

FAN Workstream 3

Converters and enabling technologies

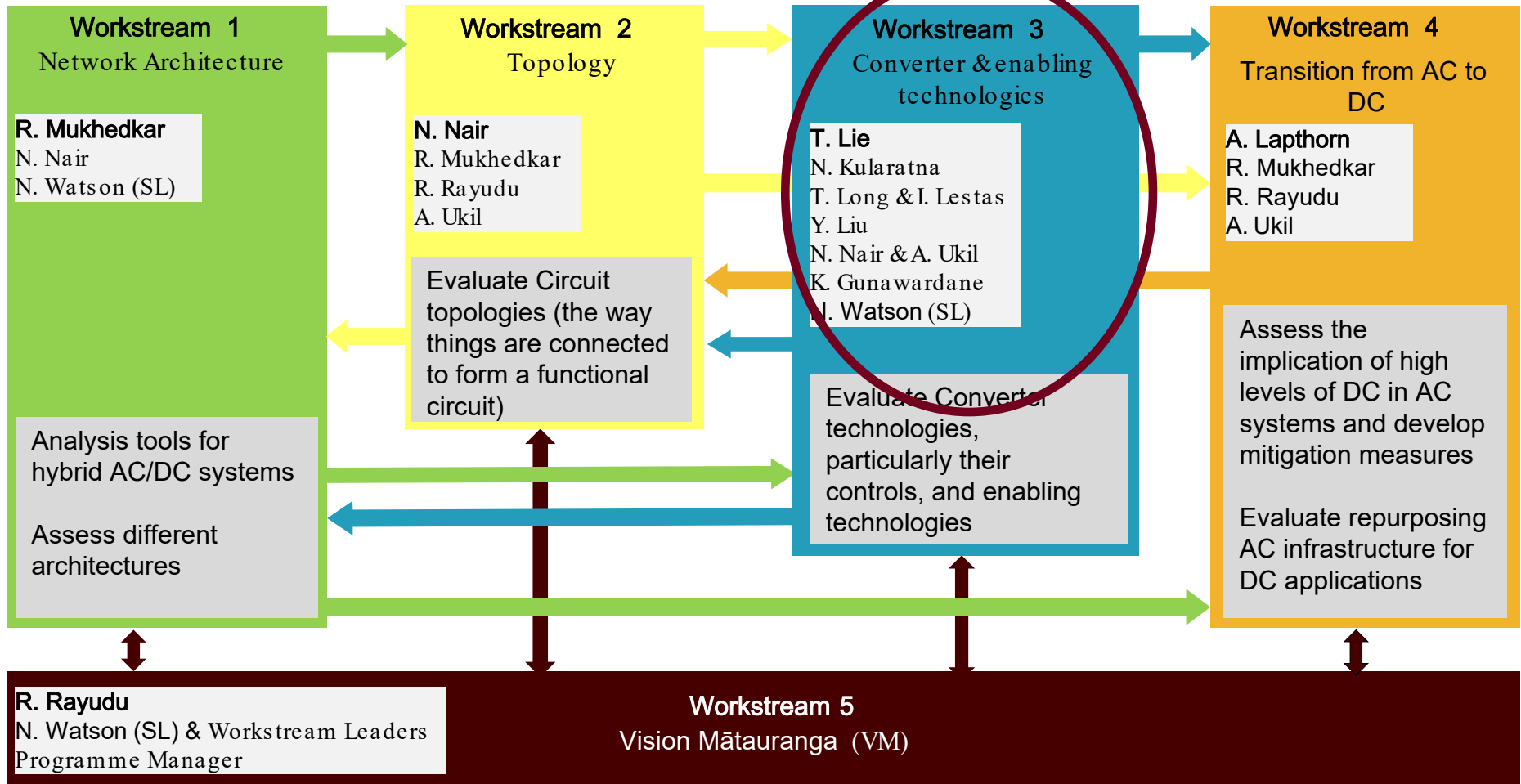
Professor Tek Tjing Lie
Auckland University of Technology
(AUT)

3 February 2026



Future Architecture
of the Network

TE WHATUNGAHIKO



Outline

1. WS3 Team
2. Objectives & Strategic KPIs
3. Achievements
4. Plan for the next 1 year (postgrad, summer projects, etc)

WS 3 - Team

Lead: Tek Lie

NZ Members:

Nihal Kularatna

Jeremy Watson

Nirmal Nair

Abhisek Ukil

Neville Watson

International Collaborators:

Kosala Gunawardane

Frede Blaabjerg

Ioannis Lestas

Teng Long

Yonghe Liu

Overseas companies collaborating- Würth Elektronik - Germany

Sécheron - Switzerland

WS 3 - Objectives

To enable proliferation of DC grids within AC grids by addressing technologies and control mechanisms for different forms of power electronic converters:

- a) The DC networks are connected to AC via converter terminals that essentially convert AC power into DC power and vice versa.
- b) DC-DC converters enable change in DC voltage levels.
- c) Converters utilised in ancillary circuits are DC breakers using enabling technologies

WS 3 – Strategic Intent KPIs

- **By mid-2026:** Working with Vendors and Transpower, we will have developed the prototype a high-power DC breaker for LVDC based on supercapacitors and verify them via experiment.
- **By mid-2027:** We will have developed and build a prototype converter with its advanced control technology to be tested in the AC weak system and verify their effectiveness to enhance the system stability. We will work with Vendors, Transpower and local manufactures to develop a prototype that works in NZ power system.

Achievements – PhD project 1: 2021-2025*

Development of Hierarchical Control Strategies for DC Microgrids Clusters

Microgrids (MGs) offer advantages in distribution systems, featuring lower losses, high reliability, and efficient integration of distributed energy resources (DERs). However, sporadic changes in load demand or generation in one unit can lead to severe disturbances, potentially causing system failure. Clustering neighbouring MGs is a solution, but coordination is crucial to tackle demand-generation mismatches.

Hierarchical control, using a consensus algorithm, is commonly applied to coordinate DC MGs in a cluster. Existing algorithms have limitations in communication requirements and may struggle with large disturbances from intermittent RESs. To address this, a novel adaptive event-triggered consensus algorithm (AETC) is proposed for faster convergence in current sharing and rapid DC-bus voltage recovery under critical conditions.

The study's second aim involves resolving primary and secondary control issues using grey wolf optimizer (GWO) and a modified fixed-time consensus algorithm, respectively. This holistic hierarchical control strategy for DC MG clusters will be implemented in MATLAB and validated using the real-time digital simulator Opal RT. The project aims to reduce reliance on existing grids, providing reliable power to remote areas..

***Not funded by FAN**

Supervisors: T. Lie, R. Zamora, and F. Blaabjerg

Outcomes: 6 Journal papers and 4 Conference papers



Achievements – PhD project 2 (2022-2025)

Control Strategies and Stabilization Techniques for DC/DC Converters

DC Microgrids (MGs) offer advantages over AC MGs in terms of efficiency, control, cost, reliability, and size. However, they are more likely to operate with a significant proportion of constant power loads (CPLs). The investigation covered a spectrum of loads, ranging from light to heavy, revealing shortcomings in both linear droop control (LDC) and nonlinear droop control (NLDC) in addressing the identified issue. Notably, LDC's droop coefficient remains constant, necessitating a fixed operating point despite changes in cable resistances over time. Conversely, research findings indicate that NLDC exhibits commendable performance under heavy loads.

The proposed approach involves implementing an optimized piecewise linear droop control (PWLDC) as a transitional solution between LDC and NLDC. Once experimentally validated, this technique holds promise for future network applications. I developed the mathematical model for PWLDC based on arithmetic regression, conducted simulations using MATLAB, and observed that an optimized PWLDC can dynamically adjust the droop coefficient for each segment based on current values. In instances where the current exceeds a specified range, PWLDC is capable of resetting the system accordingly.

Supervisors: T. Lie, K. Gunawardane, I. Lestas and N. Nair

Outcomes: 1 Journal paper, 2 Journal papers (under review) and 3 Conference papers

Achievements – PhD project 3: 2023-2025**)

Analysis of DC breaking phenomenon in DC Microgrids

A Microgrid (MG) integrates distributed energy resources (DERs) and controllable loads to operate independently or with the main grid. DC MGs streamline renewable energy integration, utilizing DC distribution with benefits such as minimal reactive power and low harmonics. DC circuit breakers (DCCBs) are crucial for system reliability in DC MGs but controlling switching effects requires attention.

Implementing DC MGs faces challenges in ensuring system protection, prompting recent research to enhance DCCB design. The main challenge involves addressing arcs during non-zero current interruption, more severe than in AC networks. Improving DCCBs is essential to prevent voltage and current surges. Two methods include (i) installing surge protection devices in low-valued circuits (technically challenging) and (ii) designing a novel circuit breaker with supercapacitor-based techniques to dampen surge severity.

Supercapacitors are increasingly favoured for surge protection due to lower corrosion, greater reliability, and faster performance compared to alternatives. Their non-chemical structure makes them stand out. The study aims to develop a novel technique redirecting circuit switching effects into a sub-circuit, dissipating released energy in that specific area.

Supervisors: T. Lie and K. Gunawardane

Outcomes: 5 Journal papers and 2 Conference papers (1 paper was awarded best student paper)

****PhD Thesis has been completed.**

Achievements – PhD project 4: 2023-2026)

Application of machine learning and big data in converter control strategy- an effort towards stability enhancement.

The main goal of this research work is to improve Medium Voltage (MV) grid stability by infusing big data and Machine Learning (ML) in its converter controls and the network at large. The following objectives will also be addressed with this research work

1. Enhanced PI current controller for VSC in MV Grid with ML
2. Fault detection, classification and localization in MVDC
3. Outage forecasting and management in MVDC

Supervisors: T. Lie, M. Stommel, and J. Watson

Outcomes: 5 Journal papers and 2 Conference papers

Achievements – PhD project 4: 2023-2026)

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Achievements – PhD project 5: 2025-2027)

Protection and Control Strategies for Multilevel Converter Topologies for MV grids.

This PhD research addresses reliability challenges in medium-voltage networks with high penetration of inverter-based resources such as solar PV and batteries. As traditional generators are replaced by power-electronic converters, fault current levels and characteristics become strongly dependent on converter control and protection, complicating reliable fault detection and clearance.

The study investigates fault responses of grid-forming converters under balanced and unbalanced faults and examines how control strategies and hardware limits can be designed to maintain synchronisation and deliver predictable, controllable fault currents that support protection coordination. Using scenario-based sampling, the research evaluates NPC, CHB, and MMC topologies with key grid-forming controls (droop, virtual synchronous machine, and oscillator-based control) across a range of grid strengths and fault conditions. Detailed modelling, real-time digital simulation, and where possible scaled hardware testing are used. The outcome is a validated fault-tolerant control framework that enhances protection reliability and network safety in converter-dominated grids..

Supervisors: T. Lie, N Nair, and F. Blaabjerg

Outcomes: 2 Conference papers and 1 Journal paper in preparation

Achievements – PhD project 6: 2023-2026

Control Design for Interlinking Converters in Hybrid AC/DC Networks

With the rise of converter-based renewable energy and DC consumer loads, future power grids are expected to adopt a hybrid AC/DC structure, with interlinking converters (ILCs) playing a vital role. However, ILC control strategies and hybrid AC/DC network stability present challenges. This doctoral research focuses on ILC control design and stability analysis, particularly for grid-following (GFL) and grid-forming (GFM) systems. Progress includes stability studies based on a small-signal model and eigenvalue analysis to ensure negative real parts. MATLAB/SIMULINK simulations validated a single ILC model connecting a DC grid to a balanced three-phase AC source via an LC filter. Results align with simulations, demonstrating stability thresholds influenced by network properties like AC grid strength (SCR), ILC parameters (inductor/capacitor), and PLL bandwidth. Key findings show GFL instability at $SCR < 2$, worsened by increasing PLL bandwidth, whereas GFM maintains stability. The research aims to develop a new ILC control design using a mixed gain-phase stability criterion, scalable for multiple ILCs. Simulations and experimental verification will compare the new method to existing controls.

Supervisors: J. Watson and T. Lie

Outcomes: 2 conference papers; 1 journal paper in preparation

Achievements – PhD project 7: 2022-2025)

Design, development and prototyping of a Supercapacitor Assisted DC circuit breaker technique

Over the last two decades, Waikato Power Electronics Research (WaiPER) group have developed a unique set of power converter and protection techniques useful in future renewable energy systems with hybrid AC-DC combined architectures. This unique family of Supercapacitor Assisted (SCA) techniques are based on a unique and recently published new theory – Supercapacitor Assisted Loss Management (SCALoM). With the success story and the international recognition achieved by the SCA techniques has encouraged the WaiPER group to develop a SC assisted DC Circuit breaker technique from concept to implementation.

Chamara Dassanayake, full FAN scholarship recipient was able to work with the supervisory team to develop a unique technique now known as SCA Transient Energy Pump (SCATEP), with a prototype built and demonstrated to their Swiss collaborator, Sécheron-Hassler (World's largest DC circuit breaker company). This project was inspected by Dr Lamara Tarek, Head of Research-Sécheron during his visit to NZ for the FAN 2025 conference as an industry speaker. This resulted in an invitation for the PhD student Chamara to spend 5 weeks at Sécheron, Geneva. Thesis is submitted and currently assessed by the external examiners.

Supervisors: N. Kularatna, Alistair Steyn-Ross

Outcomes: One Journal paper in IEEE Trans on Industry Applications and nine conference papers presented at IEEE Int'l conferences.

Achievements – PhD project 8: 2023-2026)

Design, development and prototyping of a Supercapacitor Assisted Solar Inverter Technique to reduce losses in the DC input loop

This is another new Supercapacitor Assisted (SCA) technique based on the SCALoM theory, to reduce inherent losses in the input DC loop, by creating a multi inverter system combined with supercapacitor banks. In this SCAInv technique, the commercial inverter designs are kept unmodified, but adding a SC module set with a low speed switching technique, we eliminate battery banks, while reducing the input DC loop losses.

Student Chamila Naligama was supported by a part FAN scholarship.

He has successfully completed the project with a testable inverter system with 4 supercapacitor banks. Currently he is writing his thesis. In addition, based on UoW's established collaborative relationship with the German electronics manufacturer Würth Elektronik, Chamila and a UoC team member were able to get a training on EMC testing, with a free test on the SCALDO prototype for EMC compatibility.

Supervisors: N. Kularatna, Alistair Steyn-Ross and Kosala Gunawardane

Outcomes: One Journal paper published in IEEE Trans on Industry Applications, and five published IEEE int'l conference papers. EMC testing related journal paper is currently under review.

Achievements – PhD project 9: 2023-2026)

Development and prototyping of a Supercapacitor Assisted DC-DC converter for commercial (AC) refrigerators for better energy efficiency and direct DC operation

This is another new Supercapacitor Assisted (SCA) technique based on the SCALoM theory, to reduce inherent losses in whitegoods, by combining a modified DC operable refrigerator with a SC module set with a low speed switching technique. The project uses a Fisher and Paykel refrigerator (Model RF402B) by removing rectifiers to reduce losses and working from solar without battery storage.

Student Nirashi P Gallage was supported by a part FAN scholarship.

She has successfully completed the test system with a reconfigurable 3 supercapacitor banks. Currently she is finalising the low speed switching circuit and stating with her thesis. This project when presented to Schneider Electric (US group) they have shown interest and invited WaiPER group to become member of DC systems standards group CurrentOS. **With this invitation, New Zealand has become the first Asia Pacific member of the CurrentOS to contribute towards future DC system standards.**

Supervisors: N. Kularatna and Alistair Steyn-Ross

Outcomes: One Journal paper, and several published IEEE int'l conference papers.

Achievements – PhD project 10: 2025-2027)

Design, Development and prototyping of a Supercapacitor Assisted Lossless DC transformer technique for DC voltage conversion in future DC power grids.

Current AC power grid is dominated by traditional bulky transformers combined with other AC building blocks. For high efficiency long distance high voltage DC links are available at heavy costs based on high frequency switching techniques. In this project we investigate the use of supercapacitors for transformer-less voltage conversion with SC modules supporting short term MW-second order energy storage.

This is another new Supercapacitor Assisted (SCA) technique based on the SCALoM theory, to reduce inherent losses in low and medium voltage DC-DC conversion and to eliminate bulky AC transformers for distribution end of AC grid combined with renewable energy DC sources.

Student Kalum Galmangoda is supported by a FAN scholarship.

He has successfully completed the preliminary proof of concept prototype converter system with two supercapacitor banks. Currently he is writing a short paper on his successful early implementation aimed at IEEE Power Electronic letters..

Supervisors: N. Kularatna, Alistair Steyn-Ross and Sanush Abeysekara

Outcomes: Student is confirmed in PhD. A short journal article is in preparation.



Achievements – Summer project 1 (2025/26)

Developing an Interpretable Neural Networks based on Graph Neural Network for Power System Small Signal Stability Analysis

Modern power systems increasingly rely on power electronic converters for integrating renewable energy sources, HVDC transmission, and DC microgrids within existing AC infrastructure. However, the complex, multi-timescale dynamics of these hybrid AC-DC systems present significant challenges for traditional small signal stability analysis methods. Conventional eigenvalue analysis techniques, while effective for purely AC systems, struggle with the nonlinear switching behaviours, fast control dynamics, and converter interactions that characterize modern power electronic-dominated grids.

A critical limitation of existing approaches is their computational intensity and lack of interpretability—system operators cannot quickly understand why certain operating conditions lead to instability or how converter control parameters affect overall system stability. Traditional methods may require minutes or hours for comprehensive stability assessment, making them unsuitable for real-time applications where converter control systems operate on millisecond timescales.

Furthermore, the proliferation of DC grids within AC systems creates complex interaction phenomena between multiple converters that are difficult to capture with simplified models. These interactions can lead to unexpected stability issues that threaten reliable system operation and limit confidence in DC technology deployment.

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Achievements – Summer project 1 (2025/26)-cont'd

This research addresses these challenges by developing interpretable neural networks based on graph neural network architectures that can:

- Capture complex converter dynamics and AC-DC system interactions in a unified framework
- Provide fast, accurate stability assessment suitable for real-time converter control applications
- Maintain transparency through physics-informed learning that reveals the underlying relationships between converter parameters and system stability
- Enable confident deployment of DC grid technologies through explainable AI that operators can understand and trust

By combining the computational efficiency of neural networks with the interpretability of physics-based modelling, this approach aims to bridge the gap between the speed requirements of modern power electronic systems and the transparency needs of critical infrastructure operations.

Supervisors: T. Lie and J. Watson

Outcome: Report and working towards a conference paper.

Achievements – Summer project 2 (2025/26)

The transition from conventional AC power networks toward DC or hybrid AC/DC grid architectures is a key trend shaping the future of electricity systems. This shift introduces new challenges in control and operation due to increased integration of renewable energy sources, power electronics, and distributed storage, all of which demand robust, adaptive control strategies.

This project investigates the application of Hybrid Data-enabled Predictive Control (HDeePC), a state-of-the-art approach that combines partial physical system models with data-driven predictive control methods. By leveraging both model knowledge and real-time operational data, HDeePC enhances system robustness, efficiency, and adaptability compared to traditional model-based or purely data-driven controls.

The student will develop a partial dynamic model of a representative DC grid segment including renewable generation, energy storage, and power electronic interfaces. Using simulated and real-world data, the project will implement the HDeePC algorithm and evaluate its performance in maintaining voltage stability, managing power flow, and responding effectively to disturbances under varying conditions.

Through simulation and analysis, the project aims to demonstrate the potential of hybrid control frameworks to support the reliable, efficient, and flexible operation of future DC and hybrid AC/DC grids.

Supervisors: J. Watson and T. Lie

Outcome: Report, working towards a conference paper

Achievements – Summer project 3 (2025/26)

Supercapacitor bike project: Electric bikes are typically based on rechargeable battery packs, usually sealed lead-acid or li-ion based chemistries. Few years back WaiPER group developed a supercapacitor assisted E-bike, where excess human peddle-power is utilized for hill-climbs and free-run based on a small supercapacitor module.

With the summer project the student will be enhancing its performance to make it a solar-energy supported full-version of an E-bike, without any battery packs, and with minimal electronics for lower cost and reliability.

Supervisor: N. Kularatna

Student : Siyuan Liu

Outcome: Conference or journal paper/ Report and a fully testable battery-less Ebike (BLess Ebike).

Achievements – Summer project 4 (2025/26)

SCALED DC lighting system : Supercapacitor assisted LED lighting system (SCALED) was developed by the WaiPER group, based on past PhD project. In this technique, we demonstrated how a fluctuating low-voltage DC bus can feed a pair of supercapacitor buffered LED banks with high efficiency eliminating the need for battery back up.

In this late-summer project we will be enhancing its performance by making it a full prototype where it can be field tested to work on a fluctuating low voltage DC bus (of less than 48V DC) and added electronics to make it a complete system. Required additional SC buffers and the auxiliary solar-derived DC power supplies will be tested and required PCB layouts will be completed.

Supervisor: N. Kularatna

Student : Bilby Johnson

Outcome: Conference or journal paper/ Report

Achievements – Summer project 5 (2025/26)

Supercapacitor testing based on an Arbin SC tester: DC Labs of UoW has acquired a new supercapacitor tester capable of measuring and confirming the specifications of commercial supercapacitor cells with a maximum current rating of 400A.

This summer project will test samples of commercially available different families of supercapacitors to compare the measurements results with data sheet specifications released by manufacturers. Also we will test some devices subjected to mis-use in series arrays, to see how their internal series resistance and cell capacitance gets affected.

Supervisor: N. Kularatna

Student : Ridhul Joshy

Outcome: Conference or journal paper/ Report

Achievements – Summer project 6 (2025/26)

Testing proof of concept prototypes of Supercapacitor Assisted Lossless (DC) Transformer(SCAL²T) technique

In the FAN funded second PhD project, new PhD student was guided to develop a very low frequency DC-DC converter stage to act as a DC transformer with energy buffering capability. This technique, (SCAL²T) can act as a very efficient DC transformer, which is based on SC based DC voltage divider controlled by a low speed switching circuit.

With the preliminary prototype for step-down conversion working satisfactorily, this summer project is aimed at building a testable prototype for step-down operation and extending it to a preliminary prototype of a step-up version, that can be extended into a kilovolts capable system useful in the future power grid with DC mixed and combined with renewable sources.

Supervisor: N. Kularatna

Student : Mayuranga Loku Gamage

Outcome: Conference or journal paper/ Report

Achievements – Keynote/Invited Speeches/Tutorials/Workshops (2025)

Tek Lie:

- Plenary speech on the 3rd International Conference on Smart Grid Energy Systems and Control (SGESC 2025) titled” Adaptive Mixed Time-State Dependent Distributed Event-Triggered Consensus Protocol of a DC Microgrids Cluster,”, Online, 22 Feb. 2025. ”
- Keynote Speaker at the International Conference on the Cooperation and Integration of Industry, Education, Research, and Application 2025, AI-Empowered Renewable Energy-Dominated Power System Sub-Forum, held on 21 September 2025 in Jilin City, China.

N. Kularatna:

- Nihal Kularatna delivered an invited 3.5 hour tutorial at the IEEE- Applied Power Electronics 2025 (Long Beach, CA) on the title Supercapacitor-Assisted Power Converters and Protection Systems for Renewable Energy Systems. Many industry participants participated as the audience.
- Nihal Kularatna and the senior PhD student- Chamara Dassanayake delivered an invited tutorial at IEEE- ICDCM 2025 in Estonia on the 6th June. Title is: Supercapacitor techniques for protecting future DC systems, DC appliances and DC microgrids: New Zealand experiences with FAN project outcomes.

Nihal Kularatna and Abhisek Ukil

- N. Kularatna and A. Ukil, presented an invited industry forum on Energy Storage Systems at IEEE-IECON 2025 in Madrid, Spain- Titled “Energy Storage Systems- Supercapacitors”, on 15th Oct 2025.



Achievements – Keynote/Invited Speeches/Tutorials/Workshops (2024/25) Cont'd

J. Watson:

- Jeremy Watson invited as an invited speaker at IEEE-indexed conference 2025 Asia Conference on Advances in Electrical and Power Engineering (ACEPE).
- Jeremy gave a seminar on “Stability and control of the future electrical power network”, to IEEE Lafayette Section (LA, USA) on 25 September 2025.
- Jeremy was invited to give a seminar “Future Architecture of the Network: Perspectives from New Zealand” at Imperial College London and the Universities of Manchester, Edinburgh, Aberdeen, and Leicester in Sept/Oct 2024.

Plan for next 1 year -

- Summer Projects
- Invite our international collaborators
- Attend international conferences
- Send our PhD students to work with the international collaborators
- Visits

Thank you

Questions?

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Future Architecture
of the Network

TE WHATUNGAHIKO