FAN Workstream 3

Converters and enabling technologies

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Future Architecture of the Network
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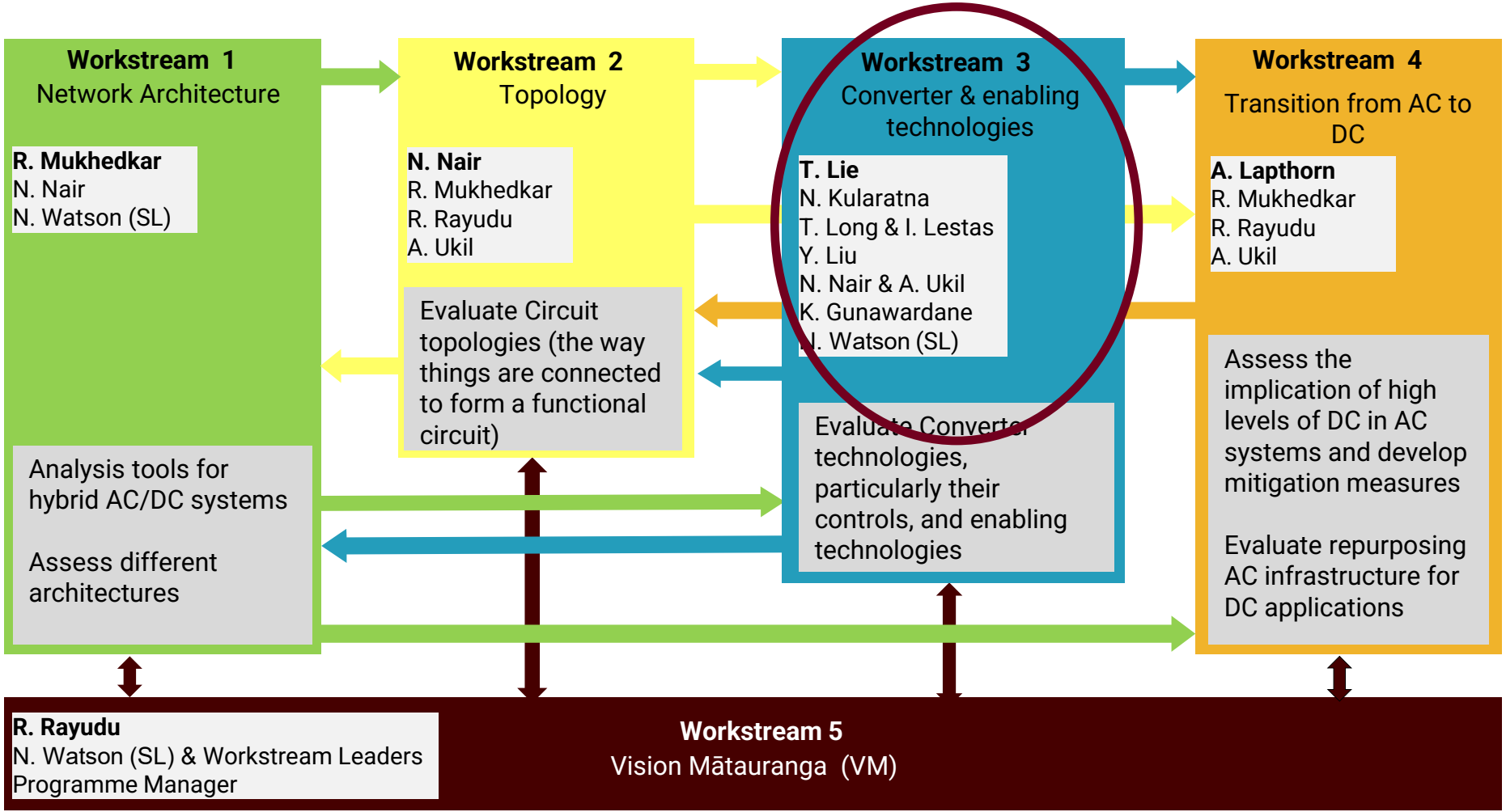
Workstream 1
Network Architecture
R. Mukhedkar
N. Nair
N. Watson (SL)
Analysis tools for hybrid AC/DC systems
Assess different architectures
Workstream 2
Topology
N. Nair
R. Mukhedkar
R. Rayudu
A. Ukil
Evaluate Circuit topologies (the way things are connected to form a functional circuit)
Workstream 3
Converter & enabling technologies
T. Lie
N. Kularatna
T. Long & I. Lestas
Y. Liu
N. Nair & A. Ukil
K. Gunawardane
J. Watson (SL)
Evaluate Converter technologies, particularly their controls, and enabling technologies
Workstream 4
Transition from AC to DC
A. Lapthorn
R. Mukhedkar
R. Rayudu
A. Ukil
Assess the implication of high levels of DC in AC systems and develop mitigation measures
Evaluate repurposing AC infrastructure for DC applications
R. Rayudu
N. Watson (SL) & Workstream Leaders
Programme Manager
Workstream 5
Vision Mātauranga (VM)

Outline

1. WS3 Team
2. Objectives & Strategic KPIs
3. Achievements
4. Plan for the next 2 years (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

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-2025**: 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 0: 2021-2024*

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: 4 Journal papers (published) and 2 Conference paper (published)

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Achievements – PhD project 1 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 (accepted) and 1 Conference paper (submitted)

Achievements – PhD project 2: 2023-2026)

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 **[Tuition fee only funded by FAN]**

Outcomes: 3 Journal papers (Published), 1 Conference paper (published and awarded best student paper)
PhD Thesis has been submitted for Examination.

Achievements – PhD project 3: (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: 1 Conference paper (published)

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Achievements – PhD project 4: (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: 1 Conference paper (published)

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Achievements – PhD project 5: 2022-2025)

Supercapacitor-Buffered DC-Operable Refrigerators for DC Homes

Recently, the research and industrial communities have focused on DC appliances and DC microgrids as a means to enhance the end-to-end efficiency of energy systems. Given the fluctuating nature of renewable energy sources, energy storage has become essential for powering households with minimal reliance on the AC grid. Rechargeable battery packs equipped with maximum power point tracking controllers and inverters are commonly used for this purpose. However, this approach is often inefficient due to power losses in the converters in energy supply path. Additionally, the limited lifespan and environmental concerns associated with battery storage present further challenges.

Rapid advancement of commercial supercapacitors, which offer longer lifespans, higher power densities, and a broader operational temperature range, makes them useful in the development in power converters.

A novel family of converters and protection systems, based on supercapacitor-assisted loss management (SCALoM) theory , has emerged as a promising approach to reduce or eliminate the need for batteries while enhancing end-to-end energy efficiency (ETEE). In this research we demonstrate how we extend SCALoM theory to develop SCA converters for whiteware, based on the example of a DC-converted commercial double-door refrigerator with implementation details.

Supervisors: N. Kularatna, Alistair Steyn-Ross and Dulsha Kularatna-Abeywardana

Outcomes: 1 Journal paper (submitted) and 5 Conference papers (published) [Tuition fee only funded by FAN]

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Achievements – PhD project 5: (2022-2025)

Supercapacitor-assisted arc management technique for DC circuit breakers

DC circuit breakers (DCCBs) have become increasingly important with the growing popularity of renewable energy sources and DC appliances, driven by the advantages of DC electricity over AC. However, designing DCCBs presents significant challenges due to two key factors: (i) compared to AC, DC lacks natural zero-crossing points, and (ii) DC faults escalate rapidly compared to AC faults because of the system's low impedance. Consequently, the electric arcs generated in DCCBs are severe, leading to reduced lifespan compared to AC circuit breakers (ACCBs).

This research effectively leverages the high-current capability of supercapacitors, enabled by their very low equivalent series resistance (ESR), to mitigate the electric arc during DC circuit breaking in a mechanical circuit breaker. This approach enhances the breaker's lifespan. A working prototype has been developed for a 2-kW system (25 V, 80 A), and the concept has been validated, demonstrating a 48.5% reduction in electric arc based on a novel supercapacitor-assisted arc management technique.

Supervisors: N. Kularatna, Alistair Steyn-Ross & Nicoloy Gurusinghe

Outcomes: Patentable circuit topology, 8 IEEE Conference papers (Published and awarded best student paper twice) and 1 IEEE Journal paper (submitted). Swiss DCCB company Sécheron has agreed to collaborate with the UoW team.

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Achievements – PhD project 5: 202x-202x)

Supercapacitor Assisted Inverter

Inverters are integral components in integrating DC-based sustainable energy sources and DC microgrids with AC grids. Developing efficient, high-voltage input inverters has been challenging, due to input-side high-voltage stresses. In such applications, high-voltage semicondcutors need to be used, and it negatively affects the component-level efficiency of the inverter. Manufacturers often need to consider expensive alternatives, such as SiC MOSFETs, to limit power losses at the individual components, despite additional cost implications. Series inverter arrangements and series DC/DC converter arrangements have been proposed as alternatives, but there are many practical difficulties in developing them into commercial solutions due to instability and high complexity in controlling them under dynamic load and input conditions.

This doctoral study focuses on developing a working prototype of an extended input-voltage-range inverter based on the supercapacitor-assisted loss management principle (SCALoM), where supercapacitor banks function as near-ideal voltage droppers and energy buffers. The proposed topology does not involve high-frequency switching schemes, reduces several input-loop losses in the inverter system, and prevents typical load-balancing issues in parallel/series inverter arrangements.

Currently, this study is at its final stage and aims to quantify the efficiency gains obtained at the component level and compare that with commercially available inverters.

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

Outcomes: 4 conference papers published. [Tuition fees only funded by FAN project]

Achievements – Summer project 1 (2024/25)

Hierarchical Control Technology of DC Microgrid Cluster

The coordination of clustered microgrids (MGs) needs to be achieved in a seamless manner to tackle generation-load mismatch among MGs. A hierarchical control strategy based on PI controllers for local and global layers has been proposed in the literature to coordinate DC MGs in a cluster. However, this control strategy may not be able to resist significant load disturbances and unexpected generated powers due to the sporadic nature of the renewable energy resources.

These issues are inevitable because both layers are highly dependent on Proportional-Integral (PI) controllers who cannot fully overcome the abovementioned obstacles. Therefore, the student is expected to develop an algorithm to enhance the performance of the global layer by optimising its PI parameters. Simulation studies will be conducted to show the effectiveness of the proposed algorithm.

Supervisors: T. Lie and J. Watson

Outcome: Report and one conference paper in preparation

Achievements – Summer project 2 (2024/25)

Data-Driven Control of DC Grids

Controlling energy storage systems (ESSs) within DC grids is an important issue in order to ensure that each ESS charges and discharges appropriately and optimally, in order to regulate the DC grid voltages and achieve state-of-charge balancing. One potential method to address this is data-driven predictive control, where the converter uses data it collects to predict the future of the system and adjust its inputs accordingly.

Since each ESS is independently controlled, a distributed form of predictive control must be used and there is little literature in this regard. The student (Cameron) has designed a hierarchical control structure which incorporates a consensus approach with data-driven predictive control in order to achieve these objectives. Simulation results show excellent performance and reliability. He is currently writing this work up as a paper.

Supervisors: J. Watson and T. Lie

Outcome: One conference paper in preparation

Achievements – Summer project 3 (2024/25)

Supercapacitor Assisted LED (SCALED) was a technique developed at UoW in a past PhD project based on a collaboration with Ports of Auckland Ltd. More recently we have developed a renewable resource based DC laboratory to test the implementation of several SCA techniques. This summer project is aimed at developing a fully working SCALED prototype to be powered solely by renewable energy.

Supervisors: N. Kularatna

Outcome: Fully working SCALED prototype and a report with test results and implementation details.

Achievements – Keynote/Invited Speeches/Tutorials/Workshops (2023/24)

Tek Lie:

- Keynote Speaker at 7th International Conference on Power and Energy Engineering (ICPEE 2023), December 2023. The title of the speech is "Enhanced Coordination in PV-HESS Microgrids Cluster: Introducing a New Distributed Event Consensus Algorithm."

- A workshop on "Future Architecture of Electricity Networks" to high school students in Surabaya, Indonesia, on the 21st and 22nd of October 2024 as part of the education fair event.

- Keynote Speaker at the 5th International Conference on Physical Instrumentation and Advanced Materials (ICPIAM), Bandar Lampung, Indonesia, 23 October 2024. The title of the speech is "Hierarchical Control Strategies for DC Microgrids Clusters in Distribution Systems."

- Keynote Speaker at University of Macau - Global Academic Symposium 2024, December 1 – 3, 2024. The title of the speech is "Adaptive Mixed Time-State Dependent Distributed Event-Triggered Consensus Protocol of a DC Microgrids Cluster."

N. Kularatna:

- Invited Speaker at IEEE-IESES 2023 Conference; Shanghai, China July 2023. The title of the speech is "Supercapacitor Assisted (SCA) Techniques for Power Converters and Protection Systems: Can Supercapacitors Change the Roadmap of Power Electronics for Renewable Systems?"

- Invited Speaker at the Renewable Energy Conference- Paris, Oct 2023. The title of the speech is "Can Supercapacitors Change the Roadmap of Power Renewable Energy and DC Microgrids."

Achievements – Keynote/Invited Speeches/Tutorials/Workshops (2023/24)

N. Kularatna (cont'd):

- Invited Speaker at IEEE-APEC 2024, Feb 2024. The title of the speech is "A Supercapacitor-based Surge Protection Technique Satisfying UL 1449 3rd Edition Tests."
- Invited Speaker at IEEE-APEC 2024, Feb 2024. The title of the speech is "DC Homes and DC Microgrids."
- Invited Speaker at IEEE-APEC 2024, Feb 2024. The title of the speech is "Supercapacitor Assisted Converter and Protection Applications for Renewable Energy Systems."
- Tutorial at the IEEE-ICDCM 2024, Aug 2024. Title of the tutorial is: "Supercapacitor-Assisted Converter and Protection Techniques for DC microgrids and DC homes."
- Tutorials at international conferences IECON 2024 in Chicago-USA and ICRERA 2024 in Nagasaki, Japan. Title of the tutorial is: "Supercapacitor Assisted Power Converters and Protection Systems for DC Homes and DC Appliances Based on Renewable Energy."

J. Watson:

- Invited Speaker at Imperial College London's lunchtime seminar series, Oct. 2024. The title of the speech is "Future Architecture of the Network: Perspectives from New Zealand".
- Invited Speaker at the Universities of Manchester, Aberdeen, Edinburgh, and Leicester, Sept. – Oct. 2024. (Same presentation as above).
- IEEE PES Seminar, IEEE NZ South Section, July 2024. The title of the seminar is "Stability and control of the future power network".

Plan for the 2025 onwards – PhD project 1

Control Strategies and Stabilization Techniques for Converter

WS 3 will enable proliferation of DC grids within AC grids by addressing technologies and control mechanisms for different forms of power electronic converters.

- **Aim of this project:** To develop control strategies and stabilization techniques for converter to regulate the point of load to enhance the stability margin.
- Tight regulation of converter tends to produce negative impedances which will create oscillation with lightly damped power supply input filters. This is due the negative impedance characteristics are within the bandwidth of their control loops. As a result, it will reduce the effectiveness of the damping and it may lead to instability of the system. Thus, the main objective of the research is to determine the minor loop gain that will ensure the system stability.
- **Expected outcomes: R**eport and 2 journal and 2 conference papers

Plan for the 2025 onwards – PhD project 2

Supercapacitor Assisted Low Dropout Regulator (SCALDO) is a patented low frequency DC-DC converter developed at UoW and it is useful in renewable DC systems. Recent set of EMC tests conducted in Germany at the EMC test laboratories of Würth Elektronik proved that it is free of EMC compatibility issues typically associated with classical high frequency switch-modes.

This new PhD project to commence in 2025 is to develop wider applications of SCALDO converter useful in renewable energy DC-DC converters, with built in DC-UPS capability.

A new PhD candidate is selected and he is currently awaiting his visa to travel to NZ.

Plan for next 2 years –

- 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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