Next-Generation SiC/GaN Three-Phase Variable-Speed Drive Inverter Concepts

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Outline

► Introduction to VSDs
► SiC Sinus-Inverter
► GaN Multi-Level Inverter
► SiC Buck-Boost Inverter
► I-DC Link Inverter & GaN AC-Switches
► Conclusions
Variable Speed Drive Concepts

- DC-Link Based AC/DC/AC OR Matrix-Type AC/AC Converters
- Battery OR Fuel-Cell Supply OR Common DC-Bus Concepts

- 45% of World’s Electricity Used for Motors in Buildings & Industrial Applications
State-of-the-Art Drive System

- Standard 2-Level Inverter — Large Motor Inductance / Low Sw. Frequency
- Shielded Motor Cables / Limited Cable Length / Insulated Bearings / Acoustic Noise

- Line-to-Line Voltage
- CM Leakage Current
- Motor Surge Voltage
- Bearing Current
State-of-the-Art Drive System

- Measures Ensuring EMI Compliance / Longevity of Motor Insulation & Bearings
- Motor Reactor | $\frac{dv}{dt}$ Filters | DM-Sinus Filters | Full-Sinus Filters | Multi-Level Inverters

- Small Filter Size $\rightarrow$ High Sw. Freq. $\rightarrow$ SiC|GaN
SiC | GaN

#1

Source: www.clipart-library.com
Si vs. SiC

- **Si-IGBT / Diode** → Const. On-State Voltage, Turn-Off Tail Current & Diode Reverse Recovery Current
- **SiC-MOSFET** → Loss Reduction @ Part Load BUT Higher $R_{th}$

1200V 100A
Die Size: 98.8mm² + 39.4mm²
Source: Infineon

1200V 100A
Die Size: 25.6mm²
Source: Cree

- **Space Saving of >30% on Module Level (!)**
- **Extremely High $dv/dt$** → Motor Insul. Stress / Reflections / Bearing Curr. / EMI
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![Graphs showing comparison between Si and SiC](image)

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Source: Fuji Electric

Source: ATZ elektronik

Source: Cree
Si vs. SiC

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### Figures

- **Source:** Fuji Electric

### Comparison

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
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<tbody>
<tr>
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Full-Sinewave Filter & ZVS Operation

- **Sinusoidal Output Voltage**
- **Triangular Current Mode (TCM)** $\rightarrow$ ZVS of Inv. Bridge-Legs
- **High Sw. Frequency & TCM** $\rightarrow$ Low Filter Inductor Volume

- Only 33% Increase of Transistor Conduction Losses Compared to CCM (!)
- Very Wide Switching Frequency Variation
Frequency-Bounded TCM — B-TCM

- Very Wide Sw. Frequency Variation of Conventional TCM
- Allow Larger Current Ripple Around Zero Crossings

99.7% Semicond. Eff.
99.5% Total Efficiency

B-TCM Bridge-Leg
1200V SiC MOSFETs

- P = 2.2kW
- $U_{dc} = 800V$
- $f_s = 50kHz...140kHz$
- $L = 52uH (106 \text{ cm}^3)$
- $C = 8.8uF$

TCM $\rightarrow$ B-TCM — 10% Further Increase of Transistor Conduction Losses
**Remark**

**Residual ZVS Losses**

- Overlap of $u_{ps}$ & Channel Current $i_{ch}$ @ High $I_{sw} > I_k$
- Temporary Turn-on Due to $u_{gs,i} > u_{th}$

- **“Kink” Current $I_K$** Dependent on Inner & Outer Gate Resistance & $u_{g,n}$

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$\frac{du_{ds}}{dt}_{max} = \frac{I_k}{C_{ds} + C_{gd}} = \frac{i_g}{C_{gd}}$

$I_k = \frac{u_{th} + u_{p,n}}{R_g} \left( 1 + \frac{C_{ds}}{C_{gd}} \right)$

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$650\text{V SiC} \ @ \ U_{dc} = 400\text{V}$
**Remark**

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**“Kink” Current $I_k$ Dependent on Inner & Outer Gate Resistance & $u_{g,n}$**

$650V$ SiC @ $U_{DC} = 400V$
Si IGBT vs. GaN Inverter System

- **Comparison of GaN Inverter with LC-Filter ($f_s=100kHz$) to Si-IGBT System (No Filter, $f_s=15kHz$)
- **Measurement of Inverter Stage & Overall Drive Losses @ 60Hz

→ 2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses)!

Source: YASKAWA
Multi-Level Inverter

Source: www.clipart-library.com
3-Level Inverter Concepts

- Higher Number of Output Voltage Levels / Lower CM Voltage Steps
- Neutral Point Clamped | Flying Capacitor | T-Type Bridge-Leg Topologies

![Diagram of 3-Level Inverter Concepts]

- Complicated Bridge-Leg Structure
- On-State-Losses of Series-Connected Switches
3-Level T-Type Inverter

- Utilization of 600V Monolithic Bidirectional GaN Switches
- 2-Gate Structure Provides Full Controllability

- Factor 4 (!) Reduction of Chip Area vs. Discrete Realization
3-Level T-Type Inverter

- Utilization of 600V Monolithic Bidirectional GaN Switches
- 2-Gate Structure Provides Full Controllability

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Flying Cap. (FC) 3-Level Converter

- 3-Level Flying Cap. (FC) Converter → No Connection to DC-Midpoint
- Involves All Switches in Voltage Generation → Eff. Doubles Device Sw. Frequency

- FC Voltage Balancing Possible also for DC Output
Scaling of Flying Cap. Multi-Level Concepts

- Series Interleaving → Reduced Ripple
- \( f_{sw,eff} = N \cdot f_{sw} \) @ \( f_{sw} \) - Determined (!) Switching Losses
- Lower Overall On-Resistance @ Given Blocking Voltage
- Application of LV Technology to HV

\[
\Delta I_{\text{max},N} = \frac{1}{N^2} \Delta I_{\text{max},N=1}
\]

\[
\frac{\Delta U_{C,\text{max},N}}{U} = \frac{\pi^2}{32} \left( \frac{f_0}{f_S} \right)^2 \frac{1}{N^3}
\]

- Scalability / Manufacturability / Standardization / Redundancy
7-Level Flying Cap. 200V GaN Inverter

- DC-Link Voltage 800V
- Rated Power 2.2 kW / Phase
- 99% Efficiency → Natural Convection Cooling (!)

- High Effective Sw. Frequency (6 x 30kHz = 180kHz) → Small Filter Inductor $L_0$

$260 \text{ W/in}^3$
Quasi-2L & Quasi-3L Flying Cap. Inverters

- Operation of N-Level Topology in 2-Level or 3-Level Mode
- Intermediate Voltage Levels Only Used During Sw. Transients

- Schweizer (2017)

- Clear Partitioning of Overall Blocking Voltage & Small Flying Capacitors
- Low Voltage/Low $R_{DS(on)}$/Low $\$$ MOSFETs $\rightarrow$ High Efficiency / No Heatsinks / SMD Packages
3-Φ Hybrid 7-Level Inverter

- Realization of a 99%++ Efficient 10kW 3-Φ 400V_{rms} Inverter System
- 7-Level Hybrid Active NPC Topology / LV Si-Technology

- 200V Si → 200V GaN Technology Results in 99.5% Efficiency
4.8MHz GaN Half-Bridge Module

- **Combination of Series & Parallel Interleaving**
- 600V GaN Power Semiconductors, $f_{sw} = 800kHz$
- Volume of $\approx 180cm^3$ (incl. Control etc.)
- $H_2O$ Cooling Through Baseplate

- Operation @ $f_{out}=100kHz$, $f_{5,eff}=4.8MHz$, $10kW$, $U_{dc}=800V$

- $820 W/in^3$
High-BW High-CMRR Current Measurement

- **Extension of Commercial Hall Sensor DC**... $f_{\text{Hall}} \approx 500\text{kHz} \rightarrow \text{DC}...10\text{MHz}$
- **Low-Pass & High-Pass Filter Network** Combining HF-Sensor & LF Hall-Sensor

- **Hall Sensor Bandwidth** $f_{\text{Hall}} = 1.4\text{MHz}$
- **Sense Wdg. Integrator Corner Frequency** $f_{\text{int}} = 350\text{ Hz}$
- **Low/High-Pass Filter Cross-Over Network** $f_{\text{filter}} = 15\text{kHz}$
Motor-Integrated Inverter Systems
Stacked-Multi-Cell (SMC) Inverter

- Fault-Tolerant VSD
- Low-Voltage Inverter Modules
- Very-High Efficiency / Power Density
- Autom. Manufacturing of Inverter Stage

- Rated Power 45kW / $f_{\text{out}} = 2\text{kHz}$
- DC-Link Voltage 1 kV

- Smart Motor / Plug & Play | Connected / Intelligent VSD 4.0
Motor-Integrated SMC-Inverter

- **Rated Power**: 9kW @ 3700rpm
- **DC-Link Voltage**: 650V...720V
- **3-Φ Power Cells**: 5+1
- **Outer Diameter**: 220mm

- Axial Stator Mount
- 200V GaN e-FETs
- Low-Capacitance DC-Links
- 45mm x 58mm / Cell

- **Main Challenge** — Thermal Coupling / Decoupling of Motor & Inverter
Compressor-Integrated DB GaN-Inverter

- **E-Mobility 5...15kW Fuel Cell Pressurized Air Supply**
- **1kW Rated Power,** $f_{sw} = 300\text{kHz}$ | $n = 280'000\text{rpm}$ / $f_{out} = 4.6\text{kHz}$
- **Low EMI / Low Cabling Effort**

- **Integration** → 2x System Power Density | 97% → 98.5% Inverter Efficiency
Motivation

- General / Wide Applicability
  - Adaption to Load-Dependent Battery | Fuel Cell Supply Voltage
  - VSDs → Wide Output Voltage / Speed Range

- No Additional Converter for Voltage Adaption → Single-Stage Energy Conversion
Example — Buck-Boost 3-Φ Inverter

- Generation of AC-Voltages Using Unipolar Bridge-Legs

- Switch-Mode Operation of Buck OR Boost Stage → Single-Stage Energy Conversion (!)
- 3-Φ Continuous Sinusoidal Output / Low EMI → No Shielded Cables / No Motor Insul. Stress
### Boost-Operation $u_{an} > U_i$

- **Phase-Module**

![Phase-Module Diagram]

- **Motor Phase Voltages**

![Motor Phase Voltages Diagram]

- **Current-Source-Type Operation**
- **Clamping of Buck-Bridge-Leg High-Side Switch** $\rightarrow$ **Quasi Single-Stage Energy Conversion**
Buck-Operation $u_{an} < U_i$

- **Phase-Module**

- **Motor Phase Voltages**

- **Voltage-Source-Type Operation**
- Clamping of Boost-Bridge-Leg High-Side Switch $\rightarrow$ Quasi Single-Stage Energy Conversion
3-Φ Buck-Boost Inverter Lighthouse Project

- Rated Power: 10 kVA
- DC Input Range: 400…750V<sub>DC</sub>
- AC Output: 0…230V<sub>rms</sub> (Phase) 0…500Hz
- 1200V SiC MOSFETs: 25mΩ | 100kHz

- No Shielded Motor Cables / Cond. & Radiated EMI Compliant to IEC 61800-3

245 W/in<sup>3</sup> 98.3%

Control Board
3Φ Output
DC Input
Main Inductors

200V/div 1V/div
3-Φ Current DC-Link Topologies

- **3-Φ Buck-Boost Inverter** → **Phase Modules w/ Buck-Stage | Current Link | Boost-Stage**
- **3-Φ Current DC-Link Inv.** → **Buck-Stage V-I-Converter | Current DC-Link DC/AC-Stage**

→ *Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches*
3-Φ-Integrated Buck-Boost CSI

- “Synergetic” Control of Buck-Stage & CSI Stage
- 6-Pulse-Shaping of DC Current by Buck-Stage → Allows Clamping of a CSI-Phase

- Switching of Only 2 of 3 Phase Legs → Reduction of Sw. Losses by ≈ 86% (!)
3-Φ AC/AC Converter Topologies

- **Current DC-Link Topology**
  - Application of M-BDSs
  - Complex 4-Step Commutation
  - Low Filter Volume

- **Voltage DC-Link Topology**
  - Standard Bridge-Legs
  - Low-Complexity Commutation
  - Defined Semiconductor Voltage Stress
  - Facilitates DC-Link Energy Storage

- **Challenging Overvoltage Protection**
- **Limited Control Dynamics**

- **High Input / Output Filter Volume**
3-Φ AC/AC Converter Topologies

- **Current DC-Link Topology**
  - Application of M-BDSs | 12 Switches
  - 4-Step Commutation
  - Buck-Boost Functionality
  - Low Filter Volume

- **Direct Matrix Converter**
  - Application of M-BDSs | 9 Switches
  - 4-Step Commutation
  - Complex Space Vector Modulation
  - Limited to Buck-Operation (!)

- **Challenging Overvoltage Protection**

\[ L_{CM} \]
Smart Inverter Concept

- Utilize High Computing Power & Network Effects in the Cloud → Cognitive Power Electronics

- Component Level | Converter Level | System Level | Application Level

- Intelligent Gate Drive Unit
  - Semiconductor protection (overcurrent, overvoltage, ...)
  - Collecting and preprocessing of sensor data (current, voltage, temperature, ...)
  - Semiconductor specific condition monitoring functions

- Communication
  - Communication protocol instead of on/off signals

- Drive Controller
  - Observer based condition monitoring functions
  - Predictive maintenance functions
  - Data Processing and data compression
  - Communication to customer automation and/or internet

- Internet / Cloud
  - Service and commissioning tools
  - Algorithms for „Big Data“ analysis
  - Smart documentation (e.g. video to support service)
  - ...
Thank you!
**SiC/GaN Figure-of-Merit**

- Figure-of-Merit (FOM) Quantifies Conduction & Switching Properties
- FOM Identifies Max. Achievable Efficiency @ Given Sw. Frequ.

FOM = \( \frac{1}{R_{ds,on} Q_{ass}} \)

- Advantage of Multi-Level over 2-Level Converter Topologies
Remark

GaN Overload Capability

- Highly Dynamic Robotics VSDs → 3x ... 5x Rated Torque for Seconds
- Smaller Chip Area → Lower Thermal Time Constant of GaN HEMTs
- Trade-Off Between Overload Rating & Rated Power Efficiency

200V GaN vs. Si (Multi-Level Inverter) Comparison

- 200V GaN vs. Si (Multi-Level Inverter) Comparison
600V GaN Monolithic Bidir. Switch

- Power America Project — Based on Infineon’s CoolGaN™ HEMT Technology ($R_{DS(on)} = 70\,\text{m}\Omega$)
- Dual-Gate Device / Controllability of Both Current Directions
- Bipolar Voltage Blocking Capability | Normally On or Off

- Analysis of 4-Quadrant Operation of $R_{DS(on)} = 140\,\text{m}\Omega$ Sample @ $\pm 400\,\text{V}$
200kHz SiC Current DC-Link AC/AC Converter

- 7kHz DC-Link Current Control Bandwidth
- PCB-Stack Construction — Power | Gate-Drive | Control Board
- Coldplate Cooling

Input 400VLine-to-Line
Output 0...300Hz
Rated Power 2.5 kVA
2.4 kVA / dm³ (40 W/in³)

230 x 80 x 65 mm³

- Low Volume Toroidal Powder Core DC-Link Inductor (320uH)
### Remark

#### 3-Φ AC/AC Matrix Converter

- **Indirect Matrix Converter (IMC)**
  - CSI GaN M-BDS AC/DC Front-End
  - ZCS Commutation of CSI Stage @ \( i_{DC}=0 \)
  - No 4-Step Commutation

- **Direct Matrix Converter (CMC)**
  - 4-Step Commutation
  - Exclusive Use of GaN M-BDSs

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- Higher # of Switches Compared to CMC
- Lower Cond. Losses @ Low Output Voltage
- Thermally Critical @ \( f_{out} \rightarrow 0 \)

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- Thermally Critical @ \( f_{out} \approx f_{in} \)
Monolithic 3D-Integration

- **GaN 3x3 Matrix Converter Chipset with Drive-By-Microwave (DBM) Technology**
  - 9 Dual-Gate GaN AC-Switches
  - DBM Gate Drive Transmitter Chip & Isolating Couplers
  - Ultra Compact → 25 x 18 mm² (600V, 10A – 5kW Motor)

5.0GHz Isolated (5kVDC) Dividing Coupler
2-Stage Full-Sinewave Output Filter

- 2kW / 400V DC-Link 3-Φ 650V GaN Inverter (I_M=5A), f_{out,max} = 500Hz
- Sinewave Output & IEC/EN 55011 Class-A
- Sw. Frequency f_S = 100kHz

\[ f_{c,1} = 7kHz \]

\[ f_{c,2} = 20kHz \]

→ Soft Saturation Toroidal Iron Powder Cores
→ Active & Passive Damping of the Filter Stages
2-Stage Full-Sinewave Output Filter

- **Exp. Verification** — 650V E-Mode GaN Systems Transistors (50mΩ)
- **Sw. Frequency** $f_s = 100kHz$, Efficiency ≈98%
- **200mm x 250mm**

- Stationary Motor Phase Curr. /Voltage @ 2.5Nm & $f_{out}=250Hz$
- Speed Increase from Standstill to $n = 3000rpm$ in 60ms
**Multi-Axis Drive Systems**

- **Common DC-Bus** — Single AC/DC Converter / Smaller Cabinet
- **Motor Integration of DC/AC Stage** — Massive Saving in Cabling Effort / Simplified Installation

- Facilitates DC-Bus Energy Buffer
- Direct Energy Exchange @ DC-Bus / Higher Efficiency / Unidir. Front-End
**IIoT in Power Electronics**

- **Digital Twin** → *Physics-Based Digital Mirror Image*
- **Digital Thread** → “Weaving” Real/Physical & Virtual World Together

* Requires Proper Interfaces for Models & Automated Design
* Model of System’s Past/Current/Future State → Design Corrections / Prev. Maintenance etc.

Source: www.railwayage.com
End