# Webinar

## 3 semiconductor technologies redefining the EV experience

**Jerry Shi**

**Texas Instruments**

# Agenda

- **Electrochemical Impedance Spectroscopy (EIS) enabled BMS**
  - What are the challenges of traditional BMS?
  - What is Electrochemical Impedance Spectroscopy (EIS)?
  - What is the value of EIS-enabled BMS?

- **Single-stage OBC powered by bidirectional GaN**
  - Why single-stage topology?
  - What are the challenges in single-stage OBC design?

- **Optimal Pulse Positioning (OPP) algorithm for traction motor control**

# Vehicle electrification challenges

Constraints that are redefining EV system architecture

**Battery internal state is becoming less observable**

- Higher voltage / larger packs → increased system complexity
- Fast charging → accelerated aging & safety uncertainty

**Onboard power conversion constraints**

- Efficiency, size and thermal limits

**Motor control constraints**

- Switching losses and noise, vibration, and harshness (NVH) tradeoffs

# BMS with integrated Electrochemical Impedance Spectroscopy (EIS) engine

# Challenges of traditional BMS | Thermal runaway

## Thermal runaway of lithium-ion cells

Thermal runaway can be triggered by:

1. **Overcharging**: When a battery is pushed beyond its limits, it may overheat and enter thermal runaway.
2. **Physical damage**: A punctured or damaged cell can lead to internal short circuits, causing rapid heating.
3. **Overheating**: Excessive heat from external sources or internal factors can trigger it.

In case of single cell thermal runaway:

**Heat generation**: The effected cell generates intense heat, further exacerbating the situation.

**Gas release**: As the battery heats up, it releases flammable gases.

**Pressure build up**: These gases, coupled with material expansion due to heat, increase internal pressure.

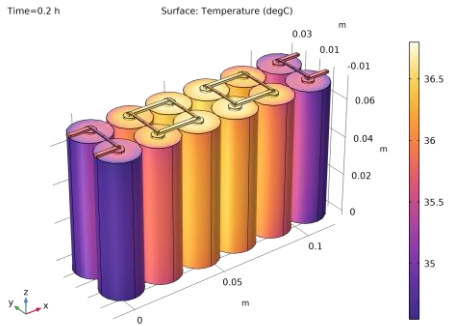
Cell rupture → Fire + propagation

## Regulations becoming stricter

- NHTSA safety initiative / NTSB
- GB 38031-2025 – mandates 5 min detection time after single cell TRA happens

## Traditional BMS measures temperature with NTC

- Delayed detection on surface of grouped cells



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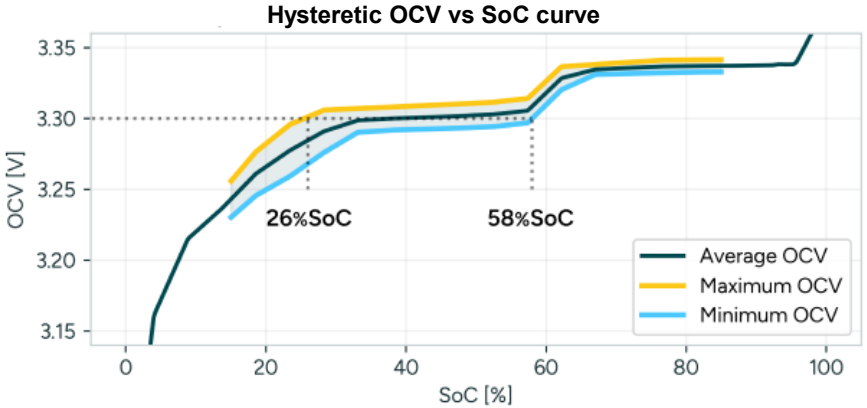
# Challenges of traditional BMS | SoX estimation

## SoC estimation

- LiFePO4's flat OCV-SoC curve is hard for SoC estimation
- Affected by temperature, aging and dynamic load

## Health and reliability

- Inconsistency, defects, and Remaining Useful Time (RUL) estimation challenges




Algorithm accuracy is essential: Getting a guaranteed state of charge, part 1 - Shyam Srinivasan 4, 2024

# What is Electrochemical Impedance Spectroscopy (EIS)?



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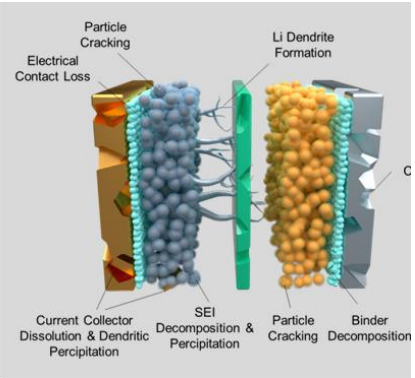
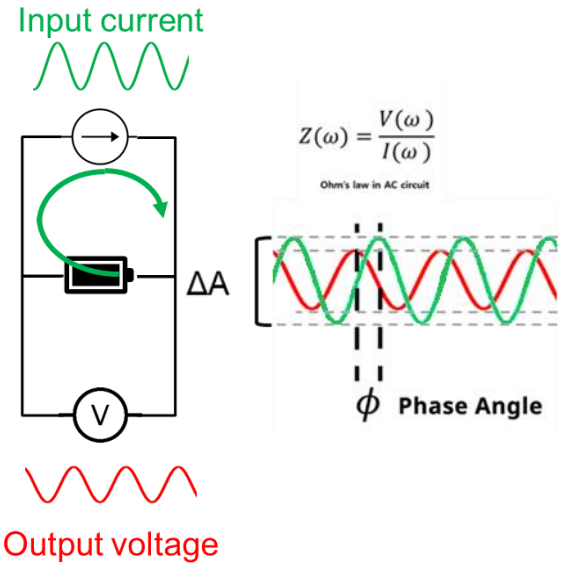
# What is EIS?

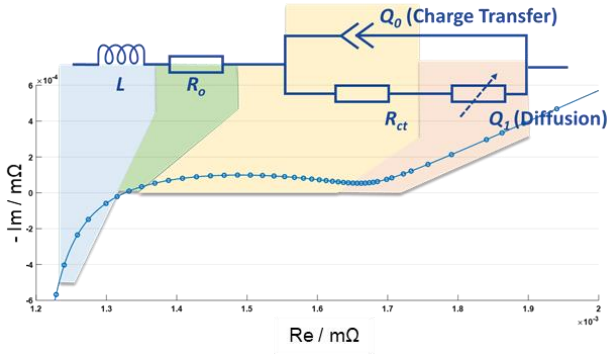
## Electrochemical




## Impedance




## Spectroscopy






*Zhou Sida, Gao Zichao, Dong Honglei, Zhou Xinan, Zheng Yifan, Ma Tianyi, Ming Hai, Lian Yubo, Chen Fei, Yang Shichun, Vehicle-cloud-collaborated prognosis and health management for lithium-ion batteries: Framework, technics and perspective, Energy Storage Materials, Volume 70, 2024, 103531, ISSN 2405-8297,*

# What is the value of EIS-enabled BMS?



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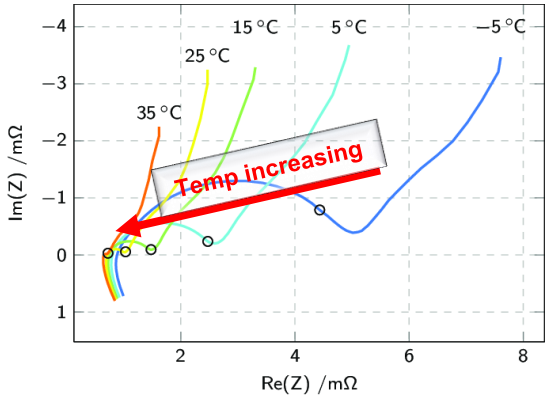
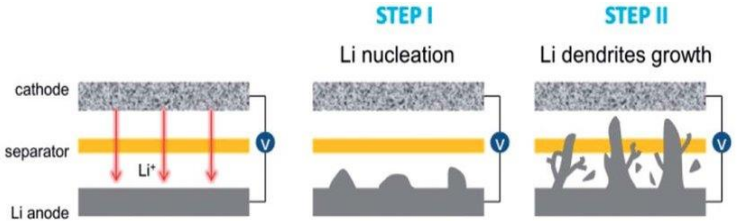
# EIS value | Early thermal runaway detection

1. **Accurate *single* cell *core* temperature measurements**
   - EIS directly measures **core temp** for **each** cell with no delay

2. **Early short detection preventing *predictable* thermal runaway**
   - Monitors lithium diffusion to prevent lithium plating and dendrite growth that can lead to overheating, shorts




Dendrite growth pierces the separator from lithium plating



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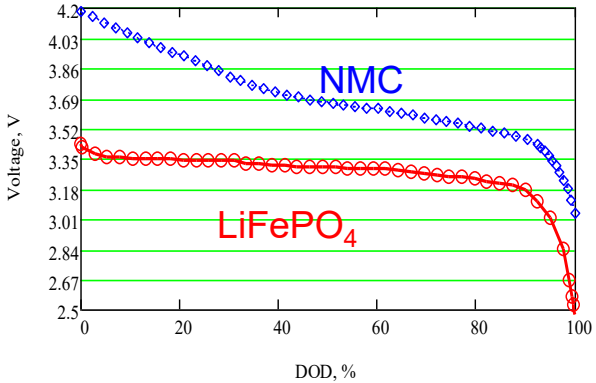
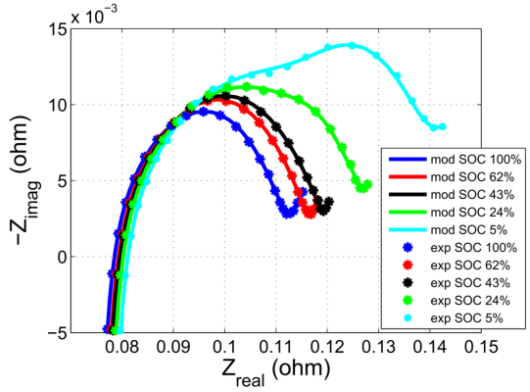
# EIS value | SoX estimation

**Higher accuracy SoC/SoH estimation (esp. LiFePO4 flat OCV cells):**

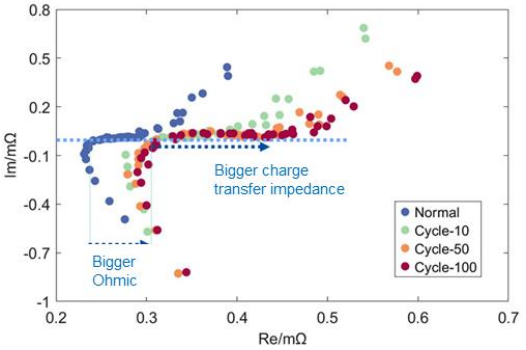
- Increased range/remaining runtime (RRT) with same pack capacity
- Prevent the EV from running out of charge roadside due to inaccurate mileage




Flat OCV brings challenges to SOC estimation




'See' SoC changes thru EIS




'See' battery aging thru EIS



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# Single-stage OBC



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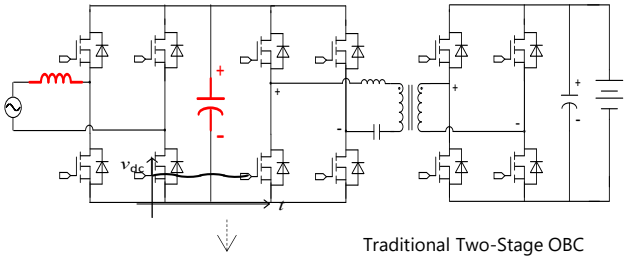
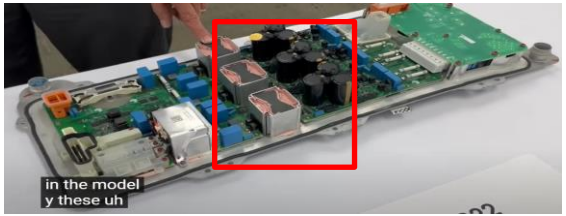
# OBC topology evolution

## Two-stage

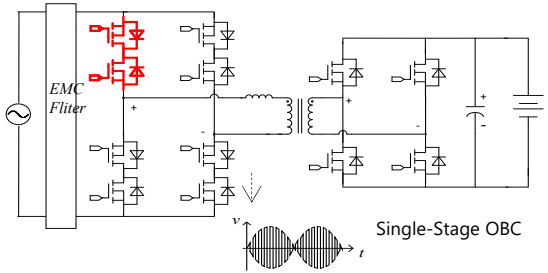



Traditional Two-Stage OBC

- PFC + DC/DC split
- Bulky inductor + electrolytic DC-link
- Mature, low-complexity

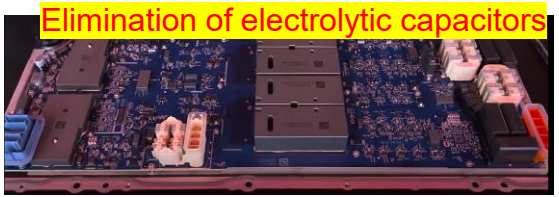



## Single-stage




Single-Stage OBC

- Direct AC-DC conversion
- Remove PFC inductor and DC-link capacitors
- Bidirectional switches




**High efficiency and power density**

Reduced component count leads to higher power density (>5 kW/L) and higher peak efficiency.

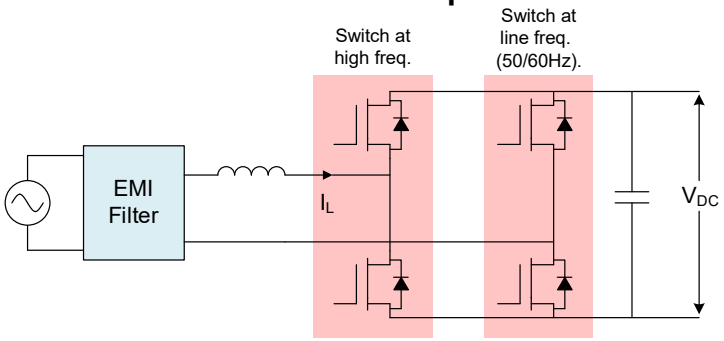
# Single-stage OBC | Design challenges

- **Optimal control and stability**
  - Unlike two-stage systems that separate PFC and DC-DC, single-stage converters require complex, fast-acting control loops to manage both power factor and output regulation simultaneously.

- **Wide bandgap semiconductors**
  - Single-stage designs must achieve high efficiency over a wide, changing output voltage (from low to high state-of-charge), particularly for 800-V systems, which can increase component voltage stress.
  - Using wide bandgap semiconductors such as Gallium Nitride (GaN) allows for high-frequency switching and better thermal performance in smaller footprints.
  - Bidirectional switches are required.

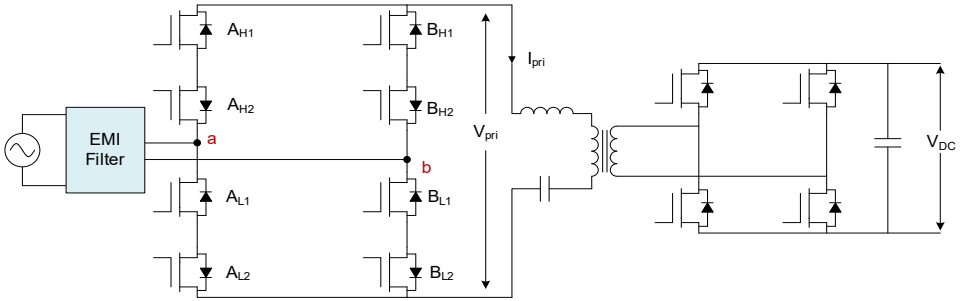
# Key challenge in SS OBC | Commutation

## Traditional totem-pole PFC



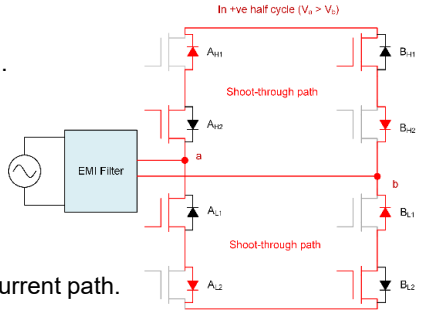

- **Potential COS event** (current overlap shoot-through)
  - Shoot-through between high-side and low-side FETs.
  - Add dead-time between high-side and low-side FETs.
  - **Conventional PWM modules' dead-band feature sufficient.**
- **Potential VOS event** (voltage open-circuit stress)
  - Maybe caused if $I_L$ is interrupted.
  - In conventional H-bridge, $I_L$ wont be interrupted even if all FETs are off
  - Diodes always provide a current path.
  - **No concern**

## Matrix, single-stage converter




- **Potential COS event**
  - FETs in shoot-through path change as $V_{AC}$
  - When $V_{AC}$ is +ve, $A_{H2}$, $B_{H1}$ should not be ON simultaneously. Similarly, $A_{L2}$, $B_{L1}$ shouldn't be ON.
  - Vice-versa for –ve half cycle.
  - With correct PWM assignment to FETs.
  - **Easy to solve**
- **Potential VOS event**
  - Is caused if $I_{pri}$ is interrupted.
  - AC switches, if switched incorrectly, will interrupt current path.
  - **Major concern, requires cross PWM module synchronization**

**Shoot-through paths when $V_{AC} > 0$ (vice-versa when $V_{AC} < 0$)**



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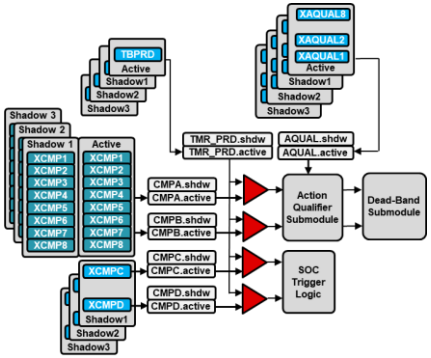
# Type-5 ePWM | Complex waveform generation

➡ **Generates up to four pulses within one ePWM period**



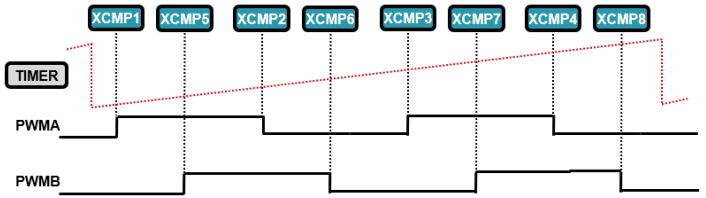

**Benefits:**

✓ Generate complex waveforms without the need for complex logic

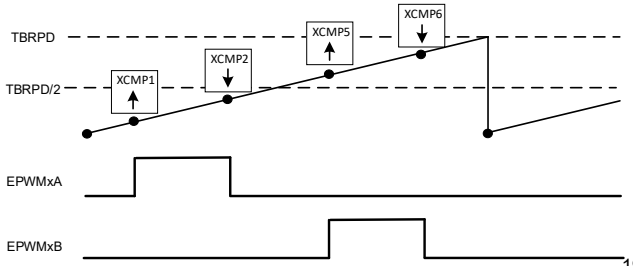
✓ Designed for High Frequency Resonant and matrix topologies

**Highlights**:

- 8 comparator values (XCMP1-8)
- 3 sets of shadows for each XCMP value
  - Action qualifier event for each XCMP value
- 8 XCMP values can be allocated to CMPA or 4 to CMPA and 4 to CMPB




- All 8 or a subset of XCMP values can be used within one period
- Simplifies complex, non-complimentary PWM generation using XCMP feature



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# F29H85x | C2000™ 64-bit MCU with C29x tri-core

## Product

Automotive C2000™ 64-bit MCU with C29x 200MHz tri-core, lockstep, functional safety compliance, 4MB

- Advanced Safety with multi core concept: C29x (200MHz, 1200 MIPS / 400LS + 400 MIPS).
- 2x computation performance than classical C2000 (C28)
- PWMs designed for future of power electronics with Matrix Converters, Multi Level Converters, Dual Active Bridge and Resonant Converters.
- Configurable Logic Block (CLB) for FPGA-like flexibility
- 3x 12b ADC and 2x 16b ADC converters with safety redundancy support
- Comparators with DAC and ramp generator for peak current mode control and hysteretic control
- Hardware Security Module (HSM) for Evita-Full Security Concept.
- ISO 26262 ASIL-D Systematic and random hardware capabilities

## Benefits & Features

### Real-time control processing

- C29 CPU: VLIW architecture and 8 parallel instructions
- 2-3x signal chain performance
- ~1us real-time motor control loop
- Optimized for Edge AI computation

### Real-time sensing and actuation

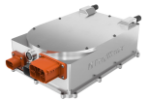
- Fast 11 cycle response to interrupt with user configurable priority
- Type 5 ADC post-processing HW with configurable averaging and filtering
- Type 5 PWM support, Multi-threshold compare, PWM HW sync and more

### Safety & security

- Lock-step ASIL-D with BIST
- FFI & Security with 0 SW overhead
- Isolated HW security context
- ADC safety checker in HW
- ISO-21434 & ISO-26262

## Key Markets

Traction inverter



OBC

DC-DC

BMS

EPS

Braking

Active suspension



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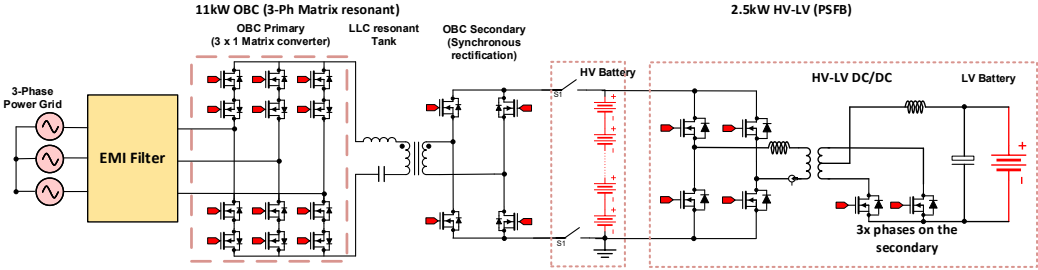
# TIDM-02021 | 11kW single-stage OBC (matrix resonant) with integrated HVLV DCDC

## Design features

- 11kW Single stage On-Board Charger with Matrix topology (80kHz - 250kHz with 150kHz resonant frequency)
- 2.5kW PSFB with Zero Voltage Switching(300kHz)
- Single TI **C2000 MCU (F29H85x)** used for control
- **Greater than** 96.5% Grid-to-Battery full-load efficiency
- 450 - 850V OBC output (HV battery voltage range)
- 9V -16V HVLV DCDC output
- Power density for OBC is 5.5kW/L (2L) & HVLV is 8.9kW/L (0.28L)



Available on ti.com

## Design benefits

- **Integrated** hardware and Firmware
- Extremely **power dense**
- **No** bulky **DC link capacitors**
- **New Type-5 ePWM** to simplify the complex PWM logic generation
- No additional discrete logic components or expensive FPGA



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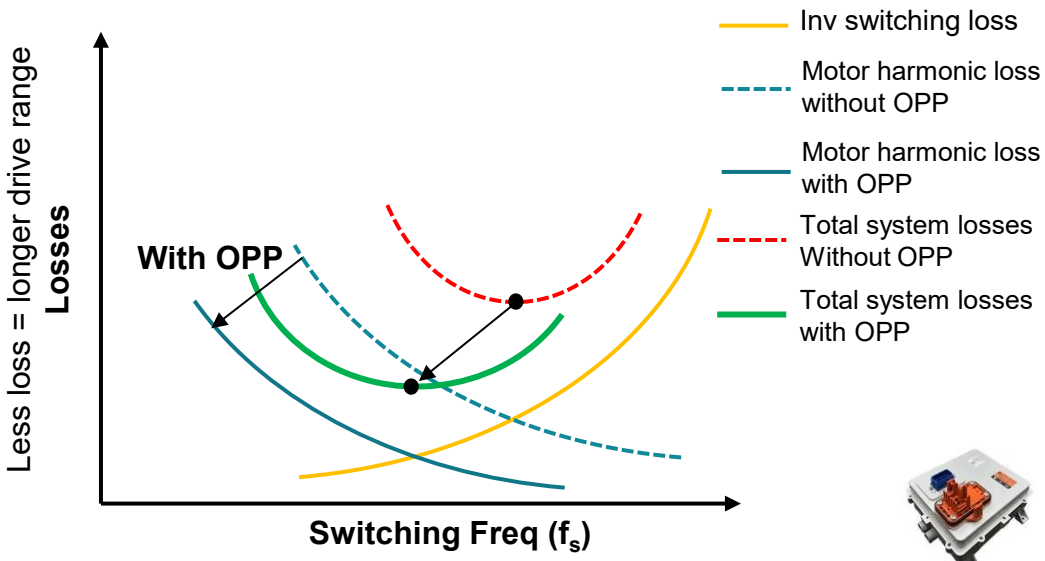
# Optimal Pulse Positioning (OPP) for traction inverters

# Higher traction inverter efficiency with OPP

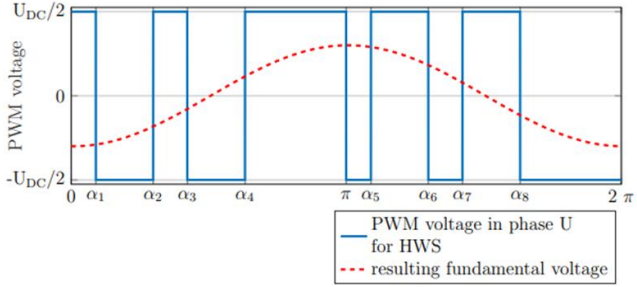
## Challenges to enable higher traction efficiency



OPP enables smooth phase current sin wave generation at lower switch freq. → optimizing driver experience (torque) while maximizing drive range

## What is OPP?

- In OPP, the switching angles within a motor fundamental frequency period are “optimized” offline to minimize current harmonics.
- Optimized switching angles are loaded into look up table.
- Based on modulation index required, a set of switching angles are chosen to switch the phase voltage.



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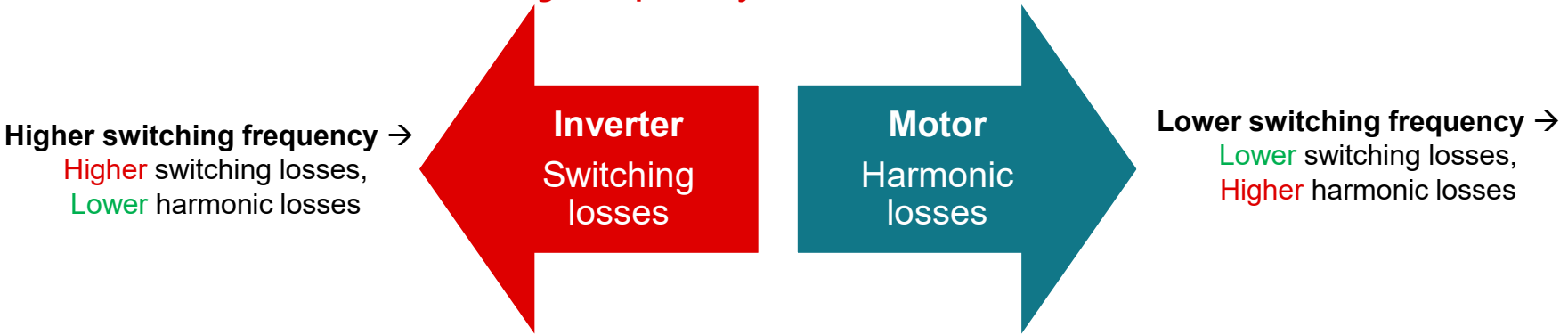
# System-level benefits of OPP

Inverter switching frequency **α** 1 / motor current harmonics




**Optimal Pulse Positioning*-**

**Best of both**

**A technique to lower switching frequency while reducing switching harmonics**

*Reference- Optimized Pulse Patterns to Minimize the Current Harmonic Content in the DC-link of a two-level VSI .

# OPP design challenges | Why F29H85x MCU?

1. OPP implementation is **complex and computation-heavy** vs. traditional SVPWM approach

2. Due to fast motor control loop enabled by F29x, **leverage spare CPU bandwidth to implement OPP**

3. F29x supports features to implement OPP: **VLIW arch** (parallel instruction execution), **HW accelerators** for complex math (TMU), state-of-art **Type 5 ePWMs**

# Achieve 1us motor control loop with F29H85x MCU

## F29 MCU

**Application**

- Multi vendor AutoSAR support
- No-cost FSQ[4] MCALS
- Higher system efficiency with OPP
- Software RDC saves system cost
- Edge AI capability

**Protection**

- Tightly integrated, mixed-signal, on-chip protection infrastructure.
- Nano-second scale trip latency.
- On-chip configurable logic for sophisticated fault response.

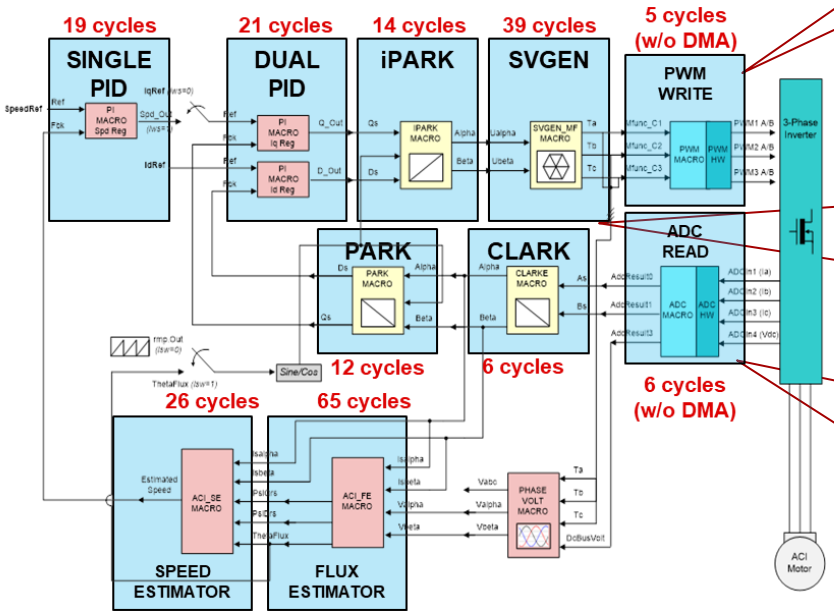
**Functional Safety**

- Configurable CPU lock-step for ASIL-D
- End-to-end safe interconnect
- SSU[1]- functional isolation at HW level.
- HW ADC redundancy checker
- Extensive safety collateral, tool support.

**Cybersecurity**

- Best-in-class dedicated HSM[3].
- HW accelerators for latest crypto standards
- SSU[1]- debug, execution safety.

**End-to-end Motor Control Loop takes only 213 CPU cycles (1.06 us)!**




- Type 5 ePWM for high-efficiency modulation schemes
- ps resolution switch edge placement

- C29 CPU's **VLIW architecture** enables **very-high instruction throughput**.
- 0-wait state RAM for program execution
- Execution from flash at 80-90% of RAM performance.
- **Trigonometric math** instructions **native to ISA**

- 12-bit 4 MSPS SAR ADCs.
- 16 bit 1 MSPS ADCs
- Ultra-fast S/H, conv times
- HW post-processing block-offset removal, oversampling, range check, ZCD
- Tightly coupled to ePWM blocks for deterministic, precise control over sampling instant vs PWM waveform.
- Filter, delta output



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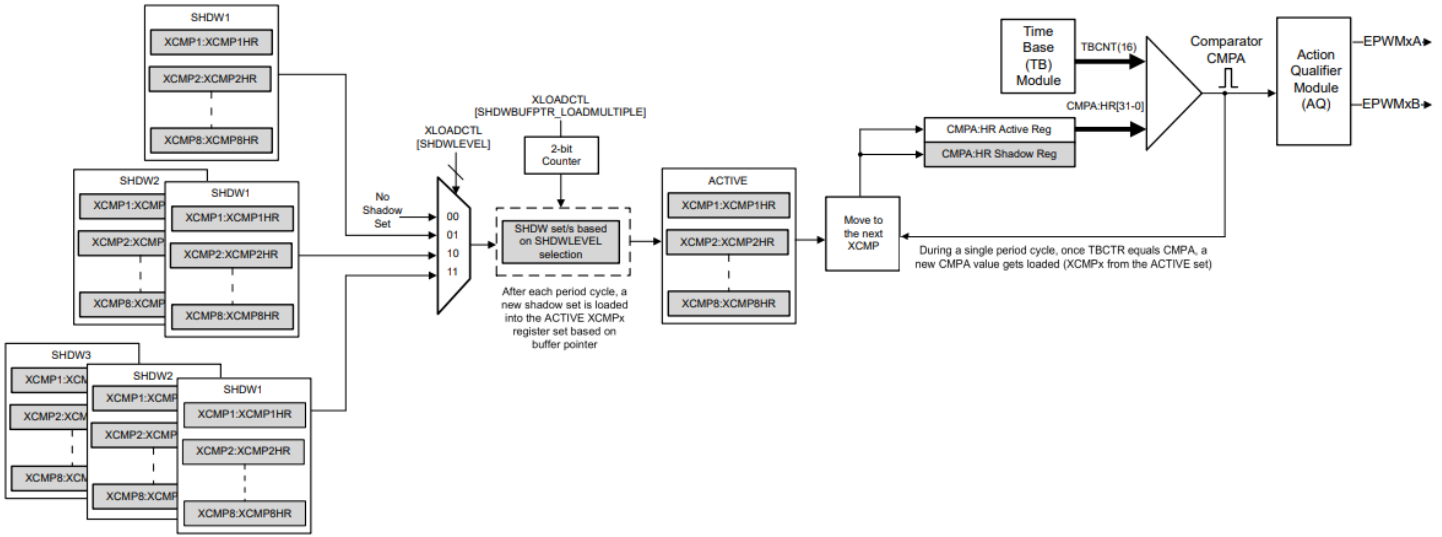
# OPP implementation with Type-5 ePWM

- XCMP Complex Waveform Generator feature allows up to 8 CMP values to be loaded in each PWM period
- Further, up to 3 shadow register sets are supported for automatic loading of CMP and PWM action settings



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# TIDM-02014 | 300kW, 800V SiC traction inverter

## Features

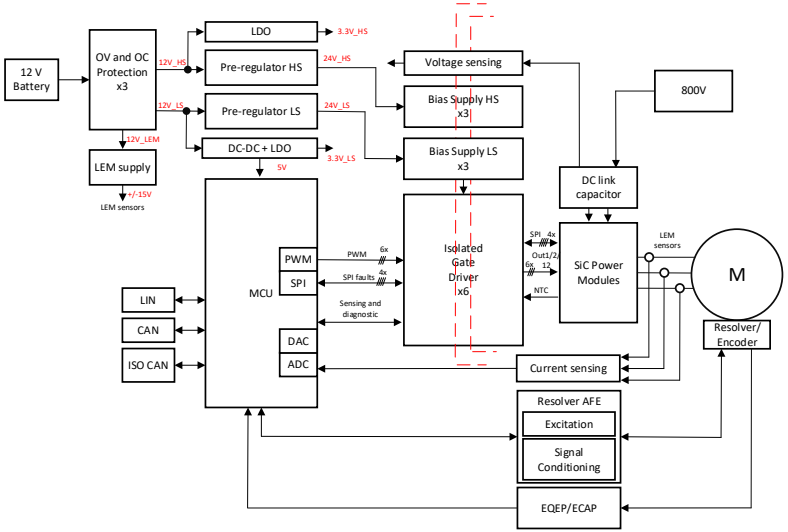
- 800V, 300kW SiC Traction inverter reference design featuring TI solutions with XM3 SiC power module from Wolfspeed
- High-performance microcontroller (MCU) with three C29 real-time digital signal processor (DSP) cores enable motor control loop with < 2µs
- System efficiency improvement by using the TI's safety compliant Isolated gate driver UCC5880-Q1 with Adjustable GD strength
- Advanced bias supply with integrated transformer technology
- Highly integrated voltage sensing devices for the direct connection to the high-voltage source
- SW based resolver to digital conversion (RDC) AFE and software

  CAN-FD support

## Tools & resources

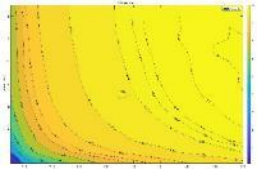
- TIDM-02014 reference design
- **Key TI devices:** F29H85x-Q1, UCC5880/1-Q1, UCC14240/1-Q1, AMC0386-Q1, AMC0381D-Q1, UCC33421-Q1, TCAN1043-Q1, TCAN1042-Q1, ALM2403-Q1, TMCS1200-Q1

## Block diagram



TIDM-02014

UCC5880-INVERTER-EVM



Test results

# Getting started

You can start evaluating this device leveraging the following:

| Content type | Content title | Link to content or more details |
|---|---|---|
| Blog | 3 semiconductor technologies that are redefining the EV experience | https://www.ti.com/about-ti/newsroom/company-blog/3-semiconductor-technologies-that-are-redefining-the-EV-experience.html |
| Product folder | F29H85x C2000™ 64-bit MCU with C29x 200MHz tri-core | https://www.ti.com/product/F29H859TU-Q1 |
| Reference design | 11kW three-phase bidirectional onboard charger and low-voltage DC-DC reference design | https://www.ti.com/tool/TIDM-02021 |
| Reference design | High-power, high-performance automotive SiC traction inverter reference design | https://www.ti.com/tool/TIDM-02014 |
| Portal page | Hybrid, electric and powertrain systems webpage | https://www.ti.com/applications/automotive/hev-ev-powertrain/overview.html |

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