IEA Technology Collaboration Programme on Energy Efficient End-Use Equipment

Electric Motor Systems EMSA

Advancing industrial inverters: the research roadmap for Wide Bandgap Industrial Inverter

Webinar #14
Motors Academy
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About the Speaker

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LinkedIn

- **Vita / Current Activities**
  - Professor for Industrial Electronics since 1996 at Bern University of Applied Sciences
  - Head of innosuisse Flagship CircuBAT (www.circubat.ch) – circular economy model for automotive lithium batteries since 2022
  - Co-founder and Member of the Board of Integrated Power Systems AG since 2009
  - Co-founder and Chairman of the Board of ennos ag since 2016
  - Head of the BFH Energy Storage Research Center (2014-2023)
  - Member of the Federal Energy Research Commission (CORE) (2015-2023)
  - Co-founder and Chairman of the Board of drivetek ag (2002-2022)
  - Deputy Head of the Swiss Competence Center for Energy Research “Mobility” 2014 - 2020
  - Inventor/Co-Inventor of 8/23 patents in the field of electric motor design and lithium-ion battery technology

IEA TCP 4E Electric Motor Systems Platform (EMSA)

Electric Motor Systems
EMSA

Technology Collaboration Programme
by iea

Energy Efficient End-use Equipment
International Energy Agency

Electric Motor Systems
EMSA

IEA TCP 4E Energy Efficient End-Use Equipment

- Energy efficient equipment
- 15 members (EMSA + CA, CN, FR, JP, KR, UK)

Electric Motor Systems Platform (EMSA)

- Raise awareness, share information, initiate collaborative projects and transfer experience *to support **effective policy development** for energy efficient electric motor systems*
  - International standards, testing, coordination
  - Digitalisation and demand flexibility in motor systems
  - Motor Systems Tool, expert pool
- 9 members (AU, AT, DK, EC, NL, NZ, SE, CH, US)

www.iea-4e.org/emsa

Source: Roland Brüniger, 2024;eemods'24 Luzern

EMSA: a source of reference for policy makers

EMSA facilitates that policy makers have:

- access **to relevant, reliable, independent, first-hand information for their decisions**
- access **to information on** expected **challenges** and gain **awareness on the most relevant issues** for successful policy implementation
- access to **best practices and tools** for their national policies to speed up the market transformation for motor systems
- a **forum for discussion through the EMSA meetings** of relevant issues for their national policy making, exchanging on differences and if deemed useful on any potentials for alignment
- the support of taking up **relevant standards** into national legislation, which are to be developed in a way that are suitable for this purpose.

Source: Roland Brüniger, 2024;eemods'24 Luzern

International Round Robin for Variable Speed Drives

Full report

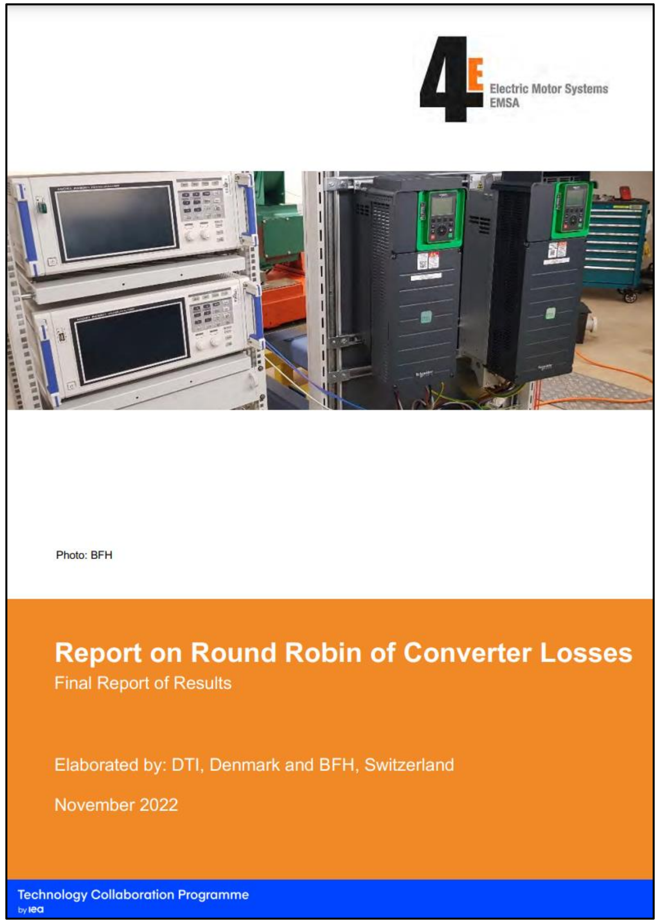

Electric Motor Systems EMSA

Photo: BFH

Report on Round Robin of Converter Losses

Final Report of Results

Elaborated by: DTI, Denmark and BFH, Switzerland

November 2022

Technology Collaboration Programme by iea

Summary of key findings: EMSA Policy Brief #6


Energy Efficient End-use Equipment International Energy Agency

ENERGY EFFICIENCY POLICY BRIEF

EMSA6 UPDATED

Round Robin for Variable Speed Drives

The 4E Electric Motor Systems Annex (EMSA) promotes the opportunities for energy efficiency in motor systems by disseminating best practice information worldwide. It supports the development of internationally aligned test standards and policies to improve the energy performance of new and existing motor systems with the aim of achieving 20% to 30% energy savings.

Variable speed drives (VSD) attached to motors adjust the power output to meet the requirements of the end-use application and this can lead to large energy savings. However, there are energy losses associated with VSDs which affect their overall energy efficiency.

EMSA in cooperation with the International Electrotechnical Commission (IEC) launched the project to determine whether the current energy efficiency test methods provide accurate and repeatable results and if the level of reference losses described in these provide a sufficient incentive to encourage greater levels of efficiency. The test method to determine the losses in variable speed drives (and hence their efficiency) is described in two IEC standards[1].

In this EMSA organised international Round Robin, independent testing laboratories in Australia, Denmark, Switzerland and the USA were funded by EMSA members.

This Policy Brief summarises the key findings of the Round Robin for converter losses.

Observations for Policy Makers

- This Round Robin ran from 2017 to 2022 and is the first publicly available independent study that has systematically examined the efficiency of VSDs.
- During the Round Robin, 8 laboratories performed a total of 172 tests on 52 different converters in the range of 0.12 kW to 55 kW according to the uniform testing protocol devised for this project.
- This protocol has proven itself by returning highly repeatable and accurate results from a broad range of VSDs on the market and helped the IEC to eliminate ambiguities in the second revision of IEC 61800-9-2.
- The participation of independent test laboratories and the cooperation with IEC were crucial to the success of this project.
- The European Union, Switzerland and the UK were the first economies to adopt Minimum Energy Performance Standards (MEPS) for VSDs in July 2021.
- MEPS in these economies are set at the IE2 level, which is currently the highest (most efficient) class for VSDs specified in the relevant standards.
- The Round Robin has shown that the introduction of additional IE classes could enable further differentiation of VSDs, however, may not bring substantial added value in terms of energy savings. For many applications, energy can be saved effectively through variable speed control, reducing the losses in part load operation.

1 IEC 61800-9-2:2017: Adjustable speed electrical power drive systems – Part 9-2: Ecodesign for power drive systems, motor starters, power electronics and their driven applications – Energy efficiency indicators for power drive systems and motor starters. IEC TS 60034-2-3:2013: Rotating electrical machines – Part 2-3: Specific test methods for determining losses and efficiency of converter-fed AC induction motors. Replaced by IEC 60034-2-3:2020 during the Round Robin Converters (RR'C).

MORE INFORMATION

Published May 2023

Further information is available here on the EMSA website: www.iea-4e.org/emsa and by contacting andrea.vezzini@bfh.ch and sbn@teknologisk.dk.

Technology Collaboration Programme by iea

EMSA: a catalyst for ISO/IEC Joint Advisory Group JAG22

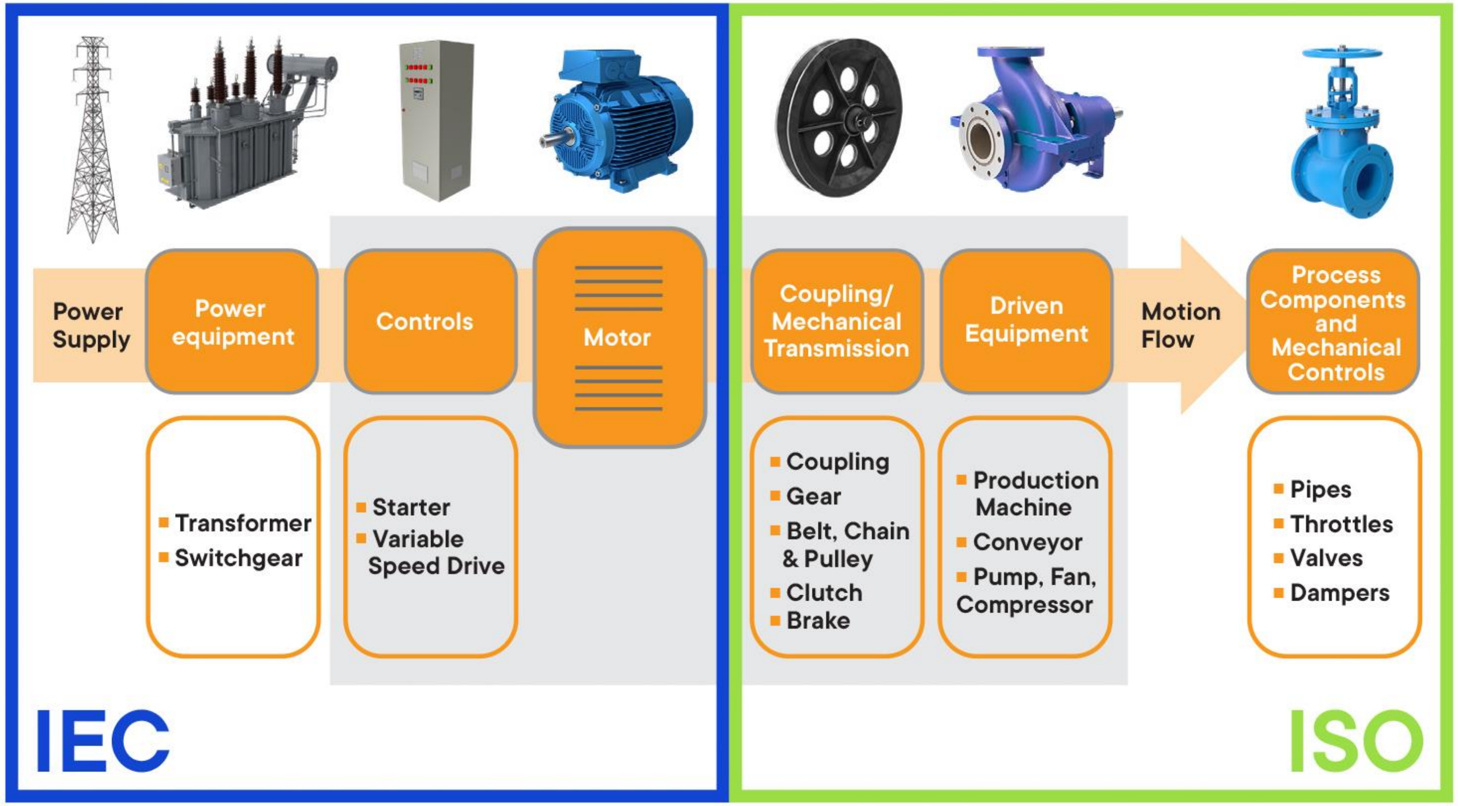


Figure 1: Scope of IEC and ISO for motor systems

More information: EMSA Policy Brief #5

EEMODS Wed 14:00 Policies IV: Conrad U. Brunner & Maarten van Werkhoven

How ISO and IEC work together to design Energy Efficient Electric Motor Driven Systems

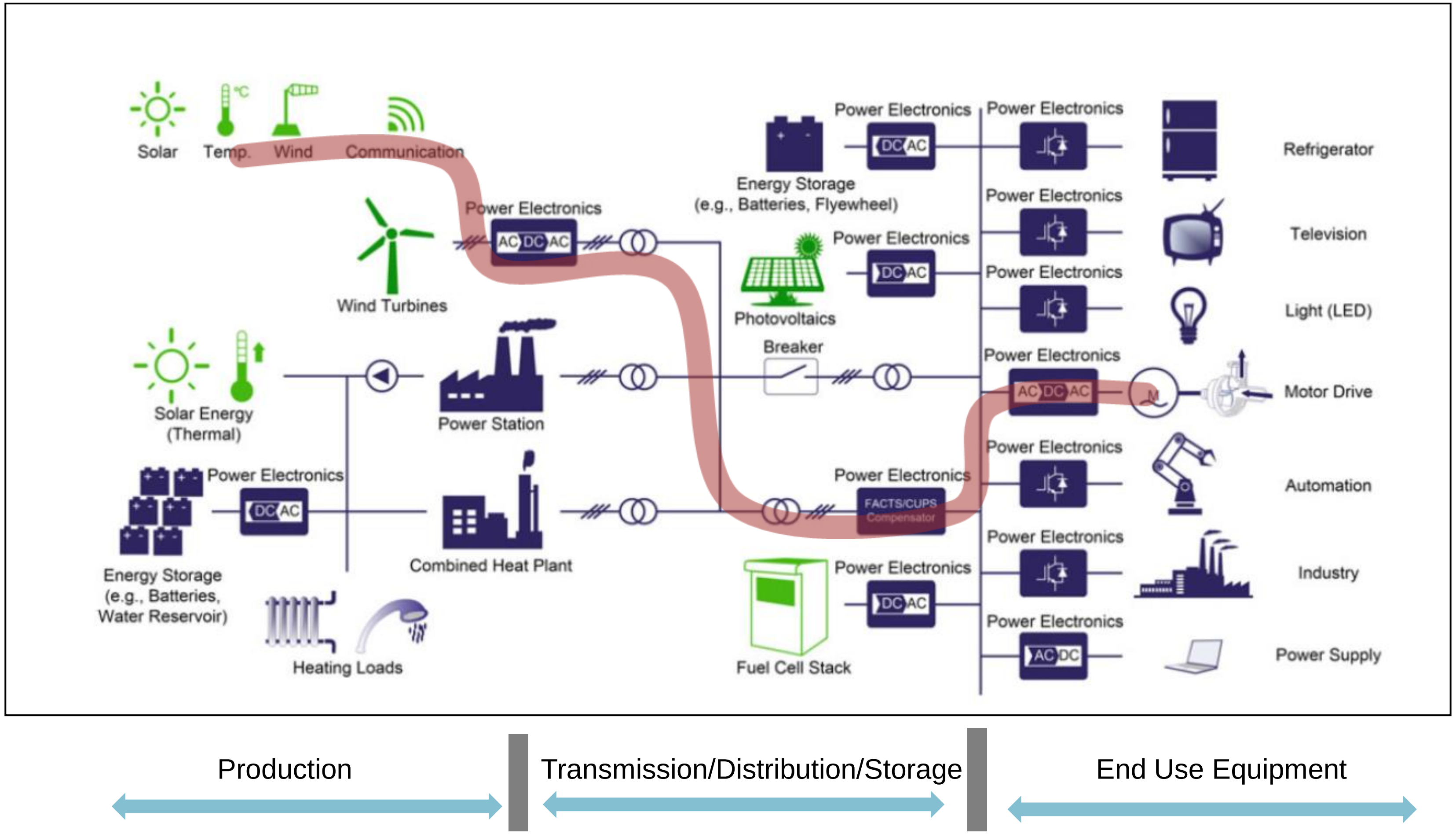
- Elements of a motor system are covered by around **10 different IEC and ISO committees**.
- EMSA initiated a project to **increase the coordination and alignment of energy efficiency standards for motor driven systems**.
- Within two years (2023) the **ISO/IEC Joint Advisory Group JAG22** started.
- Concrete work is focusing on the **systems of fans, motors and converters**.

Source: Roland Brüniger, 2024;eemods'24 Luzern

Silicon Carbide (SiC) FETs advance Power Electronics

Power electronics is everywhere, its efficiency is most relevant

Power Electronics is used in all stages in the energy flow from poduction to end use equipment



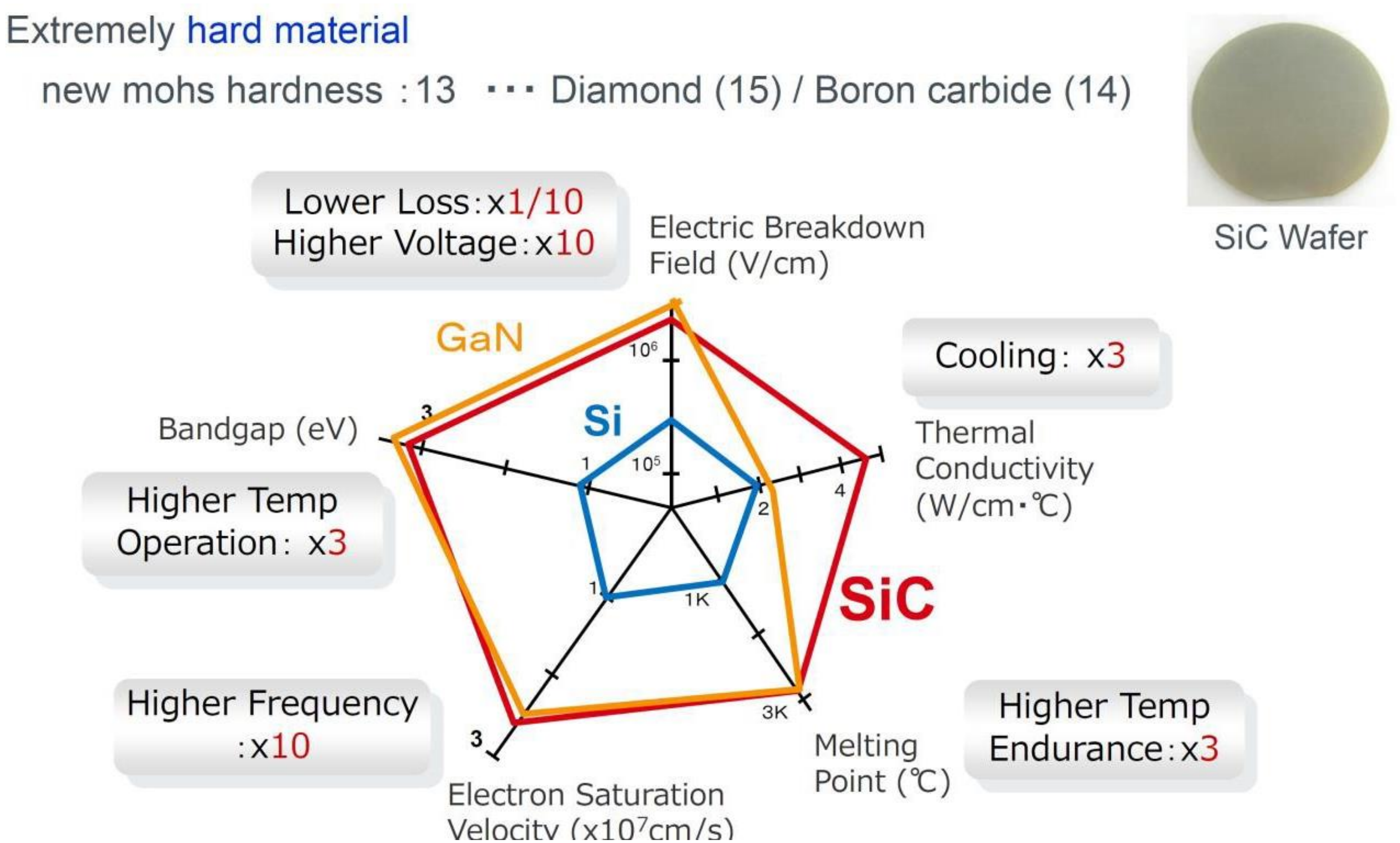
Source: PECTA Power Electronic Conversion Technology AnnexPECTA Power Electronic Conversion Technology Annex

Main Features of WBG-Technology Semiconductors

Traditional Si-based semiconductors are now being competed by new generation of wide bandgap devices, typically based on GaN or SiC materials

- SiC can improve
  - power density
  - maximum voltage level (several kV)
  - switching frequency (up to 100kHz)
  - Efficiency (by reduced conduction and switching losses)

  - Cost of SiC is generally 2-3 times higher than similar Si devices.



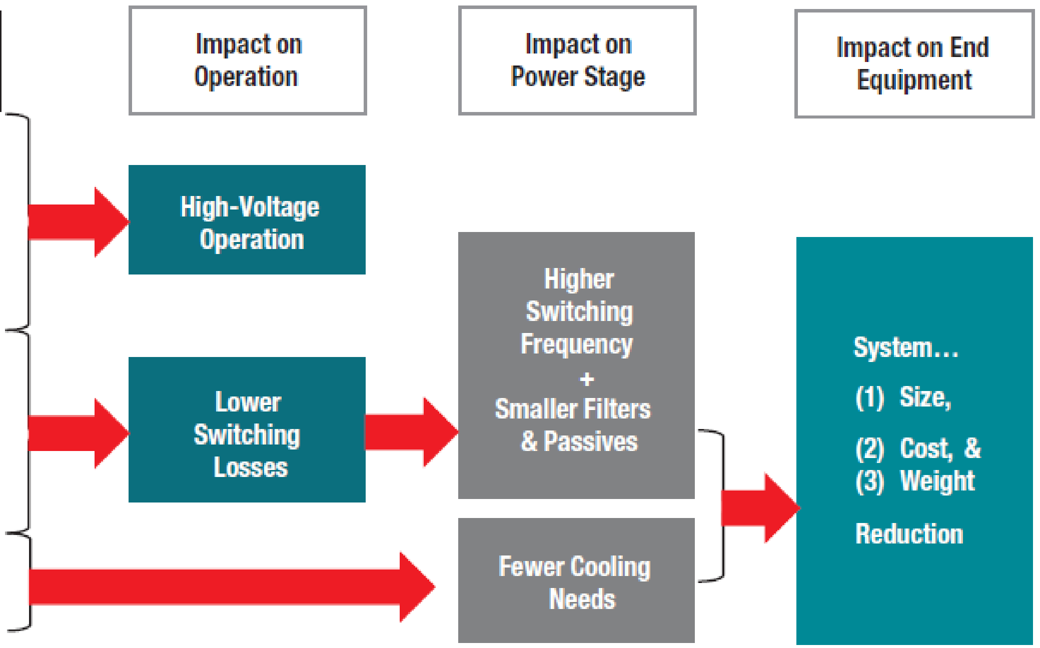
Why silicon carbide (SiC)?

Electric Motor Systems EMSA

Intrinsic Material Properties

Property	Definition	Si	SiC - 4H
E_G (eV)	Bandgap Energy	1.12	3.26
E_{BR} (MV/cm)	Critical Field Breakdown Voltage	0.3	3.0
V_S ($x10^7$ cm/s)	Saturation Velocity	1.0	2.2
μ (cm^2/V.s)	Electron Mobility	1400	900
λ (W/ cm.K)	Thermal Conductivity	1.3	3.7

Properties leading to System Benefits



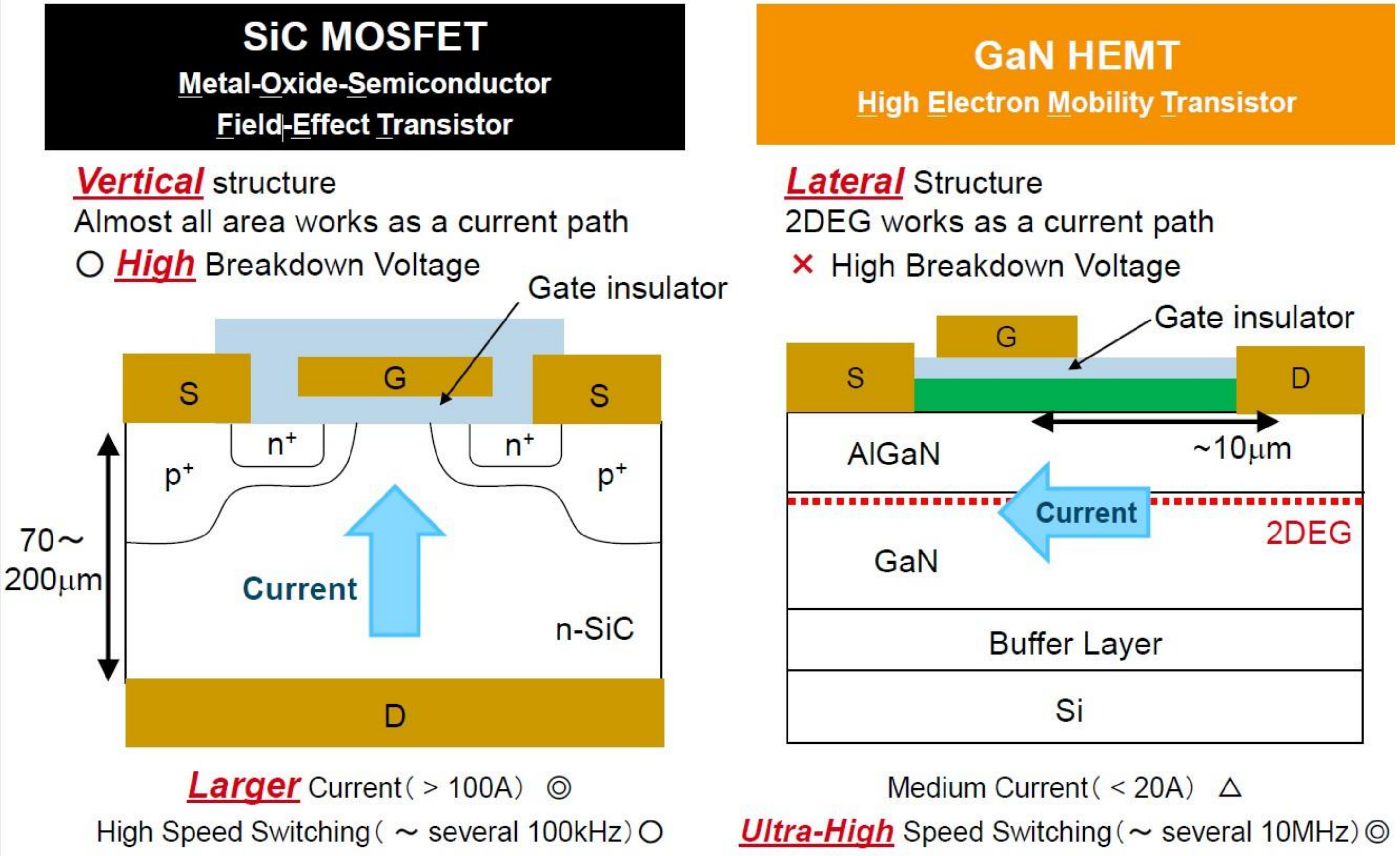
- Higher costs of SiC chips
- Reliability of SiC elements (gate oxide, load changes, ...)
- Problems due to higher di/dt and dv/dt, oscillations (EMI, motor windings, ...)

FORMS.1014 / Rev. 06

www.semikron.com

Gallium-Nitride (GaN)

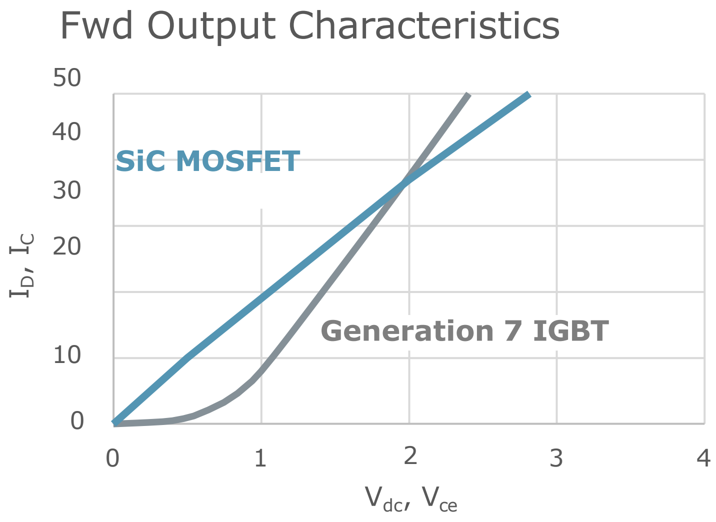
- Extremely fast unipolar switches
  - Lowest switching losses
- Lateral element, electric field only on chip top side
  - mainly 650V or less
- Lateral element requires more area
  - Current rating limits or low Yield for large areas
- Applications: RF; Low Power / Low Voltage applications
- Advantage due to established production processes for SI-Substrate



Courtesy of ROHM Semiconductor

Silicon Carbide vs. Silicon

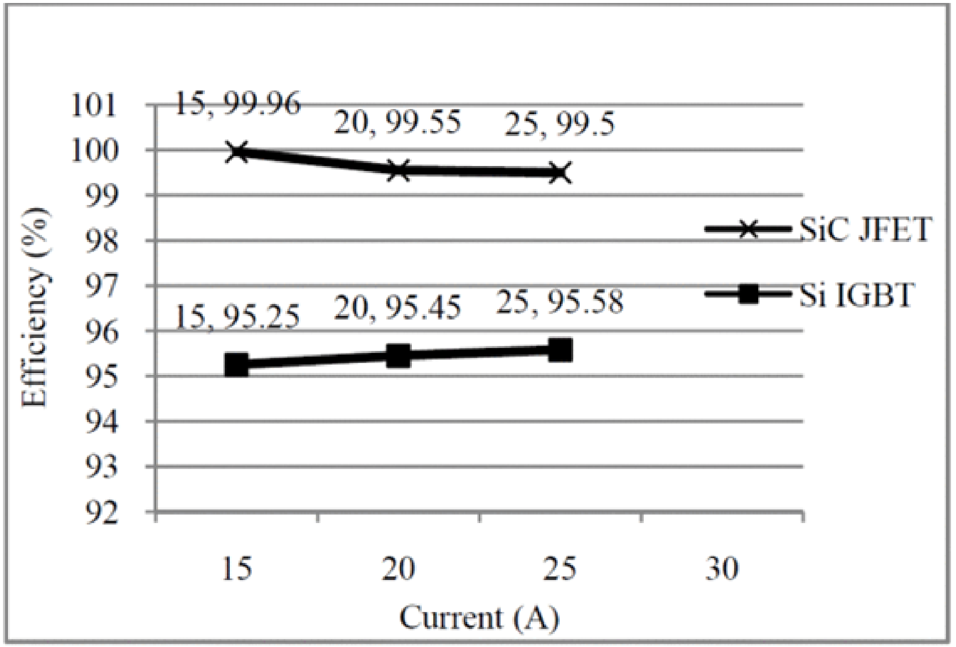
- Much lower on V_{DS} compared to Si IGBTs $V_{CE,sat}$ in partial load reduces on state losses
- Low Q_{rr} of embedded body diode reduces switching losses
- Use of MOS channel in reverse conduction reduces Δ_{TJ}
- Much faster switching thanks to unipolar channel
- 2 to 3 times better thermal conductivity for better heat spread, no hot spots



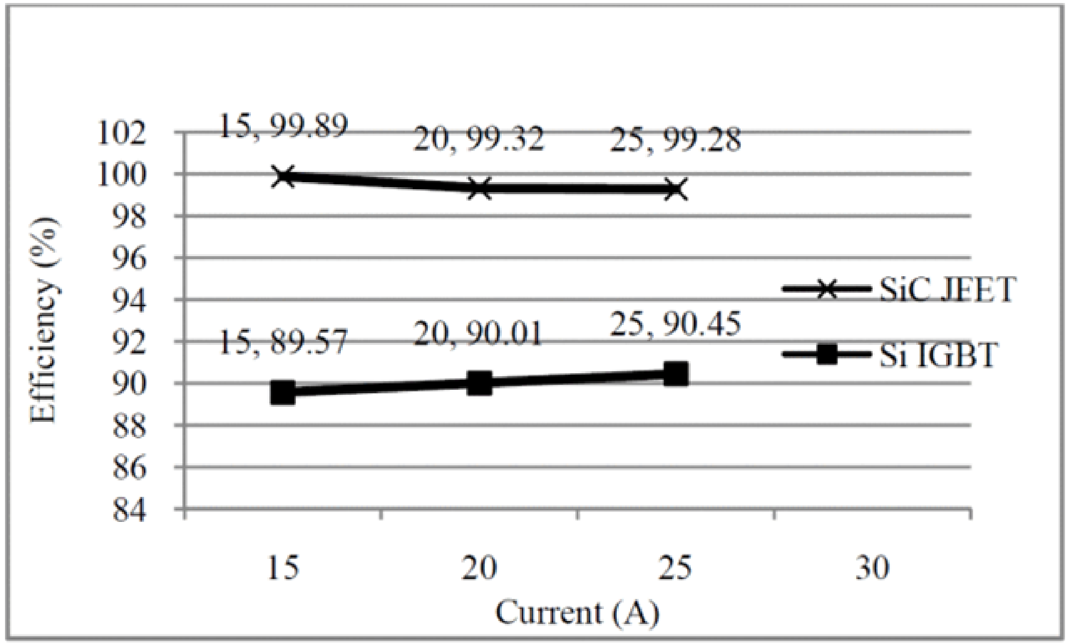
Source: Carsten Schreiter: Webinar - Silicon Carbide in AC Motor Drives, 13th June 2023; Semikron-Danfoss

Impact on high frequency switching inverters

- Given two high carrier frequency (20 kHz and 50 kHz) having taken all losses i.e. switching and conduction loss in diodes and device, the efficiency of SPWM three-phase inverter with ma=0.8 and cosϕ=0.8 is shown on the left
- The efficiency of Si-C based inverters higher than that of Si based inverter mainly due to the lower total power losses of Si-C components. These superior characteristics make Si-C JFET device the promising alternative to replace the currently popular Si-IGBT.



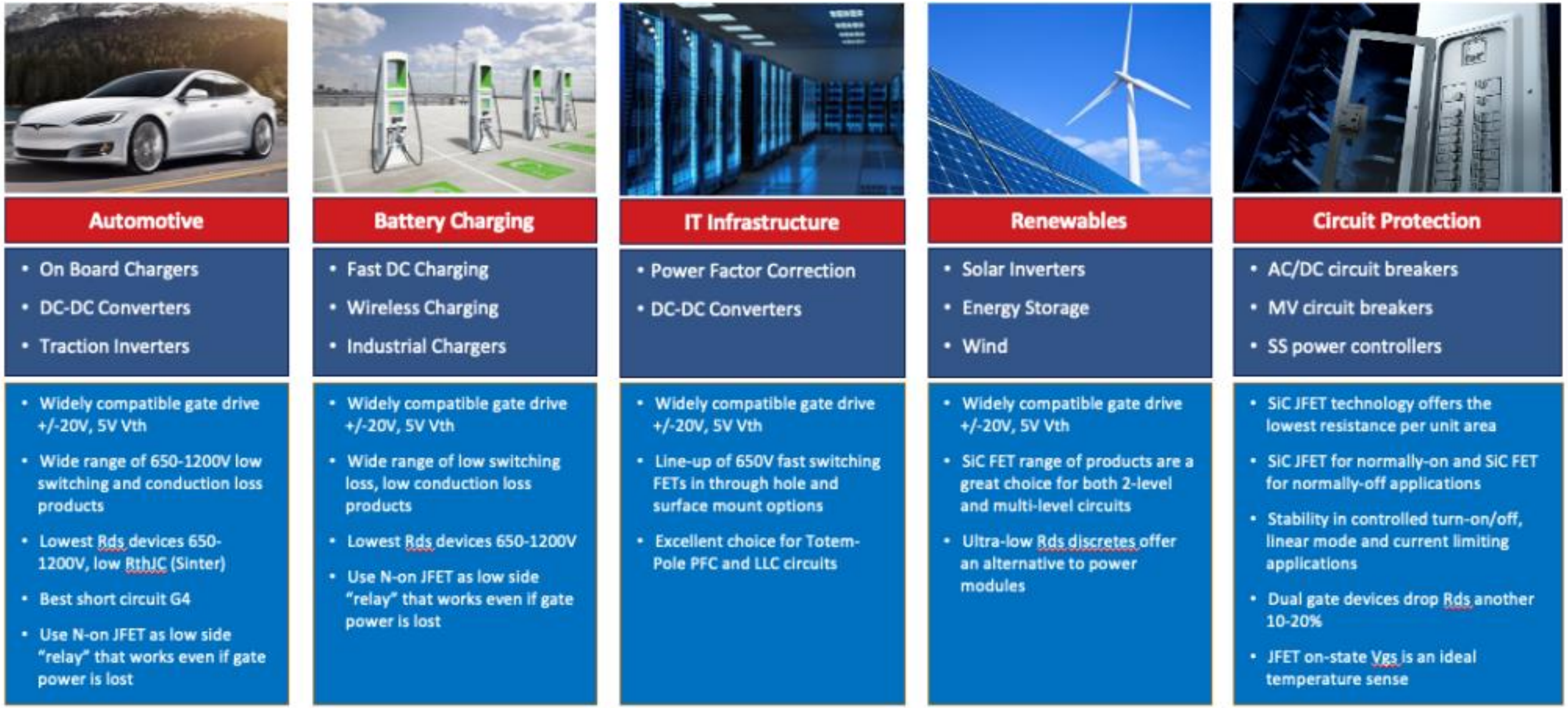
(a)Operating frequency: 20 kHz



(b)Operating frequency: 50 kHz

A. I. Maswood, P. L. A. Vu and M. A. Rahman, "Silicon carbide based inverters for energy efficiency," *2012 IEEE Transportation Electrification Conference and Expo (ITEC)*, Dearborn, MI, USA, 2012, pp. 1-5, doi: 10.1109/ITEC.2012.6243458.

Major Application Segements already adopting SiC FET benefits

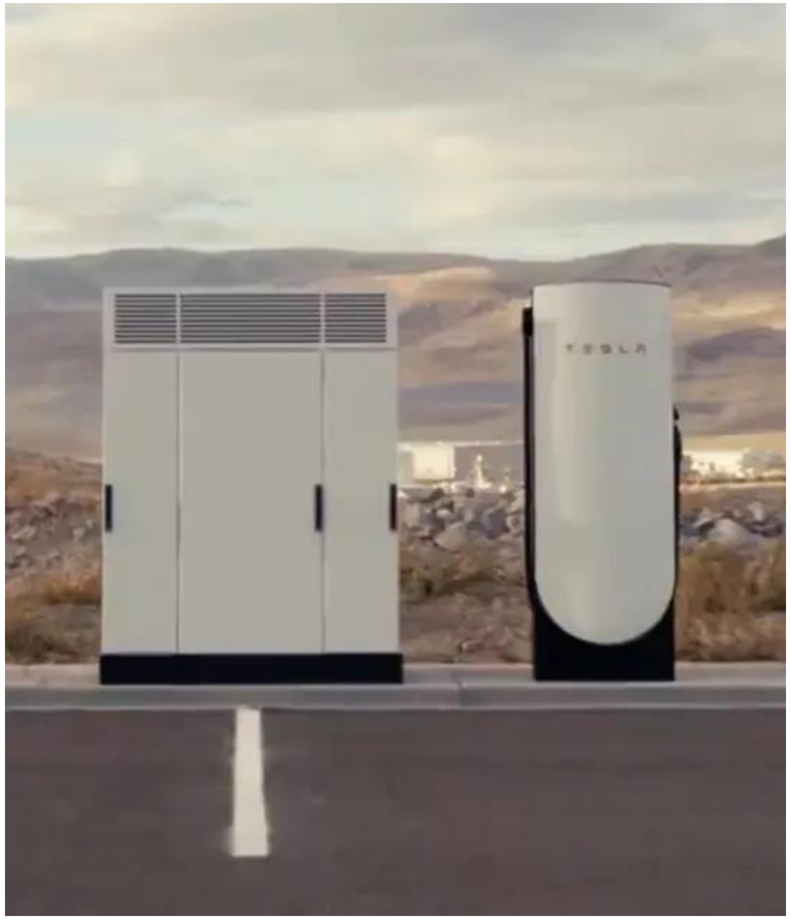


Source: UnitedSiC (now QORVO); 2020

V4 Supercharger cabinets

Tesla announces 500 kW charging as it finally delivers V4 Supercharger cabinets

- Faster charging: Supports 400V-1000V vehicle architectures, including 30% faster charging for Cybertruck. S3XY vehicles enjoy 250kW charge rates they already experience on V3 Cabinet — charging up to 200 miles in 15 minutes.
- Faster deployments: V4 Cabinet powers 8 posts, 2X the stalls per cabinet. Lower footprint and complexity = more sites coming online faster.
- Next-generation hardware: Cutting-edge power electronics designed to be the most reliable on the planet, with 3X power density enabling higher throughput with lower costs.



Source: electrek.co; Fred Lambert | Nov 14 2024

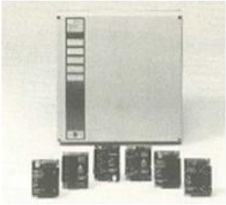
Historical evolution of drive efficiency

Efficiency increase over time

- The efficiency of drives has increased in time with the evolution of technology
- Example: the efficiency timeline for a 4 kW drive, 380/400 V (example: Danfoss)
- Similar pictures can be drawn for the products of other manufacturers

1968 VLT 5
SCR, 6 pulse PAM

91% efficiency



1983 VLT 200
transistor, 18/6 pulse PAM

95% efficiency

1993 VLT 3000 v.2
transistor, PWM

96% efficiency

1995 VLT 5000
IGBT, PWM

96% efficiency

2003 VLT FC-302
IGBT, PWM

97% efficiency

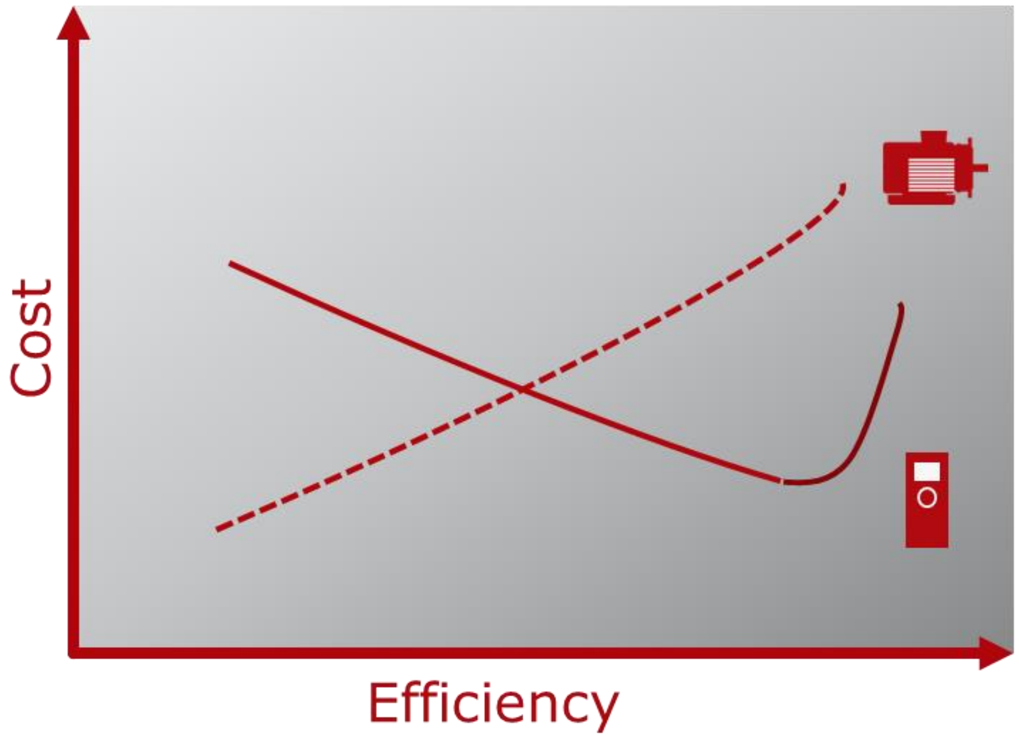
Source: Norbert Hanigovszki, Danfoss Drives: “Developments and trends in the adjustable speed drives industry “

Drive efficiency compared with motor efficiency

Predominant Opinion in the Drives Industry

- For drives: lower efficiency leads to higher cost for cooling and size increase. There is a upper limit for this relationship.
- For motors: higher efficiency leads to higher costs because more material is needed or more expensive materials are used (special low loss steels, permanent magnets)
- The incentives are different between drives and motors
- The relatively high cost for increasing efficiencies above today state of the art would drive consumers to delay the introduction of variable speed drives

Motor vs. Drive Efficiency cost curves



Source: Norbert Hanigovszki, Danfoss Drives: “Developments and trends in the adjustable speed drives industry “

Challenges and Criticisms towards SiC-Inverters for Industrial Drives

High Initial Component Cost

- The higher initial cost of WBG inverters can be a significant barrier to adoption, especially for applications where cost is a critical factor. A detailed analysis of the efficiency advantages and total lifecycle costs, evaluating both SiC and GaN, could demonstrate that the energy savings achieved, for example in part-load operation, will highly compensate for the initial higher costs.

Application Readiness

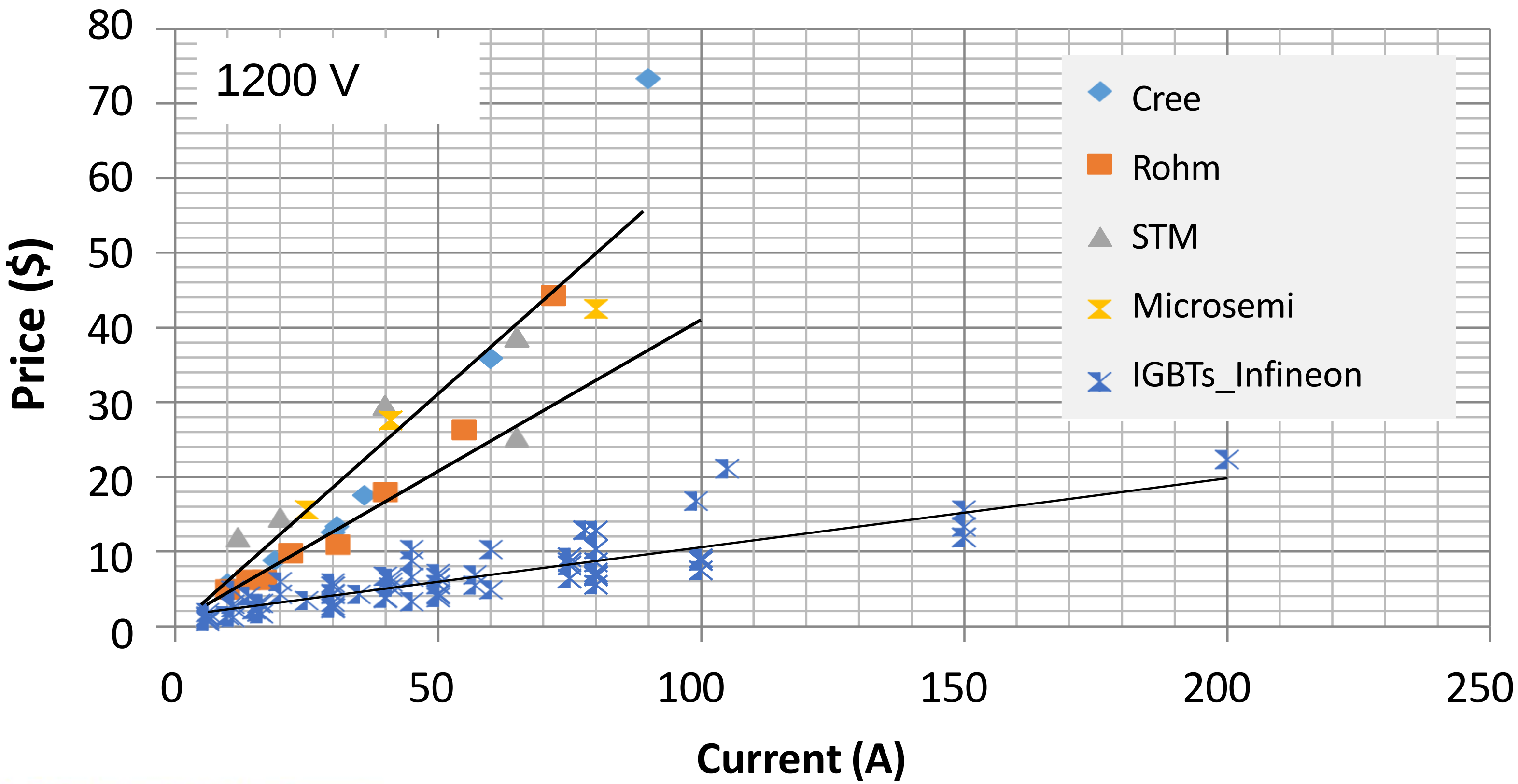
System Design and Implementation Complexity

Reliability and Durability Concerns

Risks to Equipment

1200-V SiC MOSFETs Are More Expensive Than Similarly Rated Si Devices

- Price parity can be achieved at the system level due to reduced size and weight of magnetics, and reduced system cooling requirements. Reduced system losses provide savings throughout life of the system.

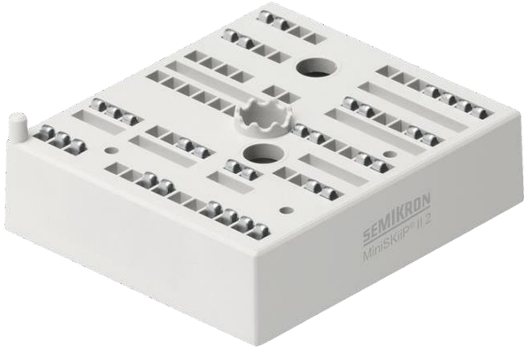


Price data:
www.digikey.com

Source: V. Veliadis

Full SiC MOSFET and Si IGBT power module comparison

Si module	Full SiC modules	
35A MiniSKiiP 2 module	25A MiniSKiiP 1 module	25A MiniSKiiP 1 module
Without base plate @5kHz	Without base plate	Without base plate
Si IGBT: 1200V/35A Si diode: 1200V/35A	SiC MOSFET: 1200V/25A No SiC diode	SiC MOSFET: 1200V/25A SiC diode: 1200V/20A



SKiiP24AC12T4V1

VS

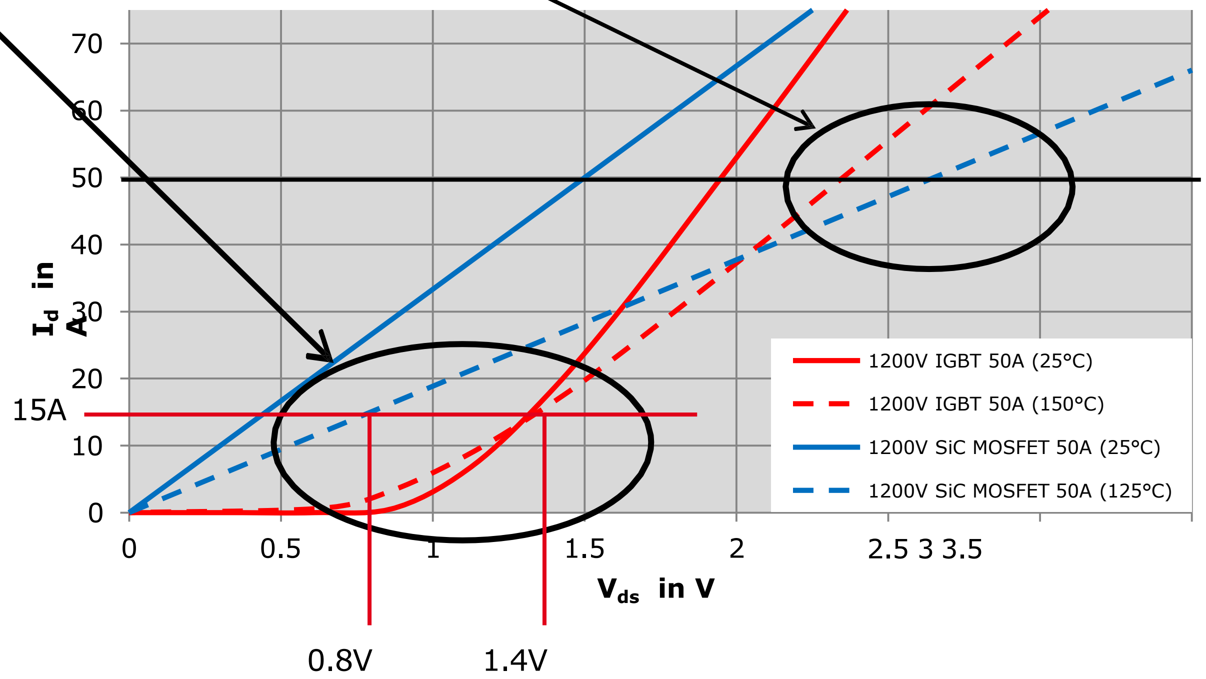
SKiiP13ACM12V18

SKiiP13ACM12V17

Detail: Forward losses in the SiC MOSFET

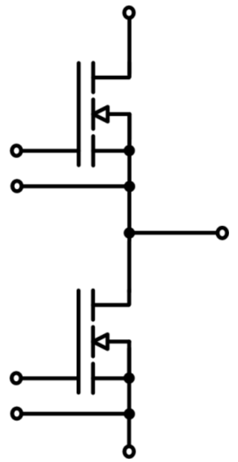
- Thanks to the linear forward characteristic of MOSFETs, the forward losses in the low load range are lower than with IGBTs.
- At 15A:
  - IGBT VCE voltage is approx. 1.4V (150°C)
  - Pcond = 21 W
  - SiC MOSFET VDS Voltage is approx. 0.8V (125°C)
  - Pcond = 12 W

- Under overload, the conduction losses of the SiC MOSFET can be greater than those of the Si IGBT. Large temperature coefficient



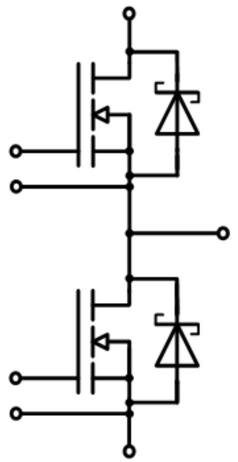
Switching losses with the Full SiC module

- SiC MOSFETs have a body diode which conducts in the reverse direction
- Body diodes have very high Vf, ~5...7V
  - MOSFET must be switched on
  - Almost the entire current flows through the MOS channel
- Body diodes have pn junction
  - SiC MOSFET Body Diode has Reverse recovery and some tail current!
  - higher switch-on losses + body Diode losses E_{rr}
- Valid for high switching frequencies (>20kHz)



100%
Losses

Full SiC without external Schottky barrier diodes



60%
Losses

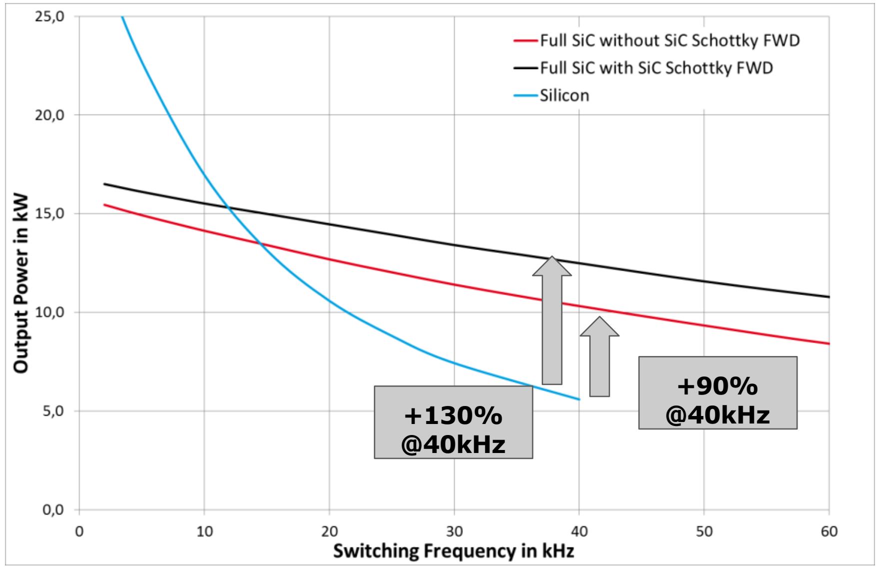
Full SiC with external Schottky barrier diodes

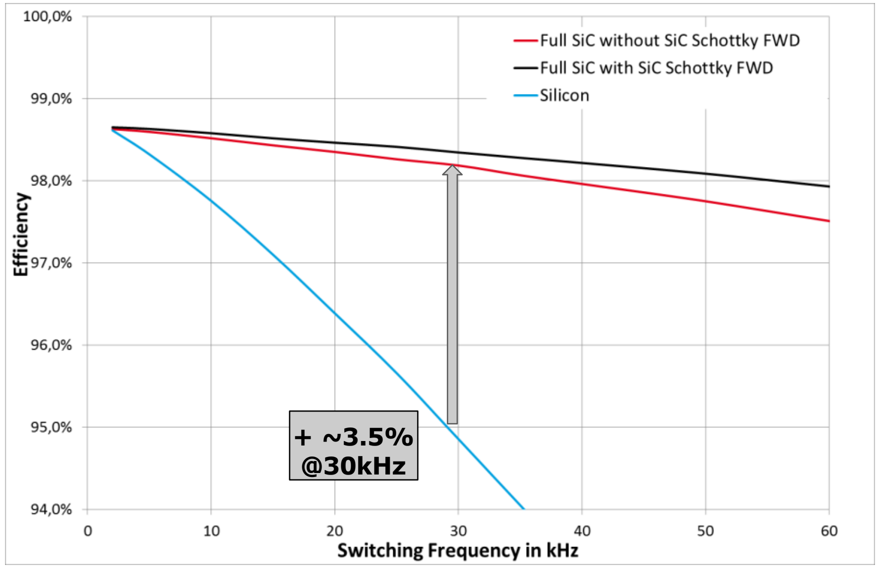
Full SiC MOSFET and Si IGBT power module comparison

25A Full SiC MiniSKiiP 1 compared to **35A Silicon MiniSKiiP 2**

Operating point with maximum output power

Maximum output power Efficiency



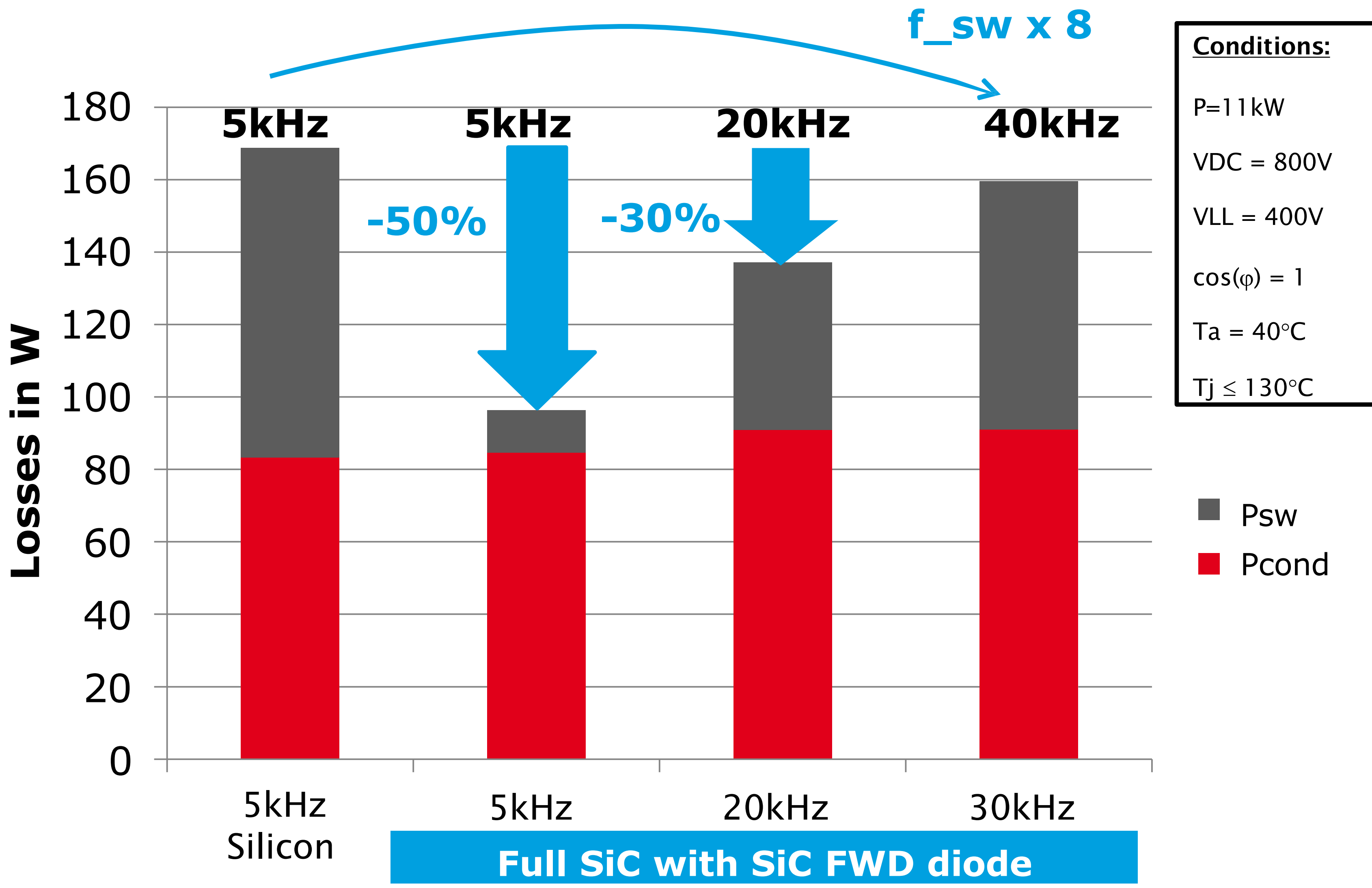


+80% output power @ 30kHz

+ 3.5% efficiency @ 30kHz

Conditions: Vdc=800V, cosphi=0.95, Tj,op=150°C;

Optimized Full SiC Power Module



Conditions:

P=11kW

VDC = 800V

VLL = 400V

cos(φ) = 1

Ta = 40°C

Tj ≤ 130°C

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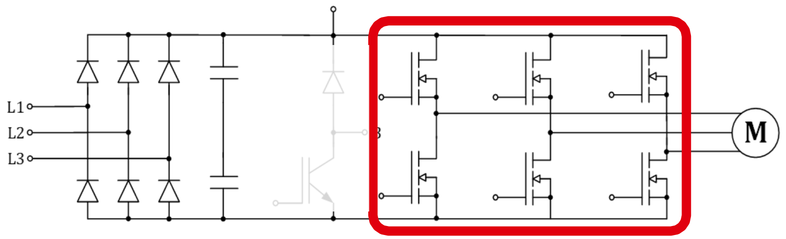
SiC-Inverter Application Example

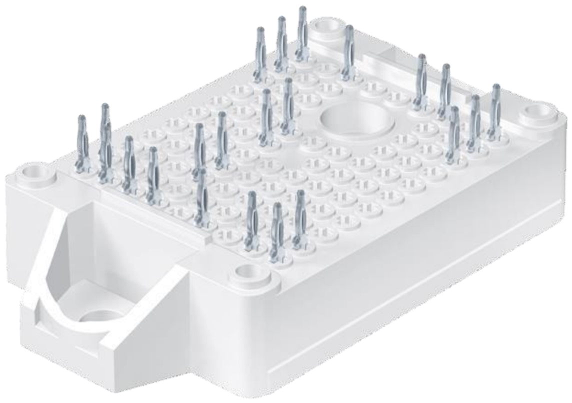
Selected power modules:

- IGBT Module: Generation 7 IGBT, 35A, 1200V
- SiC Module: Latest generation SiC MOSFET, 32mΩ (40A), 1200V



Limitations for standard drive with unknown motor and cable length

- dv/dt cannot be increased to limit over voltage at motor terminals (reflected wave)
  - RG adjusted to have 5kV/µs voltage rise time for both
- fc cannot be increased to limit leakage current (shielded motor cable, etc.)



SiC-Inverter Application Example

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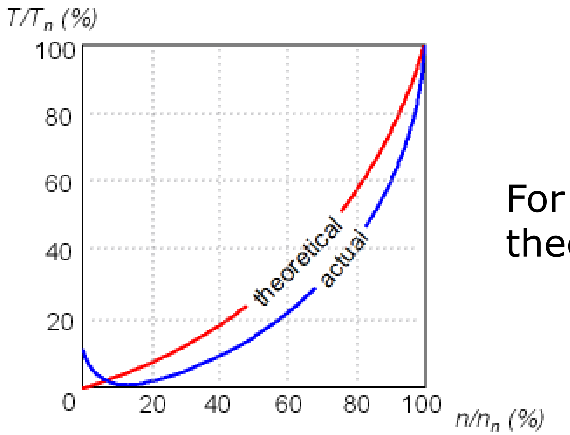
Benefits of SiC MOSFETs in a Drive

- Application parameters:
  - Centrifugal pump
  - Load characteristics: quadratic torque, T~n²~I



For simplicity, we use the theoretical curve

- Motor: Standard PM motor, 355V, 15kW, 26A, cos(phi)=0.98, 50Hz
- Drive: V_{DC}= 560V, f_{sw}=5kHz, dv/dt=5kV/µs, T_a=40°C, OL=110%/1min

Variable Torque Application - Watt Loss at Module

Watt Loss at Module

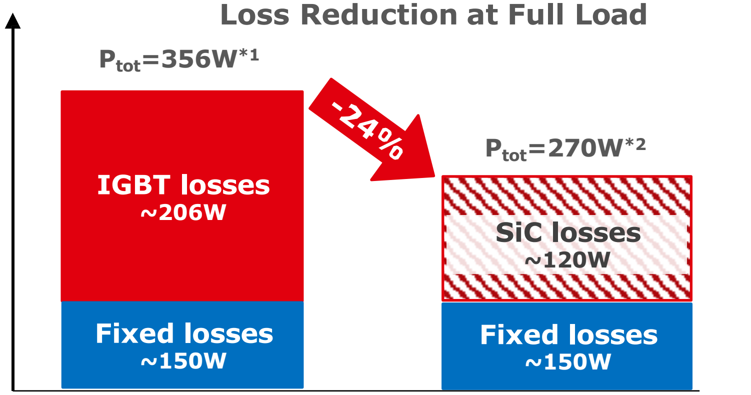
- Comparison
  - Identical switching speed, 5kHz and 5kV/µs
  - Identical cooling
- Result:
  - 62% to 54% lower losses from 40% to 80% speed
  - 1.7% to 0.8% boost in efficiency from 40% to 80% speed

Variable Torque Application - Watt Loss Complete Drive

Watt Loss Complete Drive

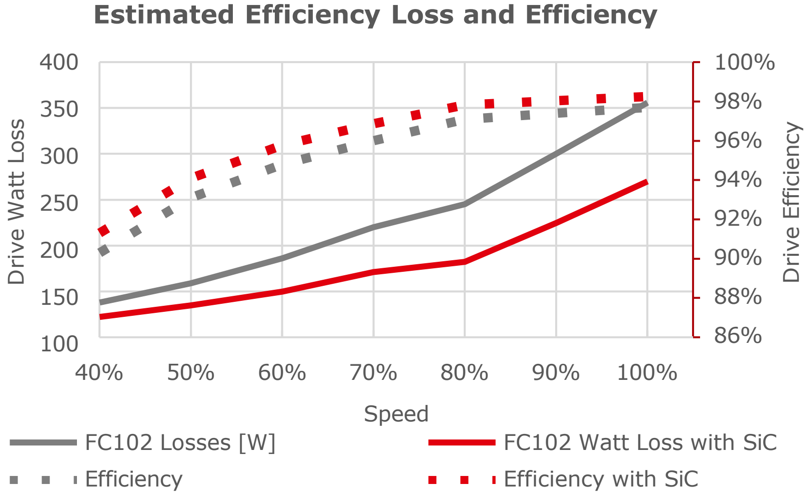
- Replace Si losses with SiC losses from step before:

Danfoss FC102, 15kW, 31A, FC-102P15KT4E20H1



*1 Drives losses calculated with energy efficiency calculator from Danfoss website

*2 $Loss_{SiC\_Drive} = Loss_{Drive} - Loss_{SI\_Mod} + Loss_{SIC\_Mod}$



- RESULT
  - Reduction of watt loss by 11% at low and by 24% at full speed
  - Efficiency increased by 1% at low speed and 0.5% at high speed

Return on Investment (ROI)

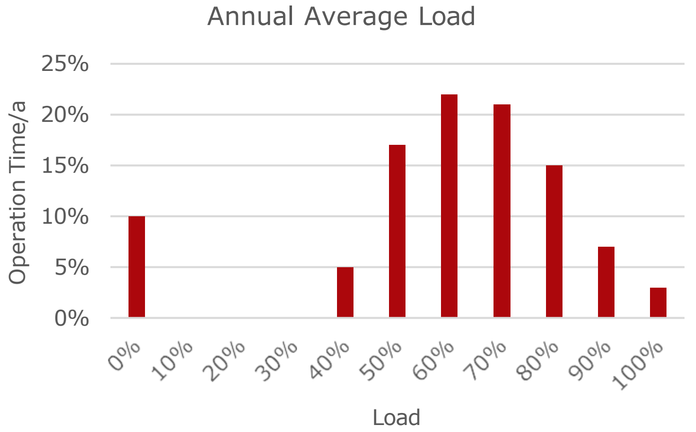
Assumptions:

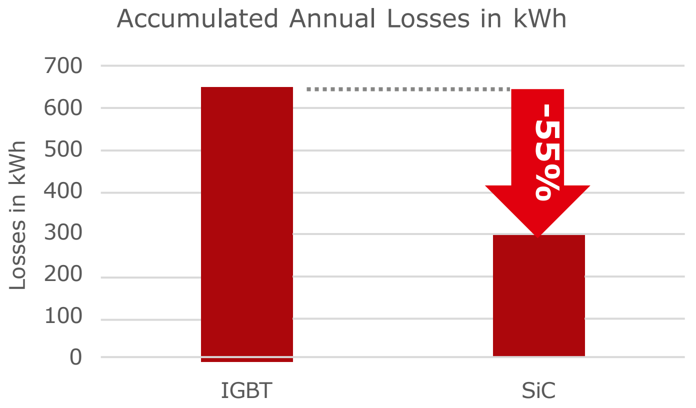
- Price difference of a 400Vac/15kW drive to end user will be 90 to 100€
- Operation profile with a speed range between 40 – 100%
- Energy Cost: 0.26€/kWh

Result:

- 55% lower accumulated losses
- 354kWh savings equaling 172 kg CO2*
- 92€/a savings with current German energy prices
- Payback for drive user in approx. 1 year
- Higher energy cost = more savings + faster payback of SiC

* CO2/kWh electricity Germany 2021





Challenges and Criticisms towards SiC-Inverters for Industrial Drives

High Initial Component Cost

Application Readiness

- Based on an evaluation of the Application Readiness Map of PECTA regarding the implementation of SiC and GaN inverters for industrial applications, one of the identified problems is the limited production capacity and availability of WBG components compared to silicon-based components. This limitation can lead to supply chain challenges for industries that require large volumes of these components.

System Design and Implementation Complexity

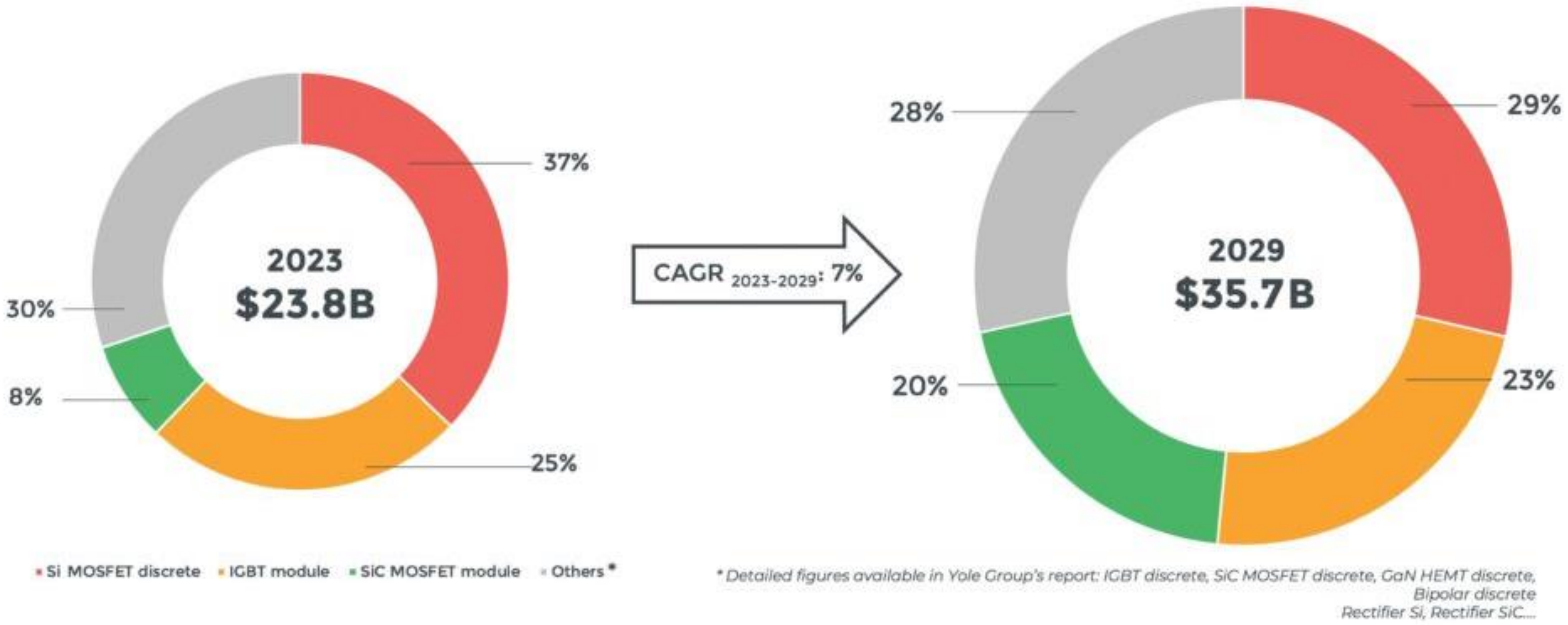
Reliability and Durability Concerns

Risks to Equipment

Discrete & Module Power Component Market -2023 – 2029 Period

Electric Motor Systems EMSA

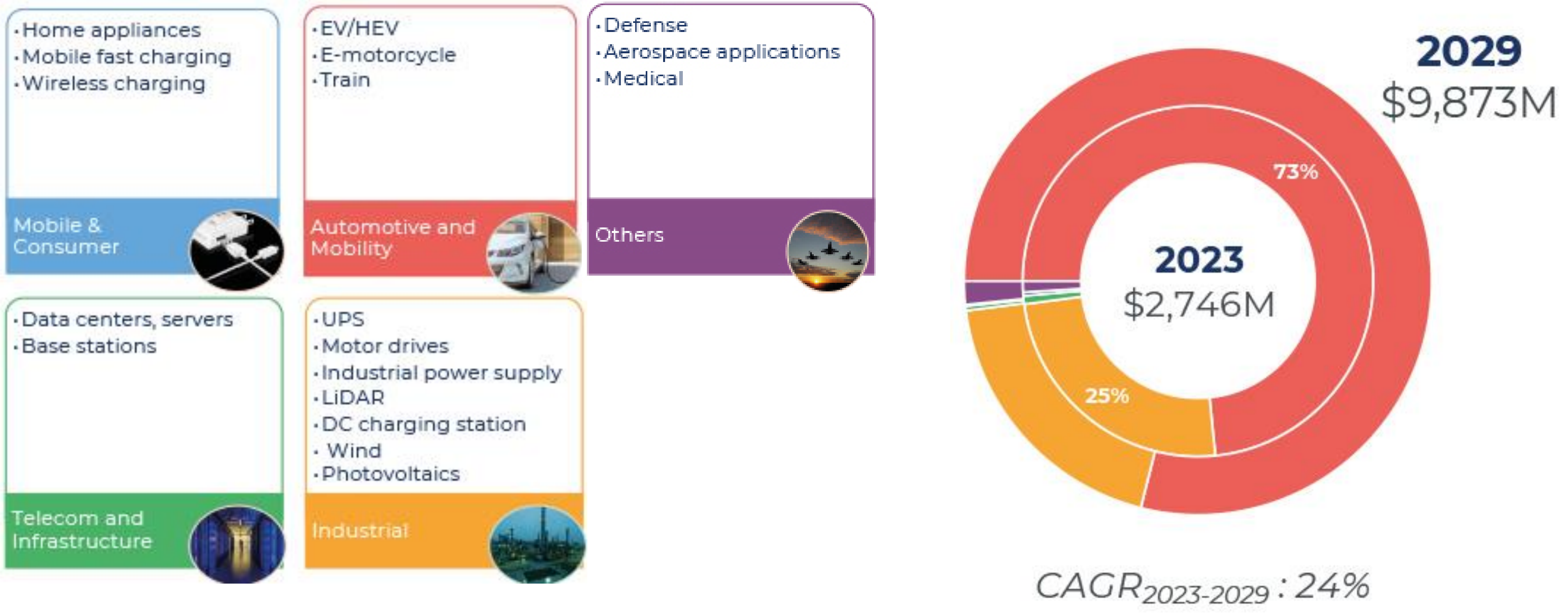
- The power electronics market is poised for steady growth, projections estimating an increase from $23.8 billion in 2023 to $35.7 billion by 2029
- Silicon carbide (SiC) technology outperforming the entire market growth by a factor of 3, especially in EV & industrial segments



Source: Status of the Power Electronics Industry Report, Yole Intelligence, 2024

2023 – 2029 Period power SiC device Market ($M)

- Numerous companies are evaluating the utilization of SiC devices, broader adoption is still hindered by industry concerns regarding the availability and cost of SiC wafers and devices in the face of much higher demand.
- Consequently, the SiC industry is investing heavily in increasing wafer and device manufacturing capacity.

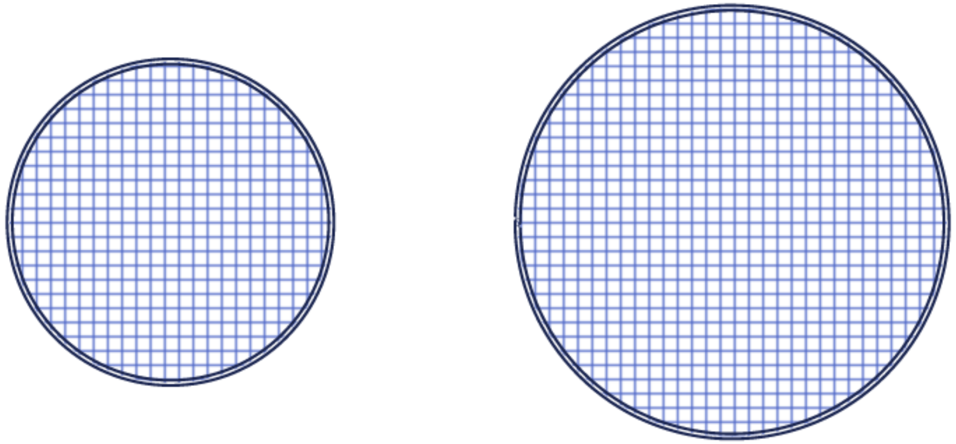


Source: Power SiC – Markets and Applications 2024, Yole Intelligence, September 2024

SiC MOSFETs Need SiC Wafers

The Future of EV Powertrains: SiC, GaN, and the Evolution of Power Electronics: IDTechEx Webinar July 2024

- The wide majority of SiC MOSFETs are grown on 150mm wafers.
- A transition from 150mm to 200mm will result in a 90% increase in die number per wafer, to meet the increasing demand from automotive OEMs and tier-one suppliers.
- The usable area of each wafer increases.
- Potential cost advantage to be realized.

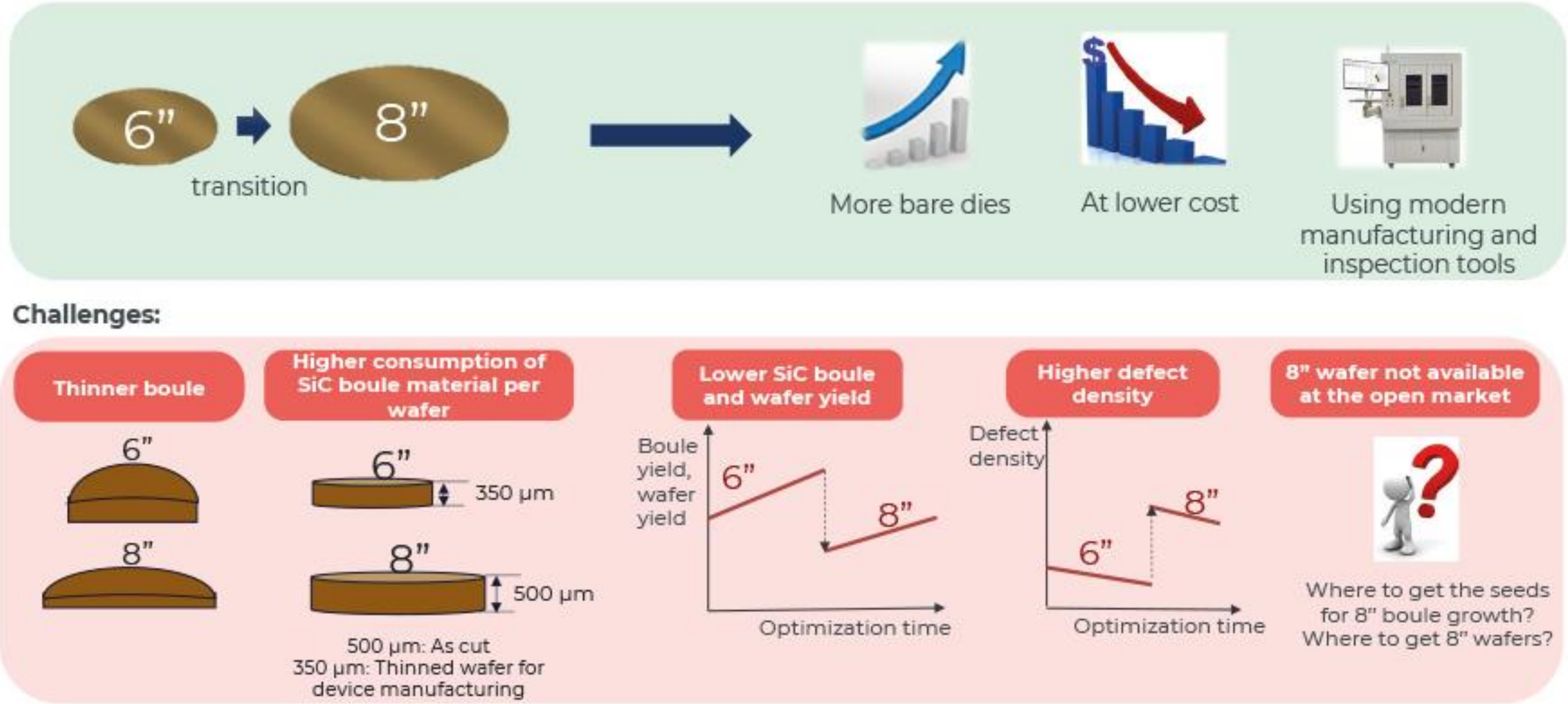


IDTechEx Research

32mm² die	150mm	200mm
No. whole die	~450	~850
% edge die	14	7

The challenges of SiC transition to 8'' (200mm)

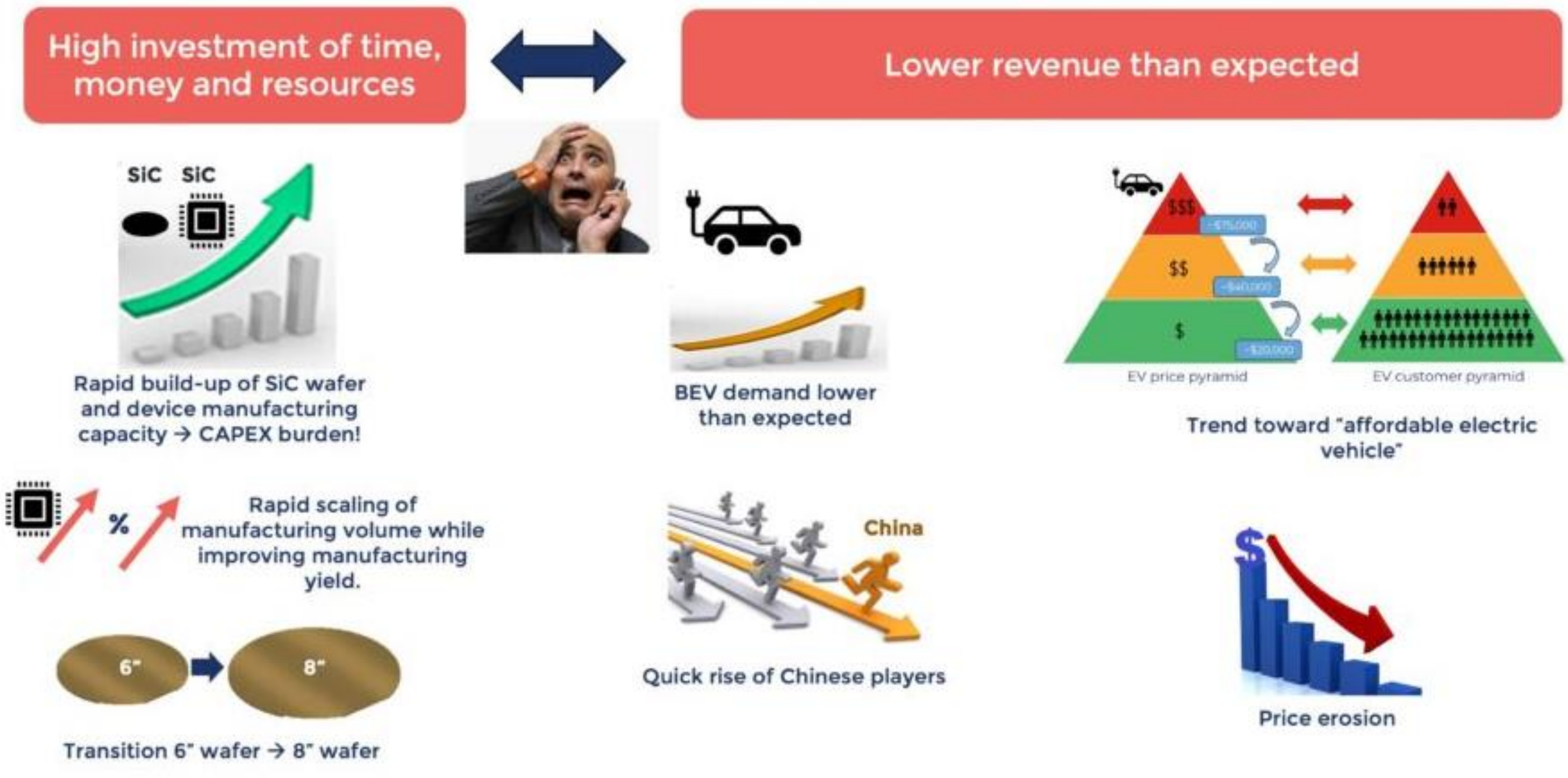
- As of 2024, 6" SiC wafers are the mainstream choice for leading players, and this is expected to remain the case throughout our forecast period until 2029.
- The technology challenges in 8" SiC manufacturing include the quality of crystal growth and wafering processes, as a thickness of 350μm is desired to be comparable to 6" wafers and maintain cost competitiveness.



Source: Power SiC – Markets and Applications 2024, Yole Intelligence, September 2024

Tumultuous Period for SiC Wafer and Device Suppliers

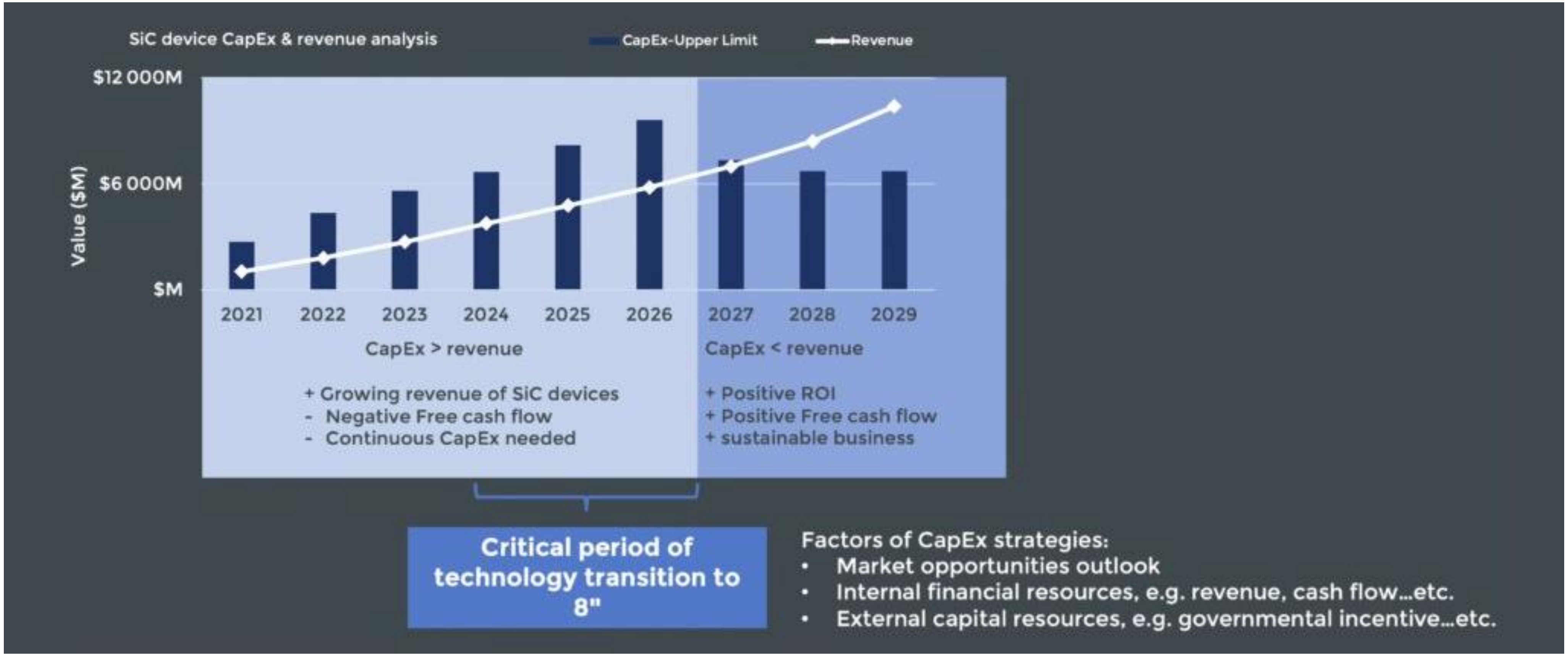
- Companies that once thrived by focusing on the rapidly growing EV market are now looking to diversify into other sectors.



Source: Status of the Power Electronics Industry Report, Yole Intelligence, 2024

SiC Front-end CAPEX & Revenue in the next 5 years

- SiC device CapEx will continue growing globally until 2026, higher than the size of the SiC device market. Starting in 2027, CapEx will peak and be surpassed by the total SiC device market.



Source: power SiC and GaN Compound Semiconductor Market Monitor, Yole Intelligence, Q3/2024

High Initial Component Cost

Application Readiness

System Design and Implementation Complexity

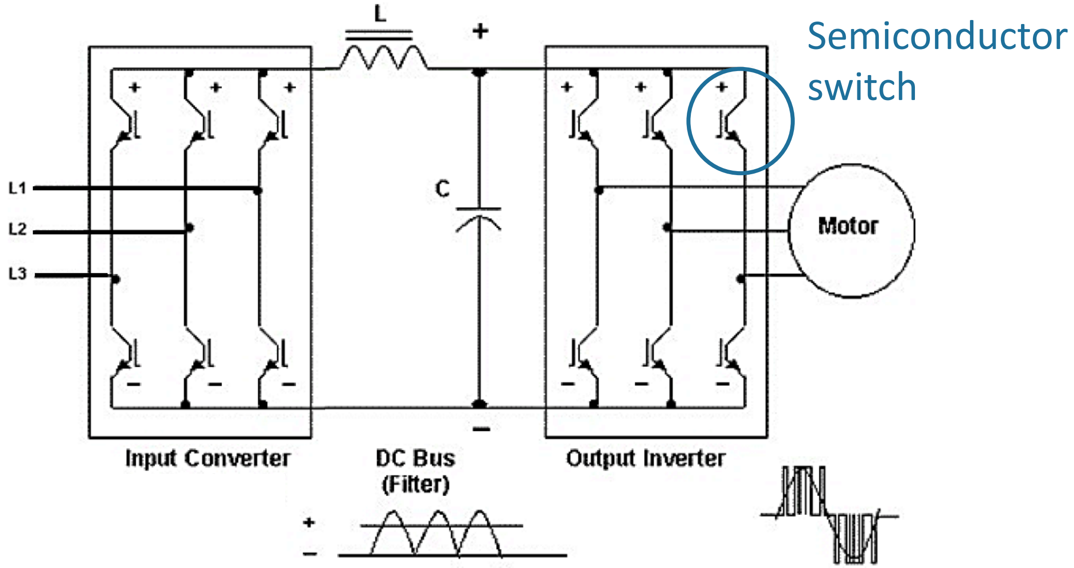
- Implementing WBG inverters requires a re-evaluation of existing system designs, including topologies (2-level vs. multi-level), and changes to gate drive circuits, protection circuits, filters (both input and output), and thermal management systems. The need for specialized design and application knowledge for SiC and GaN and the potential for increased complexity can be deterrents for some manufacturers and users.

Reliability and Durability Concerns

Risks to Equipment

SiC MOSFETs in a Drive: Starting Point

- **Low Harmonics / Active Front End Input**
  - Typically controlled rectifier (sixpack with IGBT)
  - 5~6kHz carrier frequency
  - Large LCL filters (amounts of iron and copper)
  - Drive embedded or as separate converter unit
- **Standard 3 Phase Inverter**
  - Limited to ~5 to 10kV/µs to avoid over voltage at motor, especially with long motor cable and unknown motor
  - Typically 4~6kHz, limited to low carrier (max 15kHz) to avoid too high leakage current on typically shielded motor cables

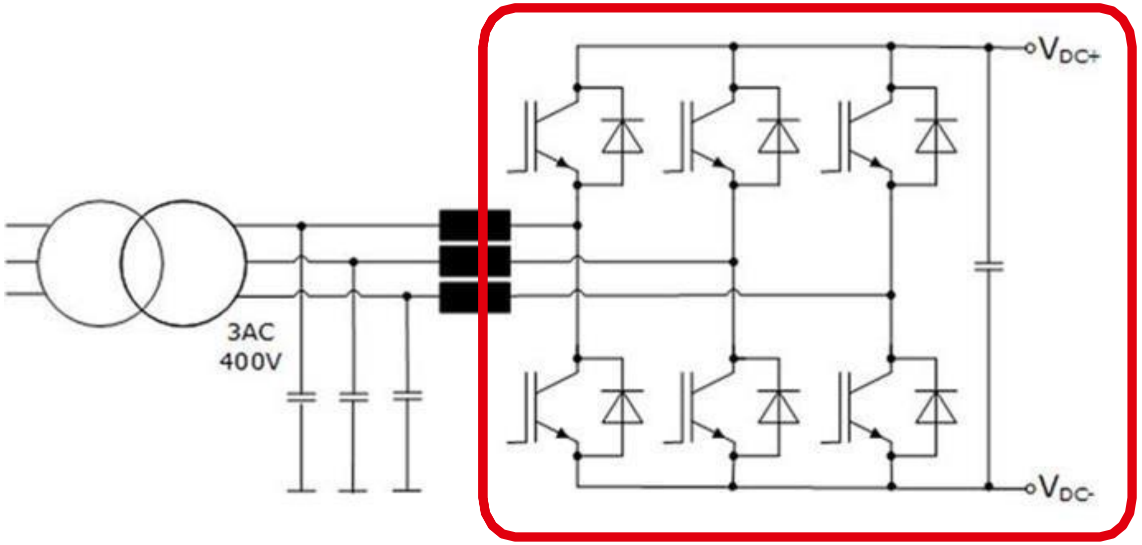


Line Side (AFE) Application Example

Benefits of SiC MOSFETs in a Drive

- Modules compared:
- IGBT Module: Generation 7 IGBT, 50A, 1200V
- SiC Module: Latest generation MOSFET, 32mΩ (40A), 1200V

- Operating Conditions:
  - V_{DC}: 750V
  - V_{Grid}: 400V
  - I_{out}: 30A
  - cos ϕ: 0.98
  - f_{out}: 50Hz
  - f_{sw}: Si=5kHz SiC=20kHz
  - $R_{th(s-a)}$: 0.31K/W
  - T_{amb}: 40°C



Line Side (AFE) Module Comparison

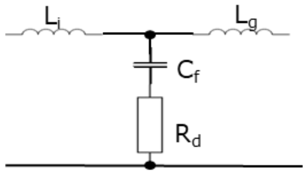
At comparable $T_{j,max}$ the SiC solution provides: Four times higher f_{sw} and 21% lower watt loss

	Si Module @5KHz	SiC Module @20kHz
Rated Voltage [V]	1200	1200
Rated Current [A]	50	40
Losses		
MOSFET/IGBT$_{,cond}$ [W]	16.32	18.27
Turn_on [W]	8.19	5.99
Turn_off [W]	8.61	2.78
Diode,$_{cond}$ [W]	4.52	2.80
Reverse Recovery [W]	3.63	2.81
Total System losses [W]	**247.61**	**195.88**
Temperatures		
$Tj_{,maxIGBT}$ [°C]	145.12	142.39
$Tj_{,maxDiode}$ [°C]	127.89	142.39

Line Side (AFE) Filter Comparison

Example filter calculation for f_{sw}=5kHz Si and f_{sw}=20kHz SiC

- Size of reactors reduced by 75(Li)/47%(Lg)
- Weight reduced by 47%
- Watt loss reduced by 37%
- More compact devices, less storage space, lower transport cost



L_i – Inverter side inductance
L_g – Grid side inductance
C_f – Filter capacitance
R_d –Damping resistance

	Si Module – 5Khz		SiC Module – 20kHz	
	Li	Lg	Li	Lg
Inductance [mH]	1.3	0.8	0.5	0.2
Capacity [µF]	3 x 20		3 x 12	
Winding weight (Al) [kg]	1.8	0.5	1.5	0.3
Winding loss [W]	200.0	92.0	90.0	41.0
Core weight (Mat) [kg]	17.0 (GO)	2.1 (NGO)	7.5 (Megaflux)	0.9 (NGO)
Weight [kg]	16.5	2.9	9.0	1.2
Core loss [W]	156.0W	15.0W	120.0W	40.0W
Dimensions	250x110x250	150x60x150	**120x90x160 → -75% in Vol**	**120x50x120 → -47% in Vol**
Total Weight [kg]	19,4		**10,2**	
Total loss [W]	463		**291**	
Relative costs for reactors	100%		105%	

Benefits of SiC MOSFETs in a Drive – Line Side (AFE) Conclusion

- Four times higher switching frequency
- Reduction of audible noise in magnetics
- Reduction of system watt losses by up to 31%
- More compact machinery or panels by smaller reactors/coolers/heatsinks (just reactors size reduction is about 75%/47%)
- Filter cost comparable at scale
- Contributes to Total Cost of Ownership (TOC) reduction:
  - Energy savings
  - Easier storage and handling
  - Lower mounting effort

Challenges and Criticisms towards SiC-Inverters for Industrial Drives

Electric Motor Systems EMSA

High Initial Component Cost

Application Readiness

System Design and Implementation Complexity

Reliability and Durability Concerns

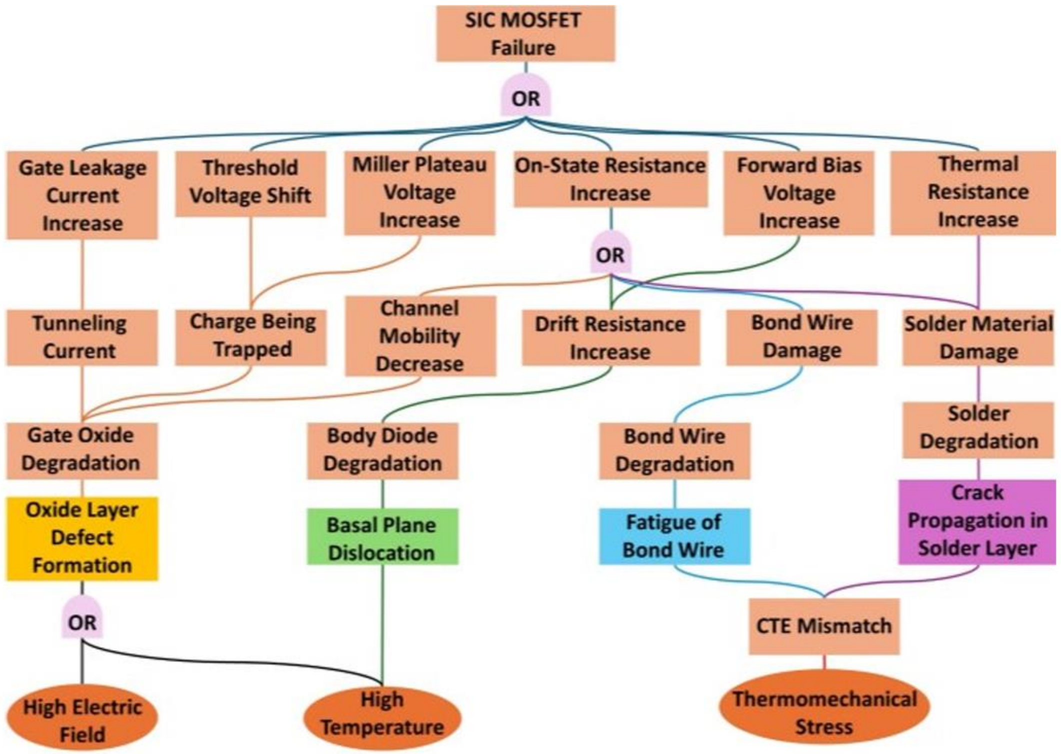
- While SiC and GaN devices offer potential improvements in efficiency and electrical and thermal performance, there are concerns about their long-term reliability and durability, especially in harsh industrial environments (e.g. continuous and intensive operation, dirt and dust). The technology is relatively new, and long-term field data may be limited compared to well-established silicon technologies.

Risks to Equipment

Efficient Aging Models for SiC - Inverter Applications

- Research on various topics in SiC power converters, such as failure mechanisms, accelerated lifetime testing, device health indicators, junction temperature monitoring, and protection systems are required to increase confidence in long term stability of SiC-based Industrial inverter.
- Compared to Si-Inverters, SiC-Inverters can operate at junction temperatures beyond 170°C; newer designs have brought this limit to greater heights, exceeding 250°C.
- Even when the junction temperature and blocking voltage are kept below the critical values, long-term degradation of the device is still possible through chip and packaging related degradations
- Accelerated life tests (ALT) can be performed using appropriate stress levels derived from mission profiles to characterize long-term reliability

SiC MOSFET fault tree analysis



Challenges and Criticisms towards SiC-Inverters for Industrial Drives

High Initial Component Cost

Application Readiness

System Design and Implementation Complexity

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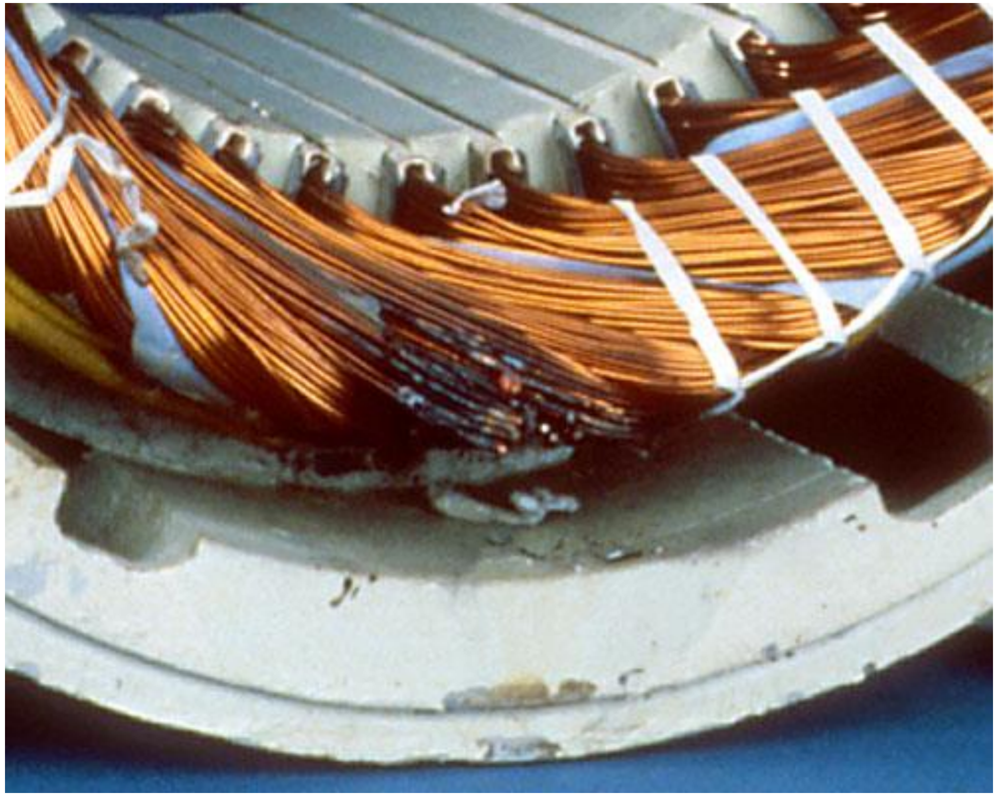
Risks to Equipment

- While Wide Bandgap Devices (SiC and GaN) inverters allow for higher switching frequencies, offering many benefits, this characteristic can also pose risks to equipment, including bearings, motor insulation, and cables. For motors, the rapid switching can exert additional strain on insulation systems and bearings due to the increased rate of voltage changes (dv/dt), potentially shortening their lifespan.

SiC Inverters for Electrical Drive Systems

- Wide bandgap semiconductors such as SiC could significantly increase the efficiency of power devices by allowing higher voltage, current and frequency than similar Si devices.
- However, the faster switching speed induces a high dv/dt which is suspected to increase ageing phenomena in windings, notably through partial discharge.
- Additionally bearing currents are generated by the high du/dt changes of the CM voltages at the motor terminals leading to bearing failures
- To provide a better understanding of the impact of SiC semiconductors on the aging of current **low voltage electrical machines**, a collaborative project managed by Bern University Applied Sciences funded by the Swiss Federal Office of Energy aims to initiate comparative testing of both technologies.

Winding insulation failure after long-term partial discharge activity

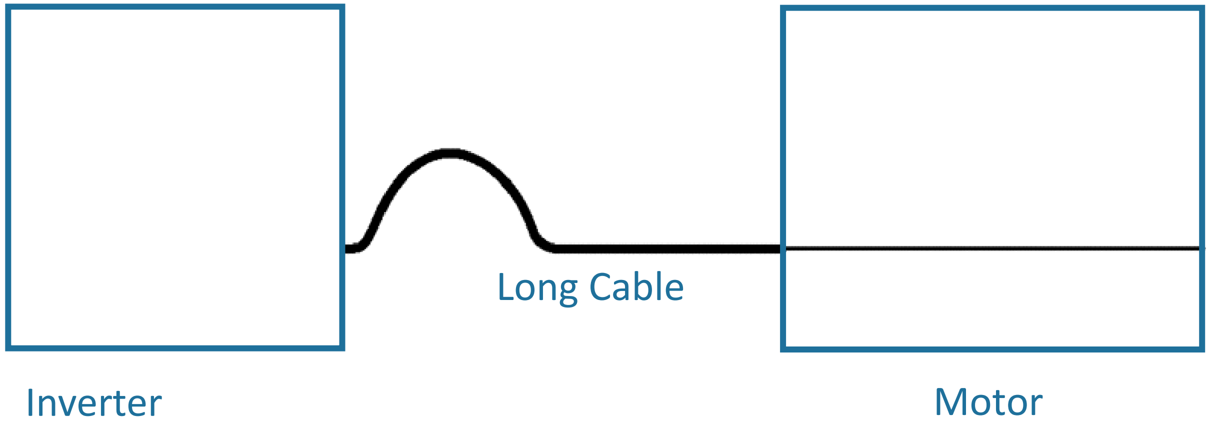


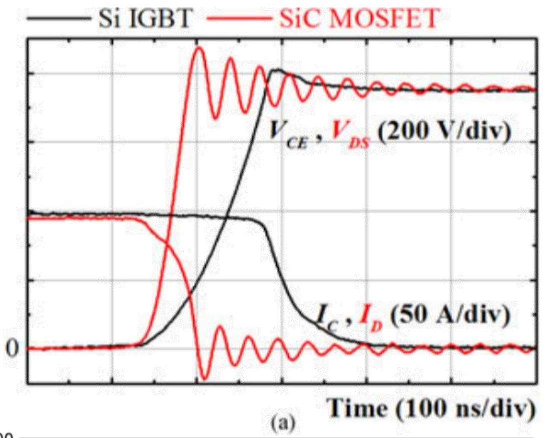
Insulation Aging Phenomena – Terminal Overvoltage

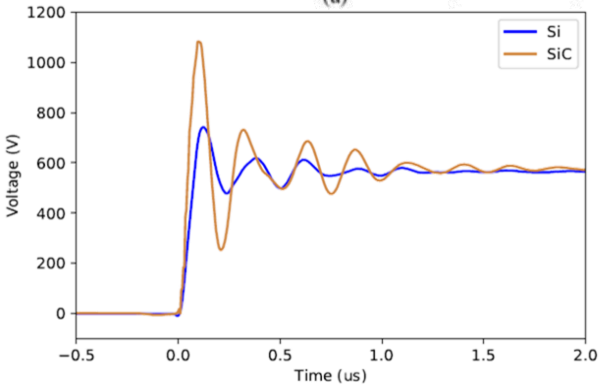
- SiC inverters reduce switching losses, which is associated with a shorter rise time, making the system prone to reflected waves and voltage overshoots on the motor side
  - Cable length and filtering are key factors
  - Maximum reflected voltage limited to twice the DC-link voltage for longer cables (max. reached at critical cable length)
- Critical cable length depends on power semiconductor rise time

$$l_{cr} = \frac{t_r v}{2}$$

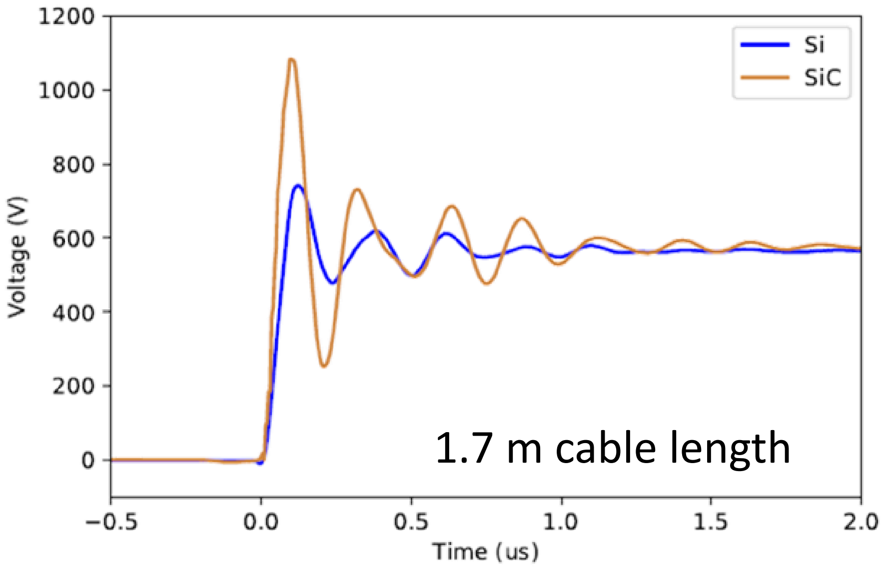
  - With t_r the rise time and v the propagation speed (150m/µs for a pulse velocity in a cable).

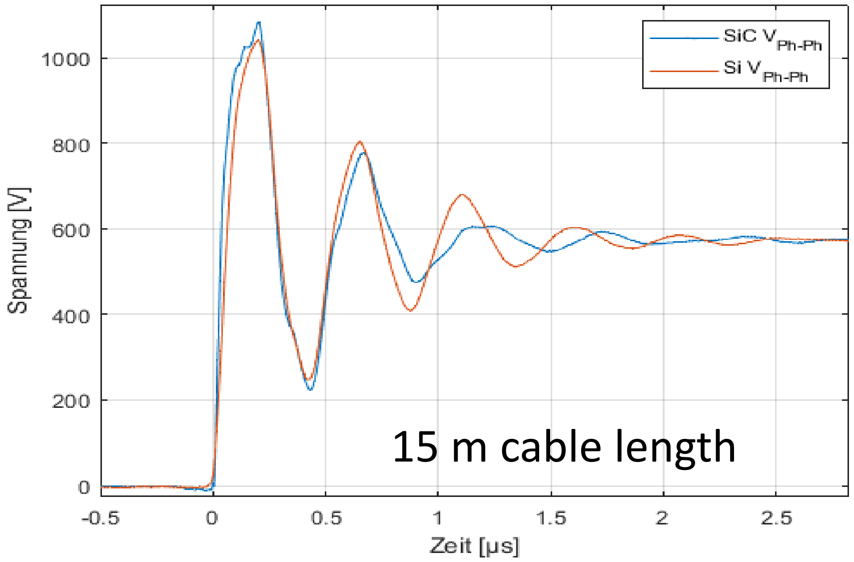






Results of the motor line-to-line voltages for the 2L SiC MOSFET inverter in the case of different lengths of the power cable





The measured rise times of 30 ns for the SiC and 80 ns for the Si inverter result in critical cable lengths of 2.25 m and 6 m respectively. In measurements with a 1.7 m cable, which is shorter than the critical cable length of both inverters, overvoltages of up to 1.1 kV were measured for the SiC inverter and 750 V for the Si inverter (Figure 9). Such high voltages could lead to partial discharges and shorten the service life of the machine.

Due to the 15 m cable length, the differences in overvoltage are no longer as great as with shorter cable lengths. On average, the overvoltage is 1090 V for the SiC and 1030 V for the Si inverter, with an intermediate circuit voltage of 580 V. The phase-to-earth voltages reach peak values of 780 V for the SiC and 680 V for the motor operated with a Si output stage. The slew rate of the SiC is 30 ns (18,000 V/µs) and 80 ns (6,750 V/µs) respectively, measured from 10% to 90% Vdc, i.e. approx. 60 to 540 V.

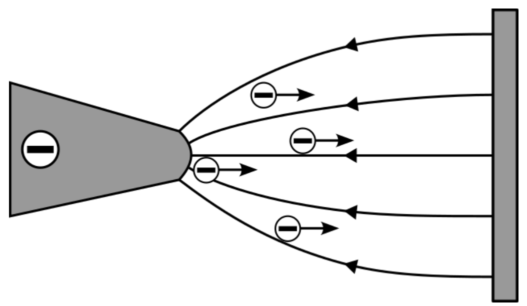
Insulation Aging Phenomena

PDs can occur above approx. 400 V
Voltage overshoot can lead to partial discharges

- Caused by heightened electrical field strength
  - Voltage level
  - Geometry
  - Environment (temperature, humidity, pressure)
- Inside the insulation system / on critical locations or interfaces
  - Sharp edges or radiuses
  - Electrode-Insulation-Air
  - Foreign particles
  - Cracks and delamination
- Mechanism of degradation in presence of PD
  - Ionized particles bombardment
  - Local temperature increase
  - UV-radiation
  - Reaction with ozone

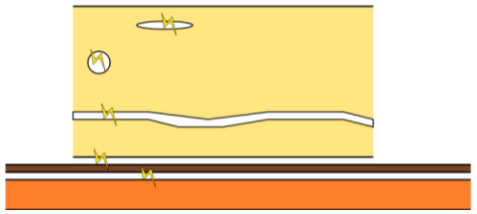
Location of partial discharges

- At winding ends



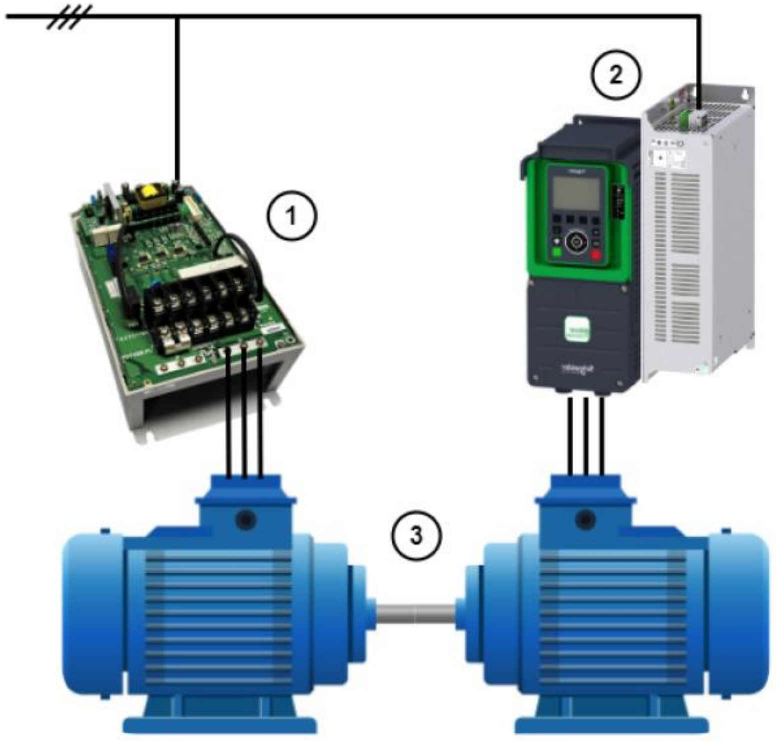
- Surfaces

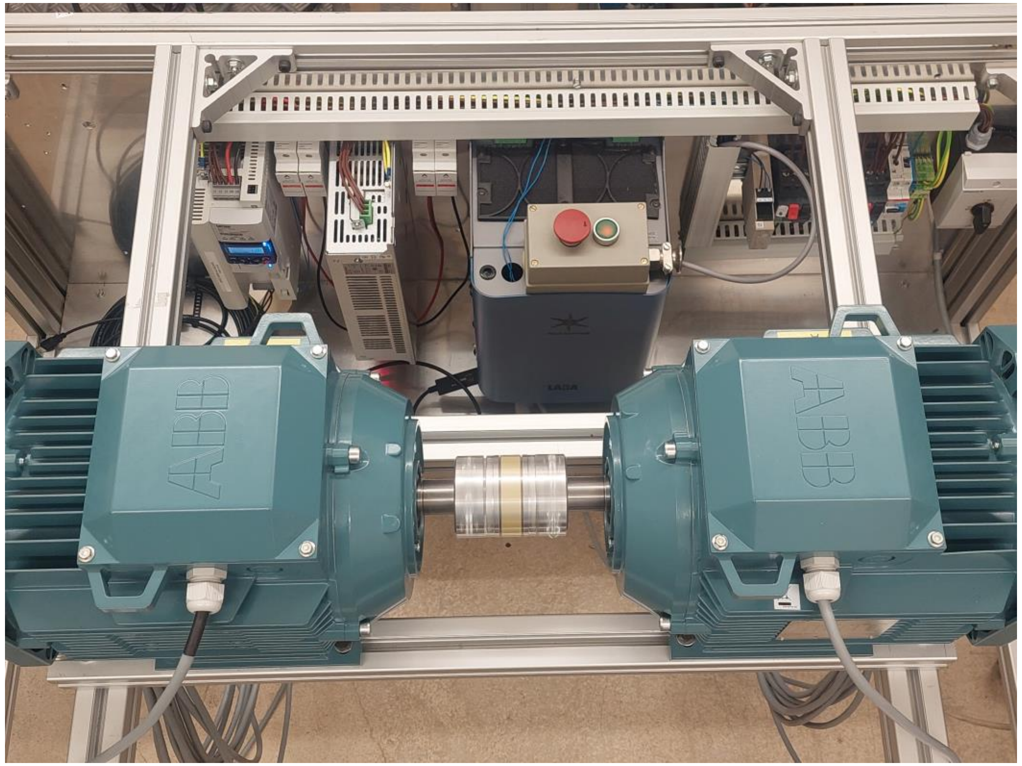
- Inside materia inhomogenities



Electric Motor Aging Testing

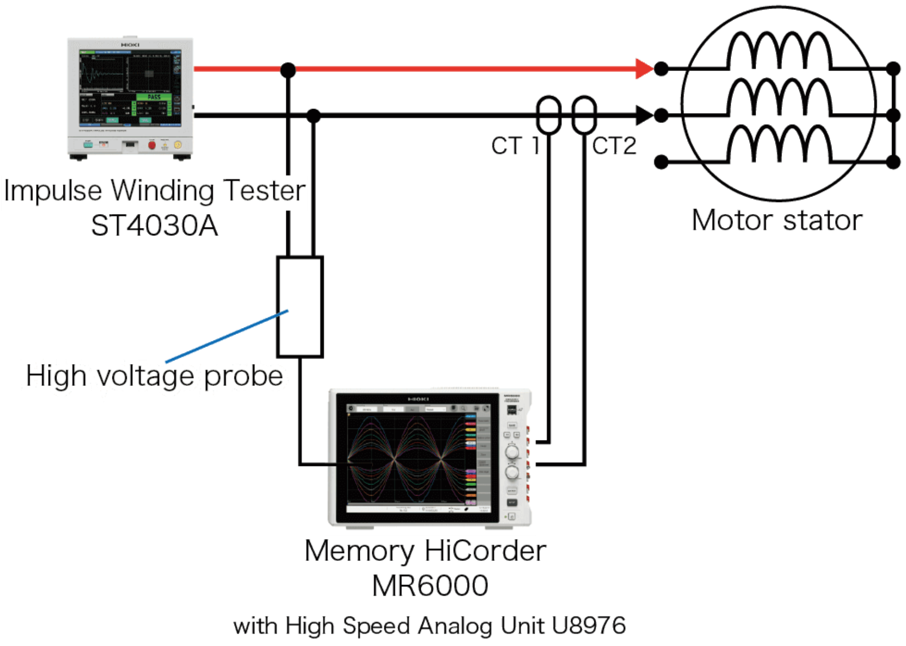
- Setup implemented in the laboratory in Quellgasse
  - 2x 4kW induction machines driven by Si and SiC inverters with long cables
  - Periodic aging measurements (100h)

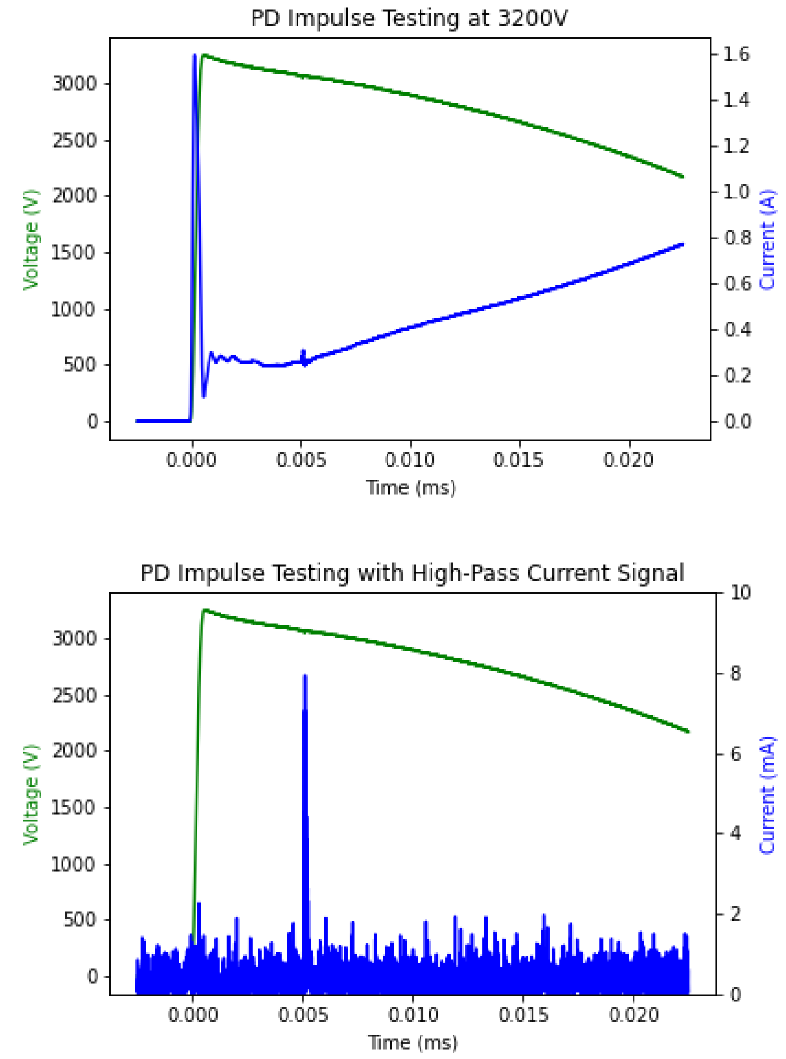




Aging Measurements

- Periodic measurement of the
  Partial Discharge Inception Voltage (PDIV)

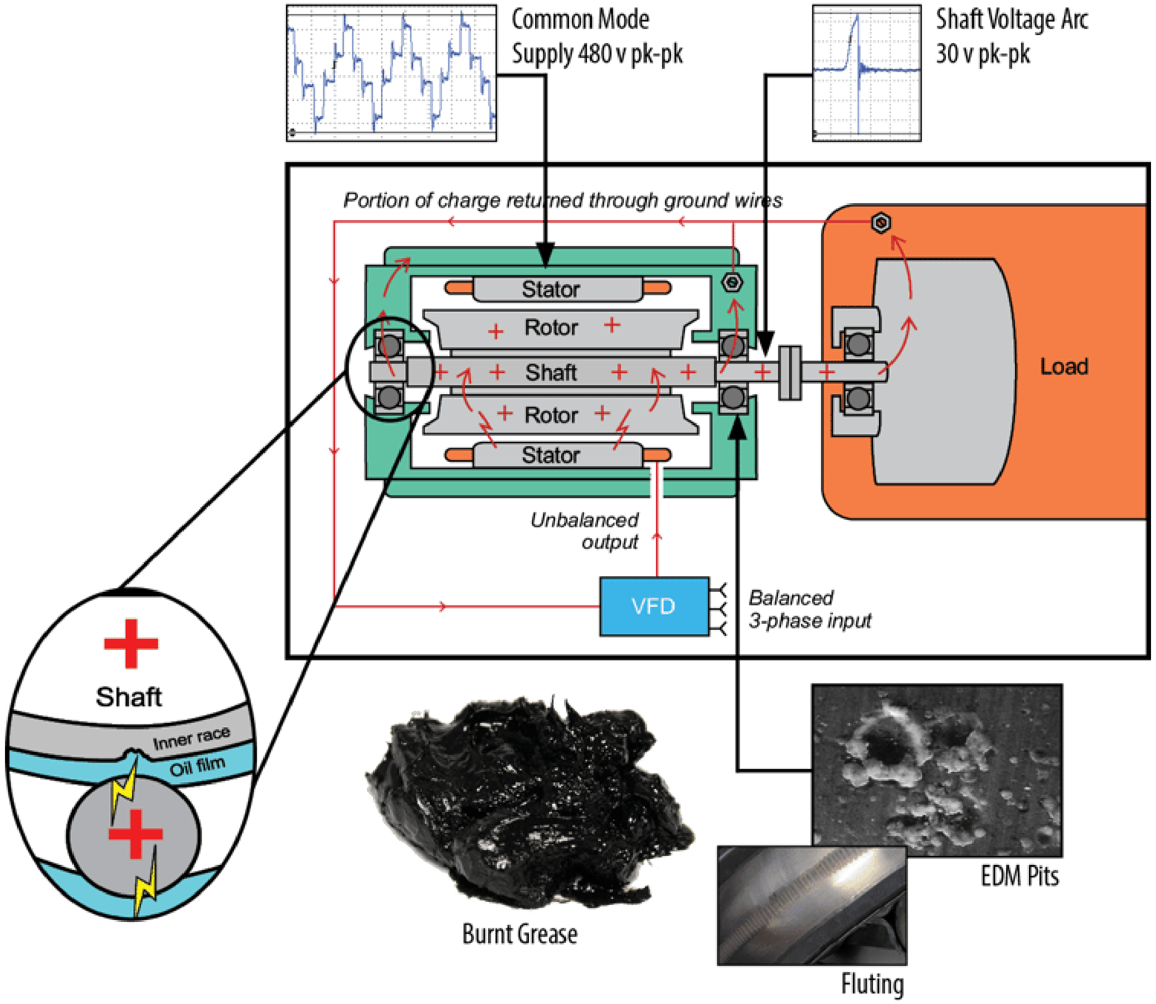




Bearing Currents

Introduction

- The common mode (CM) voltage of the voltage-source inverters causes the HF electric currents in the bearings in the inverter-fed electrical machines
- These bearing currents are generated by the high du/dt changes of the CM voltages at the motor terminals due to the fast switching of the Si-based IGBTs or SiC based MOSFETs in the inverter.
- The source of bearing currents is the voltage that is induced over the bearing. In the case of high frequency bearing currents, this voltage can be generated in three different ways:
  - Shaft voltage leakage currents
  - Grounding leakage currents
  - Capacitive discharge currents



Source: What Is the Effect of PWM Drives on Electric Motor Bearings? (est-aegis.com)

Bearing current measurement

- The circular bearing currents can be measured using Rogowski coiles in modified end shields. The measured currents are dominated by the circular currents, which are characterized by the fact that they occur in both bearings with equal magnitude and opposite current direction.

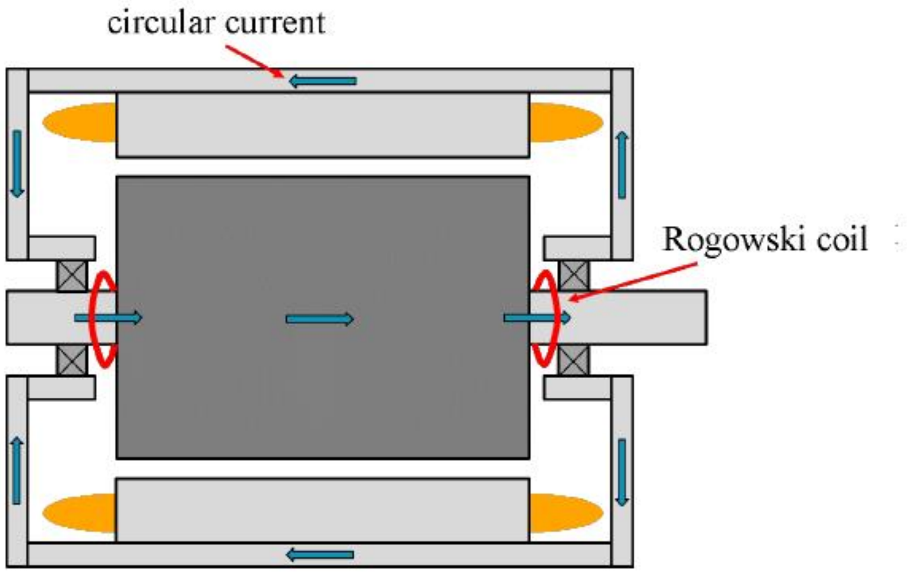


Figure 1 Motor with Rogowski coils for bearing current measurement

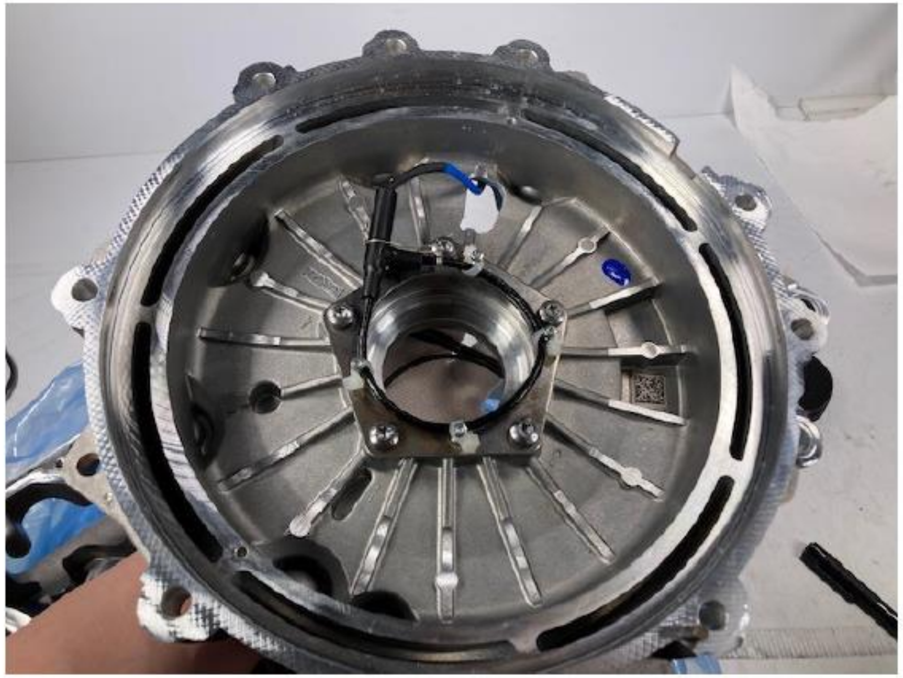


Figure 2 Rogowski coil in end shield

EMSA Wide bandgap Industrial Inverter Research Roadmap

Summary

- While these challenges are significant, ongoing research and development efforts continue to address these issues, aiming to reduce costs, improve reliability, and expand the support infrastructure for WBG technology.
- EMSA decided for their next project phase from 20205 to 2029 to document and summarize ongoing and planned research activities in fields directly related to the adoption of SiC and GaN WBG inverters in the industry
- By documenting these improvements in a White Book at the end of the project phase EMSA aims to diminish the barriers to the adoption of SiC and GaN WBG inverters in the industry.

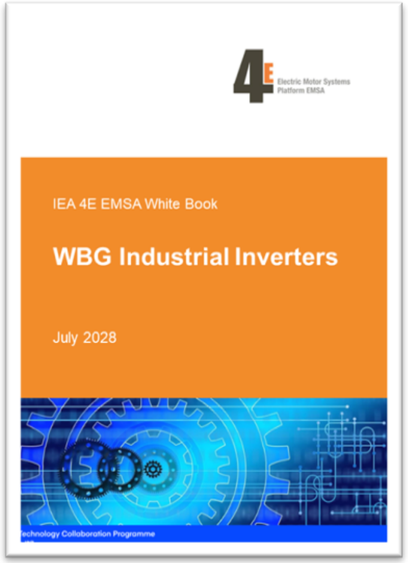
EMSA activities (2024 - 2029) in conjunction with PECTA

Electric Motor Systems EMSA

Silicone carbide converters with industrial motors
- white paper

Wide Bandgap Industrial Inverter Research Roadmap 2024-2027

Research Questions	Themes
RQ1: Application Readiness	• Cost comparison on component level • Cost comparison on system level • Cost comparison on holistic level • Production capacity and availability • Supply chain challenges
RQ2: Design and Implementation	• Comparison of WBG multilevel topologies • Potential of alternative topologies • Requirements and design of input and output filter design and topologies • Operational parameter optimization for optimal efficiency
RQ3: Reliability and Durability	• State of the art prediction of MTBF • Methods for WBG Reliability and Duration Testing • Advances in modelling of WBG power semiconductor • Standard and advanced thermal optimization technologies for WBG power semiconductors
RQ4: Risks to Equipment	• Impact on bearings and insulation aging • Impact on EMC Testing and EMC measures • Increased measurement equipment accuracy for WBG inverter testing



→ ***Inputs for relevant topics are welcome***

IEA Technology Collaboration Programme
on Energy Efficient End-Use Equipment

Electric Motor Systems
EMSA

Advancing industrial inverters: the research roadmap for Wide Bandgap Industrial Inverter

Webinar #14
Motors Academy
21 November 2024

Prof. Dr. Andrea Vezzini
Bern University of Applied Sciences