EP/I038543/1

Latest Developments in the Vehicle Electrical Systems Integration (VESI) Project

Phil Mawby
University of Warwick

Presentation

- VESI project summary
- Six research themes
- Three demonstrator projects

VESI project summary

- High cost of EVs not only due to battery cost, but also **cost of the electrical power train** which is higher than in ICE vehicle.
- Integration of functionality in an EV will deliver large cost reductions.

- Overall objective = to have a **fully integrated vehicle electrical power conversion system**.
- VESI project focuses on **electrical motor and power electronics**
- Aims: Reduce cost, increase power density, improve reliability of electrical power systems, maintain manufacturability for a mass market.

- EPSRC funding: £3,154,532
- Low technology-readiness level (1-3) to support EV technology development
- 4-year project: 1 October 2011 to 30 September 2015
- Underpinning basic research divided into **6 research themes**.
- **3 technology demonstrators (Oct 2013 to Sep 2015)**

University Partners

10 University partners in power electronics and electrical machines

Prof Phil Mawby
(Warwick)

Prof Phil Mellor
(Bristol)

Prof Keith Pullen
(City)

Prof Patrick Luk
(Cranfield)

Prof Emil Levi
(Liverpool John Moores)

Prof Andrew Forsyth
(Manchester)

Prof Volker Pickert
(Newcastle)

Prof Mark Johnson
(Nottingham)

Prof David Stone
(Sheffield)

Prof Andrew Cruden
(Southampton)

Location of Research Groups

Key Industrial Supporters

- Car manufacturing companies
- Semiconductor manufacturers
- Component manufacturers
- Energy supplier
- Consultancies

LYRA ELECTRONICS

RICARDO

JAGUAR

LAND ROVER

TATA

ARNOLD MAGNETIC TECHNOLOGIES

Liberty Electric Cars

prodrive

IST Power

TT Electronics Make Possible

PRECISION SCORPION PERFORMANCE

zytek

infineon

sse

FluxSys

JM Johnson Matthey Battery Systems

coneKt powered by TRW

International IOR Rectifier

HIFLUX

motordesign LIMITED

TECH/OPS SEVCON

TIRIUS

DYNEX

Allied Vehicles Driving for Perfection

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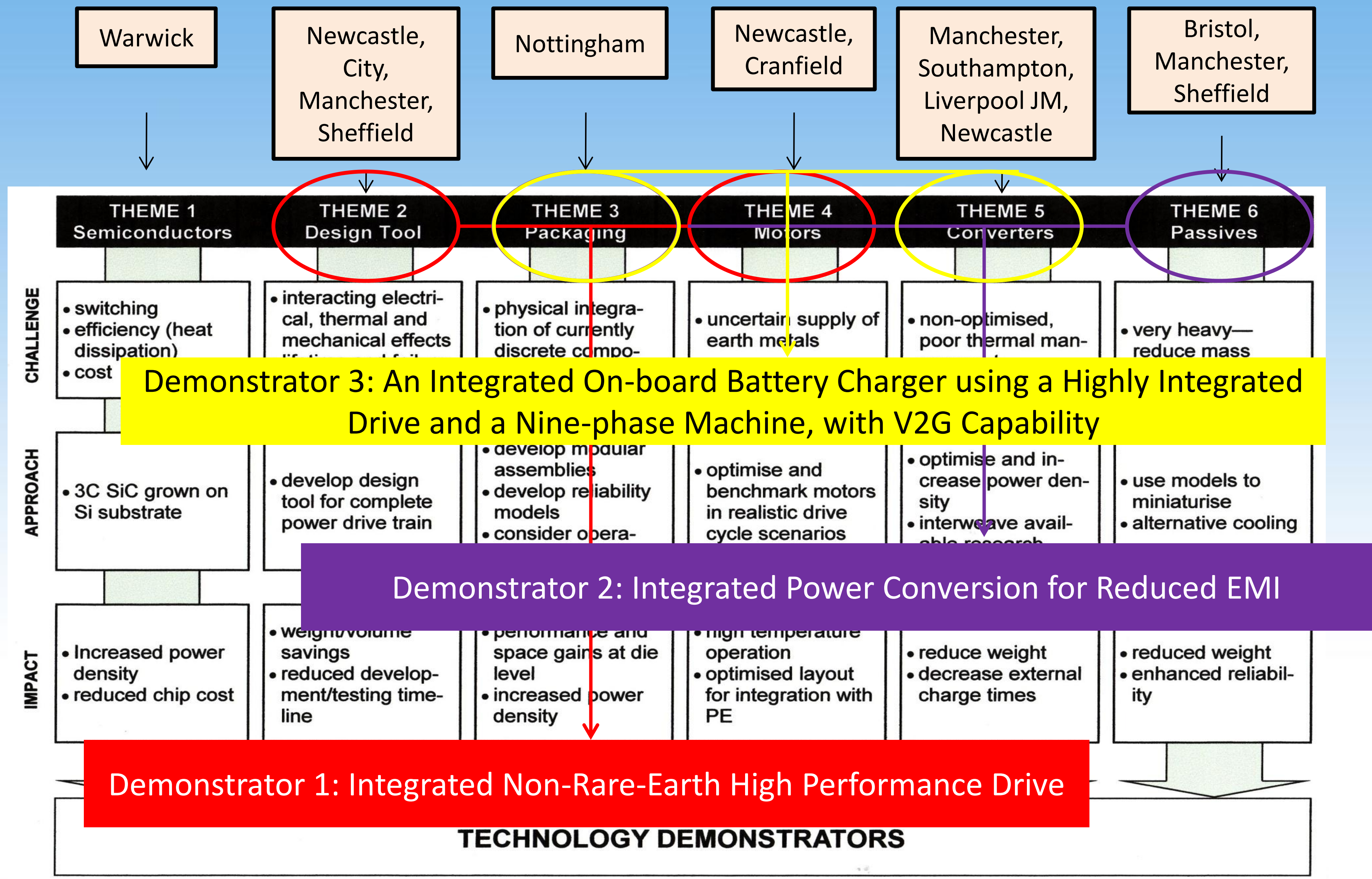
Six Research Themes

+

Three Demonstrator Projects

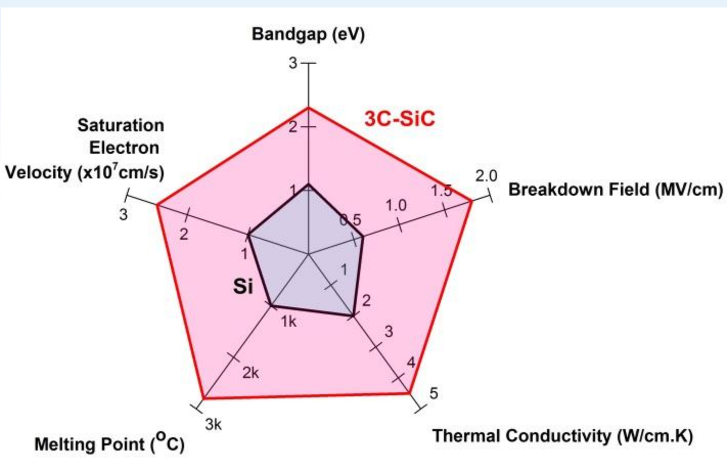


Warwick
Newcastle, City, Manchester, Sheffield
Nottingham
Newcastle, Cranfield
Manchester, Southampton, Liverpool JM, Newcastle
Bristol, Manchester, Sheffield
THEME 1 Semiconductors
THEME 2 Design Tool
THEME 3 Packaging
THEME 4 Motors
THEME 5 Converters
THEME 6 Passives
CHALLENGE
• switching
• efficiency (heat dissipation)
• cost
• interacting electrical, thermal and mechanical effects
• physical integration of currently discrete compo-
• uncertain supply of earth metals
• non-optimised, poor thermal man-
• very heavy— reduce mass
Demonstrator 3: An Integrated On-board Battery Charger using a Highly Integrated Drive and a Nine-phase Machine, with V2G Capability
APPROACH
• 3C SiC grown on Si substrate
• develop design tool for complete power drive train
• develop modular assemblies
• develop reliability models
• consider opera-
• optimise and benchmark motors in realistic drive cycle scenarios
• optimise and increase power density
• interweave available research
• use models to miniaturise
• alternative cooling
Demonstrator 2: Integrated Power Conversion for Reduced EMI
IMPACT
• Increased power density
• reduced chip cost
• weight/volume savings
• reduced development/testing timeline
• performance and space gains at die level
• increased power density
• high temperature operation
• optimised layout for integration with PE
• reduce weight
• decrease external charge times
• reduced weight
• enhanced reliability
Demonstrator 1: Integrated Non-Rare-Earth High Performance Drive
TECHNOLOGY DEMONSTRATORS

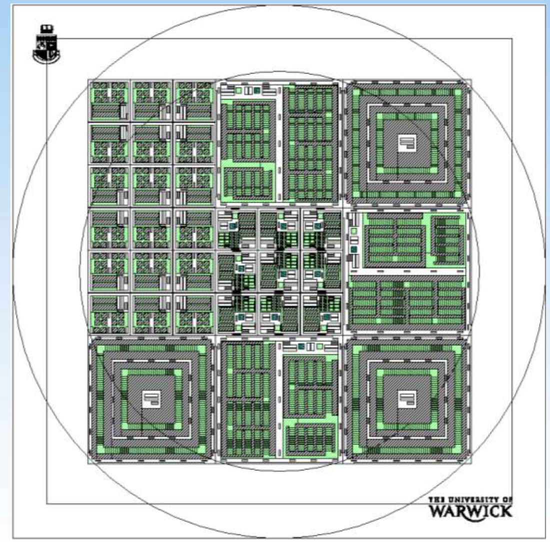
Theme 1 – Power Semiconductors (Warwick)

- Grow layers of **3C polytype of Silicon Carbide** (SiC) on a Si wafer.
- Develop 1200V **lateral Schottky power diodes** and 1200V **lateral MOSFETS** (metal-oxide semi-conductor field-effect transistors).

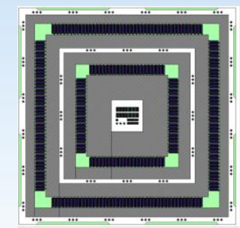

Warwick's SiC device fabrication cleanroom



SiC has higher thermal conductivity, melting point, breakdown field than Si.



Single Cells



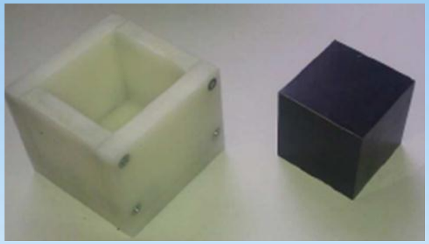
Device of 176 Cells

Mask design: Layout of some test structures being fabricated.
Devices rated in orders of 10mA to >10A.

Theme 2 - Design Tools (Newcastle, City, Manchester, Sheffield)

- Online survey of available **multi-physics simulation software packages** for power drive trains for EVs.
- New **heat removal** techniques, e.g. high thermal conductivity **potting compounds**

Potting aids **heat removal from the windings** by encasing the windings of transformers/inductors with an encapsulant (epoxy) combined with thermally conductive filler (Al2O3 powder).

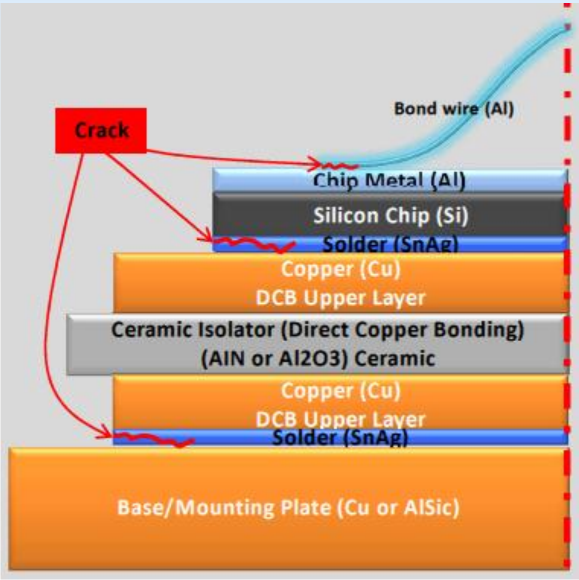


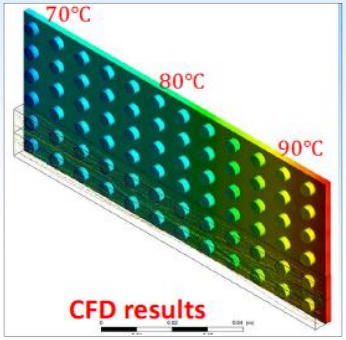
Mould and potting epoxy/ Al2O3 composite cube

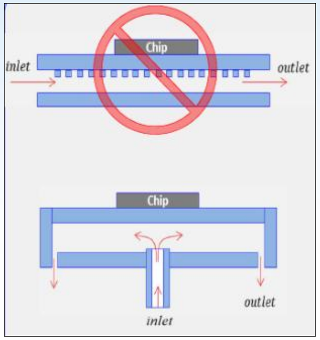
Test rig measures sample's thermal conductivity

- Novel **liquid cooler** design and simulation

Failure of power modules: solder layer **delamination + bond wire lift-off**.
Aim: Reduce chip temperature swings → lead to **higher reliability**.







CFD simulations of liquid coolers: **non-uniform temperature distribution** of the coolant in the power device.

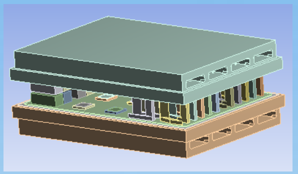
Approach:

- Use new **liquid metal materials** that have better thermal performances.

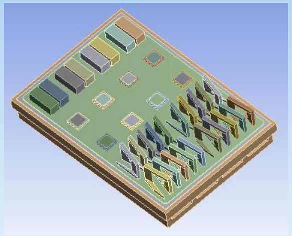
- Use **micro-pumps** that have no mechanical parts.

- High operating speed (> 1kHz) and high thermal conductivity.

Theme 3 – Packaging (Nottingham)

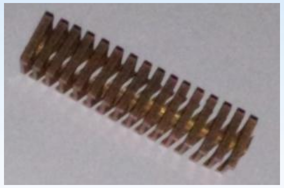


Integrated inductor, SiC chips, diodes, switches

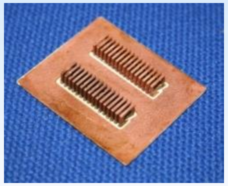


- Alternative ways to **package chips on a substrate** instead of usual wire-bond and solder technologies; use promising technologies, e.g. Ag nanoflakes sintering, jet impingement cooling.
- **Aims:** increased power density, reduced cost, improved thermal performance, reliability.
- Use **integrated, modular assemblies -** electromagnetic, thermal and mechanical functions are treated together at same time - instead of **piecemeal assemblies of components** for converter construction.
- Manufacturing an **inductor on the same DBC type substrate as the semiconductors**.

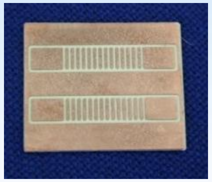
Al oxide direct bonded copper

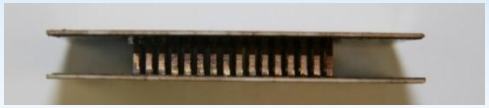


Cu inductor coil

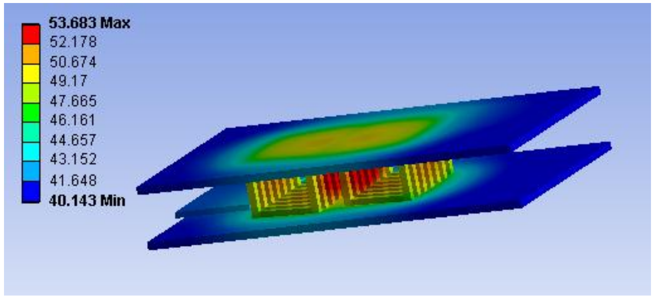


Coil soldered into place





Structures are being used in the demonstrator projects.



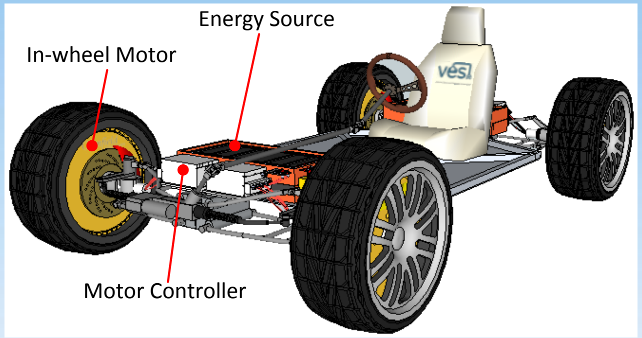
- Integrated inductor structure can be **liquid cooled from both sides**.
- Thermal modelling shows that you can put high currents through the coils but still keep them at a reasonable temperature.

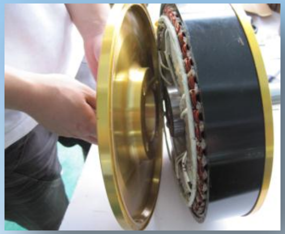
Theme 4 – Motors (Cranfield and Newcastle)

Rare-earth PM machines are most common in EVs/HEVs, but disadvantages are: **demagnetization; expensive material; limited supply. Aims:** high efficiency, reliability, low weight, low cost.

Rare-earth PM in-wheel machine (speed <1000 rpm):

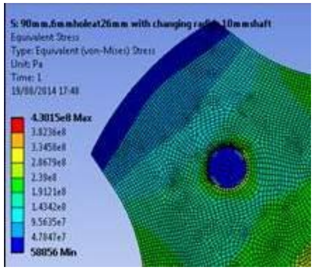
- New concept of drive train.
- Power electronics inside the motor directly turn the wheels.
- No gearbox or transmission system → save space for battery.
- Mass of the in-wheel motors cannot be too large - affects vehicle stability.





Ferrite-based PM machine (~5000 rpm):

- Can work at **100 ^{o}C higher** than rare-earth.
- Achieves **~95% power output** compared to Prius rare-earth motor under same drive conditions.



Switched Reluctance Motor (50 krpm):

- No permanent magnets. Easy to construct and recycle. High speed – so can be small in size → cost effective.
- **But:** Acoustic noise, mechanical stresses, heat dissipation.
- Needs high precision manufacturing due to its **sensitive, narrow air-gap** (otherwise vibrations can occur).
- Design has: output power of 60kW. Material's typical yield stress = 450MPa.

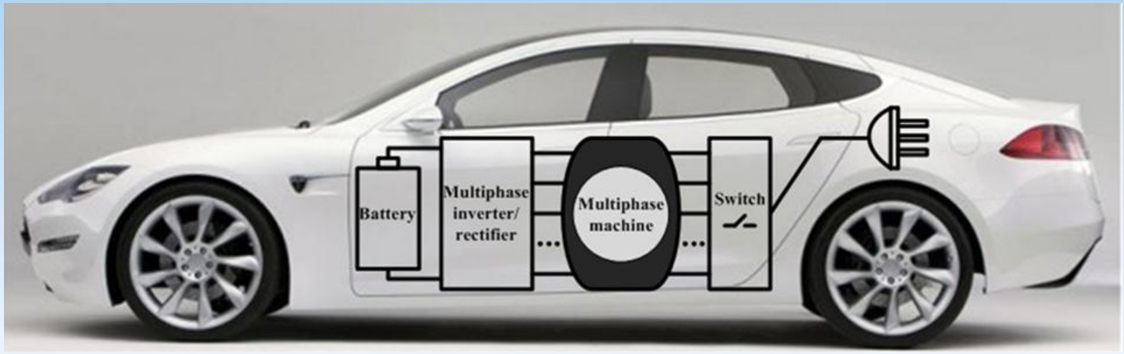
Theme 5 – Converters (Manchester, Liverpool JM, Newcastle, Southampton)

Aim: Investigate **INTEGRATED on-board battery charging/V2G operation** using single-phase (slow), 3-phase, and multiphase charging (fast).

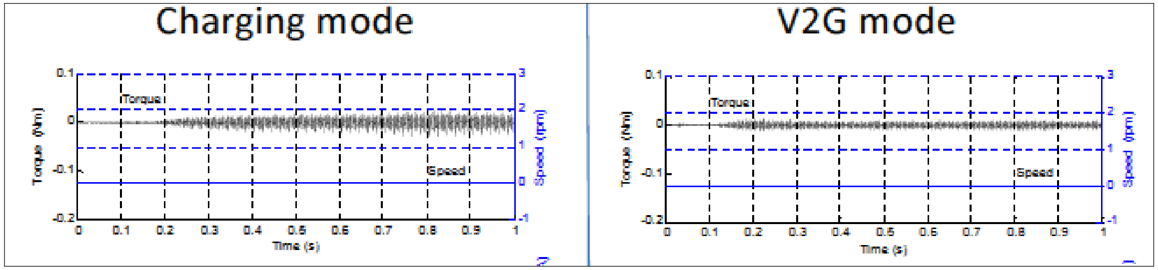
→ No separate charger, instead **RE-USE the converter and motor** installed for driving mode.

Advantages:

- Fewer new elements → lower cost
- Lower weight → faster vehicle
- Less space needed → smaller vehicle
- Can use any power socket
- V2G operation



- Inverter converts DC into AC for V2G mode, and AC into DC for the charging mode.
- Multiphase machine acts as the inductances, and filters the currents in order to do the conversion.

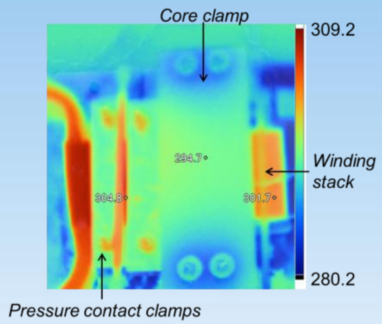


Simulation results show that no torque is produced in the vehicle during the charging or V2G process → **car does not move during charging.**

Theme 6 – Passive Components (Bristol, Manchester, Sheffield)

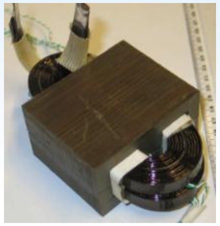
- **Improve miniaturisation** of wound components using multi-physics design optimisation.
- Investigate **inductor performance**, e.g. power loss, temp. distribution, using **3D thermal models**.

Potted inductor with embedded thermal sensors



Thermal image of an inductor holding windings between two clamps

- **Inductor topology** affects electromagnetic and thermal behaviour, and manufacture and scalability.



Laminated & wound E-core

- E-core is **easier to manufacture**: windings can be preformed and placed within the core assembly.
- But toroidal inductors need to be wound in situ.

Wound & powder Toroidal core

- Toroidal inductors give **better heat transfer** from the winding/heat source to the heat sink due to **lower thermal resistance** between the two regions.
- But in E-core, heat from windings is transferred **through the core pack** into the heat sink.

Demonstrator Project 1: Integrated Non-Rare-Earth High Performance Drive

PI: Professor Patrick Luk (Cranfield University)

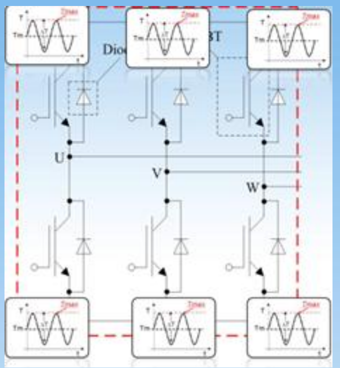
CoI(s): Professor Volker Pickert (Newcastle University)
Professor Keith Pullen (City University)
Dr Weizhong Fei (Cranfield University)

Start Date: 01/10/2013
Total Funding: £311,982

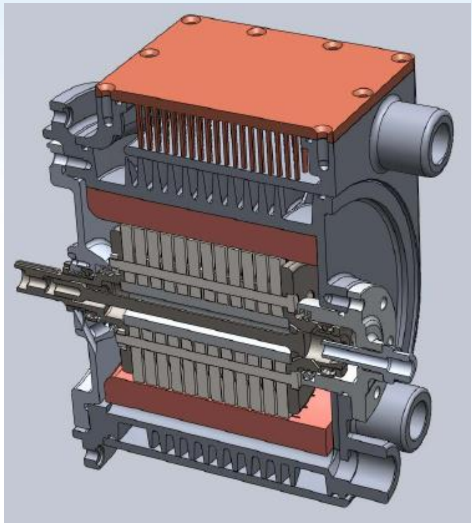
Themes involved: **Design Tool and Motors**

Industry support: Liberty E-Tech; Scorpion Power Systems; Motor Design Ltd.

High performance ferrite motor with full functional integration with its converter

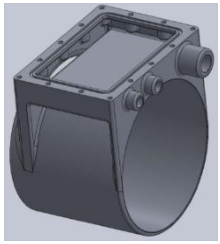


- Use **Smart cooling** in the power converter for the motor – hardware cools power devices individually.
- Optimise rotor construction:
  - **Modelling/construction of rotor:** Portunus software with high fidelity machine model.
  - **Prevent de-magnetization:** Rotor performance optimised by having **smaller diameter** and **longer axial length**.
  - **Reduce stress levels:** Reduce stress of the high rotational speed rotors (12-20krpm) to acceptable level of <250MPa.
- CAD motor assembly



Water-cooled aluminium cast body, with integrated cooling passages for semiconductors.

Helical cooling fins on motor body **maximise heat transfer** by returning water from left to right of the motor.



The outer jacket surrounds the fins and forms the **semiconductor heat sink plenum**.

Demonstrator Project 2: Integrated Power Conversion for Reduced EMI

PI: Professor Phil Mellor (University of Bristol)

CoI(s): Professor Andrew Forsyth (University of Manchester)
Professor Mark Johnson (University of Nottingham)

Start Date: 01/10/13
Total Funding: £310,661

Themes involved: **Packaging** and **Passives**

Industry support: Jaguar Land Rover; Motor Design Ltd; IST Power; Lyra Electronics; Tirius.

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MANCHESTER 1824 The University of Manchester

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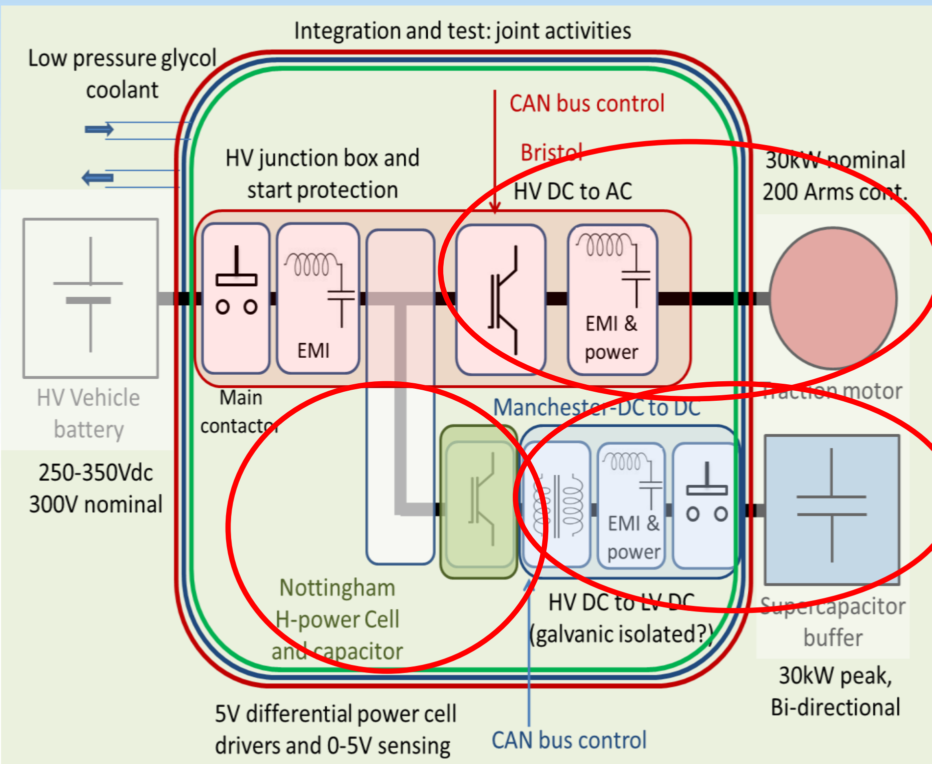
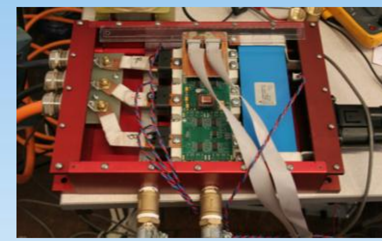
Integrated Power Conversion

Bring together all the PE from different applications into a **single enclosure** sharing a **common cooling circuit**.

→ Makes maximum re-use of PE components
→ Improves electromagnetic compatibility between units
→ Reduces electromagnetic emissions cf. individual elements
→ Volume and weight savings of the drive

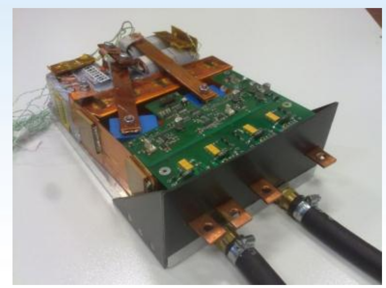


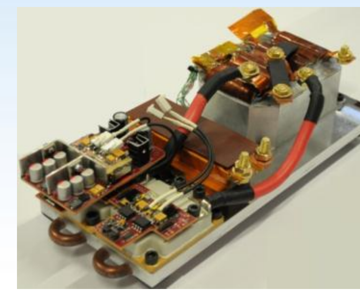
Power module for control

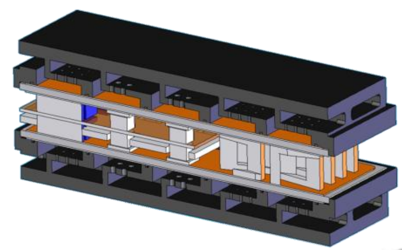


FPGA control boards

DC to DC converter for a 30kW buffer store







CAD representation of H-power cell

Demonstrator Project 3: An Integrated On-board Battery Charger using a Highly Integrated Drive and a Nine-phase Machine, with V2G Capability

PI: Professor Emil Levi (Liverpool John Moores University)
CoI(s): Professor Andrew Cruden (Southampton University)
Dr Lee Empringham (University of Nottingham)

Start Date: 01/10/13
Total Funding: £269,437

Themes involved: **Packaging** and **Converters**

Industry support: Johnson Matthey Batteries; Allied Vehicles; SSE.

LIVERPOOL JOHN MOORES UNIVERSITY

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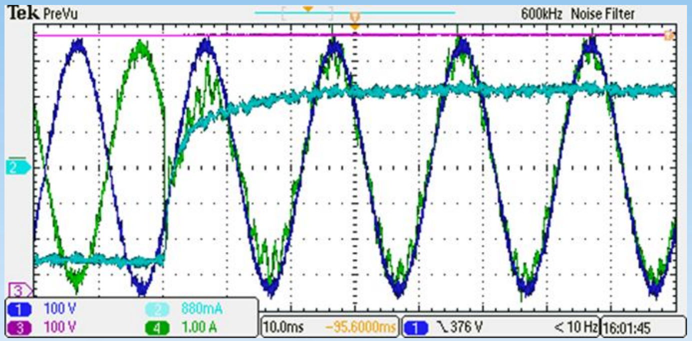
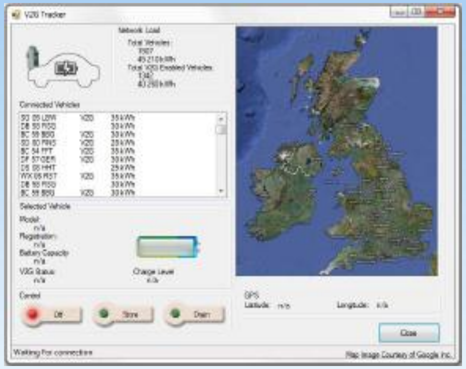
Objectives

Obj 1: Bi-directional power flow using hardware compatible with the propulsion, battery charging, and V2G operations.

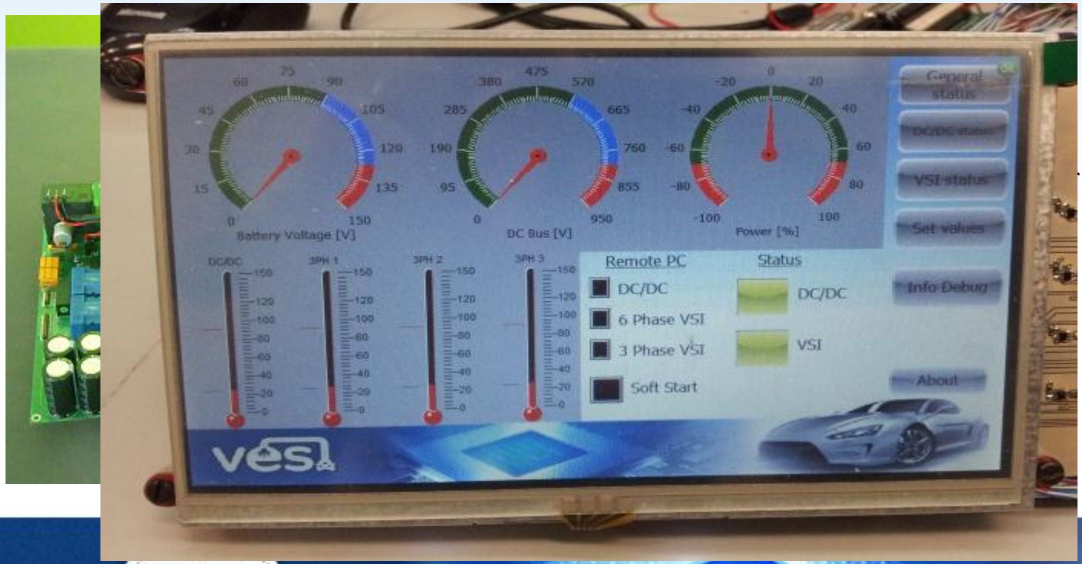


Transition from V2G operation to fast charging mode (in phase).
Battery current (light blue); grid phase voltage (green), and current (dark blue).

Obj. 3: Design hardware and software to showcase the functionality of V2G.
Looking at charging infrastructure. Regional areas show demand and vehicle availability.



Obj 2: High-power-density modular **power converter**



Touch screen control and visual display of:

- Battery voltage
- DC bus voltage
- Power Flow (To/From Grid)
- Power module temp.
- Each 3 phase output
- DC-DC converter module
- Converter status indicator
- Trip signal display

Conclusions

- VESI project focuses on electrical motor and power electronics
- Key aims: Reduce cost, increase power density, improve reliability of electrical power systems, maintain manufacturability for a mass market.
- In final year of project. Underpinning basic research will continue in the 6 research themes.
- Work on physical outputs for the 3 technology demonstrators continuing.