PROTEAN

Electric Automotive Technology

Protean Electric

SiC Inverter for In-Wheel Motor (IWM) Applications

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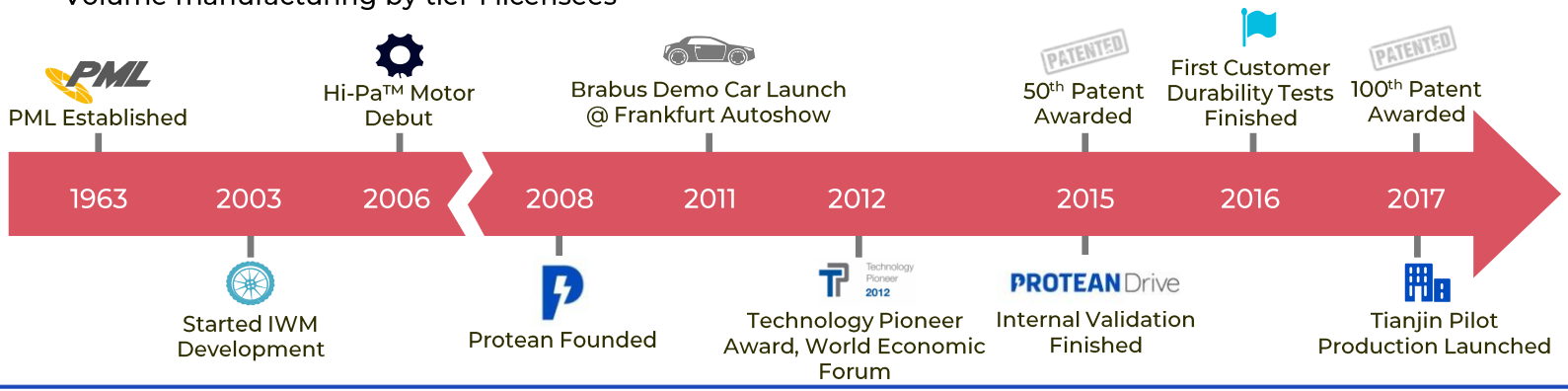
Contents

Section 1

In-Wheel Motor

Protean Electric has a strong heritage in innovation

- An automotive technology company founded in 2008
- Today we are over 130 employees based in the UK, China and US
- Our focus is the development and validation of ProteanDrive:
  - Electric in-wheel motor drive system
  - Direct drive motor
  - Inverter
  - Friction brake
- Market-ready product Pd18:
  - 4th generation design
  - Comprehensive verification completed
  - Small series manufacturing in Tianjin
  - Volume manufacturing by tier 1 licensees



The conceptual advantages of in-wheel motors are clear

Range & Efficiency: Drive Longer

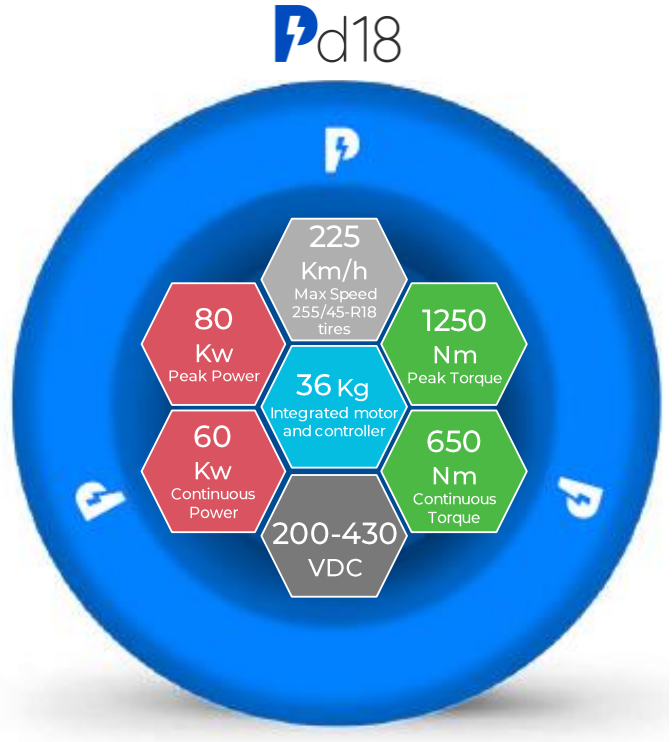
- In-wheel motors remove efficiency losses associated with gear, differential and CV joints situated around the vehicle

Meaning
- Greater range
- Reduced running costs
- Lower charging frequency

Design Flexibility: Creative Freedom

- In-wheel motors revolutionize car design
- No requirement for existing driveline components means car design is no longer compromised

Meaning
- Flexible vehicle design
- Flexible manufacturing process
- Simpler development of hybrids



Driving Experience: Better Handling

- Individual wheel motors allow torque distribution to different wheels (torque vectoring)

Meaning
- Improved driver experience
- Enhanced stability and control
- Improved ABS/ESP function

Cost Benefits: Production Efficiency

- In-wheel motors with integrated inverters do not require a gear, differential, drive-shafts or external drive electronics

Meaning
- Comparable system cost
- Reduced development cost
- More opportunity for modularity

IWM Design Challenges

- Unsprung Mass
  - Longest standing challenge
  - Independent tests have proved it is no limitation to in-wheel motor technology
- Integration of Friction Brake
  - Packaging a foundation brake within the motor that matches standard vehicle performance
- Thermal Management
  - Cooling multiple electronic subsystems effectively when closely packaged together
- Vehicle Control
  - Individual wheel control achievable in existing vehicle architectures

More details can be found at www.proteanelectric.com

Section 2

Integrated Inverter Drive

ProteanDrive Pd18

- Development in accordance with ISO26262 Functional Safety Standard
- Design lifetime of 300,000km and 15 years with verification through bench and vehicle durability testing
- Designed to exceed, and tested in line with, major automotive manufacturers' EMC standards

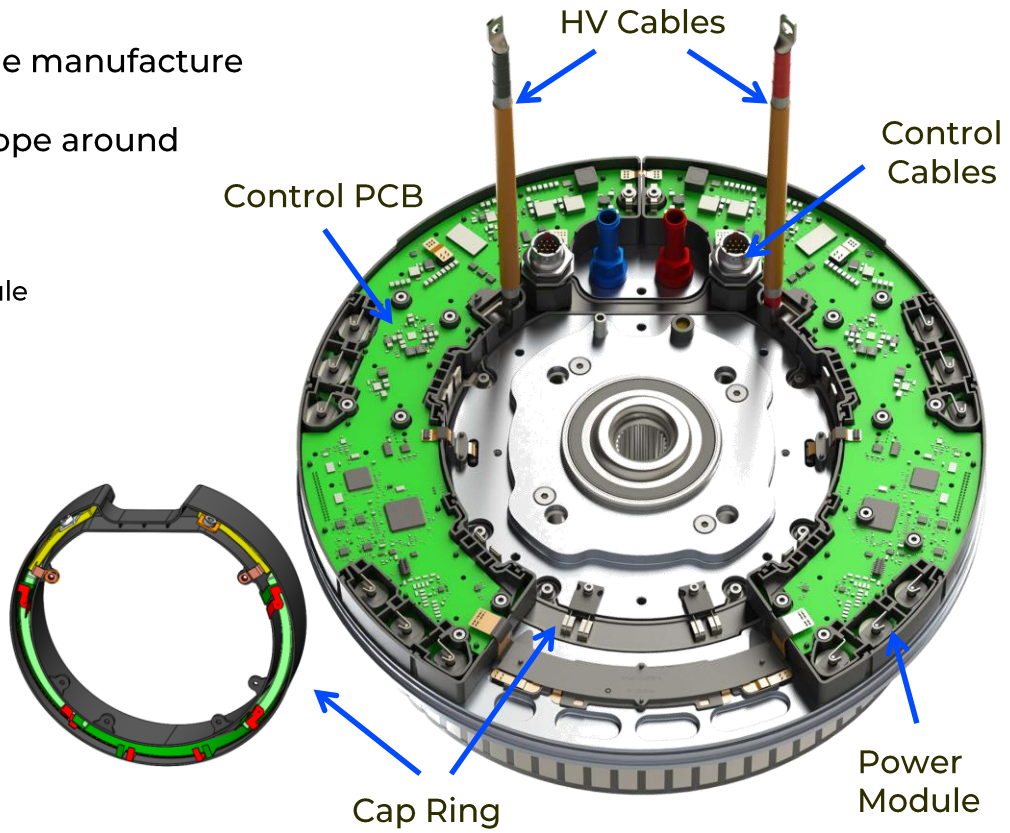
ProteanDrive Pd18 Specification

Characteristic		Pd18	Units
Peak Output Power* Continuous Output Power* Peak Torque Continuous Torque	@400 Vdc	80 60 1250 650	kW kW Nm Nm
Motor Dimensions (diameter, axial depth to rear or stator, excluding cable glands)		433, 125	mm
Motor Mass (including power electronics, excluding bearing, brake and cables)		36	kg
Maximum Speed		1600	rpm
HV DC Supply Voltage Range (for full performance)		200 to 400	Vdc
Coolant Inlet Temperature Range (for full performance)		-20 to +50	°C
Cooling Fluid		50/50 Water/Glycol	
Ambient Temperature Range (for full performance)		-40 to +90	°C
Control Interface (torque demand)		CAN 2.0b	
Ingress Protection Rating		IP6K9K	
Power and Control Electronics		Integrated	
Friction Braking Solution		Integrated	

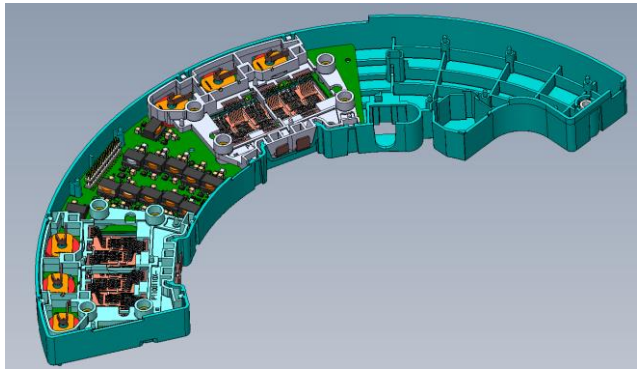
Integrated Inverter Drive

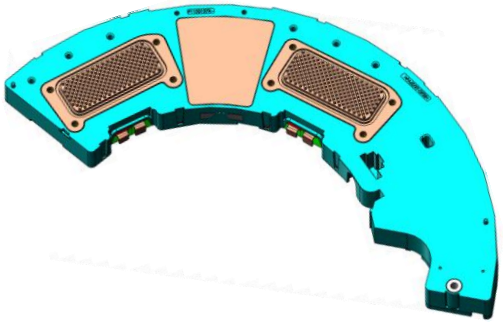
- Modular based design for high volume manufacture
- Fits within a “doughnut” space envelope around bearing
- Only two main electronic parts
  - Custom variable speed drive power module
  - Custom power distribution capacitor ring
- Ultra-high power density of 80 kW

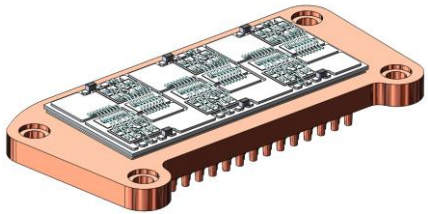
DC Bus Voltage	200-430V DC
Output	4x 3ph variable speed drive
Current out	500Arms peak capability
Power	80kW, 2.8x overload



Custom Power Module

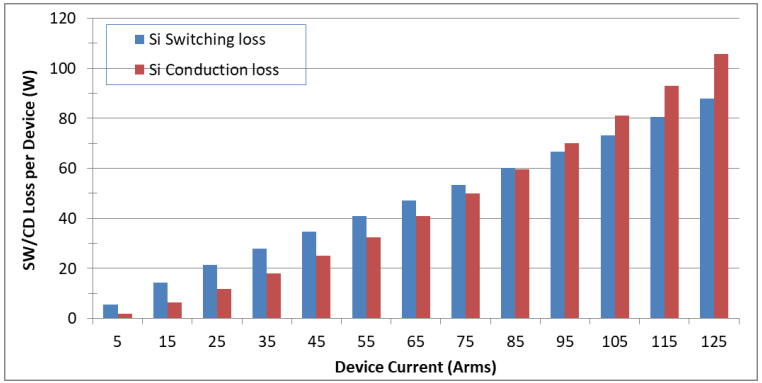


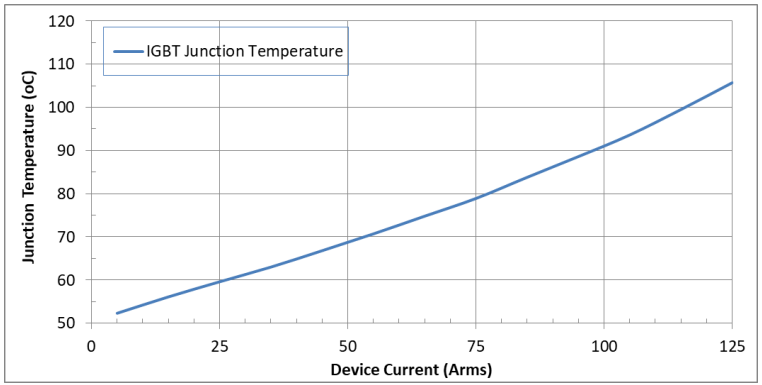


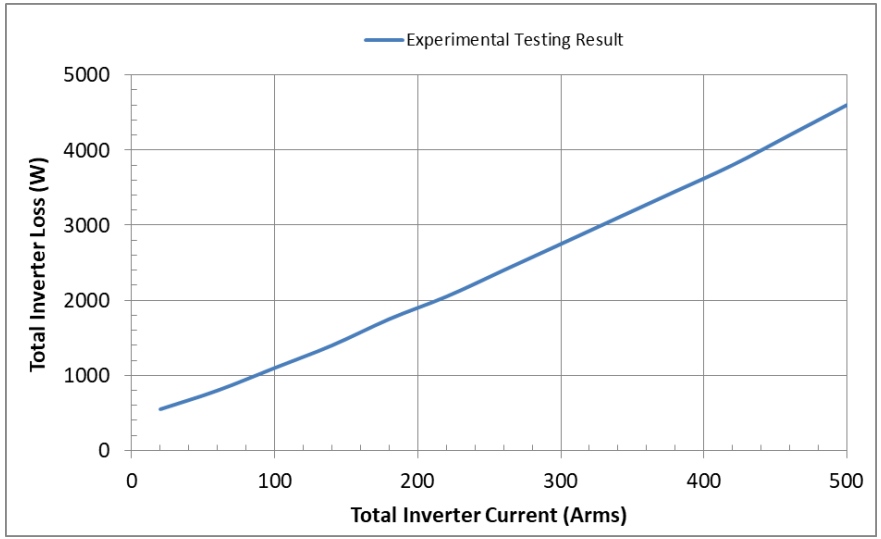


- Each module contains 2 variable speed drive inverters with integrated gate drives, controllers, and sensors
- 650V, 150A IGBT + Diode with PIN-FIN base plate
- Direct water cooling
- Excellent thermal cycling reliability
- Wake on CAN capability & functional safety design
- AEC approved components & extensive use of low profile components

Inverter Loss Assessment

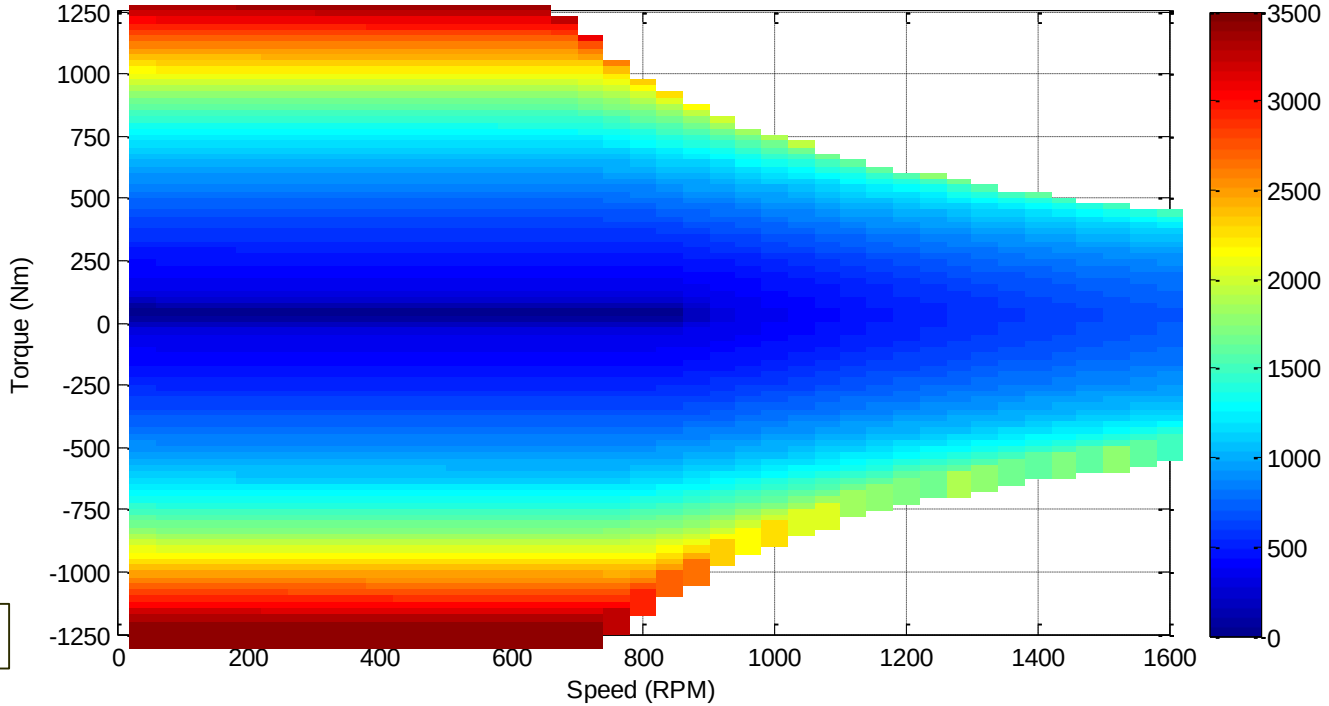






- **Top-left**: balanced switching & conduction losses
- **Bottom-right**: IGBT junction temperature
- **Top-right**: Inverter loss up to 4.6 kW when supplied with 400 Vdc

Si Inverter Loss Map

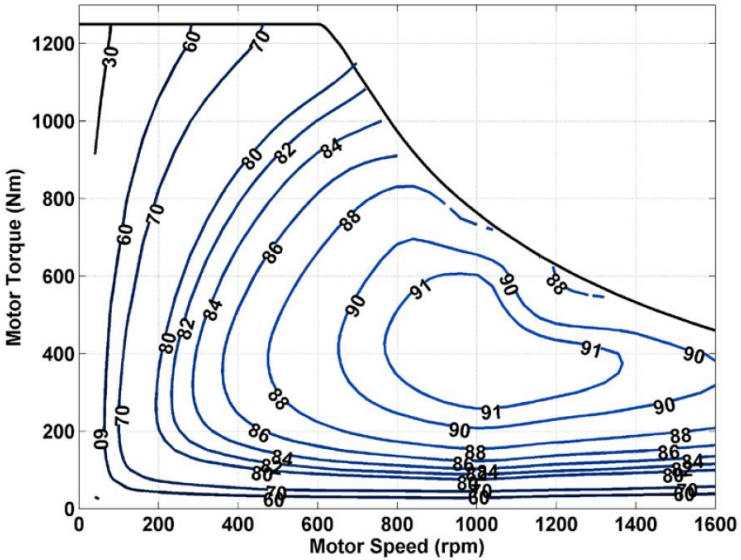


Go to SiC

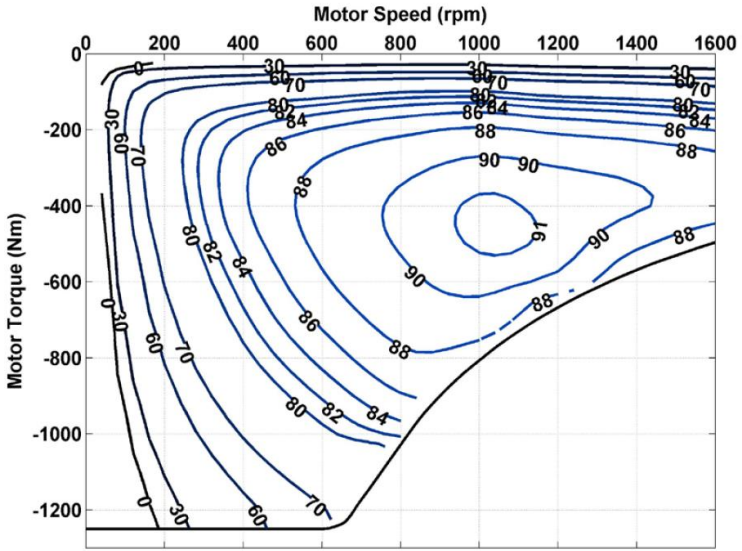
- Inverter loss map under 320 Vdc with 50/50 water/glycol coolant, at 50°C inlet temperature and 13 L/min flow

IWM System Efficiency

Motoring Efficiency



Braking Efficiency



- Losses presented include all losses from DC electrical supply to wheel:
  - Machine losses / Inverter losses / Friction and windage losses / Bearing losses
- Performance at 400 Vdc with 50/50 water/glycol coolant, at 50°C inlet temperature and 13 litres/minute flow

Section 3

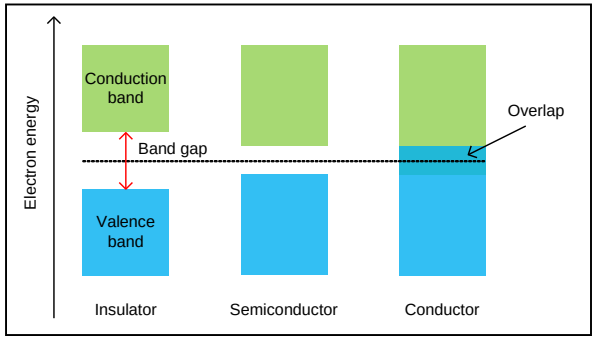
SiC Inverter Option

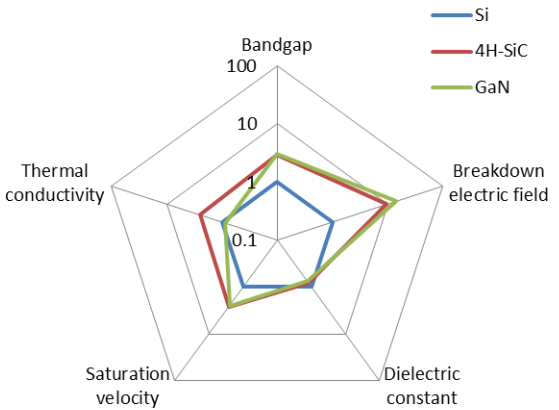
Wide band-gap Semiconductors Benefits

Benefits of Wide Band-gap Semiconductors (SiC vs. Si)

- Reduced power loss
  - 10 x dielectric breakdown field strength
  - SiC devices come with high breakdown voltage and low resistance
- High temperature operation
  - 3 x band gap width
  - SiC devices can operate at higher temperatures
- Fast heat dissipation
  - 3 x conductivity
  - SiC devices have much less cooling requirements
- High frequency operation
  - High breakdown field, high carrier concentration, majority carrier devices

High voltage, low resistance, fast switching behaviour



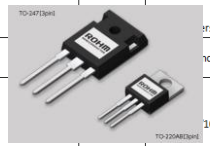


SiC Semiconductors

ID	Manufacturer	Country	Web	Products	Comments	Latest News Update
4		Germany	Link	2. hybrid modules (SBD)	2. products still in sample status	12/01/2017: samples covering 1200/1700V only
5	CISSOID			1. 1200V SiC MOSFETs / SBDs	1. leader in High Temperature & Extended lifetime products (-50°C - 225°C)	
6	ANVIL SEMICONDUCTORS					
7	MONOLITH			10A SBD samples	1. curren	
		witzerland	Link		1. MOSFE	
		USA	Link		/ SOT 227 etc	
		USA	Link			
		USA	Link			and very acti
		USA	Link	4. hybrid modules (with SBD), gate drivers	4. max temperature 210°C	and very acti

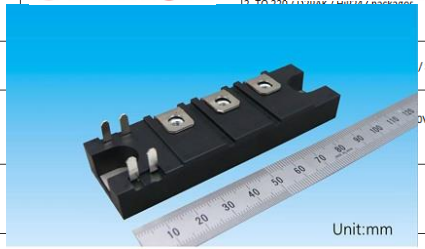
1200 V SiC MOSFET
Industry-leading 200 °C rating

life.augmented



ROHM SEMICONDUCTOR

SanRex

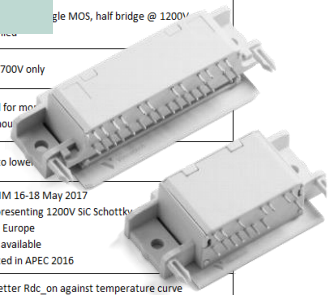


SiC Power module

MITSUBISHI ELECTRIC
Changes for the Better

IXYS INTEGRATED CIRCUITS DIVISION

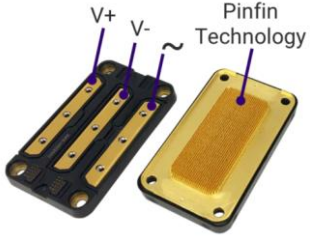
Vincotech



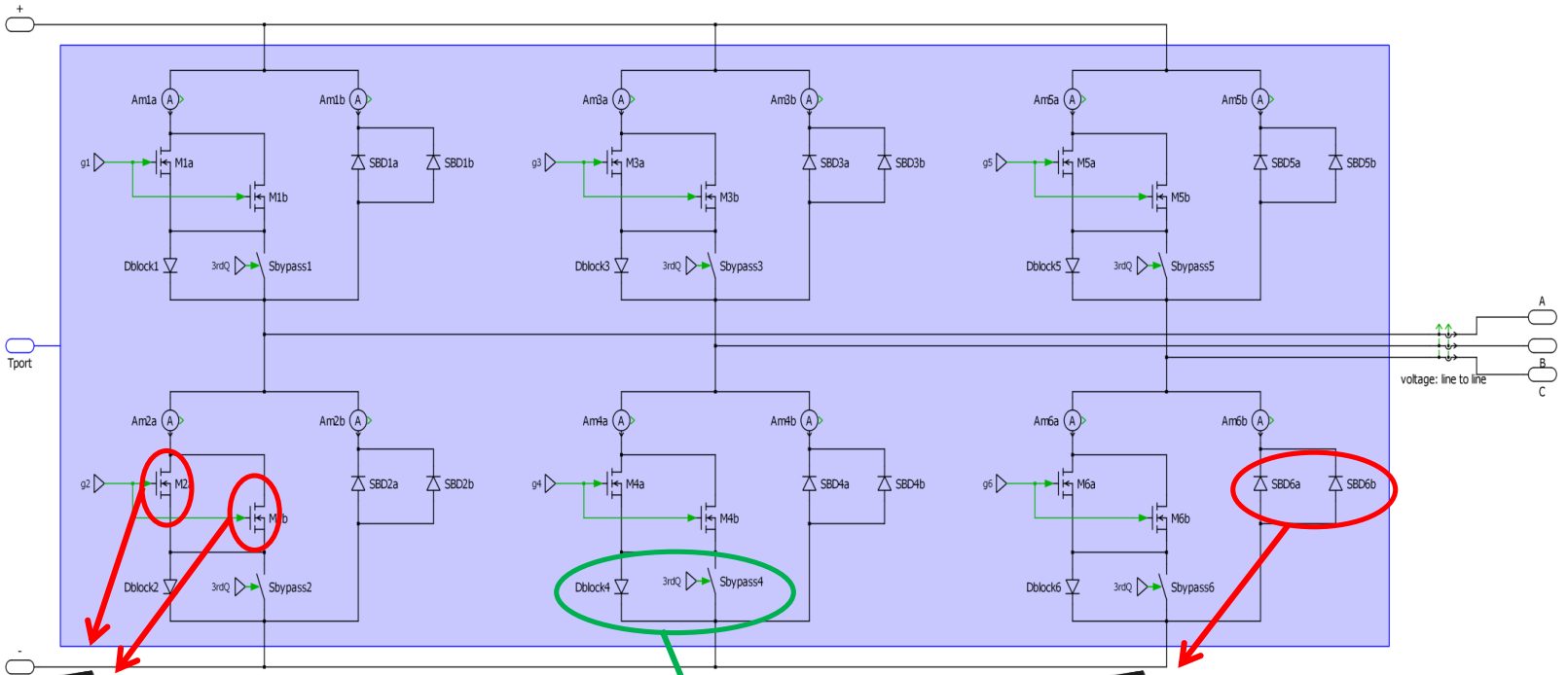
1200V 400A/600A フルSiCパワーモジュール
BSM400D12P3G002 / BSM600D12P3G001

さらなる大電流化へ
1200V 400A / 600A品ラインアップ追加

Wolfspeed
A CREE COMPANY

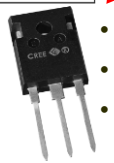


SiC Inverter with Discrete Devices



- CREE C2M0025120D
- 1200V, 25mΩ, 98A
- Highest current rating for discrete MOSFET

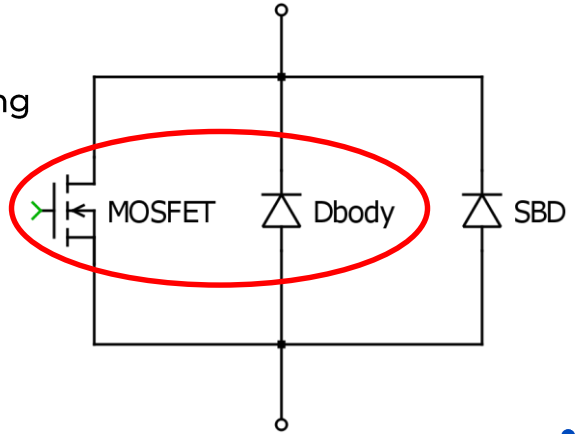
3rd Quadrant operation switch



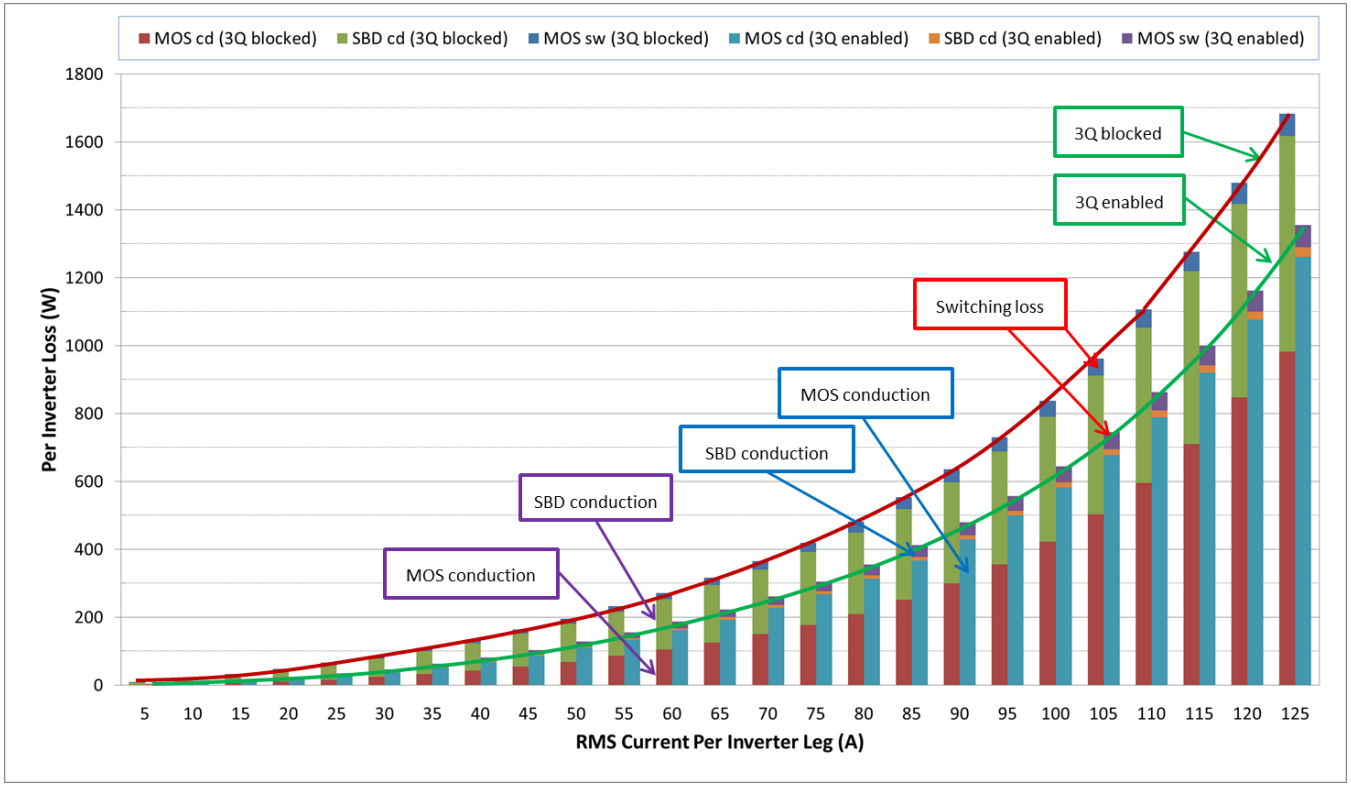
- CREE C4D40120D
- 1200V, 40A (2 in 1 package)
- Highest current rating for discrete Schottky Diodes

SiC Inverter with Discrete Devices

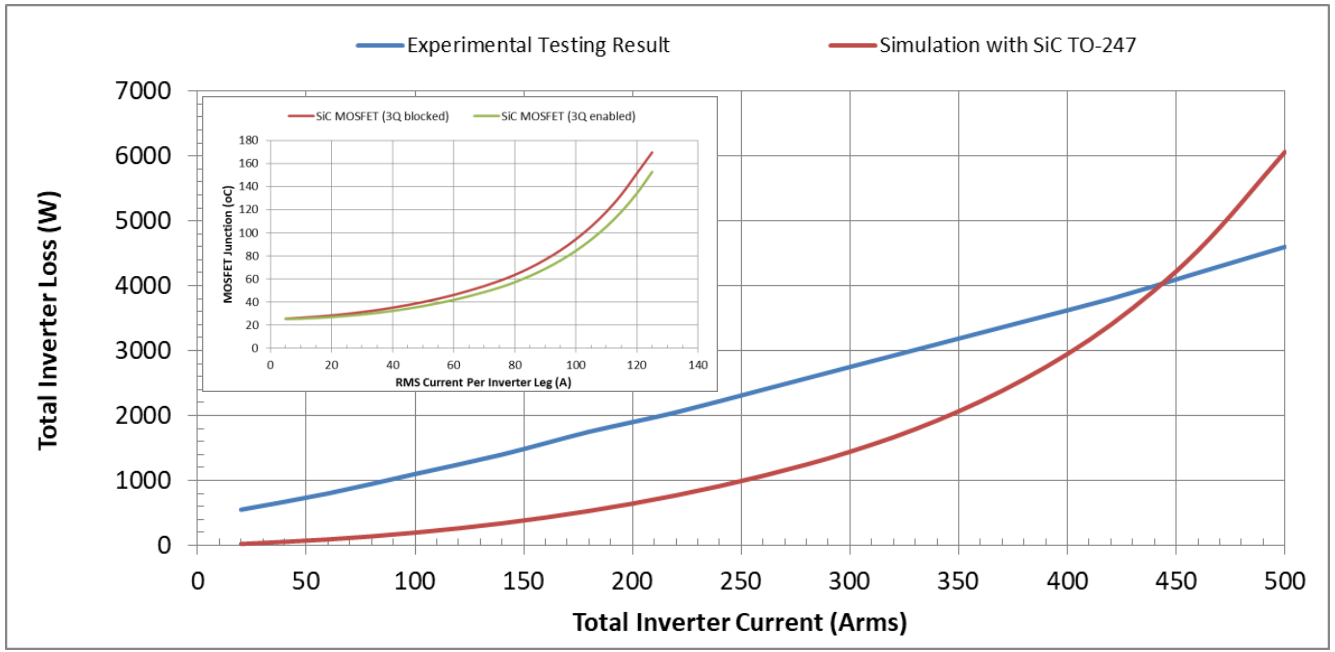
- Consider one switch position (only 1 MOSFET and 1 SBD)
- When the current is positive, it always flows through the MOSFET channel
- When the current is negative, there are three possible paths:
  - SBD whatever gate voltage is
  - MOSFET channel when gate voltage is ON (3rd Quadrant operation)
  - Body diode when gate voltage is OFF
- Assuming SBD forward voltage is sufficiently small, during dead-time period, the body diode path can be ignored and SBD is the only path
- However, when gate voltage is ON with negative current flowing
  - MOSFET and SBD would dynamically share the negative current
  - This will depend on junction temperatures, current levels and drives etc.
  - Difficult to give an accurate loss calculation
- For the chosen devices, 3rd Q path is more efficient than SBD
- Consider two extreme conditions:
  1. Current flows completely through 3rd Q
  2. Current flows only through SBD (3rd Q blocked)



Inverter Loss Breakdown

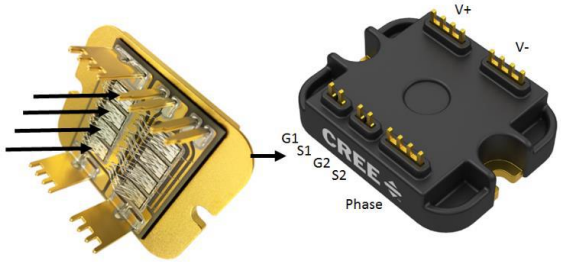


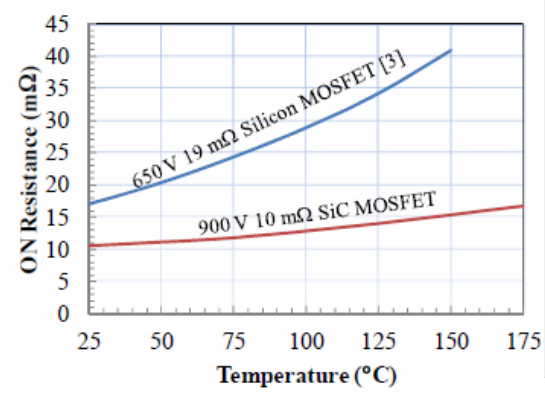
Loss Comparison

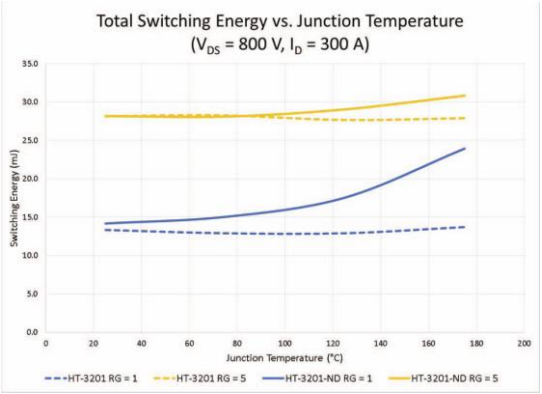


- Low-mid current level: Significant loss reduction with SiC discrete inverter solution
- High current level: Excessive conduction loss, mainly due to the very hot junction (R_{ds_ON})

SiC Power Module







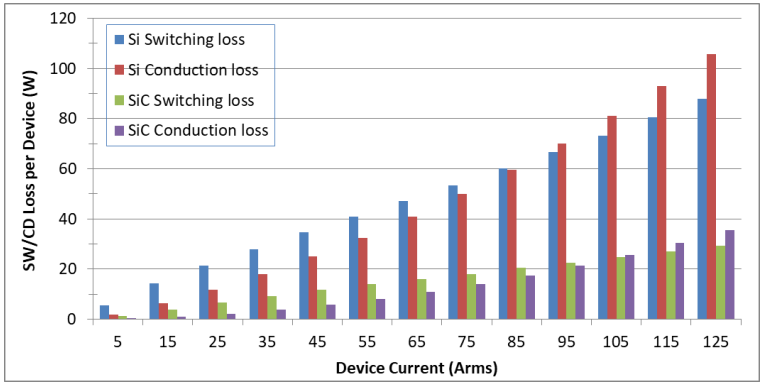
Ref[1]: J. Casady etc. PCIM 2018

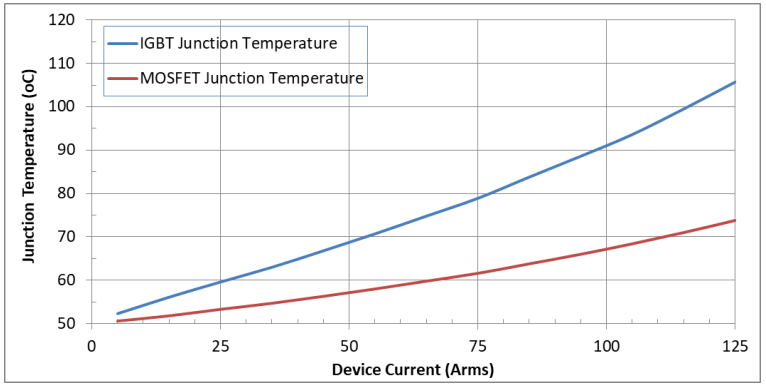
Ref[2]: V. Pala etc. APEC 2016

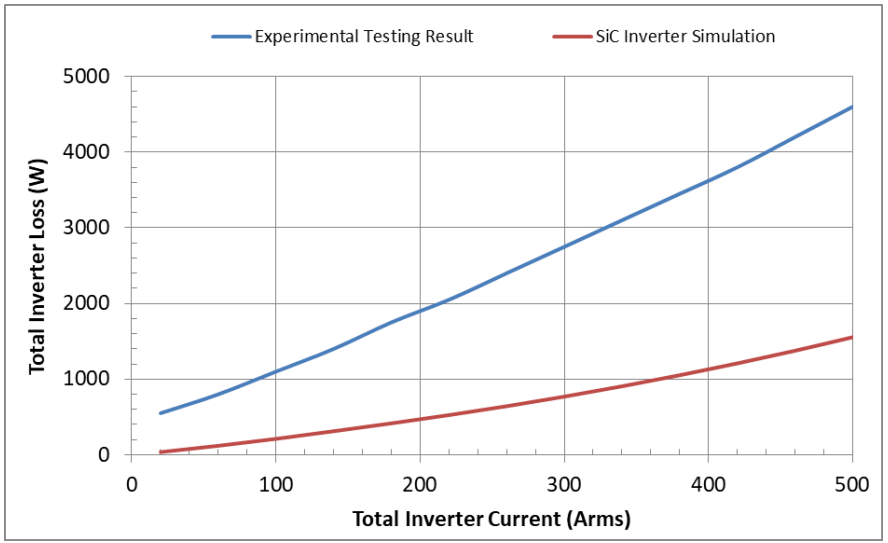
Ref[3]: D. Martin etc. WiPDA 2016

- Novel half bridge module [1] considered for the particularly high current demand
- Much better on-resistance control at high temperature [2], compared to traditional Si MOSFET
- Robust body diode enables a SBD-free design [3], i.e. more SiC chips on the substrate area
- Design considerations: low gate charge requirements, high dv/dt stress, parasitic turn-on etc.

Inverter Loss Assessment

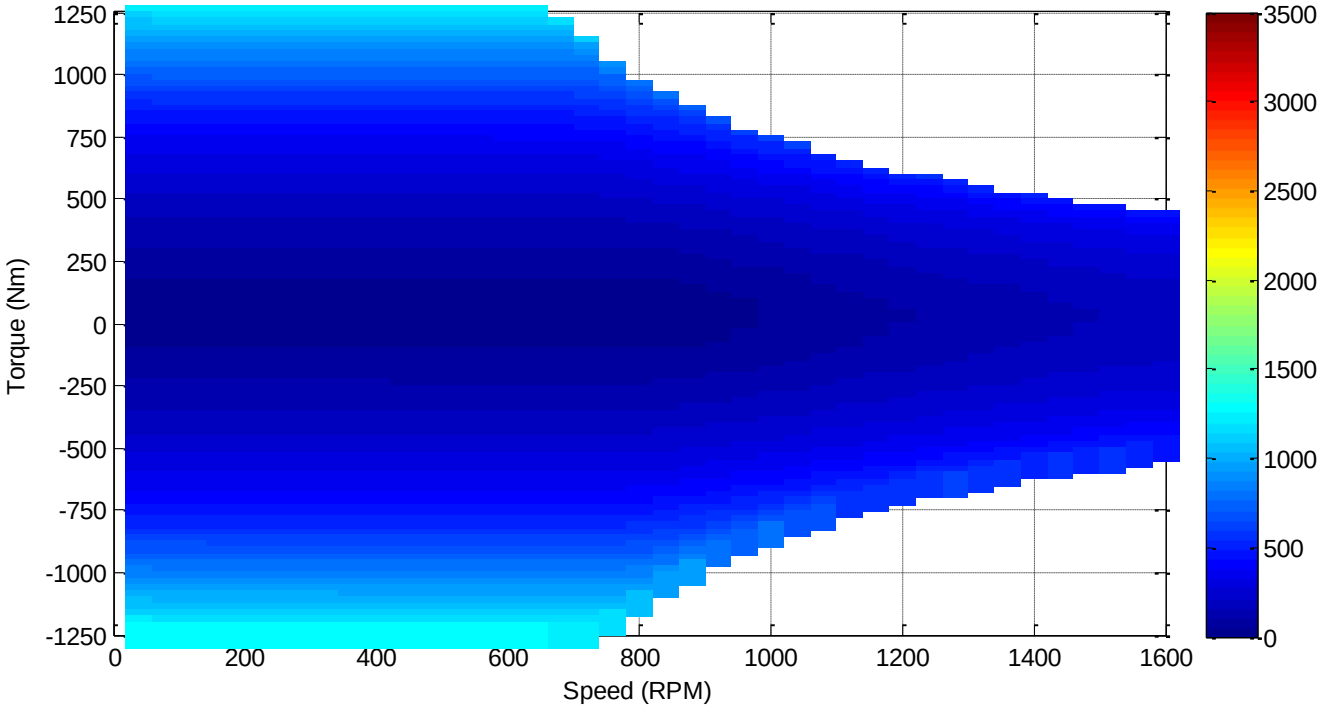






- **Top-left**: switching & conduction loss breakdown
- **Bottom-right**: junction temperatures
- **Top-right**: 4660W vs. 1609W – over 65.5% loss reduction achievable under the same test conditions

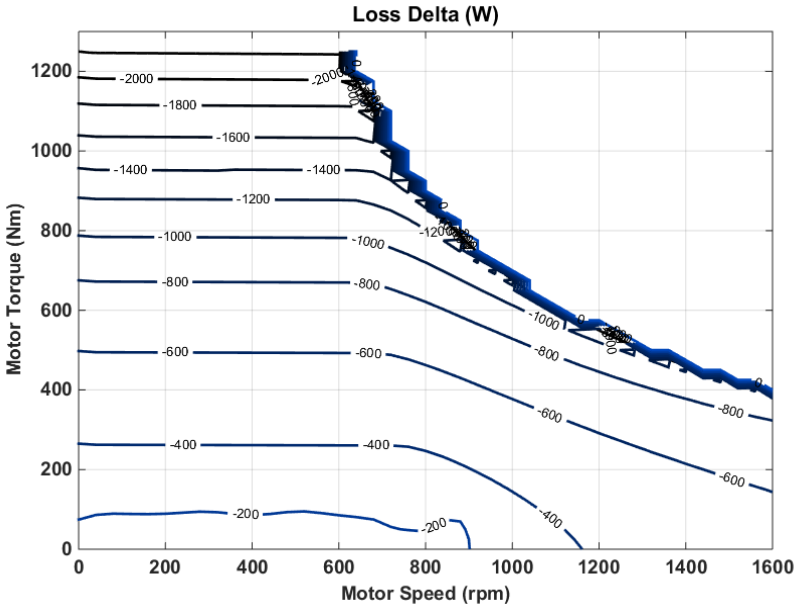
SiC Inverter Loss Map

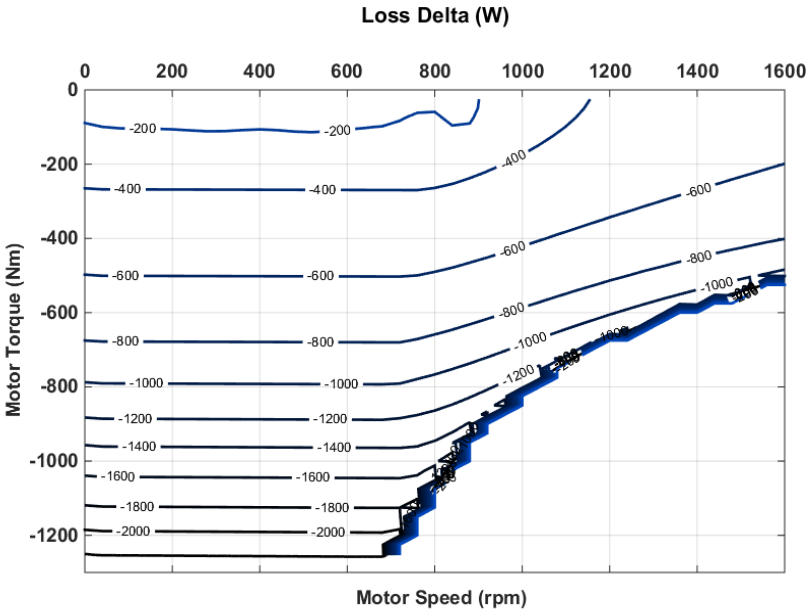


Go to Si

- Inverter loss map under 320 Vdc with 50/50 water/glycol coolant, at 50°C inlet temperature and 13 L/min flow

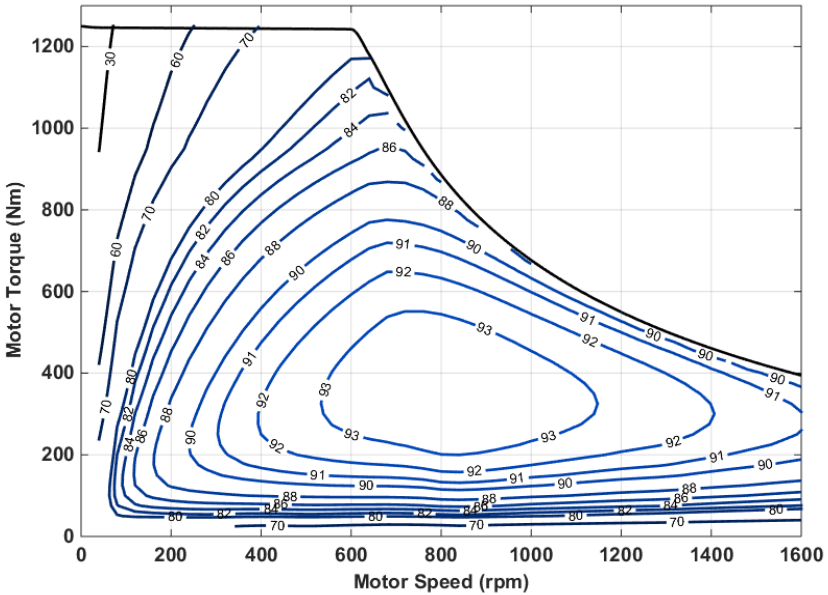
Inverter Loss Delta (SiC – Si)

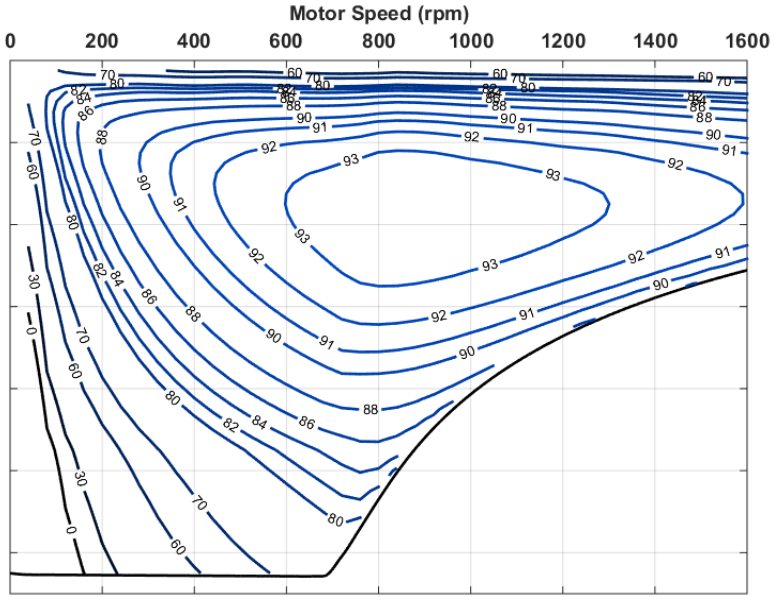




- Inverter loss delta plot (i.e. SiC MOSFET – Si IGBT)
- Performance at 320 Vdc with 50/50 water/glycol coolant, at 50°C inlet temperature and 13 litres/minute flow

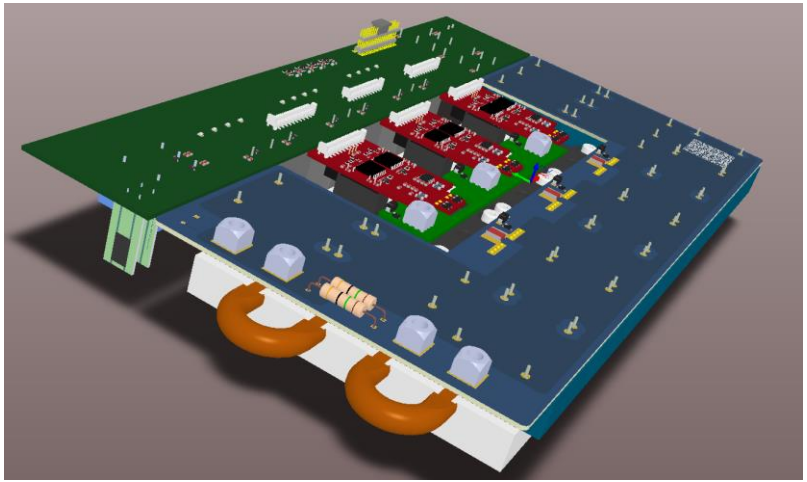
IWM System Efficiency with SiC Inverter

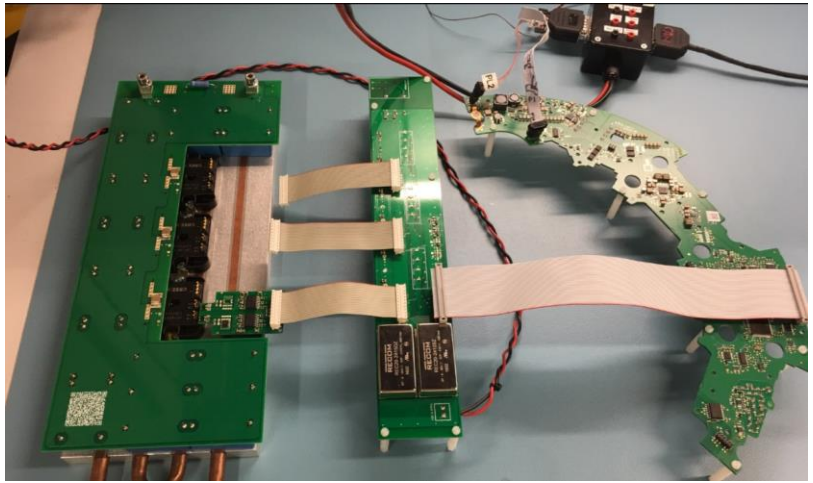




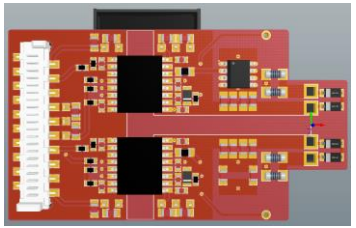
- Losses presented include all losses from DC electrical supply to wheel:
  - Machine losses / Simulated SiC inverter losses / Friction and windage losses / Bearing losses
- Performance at 320 Vdc with 50/50 water/glycol coolant, at 50°C inlet temperature and 13 litres/minute flow

SiC Demonstrator

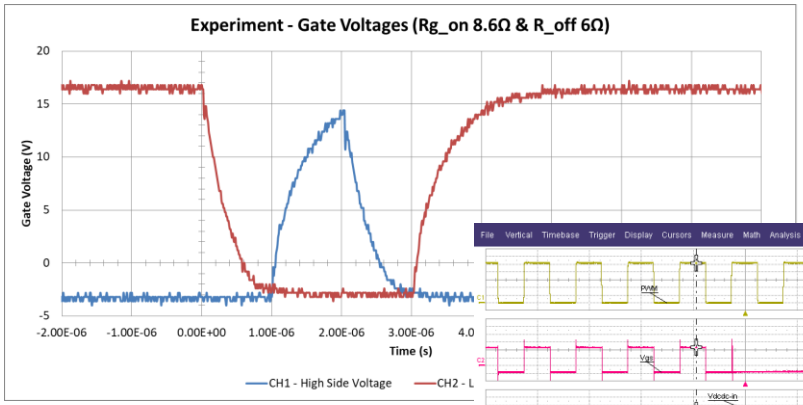


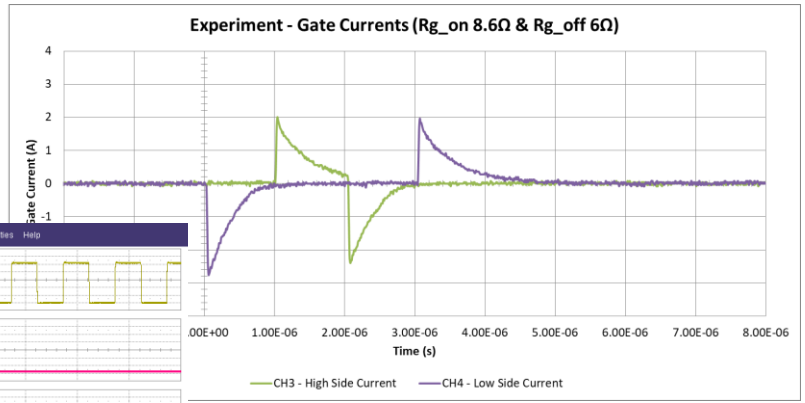


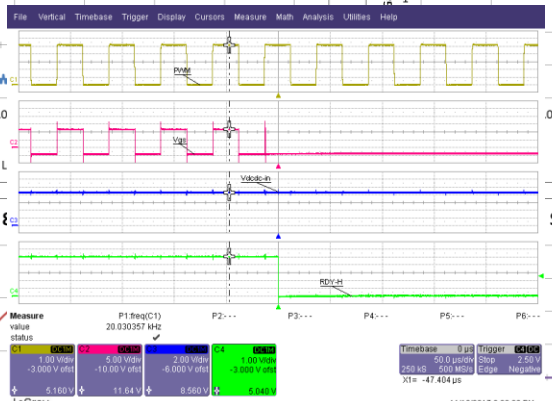
- Laboratory demonstrator developed to assess SiC inverter performance
- Capacitor bank, gate drive, measurement interface and control platform
- Lab test work ongoing & experimental results to be expected in Q4

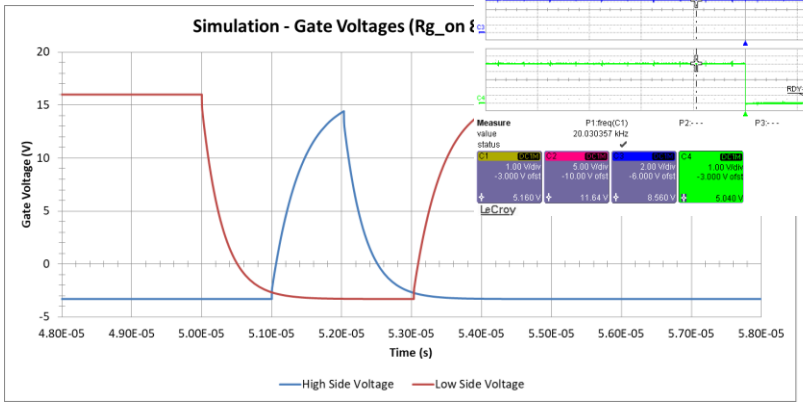


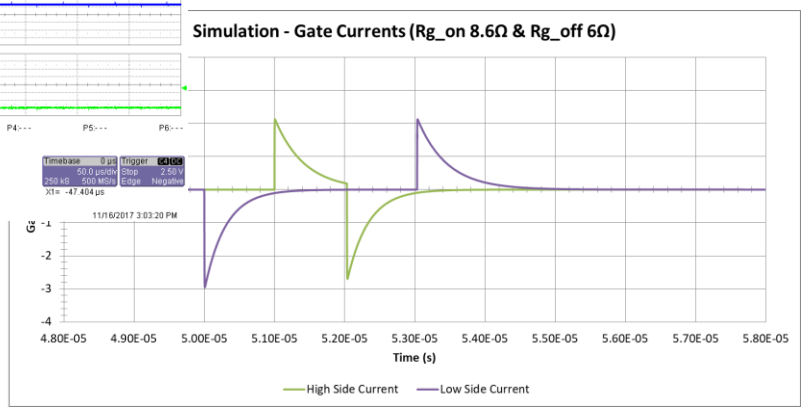
Lab Testing Results



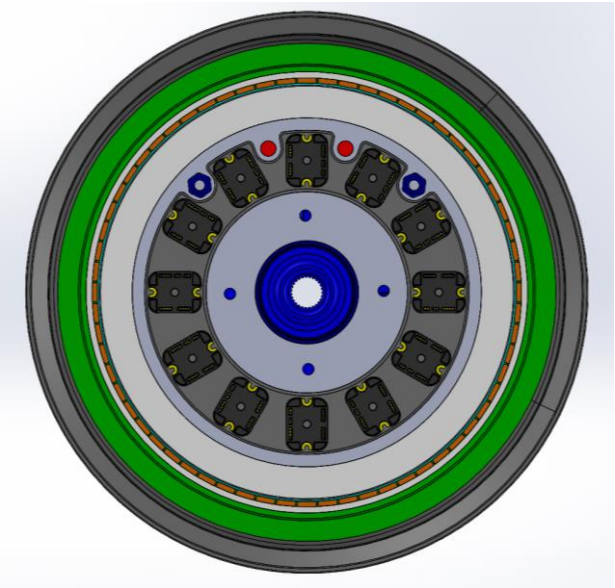


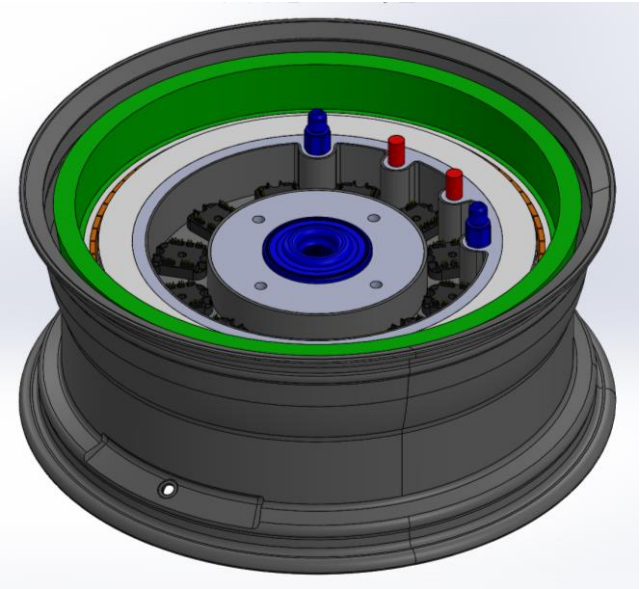






Conceptual Design

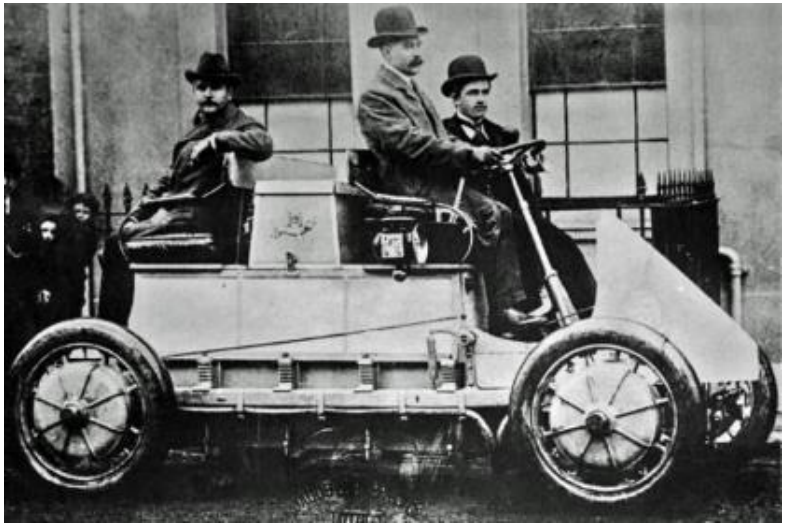




- Conceptual 3D design for 400Vdc, 180 kW IWM drive system
- 12 half bridge modules evenly distributed inside the stator cavity
- High current density design with off-the-shelf modules

Summary

- There are significant advantages to in-wheel motor powertrains that motivate the effort to develop a product
- ProteanDrive equipped with high performance, high power density, highly integrated Si IGBT inverter drive
- Up to 65% loss reduction achievable by adopting SiC MOSFET technology
- Laboratory demonstrator developed & verification tests ongoing



Lohner Porsche, 1900

Thank you

PROTEAN

Electric Automotive Technology