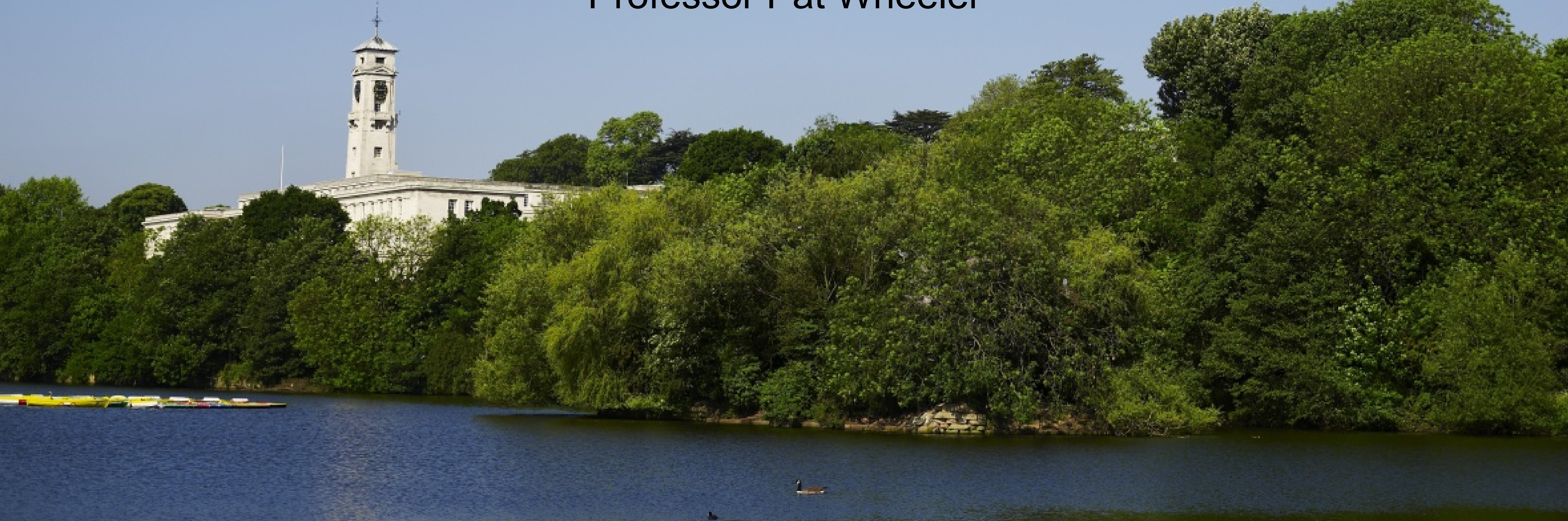
The University of Nottingham

Professor Pat Wheeler



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University of Nottingham
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DC Link Capacitors for an Electric Superbike

Professor Pat Wheeler
University of Nottingham

email: pat.wheeler@nottingham.ac.uk

Electric Vehicles – The Beginning

1828: First recorded Electric vehicle
Hungarian, Ányos Jedlik

1839: Electric-powered carriage
Robert Anderson of Scotland

1912: peak in 20th Century production
Electrical cars in early 1900s had advantages: low noise, no hand cranking engines and no adding water to steam engines

1928: all production ended due cost and range
Electric cars costs $2000
Petrol cars cost £600!

1902 Wood's Electric Phaeton

Electric Superbike Racing

The University of Nottingham Racing Team

- Capable of speeds up to 200mph (320km/hr), weighs 285kg!
- 720V DC supply, about 25kWhr of stored Energy, peak power of ~200kW
- MotoE European Race Series Champions in 2015 and 2016
- Podium finish at the Isle of Man TT Zero in 2016, 2017 and 2018
- Faster around a track than a BMW S1000RR!

Electric Superbike Racing

The University of Nottingham Racing Team

Racing since 2014

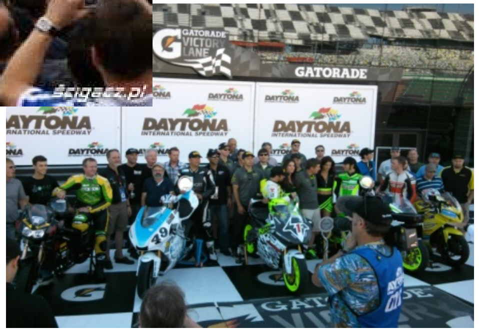
Why race?

- Promotion of Electric Vehicle Technology
  - Motor sport is a good way to raise awareness of new technology
  - TV and Media coverage is essential
- Pushing the boundaries of technology
  - Race bikes can be used to trial and test new technologies
  - Possible to take far more risks and find limits practical limits
- Testing new ideas and challenging regulations
  - Feet forward bikes are allowed – improved aero-dynamics
  - Transportation of Lithium-ion batteries by Air?

Electric Superbike Racing

The University of Nottingham Racing Team

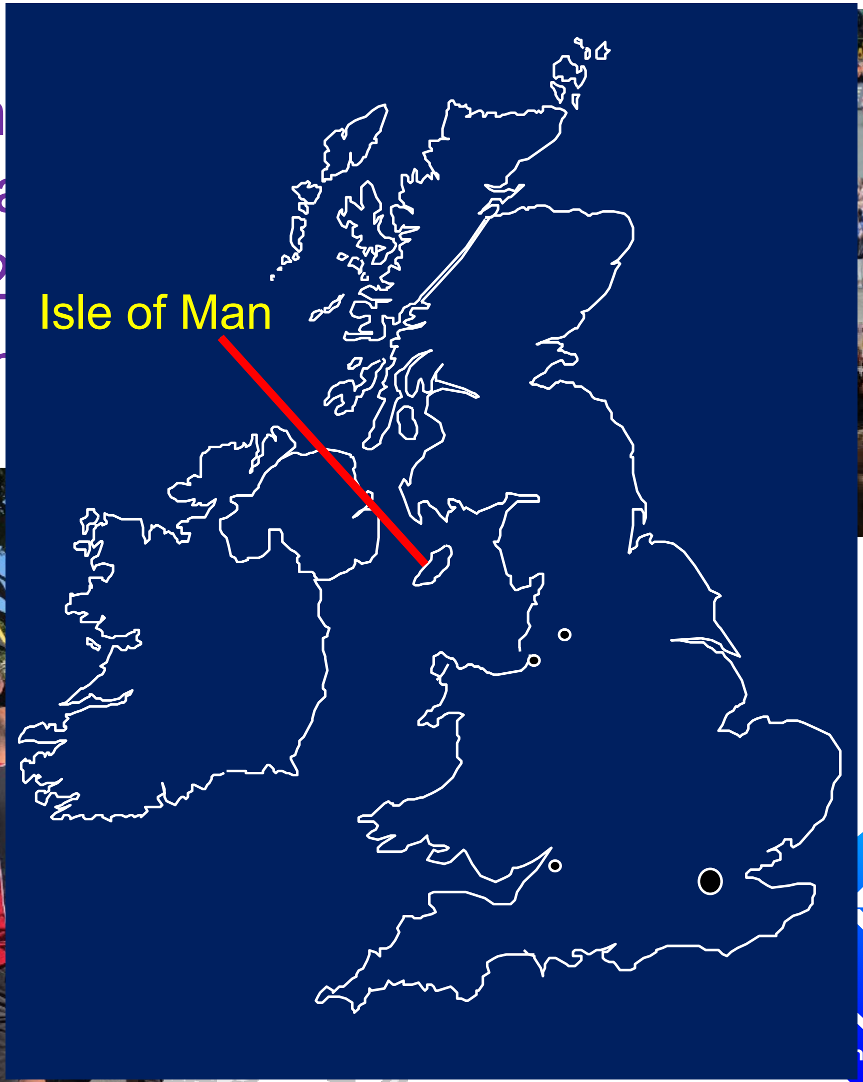
- Winning Races
  - MotoE European Champions (track series): 2015 and 2016
  - TT Zero: 3rd Place: 2016 and 2017
    2nd Place in 2018 (119.3 mph)

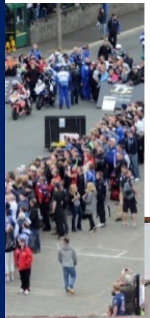


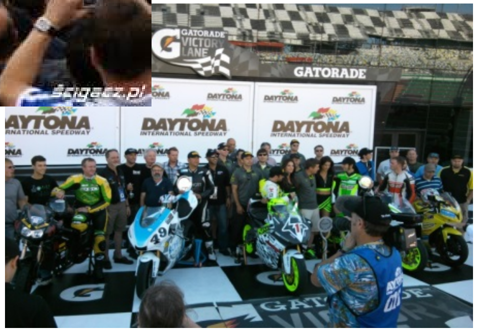
Electric Superbike Racing

The University of Nottingham Racing Team

- Winning Races
  - MotoE European Ch (track series): 2015 a
  - TT Zero: 3rd Place: 2
    2nd Place ir







Moto E
motoeracing.com

TT
ZERO
ISLE OF MAN

The Isle of Man TT

Electric Superbike Racing

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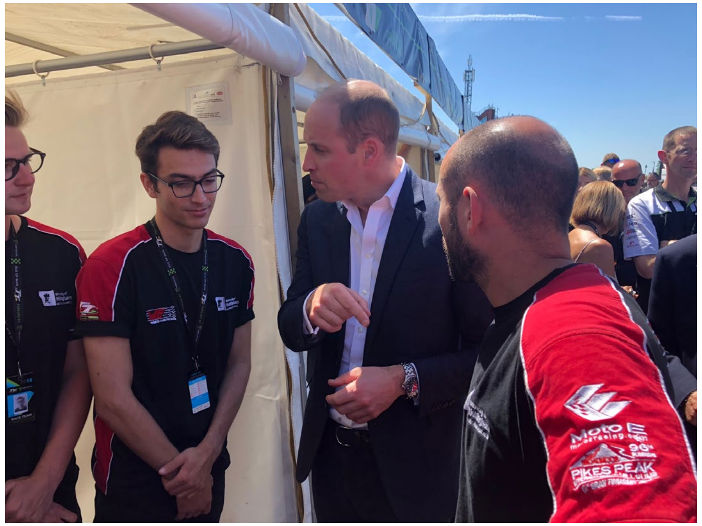
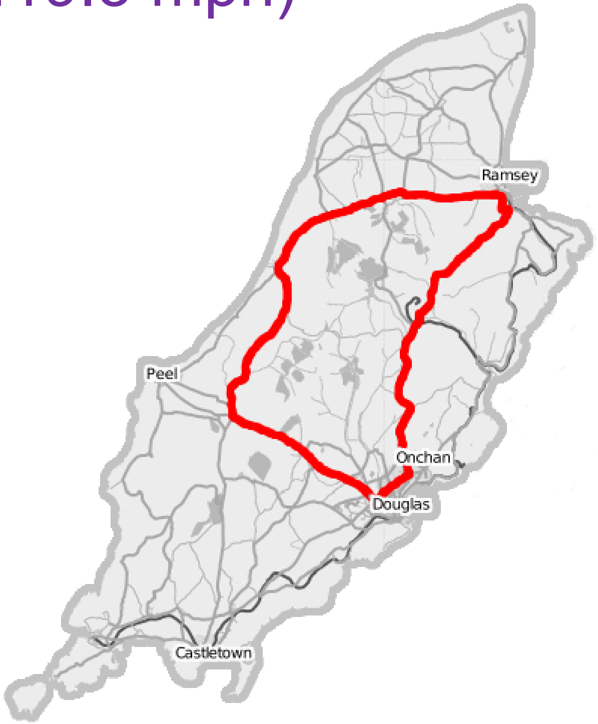
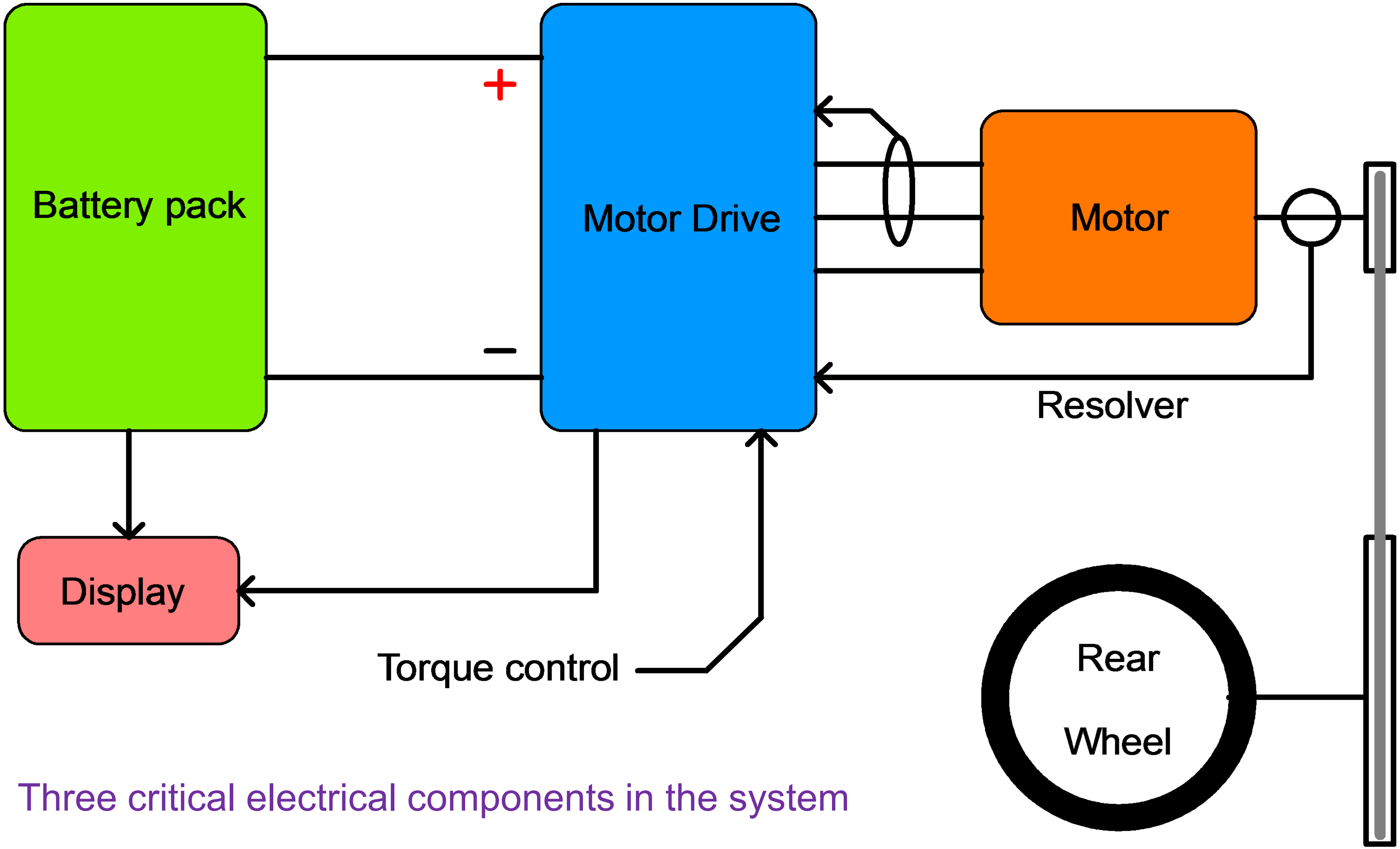


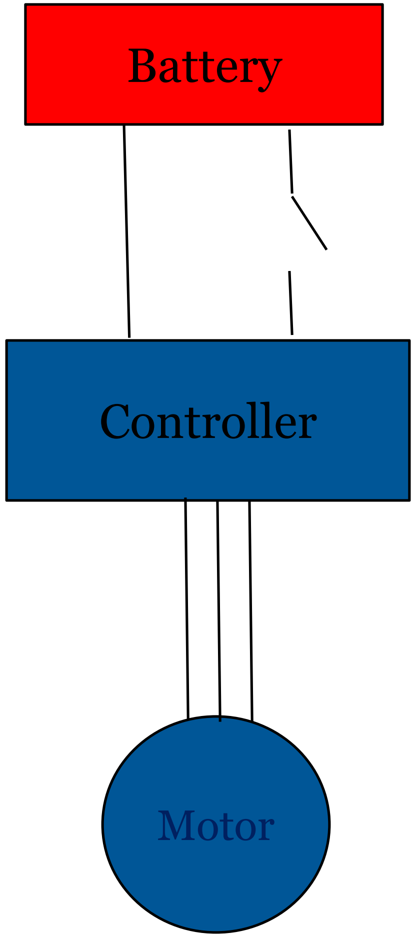


System Overview

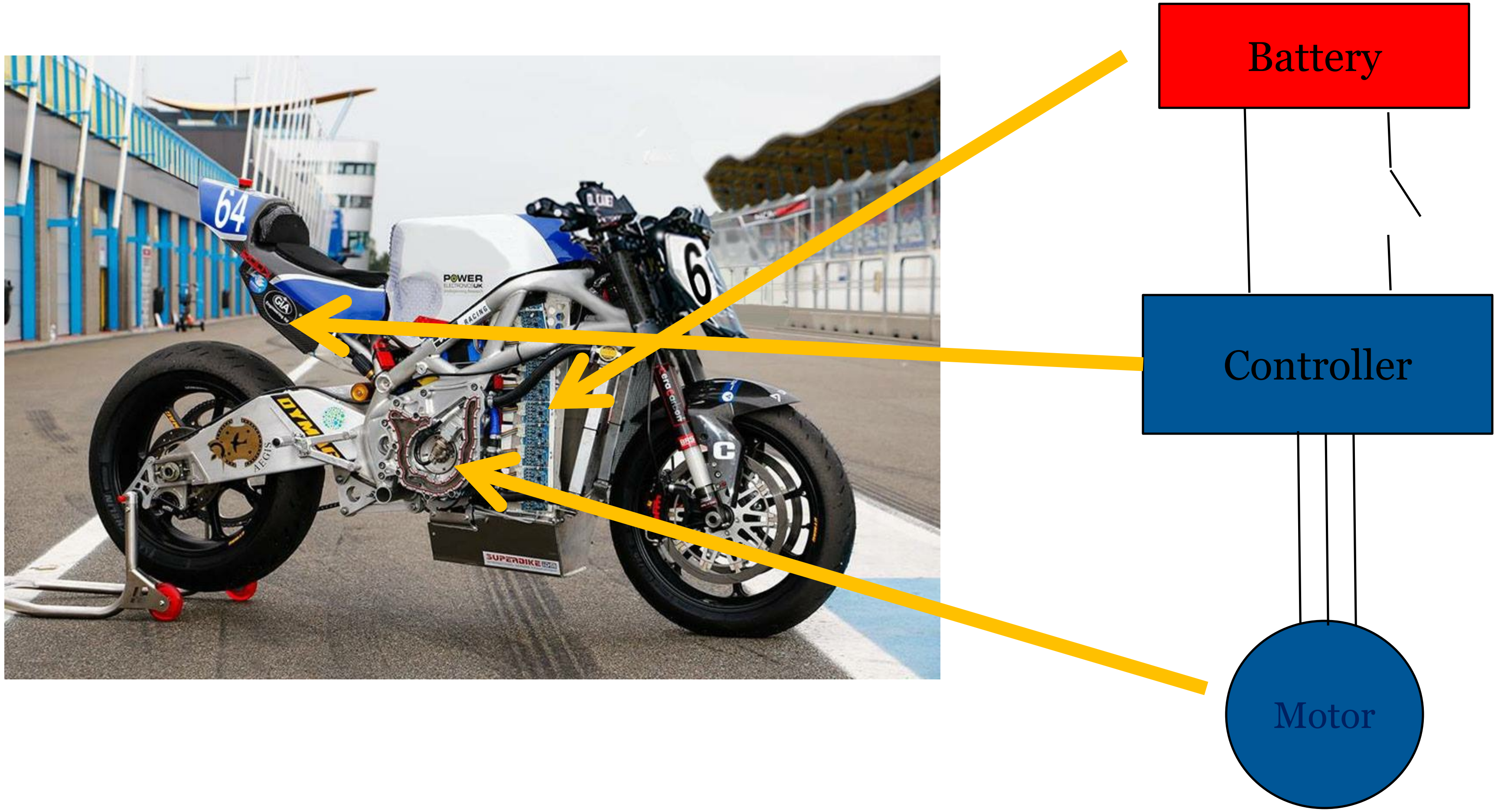


Three critical electrical components in the system

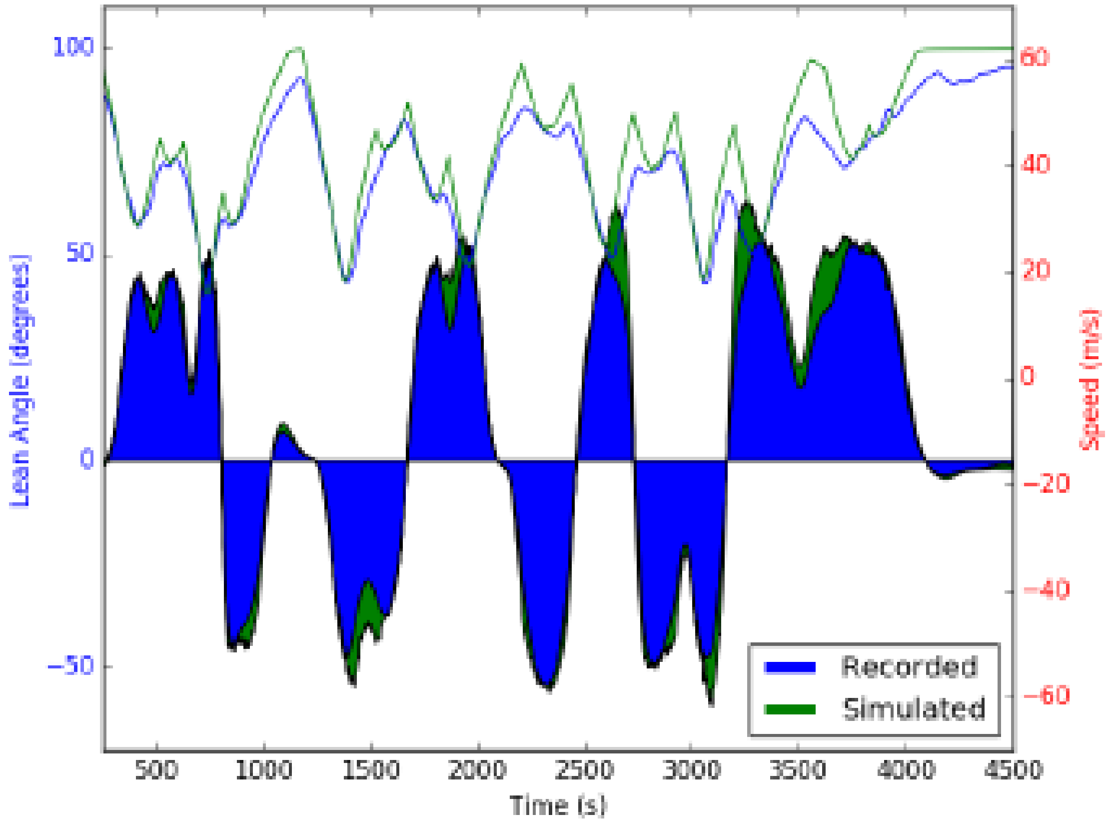
System Design



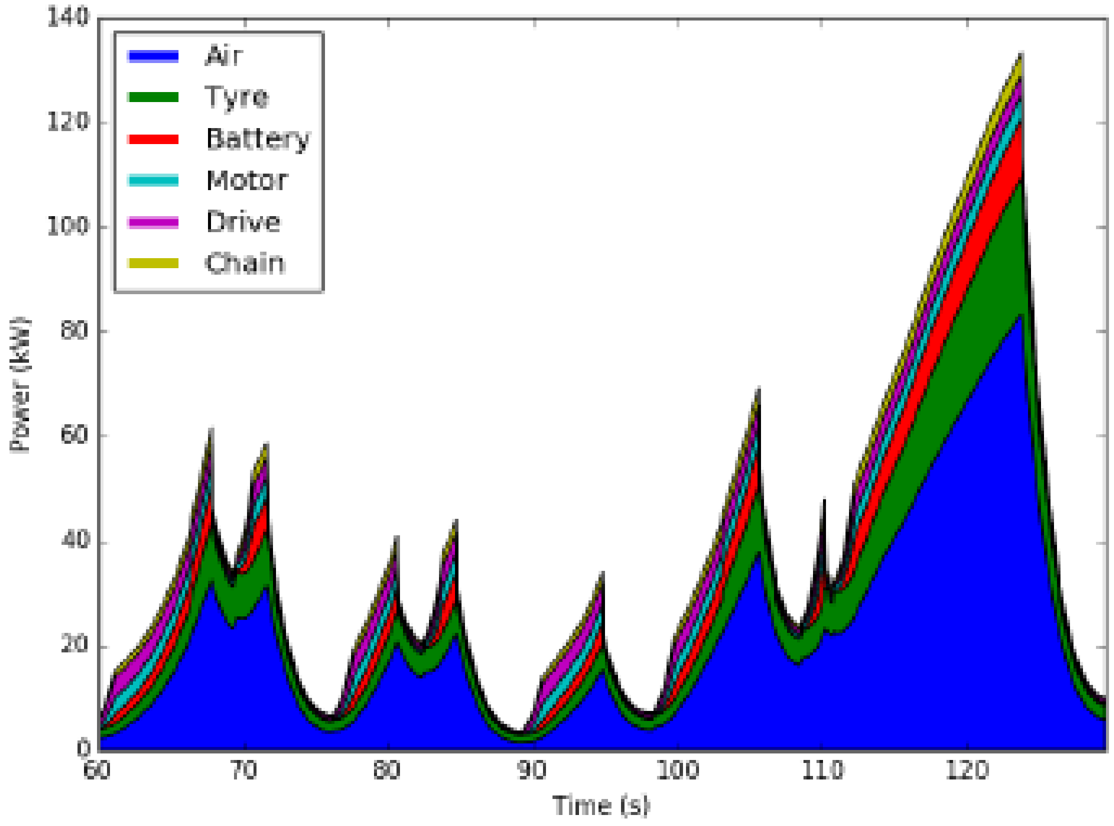
System Design



Optimisation: System Performance



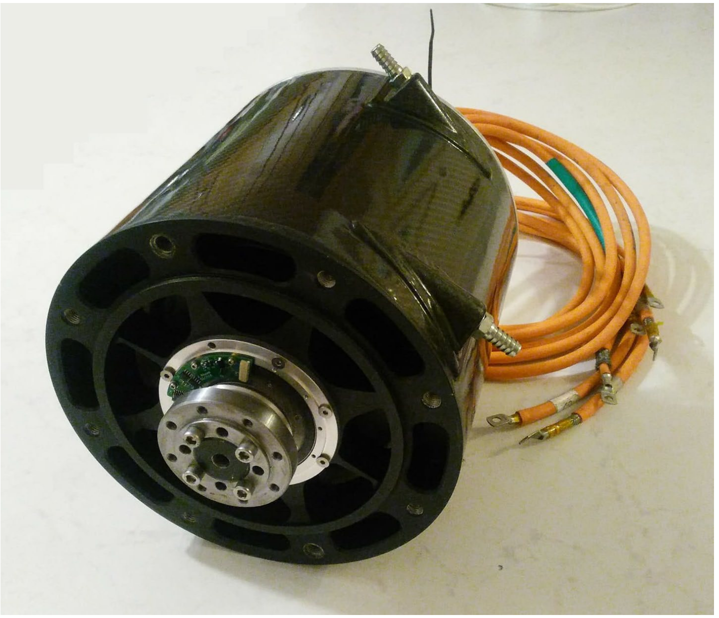
Measured and simulated lean angle

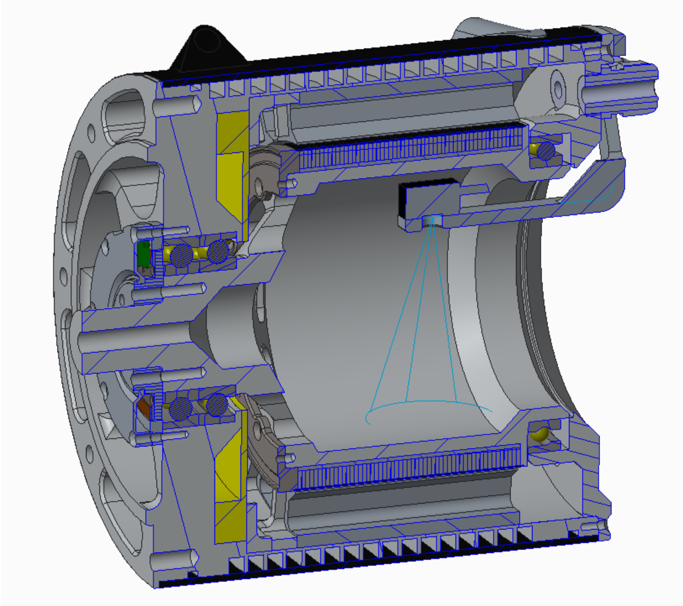


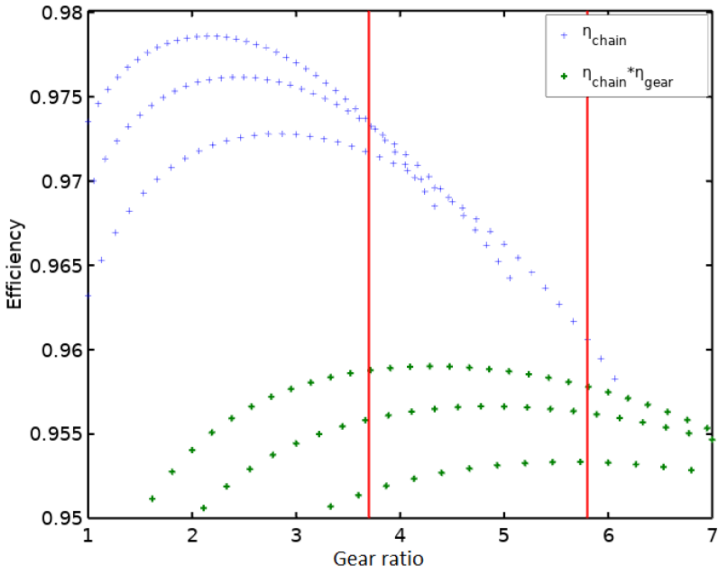
Power losses – modelled

Motor: New Design

- Vacoflux VX48 core, EP3200 potting compound, Laminated N48SH magnets
- Designed to achieve 28kg, 300Nm, 8000rpm
  - Optimised for Isle of Man TT Course
- Designed, built and tested for the electric superbike
  - Duty cycles and use case very well defined – allows a full optimisation

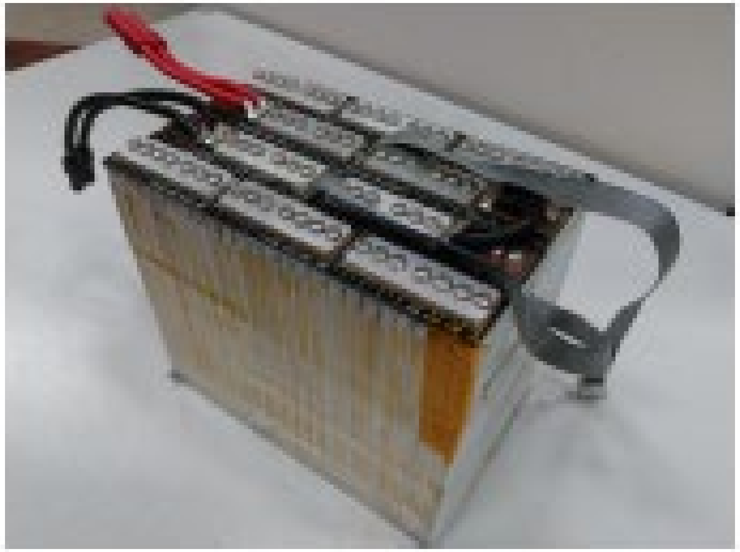






Battery Design

- Weight and Volume are critical to the design and endurance of the bike
  - Maximum speed is not the issue for the battery
  - Speed is only really an issue for the rating of the motor and controller

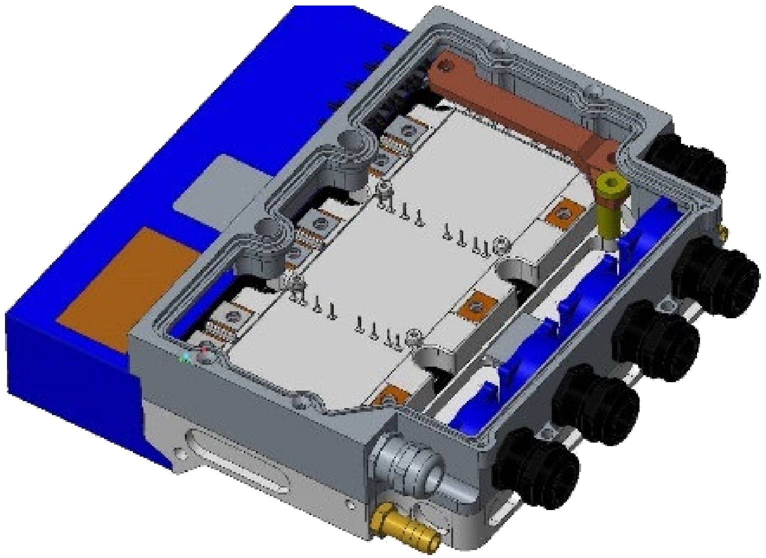


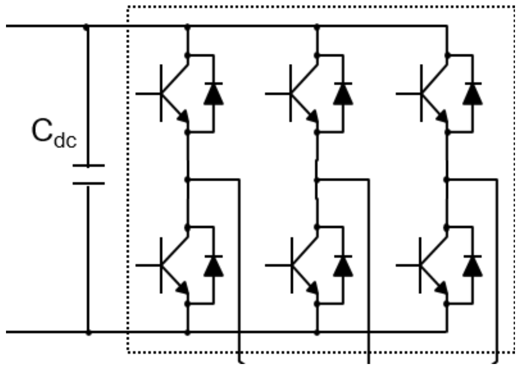
- Critical factors
  - Energy storage per kg and per litre
  - Temperature rise during the race

- Cost and lifetime are not critical for race bikes!
  - 25 Charges maximum requirement for the whole season

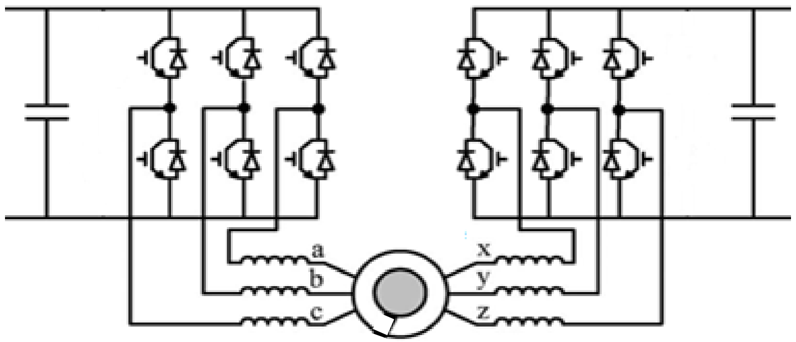
Power Converter: Design Choices

- Multiple converter designs have been used since 2015
  - Various topology choices, linked with motor design
  - Optimisation has to be linked to optimisation of the motor
- Current design
  - 750V DC, 1000Arms, SiC MOSFETs
  - Water cooled with a dedicated radiator
  - Power Electronic Converter located under the saddle

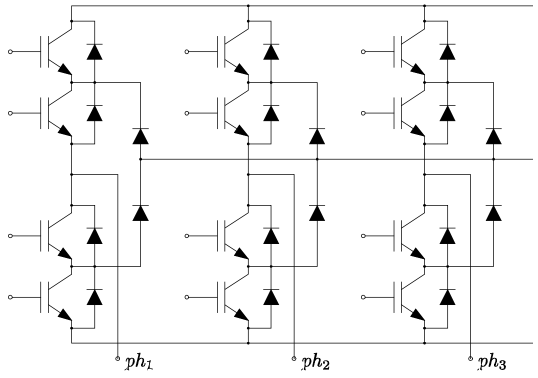




2-level Inverter



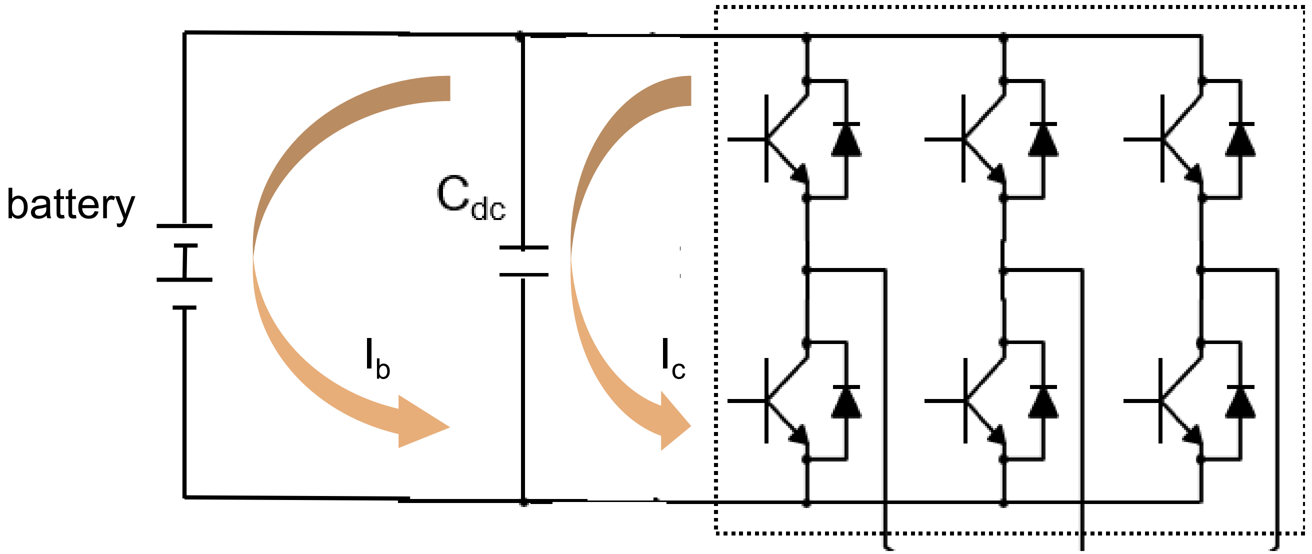
Dual-bridge Converter



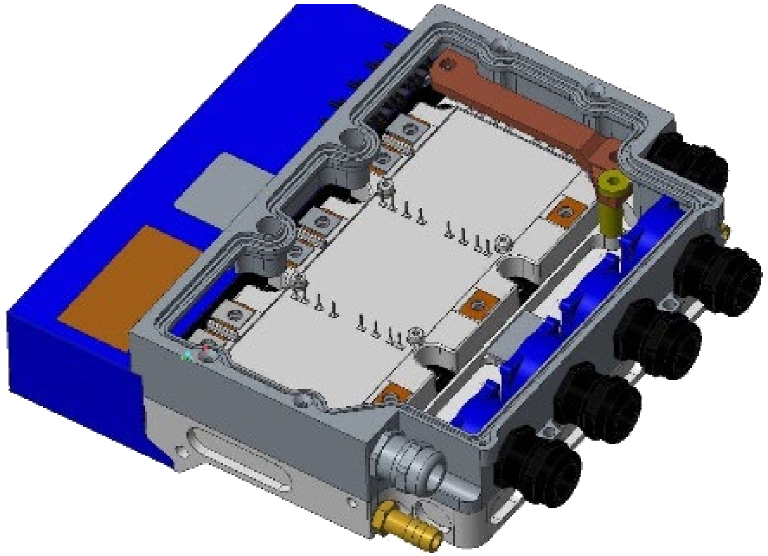
3-level NPC Converter

Power Converter: Capacitor Requirements

- Lithium Batteries tend to heat up more with higher frequencies, up to a point
  - Battery lifetime reduces with temperature (not a problem for a race bike!)
  - Critical frequencies can include typical power electronic converter switching frequencies
  - In a good design most of the ripple associated with the converter switching frequency goes through the capacitor

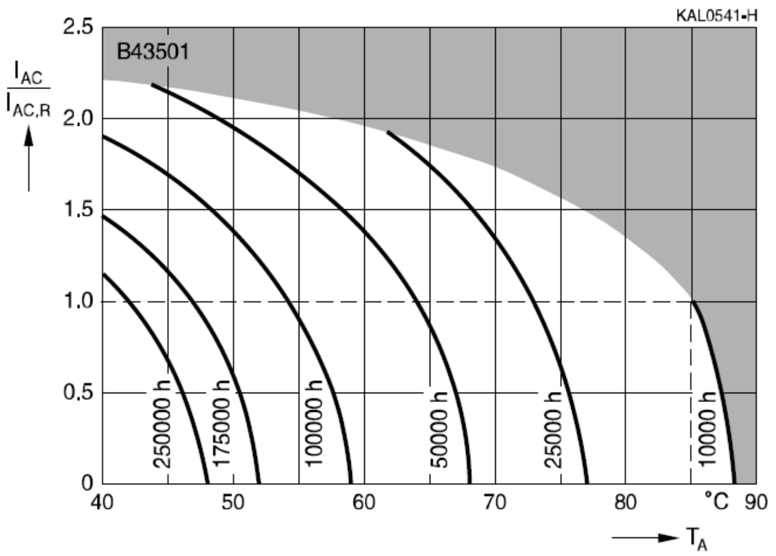


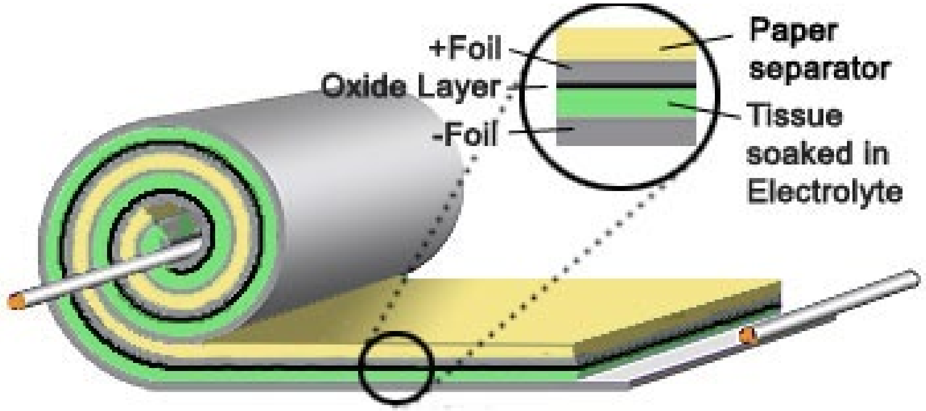
2-level Inverter



Capacitors

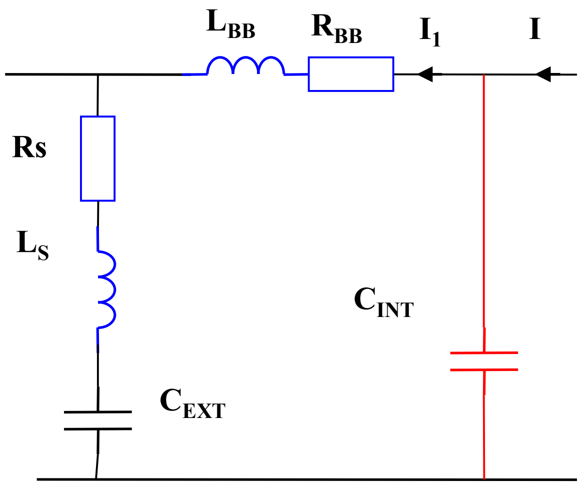
- A known life-limiting technology in many power electronic applications
- Electrolytic capacitors are particularly prone to ageing which is very sensitive to temperature and bias
  - “Drying out” of electrolyte leads to reduction of capacitance
  - Storage without bias leads to gradual loss of dielectric – effectively leading to a short circuit
  - Periodic application of bias needed if extended storage is planned

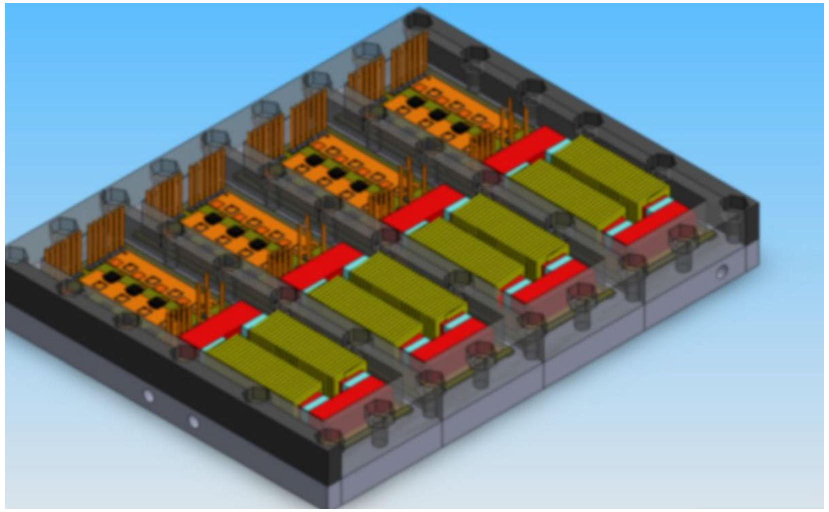


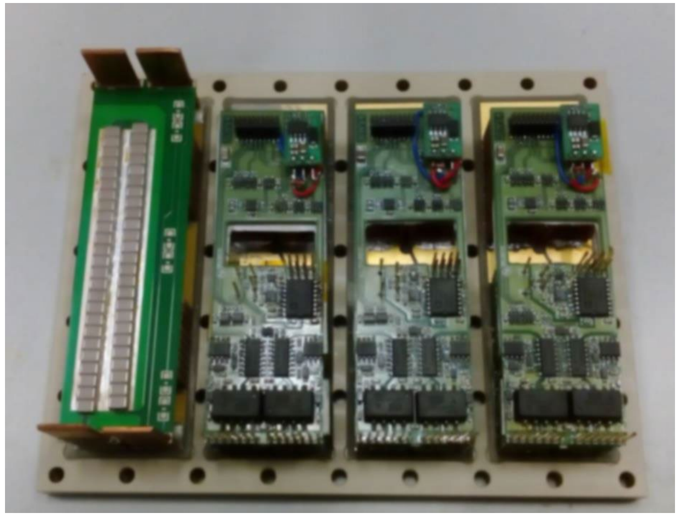


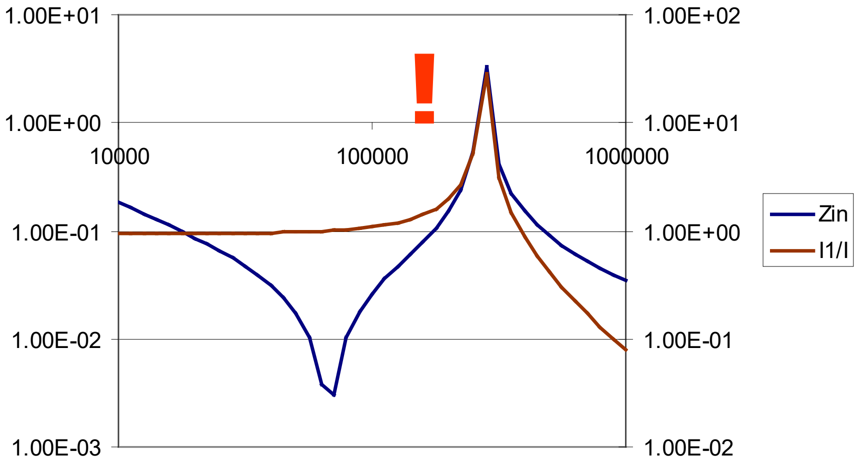
Integrated Passives

- Ceramic capacitor technology is compatible with temperature range
  - COG dielectrics are low loss and up to 0.03J/cm³
  - X7R dielectrics are higher loss and up to 0.4J/cm³
  - Good CTE match to module substrate reduces cracking
- Commutation loop decoupling can be achieved by placing ceramic chips across substrate pads
- Some care is needed to avoid unwanted interaction of internal and external capacitance – more internal capacitance not always better!



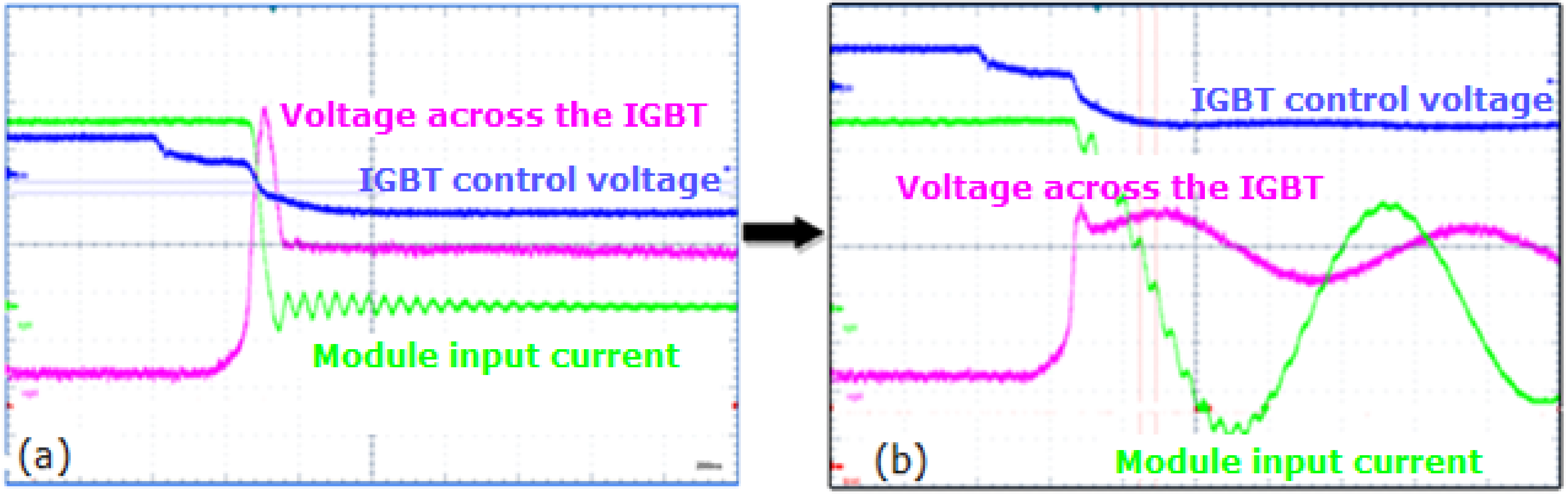






Impact of Integrated Capacitance

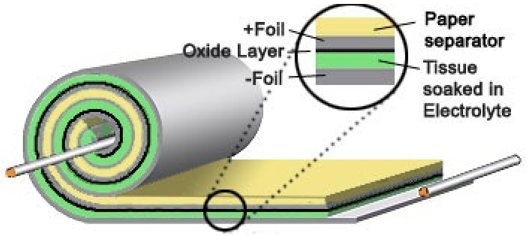
- Voltage overshoot is significantly reduced by incorporating decoupling capacitance on substrate
- Note additional oscillations introduced between internal decoupling and external decoupling capacitances

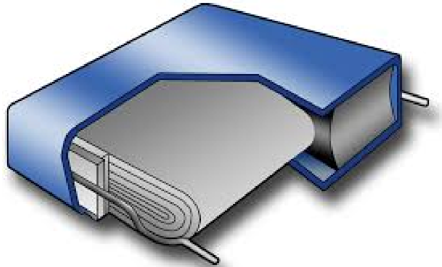


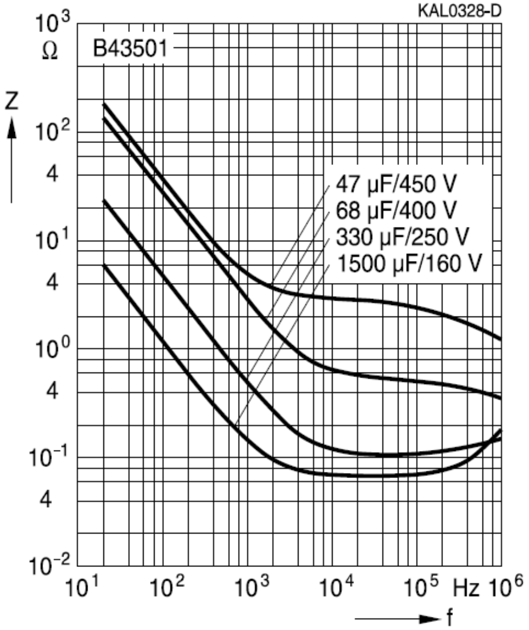
100A commutation cell with stray inductance ~100nH. Left figure without internal decoupling, right figure with internal decoupling of 200nF

Capacitor Technologies – Performance dictated by Dielectric

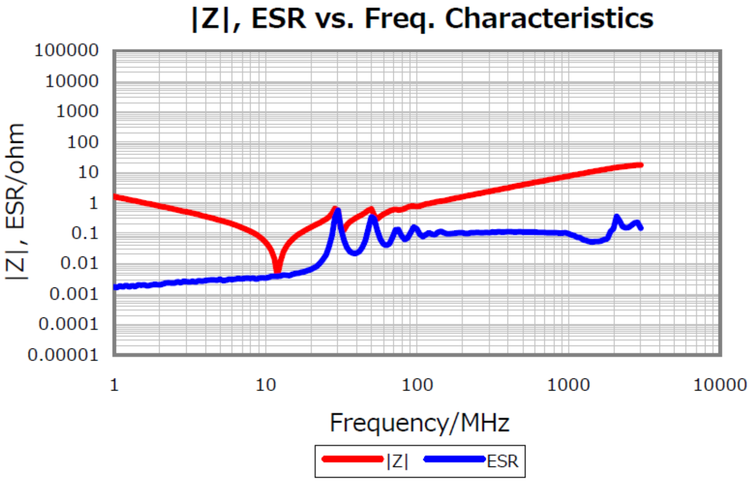
- Electrolytic:
  - highest energy density,
  - low power density,
  - limited temperature range (at best -40 to 105°C),
  - high losses and poor lifetime



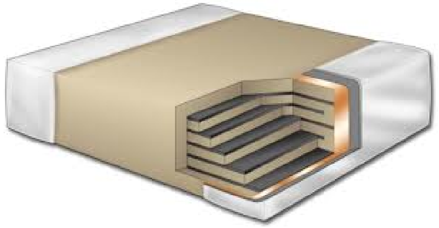




- Metallised polymer film:
  - low energy density (0.01~0.1 J/cm^3),
  - high power density,
  - limited temperature range (typically -40 to 105°C),
  - low losses and long life

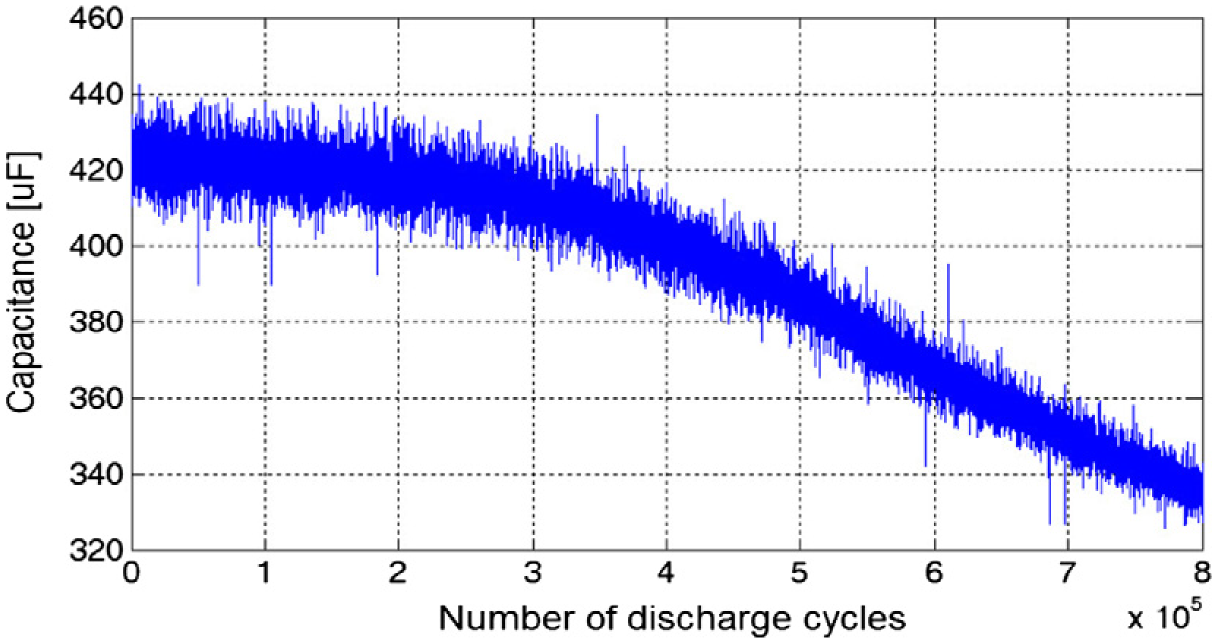


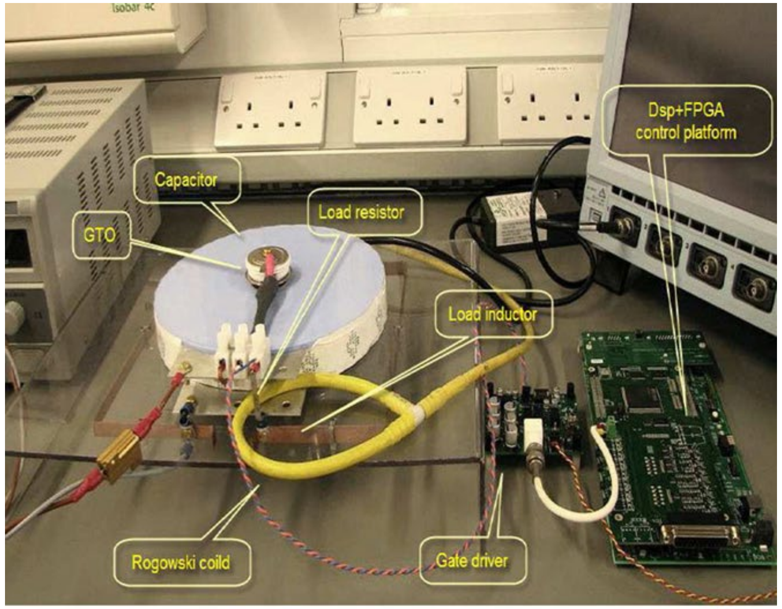
- Multi-layer ceramic:
  - low to moderate energy density (0.1~1 J/cm^3),
  - high power density,
  - wide temperature range (-60 to 125°C),
  - low to moderate losses
  - long life but mechanically fragile.

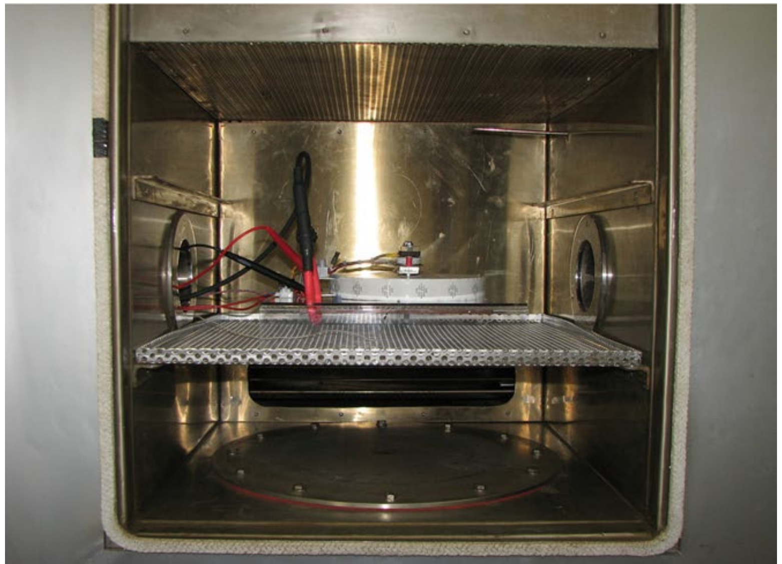


Degradation of Film Capacitors

- Pulse discharge testing of film capacitors at extreme temperatures
- Self healing leads to gradual reduction in capacitance with time
- Lower temperatures exacerbate wear-out







Summary

- Racing is a great way to enthuse students and generate impact
- With electric racing it is still possible to compete at the highest level as a small team by being innovative
- Simulation is able to accurately predict the performance of a bike in racing environment
- Good power converter design is required for performance/reliability and to minimise battery temperature
- Future developments:
  - Motor design
  - Battery sizing
  - Power Converter cooling
  - Aerodynamics
  - Chassis dynamics
  - …..

TT Zero 2018