THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

ES Cornwall Memorial Scholarship

Second Quarter Report

1st December 2022 to 1st April 2023

KEMA Labs, Arnhem, The Netherlands

The KEMA Labs campus in Arnhem, The Netherlands.

Author: Mitchell Tap

07/04/2023

THE UNIVERSITY OF QUEENSLAND
AUSTRALIA

KEMA Labs

ACKNOWLEDGEMENTS

The author of this report would like to thank the employees of KEMA Labs in Arnhem for their help and support. Facilitating a six month placement is not always an easy thing to organise, especially with different Visa and residence permit complications, therefore I am appreciative of the extra effort that has been required from a number of employees on my behalf. In particular, I would like to thank my manager Dr. Erik de Jong (Head of Flex Power Grid Lab) for being the driving force behind making this placement possible and also for providing me with great opportunities to learn and grow as part of the Flex Power Grid Lab team.

In addition, my thanks to Don McPhail, Peter Vaessen and Jos van der Burgt for their assistance during my search for employment with KEMA. It was originally Don who put me in touch with Jos who in turn connected me with Erik and Peter to help make this placement possible.

I would also like to thank my managers at Energy Queensland, Alan Louis and Terese Milford, 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 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 December 2022 – April 2023 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 second of four reports I will submit during my time as an ES Cornwall Scholarship holder and covers my final three months with KEMA Labs. This report is a follow-on from my first quarterly report which, combined with this second report, forms a record of my time with KEMA Labs. Sections 1 and 2.1 have been replicated from the first quarterly report as these serve as background information and allow the two reports to be read separately.

In the three months covered by this second quarterly report, I have continued my involvement in projects undertaken at KEMA Labs' FPGL. In this time, we have completed follow-up testing on one of the battery chargers that was previously tested in the FPGL as well as performed capacity testing of a battery energy storage system (BESS). A summary of the lessons learned during these projects is as follows:

1. Fine art of tuning control loops of inverters/converters to respond to dynamic changes in load and source and how there may not always be a 'one size fits all' solution.
2. Battery capacity testing: Safety issues and the importance of pre-commissioning testing.
3. Voltage and current characteristics of a LFP battery during charge and discharge cycles.
4. Logistical challenges of testing and transporting large BESS units.

I was also fortunate enough to be taken on a tour of KEMA Labs' HPL and HVL and received an overview explanation of how they carryout short-circuit testing and cable testing (which I will discuss later in this report).

As of the 24th of March I have concluded my time with KEMA Labs and have moved across to England to undertake a placement with National Grid ESO commencing the 3rd of April. Again, I would like to thank my teammates in the FPGL Erik de Jong and Dan Gumeni for the last six-months. I enjoyed my time in the team and learnt a lot and I look forward to keeping in touch to hear about all the exciting things happening in the FPGL.

TABLE OF CONTENTS

Acknowledgements ii
Disclaimer ii
Executive Summary iii
Table of Contents iv
Glossary v
1 Scholarship Plan / Overview 6
2 Placement 1 – KEMA Labs 8
2.1 KEMA Introduction/Background 8
2.2 KEMA's High Power Laboratory (HPL) 10
2.2.1 Short-Circuit Testing of Switchgear 11
2.2.2 Short-Circuit Withstand Testing of Transformers 13
2.3 KEMA's High Voltage Laboratory (HVL) 13
2.3.1 Cable Prequalification Testing 15
2.3.2 Lightning Impulse Testing 15
2.4 My Involvement in the FPGL: 16
2.5 Battery Charger Testing 16
2.5.1 Lessons Learned 16
2.6 Battery Capacity Testing 18
2.6.1 Lessons Learned 18
2.7 Protection Relay RoCoF and Under/Over Frequency Testing 22
2.7.1 Lessons Learned 23
3 CIGRE Working Groups 25
3.1 Working Group B5.78 25
3.2 Working Group C6.44 25
4 Key Learnings and Takeaways From KEMA Placement 26
5 Plan for Next Quarter (April 2023 – July 2023): 26
Appendix A – HPL Photos 27
Appendix B – HVL Photos 29

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
EUT	Equipment Under Test
ESO	Electricity System Operator
FPGL	Flexible Power Grid Laboratory
HIL	Hardware-in-the-Loop
HMI	Human Machine Interface
HPL	High Power Laboratory
HVDC	High Voltage Direct Current
HVL	High Voltage Laboratory
IBR	Inverter Based Resource
IGBT	Insulated-Gate Bipolar Transistor
LFP	Lithium Iron Phosphate
PHIL	Power Hardware-in-the-Loop
RoCoF	Rate-of-Change-of-Frequency
RTDS	Real-Time Digital Simulator
SIPS	System Integrity Protection Schemes
SoC	State-of-Charge
TRV	Transient Recovery Voltage

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 – Power System Engineer
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 Flexible 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 KEMA'S HIGH POWER LABORATORY (HPL)

During my time at KEMA I was fortunate enough to be given a tour of the HPL to learn about the capabilities of the laboratory and to see first-hand the impressive lab design and test equipment on display. For this tour I'd like to thank Henk Vink and Erik de Jong. KEMA's HPL in Arnhem is world leading in the field of short-circuit, power arc and high power switchgear testing. With the capability to provide up to 52 GVA in a short-circuit test, the HPL is the world's largest short-circuit laboratory. The different types of equipment which may be tested at the HPL and examples of the available types of tests that can be performed on this equipment is provided in Table 3. An aerial view of the KEMA Labs facility in Arnhem is also provided in Figure 2 highlighting the different sections of the HPL.

Table 3: Types of equipment that can be tested and the types of tests available at the HPL.

Equipment Under Test	Available Tests
- Cables and cable accessories - Insulators - Power and instrument transformers - Switchgear - Surge arrestors	- Short-circuit - Switching - Power arc test - Internal arc test

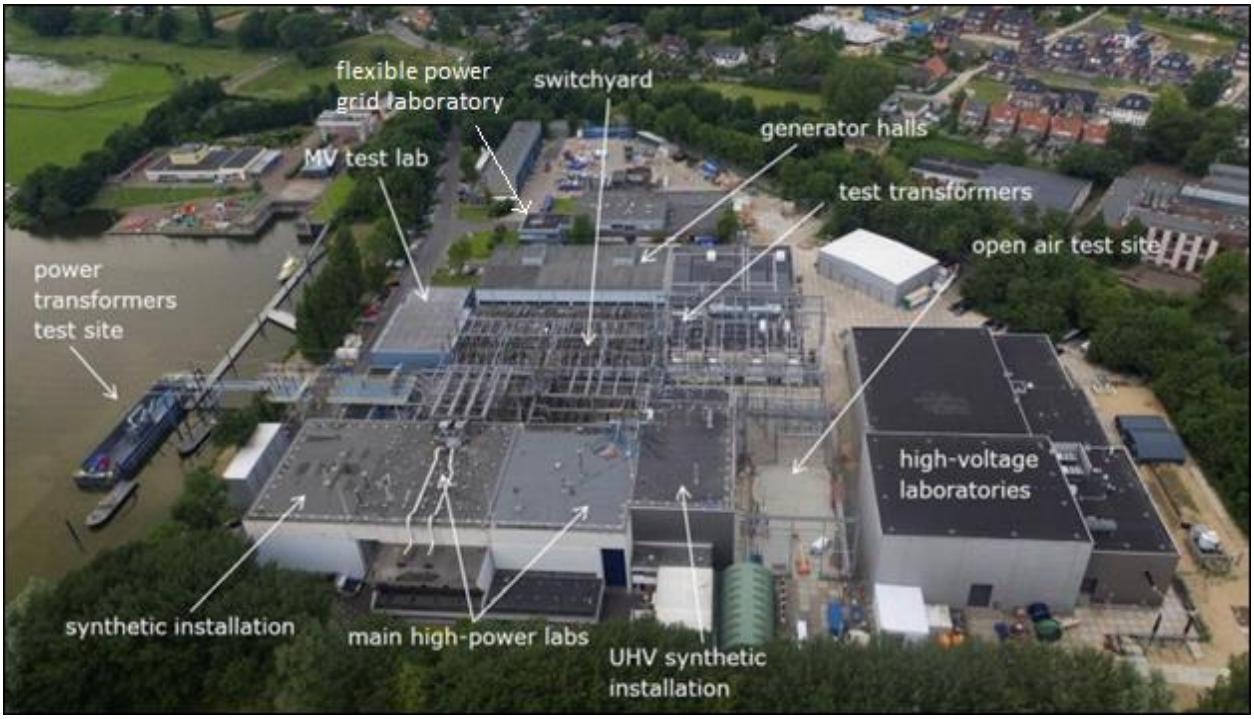

Figure 2: Aerial view of the HPL highlighting the layout of the different sections of the test facility[7].

[7] Smeets, R. 'Short-Circuit Performance Tests' (2019). Switching Equipment, CIGRE Green Books.

My key takeaways from the HPL tour are as follows:

- A few of the main ratings of the HPL's capabilities:
    - Short-circuit current of 20 kA for up to 300 ms is possible.
    - Six separate generators which can be operated in parallel to provide up to a total of 52 GVA energy for the short-circuit.
    - Maximum test voltage of 550 kV.
- Cooling for the generator, charging motors and variable frequency drives is both oil cooling for the primary side of the generator and water cooling for the remaining moving parts using water from the nearby Rhine river (at a temperature of approximately 7^{o}C).
- The generators which will issue the short-circuit current do not need to be at full voltage rating of the device as they are responsible for the current level and not the voltage. Having a generator do both would require a machine that is unfeasibly large as the power rating would need to accommodate up to 20 kA current at operating voltages as high as 550 kV.
- The test voltages are supplied by the synthetic lab which is comprised of supercapacitors, inductors and resistors that can be switched in and out to reach the desired voltage.
- Instead of using digital circuits for control signals, the PLC and other control circuits utilise compressed air at various pressures. Due to the amount of electromagnetic interference that the control circuits will get exposed to during the testing, digital circuits cannot always be relied upon. Consequently, pneumatic circuits have been used in the HPL. Optical fibre would also be possible however was not commonplace when the laboratory was originally built. In addition to this, the challenge of ensuring auxiliary voltages operate dependably at higher voltages is also overcome using the pneumatic approach.
- The generators have vibration suppression installed to separate them from the concrete building as the vibrations created during operation are enough to cause structural damage.
- There are a number of test bays utilised by the lab to provide flexibility in what can be tested. The majority of equipment under test will be tested in the indoor 'main high power labs' test bays, however an open air test site as well as a connection to a boat docking bay for large power transformer testing is also available.

2.2.1 SHORT-CIRCUIT TESTING OF SWITCHGEAR

The short-circuit testing of switchgear is performed as a synthetic test which combines a moderate voltage source that supplies the short-circuit current with a second high voltage, low current power source which injects a high voltage pulse at very precise timing near the natural zero point crossing of the primary short-circuit current. Using this method, the synthetic test is able to reproduce the conditions that the switchgear is exposed to during high current arcing and the subsequent voltage recovery periods.

KEMA's HPL uses the parallel current injection method of synthetic testing to perform short-circuit testing. The simplified circuit diagram for a parallel current injection test circuit is provided in Figure 3. Accompanying pictures taken within the HPL of some of the major components can be found in *Appendix A – HPL Photos*.

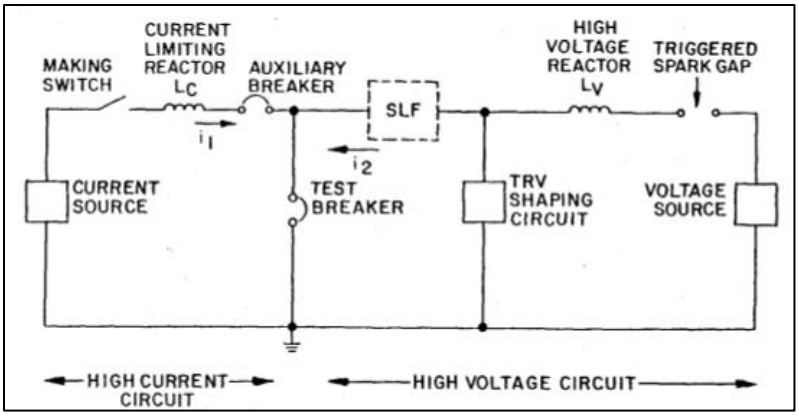

Figure 3: Simplified single-line diagram of synthetic test circuit for short-circuit testing of switchgear.

Here I will do my best to explain the major components in the synthetic test circuit that I was shown during the HPL tour with assistance from the information found here[8].

- Current Source: The HPL uses a large generator with over-excitation, and variable frequency drive to act as the current source. This will generate the short-circuit current to be used for testing.
- Master Circuit Breaker: Responsible as the last resort for protection of the test equipment in case the switchgear under test fails. The master circuit breaker must be able to break the short-circuit current as quickly as possible – In the HPL, the master circuit breaker has a clearing time of approximately 7 ms.
- Making Switch: To apply the short-circuit current at the required time during the test. The making switch will connect the generator to the test circuit and must be extremely precise and high speed to ensure minimal energy is lost due to pre-arcing.
- TRV Shaping Circuit: This circuit will control the transient recovery voltage (TRV) of the switchgear under test. The TRV of the HPL is made up of configurable resistors, capacitors and inductors which can be switched to get the desired result.
- Triggered Spark Gap: The timing for voltage injection into the test circuit needs to be very precise. The triggered spark gap ensures that the high voltage from the voltage source is applied at the desired moment. It also removes the need of having switchgear with a rating high enough to support the testing and ensures that the energy is sent from the source to the test equipment with minimal energy loses.
- High Voltage Source: A charged capacitor bank is most commonly used as the high voltage source in the synthetic circuit. Depending on the voltage required, the capacitor bank installed at the HPL can be configured to higher or lower voltages by switching more or less capacitors into the voltage source circuit.

Below is an overview of what a normal day of testing at the HPL could look like including the key steps in the short-circuit test:

1. The generator (current source) is brought up to idle speed at the beginning of the day using a 10 kV grid connection. Rate of speed increase is kept relatively low to remain below the level allowable from the grid operator.

[8] Synthetic Testing of Circuit Breakers (2015). https://harryskon.wordpress.com/2015/04/14/synthetic-testing-of-circuit-breakers/

2. When the test is ready to be performed, the generator will be brought up to required operation speed to generate either a 50 Hz or 60 Hz short-circuit current.
3. Once the generator is ready to inject the short-circuit current, it will be disconnected from the grid to ensure a disturbance is not seen by the grid. The test should be performed as soon as possible after disconnection from the grid as the generator will be losing speed the longer it is disconnected causing the resultant short-circuit current to fall. The short-circuit current from the generator will not be at full voltage, the required voltage will be supplied by the high voltage source (charged capacitor bank).
4. Prior to injection of the short-circuit current, the synthetic lab will have been configured to the correct voltage level and the TRV circuit will have been configured to the required post short-circuit recovery voltage.
5. The equipment-under-test (EUT) will be exposed to the short-circuit current for the required test time. This may be a single short pulse or it may require the current to be held for longer, for example for reclose testing.
6. Once the breaker under test opens and a voltage is detected, the triggered spark gap will bring the voltage source into the circuit just prior to the zero-crossing of the current to subject the EUT to the test voltage and desired recovery voltage.
7. After the test time expires, the breaker under test should have broken the short-circuit. Failing this, the master circuit breaker will open to safely end the test.
8. The generator will then be resynchronised with the grid and brought back to idle speed in preparation for future tests.
9. At the end of testing, the energy in the generator will be exported back to the grid again at a level agreed upon with the grid operator to not cause a disturbance on the network.

2.2.2 SHORT-CIRCUIT WITHSTAND TESTING OF TRANSFORMERS

Short-circuit testing of transformers is similar to the short-circuit testing for switchgear however the transformer is instead being tested to see if it can withstand the short-circuit current without causing damage to the transformer (such as internal windings). The transformer must withstand the short-circuit current for at least as long as the time it takes for the transformer's protection circuit breaker to clear the fault (this could be in the order of approximately 300 ms).

The test process is very similar to that described in Section 2.2.1 however the test breaker is replaced with the transformer under test and an additional circuit breaker is added in series with the transformer. This additional circuit breaker is responsible for breaking the short-circuit current as the master circuit breaker should only be used as a last resort. The synthetic lab (i.e. the voltage source) is not used in this test configuration as the generating circuit will maintain the short-circuit current for the duration of the test.

2.3 KEMA'S HIGH VOLTAGE LABORATORY (HVL)

Following the HPL tour, I was also fortunate enough to be taken on a tour of KEMA's HVL and would like to thank Peter Vaessen both for this tour and for his extra insights into the future of HVDC and high voltage transmission. During the tour I was able to witness a number of ongoing land and sea cable tests in addition to the test equipment that makes up the laboratory. Table 4 contains the usual equipment under test and the types of tests the HVL is capable of performing on this equipment. *Appendix B – HVL Photos* also contains

a few pictures of the HVL's test equipment to help gain an idea of what makes up the laboratory. The HVL located at KEMA's Arnhem facility is rated up to 1.2 MV AC. HVDC cable testing is performed at a different KEMA facility.

Table 4: Types of equipment that can be tested and the types of tests available at the HVL.

Equipment Under Test	Available Tests
- Cables (both land and sea) and cable accessories - Insulators - Power and instrument transformers - Switchgear - Surge arrestors	- Both HV AC and HV DC testing possible - Prequalification test - Dielectric test - Type test - Mechanical and material property tests

Below are my main takeaways from the HVL tour:

- Typically, the high voltage testing is performed at negligible power levels with current remaining close to zero. As a result of this, if a current greater than a few milliamps is measured at any point during the test it will likely mean something is wrong in the test setup or with the EUT.
- The wire/cable carrying the voltage is quite small (radius less than a couple of centimetres) as it does not need to carry significant current. This was a stark contrast to the large cables and busbar required in the HPL.
- The HVL also performs synthetic testing where a current generating circuit is brought into the test to subject the EUT to the required current levels.
- Due to the high voltage nature of the testing, there are a large number of anti-corona rings that must be installed around the test equipment, on the EUT and in the general lab area to safely manage the large fields that are created by the high voltage. An anti-corona ring is a toroidal core of conductive metal (aluminium is commonly used due to light weight) that has the purpose of distributing the electric field gradient around high voltage installations. They ensure the field gradient stays below the corona threshold therefore preventing any corona discharge.
- High voltage laboratories require high ceilings to ensure there is a sufficient air gap to prevent discharge from the high voltage equipment to the building roof and walls. Consequently, the height of the ceiling will typically indicate the voltage levels that can be tested in the building.
- Cables must go through prequalification testing before full manufacturing can commence.
- HVDC cable testing is becoming increasingly in demand as voltage levels get higher and the required length of transmission lines continues to grow. An example where this is especially relevant is offshore wind farms and HVDC interconnectors.
- Approximate figures for losses of HV AC is 4 % /100 km compared to only 0.4 % / 100 km for HVDC due to the reduction in heat losses from skin effect, proximity effect and corona that are associated with alternating current.

2.3.1 CABLE PREQUALIFICATION TESTING

Cables used in power systems are required to be high-quality with minimal chance of failure. As the lifetime of a cable is typically over 30 years, it is not feasible to wait until a cable can be tested for this full duration before deeming it to be suitable for installation. Instead, prequalification testing, performed as per IEC 62067:2022, subjects a 100 m sample of the cable to an accelerated thermal cycle test under voltage for a duration of one year[9]. The sample of cable being tested shall also include at least one joint section and at least one termination. The stresses placed on the cable from this testing will simulate the stress a cable endures over its lifetime. Depending on the intended installation of the cable, it may also be buried in different media, such as water or soil, for the prequalification testing and may include sections with different bending radiuses. In addition to this long-term cycling testing, a lightning impulse test will also be performed on a sample of the cable. Following these tests, an examination of the cable will be performed to determine whether there are any signs of deterioration which would indicate it may not be suitable for long-term use.

2.3.2 LIGHTNING IMPULSE TESTING

Power system equipment will likely be exposed to high voltage scenarios throughout its lifetime either as a result of a fault condition or natural phenomena such as lightning strikes. It is therefore vital that the equipment is designed to be resilient to these occurrences to prevent substantial damage, or at a minimum ensure failure modes are safe (i.e. exploding equipment does not damage other equipment or injure personnel). Lightning impulse testing, or simply voltage impulse testing, is the type of testing performed on equipment to assess its performance to such occurrences.

KEMA's HVL in Arnhem has a few voltage impulse generators capable of performing this testing at different voltage levels. For reference, a picture of one of these is provided in *Appendix B – HVL Photos*. The voltage impulse generator must have an extremely fast rise-time for voltage in order to appropriately mimic lightning strikes and other high voltage scenarios. This is why capacitor banks combined with a spark gap to simultaneously apply the voltage from all capacitors is used in the generator. The operation of the impulse generator and the test process is summarised as follows:

1. The impulse generator's capacitors are charged in parallel through resistors to allow charging at a lower voltage from a current source.
2. Once the capacitors have reached the required voltage level, they will be switched to be connected in series to achieve the required high voltage test voltage.
3. The spark gap distance within the impulse generator will be configured to ensure the correct voltage is applied to the test circuit.
4. When the test circuit is ready, the capacitor banks will be discharged simultaneously via a spark-over of the spark gaps. This applies the high voltage to the EUT and therefore performs the lightning impulse test.

[9] Pultrum, E. Sloot, W. Fernandez, J and Gu, B. 'How to Perform a Prequalification Test' (2015). 9th International Conference on Insulated Power Cables.

2.4 MY INVOLVEMENT IN THE FPGL:

As a Test Engineer within the Flexible 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 in my six 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 to 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 during the December 2022 until April 2023 period at KEMA Labs.

2.5 BATTERY CHARGER TESTING

In a follow-up to the battery charger testing that was discussed in my first quarterly report, one of the battery charger manufacturers returned to repeat power quality and dynamic performance testing of their system.

2.5.1 LESSONS LEARNED

1. Fine tuning of control loops to meet strict dynamic response criteria:

The acceptance criteria for the battery charger's dynamic performance was for the steady-state settling time to be less than 50 ms, the overall transient settling time to be less than 100 ms and the maximum voltage transient to be less than ± 15 %. Fortunately, the battery charger was able to meet this criteria as shown in Figure 4 and Figure 5 however only after some fine tuning of the voltage control loop parameters to reduce the transient settling time.

For me it was interesting to see the level of tuning of the dynamic response of the device still available with only software changes. It was also beneficial gaining further insight into how the response of the device will slightly differ depending on where it is installed and the characteristics of both the source and load it is connected to. This suggests that even though the device passed the acceptance criteria during lab testing, it may need retuning once installed in its final destination. This highlights the need to repeat certain tests of devices following final commissioning to ensure its performance is as required.

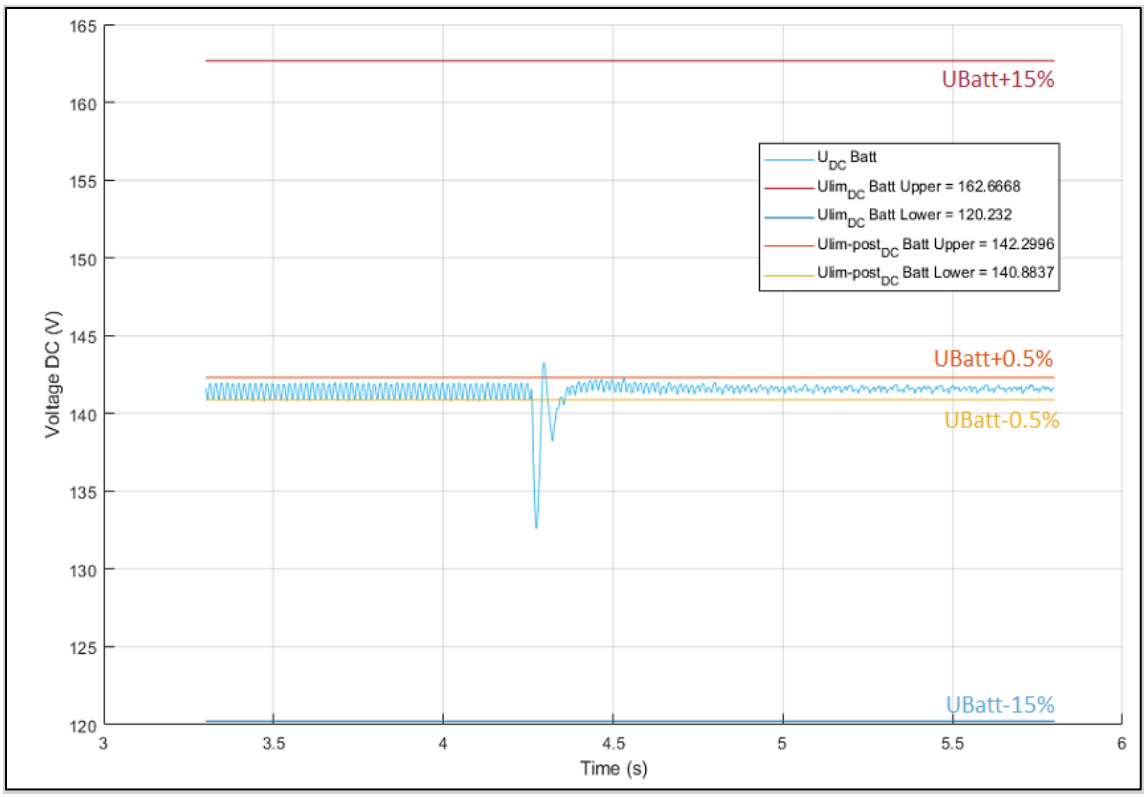

Figure 4: Dynamic voltage response of battery charger to a load jump of 0 % - 100 %.

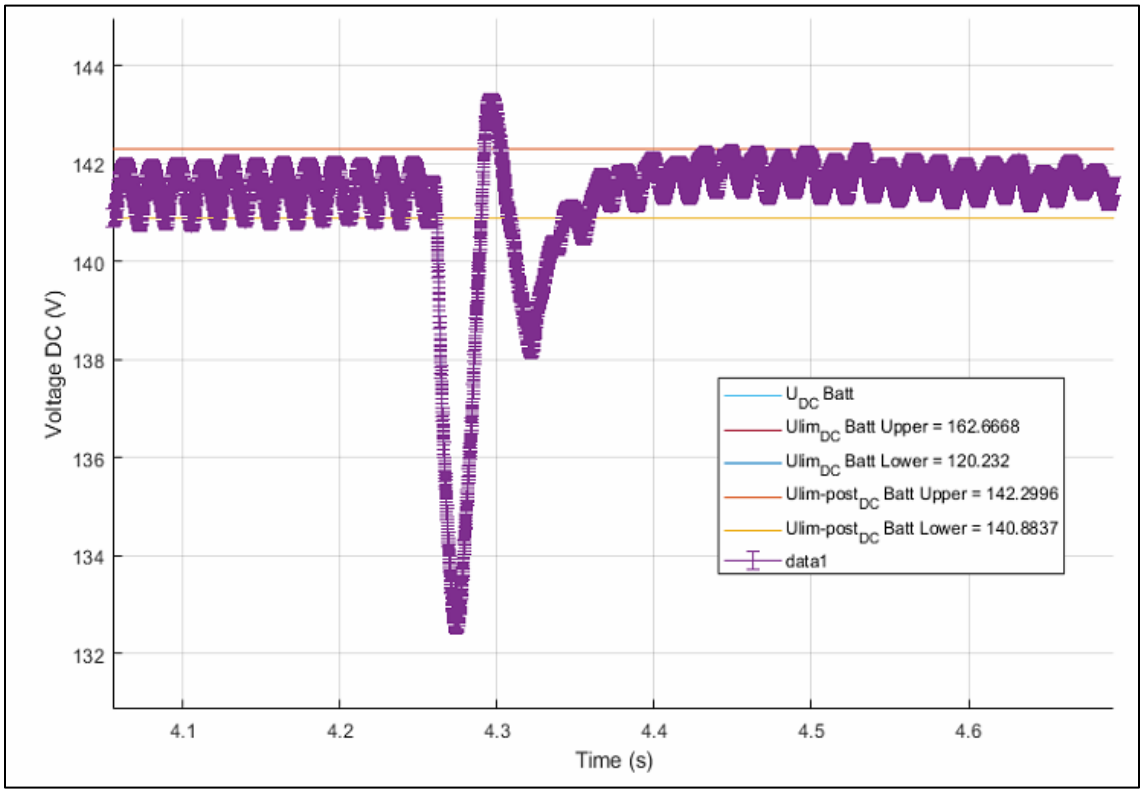

Figure 5: Zoomed-in capture showing return to steady-state voltage (with measurement sensor error bars included).

2.6 BATTERY CAPACITY TESTING

In February, a 1330 VDC, 2.6 MW, 2.6 MWh lithium iron phosphate (LFP) battery system was tested at the FPGL. The BESS was to undergo capacity and chiller control testing along with other commissioning checks prior to being transported to its final installation site in Greece. Once installed, the BESS will be paired with an existing solar installation to solar soak during the day and provide energy during the night as well as act as a backup service in the event of a grid failure. The BESS as it was installed at the FPGL is pictured in Figure 6.

Testing performed on the BESS was purely DC, except for the AC connection required for auxiliary devices such as the chiller, as the accompanying AC/DC converter was not involved in this testing. The goal of the capacity test was to firstly confirm that the complete BESS was working as expected and secondly to verify the capacity of the batteries. Capacity testing was a simple full charge at a constant power rate of 1.2 MW followed by full discharge at 1.2 MW. The efficiency of the BESS was also calculated from this test.

Figure 6: BESS installation for capacity testing at the FPGL.

2.6.1 LESSONS LEARNED

1. Logistical challenges associated with transporting and moving a heavy BESS:

The BESS tested at the FPGL consisted of five separate blocks each 2896x1640x3050 mm and weighing in the range of several tonnes (combined weight of the five units was 37 tonne). To install at the test location a forklift could not be used to position the blocks and a crane was required. Luckily the test location had sufficient room to allow a crane to be used, however this could lead to installation difficulties depending on the final installation site of the system.

In addition to this, there are safety requirements in place for the transport of lithium battery cells. One of these that became a problem during testing was the requirement to not transport the lithium batteries at a SoC greater than 30 % of their rated capacity as per the 2023 Lithium Battery Shipping Regulations. Care should also be taken to not transport the batteries at a SoC too low as this could lead to longer term battery damage if the SoC naturally drops below safe levels due to inherent loses during transportation.

2. Thermal safety systems and fire suppression in battery cabinets:

While I was already well aware of the fire risk posed by batteries, and in particular lithium-based batteries, it was good to see first-hand some of the detection, prevention and suppression tactics used in the BESS. These include:

- The different stacks were separated with an air gap to attempt to limit the further spreading of a fire if one of the stacks was to experience a fault leading to fire.
- Cell temperature monitoring on all battery cells with protection in place to cease operation if higher than expected temperatures are detected.
- Fire detection and suppression units in every stack.
- Fire suppression unit is used as a last resort. Although the suppression unit should be able to extinguish a fire in most cases assuming it is detected early enough, the battery cells will no longer be usable after being exposed to the fire suppression chemicals.

Despite all of these measures in place it is still possible for a fault to result in one of the cells catching fire. In this instance there is enough energy in the system that it may not be possible to extinguish the fire. Best practices for how to control and extinguish battery fires are still a work-in-progress however current recommendation is to try to prevent the further spreading of the fire to adjacent battery stacks. A battery fire will also release potentially toxic gaseous chemicals therefore a BESS risk management manual also needs to consider when and how to evacuate personnel in the case of a fire.

3. Voltage and current characteristic of the batteries during charging and discharging cycles:

During the constant power capacity test it was interesting to observe how the voltage and current of the batteries varied at different levels of SoC despite the charging and discharging power being held constant at 1.2 MW. As can be seen in Figure 7, the battery voltage and current are mostly steady throughout the charge and discharge periods except for the very low and very high SoC regions. The battery voltage can be seen to decrease sharply at low SoC and increase sharply at high SoC. Conversely, the battery current increases sharply as the battery cells approach very low SoC and it requires a higher current to perform charging at these low SoC levels. Aside from this low SoC region however, the charging and discharging current is mostly constant with a slight decrease for higher SoC levels inversely proportional to the increase in voltage.

Amongst other things, this characteristic of a sharp increase/decrease near maximum and minimum SoC emphasises the importance of a reliable battery management system to control the charging and discharging. If the battery cells were to accidentally be overcharged or overdischarged as a result of maintaining unsafe current levels and cause the cell voltage to leave the operability region, it is possible for the damage to be irreversible or in the worst cases lead to catastrophic failure. Careful attention must therefore be taken to

ensure the battery management system knows the charge and discharge characteristics of the batteries and how to best prevent unsafe operation of the battery.

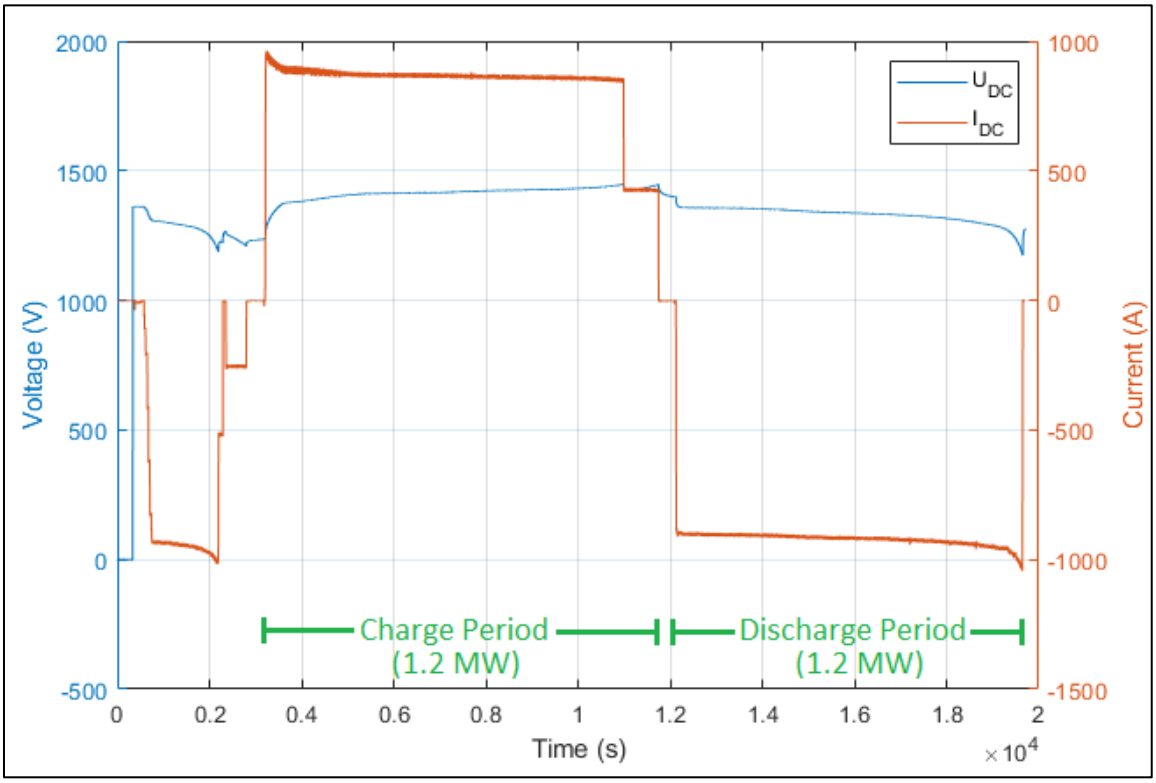

Figure 7: Voltage and current characteristics during charge and discharge periods.

4. Effect of cell temperature on the possible charge and discharge rates:

In addition to performing capacity tests of the BESS, the FPGL testing presented a good opportunity to verify the performance of the BESS's chiller and heater units. The battery cells have a predefined temperature operability range in which they must be maintained in order to perform to specification. Not only does this relate to battery performance, operating the battery cells outside their recommended range may lead to long term damage and/or catastrophic failure such as fires. Below are number of potential effects that can arise due to operating the battery outside of its operability region:

- Charge and discharge rates will be restricted,
- Battery capacity will be decreased at both high and low temperatures,
- The battery efficiency will be reduced,
- Overheating can lead to thermal runaway events, and
- Time spent at unsafe temperatures, even if the cell is not being operated, may have long term effects on battery state of health and can permanently damage the chemistry of the battery.

5. Importance of the chiller and heater in ensuring batteries are within operability region:

The particular BESS that underwent testing at the FPGL had both chiller and heater capabilities installed with a control system used to ensure all cells were kept within their required temperature range. Each battery stack had liquid cooling hoses filled with glycol that was circulated throughout the system. The cooling liquid was heated or cooled, depending on what was required, to a suitable temperature by the chiller or heater prior to being circulated throughout the system.

I enjoyed learning about the importance of cell temperature with respect to battery safety and performance and now understand why it is so vital to ensure the cooling/heating system is reliable with accurate cell temperature measurements being taken. Not only do the chiller and heater add additional maintenance requirements to the overall BESS unit, but the pumps used for liquid cooling also require frequent maintenance to prevent their failure from limiting operation of the BESS.

6. Bolt torque and the effect of loose joints:

This BESS was my first experience of testing a device at a power level greater than 1 MW. One aspect of this installation that caused me to gain a further appreciation was the importance of bolt torque on ensuring a solid joint both mechanically and electrically. With any of the electrically conductive joints, such as connections to the busbar, the role of the bolt, nut and washers is not only to ensure a solid mechanical connection but also to ensure losses and potential hazards resulting from a poor electrical connection are minimised. Poor electrical connection may even cause failure due to overheating of the joint. Below are a few takeaways for ensuring correct fastening of connections:

- Bolts can be both too loose and too tight therefore it is not sufficient to simply tighten a bolt as much as possible.
- A wrench with a torque reader should be used to tighten all nuts and bolts to the specified level for that particular nut and bolt.
- All connections should be marked with a permanent marker to show how tight the bolt was at the time of installation to allow later checks of the joint during maintenance to see if the bolt has loosened over time.
- Throughout commissioning, a temperature sensor/reader should be used to check if any of the joints are exceedingly hot both during and after operating the system. This could indicate a poor connection and will likely be a weakness in the system which may accelerate failure.
- All connections should be visually checked after commissioning tests and during maintenance runs to ensure there are no signs of arcing or welding.

During the capacity test it was noticed that one stack of battery cells was performing worse than the other six stacks leading to further investigation of the charging current. Looking closely at the measured charging current for that particular rack instead of the BESS as a whole showed signs of arcing. This necessitated a visual inspection of the stack and its connections which ultimately led to the finding of a loose connection with visible signs of arcing as shown in Figure 8. Had this not been noticed and left as is after final commissioning this will likely have led to accelerated deterioration of the joint over time and eventually catastrophic failure.

Figure 8: Visible signs of arcing resulting from loose joint on busbar.

2.7 PROTECTION RELAY ROCOF AND UNDER/OVER FREQUENCY TESTING

Similar to the solar inverter testing performed in my first three months at KEMA, the OPAL-RT was used to conduct RoCoF and under/over frequency tests on two feeder protection relays. The extra complexity in the tests which necessitated the use of the OPAL-RT and amplifier was the requirement that the source voltage had a number of certain harmonics present as per the standard IEC 60255-181:2019 Section 6.6 (*Performance with harmonics*) and shown in Table 5 and Figure 10. The test procedures followed were also stipulated by this standard. Tests were conducted in closed-loop with the OPAL-RT with the relay's trip signal being sent back to the OPAL-RT to trigger data processing and results saving as per Figure 9.

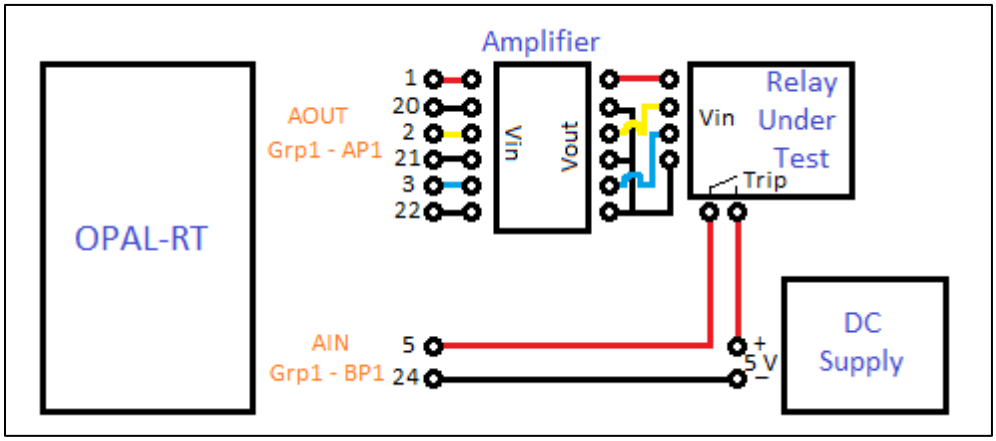

Figure 9: Test setup for feeder protection relay testing.

Table 5: Superimposed harmonics for testing frequency performance of protection relay.

Harmonic Order	Harmonic Percentage (%)	Harmonic Order	Harmonic Percentage (%)	Harmonic Order	Harmonic Percentage (%)
2	3.0	11	5.0	20	1.0
3	6.0	12	1.0	21	1.75
4	1.5	13	4.5	22	1.0
5	8.0	14	1.0	23	2.8
6	1.0	15	2.0	24	1.0
7	7.0	16	1.0	25	2.6
8	1.0	17	4.0	26 to 40	1.0
9	2.5	18	1.0		
10	1.0	19	3.5		

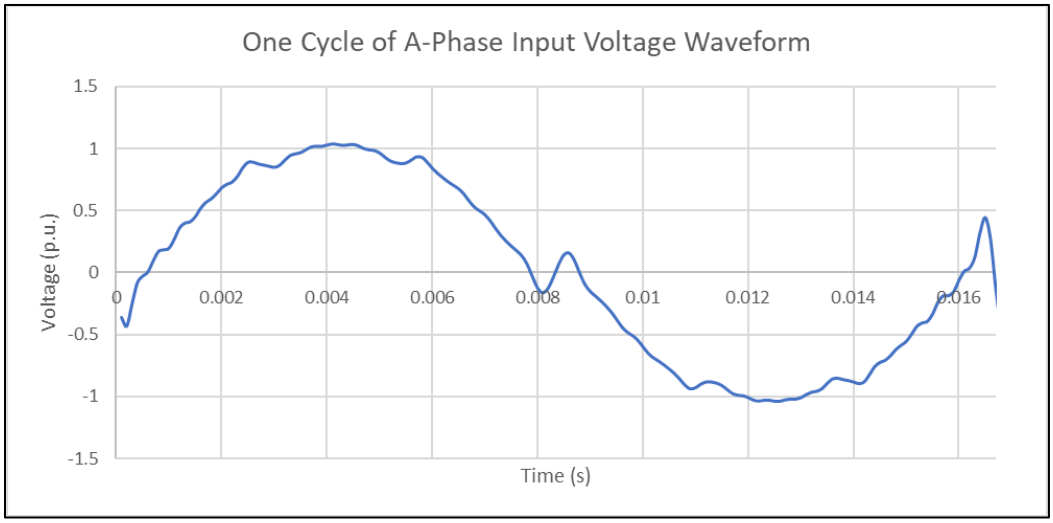

Figure 10: One cycle of input voltage waveform (phase A only) for testing relay performance with harmonics present.

2.7.1 LESSONS LEARNED

1. Digital relay control algorithms and programmable hysteresis:

Both relays under test were digital relays – meaning that the relay would take measurements of the incoming voltage and current, digitise these measurements, and process and react based on the control logic programmed into the relay.

During testing there were a significant number of protection operation points where the trip signal contact would oscillate ('chatter') repeatedly at the edge of the desired operation boundary. This is a result of the digital relay's settings for trip and reset values being too close. In older mechanical relays there is an inherent hysteresis which prevents this from happening as the trip value will be higher than the reset value by a margin determined by the characteristics of the components which make up the relay. This means that the trip contact will not oscillate on the protection boundary value as there will be a buffer. For example, a trip value of 60.8 Hz may have a reset value of 60.75 Hz (i.e. a 0.05 Hz buffer) meaning that any slight inaccuracies in measurements will not cause the contact to repeatedly operate as this inaccuracy will be less than the hysteresis buffer. For a digital relay, this hysteresis value must be programmed into the control algorithm. For one of the tested relays, there was a level of hysteresis programmed while for the other this

was not the case. The trip contact of the second relay was seen to experience significant chattering at the protection operation points. While in reality this is not likely to be an issue, as it is very unlikely for the monitored signal to be exactly at the protection operation point (with an accuracy at the scale of a few millihertz), it is still worth considering as this will place additional stress on the relay's contacts during commissioning and maintenance and may reduce the lifetime of the relay.

2. Effect of superimposed harmonics on the relay's operation:

During testing of the relay's under/over frequency and RoCoF algorithms, it was consistently seen that the operation would slightly change when the incoming voltage signal contained harmonics. This served as a good reminder that the voltage and current signals that real-world devices will be subjected to are not the clean waveforms that are often used during design and testing. Device testing should therefore also include testing to verify the performance of the device in non-ideal, but realistic, power quality conditions. In addition to source signals with different power quality levels, it is also beneficial to test devices with different strength source networks as they may behave differently when connected to strong or weak networks.

3 CIGRE WORKING GROUPS

3.1 WORKING GROUP B5.78

Topic: *New Requirements of Network Protection and Control for Renewable Energy Integration*
Terms of Reference: Available here[10]
Objective:
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.

Updates:
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.

3.2 WORKING GROUP C6.44

Topic: *Nodal Value of Distributed Renewable Energy Generation*
Terms of Reference: Available here[11]
Objective:
To discuss and analyse in practical terms how the variable renewable energy nodal value concept could be applied more broadly and systematically by public and private power sector planners and investors. This would allow for the joint optimisation in distribution and generation expansion of the scaling up of distributed variable renewable energy investments in different countries and energy system contexts.

Updates:
I am currently awaiting my first working group meeting since joining the working group to learn how I can best get involved. I hope to provide a better update in my third quarterly report.

[10] CIGRE. (2022). *CIGRE Study Committee B5 – Proposal for Creation of a New Working Group, B5.78*
[11] CIGRE. (2021). *CIGRE Study Committee C6 – Proposal for Creation of a New Working Group, C6.44*

4 KEY LEARNINGS AND TAKEAWAYS FROM KEMA PLACEMENT

During my placement at KEMA I have really enjoyed getting to be more hands-on and predominantly focused on the testing of power electronics devices. I believe that working in this area on a day-to-day basis has allowed me to accelerate my understanding of the technology and I hope that this will set me up in good stead when it comes to using similar technology in my future endeavours.

Probably my most significant takeaway from my time spent working in the FPGL is the variability in power system devices and therefore the required flexibility in the equipment used to test these devices. As the industry continues to see rapid advancements in technology and is experiencing a significant transition in the way the power network is operated, there are a large number of device types that are being developed and tested for the first time. It is therefore vital that the test techniques and equipment used to test these devices maintains pace with the changes.

While at the FPGL I grew my understanding of power electronics as a test device through the use of amplifiers and bi-directional DC supplies as grid simulators, loads and hardware interfaces for power-hardware-in-the-loop testing. Therefore, not only did I gain experience through working on the devices we were testing, but also through the different ways we could use the test devices. This helped me understand the characteristics of power electronics from a power quality perspective and therefore also their limitations. With the electricity industry seemingly heading towards a network with significant penetration of inverter based generation along with network stability being provided by technology such as grid-forming inverters, I am hoping that this experience will help me with future projects I come across in my nominal role at Energy Queensland.

5 PLAN FOR NEXT QUARTER (APRIL 2023 – JULY 2023):

I have now moved across to Warwick in England to commence a role with National Grid ESO. I have joined the Operability Product team as a Power System Engineer and I'm looking forward to immersing myself in all things relating to network stability, voltage management, short-circuit levels and grid-forming inverters.

Having not worked at an energy network/system operator before I am keen to learn all I can about what it takes to operate the network in more detail than what I am familiar with from my time working at the distribution network level. Given that the UK network is at a similar stage in the energy transition as Australia I know there will be a lot of similarities between the two networks and I am looking forward to seeing the different successes and challenges that have already been experienced in the UK. In particular I will be trying to learn as much as I can about the ongoing work relating to using grid-forming inverters to support network stability and inertia as this is a hot topic currently in Australia as the closure of baseload synchronous generators continues.

Also in the next three months I am hoping to attend the CIRED 2023 Rome conference in June if timing and my work schedule allows for this.

APPENDIX A – HPL PHOTOS

Figure 11: HV switchyard between generator (current source) and the test bays.

Figure 12: Synthetic lab highlighting a few of the key components that are configured for the high voltage source and the transient recovery voltage.

APPENDIX B – HVL PHOTOS

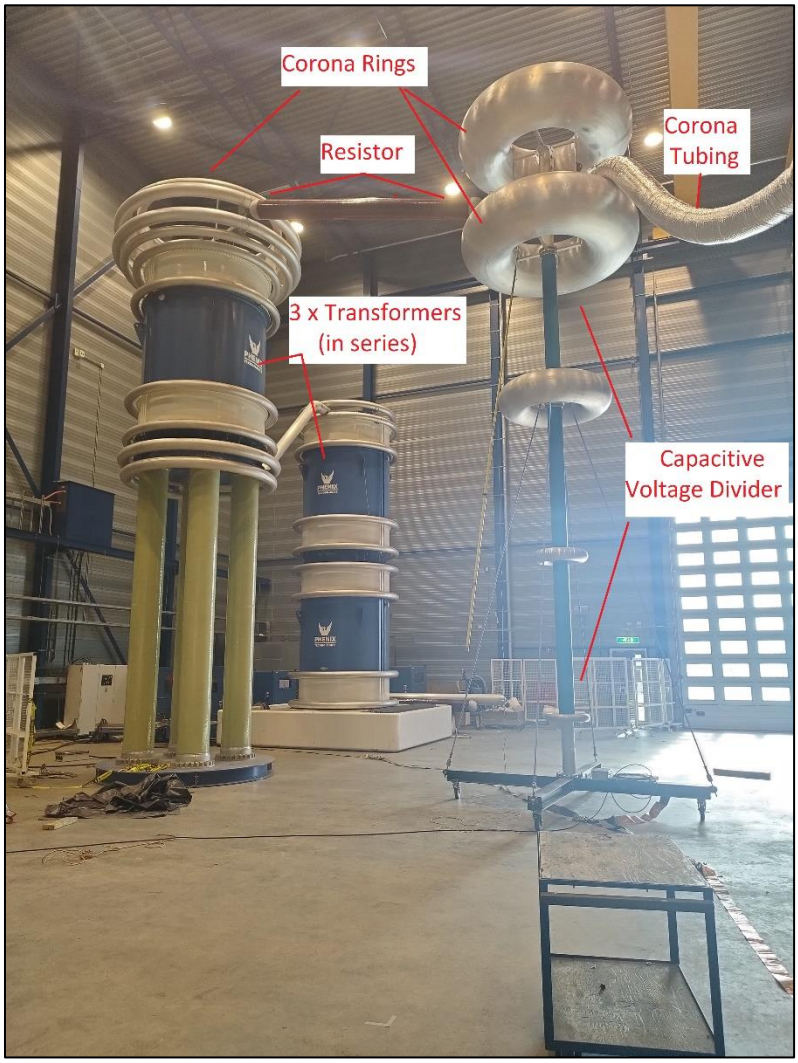

Figure 13: Transformers and voltage divider used as one of the high voltage sources in the HVL.

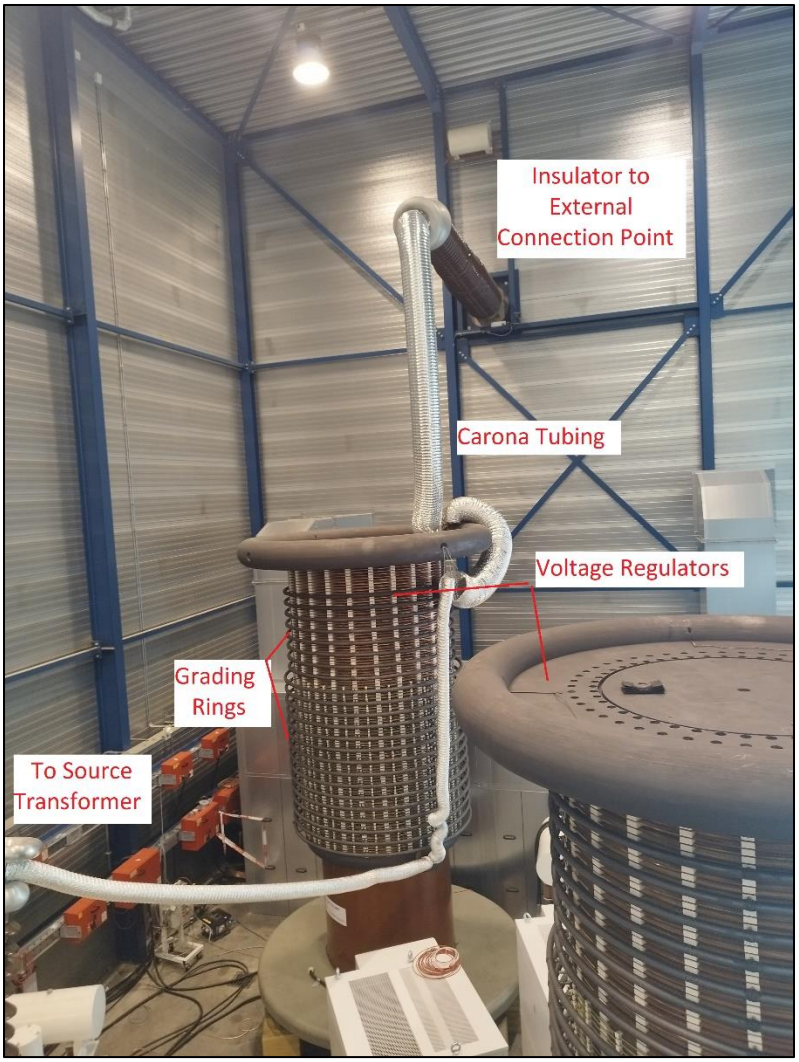

Figure 14: Voltage regulators used to step-up source transformer voltage to required voltage level for outdoor prequalification cable testing.

Figure 15: Voltage impulse generator used in HVL for lightning impulse tests and dielectric tests.