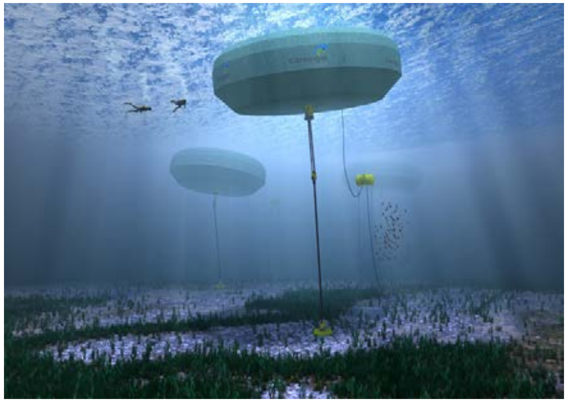
Developing an all-electric power take off for Wave Energy Converters

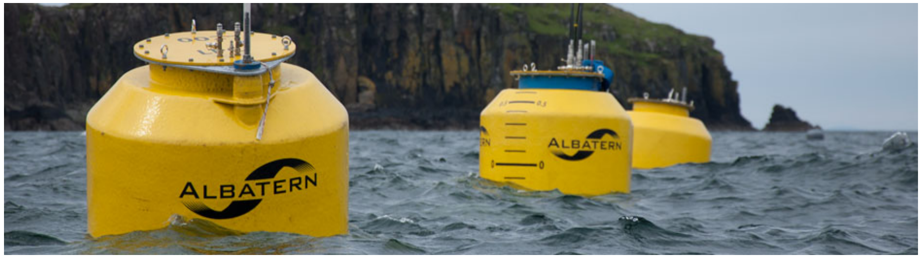
Dr. S.P. McDonald
Dr. N. Baker

Department of Electrical and Electronic Engineering at Newcastle University, Newcastle Upon Tyne, NE1 7RU, U.K.
(email: Steve.McDonald@ncl.ac.uk or Nick.baker@ncl.ac.uk)
Institute for Energy Systems, School of *Engineering , Edinburgh University, Faraday Building, King's Buildings Colin Maclaurin Road*
Edinburgh EH9 3DW U.K
(email: mmueller@staffmail.ed.ac.uk)

- What is E-drive?
- Energy capture
- Generator
- Converter
- System control
- Grid integration



Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/



Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

E-drive is about energy from waves

- Wave devices
  - Difficult environment
  - Remote locations
  - Poor energy yield
- But
  - Significant worldwide resource of low carbon energy
  - 69 TWh/year in the UK alone

Source: the Crown Estate

- The E-Drive project aims to tackle a fundamental weakness of Wave Energy Converters, namely the electro-mechanical Power Take Off (PTO)
- Improving the PTO chain, from the generator through to the grid interface to create an all-electric solution.
- Addressing reliability and maintainability along the way.

Newcastle University

e-DRIVE

THE UNIVERSITY of EDINBURGH
School of Engineering

Focus today

WP1
- Integrated Electrical Generator
- Speed Enhancement

WP2
- Integrated Power Converter
- Grid interface

WP3
- System Modelling and Control
- Wave to wire

WP4
- Design for Survivability

WP5
- Experimental Demonstration

WP6
- Design Case Studies

WP7
- Industrial Engagement & Impact Management

TU Delft

Universidad de Chile

UNAM
Universidad Nacional Autónoma de México

Academic partnership

- Edinburgh University
  - Principle investigator
- Newcastle University
  - Co-investigator
- In collaboration with:
  - TU Delft
  - Universidad de Chile
  - Universidad National de Mexico

http://www.edrive.eng.ed.ac.uk/

THE UNIVERSITY of EDINBURGH
School of Engineering

Newcastle University

TU Delft

Universidad de Chile

Universidad Nacional Autónoma de México
UNAM

Industrial associates

- Albatern Wave Energy
  - WaveNET
- Columbia Power Technologies
  - StingRAY
- Technalia
  - Technology development
- Carnegie Wave Energy
  - CETO
- Turbo Power Systems
  - Power electronics and converters

ALBATERN Wave Energy

COLUMBIA POWER TECHNOLOGIES power from the next wave

tecnalia Inspiring Business

Carnegie wave energy

tps

e-DRIVE

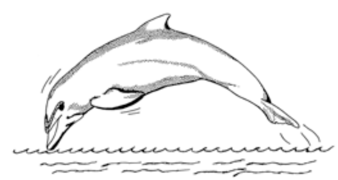
Newcastle University

EPSRC

Engineering and Physical Sciences Research Council

THE UNIVERSITY of EDINBURGH
School of Engineering

Newcastle University



Electrical Power Research Group

Power Electronics

Drives and Control

Machines

Power Systems

20 academics, including 6 in Singapore
28 research staff
~50 PhD students
>100 MSc students

Transport
(Air, Land, Sea)



Power Systems and Energy (Small/Large)



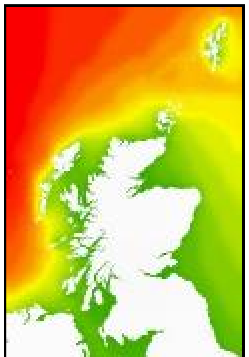
High Volume Products
(Low cost, Efficiency)



Institute for Energy Systems

IES

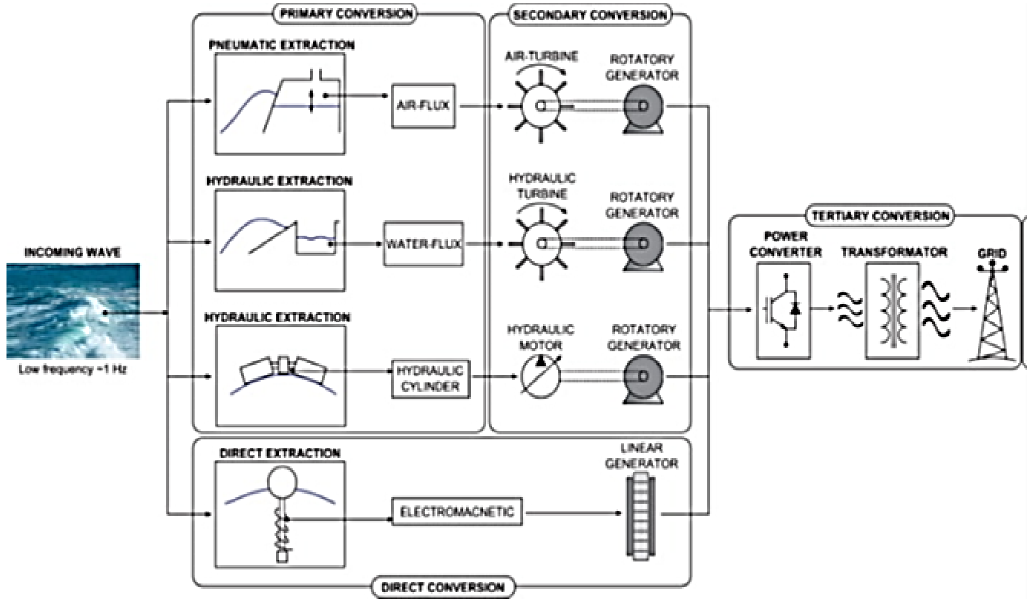
Resources	Capture	Conversion	Delivery

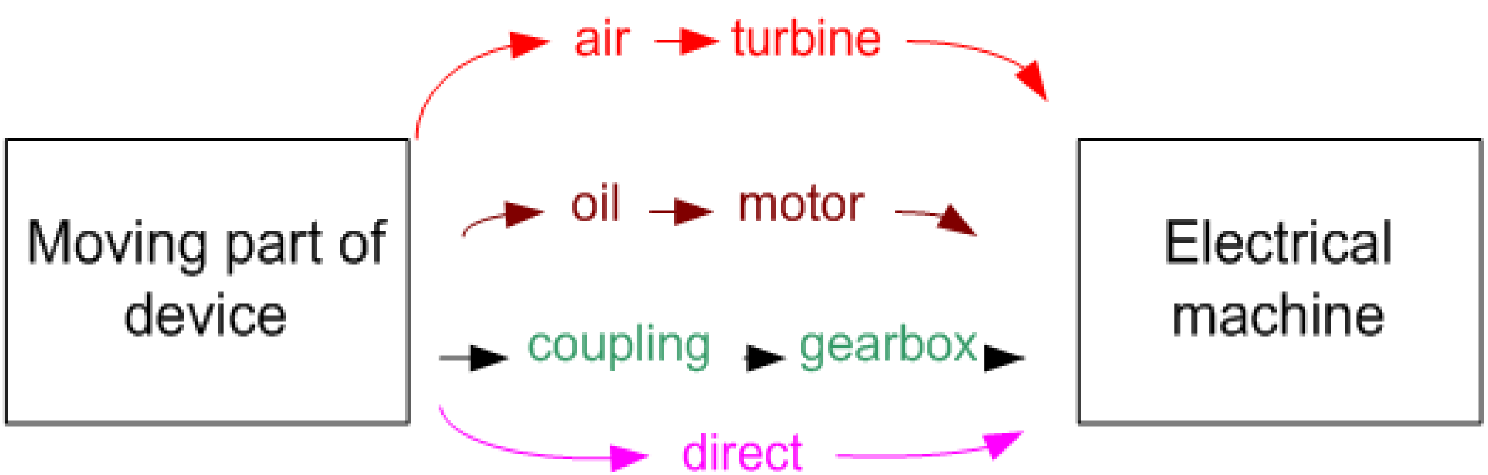


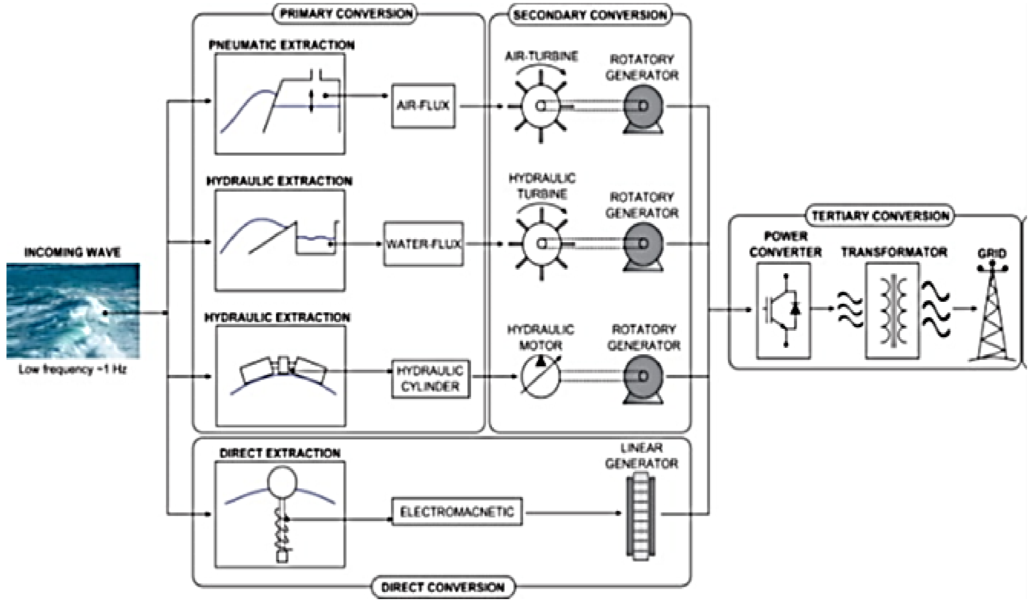
Energy and Climate	Marine & Wind Energy	Machines Power Electronics & Control	Power Systems Smart Grids Energy Storage

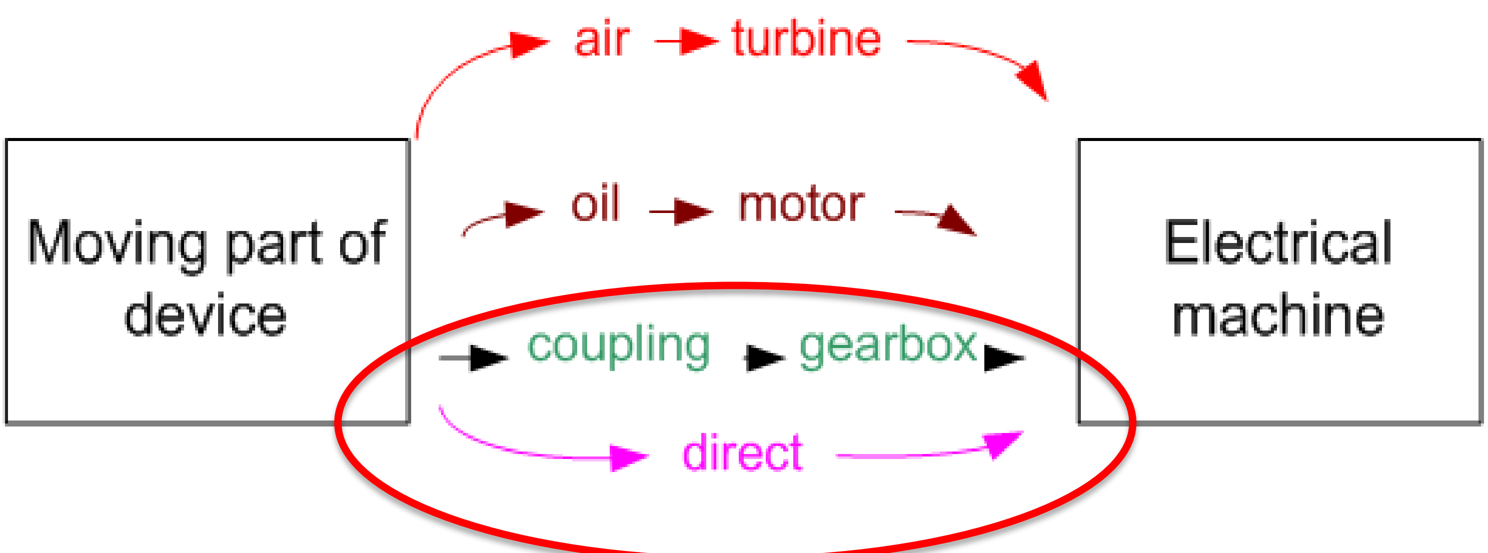
Innovation   Policy and Regulation   Standards   Environment

IES research spans and maps to the renewable energy supply chain

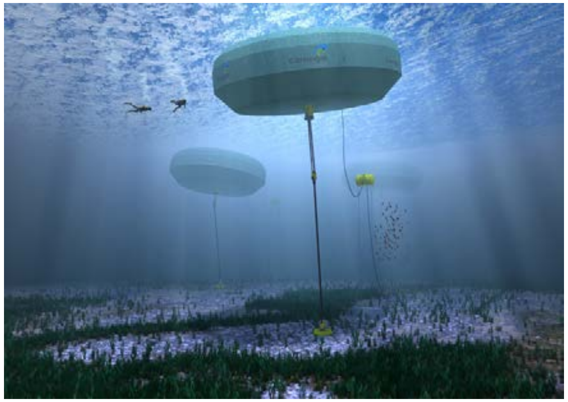

PRIMARY CONVERSION
SECONDARY CONVERSION
PNEUMATIC EXTRACTION
AIR-FLUX
AIR-TURBINE
ROTATORY GENERATOR
HYDRAULIC EXTRACTION
WATER-FLUX
HYDRAULIC TURBINE
ROTATORY GENERATOR
INCOMING WAVE
Low frequency ~1 Hz
HYDRAULIC EXTRACTION
HYDRAULIC CYLINDER
HYDRAULIC MOTOR
ROTATORY GENERATOR
TERTIARY CONVERSION
POWER CONVERTER
TRANSFORMATOR
GRID
DIRECT EXTRACTION
ELECTROMAGNETIC
LINEAR GENERATOR
DIRECT CONVERSION


Moving part of device
air
turbine
oil
motor
coupling
gearbox
direct
Electrical machine

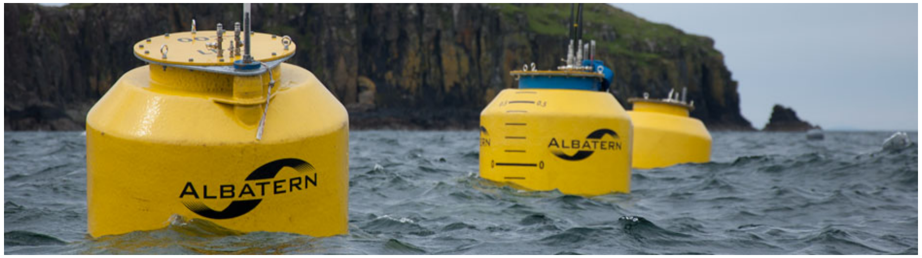

PRIMARY CONVERSION
SECONDARY CONVERSION
PNEUMATIC EXTRACTION
AIR-FLUX
AIR-TURBINE
ROTATORY GENERATOR
HYDRAULIC EXTRACTION
WATER-FLUX
HYDRAULIC TURBINE
ROTATORY GENERATOR
INCOMING WAVE
Low frequency ~1 Hz
HYDRAULIC EXTRACTION
HYDRAULIC CYLINDER
HYDRAULIC MOTOR
ROTATORY GENERATOR
TERTIARY CONVERSION
POWER CONVERTER
TRANSFORMATOR
GRID
DIRECT EXTRACTION
ELECTROMAGNETIC
LINEAR GENERATOR
DIRECT CONVERSION


Moving part of device
air
turbine
oil
motor
coupling
gearbox
direct
Electrical machine

- What is E-drive
- Energy capture
- Generator
- Converter
- System control
- Grid integration



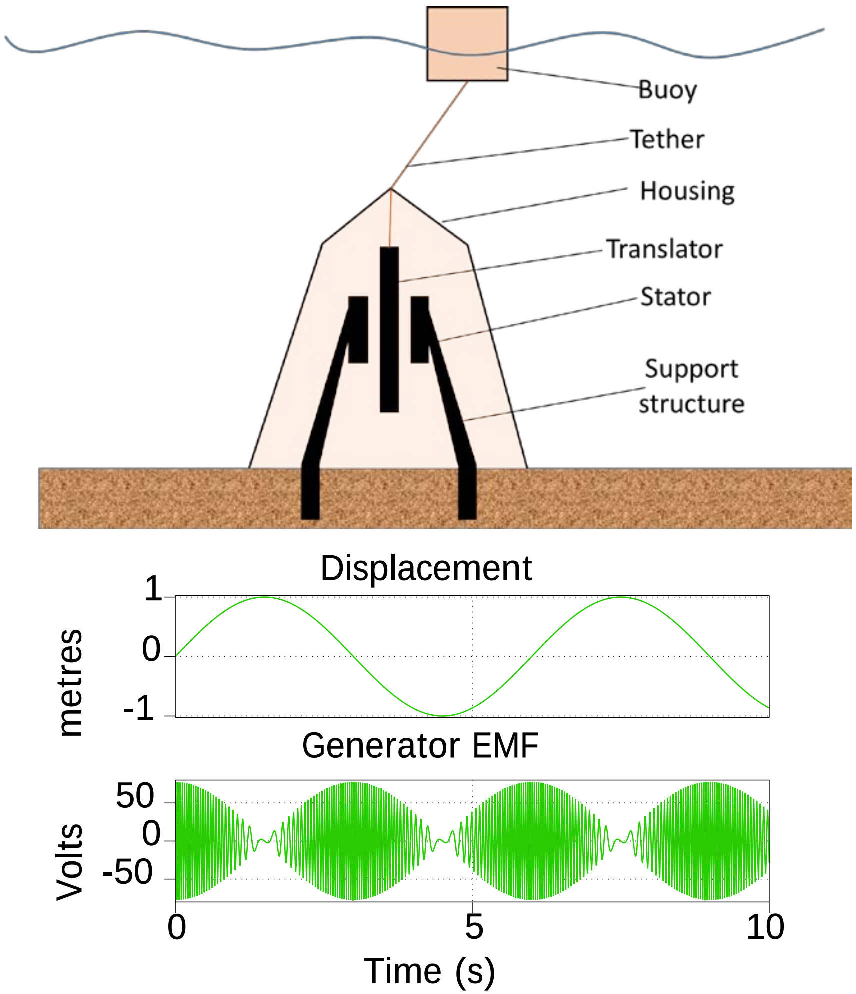
Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/



Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

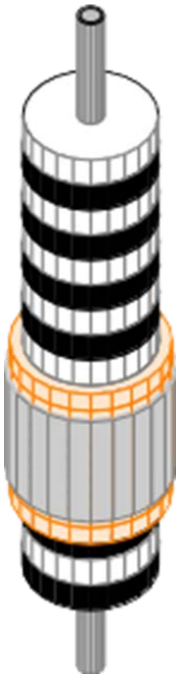
Energy Capture

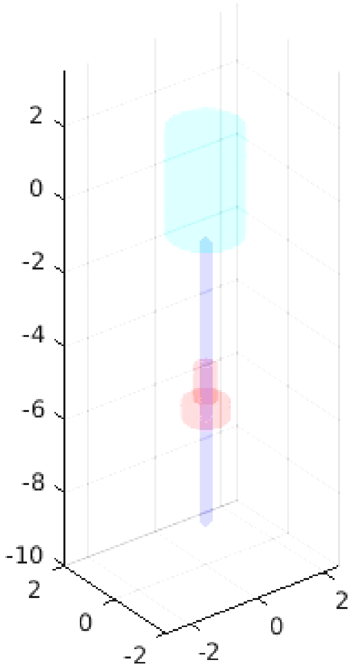
- Intermittent power flow from WEC
- Bi-directional power flow required to enable tuning of WEC
- Magnitude of peak power flows >> average power from device



WEC PTO modelling

- Buoy 2m diameter, 1m draft
- Air Cored Tubular Machine
- Multibody Model
  - Buoy
  - Translator
  - Stator
  - Base (fixed body for ref)
  - Hinge joint
  - Sliding (prismatic) joint
  - Sensors
- Waves: single frequency 0.5m amplitude, 0.2Hz

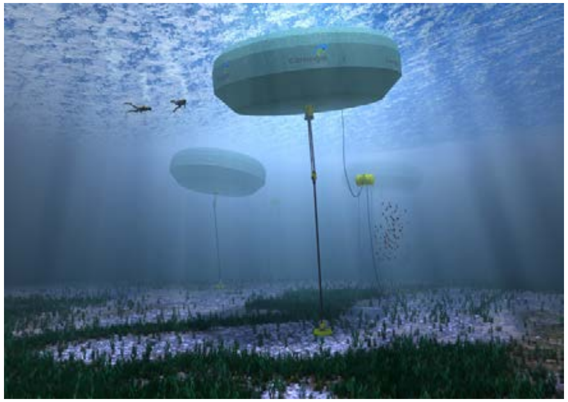




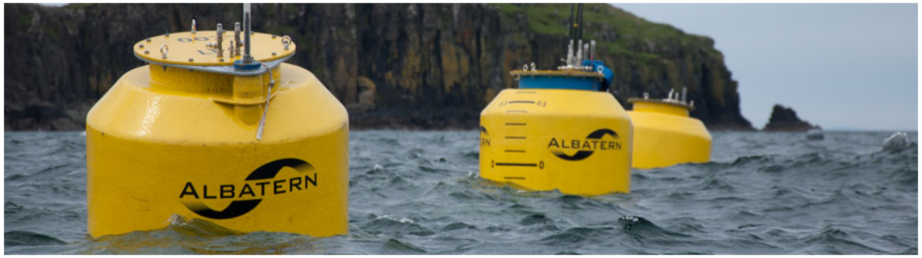
THE UNIVERSITY of EDINBURGH
School of Engineering
Dr. R. Crozier r.crozier@ed.ac.uk

E-DRIVE

- What is E-drive
- Energy capture
- Generator
- Converter
- System control
- Grid integration



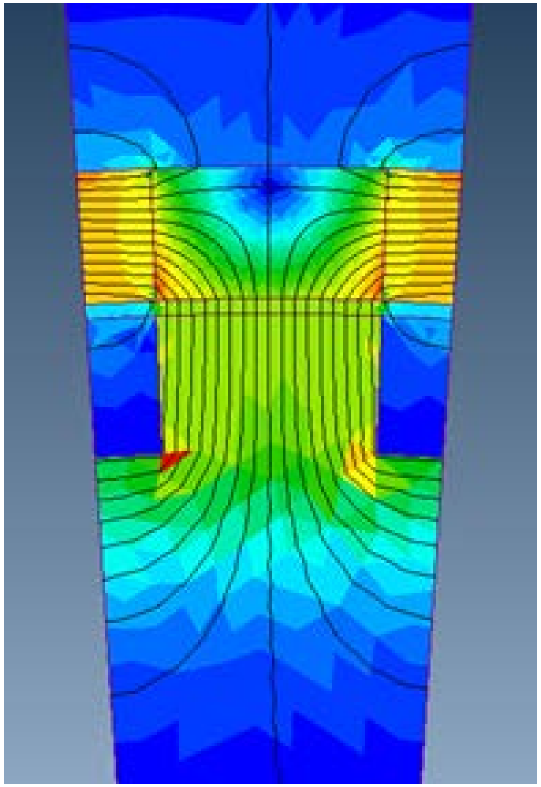
Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/



Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

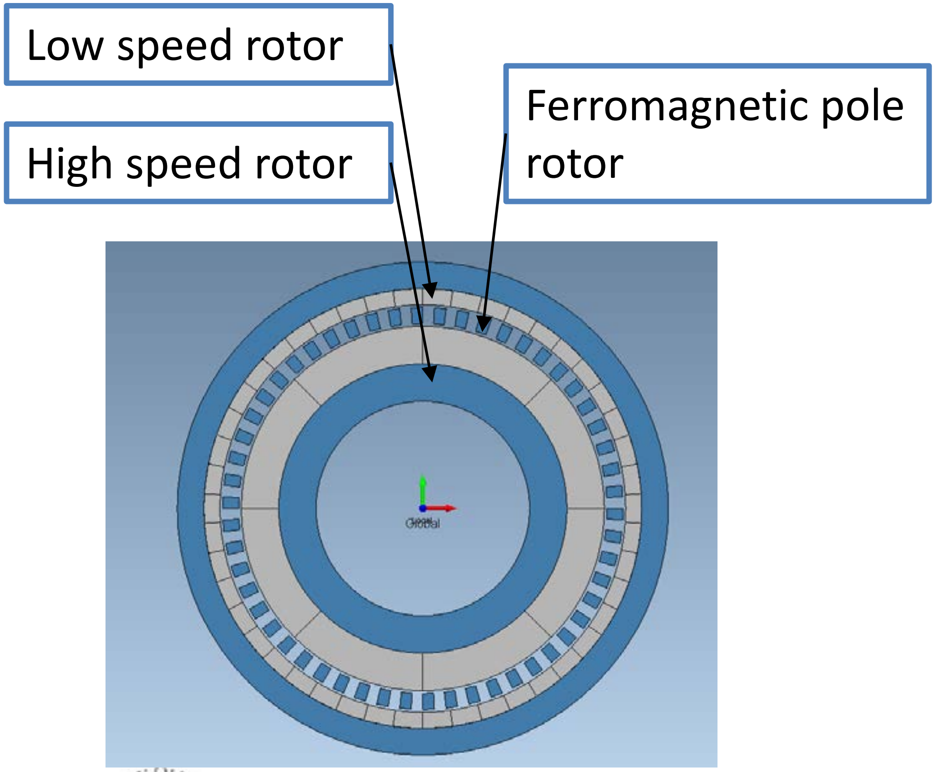
Direct drive challenges

- Electrical machines work best with **<u>high speed rotary motion</u>**
- Wave devices - low speed oscillatory (linear) motion
- Eg 3000rpm electrical machine active diameter of 200mm has an air gap speed of 30 m/sec.
- Typical WEC **<u>linear</u>** oscillatory motion with velocities in the region of **<u>0.5-2m/s</u>**
- Options being investigated:
  - Speed enhancement
  - linear and rotary generators suited for low speed operation



Speed enhancement – magnetic gears

- Advantages
  - Contactless torque transfer
  - Reduced wear of mechanical elements
  - Reduced lubrication requirements
  - Inherent overload protection
  - Overall, magnetic gears have the potential to greatly reduce operation and maintenance costs for wave and tidal energy devices while maintaining high efficiency.



THE UNIVERSITY of EDINBURGH
School of Engineering

Ben McGilton Ben.McGilton@ed.ac.uk

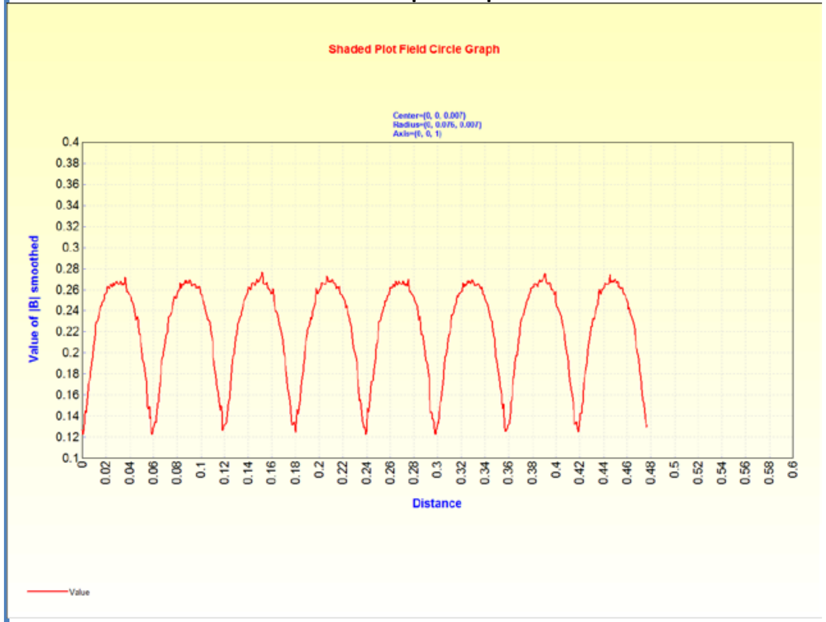
Magnetic Gear Operation

- Ferromagnetic poles placed in the airgap between rotors modulate the magnetic field such that rotors “see” a speed change.
  - Developing analytical and modelling tools to enable magnetic gear design for a wide variety of marine energy devices.
  - 2D and 3D FE modelling
  - Basing designs on the ferromagnetic pole, field flux modulating type magnetic gears
  - The speed change comes from the ratio of magnetic poles ion each rotor
  - Examples for 5.75:1 follow

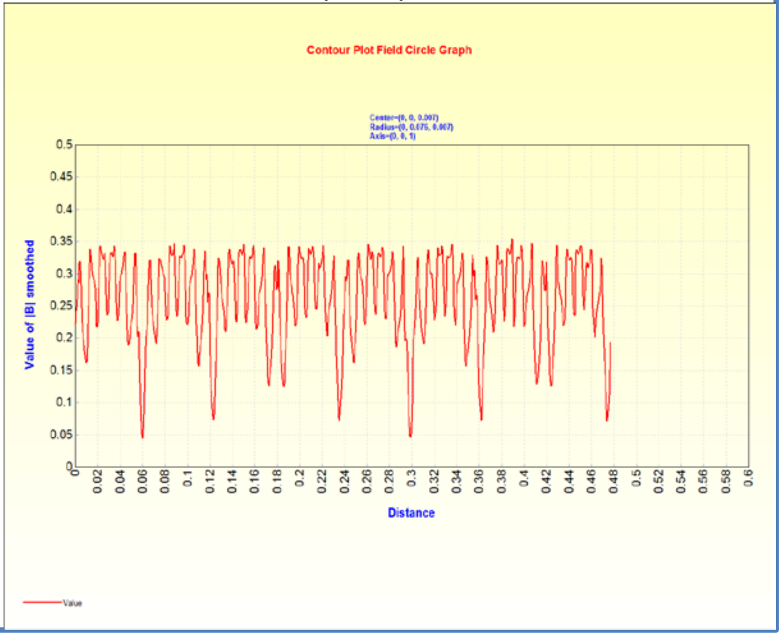
Magnetic gear – outer rotor

Magnetic flux magnitude produced by the inner rotor magnets at outer rotor

Without FM pole pieces:



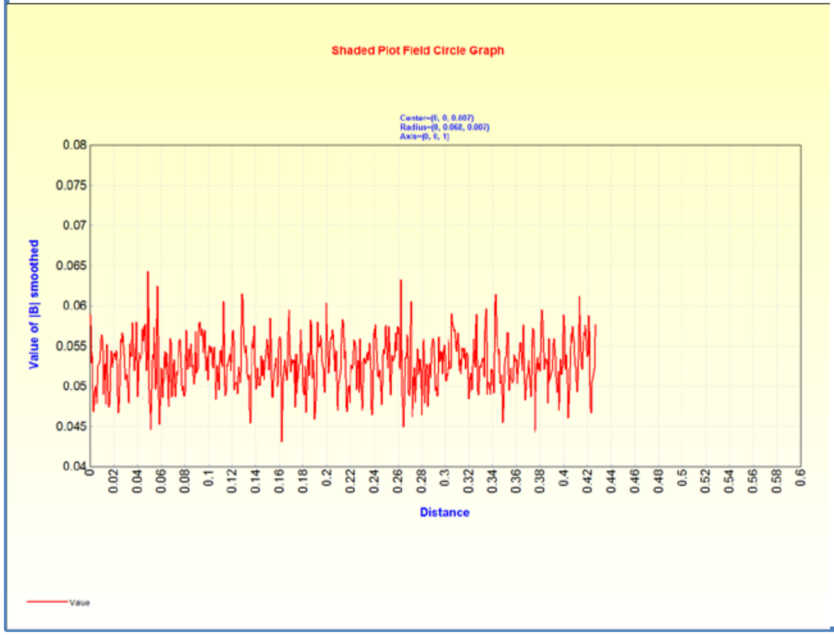
With FM pole pieces:



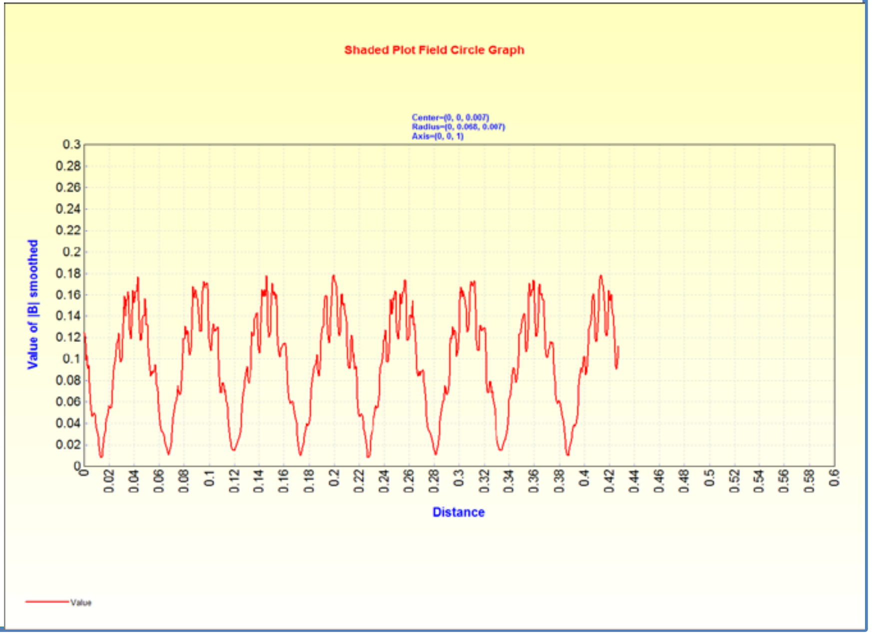
Magnetic gear – inner rotor

Magnetic flux magnitude produced by outer rotor magnets at inner rotor.

Without pole pieces:

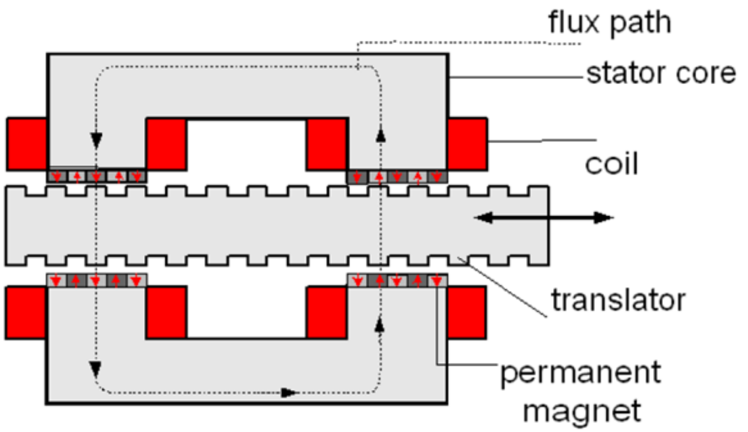


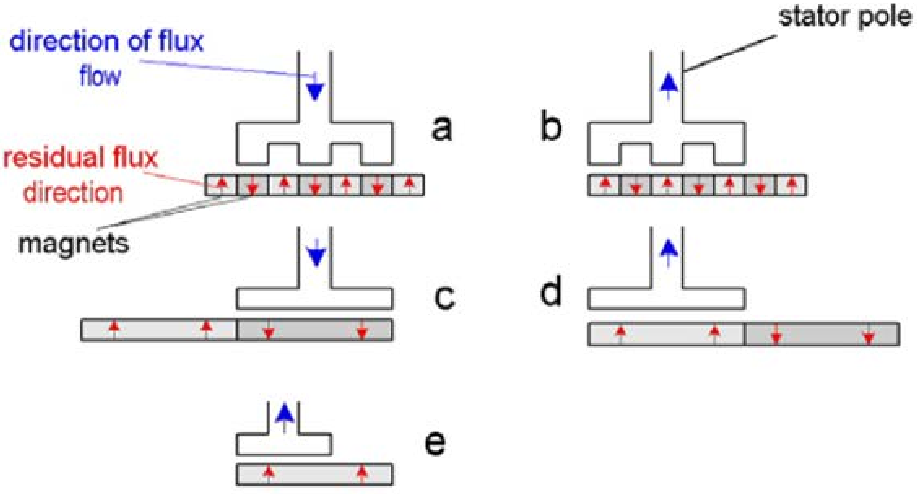
With pole pieces:



Linear generators

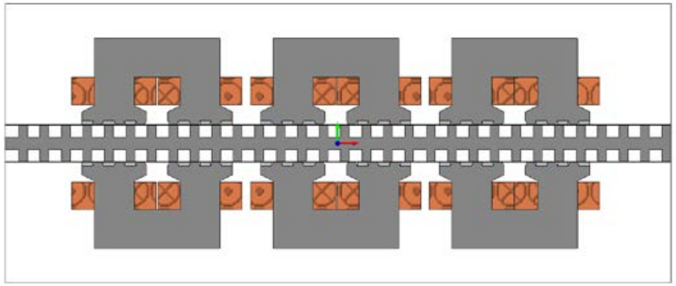
- Vernier hybrid machines
  - Inherent magnetic gearing
  - High Shear Stress at the airgap
  - Up to 200kN/m^2 reported. i.e. 4-5 times conventional PM synchronous machine
  - Construction is challenging
  - Low power factor is an issue

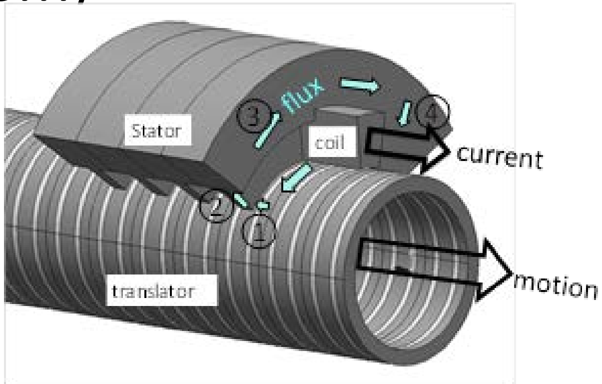


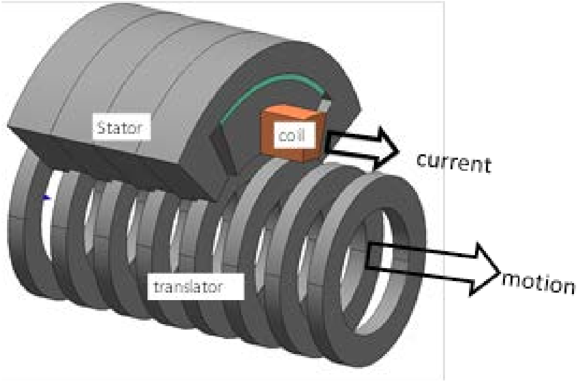


Linear generator development

- Various topologies being designed and built including:
  - Consequent pole Vernier hybrid machine (VHM)
  - Transverse flux (TFM)
  - Flux switching (FSM)







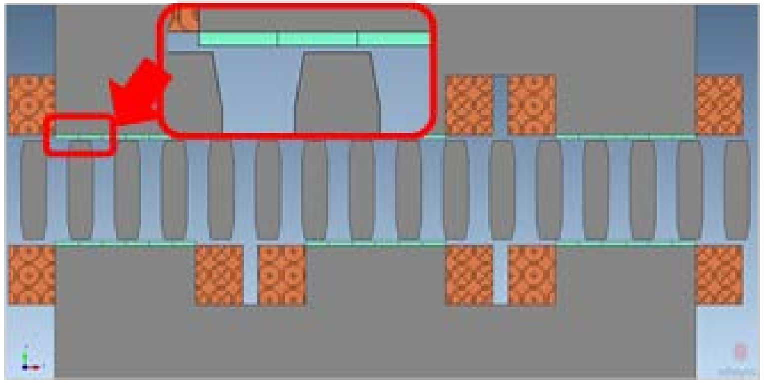
- Optimising various machine designs with converter is part of this process

Machine characteristics

- TFM – best force density
  - Not great for linear machines with long strokes
- VHM – 2^{nd} best force density
  - Better for linear but requires lots of magnets glued on the translator surface, few coils but high fill factor
- FSM - 3^{rd} best for force density
  - Better power factor, odd to construct, but a more conventional winding

Linear generator fault tolerance

- Modular concept
  - Multiple sections of the generator
  - Each section has its own generator interface converter
  - Failure of a number of sections will reduce wave device maximum power only
  - Option to "shut off" sections when not needed for efficiency improvement in low sea-states



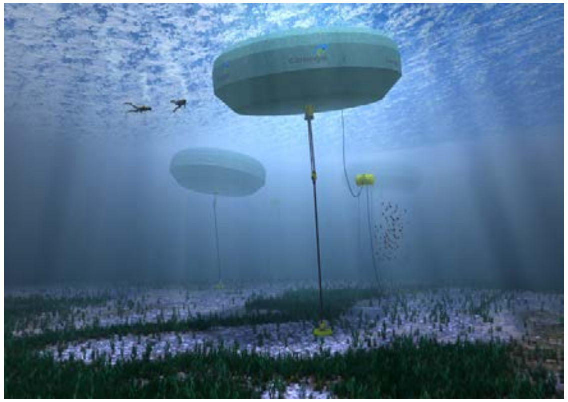
Improved performance vernier hybrid machine

Newcastle University

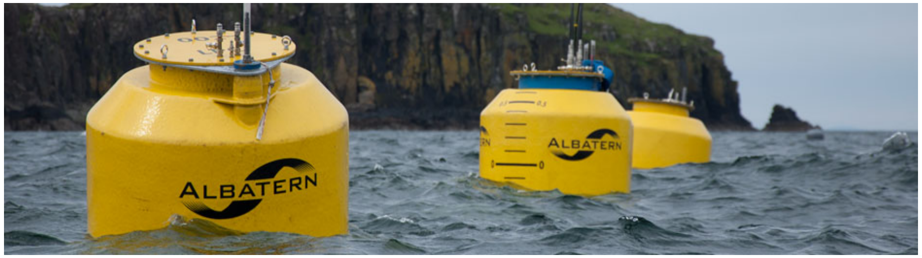
e-DRIVE

THE UNIVERSITY of EDINBURGH School of Engineering

- What is E-drive
- Energy capture
- Generator
- Converter
- System control
- Grid integration



Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/

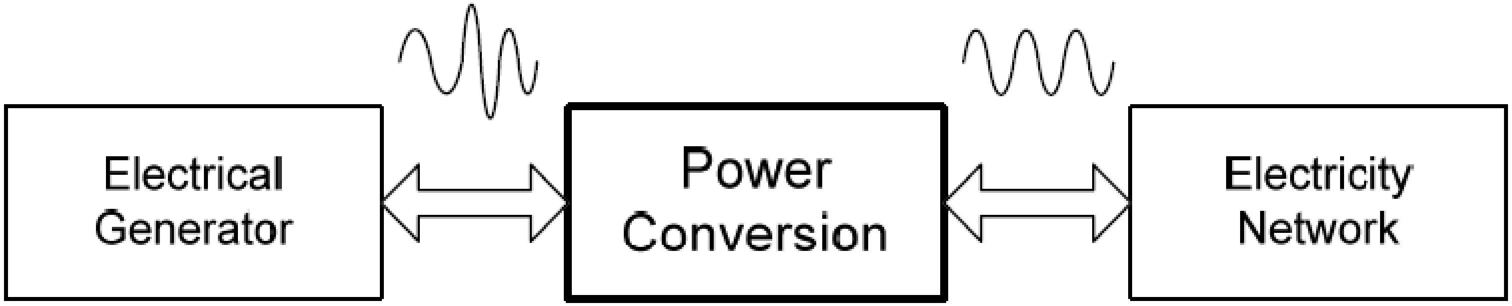


Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

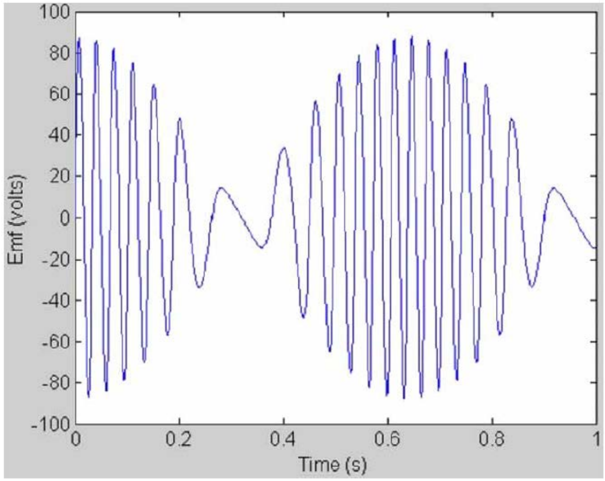
The Electrical power converter (EPC) top level specification

- Generator interface (converter)
  - Optimal power flow and 4Q control of the generator
- Electrical Energy storage (ESS)
  - Integrated with the DC link
  - High cycle capacity
- Grid interface (Inverter)
  - High power quality
  - 11kV to minimise losses in cable

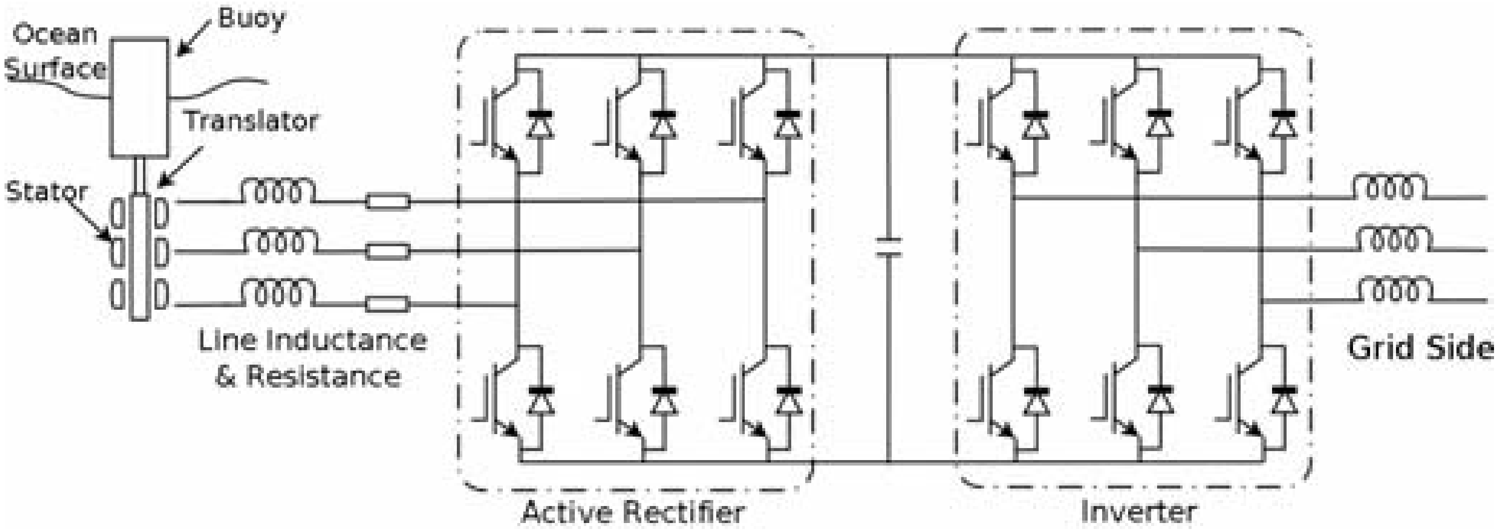
Challenges for power conversion

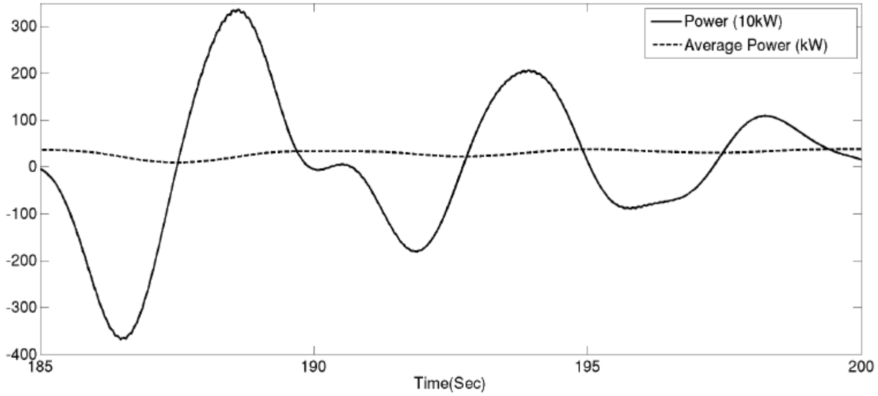


- Pulsating EMF from generator reflects motion of waves
- Reactive power required for device mechanical tuning



Power required to achieve tuning



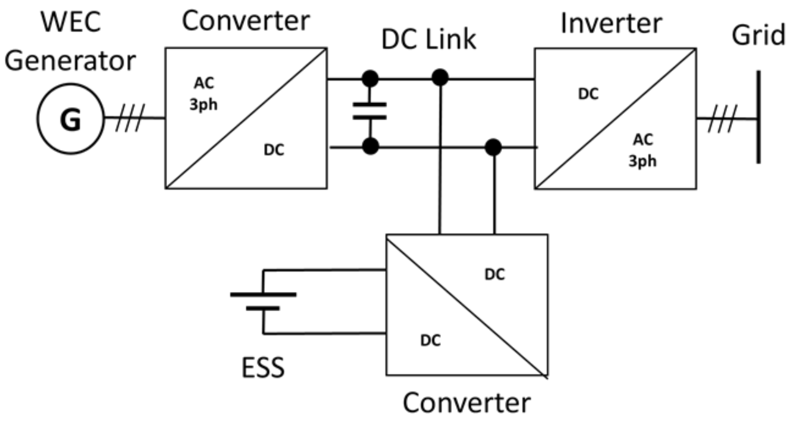


"Instantaneous power for mechanical tuning can be hundreds of times more than the average power extracted" [1]

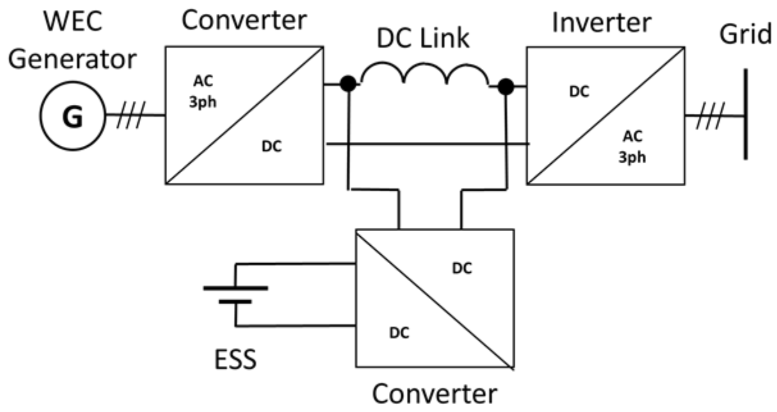
[1] B. Li, D. E. Macpherson, and J. K. H. Shek, "Direct drive wave energy converter control in irregular waves," in *Renewable Power Generation (RPG 2011), IET Conference on*, 2011, pp. 1-6.

Topology selection

Voltage source



Current source



Current source or voltage source

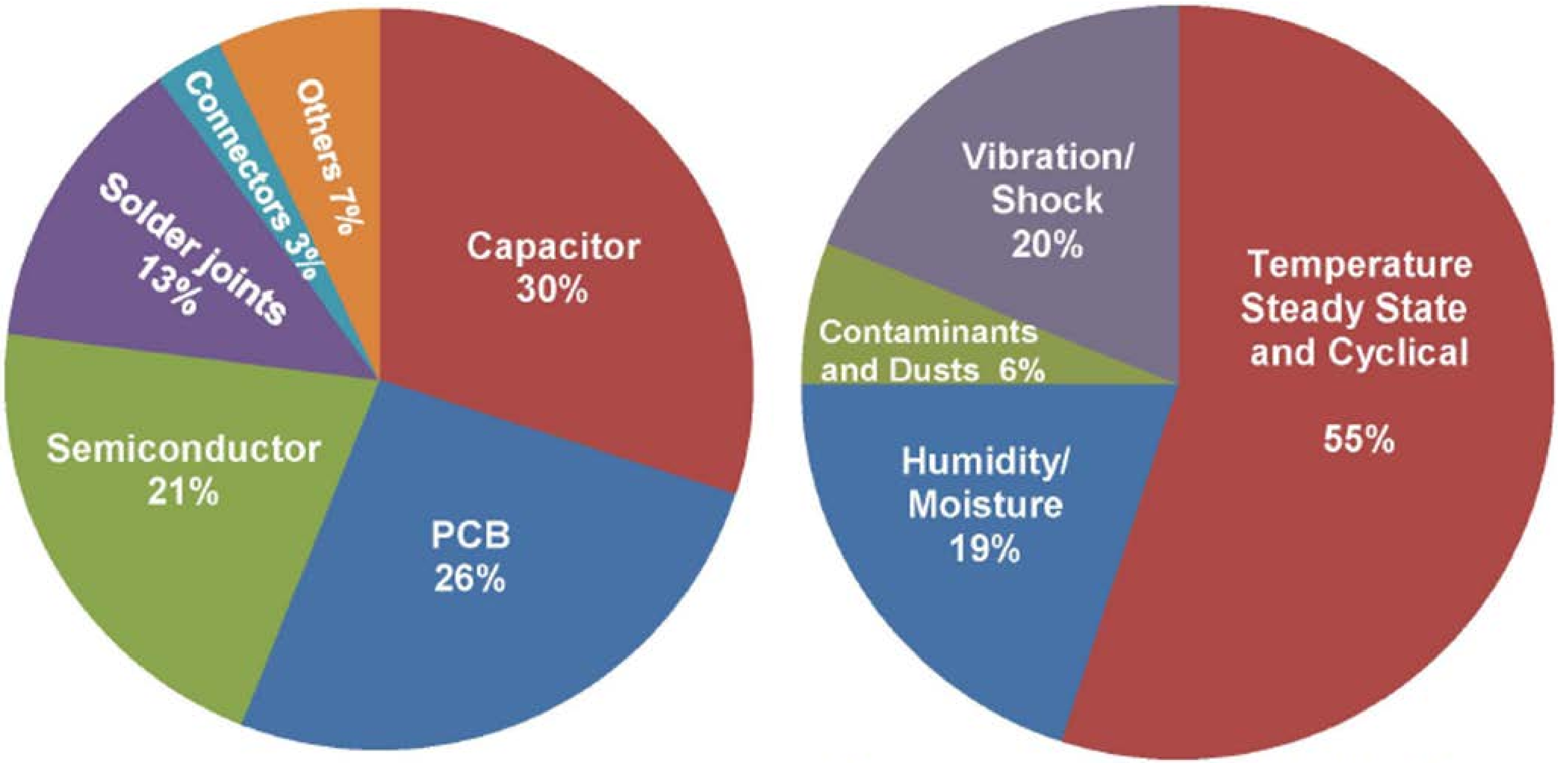
CSI

- Advantages
  - Can make use of slower switching devices
  - Low dv/dt and naturally sinusoidal currents to machine make the topology more machine friendly
- Disadvantages
  - Commutation capacitors required
  - Resonance
  - Large DC link inductor
  - Efficiency can be an issue

VSI

- Advantages
  - Industry standard topology for VSD below 1MW and 690V AC
  - Wide range of IGBT's in modules etc
  - Full 4Q operation possible
- Disadvantages
  - DC link must be held at higher voltage than $V_{pk\ line\ -\ line}$ leading to poor device utilisation
  - High dv/dt
  - Large Electrolytic capacitors

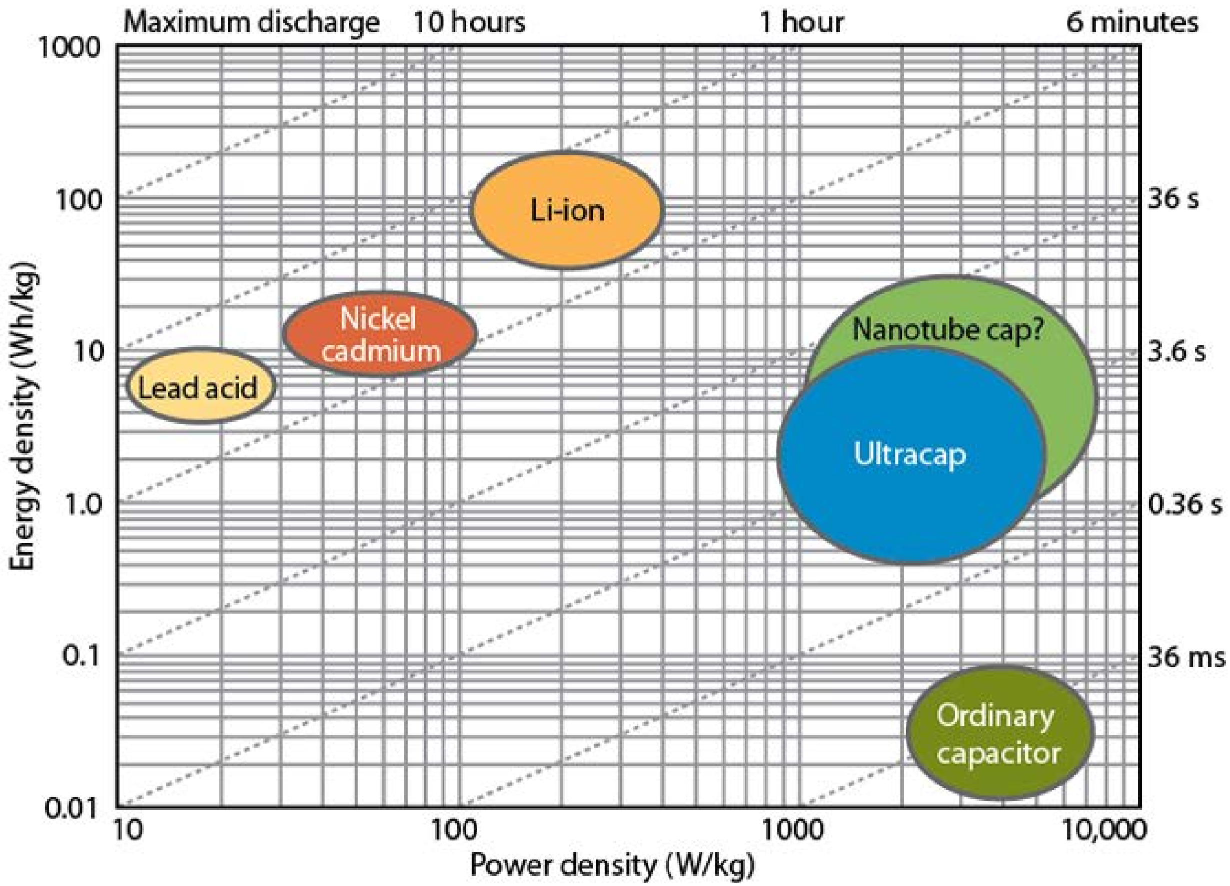
Addressing converter reliability



(a) Failure root cause distribution. (b) Source of stresses distribution.

S. Yang, A. Bryant, P. Mawby, D. Xiang, L. Ran, and P. Tavner, "An industry-based survey of reliability in power electronic converters," in *2009 IEEE Energy Conversion Congress and Exposition*, 2009, pp. 3151-3157.

Energy storage options



E. Chemali, M. Preindl, P. Malysz, and A. Emadi, "Electrochemical and Electrostatic Energy Storage and Management Systems for Electric Drive Vehicles: State-of-the-Art

Energy Storage

	Supercapacitor	LiNiMnCo battery
Specific Power (W/kg)	500-100,000	500-2400
Energy Density (Wh/L)	10-30	230-550
Specific Energy (Wh/kg)	2.5-15	126-210
Cost ($/kWh)	300-2000	300-600
Cycle Life	>100000	1200-1950

Other investigators have suggested that supercapacitor ESS could be applied to WEC's [1]. The advantage of the supercapacitor is the relatively high power capability and cycle life, but the energy density is quite low.

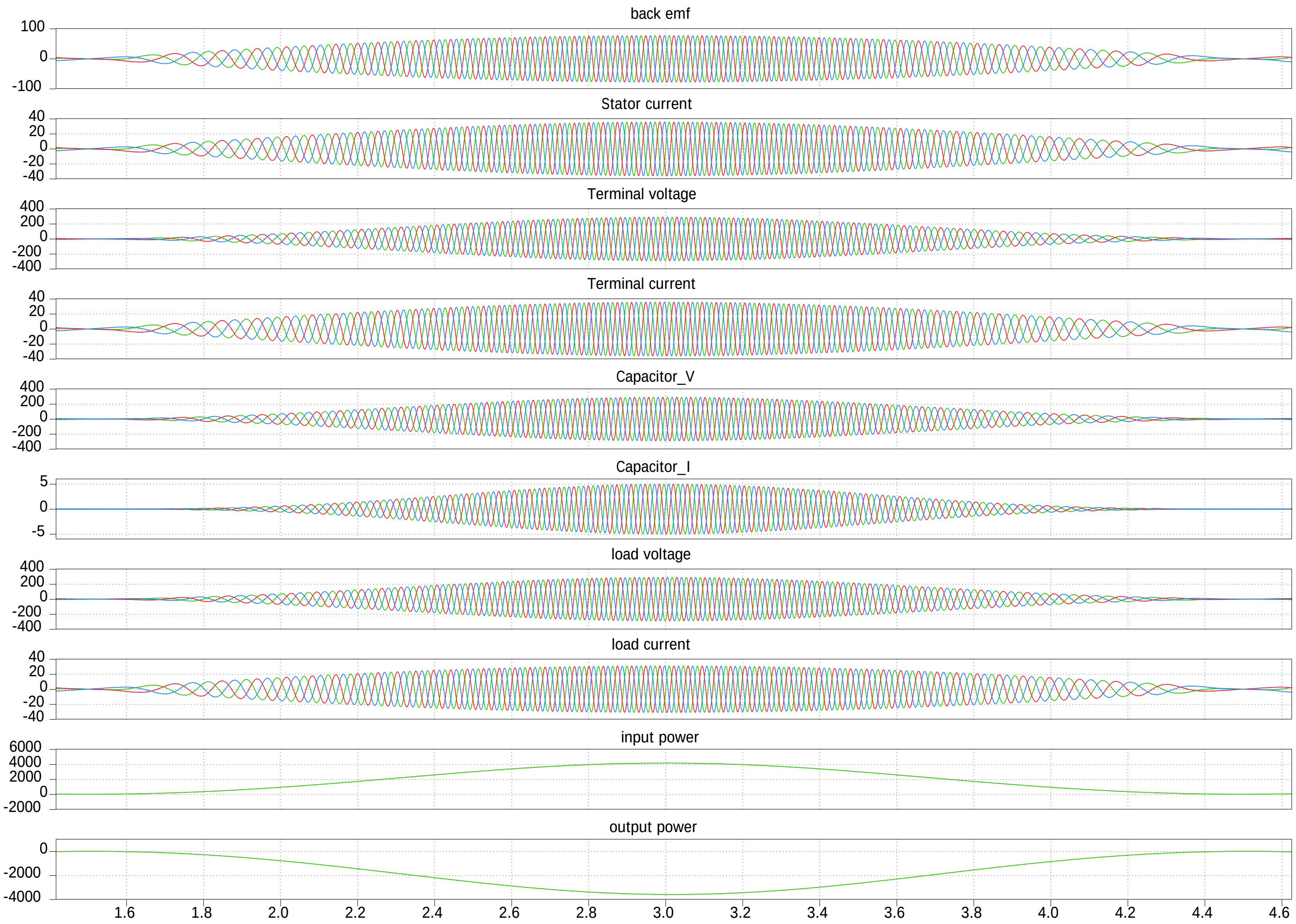
[1] G. Brando, A. Dannier, A. D. Pizzo, L. P. D. Noia, and C. Pisani, "Grid connection of wave energy converter in heaving mode operation by supercapacitor storage technology," *IET Renewable Power Generation,* vol. 10, pp. 88-97, 2016.

Converter functionality

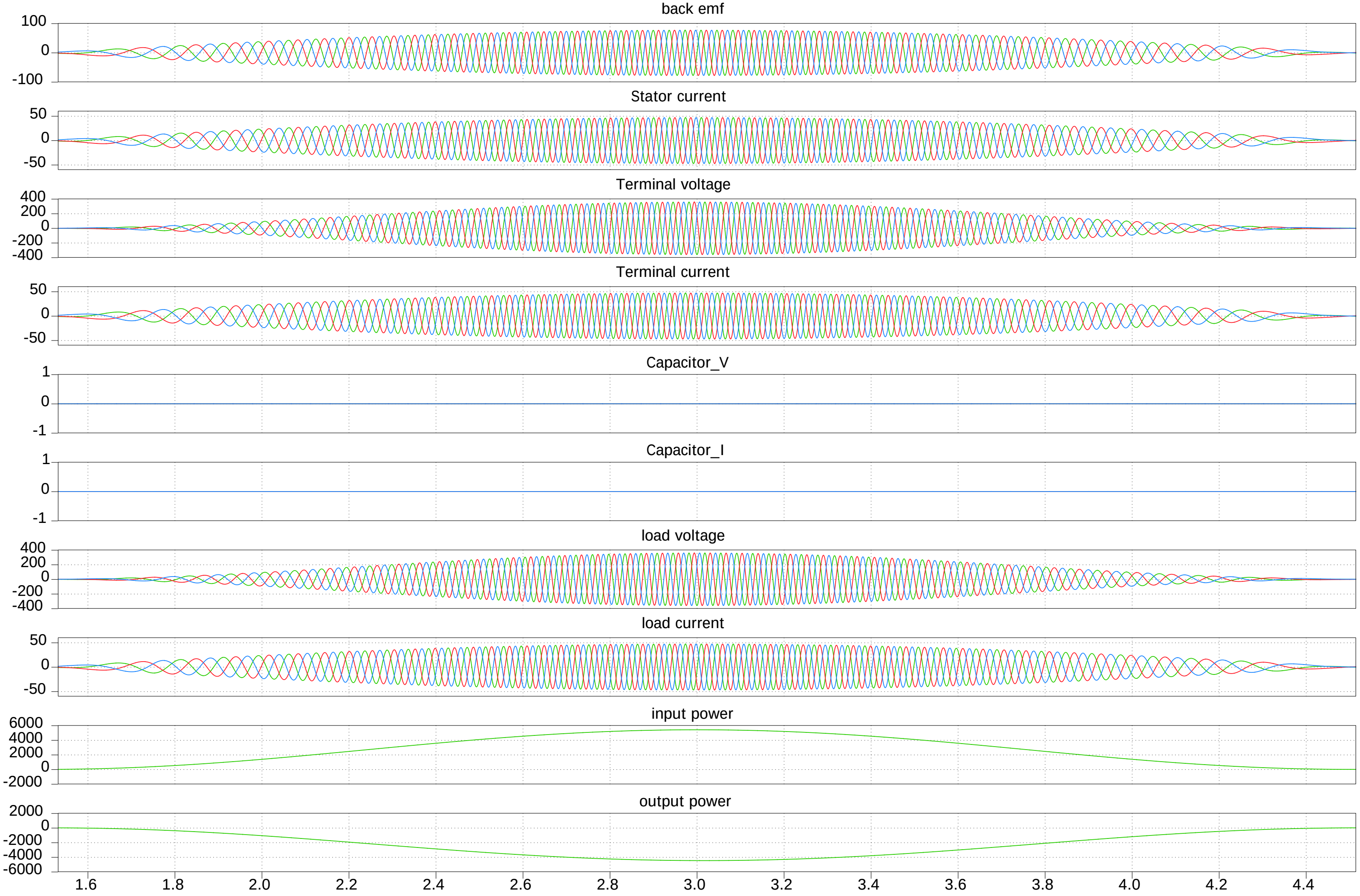
- VSI or CSI?
  - Focus of current work is generator interface and optimal energy storage topologies.
  - Grid/Transmission interface for multiple sections
  - Can it be engineered for installation within the WEC?

Trident converter and control equipment

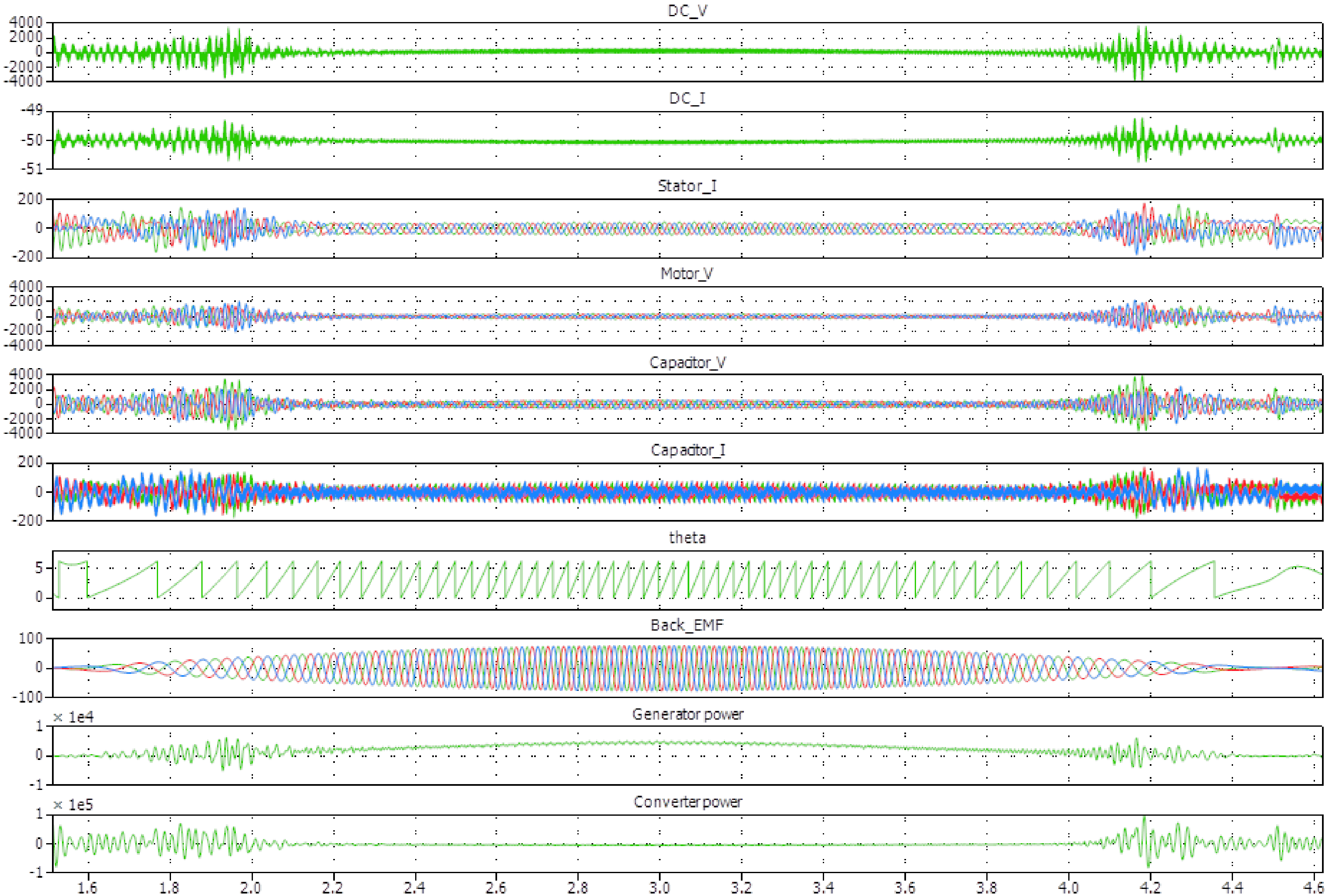
Ideal CSI behaviour



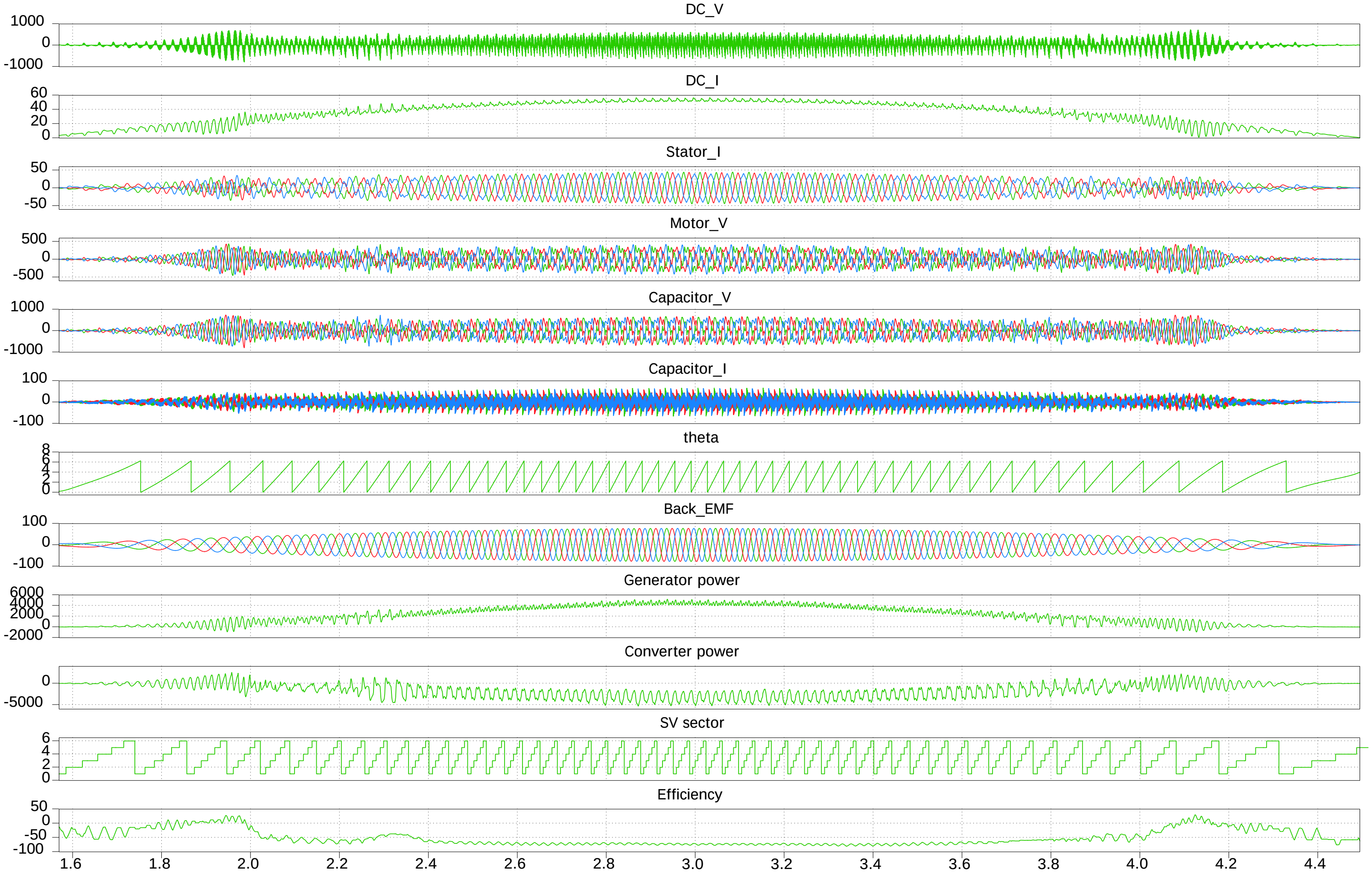
Ideal VSI behaviour



Practical CSI behaviour

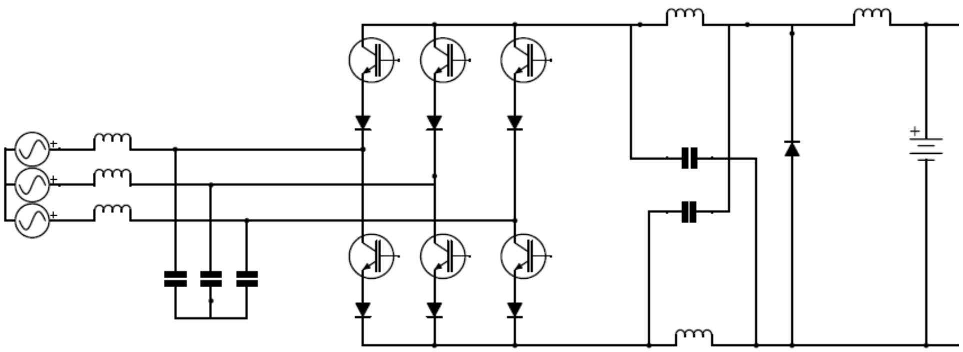


CSI with active damping

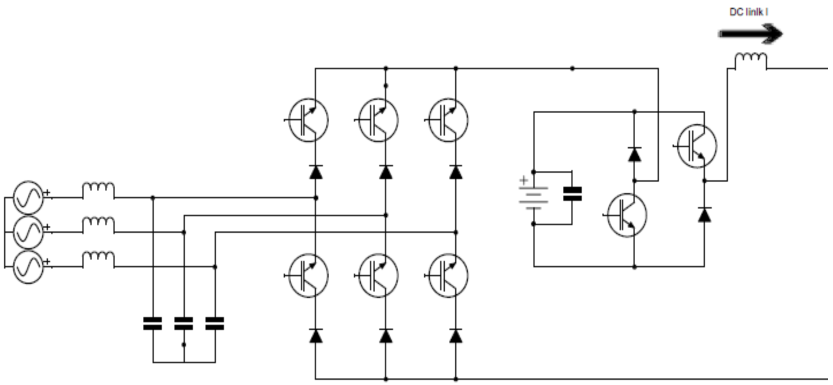


Converter development next steps

- Further investigation into mitigating commutation issues within CSI or revert to VSI
- Optimal integration of the ESS, perhaps using Z-source approach.
- Grid interface concept

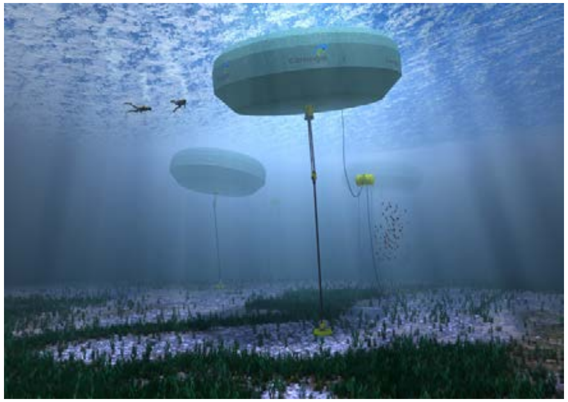


CSI with Z-source inverter and ESS

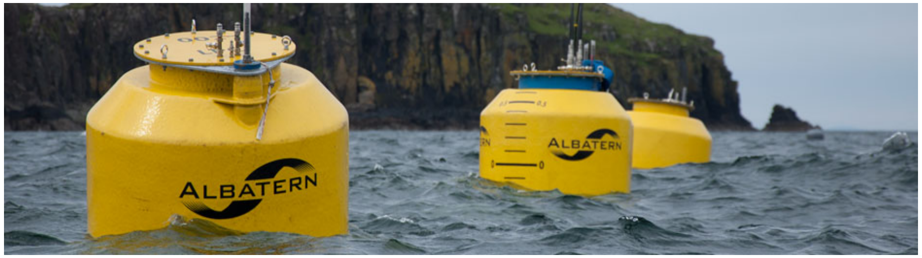


CSI with ESS

- What is E-drive
- Energy capture
- Generator
- Converter
- System control
- Grid integration



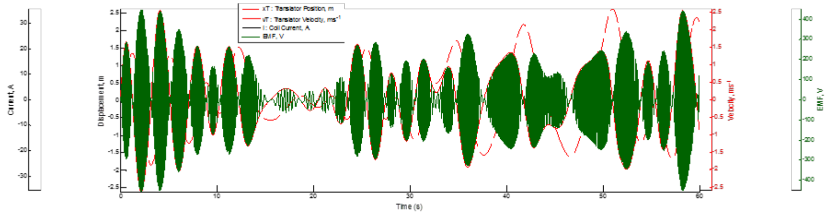
Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/

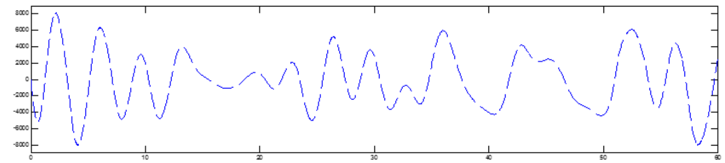


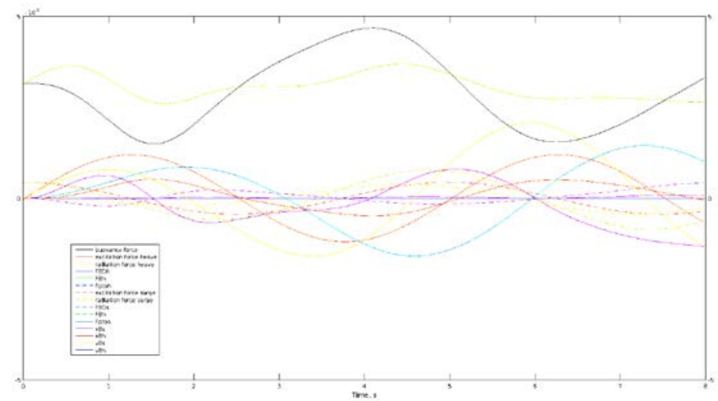
Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

System modelling and Control

- Linking Together
  - Generator model
  - Multibody dynamics model
  - Hydrodynamic model
  - Grid/Transmission Network Model
- Creating multi-rate model
- Generator takes multiple steps between each multibody/hydro model step
- Forces communicated between models at larger step intervals
- Allows more faster simulation and more appropriate algorithms for each model component





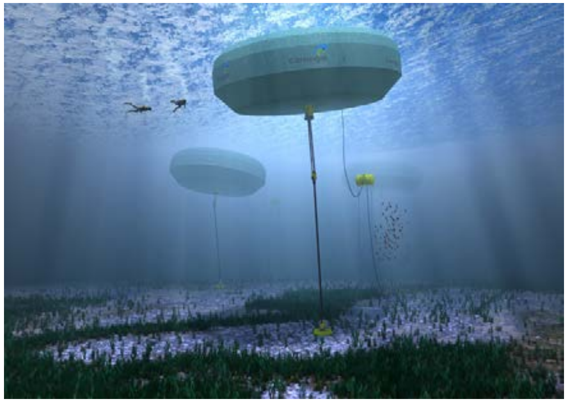


Newcastle University

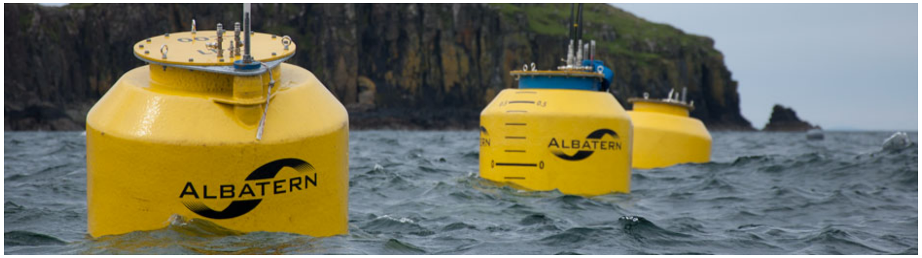
e-DRIVE

THE UNIVERSITY of EDINBURGH
School of Engineering

- What is E-drive
- Energy capture
- Generator
- Converter
- System control
- Grid integration



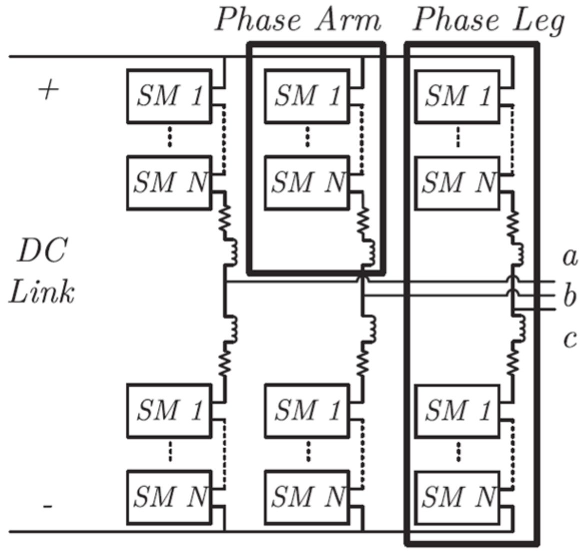
Carnegie CETO 6
http://carnegiewave.com/projects/ceto-6/



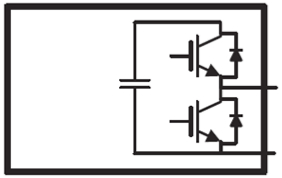
Albatern WaveNet
http://albatern.co.uk/wavenet/wavenet/

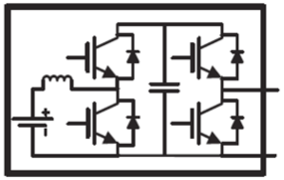
Grid interface

- Assumption is that multiple modules of the generator converter and ESS will be interfaced and integrated to modules of a multilevel grid interface
- Details to be developed in collaboration with Universidad de Chile



(a)


(b)


(c)

Grid interface challenges

- If there is no galvanic isolation between the generator module and the individual multilevel converter module circuit then the whole chain will need to be insulated sufficiently well to withstand MV potential to ground and between generator modules.
  - This would pose excessive challenges in the machine design and increase the failure risk should one module fail.
  - Incorporating galvanic isolation by utilising a high frequency transformer within the chain is desirable.
- Tolerance of the multilevel inverter to a range of DC voltages at the module level requires further consideration.
  - If the ESS terminal voltage is coupled directly an individual module the overall step levels will change accordingly.
  - There are a number of multilevel inverter topologies based upon the Z-source concept that have built in buck-boost capability and could advantageously be combined with the generator interface and ESS.
- Optimising component count, cost, and reliability and ensuring overall complexity remains manageable.

EPC development summary

- Top level sizing and sanity checks
- Basic CSI integration with the Linear generator
  - Does it work as expected?
  - Are the component dimensions realistic?
  - Is the dynamic performance acceptable?
- Integrating ESS (emulated?)
- Integrating Z-source network
- Integrating with multilevel grid interface (concept)

Summary

- Project aims to develop an all electromagnetic power take off
- The peak power requirements are a challenge
- Bringing together magnetic gearing, machine design and converter development together with optimal energy storage and system control is the current focus

Laboratory drivetrain testing

Questions

Dr. S.P. McDonald

Department of Electrical and Electronic Engineering at Newcastle University, Newcastle Upon Tyne, NE1 7RU, U.K. (email: Steve.McDonald@ncl.ac.uk)

http://www.edrive.eng.ed.ac.uk/