TRACTION INVERTER TESTING, VERIFICATION AND DEBUGGING FOR OPTIMIZED EFFICIENCY

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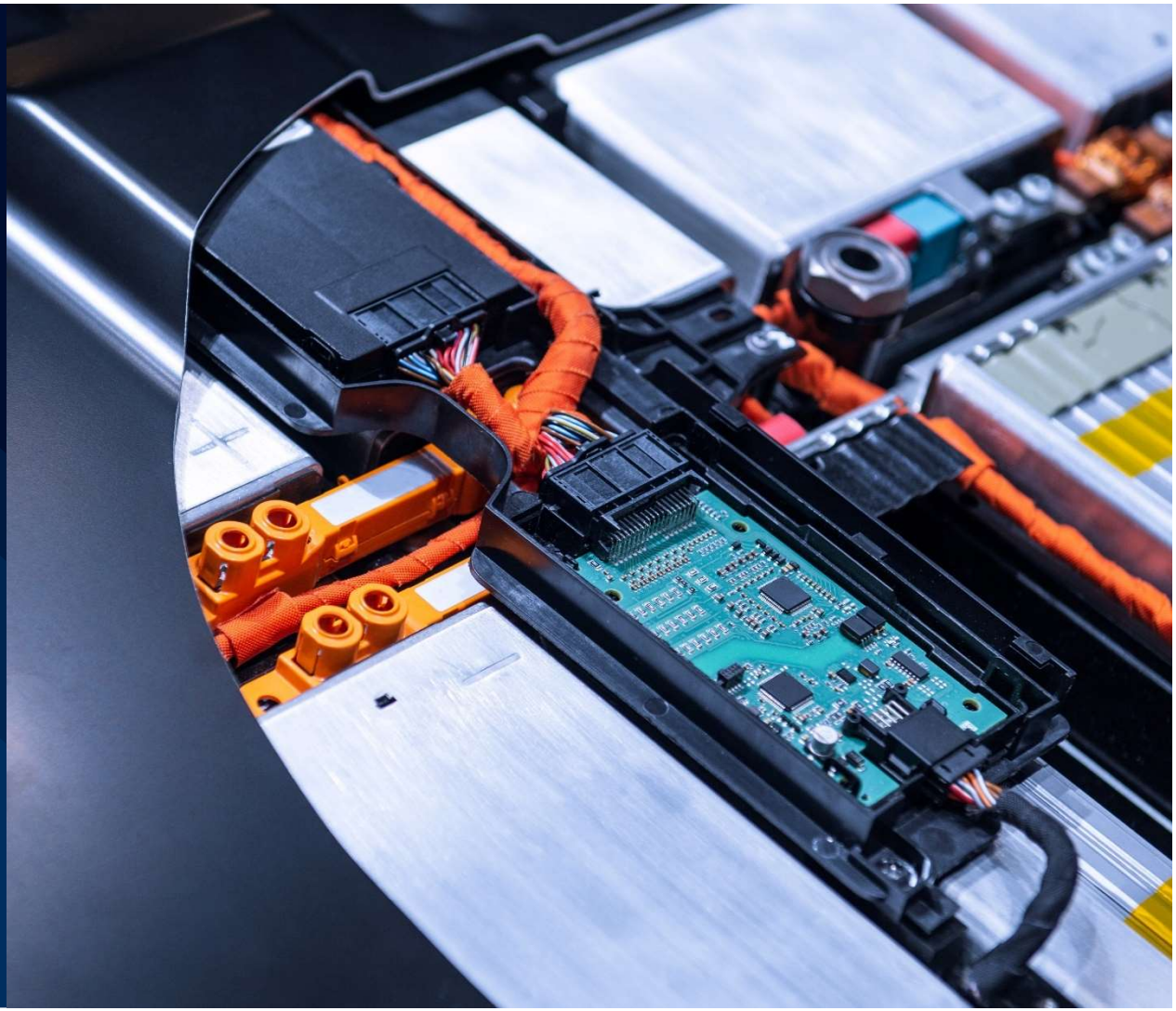
ROHDE&SCHWARZ
Make ideas real

CONTENT

- Electric drivetrain technology & market trends
- Traction inverter development challenges
- Test applications & solutions
  - Oscilloscopes
  - Power Supplies
  - Impedance Analyzers
- Summary and learnings



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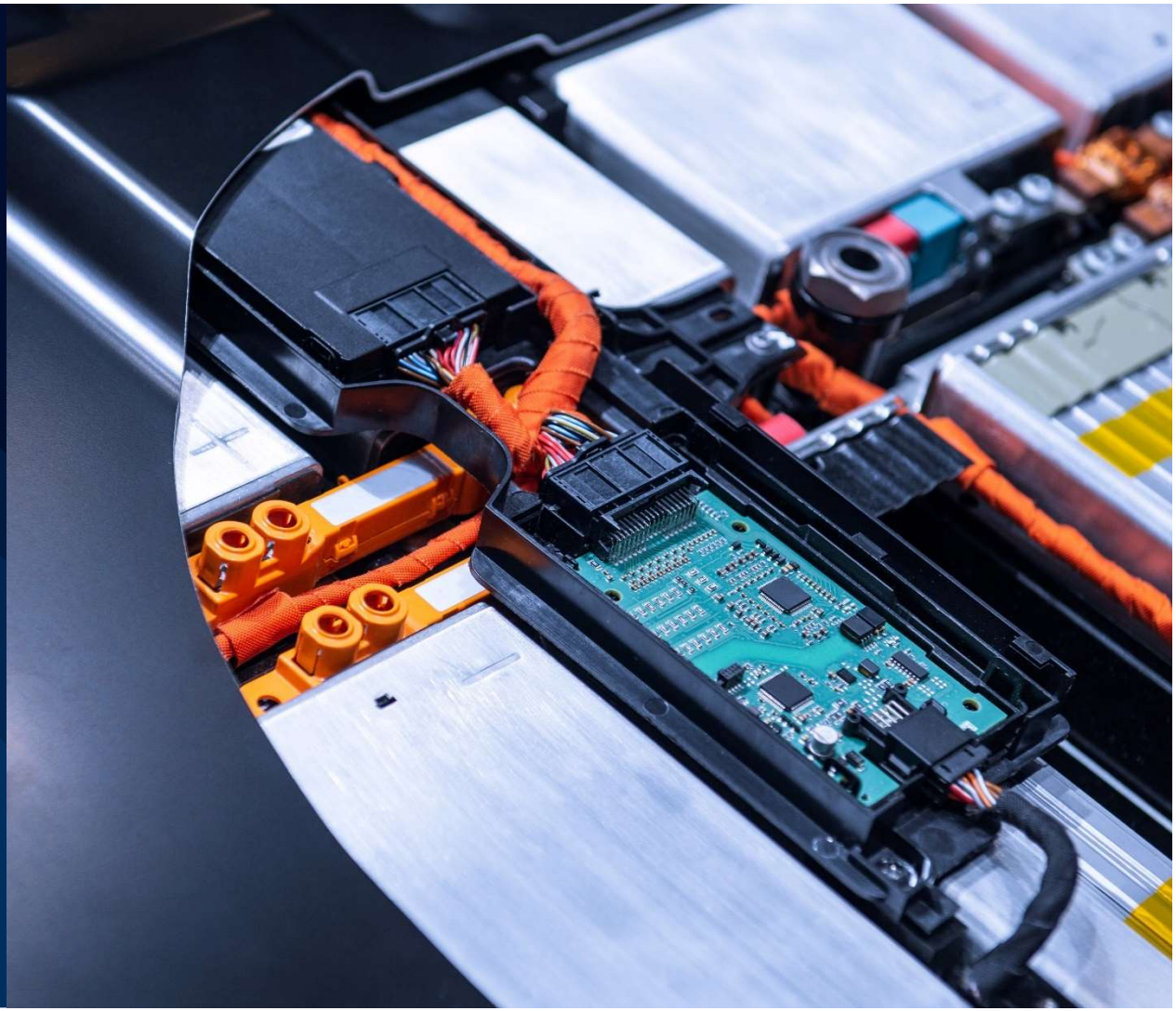
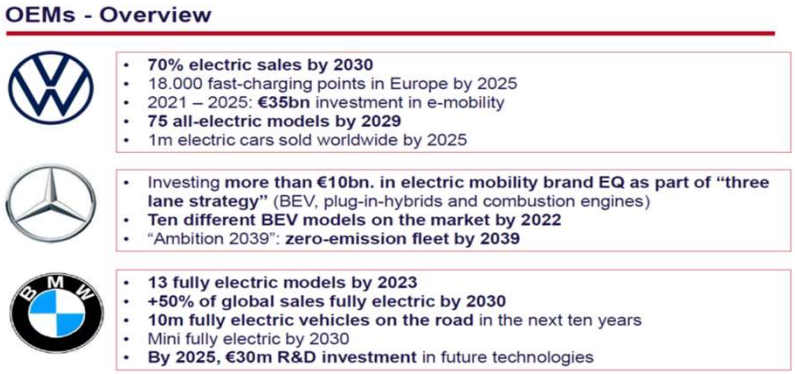
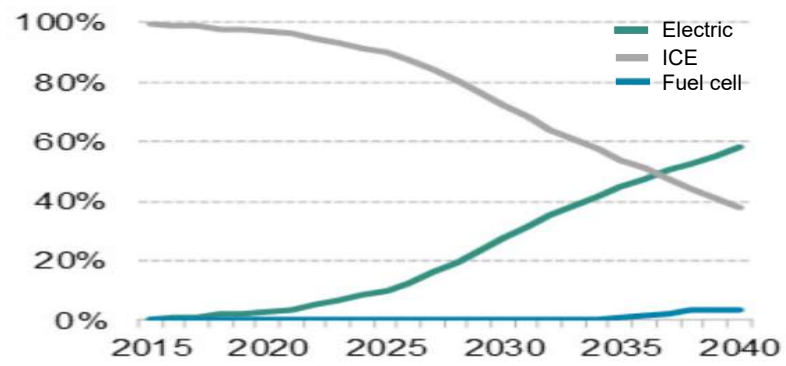


ELECTRIC VEHICLE MARKET TRENDS

- By 2035 most industrial countries will ban the sales of new combustion engine vehicles.
- Further improvement of electric vehicle charging time, driving range and reduction of price and weight is required for mass adoption by consumers.
- Car manufacturers heavily invest in new technologies and models.

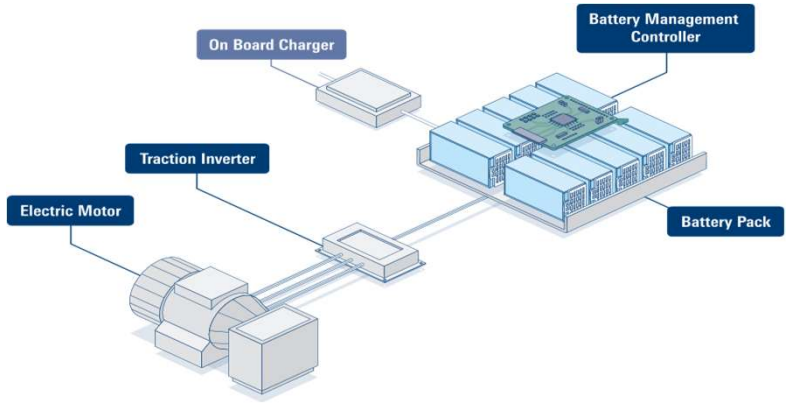


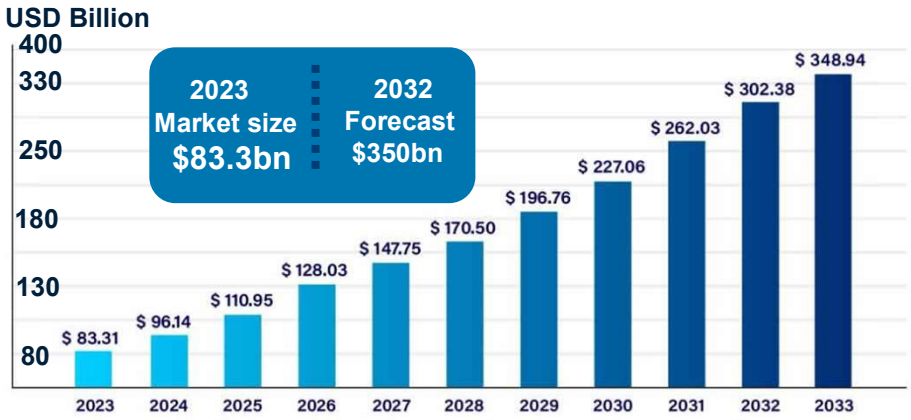


Source: Statista Feb-2023: Global share of vehicle sales by drivetrain

ELECTRIC DRIVETRAIN MARKET TRENDS

- Electric drivetrain market expected to grow from 2023-2033 at CAGR of 15.4%
- New battery technologies under development
- Electric drivetrain suppliers and OEMs focus on performance, cost, space, safety and efficiency.



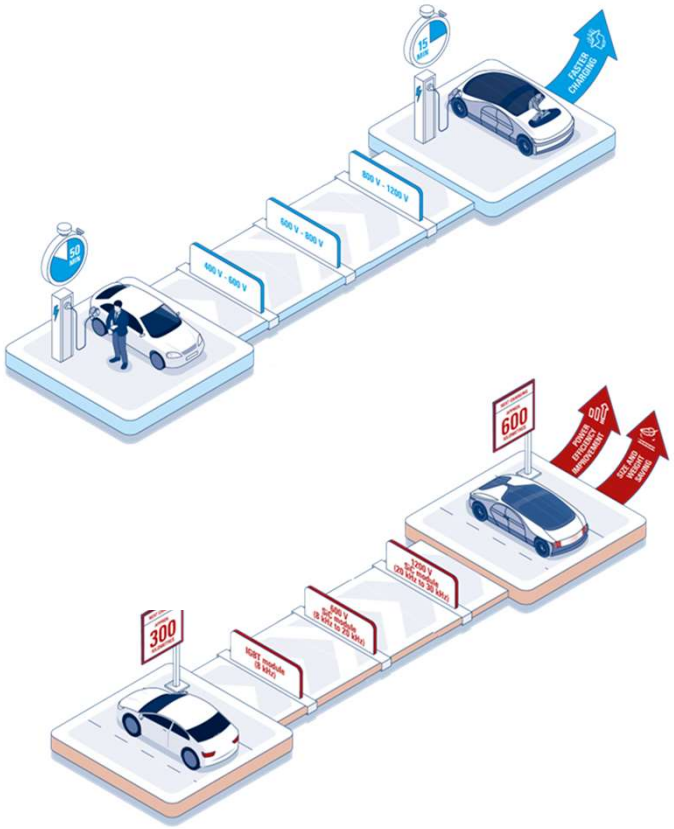


Electric Drivetrain market Size 2023 to 2033 (USD Billion)

Source: Novaoneadvisor, Feb 2024.

TECHNOLOGY TRENDS

- **Increased battery voltages**: Battery voltages go up to 800V to achieve faster charging times, reduce power loss and weight
- **Wide bandgap Semiconductor technologies** such as Gallium Nitride (GaN) & Silicon Carbide (SiC) offer high efficiency, increase power density & higher switching frequencies.
- **Wireless battery management:** to eliminate the wiring structure and thereby reduce weight and cost, as well as improve reliability, scalability, and serviceability.



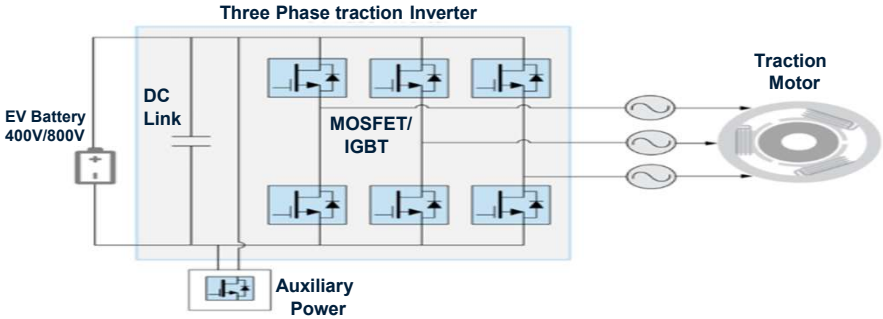
ELECTRIC VEHICLE TRACTION INVERTER

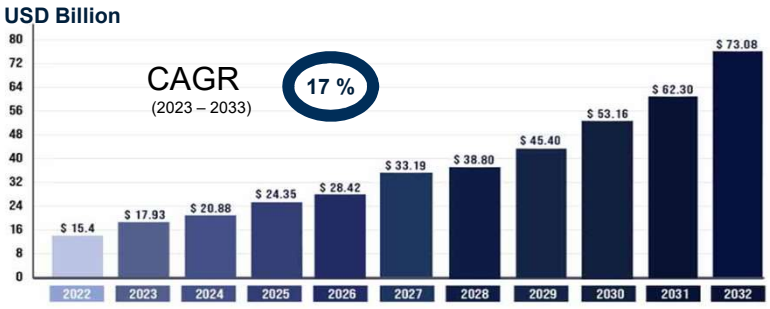
Function: The traction converts the DC voltage from EV battery into the AC current to drive the traction motor

Technology: The circuit typically consists of MOSFETs or IGBTs & control circuitry that switch the DC Power into AC Power

Power Range: The traction inverter delivers the high-power levels from 20kW to ~ 400kW

Trends: Increased integration, reduced size, higher power density & improved efficiency.





Traction Inverter market Size 2023 to 2032 (USD Billion)

Source: precedenceresearch, Apr 2023.

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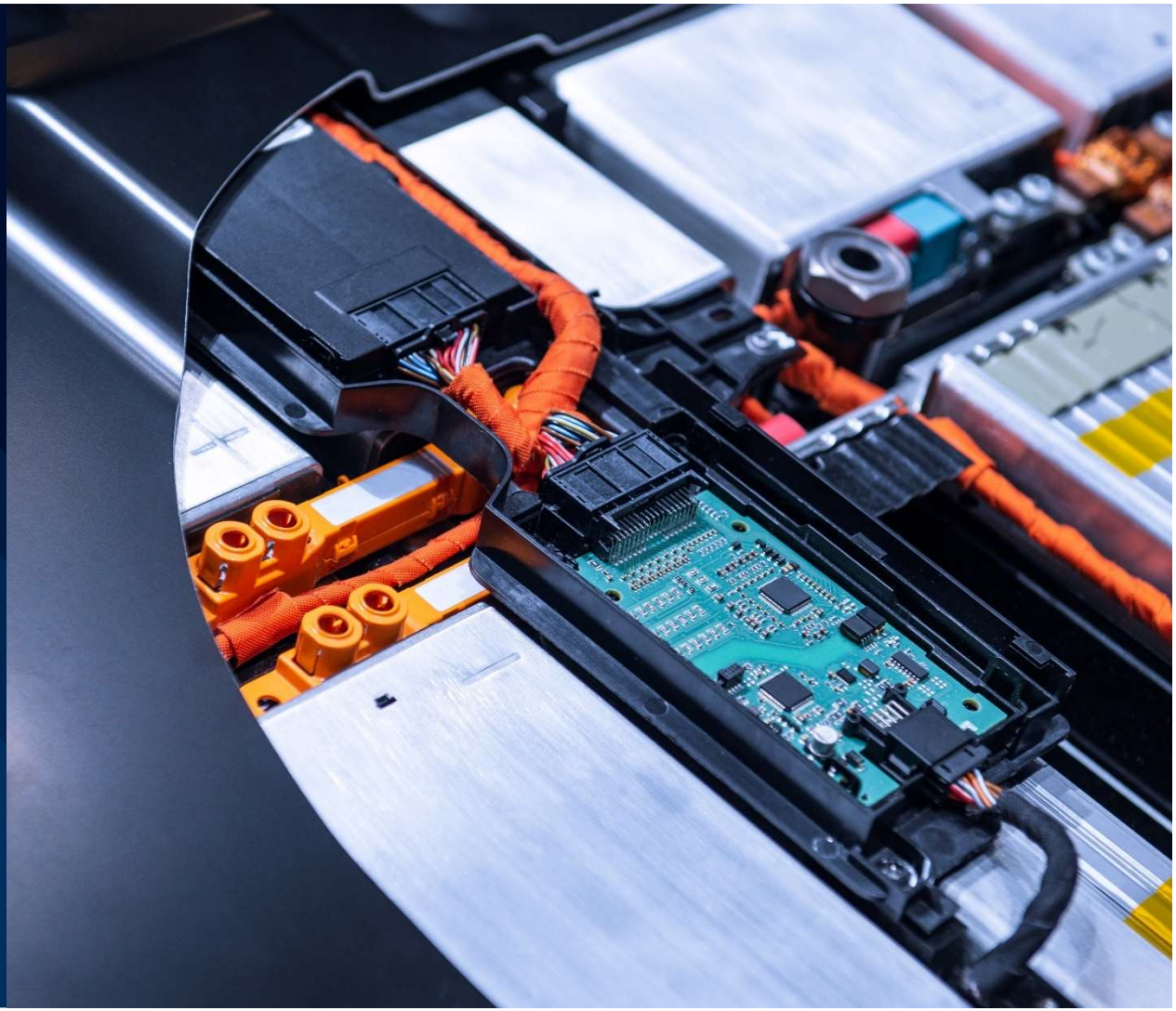
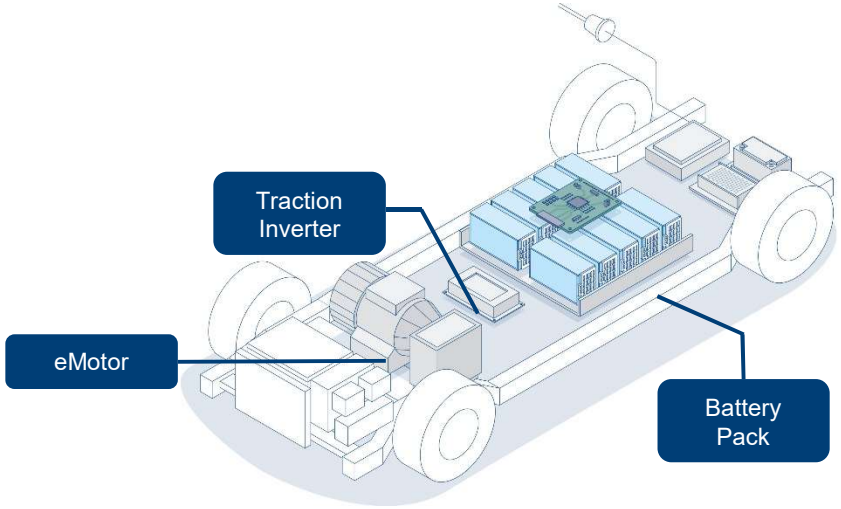
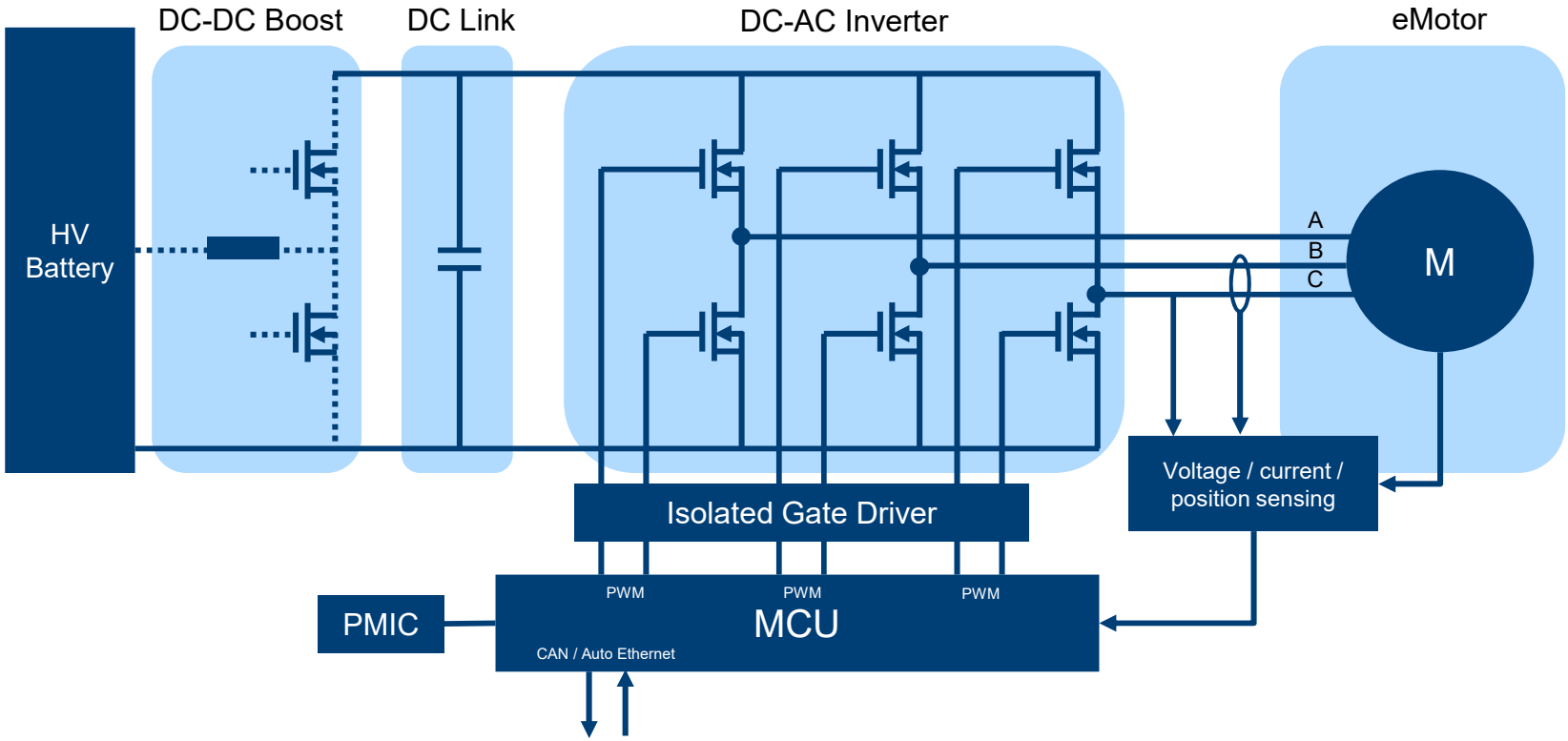


TRACTION INVERTER - INTRODUCTION

- The term ‘Traction’ is the act of pulling or drawing something over a surface
- Responsible for accurately, safely and efficiently controlling the e-motor for improving driving range, responsiveness, smoothness, traction and handling
- Has multiple roles:
  - Traction
    - *Forward/backward motion*
    - *Eco/Sports mode*
    - *Hill hold*
  - Powertrain
    - *Regenerative braking*

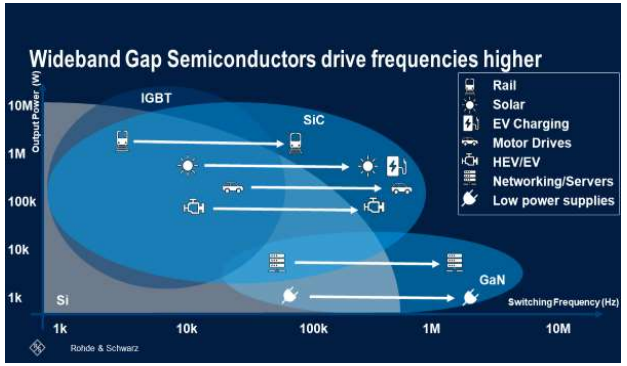


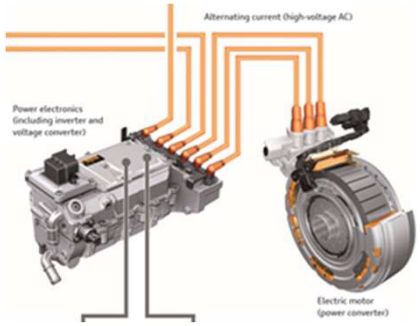
TRACTION INVERTER SCHEMATIC



INVERTER DESIGN CHALLENGES

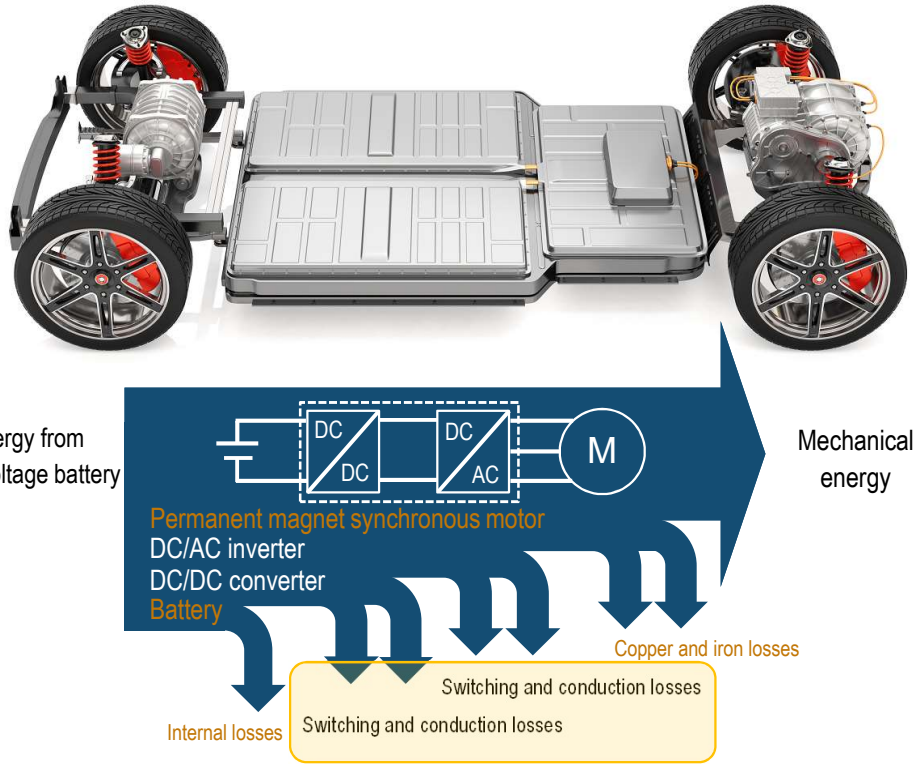
- Minimize switching losses and maximize thermal efficiency with proper design of inverter/converter electronic
- Verify stability under different loads & environmental conditions
- Ensure maximum efficiency at higher switching frequencies and multiple output voltages
- Ensure the timings of switches to verify control algorithms
- Achieve EMI compliance when using new wide-bandgap materials
  - High switching frequencies
  - Steep rising edges



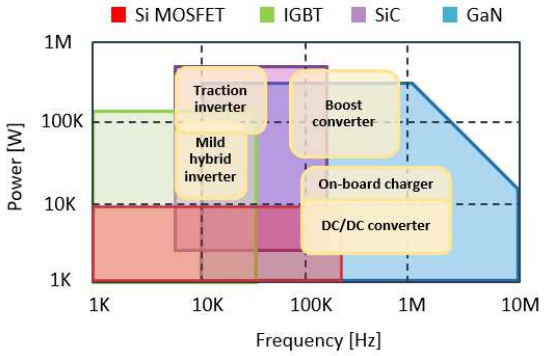


FURTHER INVERTER DESIGN CHALLENGES

The deeper the dive into the system, the more challenging it gets



- Switching frequencies of even few 100 kHz
- Up to 800 V at up to 500 kW rated power
- Transistor switch-on/off operations within few 100 ns
- Current oscillations of transistor switching of few MHz
- Up to 6-phase AC output and 2-stage topology trend
- Output ripple & noise in up to few MHz range



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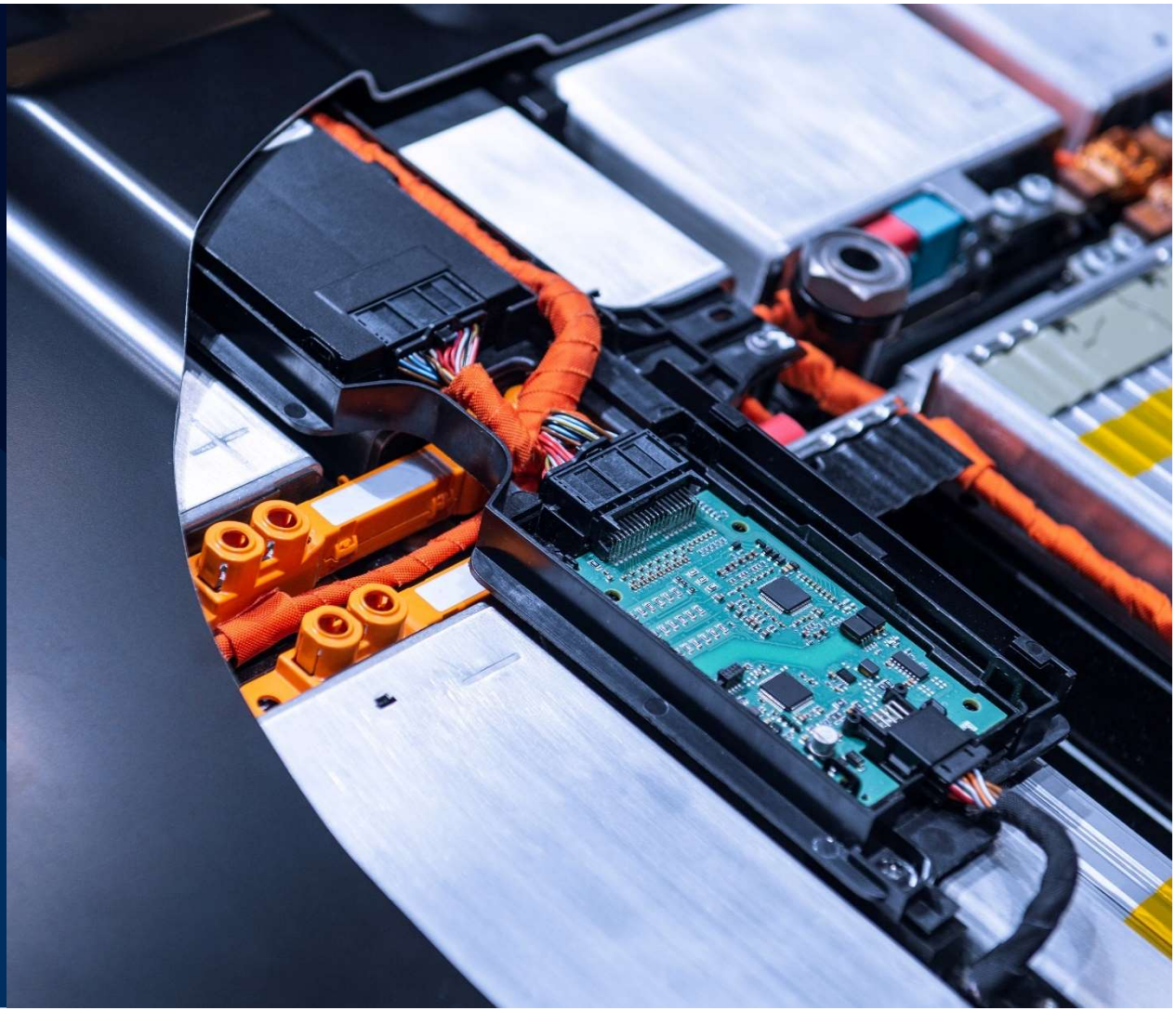


TRACTION INVERTER TEST SOLUTIONS

DC AC Traction Inverter

- Switching analysis
- PWM signal analysis
- Stability verification

Power Modules

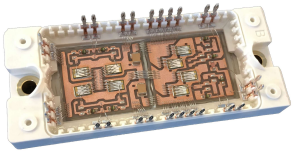
- Device characterization

DC Link Capacitor

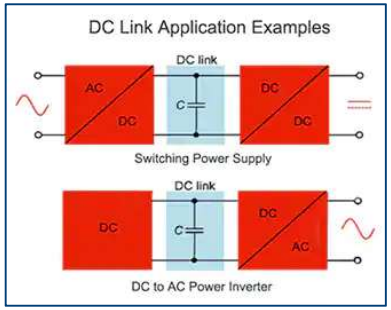
- ESR + ESL measurement

DC AC Traction Inverter

Power Module



DC Link Capacitor



R&S Power Supply

R&S Oscilloscope

Double Pulse Tester
by PE Systems

Impedance Analyzer
by Zurich Instruments

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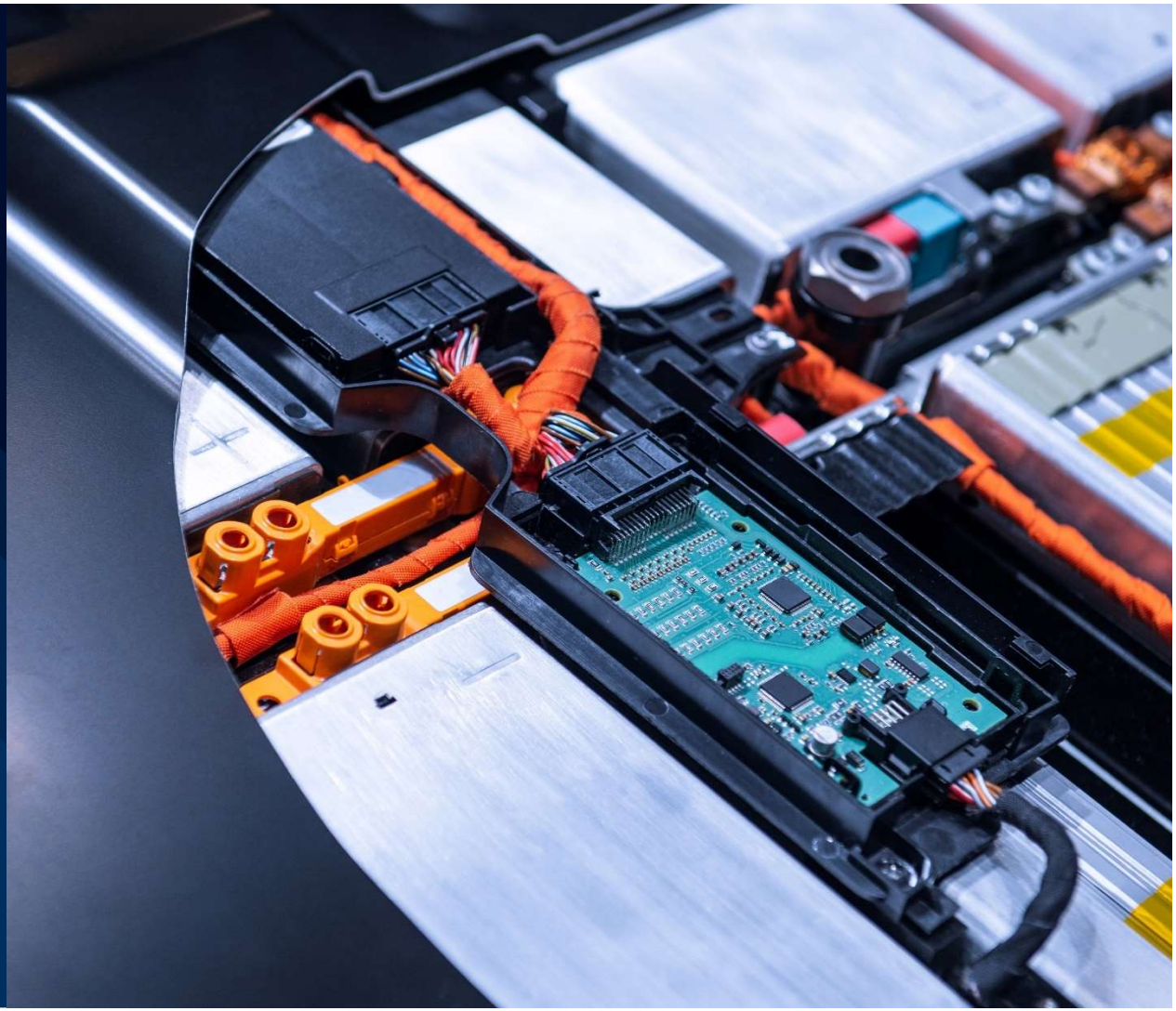
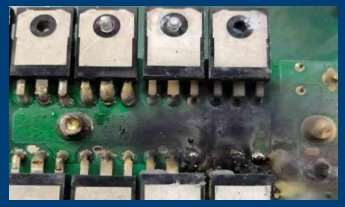


TECHNOLOGY DEVELOPMENTS LEAD TO MEASUREMENTS CHALLENGES

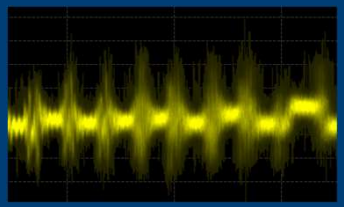


Increased voltage and current measurement range

- Accuracy across wide dynamic range
- Appropriate probes and current sensors

High vertical resolution

More probes selections



High-frequency noise and ripple analysis

- Small ripple voltages in the presence of large DC voltages
- System noise vs measurement-induced noise

High sensitivity

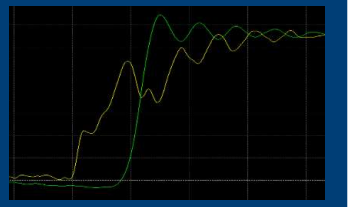
Fast acquisitions

Complex Inverter Phase control algorithms

- Timing relationships between multiple phase outputs and switch on/off
- Complex feedback control

More channels

Deep Memory



Transient response characterization

- High-speed transient events without aliasing
- Correlating transient events across different voltage domains (DPT)

High CMRR

Specialize solution

ELECTRIC DRIVETRAIN – DESIGN & TEST
OSCILLOSCOPE AND PROBING SOLUTIONS

RTM3000

MXO 4

RT-ZHD HV differential Probes

- Up to 6kV
- Up to 200MHz BW
- +/- 2000V Offset compensation

MXO5 | 5C

RTO6

RTH
Isolated Channels

RT-ZC Current Probes

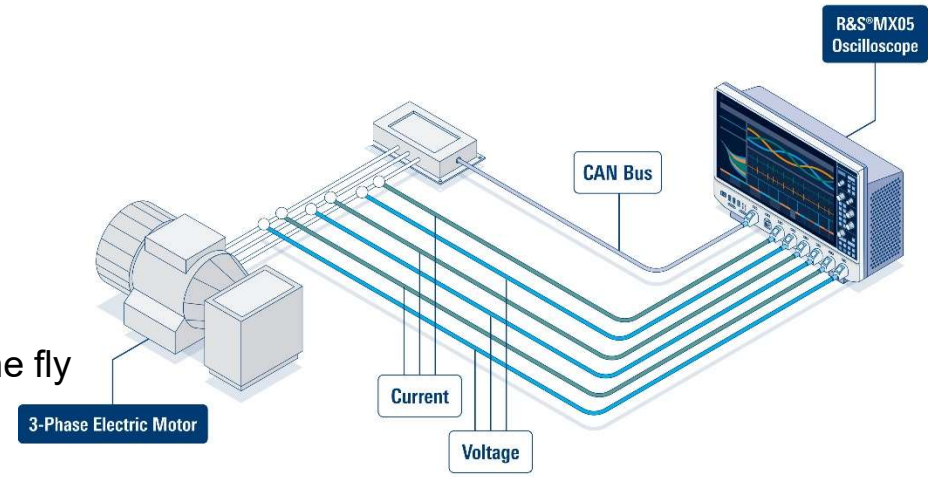
- Up to 300A
- Up to 120 MHz BW

RT-ZISO Current Probes

- Up to 3kV
- Up to 1 GHz BW
- Up to 145 dB CMRR

OSCILLOSCOPE APPROACH

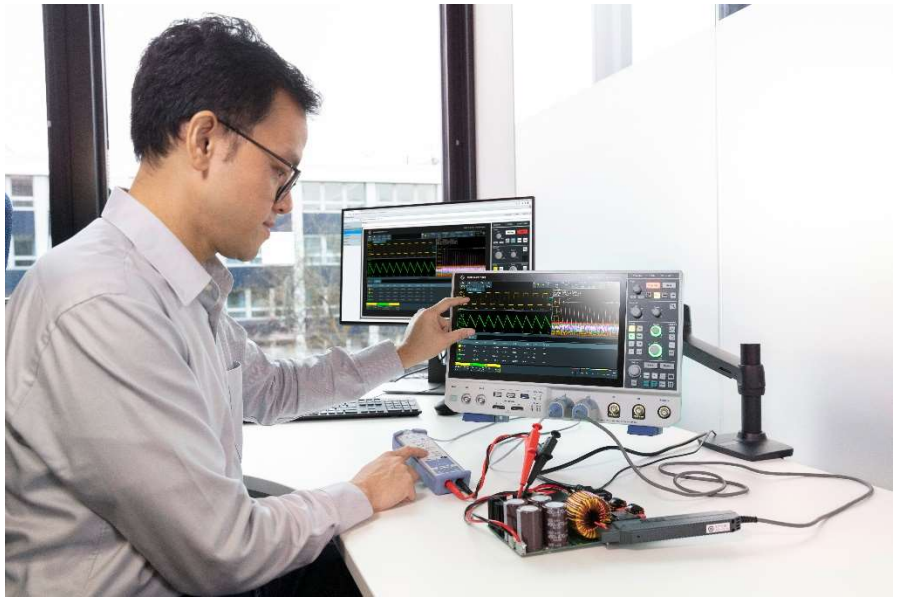
- **More channels**
  - Observe 3-phase inverter output
  - Switching behavior
- **High-frequency analysis**
  - PWM waveforms
  - Motor commutation signals
- **Real-time analysis**
  - Diagnose issues and make adjustments on the fly
- **Ability to capture transients**
  - Voltage spikes
  - Noise
- **Ability to analyze individual components**
  - Motor, Inverter, Power supply, Transistors…



ANALYSIS TOOLS

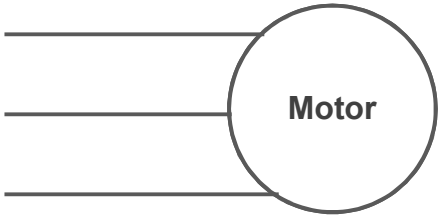
- Oscilloscopes include different automated measurements for power analysis:
  - Efficiency
  - Switching losses
  - Switching behavior
  - Power quality
  - Input harmonics
  - Inrush currents

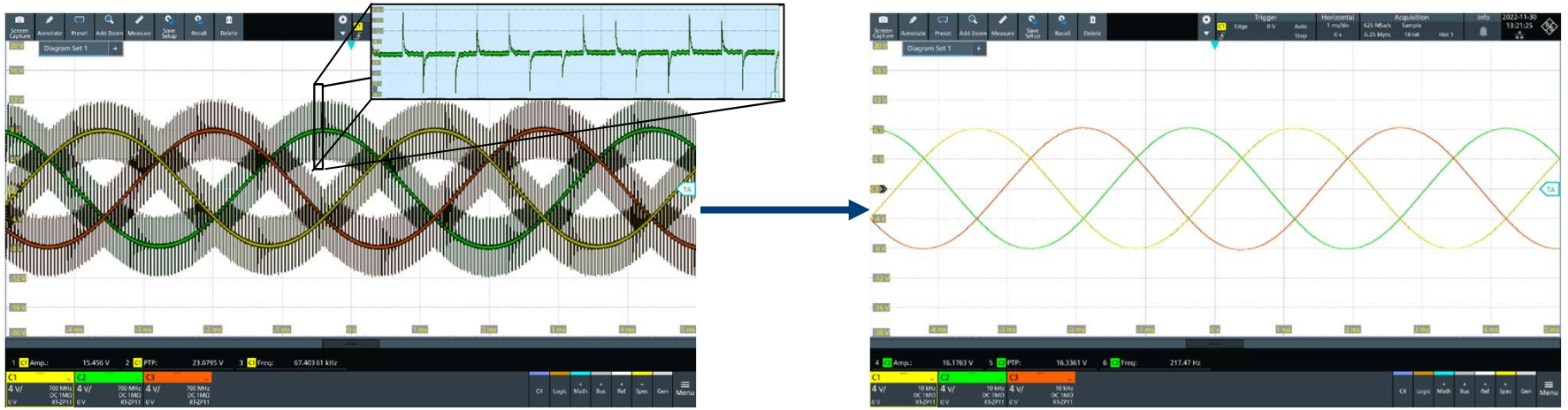
- For high precision, dedicated power analysis tasks, a power analyzer is the preferred choice.



ELECTRIC DRIVETRAIN
ANALYZE MOTOR SIGNALS

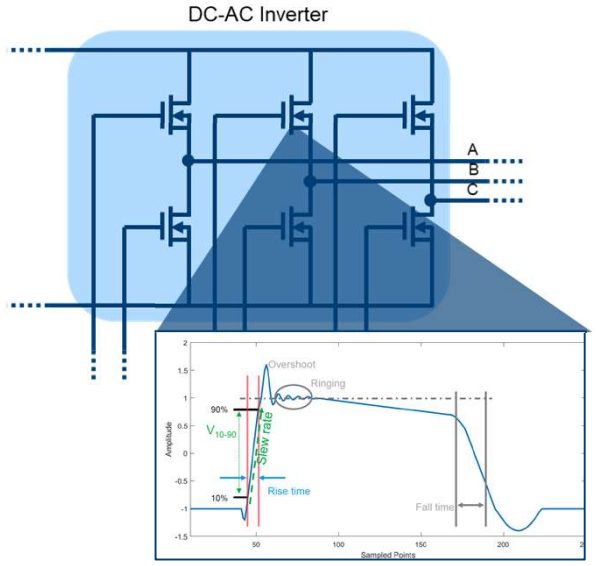
- The switching behavior of the inverter in a motor drive system can have significant impact on the motor.
- Negative effects in the performance: Reduced efficiency, increased temperature, acoustic noise, reduced torque and EMI.





ELECTRIC DRIVETRAIN SWITCHING BEHAVIOR

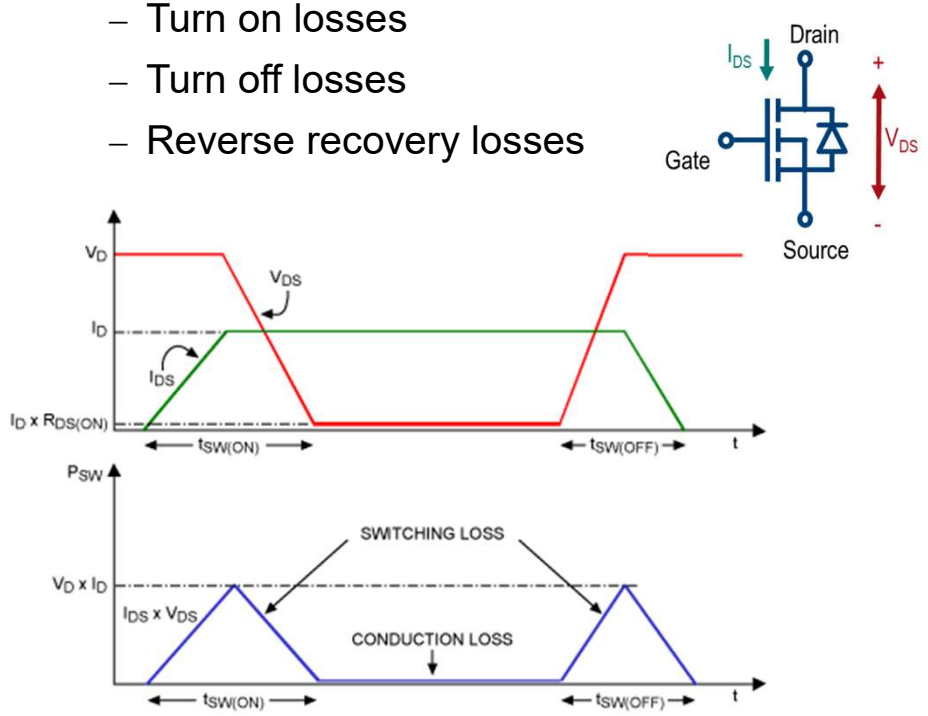
- Analyzing the switching behavior of an inverter in an electric vehicle is crucial for improving efficiency, reducing EMI noise, preventing damage and enhancing safety
- Voltage and current probes must be selected accordingly
- As a rule of thumb, it should be checked:
  - ✓ V_{GS} and V_{DS}
  - ✓ Rise times and fall times (10/90 or 20/80)
  - ✓ Overshoot, ringing
  - ✓ General timing of high- and low-side switch (synchronous converter)
  - ✓ Robustness test
  - ✓ Relation between the three phases of the inverter



ELECTRIC DRIVETRAIN
QUANTIFY LOSSES

- **Semiconductors operation generate losses**
  - Conduction losses
  - Switching losses
- **Conduction Losses** occur when the transistor is in the on-state and is conducting current
- **Switching losses** can lead to various effects
  - Reduced Efficiency
  - Increased Temperature
  - Voltage and Current stress
  - EMI
  - Design Complexity

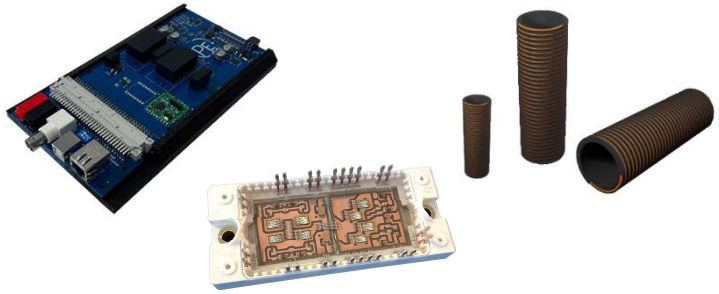
- **Switching losses to be evaluated**
  - Turn on losses
  - Turn off losses
  - Reverse recovery losses

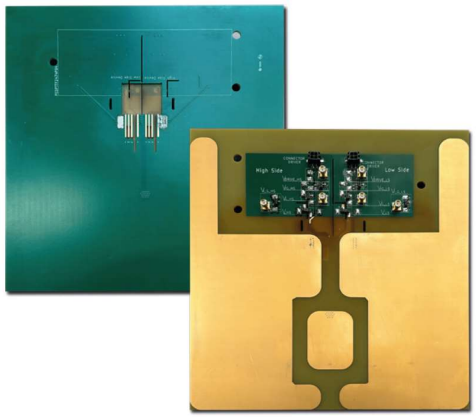


ELECTRIC DRIVETRAIN MODULAR DOUBLE-PULSE TESTER

PE·SYSTEMS

- ≤ 2 kV and 3.6 kA
- -55°C to 250 °C
- Discretes and Power Modules
- Si, SiC and GaN
- ±20 V, < 90 A – Flexible Gate Drivers
- < 30min from power on to measurement start





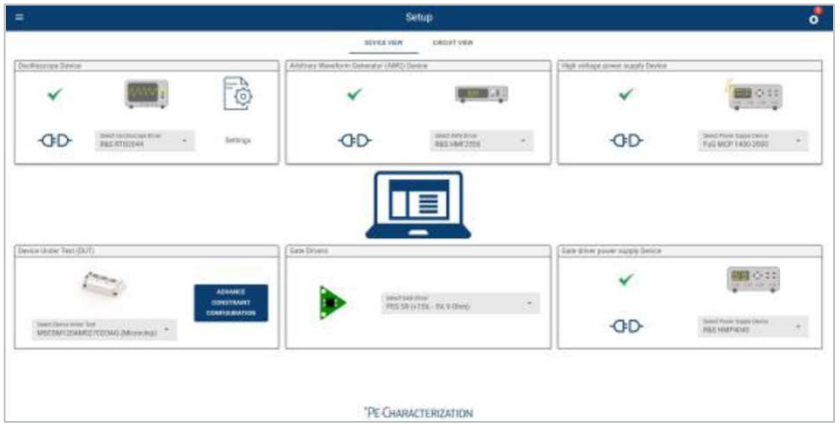
Rohde & Schwarz

ELECTRIC DRIVETRAIN
DOUBLE-PULSE TESTING SOLUTION

Rohde & Schwarz

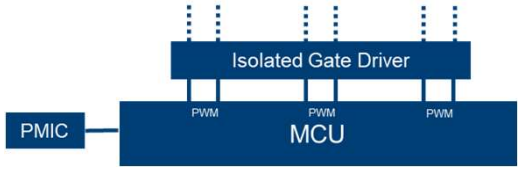
Software is the key

- ▶ Automated device tests
- ▶ Measurement across various temperature cycles
- ▶ Conflict manager for human error reduction
- ▶ Data analysis and management
- ▶ Uncertainty quantification and device modelling
- ▶ Innovative de-skew function



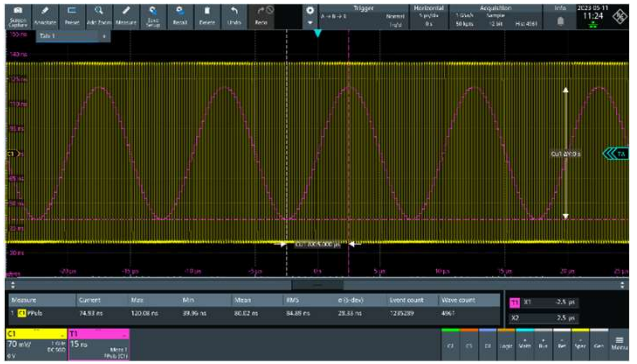
ELECTRIC DRIVETRAIN GATE DRIVER CHARACTERIZATION

- The Gate driver is responsible for controlling the switching of the semiconductor devices
- PWM signals are generated from the MCU using the space vector modulation (SVM) scheme.
- From the motor the voltage, current and position signals are sensed and fed back to the controller to modify the modulation of the inverter.
- Oscilloscopes with more channels
- Verify PWM Control Algorithm
- Debug of parasitic coupling from the switch node to the gate causing shoot-through conditions
- Power supplies to power and mimic the MCU



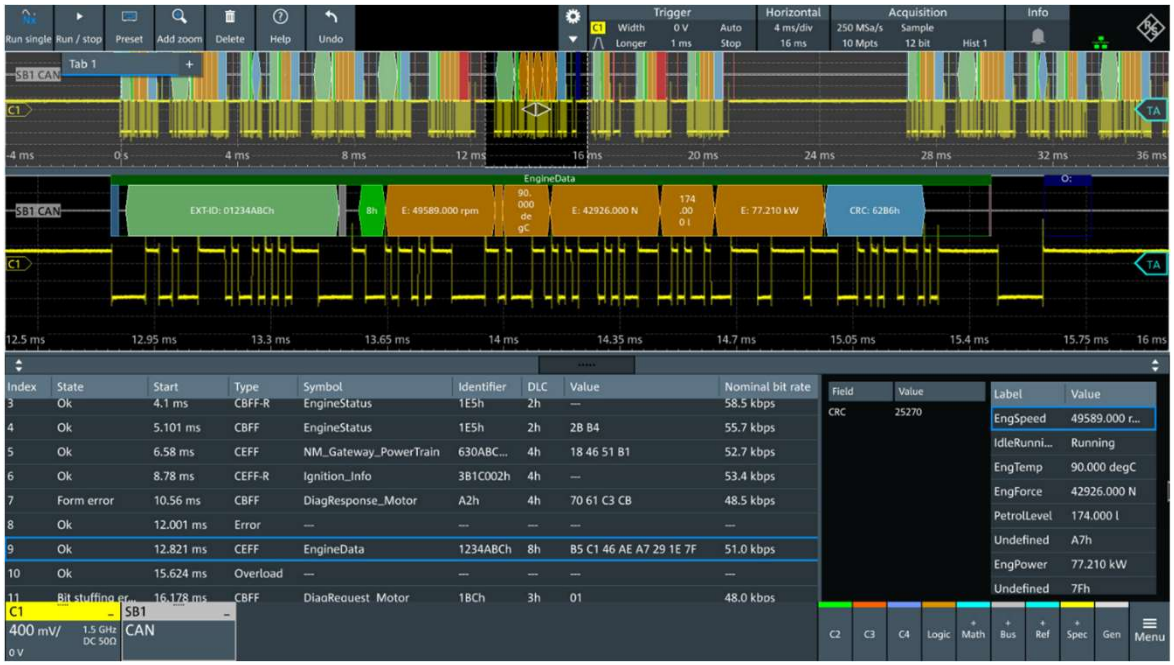
ELECTRIC DRIVETRAIN
ISOLATE FAULTS

- **Measure voltage and current waveforms**
  - Identify anomalies
- **Capture transients**
  - Digital trigger capabilities
  - Diagnose faults
- **Monitor signals**
  - PWM
  - Feedback
  - Control
- **Measure timing**
  - Timing issues occur if signals are not synchronized correctly

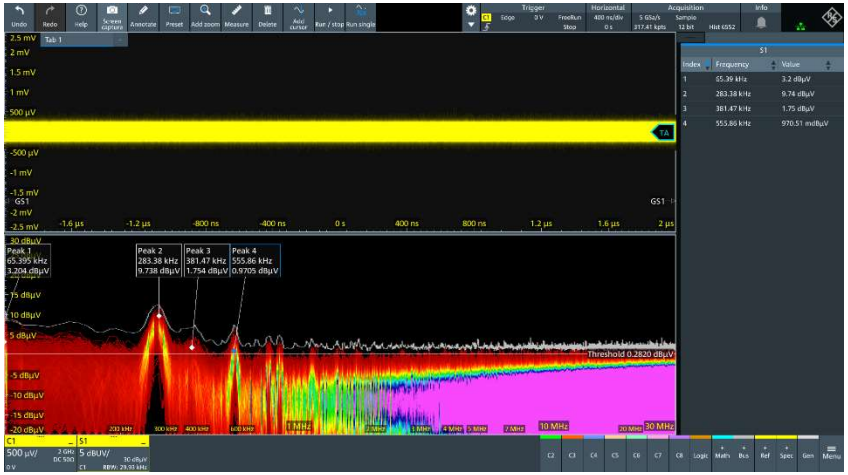


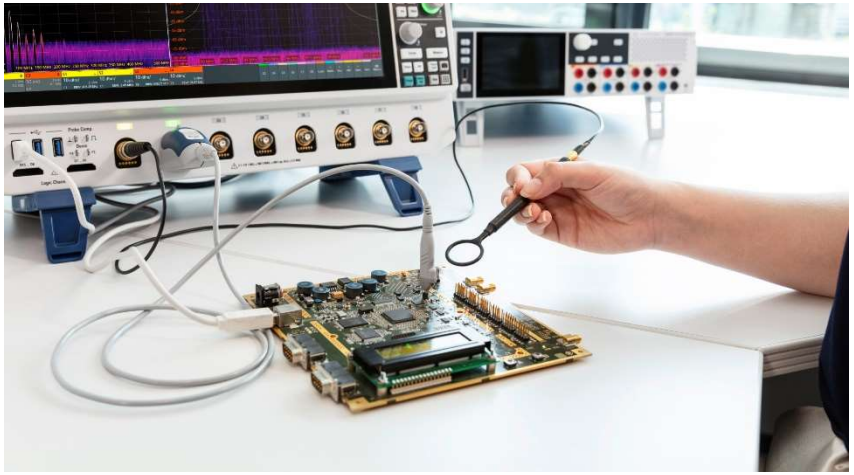
ELECTRIC DRIVETRAIN PROTOCOL ANALYSIS

- Supports CAN, CAN FD, CAN XL, LIN, Auto Ethernet, etc.
  - Motor control
  - BMS
  - Regenerative braking
  - Safety systems
- Hardware-based decoding ensures spotting and capturing errors on the bus
- Time-correlated decoding to the captured analog waveform
- Flexible display of decoded data
  - Color coding for each sections of the frame
  - Data can be displayed in ASCII, Hex or binary
- Powerful trigger capabilities to isolate specific ID, data or errors



ELECTRIC DRIVETRAIN EMI DEBUGGING





- Standard fast spectrum with 45k FFTs/second
- Support log-log scale and dBuV display of unit
- Peaklist, min/max-hold and intensity grading

EZ-17 Current clamps support 20 Hz to 245 MHz
HZ-17 Near Field Probes support 30MHz to 3GHz
HZ-16 Amplified extend HZ-17 down to 9kHz

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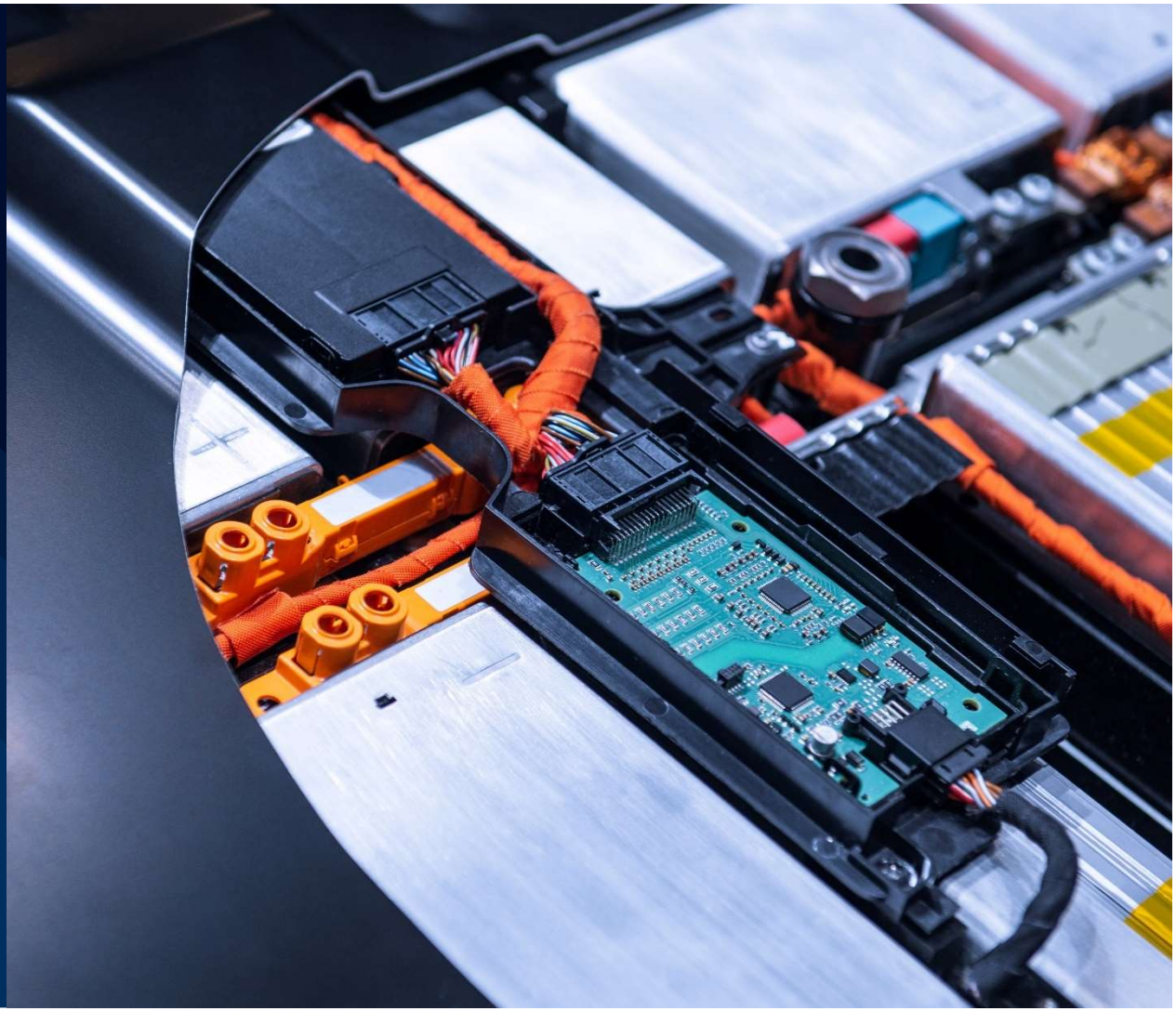
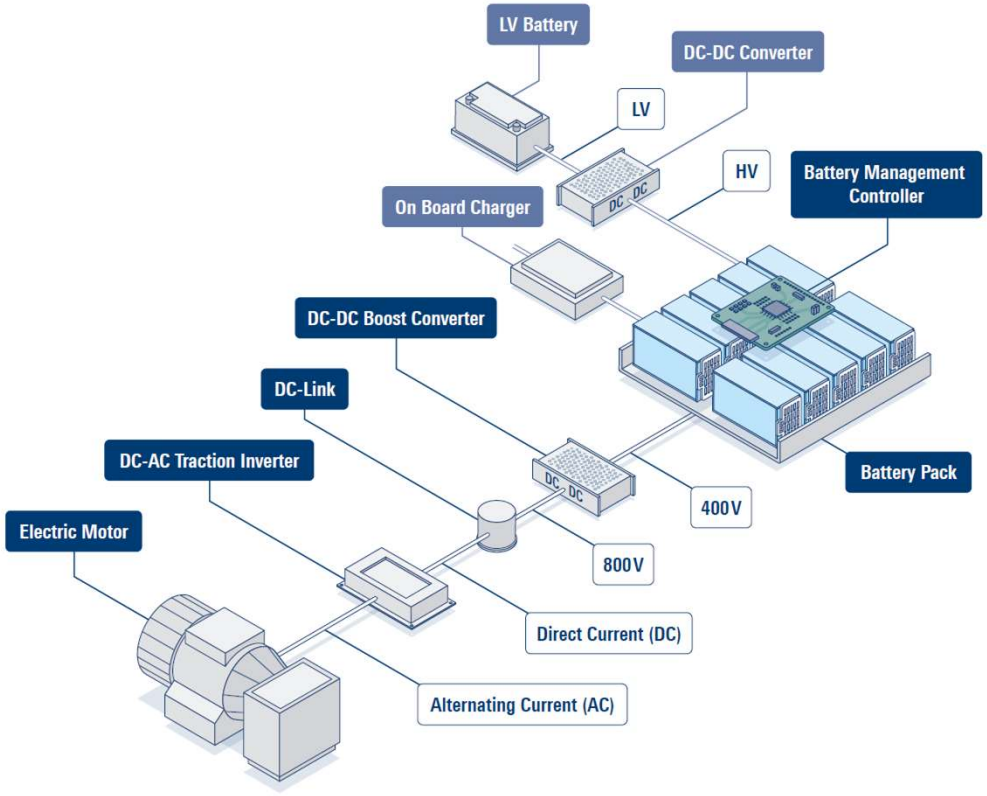


POWER SUPPLIES

Are needed to test the different blocks of the electric drivetrain

- On-board charger:
  - AC and DC bidirectional power supplies
- HV to LV DC-DC converter:
  - DC power supply and DC load
- Battery pack
  - DC bidirectional power supplies to emulate the battery cells in the BMS
- Traction inverter:
  - DC power supply
- Electric motor:
  - AC 3-phase power supply



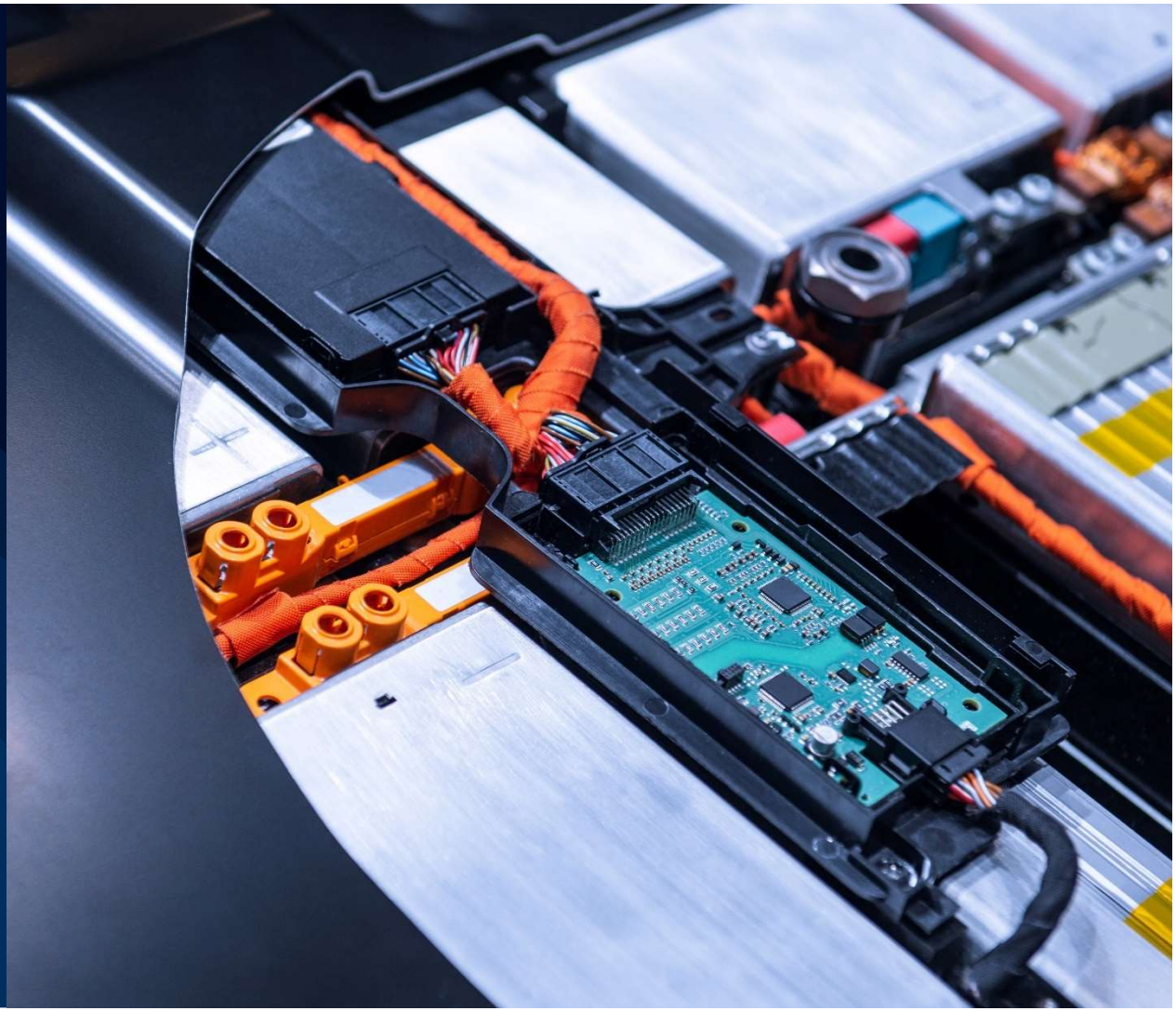
CONVERTER TESTING

- The DC-DC converters in the drivetrain are powered by the 400 V / 800 V battery pack.
- These converters must be tested under various conditions, which are challenging to emulate using a battery pack alone.
- Consequently, a dedicated power supply is required to conduct comprehensive tests on the converters within the electric drivetrain.

- The NGT series power supplies can be used for the higher power applications in the electric drivetrain
- Low voltage and current ripple
- A voltage of 400 V is achieved by connecting three units in series

CONTENT

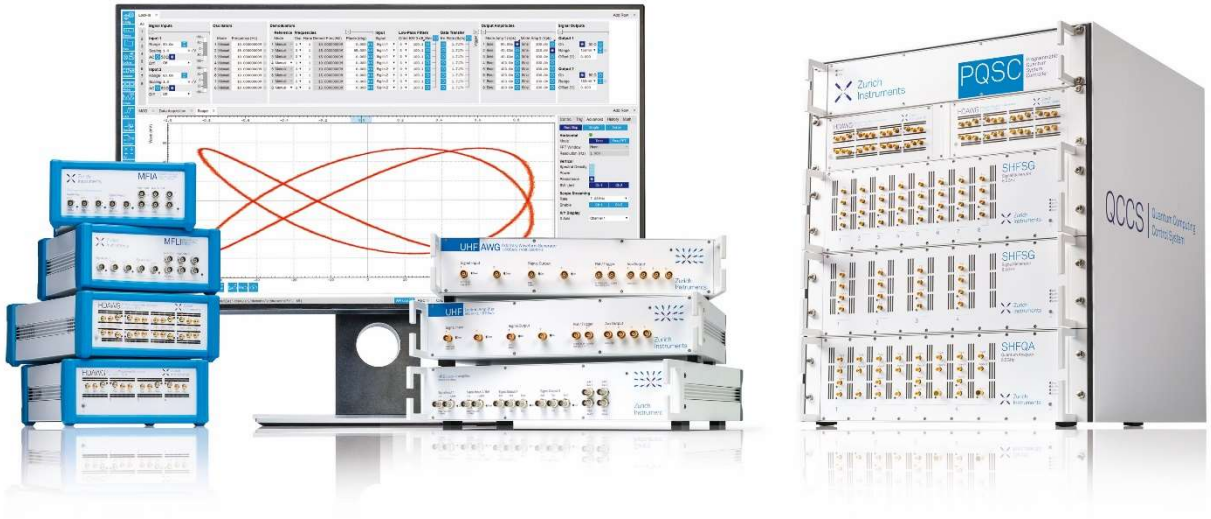
- Electric drivetrain technology & market trends
- Traction inverter development challenges
- Test applications & solutions
  - Oscilloscopes
  - Power Supplies
  - Impedance Analyzers
- Summary and learnings



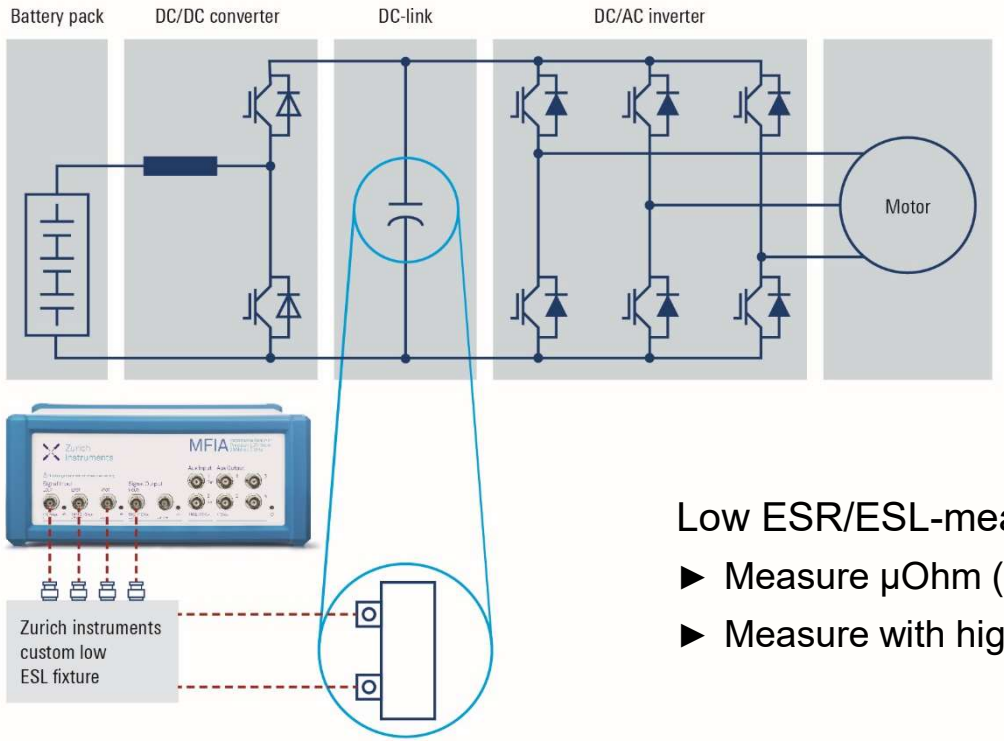
ZURICH INSTRUMENTS – OUR MISSION

Provide the best-in-class dynamic-signal instruments for advance R&D labs

Since 2021: Part of the Rohde & Schwarz family



PRECISE IMPEDANCE MEASUREMENTS IN AUTOMOTIVE



Low ESR/ESL-measurements of DC-link capacitors

- ► Measure µOhm (ESR) and nH (ESL) with high accuracy
- ► Measure with high reproducibility and repeatability

CHARACTERIZATION OF LOW-ESL/ESR DC-LINK CAPACITORS

What does a DC-link capacitor do?

- ► Balancing electrical storage device
- ► Reducing ripples and transients during switching

Why are ESR/ESL important parameters?

- ► Maximizing efficiency by reducing heat
- ► Reducing voltage spikes during switching

Who is interested in knowing these parameters?

- ► E-mobility manufactures have interest in integrating parts with lowest possible ESR and ESL
- ► Component manufactures need to make solid claims about ESR and ESL in specs sheet

THE MFIA IMPEDANCE ANALYZER

Innovative architecture of the MFIA enables

- ► Measurements in a broad impedance range from 1 mOhm to 1 TOhm
- ► Measurements in a broad frequency range from 1 mHz to 5 MHz
- ► Fast impedance measurements, fastest LCR mode available (10 µs at 1 MHz)

LabOne Instrument Control Software provides

- ► Time domain and frequency domain toolset; Sweeper, Plotter, DAQ, Scope and many more
- ► Advance control via API suite (C, MATLAB, LabVIEW, Python, .NET)

Accurate and precise over a wider range than most impedance analyzers

CHARACTERIZATION OF LOW-ESR/ESL DC-LINK CAPACITORS

Your challenges

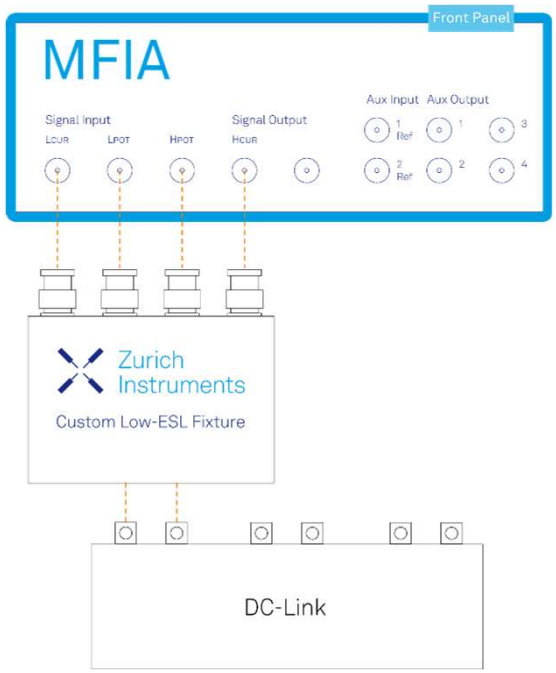
- Understanding ESR and ESL characteristics for the actual frequency of operation, not just the frequency specified in the specs sheet
- Having a demand for an instrumental setup with high reproducibility and repeatability
- Performing accurate low-Z measurements involving zero-reference plan for changing setups
- Requiring well-defined connections when measuring low inductances
- Precisely studying component aging effects

Our solution

- Measure ESR & ESL in the µOhm & nH range as well as other relevant parameters such as d or C
- Perform application-specific user compensations for accurate measurements
- Sweep f to measure ESR, ESL, d and C at frequencies relevant to your application
- Simultaneously display ESR, ESL, D and C using our Plotter and Sweeper tab

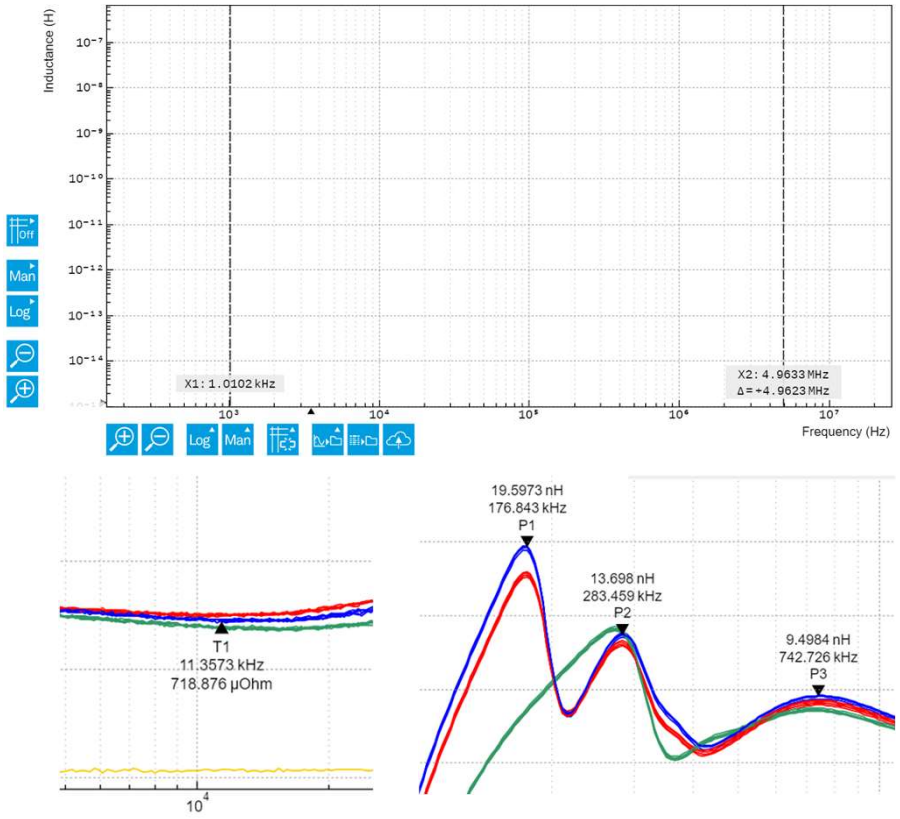
LIVE DEMO:
CHARACTERIZATION OF DC-LINK CAPACITORS

- Impedance spectroscopy of application related parameters over 1 kHz to 5 MHz
- Perform short user-compensation with low measurement baseline for high accuracy
- Measure and record ESR/ESL as a function of frequency and time
- Employ mathematical tools (average, min/max, histogram) for statistical analysis
- Display multiple relevant parameters on the same chart in the Plotter or Sweeper tab
- Display multiple traces on the same chart to show high repeatability and reproducibility



YOUR BENEFITS

- ► Reduce risk of overheating and voltage spikes by confirming the ESR/ESL before design or assembly
- ► Study aging effects of your components
- ► Enhance your component product offering with reliable and credible ESR/ESL spec-sheet values over a frequency range, not just at fixed value
- ► Support the development of innovative DC-Link capacitors by measuring the ESR/ESL quickly and easily during the R&D stage
- ► Optimize your setup by integrating the MFIA into your test set-up thanks to well-developed API control
- ► Provide flexible impedance measurement modes for your R&D lab



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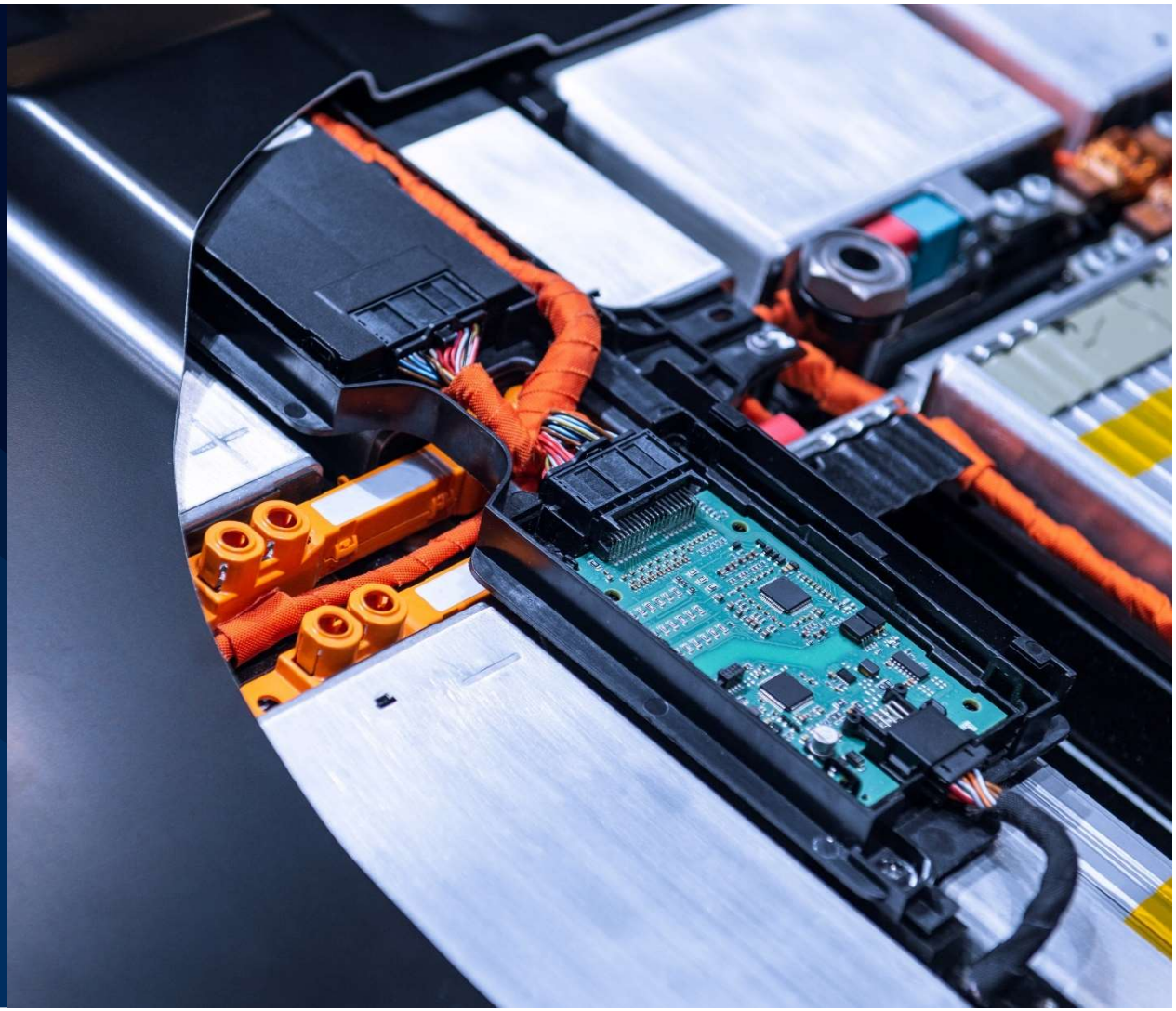

SUMMARY AND LEARNINGS

- The traction inverter fullfills a critical role in the electric drivetrain, influencing overall EV performance
- Rapid developments in inverter technology towards higher voltage, fast switching semiconductors & closer integration as OEMs seek to balance output against space, weight, cost & sustainability
- These translate to new measurement challenges and test equipment evolution. High performance analytics tools required
- Multi-channel, high-performance oscilloscopes & probes from R&S provide awareness of transients in real time as well as EMC, protocol, power efficiency and switching behavior
- Reduced risk for DC-Link / Bulk Capacitor overheating and voltage spikes by early validation with accurate impedance analyzers and LCR meters
- **Holistic approach to testing enables marginal gains to be identified in development and de-bugging process to optimize traction inverter efficiency**


Find out more:
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