European Conference on Nanoelectronics and Embedded Systems for Electric Mobility

Electric Mobility

“eMobility eMotion”

25-26th September 2013, Toulouse, France

6-phase Fault-Tolerant Permanent Magnet Traction Drive for Electric Vehicles

CASTOR
Car Multi Propulsion Integrated Power Train

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The University Of Sheffield.

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infineon

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Radovan Vuletic

Jonas Tousen
Jan Klenner

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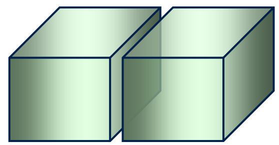
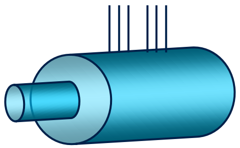
High Power Motor

Role of partners in supply chain

IGBT 650V



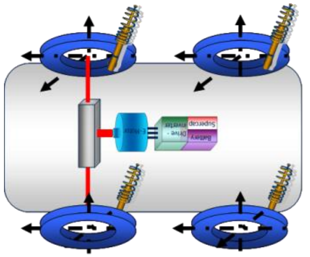
22 kW 22 kW
320 V 320 V



6~

41 kW
320 V

Gear ratio (8-10)



41 kW

IFAG → USFD → VW

infineon

The University Of Sheffield.

Multi-phase inverter with independent control

Fault tolerant multi-phase motor having wide speed range with high efficiency

Specifications and Workbench tests

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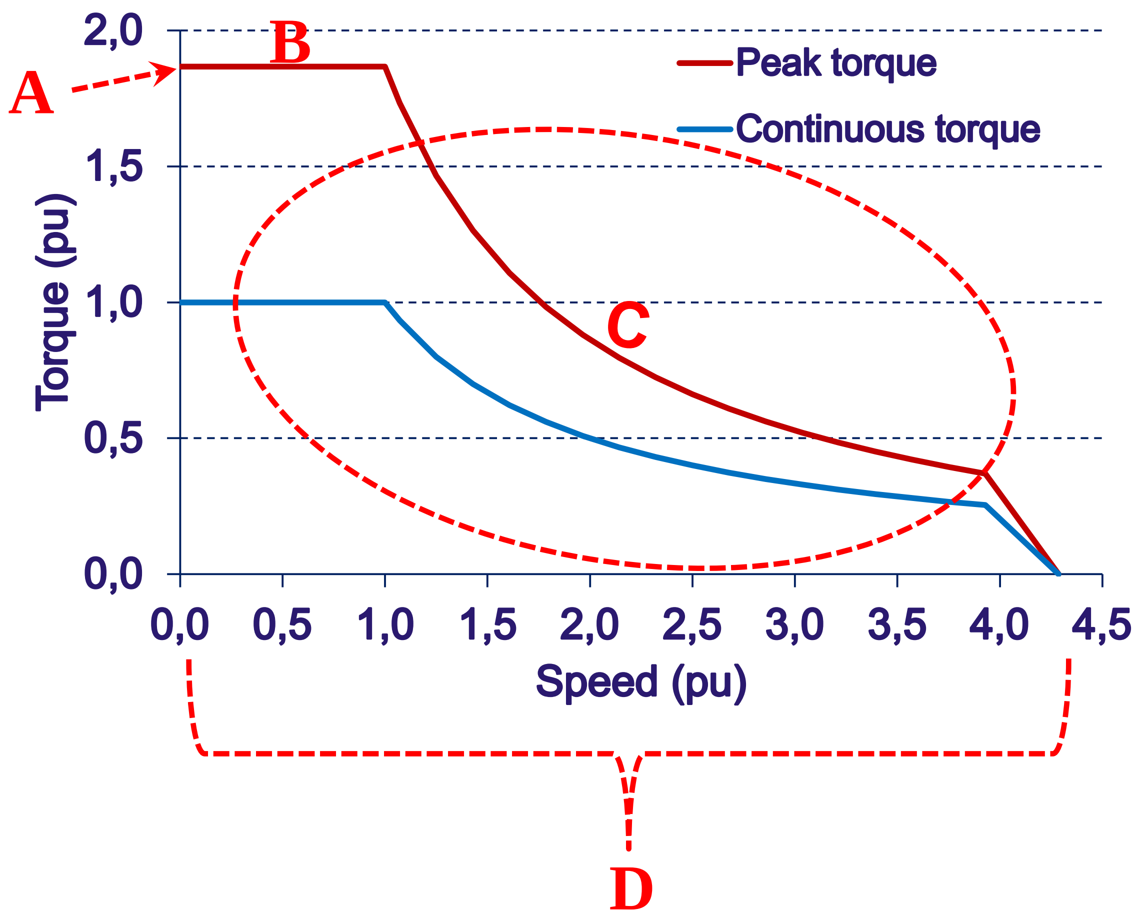
Key challenges for EV traction



A. Starting torque at low speed
B. Acceleration
C. Efficiency
D. Speed range
E. Power density
F. Torque ripple
G. Reliability & fault tolerance
H. Flexibility of control

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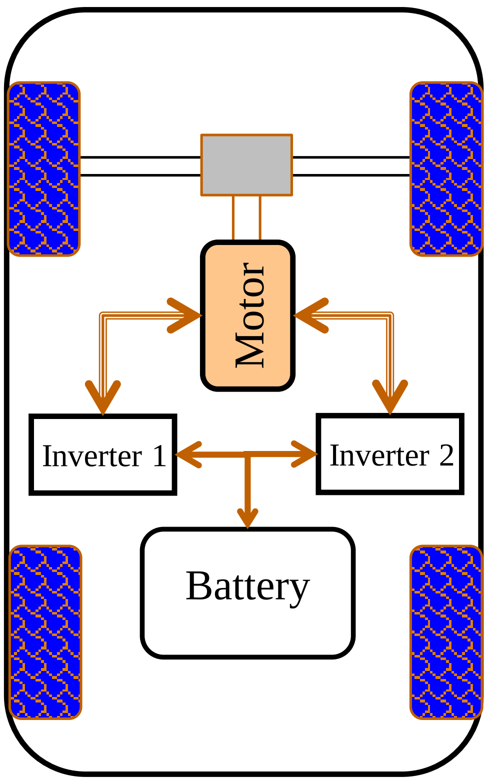
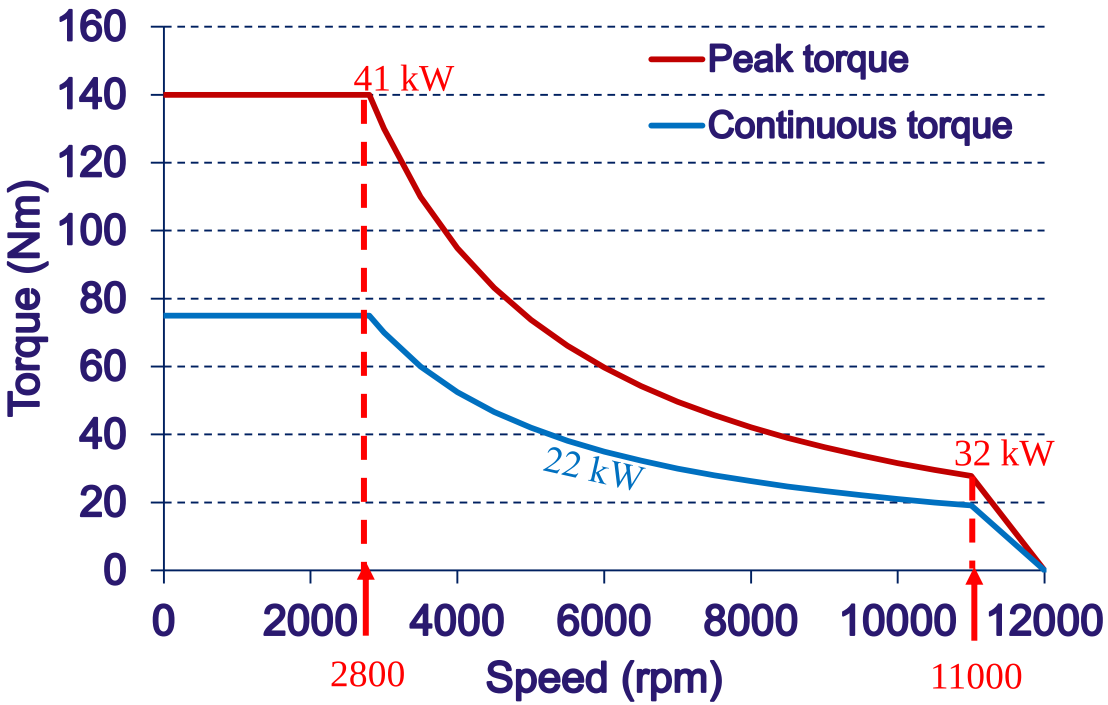
Drive train & design specifications



Power train drive for segment A vehicle



Nominal DC link voltage	320 V
Maximum line-line voltage	650 V
Cooling medium	Water

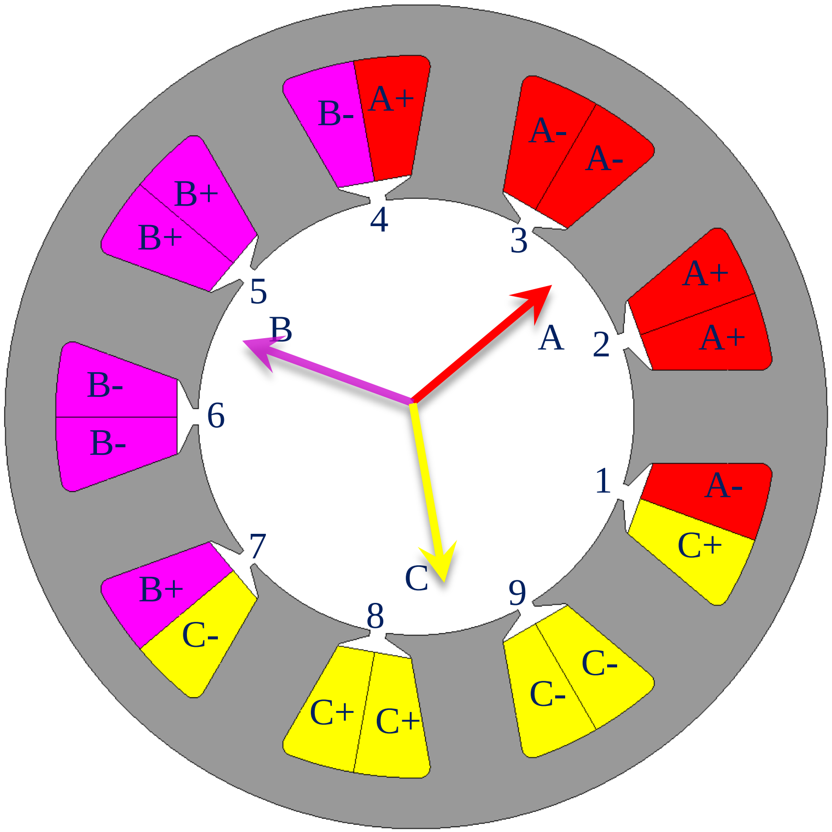
Novel fault-tolerant 6-phase electric motor

Novel 6-phase, 18-slot, 8-pole winding configuration

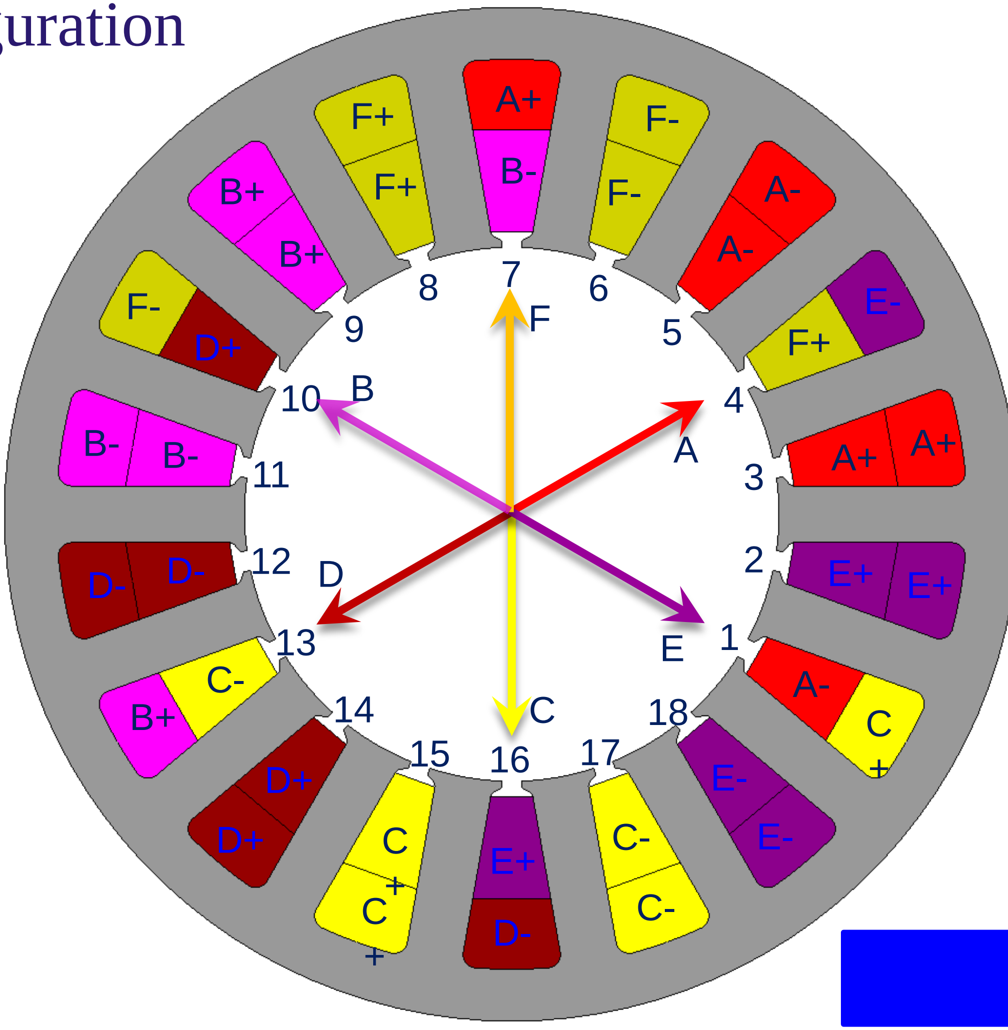
- Improvement of safety and availability by designing the machine topology as two independent balanced 3-phase systems in single stator
- Fault tolerant as vehicle will continue to run with 50% power/torque output even with loss of one 3-phase system
- Lower torque ripple & cogging torque
- Lower eddy current losses in rotor PMs
- Lower copper losses due to shorter end-windings

Novel fault-tolerant 6-phase motor

- Development of winding configuration



3-phase, 9-slot, 8-/10-pole winding



6-phase, 18-slot, 8-/10-pole winding

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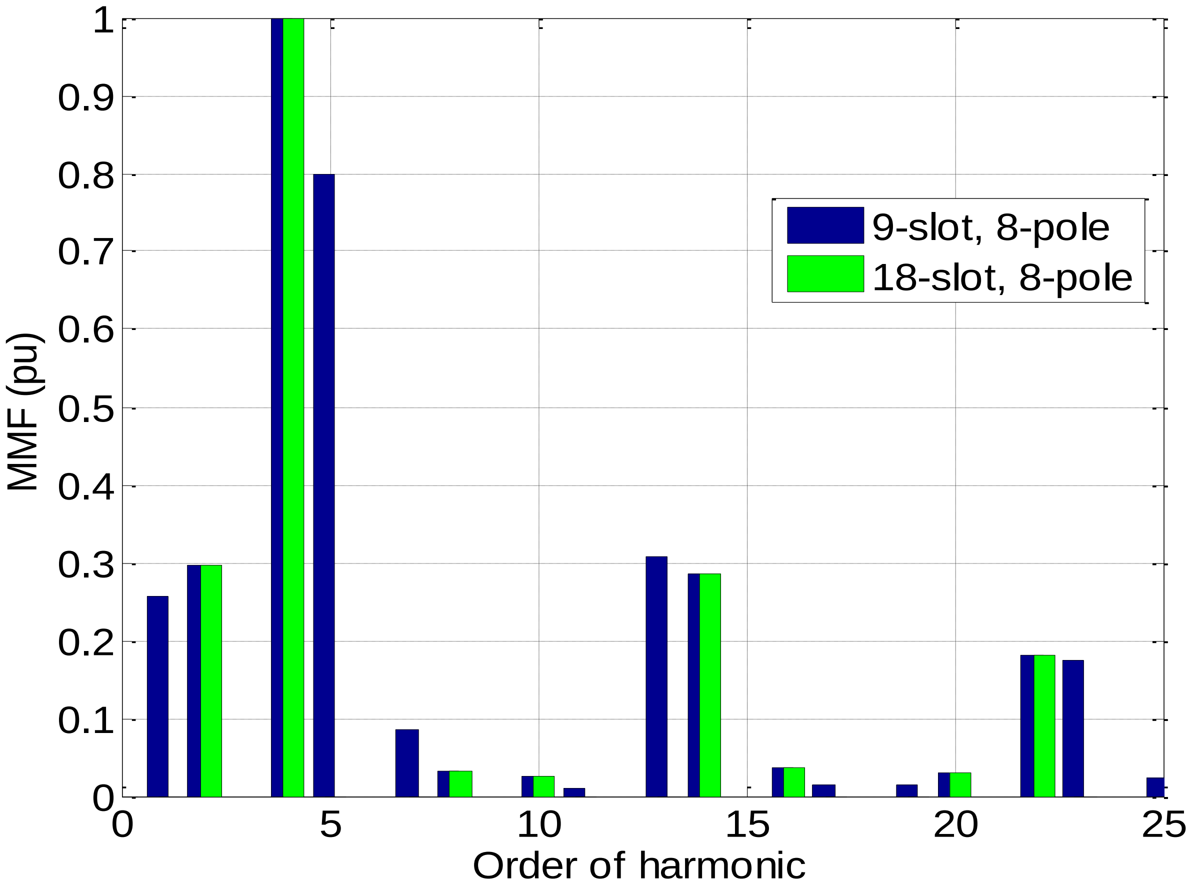
Novel fault-tolerant 6-phase motor

- Normalized MMF space harmonics distribution



✓ The novel winding configuration eliminates many harmonics, which leads to lower eddy current loss in PM and lower torque ripple in a machine.

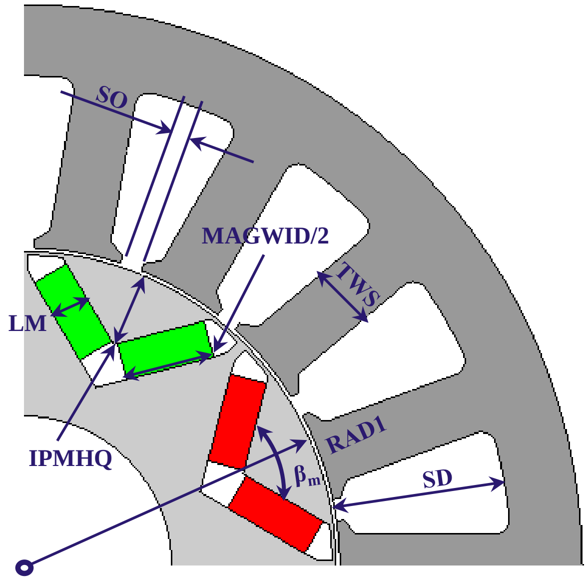
Novel fault-tolerant 6-phase motor

➢ Design Constraints for EV traction motor with PMs

Type of constraints	Design parameter		Constraints
Volumetric	Stator outer radius	mm	≤ 75.00
	Stack length of the motor	mm	≤ 150.00
	Mass of PM material	kg	≤ 1.2
Electromagnetic	Maximum flux linkage (derived from maximum line-to-line voltage)	mWb	≤ 74.7
	Inductance (to achieve peak torque)	mH	> 0.256
	Inductance (to achieve high efficiency in field weakening region)	mH	≤ 0.721
Thermal	Copper winding temperature	˚C	≤ 180˚
	Steel lamination temperature	˚C	≤ 225˚
	PM temperature	˚C	≤ 150˚

Novel fault-tolerant 6-phase motor

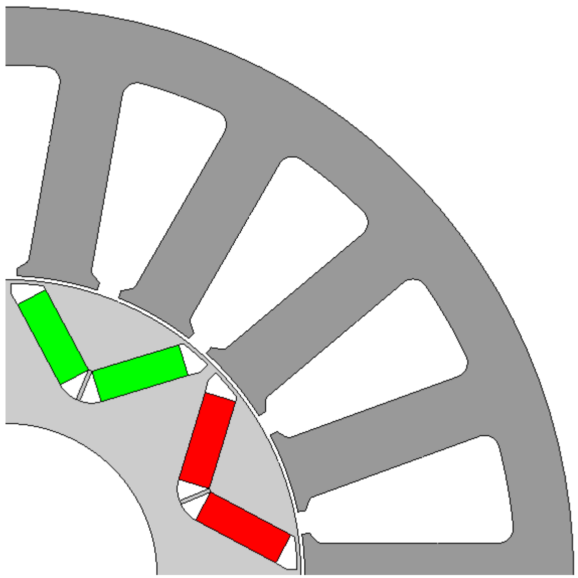
- Design optimized against specifications, mechanical and thermal constraints for maximum efficiency over NEDC
- Cross-section of optimized design



Conceptual design

1.1 kg PM material

94.4% energy efficiency over NEDC



Optimized design

0.9 kg PM material

94.9% energy efficiency over NEDC

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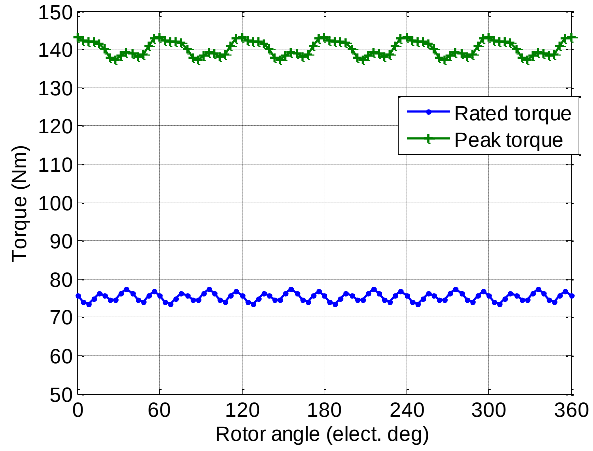
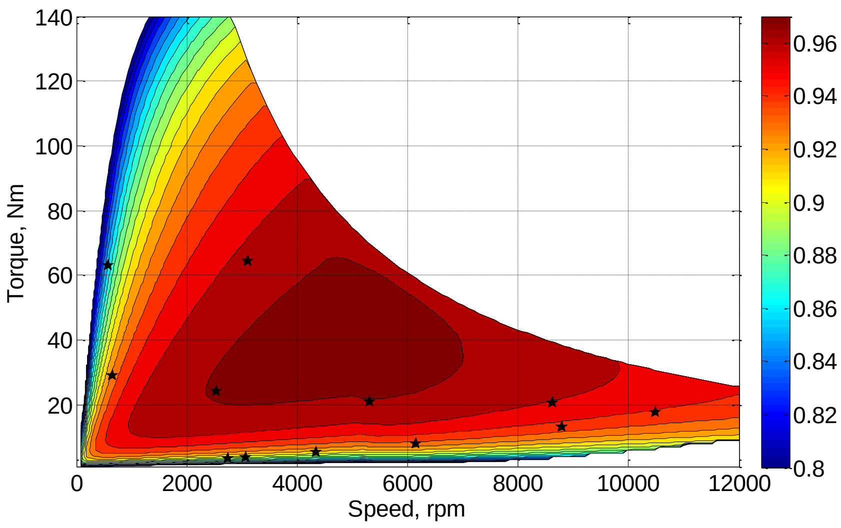
Novel fault-tolerant 6-phase motor

➢ Performance of the optimized design – at rated & peak torque

		Rated Torque	Peak Torque
Torque	Nm	75	140
Torque ripple	%	2.5	4.2
Speed	rpm	2800	2800
Peak current	A	74.0	172.5
Current density	A/mm^2	9.7	22.7
Copper loss	W	809	4394
Iron loss	W	181	273
PM eddy current loss	W	8	56
Efficiency	%	95.7	89.7
NEDC energy efficiency	%	94.9	

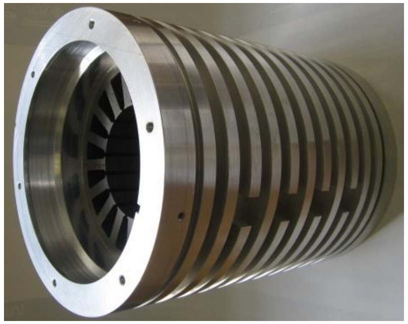




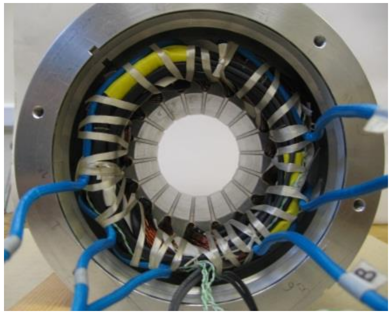
Novel fault-tolerant 6-phase motor

➢ Prototype motor & inverter

Laminations



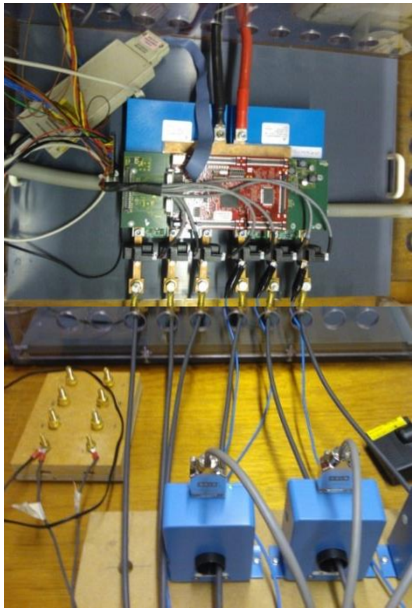
Stator frame



Stator assembly

Rotor assembly

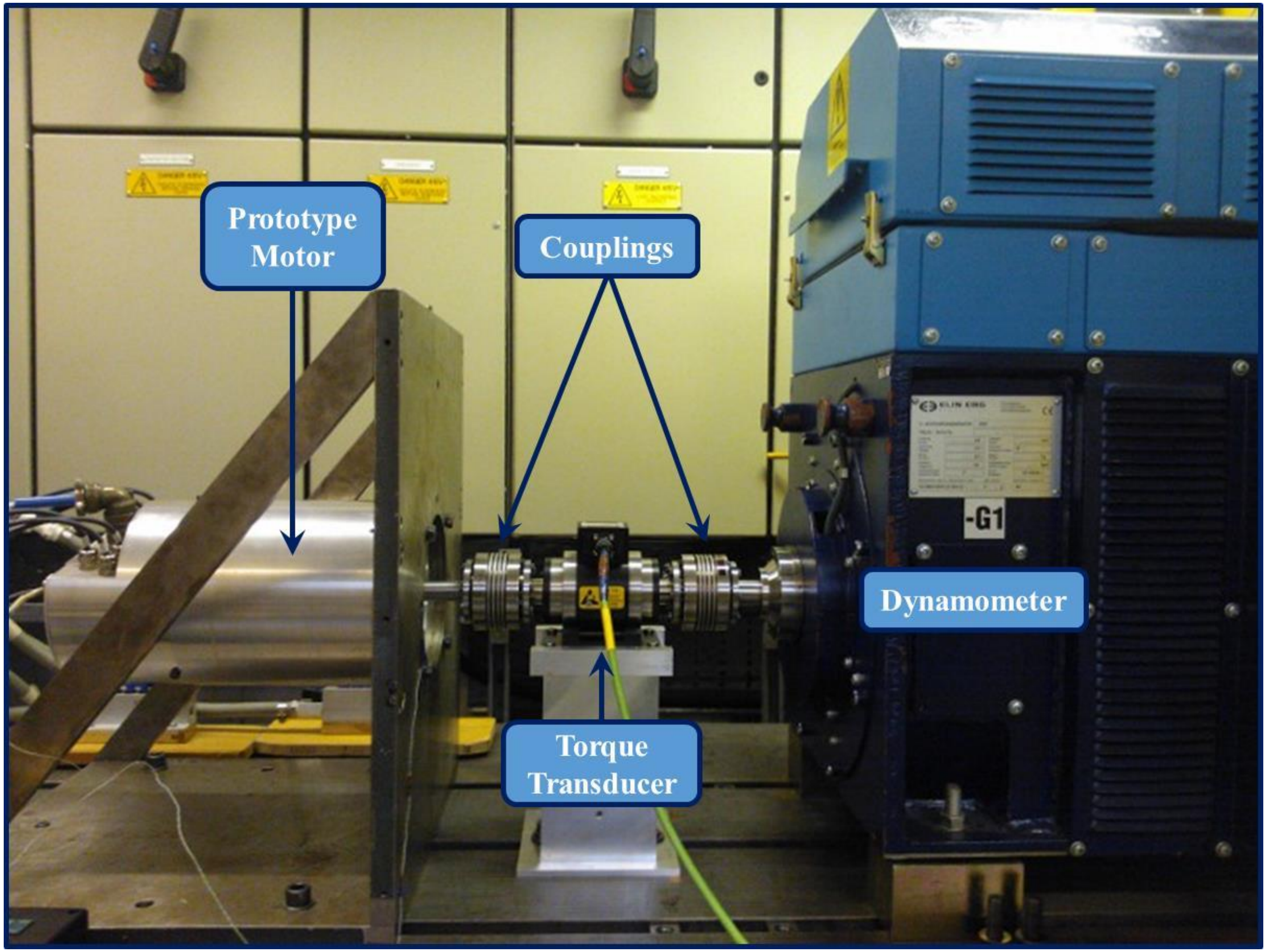
Motor assembly



Inverter with instrumentation

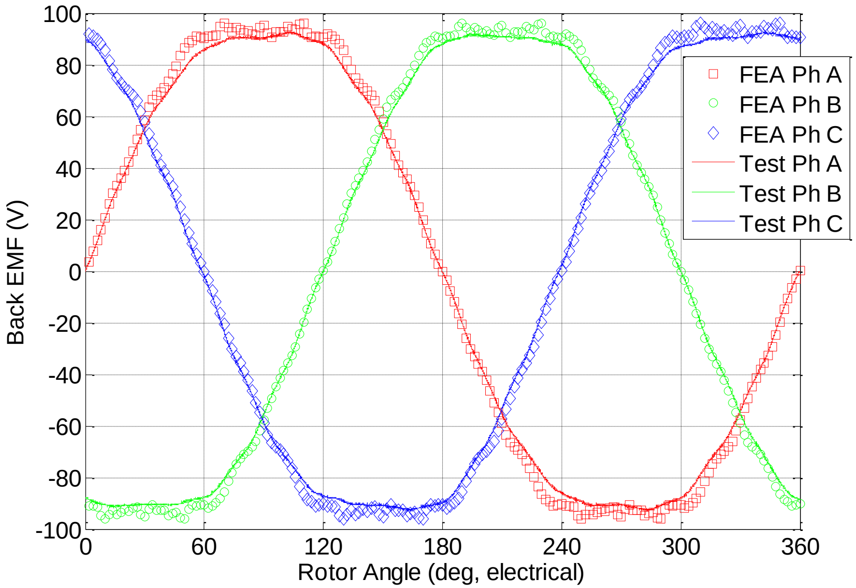
Novel fault-tolerant 6-phase motor

- Test bench for direct measurement of efficiency at USFD

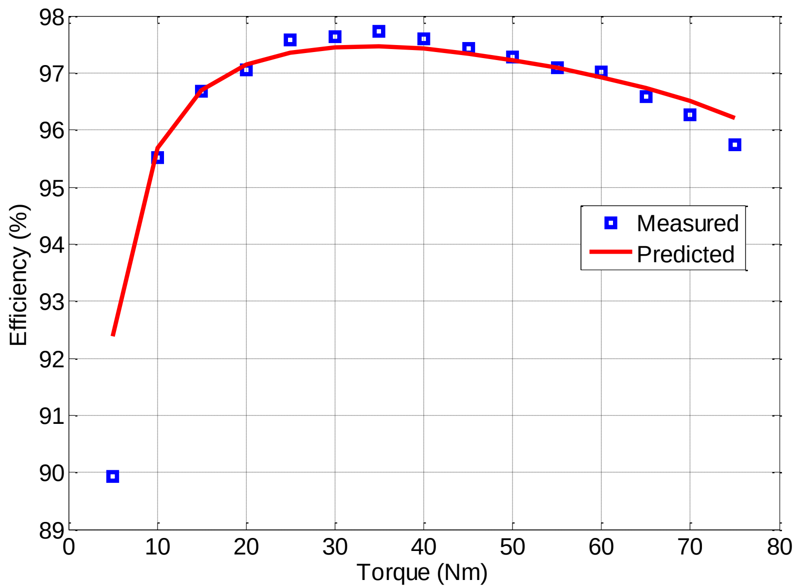


Novel fault-tolerant 6-phase motor

➢ Comparison of prediction and test results at USFD



Back EMF at 2800 rpm

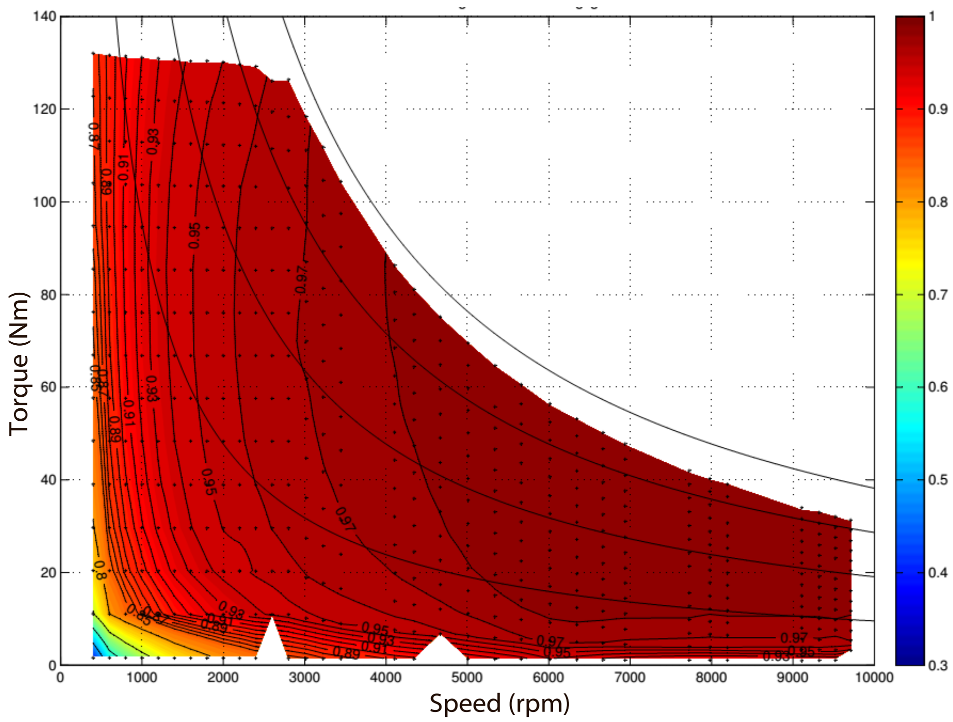


Efficiency at 2800 rpm

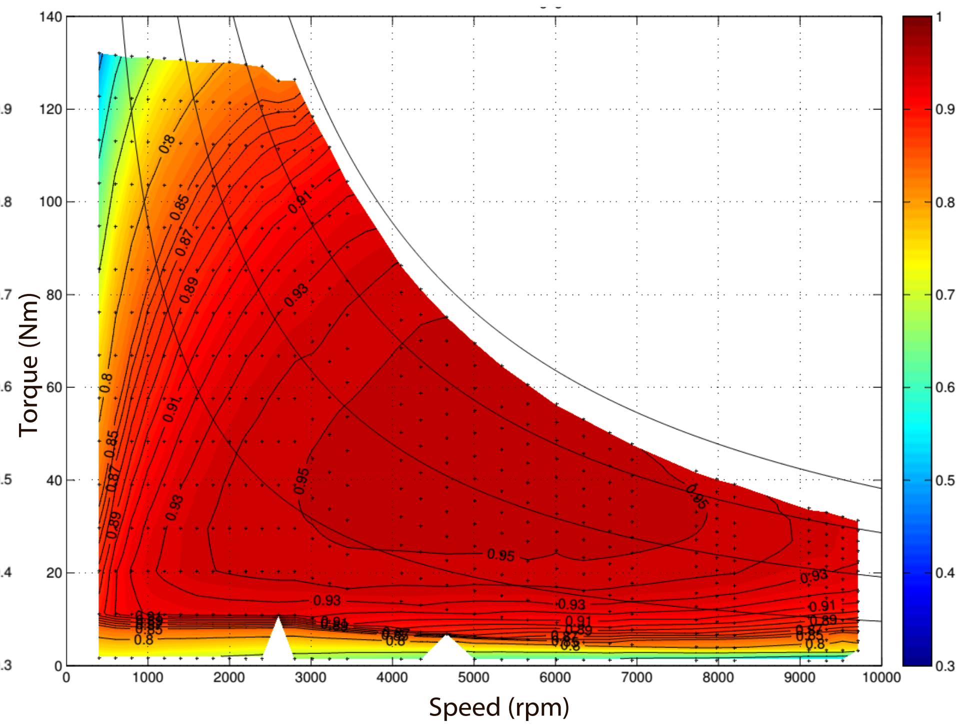
- ✓ The measured back EMF matches very well with the finite element analysis predictions with a difference being just 2.7%.
- ✓ The efficiency at the base speed of 2800 rpm matches closely with the prediction.

Novel fault-tolerant 6-phase motor

➤ Measured efficiency map of inverter & motor with 320V at VW



Efficiency map of 6-phase inverter

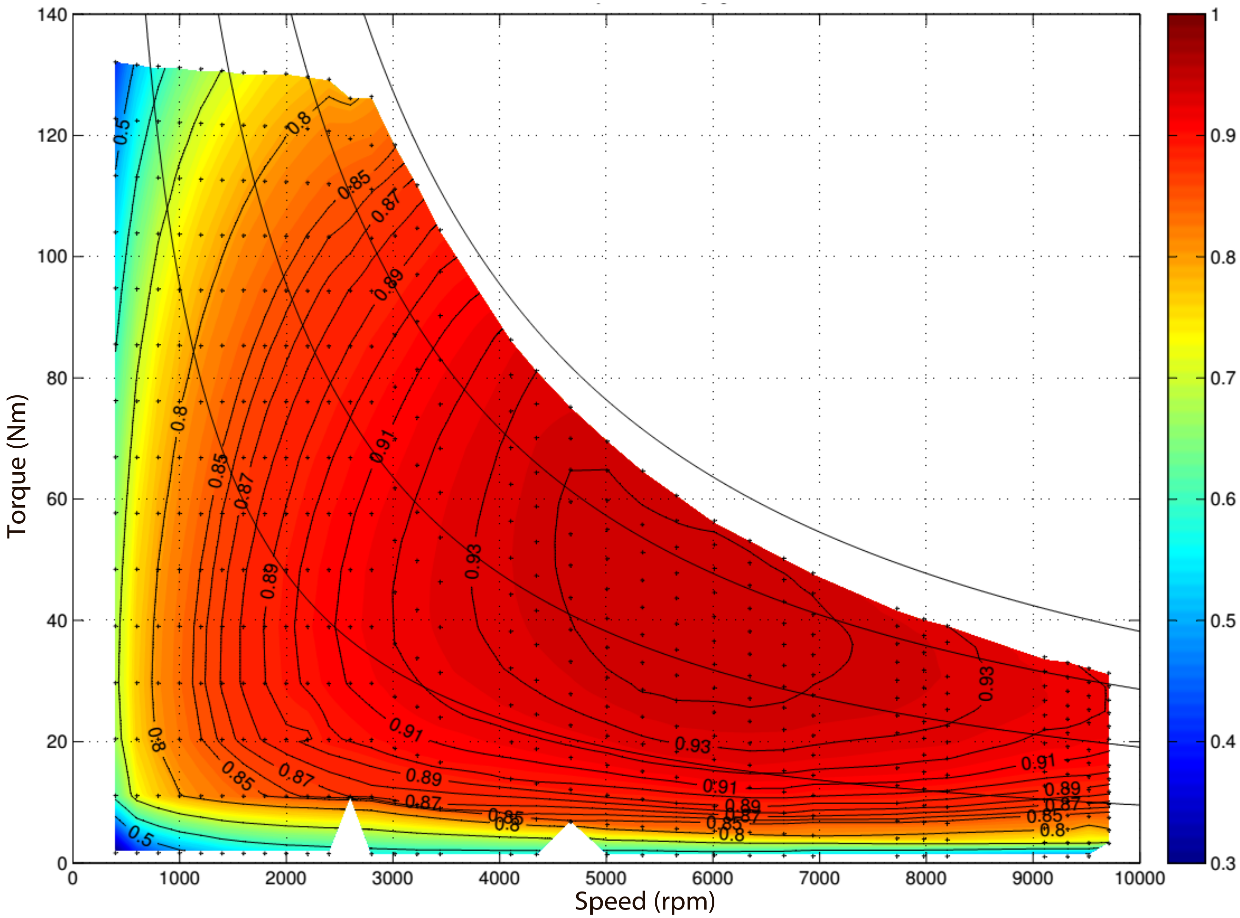


Efficiency map of 6-phase motor

✓ Both the inverter and the motor exhibits high efficiency over the wide speed range.

Novel fault-tolerant 6-phase motor

➢ Measured efficiency map of power drive train at VW



✓ The novel fault-tolerant motor-inverter drive system has a high efficiency over wide speed range.

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Conclusions

- Novel 6-phase motor is designed and developed to enhance safety and availability of power train drive.
- The motor is inherently fault tolerant. Loss of one 3-phase system does not result into complete loss of traction power.
- The new motor configuration exhibits high efficiency over a wide speed range, which is one of the key requirement for EV traction.
- Series of experimental measurements on a prototype motor and inverter have validated the novel fault-tolerant motor.