The Australian Energy Research Institute, at the University of New South Wales

UNSW AUSTRALIA

Never Stand Still | Faculty of Engineering | Australian Energy Research Institute

AERI
Australian Energy Research Institute

Ricardo P. Aguilera
Senior Research Associate

Josep Pou
Professor

Sydney, Australia

University of New South Wales (UNSW)

At UNSW we develop leaders who shape the future

FAST FACTS

Founded
1949
Located in
Sydney

54,517
Student Enrolments

8 Faculties

- Art & Design
- Arts & Social Sciences
- Business School
- Built Environment
- Engineering
- Law
- Medicine
- Science

$186m investment
in infrastructure

Most Innovative University
Thomson Reuters Citation and Innovation Awards 2012

Produced more technology entrepreneurs in the past 15 years than any other Australian university.
(CrunchBase 2013)

13,603
International Students

21,762
Commencing Enrolments

1 University College
UNSW Canberra at the Australian Defence Force Academy

48 Schools

129 Affiliated Institutes

16 Residential Colleges

6,104
Staff

250,000
Alumni

UNSW AUSTRALIA

UNSW Students

- More of Australia's top CEOs who lead ASX100 companies studied at UNSW than any other university.
  Leading Company (2012)
- Our diverse student population is career focused and in high demand
- Innovative teaching and extensive international and industry links give our graduates a competitive edge.
- UNSW has one of Australia's most diverse student populations
- One-third of our students are the first in their family to attend university.
- UNSW has international students from more than 125 countries and extensive global links, with international universities.

Alliances

The Group of Eight (Go8) is a coalition of leading Australian universities, intensive in research and comprehensive in general and professional education.

APRU is a network of 45 premier research universities from 16 economies around the Pacific Rim.

Universitas 21 is the leading global network of research-intensive universities.

The Global Alliance of Technological Universities is a network of the world's top technological universities

UNSW AUSTRALIA

Energy Research
Impact Through Partnerships

Never Stand Still

Australian Energy Research Institute

AERI

Tyree Energy Technologies Building (TETB)

- The TETB is the newly opened building housing the leading energy research at UNSW
- It was designed under ecologically sustainable development principles
- It is targeting as a 6-Star Green Education Design Rating
- Cost $140M

Australian Energy Research Institute (AERI)

AERI is Australia's leading scientific energy research institute, focused on developing practical applications for industry, government, and consumers.

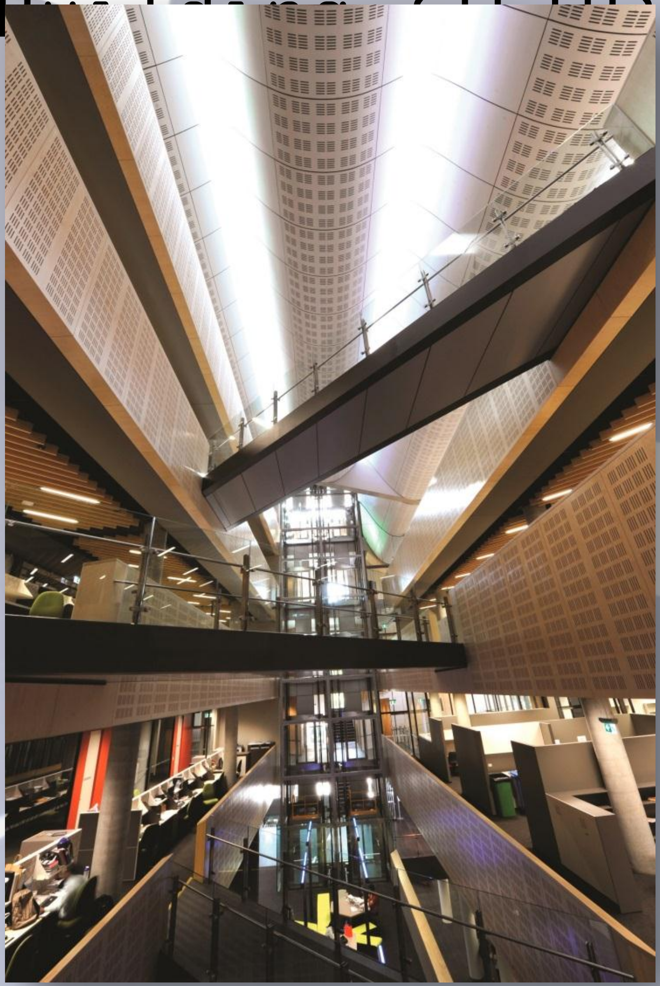
Based in the leading edge **Tyree Energy Technologies Building (TETB)** on the UNSW Kensington campus, AERI is the only physical, energy-focused research institute in Australia that is linked to a top tier Australian university, and leverages 30 years of energy research excellence at UNSW.

Australian Energy Research Institute (AERI)

AERI's <u>vision</u> is to:

- Impact our society with the benefits of long lasting partnerships across sectors
- Deliver scientifically sound and economically viable technologies and solutions for current and future energy challenges
- Inform energy policy with strong scientific and research-based evidence
- Enable collaboration with industry and the community to bring cutting-edge solutions to market
- Educate industry practitioners about the latest developments in energy technologies, systems, issues and solutions

The Tyree Energy Technologies Building (TETB)



- AERI is headquartered within the TETB – the home of energy research at UNSW
- Co-location of a wide variety of energy-related disciplines in TETB enables effective collaboration
- The building itself is a 6-Star energy efficient structure and a physical expression of the ground breaking research conducted within its walls

Australian Energy Research Institute (AERI)

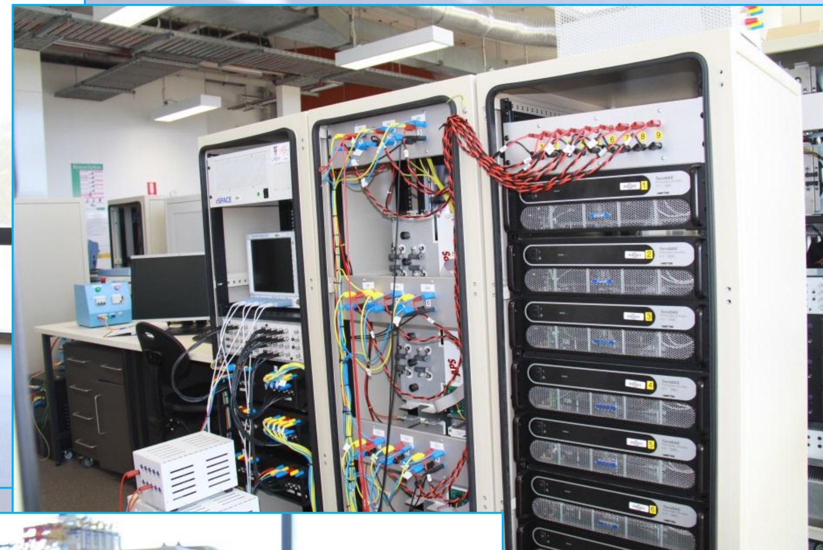
AERI is focused on delivering innovation in all areas of energy-related research, including:

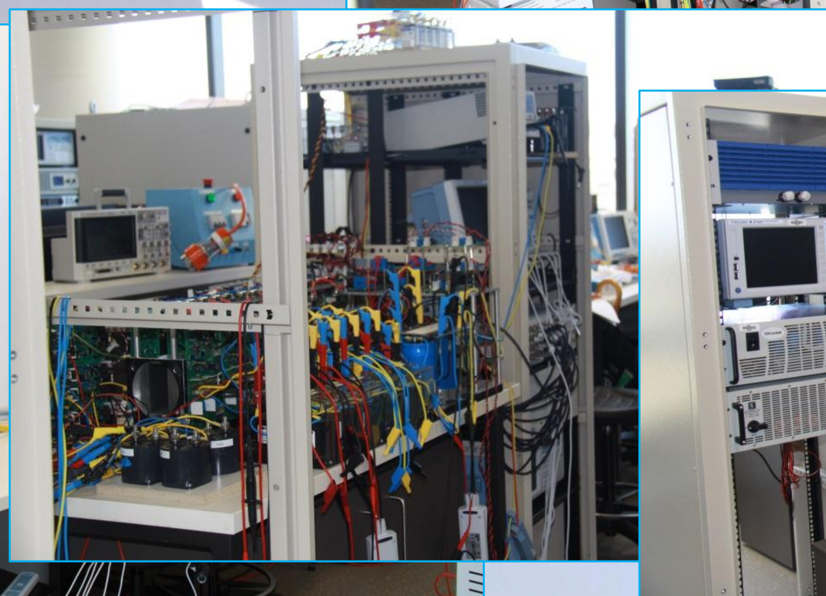
- Fuels & resources
- Electricity generation
- Transmission & distribution networks
- Energy conservation & efficiency
- Renewable energy technologies & integration
- Energy storage & conversion
- Energy policy & regulation
- Energy markets & economics

Australian Energy Research Institute (AERI)

Power Engineering Team within the AERI:

- Academics
  - Prof. Vassilios G. Agelidis (AERI Director)
  - **Prof. Josep Pou** (Research Leader)
  - Prof. Faz Rahman
  - Prof. John Fletcher
  - A/Prof. Iain MacGill
  - Dr. Baburaj Karanayil
  - Dr. Mihai Ciobotaru
  - Dr. Christopher Townsend
  - **Dr. Ricardo Aguilera**
  - Dr. Georgios Konstantinou
  - Dr. Branislav Hredzak
  - Dr. Minsoo Jang
  - Dr. Pablo Acuna
  - Dr. Muhammad Khalid
- Mr. Timothy Dixon (AERI Manager)
- 4 postdocs and 16 PhD students
- 5 visitors from industry and academy





Solar Flagships Research Agenda

AERI's Power Engineering research streams currently include:

- Solar PV Interface and Energy Conversion
- Grid Interaction and Impact
- Solar Farm Architecture
- Real-Time Systems and Control
- Energy Storage
- Monitoring and Diagnostics
- NEM Integration and Operation
- Forecasting and Prognosis
- Informatics and Analytics
- Virtual Power Plants and Integration
- Supergrids

RTDS Lab

- The Real Time Digital Simulator (RTDS) provides the capability to process and analyse real data for renewable sources of power generation to design solutions.

- The RTDS can test large-scale continuous integration of intermittent renewable photovoltaics and wind-energy deployment and find the technical and economic limits.
- **Largest** real-time digital simulation energy systems laboratory of its type at any research institution in the world.

AERI Research Projects

Never Stand Still | Faculty of Engineering | Australian Energy Research Institute

AERI
Australian Energy Research Institute

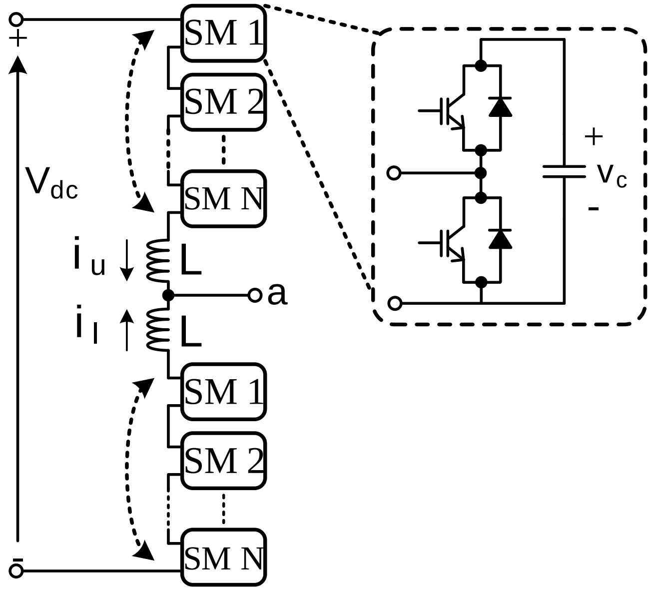
Current research at the AER

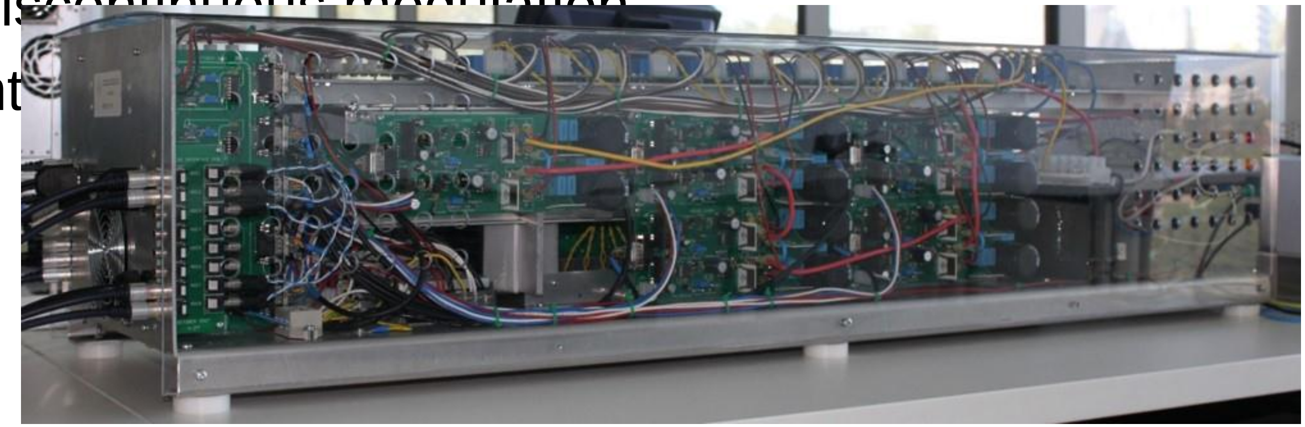
- Modular multilevel converters (MMCs)
- Converters for photovoltaic applications
- Storage energy systems
- Multilevel converter topologies
- HVDC transmission systems
- Inverter legs connected in parallel
- Integration of renewable energy into the electrical grid
- PLL-based grid voltage monitoring and synchronization
- Using film capacitors to increase the reliability of inverters
- SiC-based converters
- Configuration structures of solar and wind farms
- Solid-state transformers (SSTs)
- etc…

Power Conversion

Modular Multilevel Converters

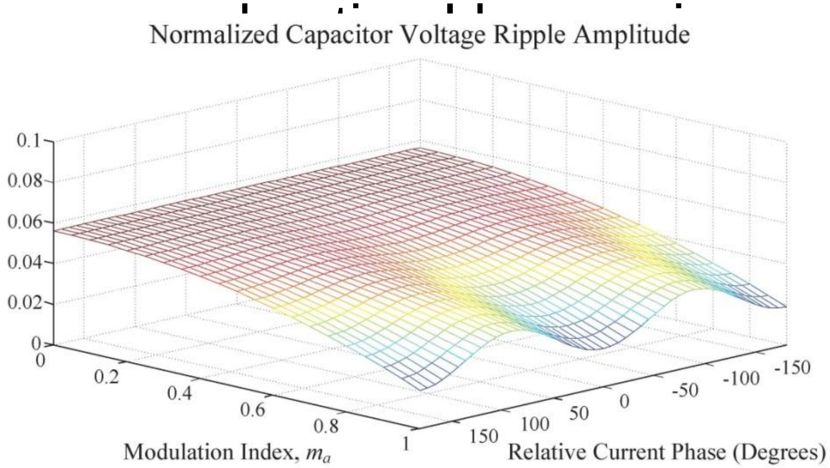
- Clue technology for HVDC applications
- Research on modulation techniques:
  - Staircase modulation
  - Carrier-based PWM
  - Selective harmonic elimination
  - Dis
  - Int

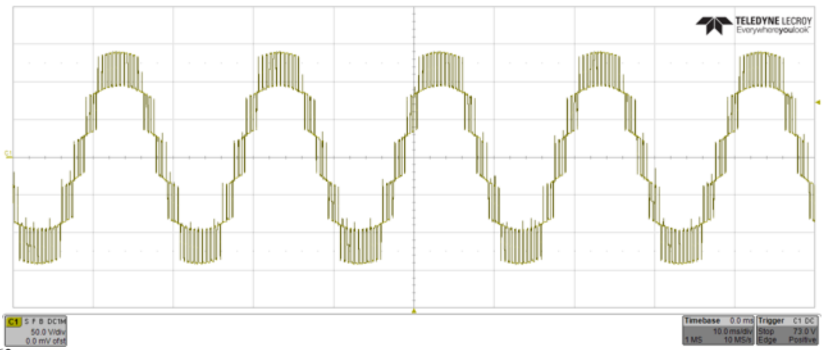


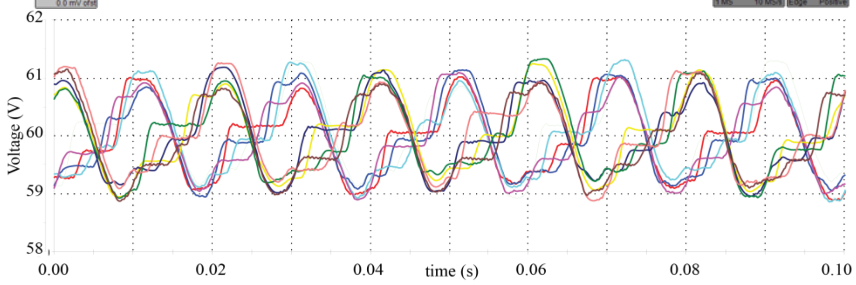


Modular Multilevel Converters

- Research:
  - Average modelling of MMCs
  - Reduced switching voltage balancing methods
  - Circulating current control
  - Active redundancies and fault tolerant operation
  - Parallel phase-legs for higher power operation



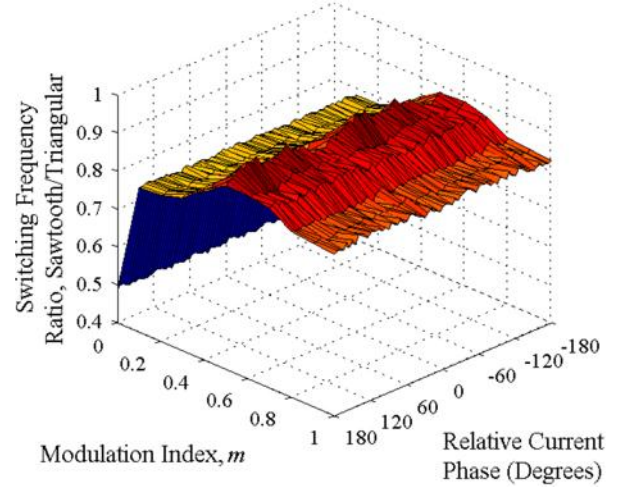


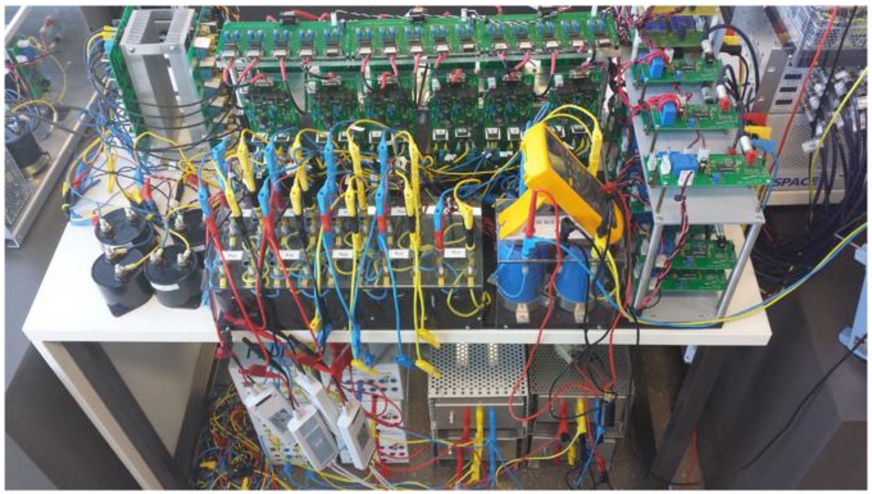


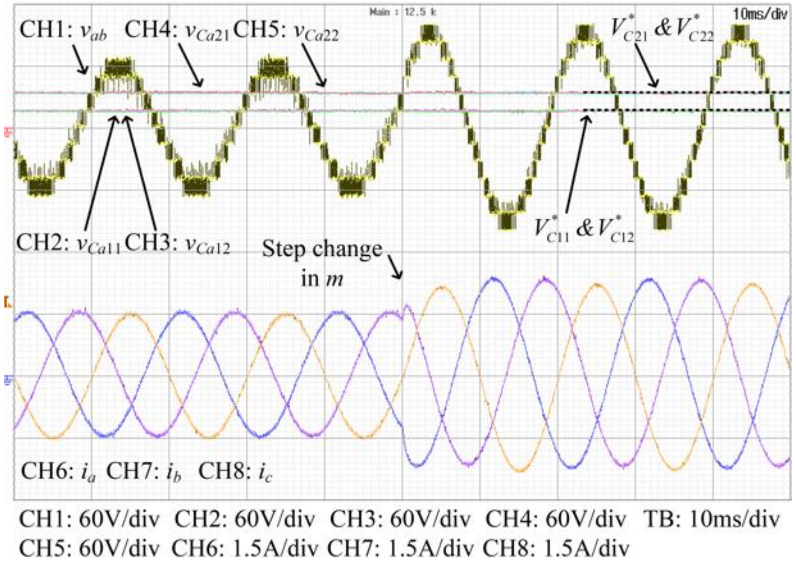
UNSW AUSTRALIA

Flying Capacitor – Stacked Multicell Converters

- Increased FC –SMC efficiency
- Advanced voltage balancing and control methods
- Lower harmonic distortion

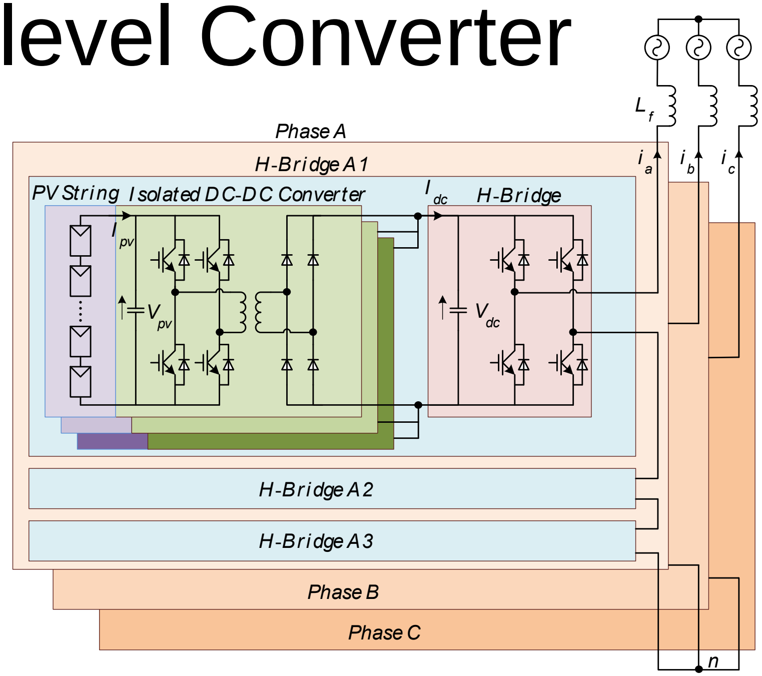






Cascaded H-bridge Multilevel Converter

- STATCOM
- High power PV converters

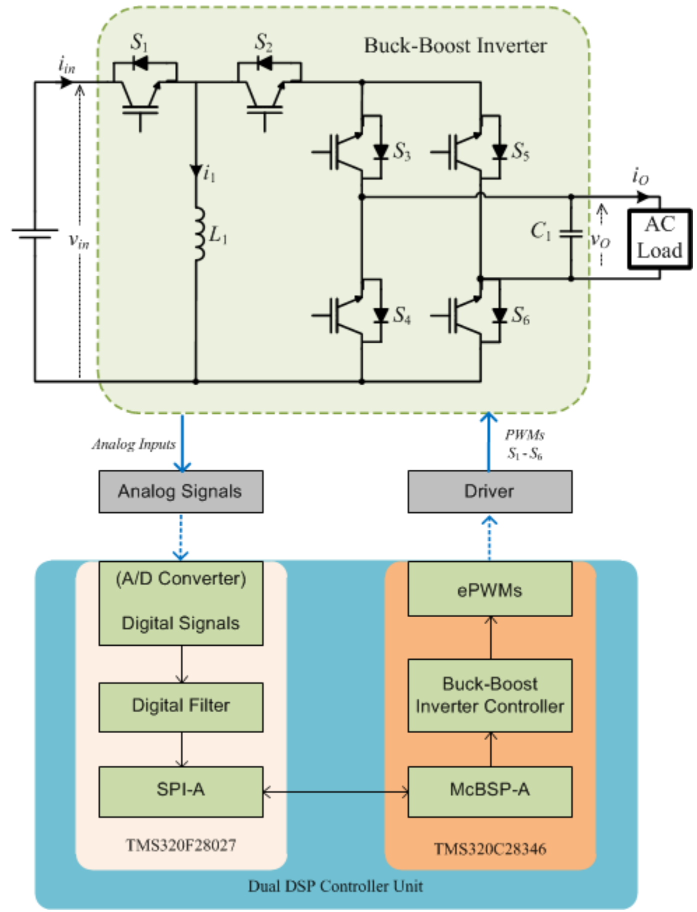


Projects:

- Operation under power unbalance
- Fault toleration
- Efficiency optimization

Single-Phase Bidirectional Buck-Boost-Inverters

- Bidirectional buck-boost converter + full bridge switches provide bipolar output.
- DC → Fundamental frequency AC (boosting and inversion in a single stage)
- S1 and S2 switches are operating at high frequency and the full bridge is working at fundamental frequency
- Less number of passive components and sensors

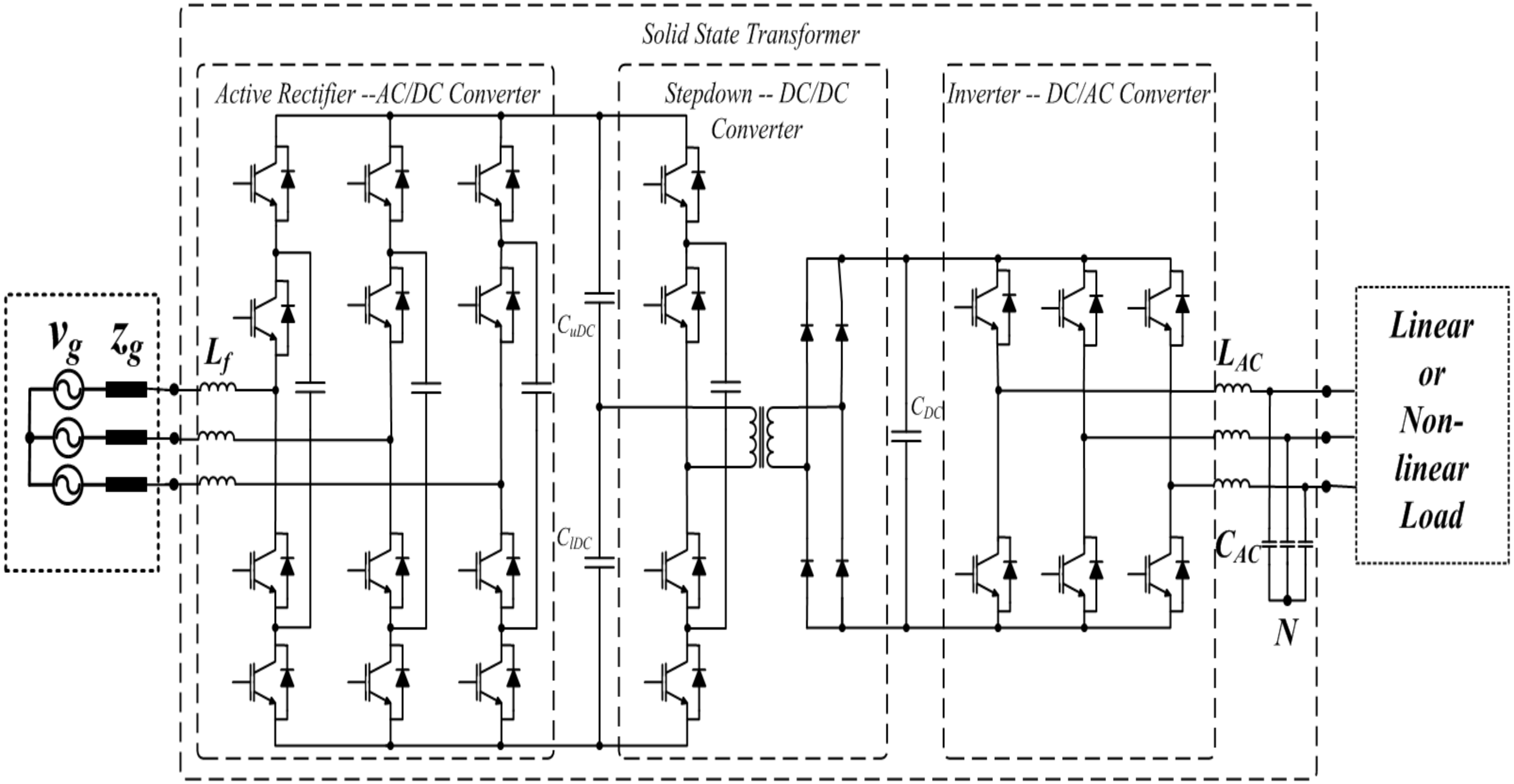


Solid-State Transformer

- The fundamental components in a solid-state transformer (SST) are power converters, a high-frequency transformer, and control circuitry
- Main features:
  - Different input/output voltages and frequencies
  - Possible AC or DC input and output
  - Improve power quality (reactive power compensation and harmonic filtering)
  - Provide effective routing of electricity based on communications
  - Reduced physical size and weight
  - Integral components of the future smart grids
- Main challenges:
  - Increase efficiency
  - Reduce cost

Solid-State Transformer

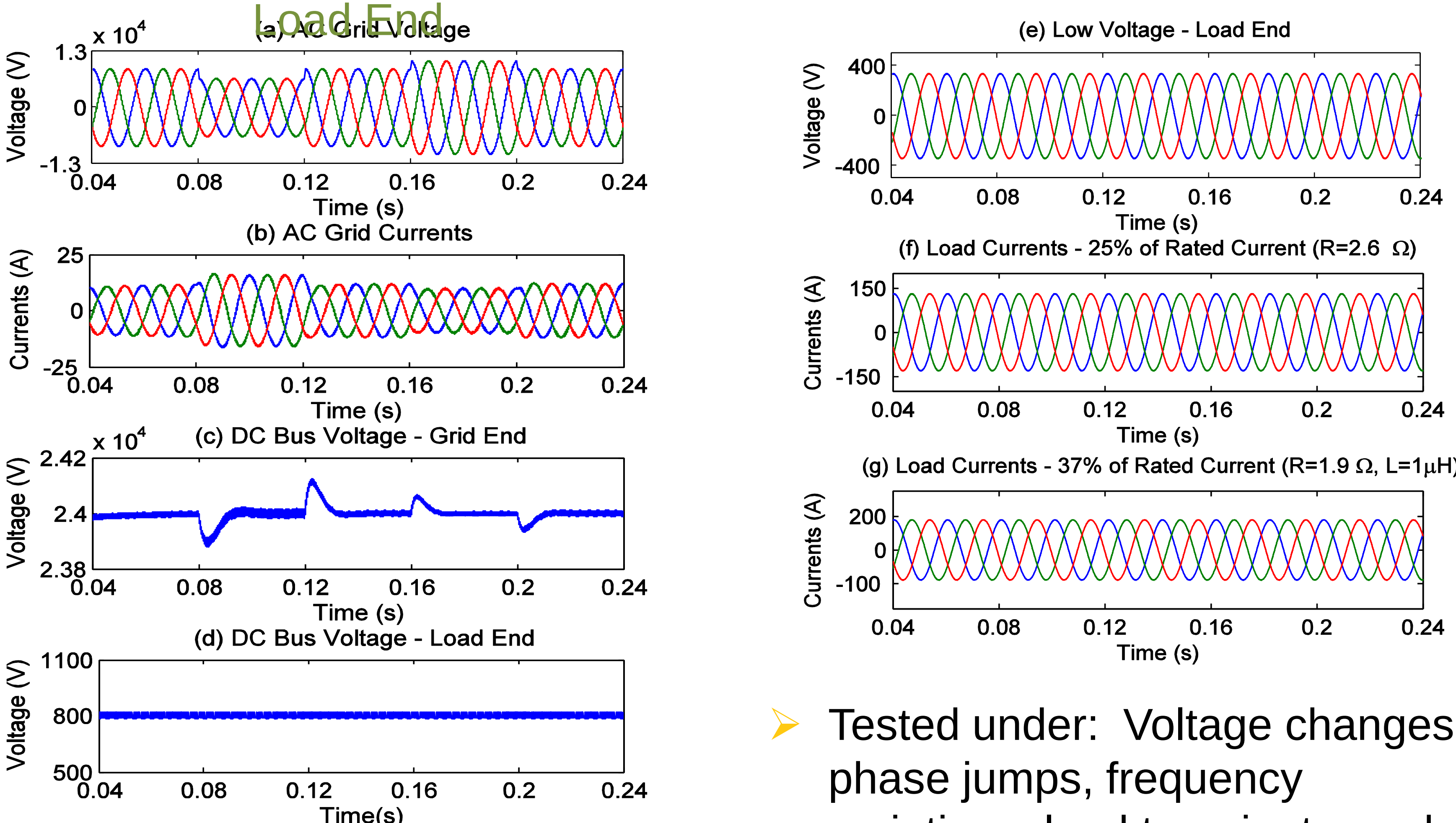
Proposed Solution Based on Multilevel Converters



Solid-State Transformer

Grid End

Load End



- Tested under: Voltage changes, phase jumps, frequency variations, load transients, and non-linear loads

UNSW AUSTRALIA

PV Solar Systems

Project Founded by Australian Gas Light (AGL) Company

Solar Flagships Research Agenda

- In 2013 AGL Energy Limited (AGL) was awarded the contract to construct the largest solar power stations in the southern hemisphere by the Australian Government.

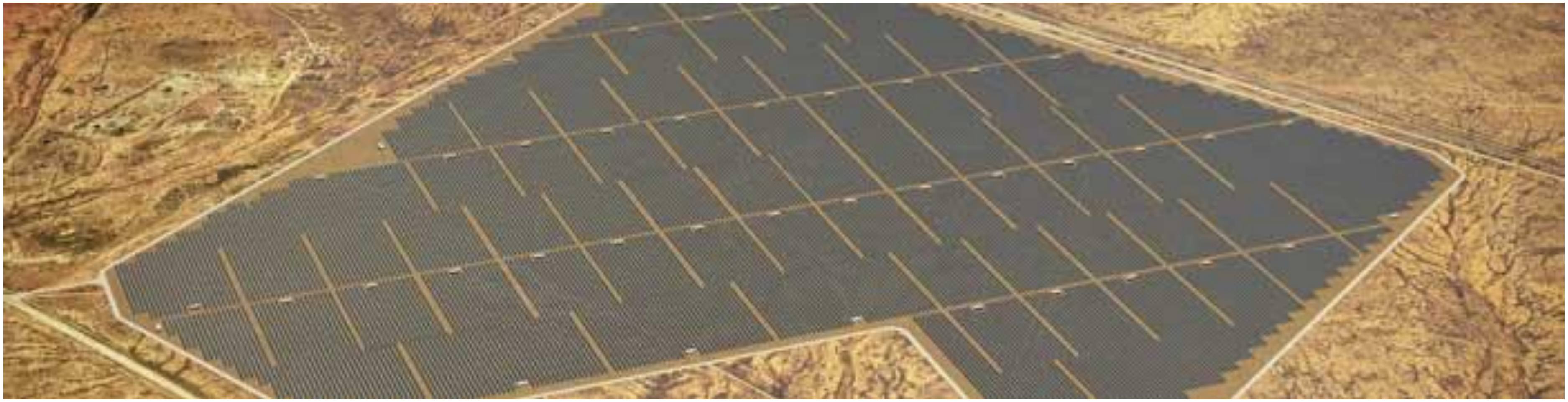
- $19 million was provided to AERI to construct the UNSW Power Systems Interface Laboratory in the TETB

- AERI has around $12 million worth of power electronic and energy storage equipment in its laboratories.

UNSW AUSTRALIA

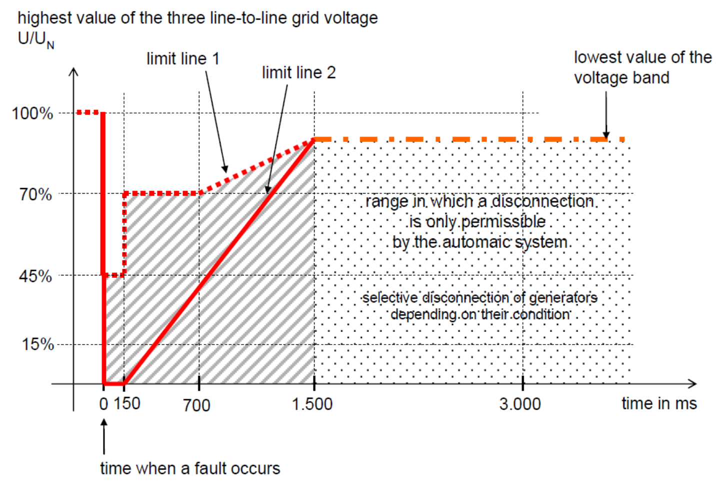
Broken Hill Solar Plant

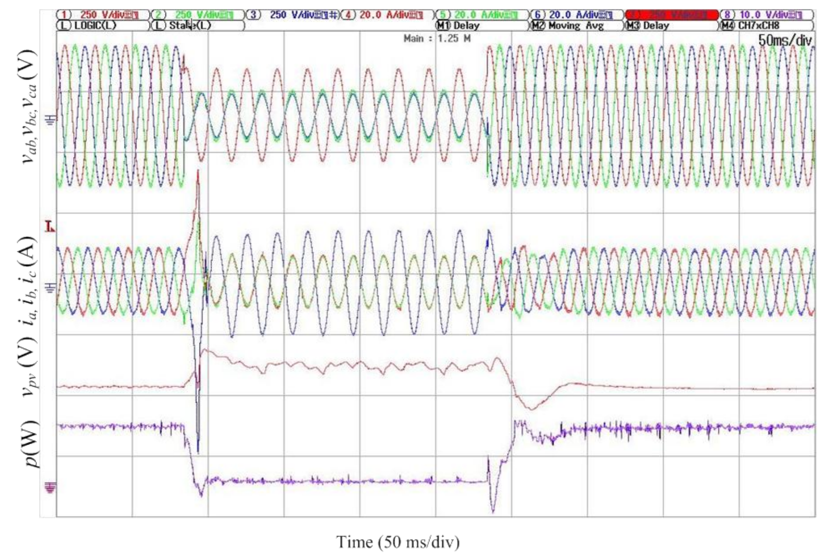
- Located in Broken Hill, 1200km from Sydney, 518km from Adelaide.
- Total Capacity: 155MW
- It is a $231 million investment. 70% from the Australian government, and 30% from the NWS government.
- From this, $40 million was assigned to Queensland ($21m) and NSW ($19m) Universities as Education Infrastructure Fund.



PV Inverters with Thin Film Capacitors

	ELECTROLYTIC	POLYPROPYLENE (Thin Film)
Design lifetime	50 000 h (≈ 6 years)	200 000 h (≈23 years)

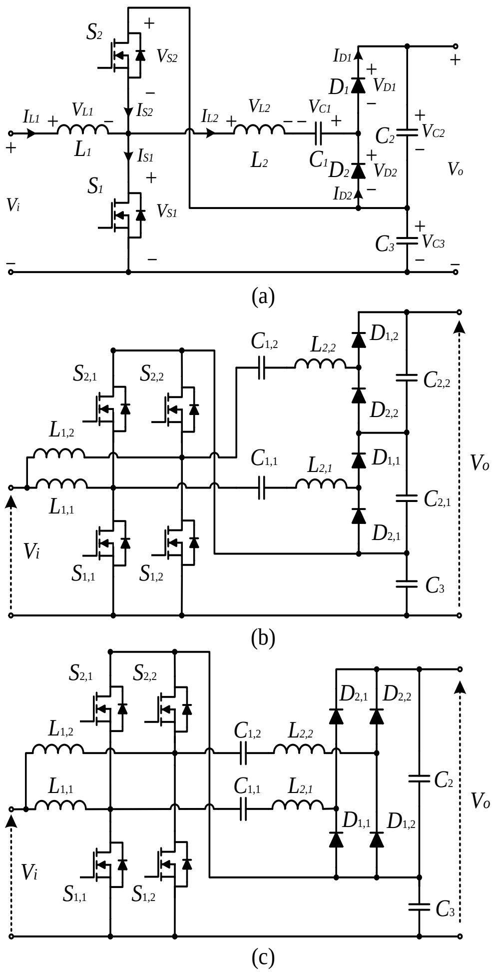


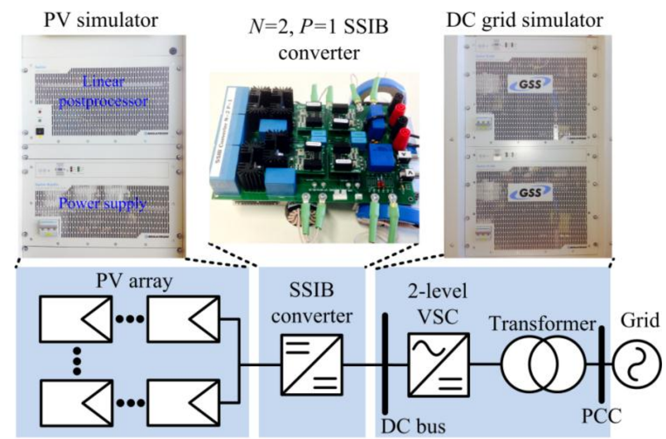


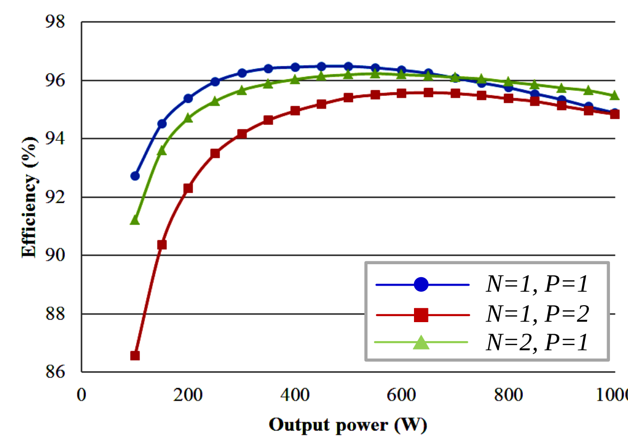
- PV inverters with thin film capacitors can match operating lifetime of PV panels
- Improved controllers are required because of the lower capacitance of film capacitors
- Low-voltage ride through tests with a laboratory prototype

Soft-Switched Interleaved Boost DC/DC converter for Large-Scale PV System

- Soft-switched interleaved boost (SSIB) converter
  - High voltage gain
  - High power rating
  - ZVS and ZCS
  - High efficiency
- Grid integration of large-scale PV systems with SSIB converter
  - Direct medium voltage DC bus
  - Reduced transformer stages

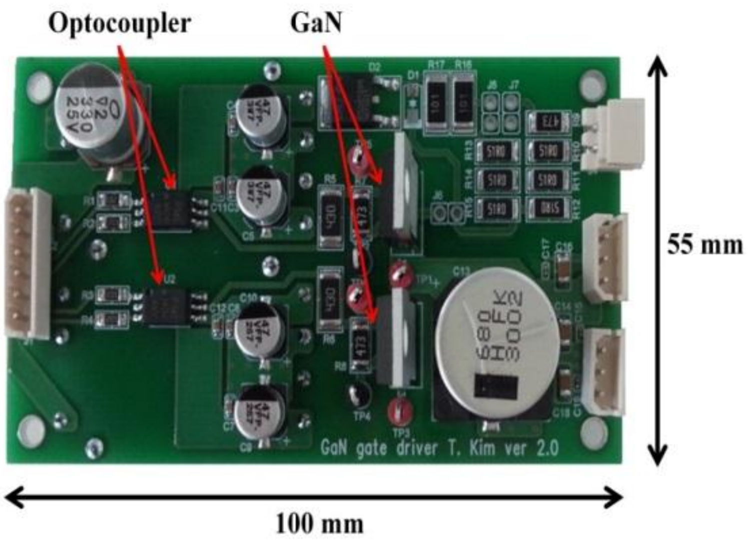


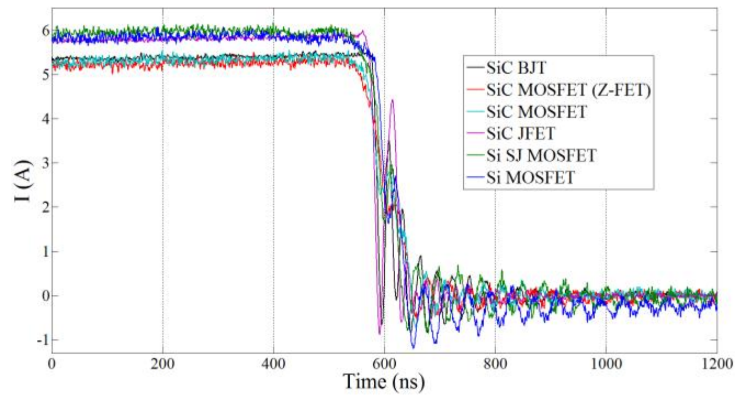


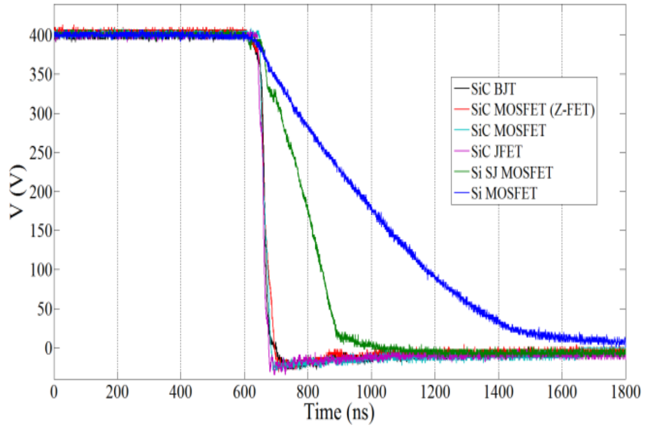


High Frequency SiC dc-dc Converters for PV Applications

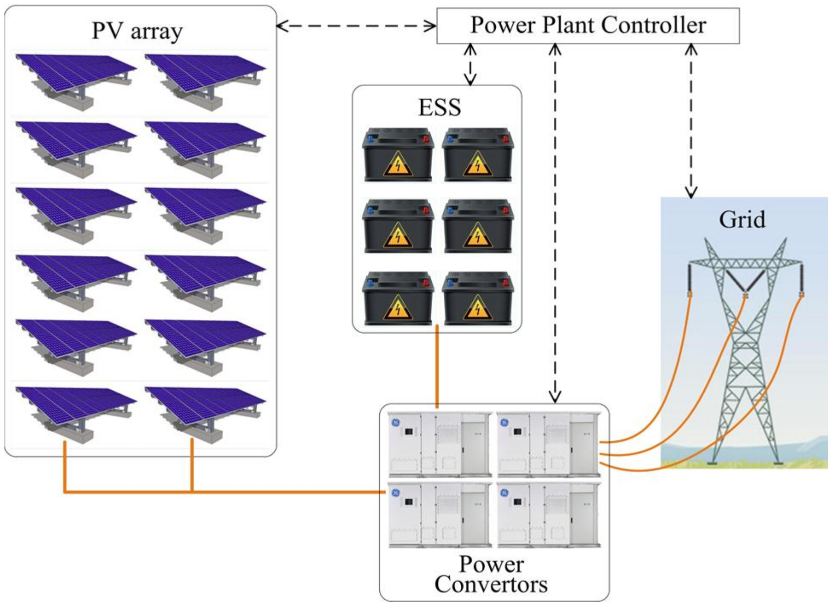
- Practical implementation of a SiC-based 300 KHz, 1.2 kW hard-switching boost converter
- Ultra-fast 1 MHz isolated gate-driving circuit for SiC MOSFET using GaN semiconductors for bipolar half bridge

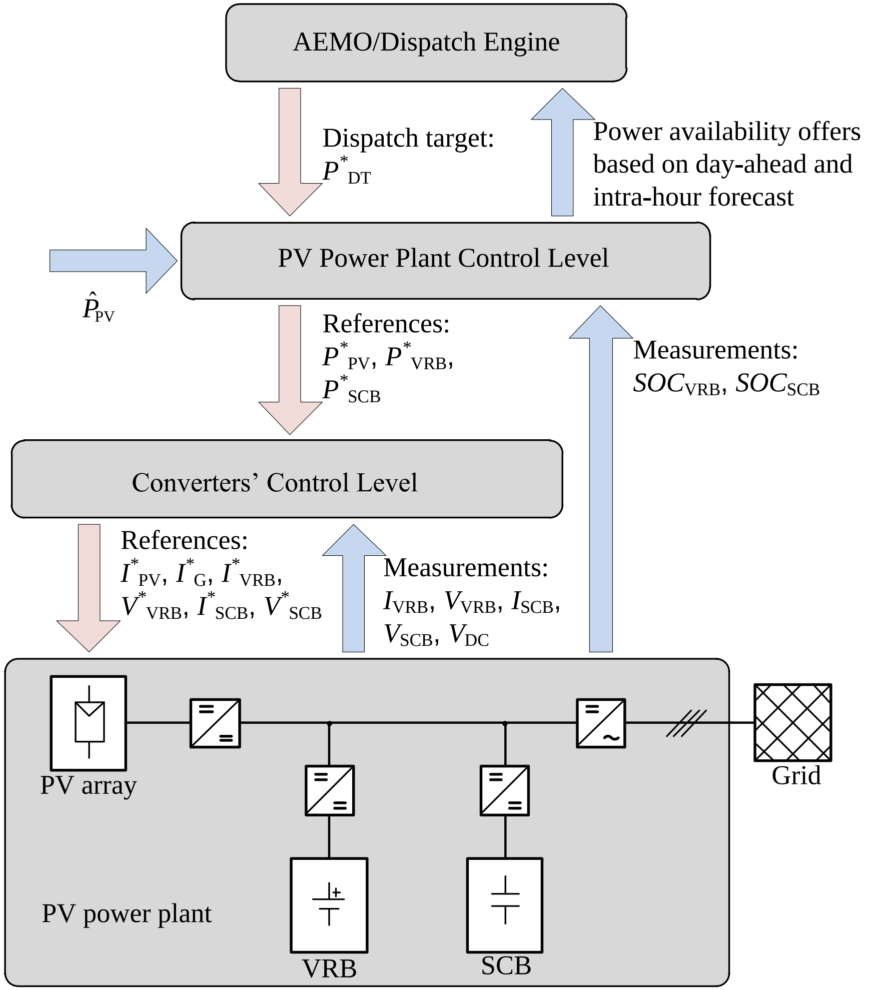






Hybrid Energy Storage System Supporting Large-Scale PV Plants



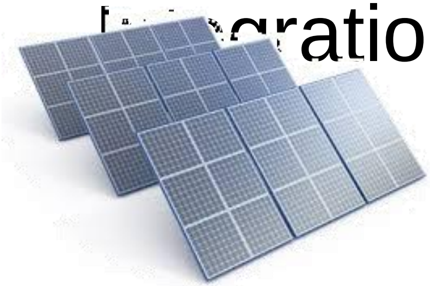


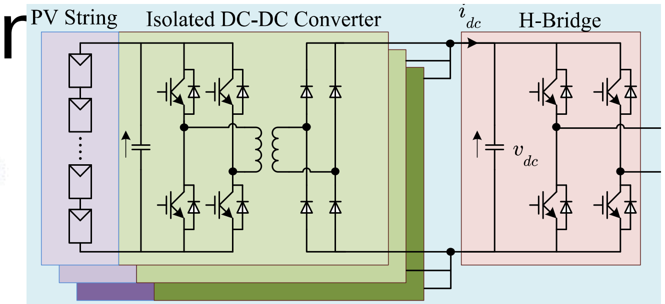
- Hierarchy power plant controller enabling PV plants to be dispatched in accordance to Australian NEM rules
- Developing electrical model of vanadium redox battery

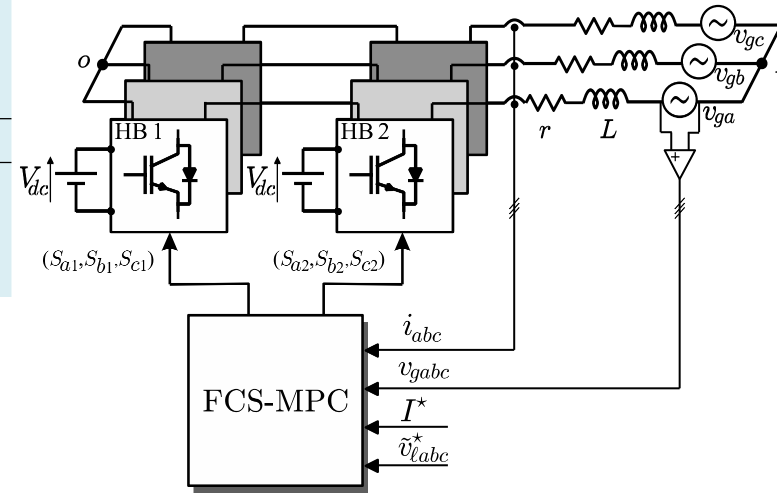
Power Balance of Cascaded H-Bridge Converters for Large-Scale Photovoltaic Integration

- Due to its large extension, large-scale photovoltaic plants are likely to be affected by partial shading. .
- Therefore, PV strings may deliver different amount of maximum power
- Due to grid-codes, these plants are required to deliver balanced power to the grid.

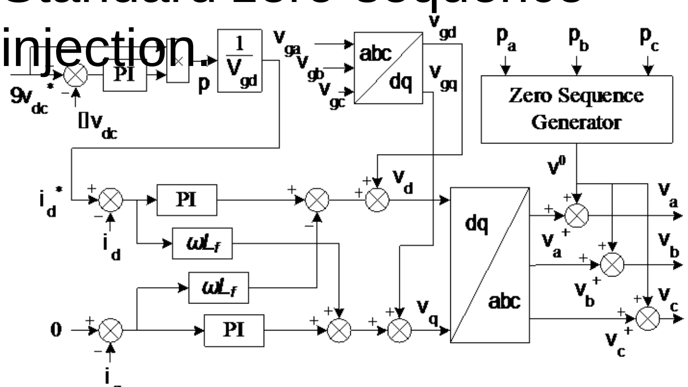
Power Balance of Cascaded H-Bridge Converters for Large-Scale Photovoltaic Integration







Standard zero-sequence injection.



Proposed Predictive Control.

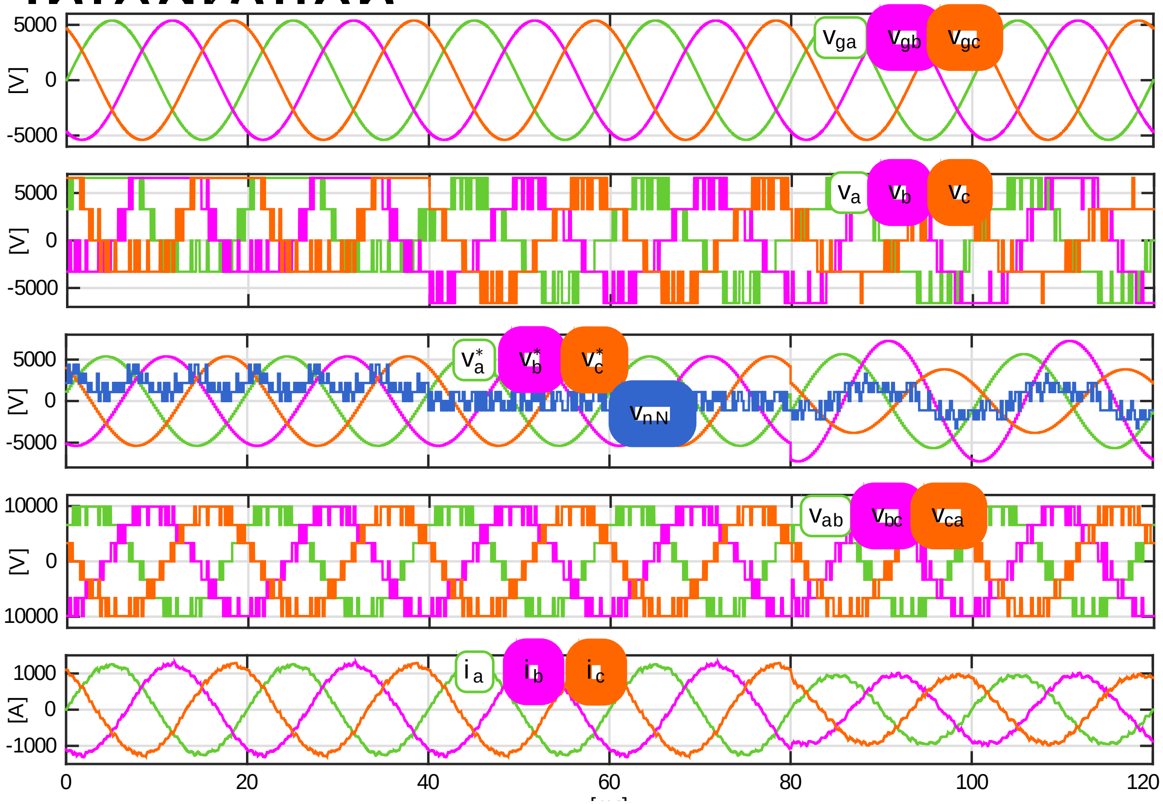
$$i_{ab}(k+1) = A i_{ab}(k) + B v_{abc}(k), \quad ia + ib + ic = 0$$

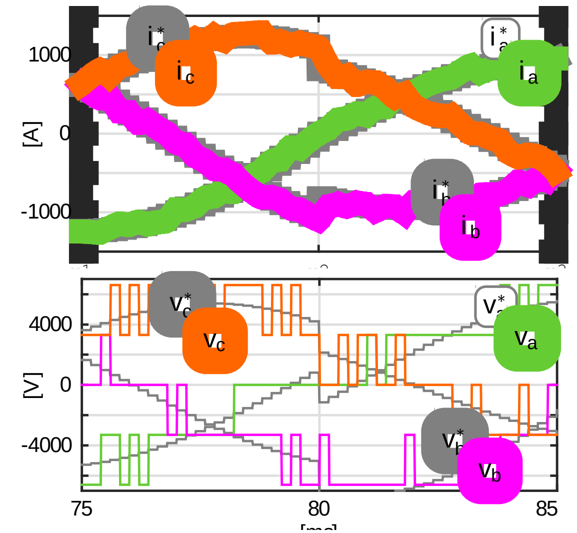
$$I^\star = \frac{3}{2}\frac{P_{nom}}{\hat{V}_g}\frac{(\lambda_a + \lambda_b + \lambda_c)}{3}, \quad \tilde{v}_y^*(t) = v_y^+(t) + v^0(t), \quad y \in \{a, b, c\}$$

$$J(k) = \|i'_{ab}(k+1) - i^\star_{ab}(k+1)\|_2^2 + \sigma\|v'_{abc}(k) - v^\star_{abc}(k)\|_2^2,$$

$$v^{opt}_{abc}(k) = \min\{J(k)\}$$

Power Balance of Cascaded H-Bridge Converters for Large-Scale Photovoltaic Integration

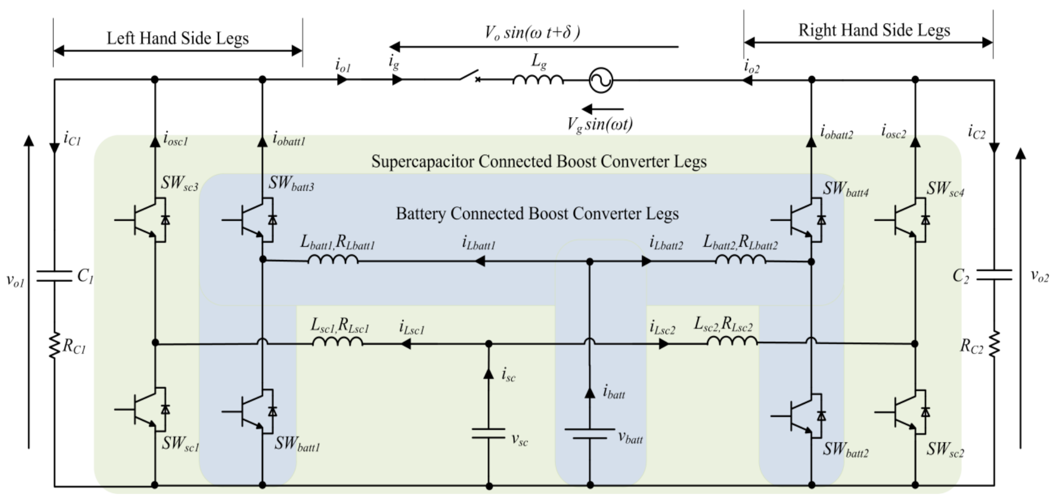




Battery Energy Storage Systems

Project Founded by ABB Research Centre, Sweden

Single Phase Grid-Connected Battery-Supercapacitor Hybrid Energy Storage System



Battery and supercapacitor current waveforms when delivering 30W active power to the grid

- A lithium iron phosphate (LiFePO4) battery and a supercapacitor are employed
- The hybrid energy storage system is designed based on the boost inverter topology
- High frequency current variations are allocated to the supercapacitor
- Reduction of the battery current variations will reduce the internal heating of the battery and will extend the battery lifetime

Sensing of Supercapacitor Strings

- Temperature monitoring system able to estimate temperature distribution in a supercapacitor string
- Developing verified supercapacitor string thermal model
- Verifying / evaluating:
  - Optimal number and placement of sensors based on observability analysis
  - Performance of estimator with minimum number of sensors under abnormal cell overheating

UNSW AUSTRALIA

Thermal Sensor Placement in a Battery String

System Model

$$\dot{x} = Ax + Bu$$
$$y = Cx$$

$$x = \begin{bmatrix} T_{c1} & T_{s1} & T_{c2} & T_{s2} \end{bmatrix}'$$
$$u = \begin{bmatrix} I^2 & T_f \end{bmatrix}'$$

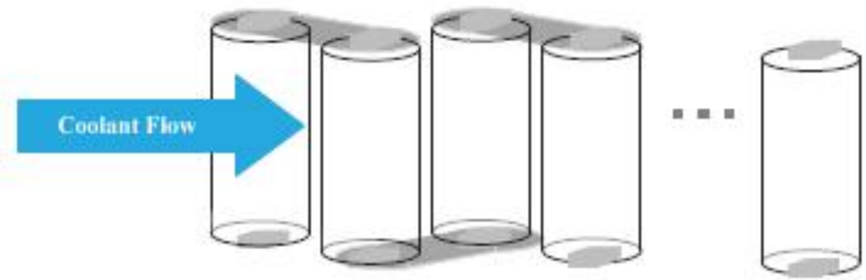


Figure 1. Example of a simplified battery string: 1-string battery of k cells

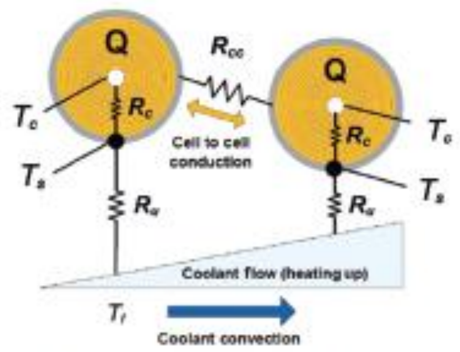


Figure 2. Thermal model of two adjacent battery cells [1]

$$B = \begin{bmatrix} \frac{R}{C_c} & 0 \\ 0 & \frac{1}{R_u C_s} \\ \frac{R}{C_c} & 0 \\ 0 & \frac{R_u C_f - 1}{R_u^2 C_s C_f} \end{bmatrix}, \quad C = ?$$

$$A = \begin{bmatrix} -\frac{1}{R_c C_c} & \frac{1}{R_c C_c} & 0 & 0 \\ \frac{1}{R_c C_s} & -\left(\frac{1}{R_c C_s} + \frac{1}{R_u C_s} + \frac{1}{R_{cc} C_s}\right) & 0 & \frac{1}{R_{cc} C_s} \\ 0 & 0 & -\frac{1}{R_c C_c} & \frac{1}{R_c C_c} \\ 0 & \left(\frac{1}{R_u^2 C_f C_s} + \frac{1}{R_{cc} C_s}\right) & \frac{1}{R_c C_s} & -\left(\frac{1}{R_c C_s} + \frac{1}{R_u C_s} + \frac{1}{R_{cc} C_s}\right) \end{bmatrix}$$

Thermal Sensor Placement in a Battery String

Observability Gramian

$$W_o = \int_0^\infty e^{A't} C' C e^{At} dt$$

$$W_o = U \Sigma U$$

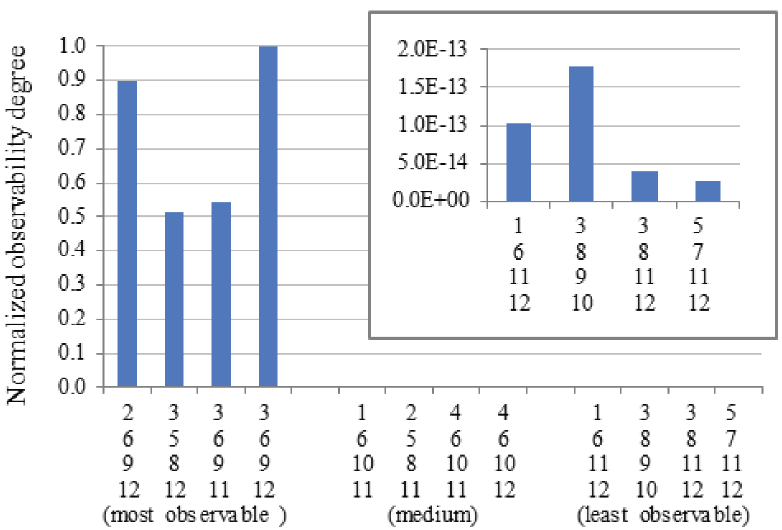
$$\Sigma = \text{diag}\{\sigma_1, \ldots, \sigma_n\}$$

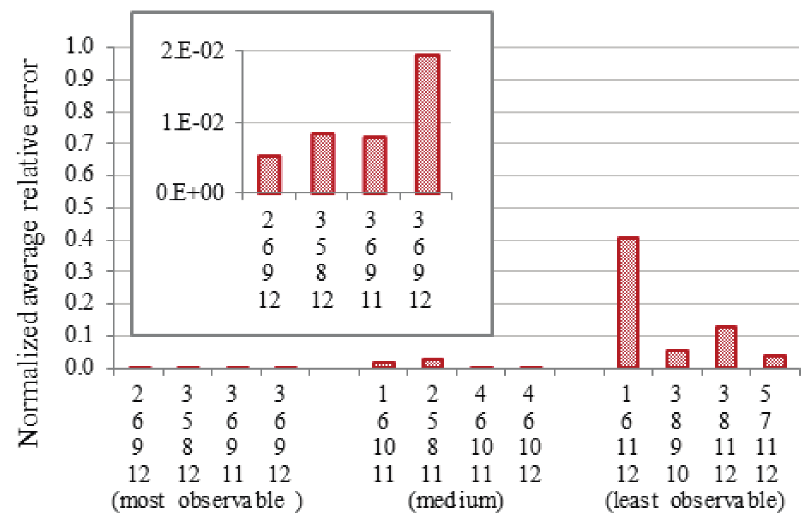
σ_i: Eigen values

Observability Criteria

Criterion	Equation	‘Best’ configuration
Spectral radius [3, 4]	$\rho(\mathbf{Wo}) = \sigma_{\max}(\mathbf{Wo})$ (6)	$\{\max\}\rho(\mathbf{Wo})$
Trace [2-4]	$\text{trace}(\mathbf{Wo}) = \sum_{i=1}^{n} \sigma_i(\mathbf{Wo})$ (7)	$\{\max\}\text{trace}(\mathbf{Wo})$
Near singularity [2-4]	$\text{NS}(\mathbf{Wo}) = \sigma_{\min}(\mathbf{Wo})$ (8)	$\{\max\}\text{NS}(\mathbf{Wo})$
Condition number [2, 4]	$\text{CN}(\mathbf{Wo}) = \frac{\sigma_{\max}(\mathbf{Wo})}{\sigma_{\min}(\mathbf{Wo})}$ (9)	$\{\min\}\text{CN}(\mathbf{Wo})$
Determinant [8]	$\det(\mathbf{Wo})$ (10)	$\{\max\}\det(\mathbf{Wo})$

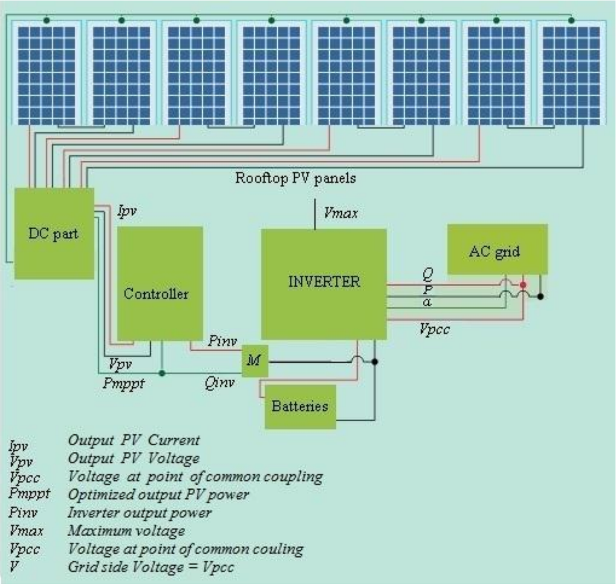
Results: 6-Battery String





Optimal Control of Renewable Energy Systems

Impact of PV Penetration in Distribution S

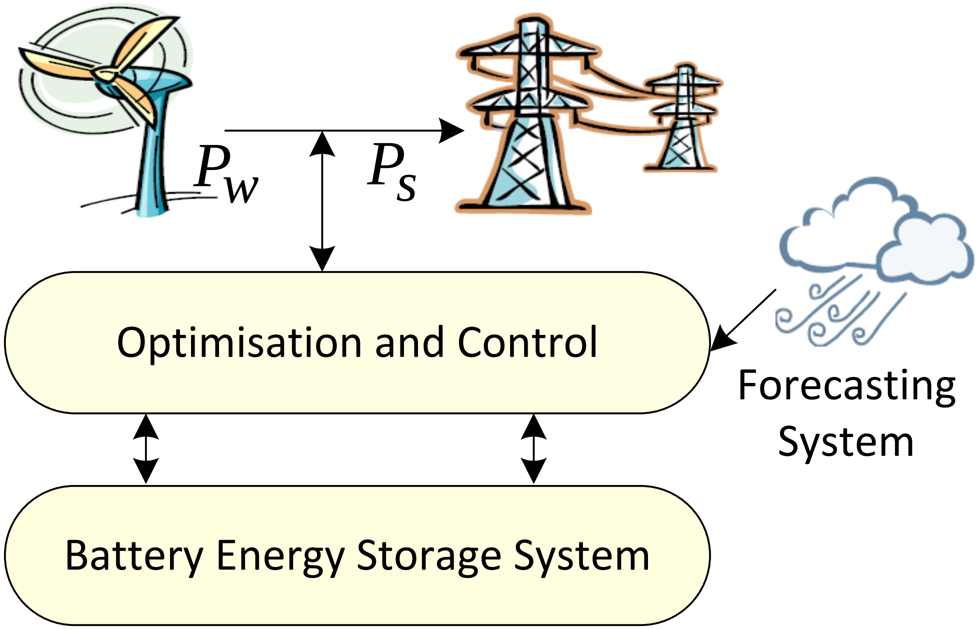


- With High Penetration of PVs, if the PV Generation Exceeds Consumption:
  - Reverse power flow occurs
  - The grid voltage may rise in different points of the network which can cause disconnection of the PV inverters
- Research:
  - Comprehensive impact study
  - Mitigation Methods

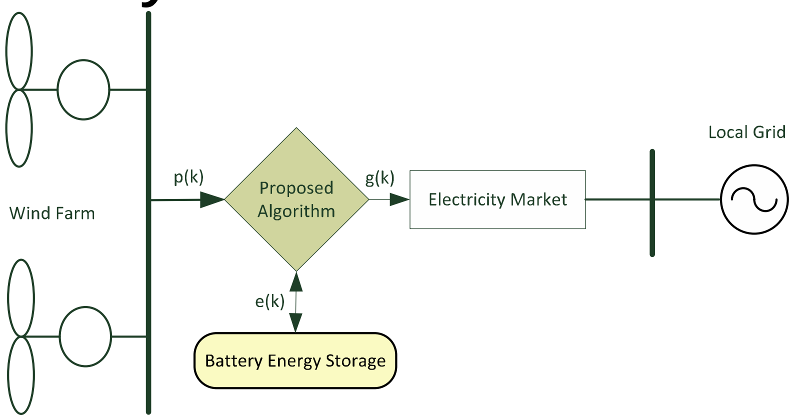
UNSW AUSTRALIA

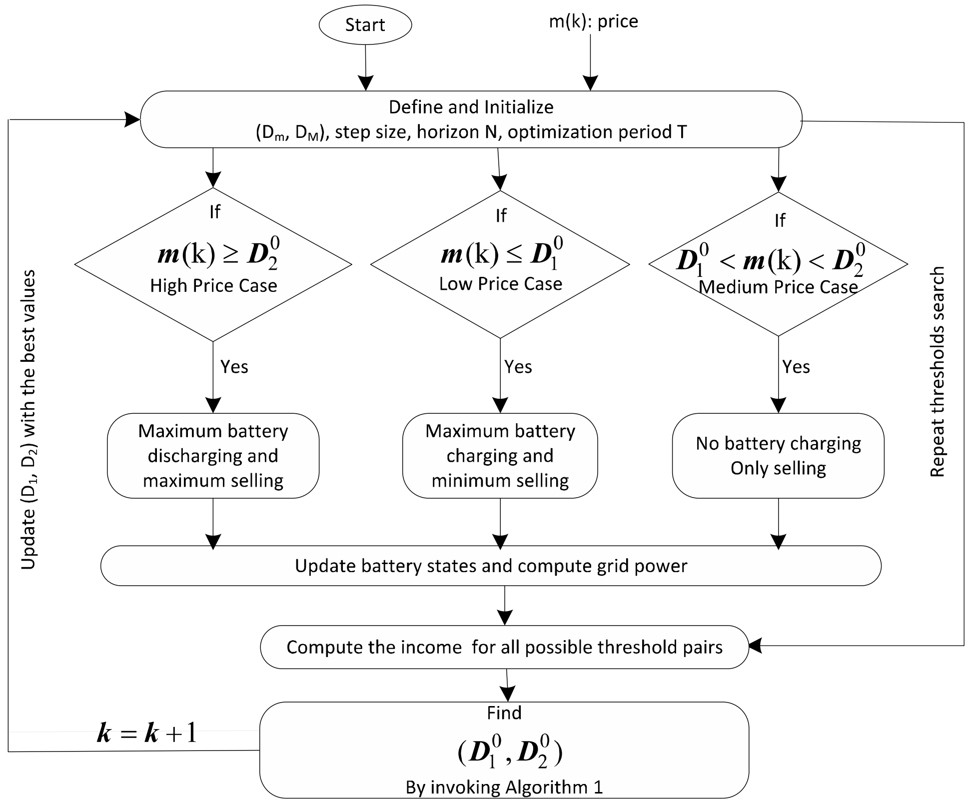
Optimization and Control for Renewable Energy Systems

- Constraint-based optimal control of battery energy storage system (BESS) for renewable energy applications
- Capacity optimisation of BESS using monotonic charging and discharging strategies
- Optimal dispatch strategies utilising BESS and potential inputs from the forecasting system and energy market



Optimization and Control for Renewable Energy Systems





$$(D_1^0, D_2^0) = \max_{D1,D2} \left\{ J = \sum_{i=k-N}^{k} g(i)m(i) \right\}$$

s.t.

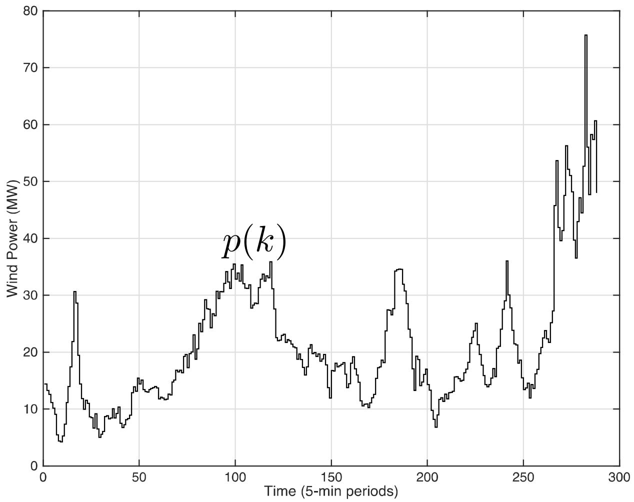
$$x(k+1) = x(k) + p(k) - g(k)$$

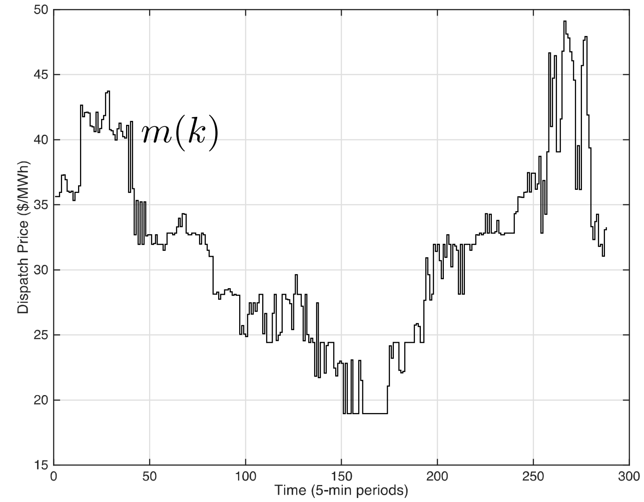
$$\alpha_m c \leq x(k)\alpha_M c$$

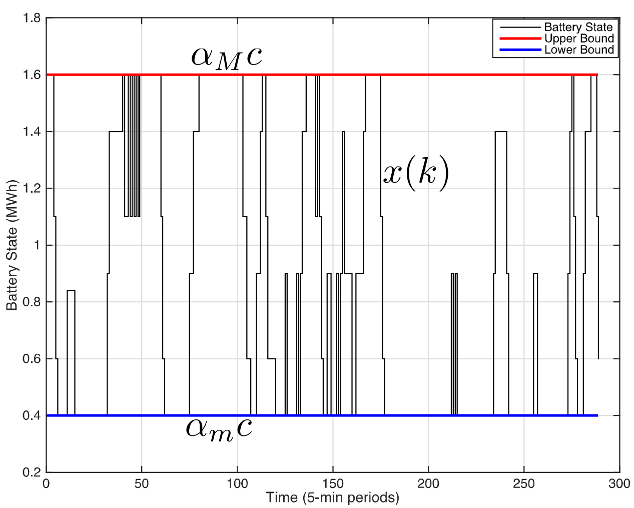
$$r_d \leq x(k+1) - x(k) \leq r_c$$

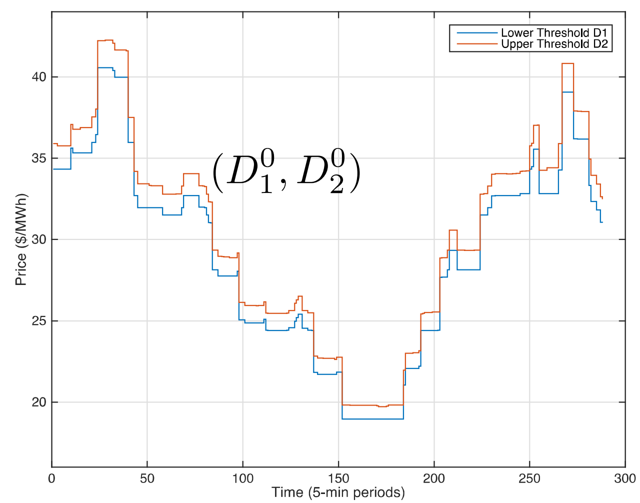
$$g(k) = \begin{cases} p(k) & \text{if } D_1 < m(k) < D_2 \\ p(k) - \min\{p(k), r_c, \alpha_M c - x(k)\} & \text{if } m(k) \leq D_1 \\ p(k) + \min\{r_d, x(k) - \alpha_m c\} & \text{if } m(k) \geq D_2 \end{cases}$$

Optimization and Control for Renewable Energy Sy



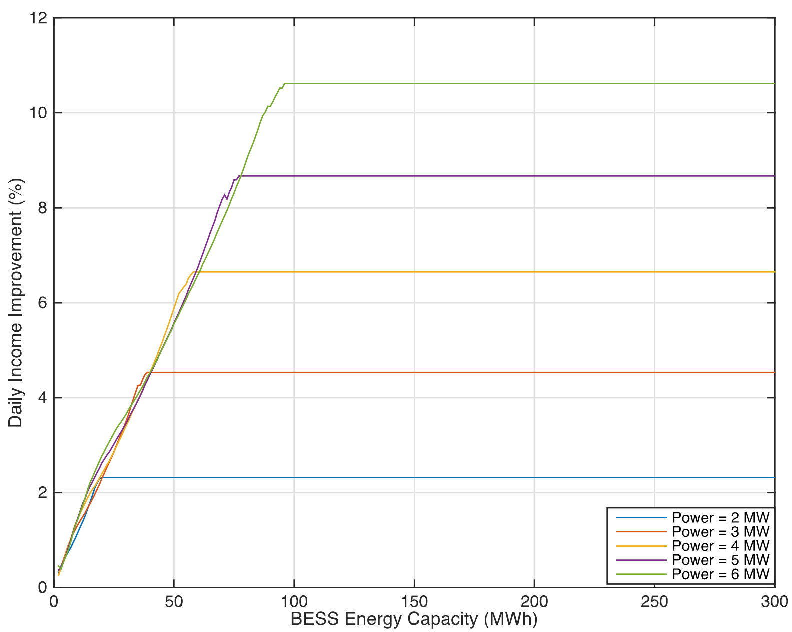






N	10 (50min)
T	288 (24hrs)

Optimization and Control for Renewable Energy Systems



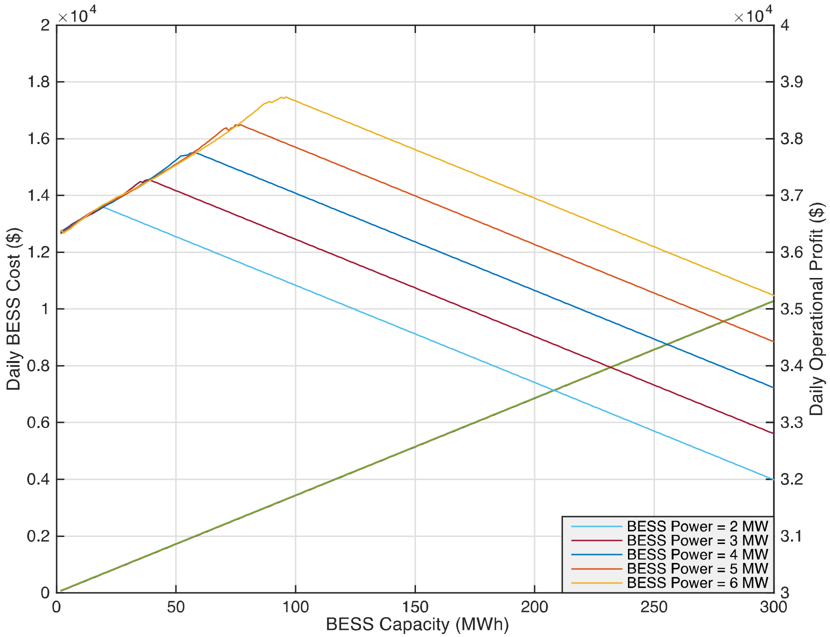


Table 1: Cost of a BESS

BESS	Capacity	Cost of Subsystem			Total Cost
		Storage (US$/kWh)	PCS (US$/kW)	BoP (%)	(US$/kWh)
Crescent	550kW, 550kWh	518	506	19	1272

UNSW AUSTRALIA

Energy Research
Impact Through Partnerships

Never Stand Still

Australian Energy Research Institute

AERI

Thank you for your time!!!

Australian Energy Research Institute, The University of New South Wales

UNSW AUSTRALIA

Never Stand Still | Faculty of Engineering | Australian Energy Research Institute

AERI
Australian Energy Research Institute

Ricardo Aguilera
raguilera@ieee.org
Josep Pou j.pou@unsw.edu