Mannheim, Milan, Prague and Shanghai[5].

At the Arnhem site in the Netherlands, KEMA Labs' High Power Laboratory (HPL), High Voltage Laboratory (HVL) and Flex Power Grid Laboratory (FPGL) cater to all sectors of the industry within the electricity delivery supply chain, including research, manufacturing and network operators. The customer base of KEMA Labs extends beyond Europe with global companies electing KEMA to undertake their device testing and compliance certification based on a strong record of providing high quality and reliable testing services. The testing services offered at the Arnhem laboratories include:

- High voltage cable testing (dielectric test, endurance testing, thermal constraints, fault condition assessment).
- High power testing of equipment including cables and cable accessories, insulators, power and instrument transformers and switchgear for tests such as short circuit, switching, power arc and internal arc.
- Substation automation and protection device testing with ISO 17025 accreditation for applicable tests relating to functionality, electromagnetic compatibility (EMC), climactic environmental conditions, communication interfaces, mechanical environment conditions, product safety and output contact performance.
- Smart meter testing with accreditation for a range of international standards including, IEC 62052, IEC 62053, IEC 62054, IEC 62055, ANSI C12 and OIML R46.
- Certified measuring equipment calibration (for example, IEC 60060-2 and IEC 62475).
- Testing of power electronics based devices relating to electric vehicles, solar inverters and energy storage systems within the FPGL.

The FPGL, pictured in Figure 1, utilises a range of flexible devices and test equipment to create fully-controllable grid equivalent test scenarios. Capable of operating over a range of input frequencies, harmonics, voltages and power levels, the FPGL facilitates complex testing of power devices that are themselves becoming increasingly complex. The electricity supply industry is currently experiencing a rapid uptake of power electronics and inverter-based resources as global electricity networks transition to a future grid with a higher penetration of renewables. The lab aims to assist with this transition by playing an integral role in the development and commissioning of these devices before they are installed at a network wide scale. The FPGL is flexible and configurable enough to assist in the research and development stages of product design right through to the final commissioning checks[6].

[5] KEMA Labs (2020). https://www.cesi.it/about-us/overview/kema/
[6] Flex Power Grid Laboratory (2022). https://www.cesi.it/testing-certification-inspection/testing-labs/flex-power-grid-laboratory/

Figure 1: Snapshot of KEMA Labs' FPGL in Arnhem.

Below is an overview of the ratings and electrical capabilities of the FPGL:

- AC three-phase voltage range up to 24 kVac
- DC voltage range up to 2 kVdc
- Fundamental frequency range controllable from DC up to 75 Hz
- Continuous power up to 1 MVA
- Independent control of harmonics up to 25th harmonic
- Synchronisation with external sources
- Controllable bi-directional power flow in four quadrants
- Adjustable passive loads (0.5 MW, ±1 MVAr)

Example applications and testing services:

- Replicate network disturbances to verify response of equipment under test.
- Power quality performance assessment of power electronics devices.
- Grid compliance tests.
- Dynamic performance tests.
- Power-hardware-in-the-loop capabilities to perform system level testing on products.
- Model validation and verification of blackbox models by providing the opportunity to compare the actual performance of the device to the simulated equivalent.

2.2 MY INVOLVEMENT:

As a Test Engineer within the Flex Power Grid Lab at KEMA, my role includes supporting the testing activities of the laboratory, ensuring safe operation of equipment within the laboratory, performing power quality data analysis and producing high quality technical results reports detailing test procedures and findings. To this end I have been involved in a number of projects so far in my three months at KEMA Labs. Each of these have allowed me to continue growing my power engineering skills, particularly in the power electronics field of study, as well as exposing me to new work that I had not yet had the opportunity to experience.

Working in a laboratory dedicated to the testing of power equipment has allowed me to gain a more hands-on understanding of the operation of power electronics devices and the different complications and challenges that may arise from their connection to an electricity network. I have enjoyed being able take part in deep dives into the analysis of power quality results of inverter-based devices to learn how to identify characteristics attributed to different technology types, such as harmonics.

In addition to these technical skills, I have also enjoyed learning more about the processes that allow the FPGL to provide high quality, reliable and valuable testing services to its customers. There is a lot more that goes into power equipment testing than performing the actual testing and being able to gain insight into the professional service the FPGL provides will see me in good stead when I undertake device testing in my nominal role at Energy Queensland.

Below is a quick overview of the main bodies of work I have been involved with over the past three months at KEMA Labs.

2.3 BATTERY CHARGER TESTING

Upon joining the FPGL team I quickly became part of the testing of two 50 kW battery charger units to be used to supply substation DC load and provide charging to a backup battery system. These battery chargers were being tested for compliance to a set of criteria clearly defined by the utility company looking to install these units, however more broadly these tests are similar to those discussed in IEC 60146-1-1.

I was tasked with writing a MATLAB data analysis script that would streamline the results analysis process by quickly processing raw voltage and current measurements and extracting key information depending on the particular test that the raw data corresponded to. Examples of these tests include harmonic analysis, dynamic response, efficiency, thermal stability and performance under different input conditions. As the measurement data captured by the field measurement sensors was always guaranteed to be in the same format and nicely timestamped, the MATLAB script was able to quickly perform calculations and graph the results that would later be used in the final testing analysis report. Working with the data at this level also allowed me to gain a better understanding of the power quality performance and limitations of the different chargers as it involved really zooming-in on the data at the waveform level and assessing whether the strict performance criteria was being met.

2.3.1 LESSONS LEARNED

1. Using silicon controlled rectifier (SCR) thyristors:

Both battery chargers that were tested utilised SCR thyristors, a type of switching device I did not previously have experience with. Working with these here allowed me to see first-hand the differences between it and similar devices that utilise different switching technology such as insulated-gate bipolar transistors (IGBTs). These differences included the limitations of the SCR technology relating to its reliance on a clean and steady AC input signal. I was also able to see the difference between a 6-pulse and 12-pulse AC-DC converter and assess the power quality results of both options as well as learn how this technology controls its DC output using the firing angle.

2. The effect of the source's impedance on the power quality performance of the device:

Initially the test setup utilised a power electronics based amplifier to convert the 50 Hz grid supply into a 60 Hz input signal for the battery charger (as the battery charger was to be installed with a 60 Hz grid supply). Problems were encountered in the commissioning of the device before testing was commenced with the DC output showing higher levels of noise and causing greater harmonic disturbance than what was expected from factory testing. After trying a few different solutions, eventually it was determined that the lower source impedance of the power amplifier as opposed to a strong (stiff) grid supply could be contributing to the poor performance of the SCR thyristor based DC-AC converter. To overcome this, a diesel generator significantly larger than what would be required to power the battery charger (i.e. a 500 kVa generator to supply a 50 kW battery charger) was used.

While this was only a very specific test case using a specific switching technology, it hints at the complications that are beginning to be realised with grid stability in the broader distribution and transmission networks as the penetration of inverter-based generation continues to increase. While grid stability is beginning to be addressed using technologies such as synchronous condensers and grid-forming inverters, it was nice to see first-hand the effect of lower grid stability and system strength on the performance of this power electronics based equipment.

3. Modelling an AC-DC converter in Simulink:

To help reinforce what was being observed on the physical AC-DC converter, I additionally worked to model a AC-DC converter in Simulink. Not only did this allow me to improve my modelling skills in Simulink, I also found this highly rewarding as I was able to go right down to the control of the PWM gate pulsing signal for the transistors and see how these need to be controlled in order for the converter to function correctly. This also has parallels with inverter operation and the control of grid-following versus grid-forming inverters and therefore allowed me to grow my understanding in these areas also. Notes taken while learning about the operation of a AC-DC converter and how to model this in Simulink have been included in Appendix A – AC-DC Converter Overview.

2.4 SOLAR INVERTER TESTING USING THE OPAL-RT

Following the battery charger testing, the FPGL hosted a European research project group to facilitate solar inverter testing for a few specific types of tests. To perform these tests, the FPGL's OPAL-RT and attached power amplifier were used as grid supply to the inverter's AC terminals. The OPAL-RT allowed very precise control of the incoming AC signal to the solar inverter which enabled more complex tests

relating to rate-of-change-of-frequency (RoCoF) and under/over voltage ride-through to be performed. The aim of the testing was to investigate the performance of the inverters under different RoCoF and under/over voltage conditions to help understand how other inverters installed in the field could be expected to behave.

Interestingly, this testing shared a number of similarities with testing I was involved with in my nominal role relating to the compliance of a three-phase solar inverter to the RoCoF requirements stipulated in AS/NZS 4777.2:2020. One key difference in the two setups was the use of an OPAL-RT instead of a real-time digital simulator (RTDS) from RTDS Technologies. While both real-time simulators have similar capabilities, the way they achieve these and their operation is quite different. Learning how to work with the OPAL-RT is an experience I found quite valuable as I have a keen interest in real-time simulation and hardware-in-the-loop (HIL) testing and understanding the difference between the two systems has improved my understanding of the topic as a whole.

Reassuringly, the results observed from the tests conducted in the FPGL aligned with the results obtained during my previous testing and the group conducting the research were able to use the observations and power quality measurements recorded for their investigation.

2.4.1 LESSONS LEARNED

1. Differences between OPAL-RT and the RTDS:

Although only a very basic function of the OPAL-RT was required for this testing, controlling a power amplifier to provide a input signal to the solar inverter, I am starting to see the differences between the OPAL-RT and the RTDS that I have worked with in the past. Admittedly I still have limited experience using the OPAL-RT and I am still learning its full capabilities therefore some of the differences mentioned below may be due to my lack of familiarity as opposed to an actual difference between the systems.

- OPAL-RT uses Simulink as opposed to the RTDS which uses RSCAD:

As the OPAL-RT uses Simulink for model development it has the advantage that Simulink is already a relatively well known product in the industry and therefore users of the OPAL-RT will have an easier learning curve if they already have a background in Simulink.

On the other hand, the RTDS uses RSCAD which is a proprietary software developed in-house by RTDS Technologies that allows the user to configure, execute and analyse results from the RTDS. This means that RSCAD is designed to integrate seamlessly with the RTDS however it has a slight disadvantage that it is not as widely used as other packages. Fortunately RSCAD is not too dissimilar from other popular modelling packages such as PSCAD and Simulink therefore the time taken to get up to speed is not a significant obstacle. RSCAD also offers a conversion tool from PSSE, Simulink and PSCAD which is helpful, although I have not used this tool enough yet to know the accuracy and reliability of the conversion.

Overall, my personal opinion is that the two software packages, Simulink versus RSCAD, are both easy enough to use and offer all of the capability, in terms of what they can model, that I have required to-date. I am looking forward to working more with the OPAL-RT in the coming months to perform full hardware-in-the-loop testing to better understand what it can do.

- Model development and testing/debugging the model:

Model development for the OPAL-RT is performed in Simulink. The user is able to build their model and test it is working as required as they would for a normal, non-real-time, Simulink simulation. Once the user is happy with the model, they will then need to compile this for integration with the OPAL-RT. A disadvantage of the model development taking place on the user's computer and not on the OPAL-RT itself, is that the user's computer will likely be slower and have significantly less processing capabilities than the OPAL-RT. This can make model development quite tedious and time consuming especially when the time taken to compile the model and then execute on the OPAL-RT is also not insignificant.

For the RTDS, although model development still takes place on the user's computer, all debugging and running of the model takes place on the RTDS itself and makes use of its superior processing capabilities. Compiling the model to run on the RTDS also seems to be quite quick. My experience from this is that model development and debugging is much faster within the RTDS and is ultimately more efficient.

- Interacting with and monitoring the system when running in real-time:

The RTDS and OPAL-RT have slightly different approaches when it comes to interacting and monitoring the system while it is in operation. The OPAL-RT's real-time simulation environment is split into two simulation blocks, the "SM_Model" and the "SC_Console". Information is passed between these two simulation blocks asynchronously as the model is operating at real-time, while the console (HMI) is operating at a timestep dependent on the computer/server that the user is using to run the model. In comparison, the RTDS does not distinguish between the model being executed in real-time and the HMI. Even though there will be a latency from when the user interacts with the HMI (e.g. changes the position of a switch), this latency does not affect the ability of the HMI to operate at real-time.

Having the HMI not operate in real-time makes monitoring of the system quite difficult as any results plotted by the scope cannot be viewed in real-time fidelity and therefore making decisions based on the current state of the system is not possible. Although the OPAL-RT does not allow real-time monitoring and interaction with the model from the console HMI, it does have integration with an additional display panel and I/O interface panel. While these overcome the limitation of not being able to interact with the model in real-time, my limited experience so far has found this is not as intuitive to operate and requires a bit more setting up to get it to work when compared to the RTDS. I believe this will become easier to use with familiarity therefore I am looking forward to seeing whether this will eventually put it on par with the RTDS' implementation.

The RTDS is capable of monitoring the system in real-time through the same HMI that is used to run the model. This is a clear capability advantage as this means the user can operate the system, as they would for example as a network operator performing switching to relieve system constraints or restore power following an outage, and can see completely how the system is performing.

2.5 HIL BEST PRACTICE GUIDE

In November, the members of the IEEE P2004 working group were asked to perform a review of a draft copy of their recommended practice guide. IEEE P2004 are currently working to produce a recommended

practice guide titled, "Recommended Practice for Hardware-in-the-Loop (HIL) Simulation-Based Testing of Electric Power Apparatus and Controls"[7]. Fortunately Erik, my manager at KEMA, is a member of the working group and was able to provide me with a copy for review. Despite still being in the drafting stage, the guide already has a number of points and considerations that I will be looking to implement in future testing either in my role at KEMA or upon returning to Australia.

HIL testing and Power-HIL (PHIL) are becoming increasingly important when it comes to testing complex power electronics and controllers. HIL testing helps bridge the gap between the modelling and physical worlds and can help accelerate equipment development and commissioning by allowing physical devices to be tested in complex scenarios that are typically very difficult and/or expensive to recreate in a physical setup. Additionally, developing equipment in a purely modelled world can also be time-consuming and may not always be accurate as perfectly replicating the performance of a real system can be extremely complex. As such, HIL testing is finding applications for example in grid connection assessments and microgrid control development and is becoming the go-to for system operators. For example, AEMO includes HIL as an approach to validate equipment performance and model reliability in their "Power System Model Guidelines"[8] and "Dynamic Model Acceptance Test Guideline"[9].

With the industry seemingly trending to have a bigger reliance on HIL testing, I am glad that I have been able to get some more experience in this space during my time at KEMA. I am hoping that this experience will help set me in good stead to incorporate HIL best practices for the device testing I am involved with in my nominal role at Energy Queensland.

2.5.1 LESSONS LEARNED

Below are a few of my key takeaways from the IEEE P2004 best practice guide:

1. PHIL Test Execution Procedure:
    a. Commissioning tests – confirm all equipment is installed correctly and operating as expected.
    b. Check performance in open-loop steady-state.
    c. Perform impedance measurements and preliminary stability analysis.
    d. Engage PHIL interfaces for closed-loop operation.
    e. Reperform impedance measurements and stability analysis in closed-loop.
    f. Execute planned tests and scenarios.
    g. Shutdown experiment.

2. Additional protections for closed-loop testing:

In addition to the standard protections that all test devices will have to protect themselves from unsafe conditions, it is also recommended to include the following precautions for PHIL experiments:

- Set limits, in software and/or hardware, to ensure the power amplifier used as interface between the simulator and device under test does not exceed acceptable values.

[7] IEEE P2004. (2022). *P2004/D3 Draft Recommended Practice for Hardware-in-the-Loop (HIL) Simulation-Based Testing of Electric Power Apparatus and Controls*
[8] Australian Energy Market Operator (AEMO). (2018). *Power System Model Guidelines*.
[9] Australian Energy Market Operator (AEMO). (2021). *Dynamic Model Acceptance Test Guideline*.

- Add additional checks for instability in the test setup. This should go beyond checks for absolute levels being exceeded to also include things like rate-of-change limits to help detect instabilities in the test setup before they are amplified to unsafe levels.
- PHIL test arrangements should always be tested first in open-loop to ensure accuracy and safety of steady state operation before progressing to the closed-loop dynamic system.
- Care should be taken to minimise measurement noise as even the finest of errors in sensors can amplify in a closed-loop configuration to something more problematic.

3. Restrictions on model and controller time steps:

In order for the test to be conducted at real-time and allow the modelled components of the test to interact with the physical components in the test, the model timestep must be sufficiently low enough. This means that the model complexity is restricted by the processing power of the real-time simulator executing the model as the time required for the model to be solved must always be less than the real-time timestep. This is typically in the microsecond range and should not exceed 50 µs as a worst case.

Similarly, for controller-HIL (CHIL) testing, the timestep of the controller under test should be at least an order of magnitude larger than the execution timestep of the model. This means that the model timestep may be increased, for example to the millisecond range, as long as the timestep of the controller under test is sufficiently greater.

4. Selection of the model to hardware interface (amplifier or otherwise):

Due to the strict accuracy requirements of the interface between the model operating on the real-time simulator and the hardware under test, it is vital that care is taken in the selection of the equipment used in this interface. Some of the key things to be aware of include:

- The selected amplifier must meet the required bandwidth, resolution/accuracy, voltage rating, current rating and power rating for the specific test case.
- There may be multiple interfaces, for example physical voltage and current as well as communication over Modbus, therefore the interface must be able to accommodate all of these and maintain synchromism amongst its signals.
- Distortion introduced by the amplifier must be minimised as this will lead to instabilities and inaccurate tests. This distortion could include things like the harmonics introduced by the frequency of a switch-more amplifier.
- Depending on the hardware under test, care should be taken to ensure the amplifier acting as the source is sufficiently ‘strong’ to ensure the hardware under test does not artificially distort the input signal and therefore ruin validity of the test. This could happen for example if a power electronics device requires its source to have a large short-circuit ratio which may not be achievable by some switch-mode power amplifiers.
- Ensure the time delay between the model sending a signal and the device under test receiving this signal (and vice versa) is not too large. If this delay is significant, the accuracy of the test will be compromised as the model and physical device will always be acting on old information.

3 2022 CIGRE PARIS SESSION

From August 28th to September 2nd, I had the fortunate opportunity, thanks to the support of the CIGRE Australian National Committee, to attend the 2022 CIGRE Paris Session. As one of the leading power system events, the Paris session hosted by CIGRE is a biennial event that brings together the global CIGRE community. Unlike the traditional conference format I have grown accustomed to in Australia where papers are selected to be presented during the conference, the CIGRE session takes on a more interactive approach where all papers are submitted and made available to attendees ahead of time. The week long session then facilitates in-depth debates and conversations regarding the papers in group discussion meetings as well hosting several different session types such as poster sessions, tutorials and workshops. The 2022 edition of the session was attended by over 3,000 delegates and hosted over 200 exhibitors from all aspects of the electricity supply industry.

Leading into the session my intention was to attend as many of the different session types as possible with a particular focus on the B4, B5, C4 and C6 study committees. In addition to this, I was able to spend some time at the CIGRE Next Generation Network (NGN) booth meeting delegates from the other international NGN groups. From a personal perspective, the opportunity to meet so many young engineers at the NGN booth was a highlight of session. Being able to share experiences and discuss the different challenges that are being experienced within our home countries with someone at a similar stage in their career as myself was very rewarding. I am hoping to stay in touch with a number of the connections made during the week as we continue growing as engineers and potentially collaborating on different CIGRE working groups.

On the technical front, I was able to attend a number of the organised sessions and also give a short presentation during the NGN forum. Below is a summary of my key takeaways from a few of the sessions I was able to attend.

- NGN Forum:
    - As an active participant in this forum I gave a presentation on “Hardware-in-the-Loop Testing of a Microgrid Controller and LV STATCOM”. Having not submitted anything for the main session program, this presentation gave me a great opportunity to gain experience giving a technical presentation to an audience consisting of NGN members with various backgrounds. The presentation led to a few follow-up questions afterwards with members of the audience who had completed similar work and getting to share our findings and challenges was beneficial.
    - The presentations from other NGN members covered a broad range of topics and it was a good opportunity to learn a few techniques that will serve me well and help increase engagement in future presentations.

- B5 and C6 Poster Sessions:
    - I found the poster sessions to be the most beneficial of the session types on offer throughout the Paris session mainly due to how interactive they were. As the papers were available to delegates ahead of time, I was able to peruse the posters prior to attending the session and identify which of the poster authors I would like to talk with. This lead to

some really in-depth conversations and knowledge sharing with the presenters and I left with several takeaways to consider in my ongoing work.
    - In particular, I really valued the conversations I had with a couple of engineers from the Greek distribution system operator responsible for the operation of the islanded networks in the Greek isles. The power networks on the Greek islands share a lot of similarities with the islands in the Torres Strait that are part of Energy Queensland's network and are undergoing a very similar transition from diesel generation to renewable sources. It was great to discuss the different challenges being faced to gain an understanding of the approaches being taken in Greece and consider how these approaches could be applied in the Torres Strait.
    - A number of posters discussed the topic of dynamic operating envelopes and I enjoyed talking with these authors about some of the difficulties we are having with such a high penetration of rooftop solar in Energy Queensland's low voltage networks. It was nice to see that the work being undertaken within Energy Queensland is at the forefront of developments in this area.

- C4 Group Discussion Meeting:
    - A few of my key takeaways from the topics raised during the group discussion meeting:
        - There is concern about how harmonics are calculated in models of networks consisting of a high level of inverter-based resources (IBRs).
        - Low damping of harmonics characterises weaker networks with a high density of IBRs.
        - The power triangle capabilities of an IBR should consider a distortion factor when operating on weak networks as their output capabilities will vary depending on system strength.
        - In particularly weak networks, IBRs may need to be forcibly tripped when certain network conditions that could lead to a domino of disturbances are detected.
        - It seems that installing a BESS with higher rating than would normally be needed to provide sufficient fault current and in-rush currents is currently the preferred approach.
        - Positive results have been seen from setting a maximum admissible RoCoF to limit stability issues in a low inertia system.
        - Inertia is a real power service, therefore analysis needs to consider the real power response of the inverter. System strength is a reactive power service, therefore analysis needs to consider the reactive power capability of the inverter.

- Tutorial – System Integrity Protection Schemes (SIPS) in the Context of Evolving Power Grids:
    - The goals of SIPS is to detect contingencies and take necessary control actions in order to preserve system integrity. It goes beyond traditional protection which focuses on detecting a fault and making it safe. SIPS is about detecting potential conditions that may lead to something bigger such as a cascading of events.

  - In the future, more SIPS will be needed thanks to the growing complexity in power networks owing to the large increase in renewables. Load growth will also lead to potential problems and the consequences of outages will be greater.
  - Centralised SIPS is where the action is taken at one location from remote information. Decentralised SIPS is where the action to take is decided at several locations from information taken locally at those locations.
  - The concept of using digital twin networks as a SIPS has been experimented on with varying levels success. The accuracy of the model and how well it replicates the physical system is key.

- Workshop – Oscillatory Instability in IBR Dominated Grids:
  - Areas with high penetration of IBRs are now also starting to see subsynchronous oscillations. Subsynchronous oscillations are defined as oscillations having frequency less than the network's synchronous frequency (i.e. 50 Hz or 60 Hz).
  - Studies conducted with increasing levels of IBRs on the network have identified that subsynchronous oscillations increase with growing IBR levels.
  - Availability and validity of models is essential (including inverter models) since subsynchronous studies rely on highly detailed modelling.
  - Verification of the model against a real system is ideal, but time, cost and complexity constraints mean this is often not possible.

- Working Group Participation – B5.78 "New Requirements of Network Protection and Control for Renewable Energy Integration":
  - Attending the 2022 CIGRE Paris session increased my interest in getting more involved in the technical side of CIGRE's activities. Resulting from this, I have joined the technical working group B5.78.
  - The objective of B5.78, as defined in the terms of reference found here[10], is to review existing codes of practices and standards for protection automation and control systems to identify distinguishable boundaries which will help ensure selectivity and effective coordination of networks across the world. This is particularly relevant with the growing penetration of renewables and inverter based resources that are changing the status quo of how protection networks have traditionally operated.
  - To date, I have attended one work group meeting and I'm looking forward to getting involved in the technical review of current best practices. I will provide a progress update in following ES Cornwall Scholarship quarterly reports.

[10] CIGRE. (2022). *CIGRE Study Committee B5 – Proposal for Creation of a New Working Group, B5.78*

4 NOTES FOR FUTURE SCHOLARSHIP HOLDERS

Below are a few notes for future ES Cornwall Scholarship holders in terms of complications I faced when moving overseas. It should be noted that some of these points may be resolved/relieved in the near future as a new post-Covid19 normal is reached.

1. Visa Application: For the Netherlands, the current waiting period to process a visa application is approximately three months depending on the type of visa you are applying for. From what I have seen, most other European countries seem to have similar application times. Fortunately I had assistance from my employer to go through this process and was able to submit my application in June (well before my September starting date). I would recommend getting this process started as soon as possible to hopefully prevent any complications arising where your visa is not ready in time for you to start working.
2. Rental Accommodation: Be prepared to experience difficulty finding suitable rental accommodation. This will be highly dependent on where you are looking to move and the availability of rental properties. Despite submitting rental applications at a number of properties from approximately one month ahead of time, I was unable to secure something suitable until October. This meant one month of hopping between several temporary accommodation options such as Airbnb. To help make this process easier, I would recommend asking for advice from your employer and potentially exploring the option of having someone attend in-person rental inspections on your behalf. At the time I was applying, properties were finding new tenants on the same day as listing and therefore being someone applying only online did not help my chances.

5 PLAN FOR NEXT QUARTER (DECEMBER 2022 – MARCH 2023):

For the December 2022 – March 2023 period I will continue working with KEMA Labs in my current role. There are a few exciting projects already planned for the new year and I'm looking forward to the opportunity to gain more hands-on power electronics experience. At this stage, my end date with KEMA Labs will be the 24th of March.

Following this, the current plan is to commence working with National Grid ESO in Warwick (United Kingdom) on the 3rd of April. In the time leading up to this I will be busy submitting an application for a Skilled Worker Visa and organising rental accommodation in Warwick or the nearby area. Knowing now the delays and difficulties I am likely going to experience, I'll be submitting this application as soon as possible.

APPENDIX A – AC-DC CONVERTER OVERVIEW

The simplified schematic of a 3-phase AC-DC converter is shown in Figure 2. The switchmode AC-DC converter is more efficient than a simple rectifier diode based rectifier as it is able to better sample the incoming AC signal to produce an output closer to DC prior to the filtering stage.

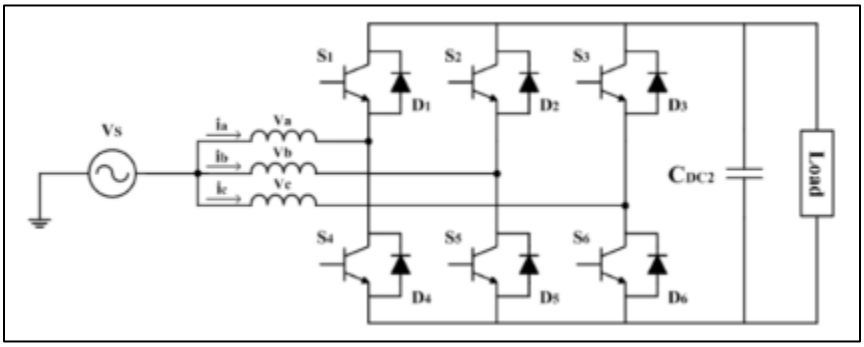

Figure 2: Simplified AC-DC converter schematic.

Breaking the converter down into two key stages, the rectifier bridge contains the switching transistors which chops the AC waveform into something closer to a DC signal and the output filter which can be a simple smoothing capacitor. It is vital to get the timing of the gate switching signals correct as this is what controls the DC output voltage of the converter. This is demonstrated in the timing diagrams shown in Figure 3 and Figure 4, where the output DC voltage can be seen to vary in relation to the firing angle of the gate pulsing signals.

Notes:

- To control the voltage level, the firing angle for the gate switching signals can be changed to sample different parts of the incoming AC signal.
- Output voltage (V_{DC}) can be calculated as a relationship with incoming AC voltage (V_{rms}) and the firing angle (α):

$$V_{DC} = \frac{3\sqrt{3}\sqrt{2}\,V_{rms}}{\pi}\cos(\alpha)$$

- AC-DC converters often also include a DC-DC converter on the output in order to further control the DC output of the converter.
- A faster switching speed allows for the pulsing to be performed more accurately and can result in greater efficiency.
- As the AC-DC converter is effectively shorting together different phases at different times during the rectification stage, the AC input signal will have some level of 'notching' which will result in harmonics being induced on the input signal. This distortion is one of the negative effects power electronics can have on an AC network.
- A simply AC-DC converter can be modelled in MATLAB Simulink as per Figure 5.

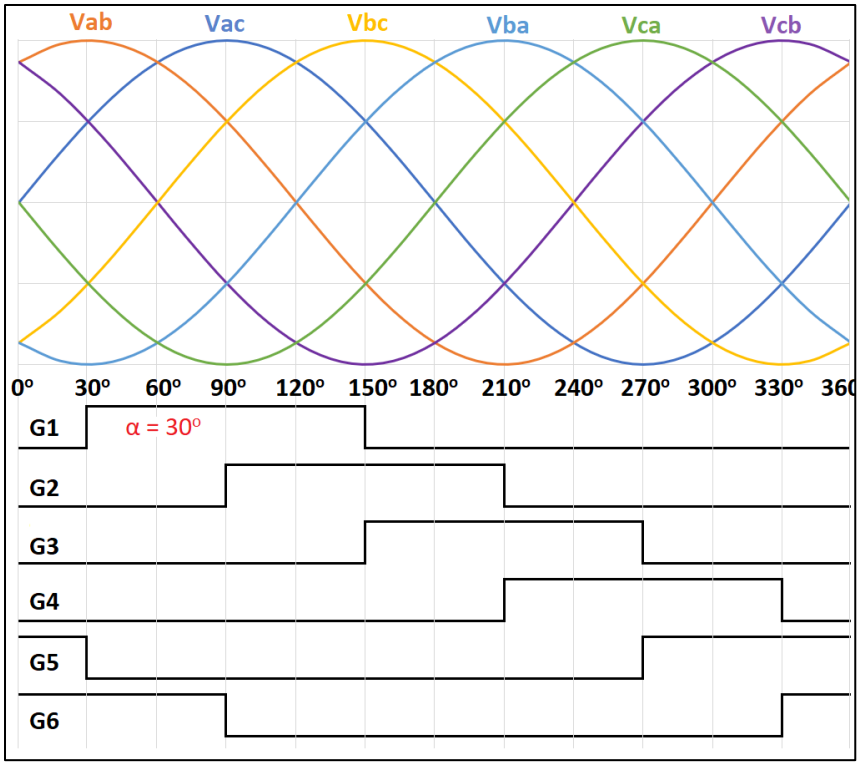

Figure 3: AC input waveforms and gate pulsing signals for a firing angle of 30°.

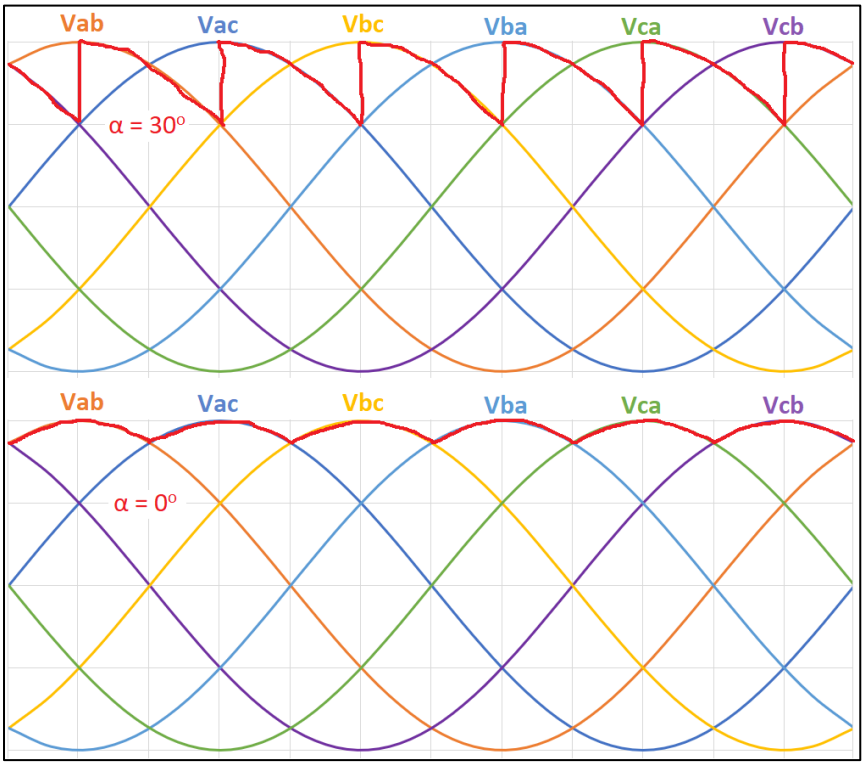

Figure 4: Comparison of resulting DC voltages (before smoothing capacitor) from a firing angle (α) of 30° and 0°.

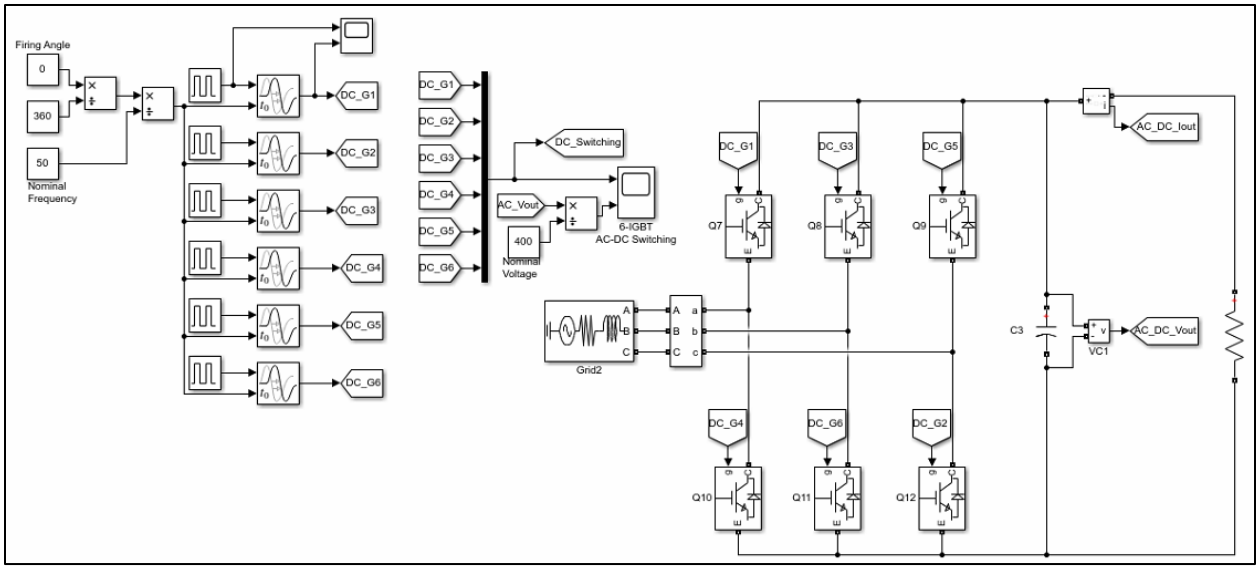

Figure 5: Example simple AC-DC converter model in MATLAB Simulink.