Robust Gate Driver Solution for High-Power-Density xEV Chargers using Silicon Carbide (SiC) MOSFETs

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Outline

• Introduction of SiC MOSFET and its Application for xEV chargers
  – SiC MOSFET Application Positioning
  – SiC MOSFET vs Si MOSFET & IGBT
  – Typical xEV charger topology

• Key Gate Driver Requirements for SiC MOSFET in xEV chargers
  – Driver voltage
  – CMTI (dv/dt) capability
  – Short circuit /Over current protection
  – Isolation

• TI Designs
  – TIDA-01604: 98.6% Efficiency, 6.6-kW Totem-Pole PFC Reference Design for HEV/EV Onboard Charger
  – TIDA-01605: Automotive Dual Channel SiC MOSFET Gate Driver Reference Design with Two Level Turn-off Protection
SiC MOSFET Application Positioning

- **EV charger:** 3.3kW - 22kW
- **Traction inverter:** 15kW - 400kW

Diagram:

- **Si:** 10W - 1kHz
- **Si SJ:** 10W - 10kHz
- **SiC:** 10W - 100kHz
- **GaN:** 10W - 10MHz
- **IGBT/GTO:** 1MW - 1MHz
SiC MOSFET Advantages over Si SJ MOSFET

- Lower specific Rds(on) especially for >650V devices;
- Low body diode reverse recovery.

Use SiC, GaN devices or Si IGBT!
SiC MOSFET Advantages over Si IGBT: Conduction

- No 0.5-1.0V knee voltage;
- Has “body diode”;
- 3rd quadrant operation mode.

![Graph showing forward current and voltage comparison between SiC MOSFET and Si IGBT.](image)

![Diagram illustrating power grid and switching elements.](image)
SiC MOSFET Advantages over Si IGBT: Switching

- **Low switching loss:**
  MOSFET (unipolar) vs IGBT (bipolar)- fundamental difference;

- **Switch loss less increase at elevated temperatures:**
  For 1000V SiC MOSFET, $E_{sw}@25^\circ C = E_{sw}@150^\circ C$

- **Low reverse recovery for the body diode:**
  Silicon PiN diode has significant reverse recovery which has reverse recovery loss and also adds more turn on loss.

[Typical switching waveforms]
OBC Charger PFC Topology - Single Phase Unidirectional

- Traditional Boost PFC
- Interleaved CCM Boost PFC
- Dual Boost Bridgeless PFC
- Semi-Boost Bridgeless PFC
OBC Charger PFC Topology - Single Phase Bidirectional

- Bidirectional power flow capability
- Further reduce conduction loss

Totem-Pole Bridgeless PFC

High freq SiC bridge

Low freq Si bridge

Q1

Q2

Q3

Q4

Power Grid

L

Vdc

Co

- Bidirectional power flow capability
- Further reduce conduction loss
Interleaved Bidirectional Totem-Pole Bridgeless PFC: Three phases interleaved design with 120° phase shift to reduce input current ripple
Interleaved Bidirectional Totem-Pole Bridgeless PFC Current Ripple
Bidirectional Totem-Pole Bridgeless PFC Current Ripple: without interleaving
OBC Charger PFC Topology - Three Phase Unidirectional

Boost Vienna Converter

System specs (example):
Vac_in: 3phase, 380Vac
Vdc: 750V
OBC Charger PFC Topology - Three Phase Bidirectional

T-type NPC

1200V SiC MOSFET or IGBT

650V SiC MOSFET or IGBT

System specs (example):
Vac_in: 3phase, 380Vac
Vdc: 750V
OBC Charger PFC Topology- Three Phase Bidirectional

System specs (example):
Vac_in: 3phase, 380Vac
Vdc: 750V
OBC Charger PFC Topology- Three Phase Bidirectional

System specs (example):
Vac_in: 3phase, 380Vac
Vdc: 750V

Three Phase Full Bridge

1200V IGBT or SiC MOSFET

L
OBC Charger DC-DC Topology - Unidirectional

**Phase Shift Full Bridge**

For $V_{bus} <= 400V$, $\sim 100kHz$: typically using 650V Si MOSFET;

For $V_{bus} > 400V$, $> 200kHz$: using SiC MOSFET.

**LLC (without or with synchronized rectifier)**

For $V_{bus} <= 400V$, $\sim 100kHz$: typically using 650V Si MOSFET;

For $V_{bus} > 400V$, $> 200kHz$: using SiC MOSFET.
OBC Charger DC-DC Topology- Bidirectional

For \( V_{bus} \leq 400\text{V}, \sim 100\text{kHz} \): typically using 650V Si MOSFET;

For \( V_{bus} > 400\text{V}, > 200\text{kHz} \): using SiC MOSFET.

For very high power, parallel and/or interleaving method will be adopted.
SiC MOSFET Driver Key Requirements

1. Driver voltage;
2. CMTI (dv/dt) capability;
3. Short circuit / Over current protection;
4. Isolation.
SiC MOSFET Driver Key Requirements: Driver Voltage

- Recommended positive driver voltage ranges from 15V to 20V, higher than typically 12V needed for Si MOSFET;
- Recommended positive driver voltage is close to absolute max, well regulated Vdd is required;
- Threshold voltage is low, and it is even lower for high temperature 150°C;
- Negative gate voltage -5V to -2V is recommended by most manufacturers to avoid parasitic dv/dt turn-on;
SiC MOSFET Driver Key Requirements: CMTI

Definition: Common mode transient immunity, CMTI, is the maximum tolerable rate-of-rise (or fall) of the common-mode voltage.

\[ V_{CM} \]

\[ \frac{dV}{dt} \quad (V/\text{ns}) \]
SiC MOSFET Driver Key Requirements: CMTI

UCC21521x CMTI Test Waveforms: ≈200V/ns
SiC MOSFET Driver Key Requirements: CMTI

CMTI Test Results (VCCI=12V VDD=25V) for TI driver UCC2152x
SiC MOSFET Driver Key Requirements: SC/OC Protection

Overcurrent/Short Circuit Fault

Short circuit happens at t1:
Overcurrent/Short Circuit Fault Mechanism: Thermal limitation

- The short circuit withstand time $t_{sc}$ is determined by the critical energy
  - minimal dissipated energy leading to device failure for one short circuit pulse
  $$E_c = \int_{t_1}^{t_3} V_{ds} \cdot I_d \cdot dt$$
  - $V_{ds}$ is the DC link voltage, $I_d$ will be the device saturation current.
- SiC MOSFET short circuit withstand time is shorter than IGBT due to smaller chip size, less thermal capacity.
SiC MOSFET Driver Key Requirements: Isolation

Digital control loop example: isolated gate driver is needed
SiC MOSFET Driver Key Requirements: Isolation

Isolation Technologies

Optical
Signal transfer between two isolated circuits using light – LED + phototransistor, 1970s

Inductive
Integrated micro-transformer and electronic circuitry, 2001~

Capacitive
Signal transmission through capacitive isolation with On-Off-Keying (OOK) modulation, 2004
Optical Technology

- Low performance
  - Long propagation times
  - Higher quiescent current

- Low robustness and reliability
  - Low noise immunity: Low common mode transient immunity
  - LED Degradation associated with temperature and age

Magnetic Technology

- Low robustness
  - Lower working voltage → Translates to limited applications
  - Low noise immunity: Low common mode transient immunity
  - High EM emissions – noise issues

- Lower reliability
  - Higher quiescent current
  - Insulator degradation over time

✓ Capacitive isolation technology does not suffer from these issues
SiC MOSFET Driver Key Requirements: Isolation

TI’s Capacitive Signal Isolation Technology: Increased System Robustness over Lifetime

- Industry-leading Integrated Capacitive Isolation
- SiO\(_2\) is the most stable dielectric over temperature & moisture
- Leverage advantages of TI’s customized CMOS process:
  - High precision
  - Tight part-to-part skew
  - No wear out mechanisms
  - Low defect levels
  - Highest lifetime in the industry: >1.5 kV\(_{\text{RMS}}\) for 40 years
  - Superior transient protection for harsh environments: >12.8kV
SiC MOSFET Driver Key Requirements: Isolation

“Fail Open” – TI Capacitor vs Opto Coupler

TI capacitive coupler

Isolation build with 2 series SiO₂ Caps

- “Fail Open” due to series Cap
- Maintain basic isolation if EOS on either side of isolation barrier

Opto coupler

Isolation build with transparent silicone

- Easily extend into insulation through heat or electrical overstress
- Isolation performance degraded

High Voltage/Current/Power Event on one side of isolator
Design Features

- 6.6kW Totem-pole PFC using SiC MOSFETs
- System Specifications:
  - Input: 85-264 Vac, 50/60Hz
  - Output: 400V-600V DC
  - Power: 6.6kW at 240Vrms
  - Efficiency: > 98.5% peak efficiency
  - PWM frequency: 100kHz

- Uses UCC21520-Q1 gate driver & C2000 MCU controller
- Low total harmonic distortion (THD) ~ 2-3%
- Soft start + Short circuit protection with 2-level turn off
- High Common Mode Transient Immunity (CMTI) of >100 V/ns
- Phase shedding to enable higher efficiency
- Variable output voltage for optimizing DC/DC stage efficiency

Tools & Resources

- TIDA-01604 Tools Folder
- Test Data/Design Guide
- Design Files: Schematics, BOM and BOM Analysis, Design Files
- Key TI Devices: UCC21520-Q1, SN6501-Q1, TMS320F28004x, ISO7721-Q1, UCC28700-Q1

Design Benefits

- High power, high efficiency PFC design with liquid cooling for powering the systems up to 6.6kW
- SiC MOSFETs with TI Drivers offering higher integration for the customers
- Full digital control with high performance C2000 controller enabling advanced control scheme
- High power factor and low total harmonic distortion (THD)
- 3Phase Interleaved operation with phase shedding control.

http://www.ti.com/tool/TIDA-01604
**TI Design:** TIDA-01604

98.6% Efficiency, 6.6-kW Totem-Pole PFC Reference Design for HEV/EV Onboard Charger

**Total Size:** 235mm x 85mm x 85mm

TI Design: TIDA-01604
98.6% Efficiency, 6.6-kW Totem-Pole PFC Reference Design for HEV/EV Onboard Charger

Measured Waveforms
Vin=240Vac, Pout=6.6kW, Fsw=100 kHz

Measured Efficiency (vs) Load
98.67% Peak Efficiency at Half Load (3.3kW)

Measurements
http://www.ti.com/tool/TIDA-01604
### Design Features

- 6-A peak sink and 4-A source output drive current
- Up to 25V output drive voltage suitable for SiC MOSFETs with operating PWM frequency up to 5MHz
- 18ns prop delay (typ), <5ns delay matching, <5ns Max PWM Distortion
- 5.7kVrms reinforced isolation capability
- Up to 12.8kV isolation surge Immunity
- Short circuit protection with two-level turn off circuit
- High Common Mode Transient Immunity (CMTI) of >100V/ns (Min)
- Built-in compact push-pull architecture-based isolated bias supplies
- Adjustable negative gate voltage for SiC MOSFET turn-off
- Short circuit fault and reset diagnostic function
- Programmable dead-time control & Enable feature

### Design Benefits

- Compact/small form factor dual channel gate drive solution (40mm x 40mm)
- Discrete short circuit protection with easily adjustable current limit and delay (blanking) time
- Flexible in optimizing mid-level turn off voltage and delay time
- Easy interface with both digital and analog controllers

### Tools & Resources

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### Short Circuit Protection

(Turn ON into short)

2-Level Turn OFF Implementation

Size: 40mm X 40mm

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http://www.ti.com/tool/TIDA-01605
Half-Bridge Isolated Driver Board using UCC21520/1C Driver

- Discrete short-circuit protection with easily adjustable current limit & blanking time
- Flexible in optimizing mid-level turn off voltage and delay time
- Easy interface with both digital and analog controllers

Fast Short Circuit Protection

2-Level Turn OFF Implementation

(Turn ON into short)

Short-Circuit Protection and Two-Level Turn off

http://www.ti.com/tool/TIDA-01605
TI Design: TIDA-01605

Automotive Dual Channel SiC MOSFET Gate Driver Reference Design with Two Level Turn-off Protection

1: De-sat;
2: Mid-level voltage generator;
3: Disable through input pin;

Two-Level Turn off

http://www.ti.com/tool/TIDA-01605
Bias Voltage for the Driver

PWM Input and Output

Bias Voltage for the Driver

http://www.ti.com/tool/TIDA-01605
Summary and key takeaways

- SiC MOSFET has superior performance than Si devices for both conduction and switching;

- SiC MOSFETs are suitable for xEV on-board/off-board chargers especially for bidirectional and high power cases;

- Key requirements for driving SiC MOSFET: driver voltage, CMTI, protection and isolation

- Two TI Designs introduced, please check ti.com for more detailed information