Wide-Band-Gap-Antriebsumrichter
Aktuelle Trends und technische Lösungen

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VDE DACH-Fachtagung “Elektromechanische Antriebssysteme 2021”

November 10th, 2021
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18 Ph.D. Students
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3 Research Fellows
Outline

► Introduction
► WBG Trends and Challenges
► Full-Sinewave Filtering
► Multi-Level Inverter
► Filter-Integrated Converter Structures
► Conclusions
3-Φ Variable Speed Drive Inverter Systems

State-of-the-Art Trends and Future Requirements
Variable Speed Drive Inverter Concepts

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

- **High Performance @ High Level of Complexity / High Costs (!)**
- **All Separated → Large Installation Space / Complicated / Expert Installation**
VSD Inverter - Future Requirements

- "Non-Expert" Installation → Motor-Integrated Inverter OR "Sinus-Inverter"
- Low Losses & Low HF Motor Losses / Low Volume & Weight
- Wide Output Voltage Range / High Output Frequencies (High Speed Motors)

- Main "Enablers" → SiC/GaN Power Semiconductors & Digitalization ("X-Technologies")
  → Adv. Inverter Topologies & Control Schemes ("X-Concepts")
“X-Technologies”
WBG Semiconductors

Source: www.terencemauri.com
Si vs. SiC

- Higher Critical E-Field of SiC $\rightarrow$ Thinner Drift Layer
- Higher Maximum Junction Temperature $T_{j,max}$

<table>
<thead>
<tr>
<th></th>
<th>Si</th>
<th>GaAs</th>
<th>4H/6H-SiC</th>
<th>GaN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>1.12</td>
<td>1.4</td>
<td>3.0-3.2</td>
<td>3.4</td>
</tr>
<tr>
<td>$E_c$ (MV/cm)</td>
<td>0.25</td>
<td>0.3</td>
<td>2.2-2.5</td>
<td>3</td>
</tr>
<tr>
<td>$\mu_n$ (cm$^2$/Vs)</td>
<td>1350</td>
<td>8500</td>
<td>100-1000</td>
<td>1000</td>
</tr>
<tr>
<td>$\varepsilon_r$</td>
<td>11.9</td>
<td>13</td>
<td>10</td>
<td>9.5</td>
</tr>
<tr>
<td>$V_{sat}$ (cm/s)</td>
<td>$1 \times 10^7$</td>
<td>$1 \times 10^7$</td>
<td>$2 \times 10^7$</td>
<td>$3 \times 10^7$</td>
</tr>
<tr>
<td>$\lambda$ (W/mK)</td>
<td>1.5</td>
<td>0.5</td>
<td>3 - 5</td>
<td>1.3</td>
</tr>
</tbody>
</table>

For 1kV:

$R_{on}^* = \frac{4V_B^2}{\varepsilon \mu_n E_C^3}$

$R_{on, SiC}^* \approx \frac{1}{300} R_{on, Si}^*$

- Massive Reduction of Relative On-Resistance $\rightarrow$ High Blocking Voltage Unipolar Devices
Si vs. SiC Switching Behavior

- **Si-IGBT** → Const. On-State Voltage Drop / Rel. Low Switching Speed
- **SiC-MOSFETs** → Resistive On-State Behavior / Factor 10 Higher Sw. Speed

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

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

- Extremely High di/dt & dv/dt → Challenges in Motor Insulation / Bearing Currents / EMI
- Small Chip Size & Integration → Challenges in Gate Drive & PCB / Packaging & Thermal Management
Inverter Output Filters

Full-Sinewave Filtering
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**

![Diagram of a drive system with various components and connections, illustrating the system's structure and operation.](source: YASKAWA)

- **Line-to-Line Voltage**
- **CM Leakage Current**
- **Motor Surge Voltage**
- **Bearing Current**

**ETH Zürich**
Output Voltage Filtering

- Measures Ensuring EMI Compliance / Longevity of Motor Insulation & Bearings
- Motor Reactor | $dv/dt$ Filters | DM-Sinus Filters | Full-Sinus Filters

Small Filter Size $\rightarrow$ High Sw. Freq. $\rightarrow$ SiC | GaN
3-Φ 650V GaN Inverter System

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

- **Sinewave LC Output Filter** → **Corner Frequency $f_c=34kHz$**
- **2% Higher Efficiency of GaN System Despite LC-Filter (Saving in Motor Losses)!**
Multi-Level Inverters

Flying Capacitor Inverter

G. Rohner, S. Miric, D. Bortis, J. W. Kolar, M. Schweizer,
Comparative Evaluation of Overload Capability and Rated Power Efficiency of 200V Si/GaN 7-Level FC 3-Phase Variable Speed Drive Inverter Systems,
Scaling of Flying Cap. Multi-Level Concepts

- Clear Partitioning of Overall Blocking Voltage  → Lower Voltage Steps / Lower EMI / Reflections
- Higher Effective Switching Frequency @ Output  → \( f_{sw,eff} = N \cdot f_{sw} \)
- Low Output Inductance & Application of LV Technology to HV

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

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

- Scalability / Manufacturability / Standardization / Redundancy
SiC/GaN Figure-of-Merit

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

\[
FOM = \frac{1}{R_{ds,on} C_{oss}}
\]

Advantage of LV over HV Power Semiconductors
- Advantage of Multi-Level over 2-Level Converter Topologies
  - Lower Overall On-Resistance @ Given Blocking Voltage
Motor Integrated 7-Level FC Inverter

■ Specifications
- DC Input Voltage: 800V
- Nominal Operation: 15A peak, 350V peak (7.5kW)
- Overload Operation: 45 A peak for 3s
- Temperature Aluminum (Flange): 90°C

● 7-Level Flying Capacitor Inverter enables Usage of 200V Devices (Si or GaN)

● Nominal Efficiency Target 99% (only Semicond.) ➔ # Semicond. Devices

ETH Zürich
Nominal Load Operation

- **99% at Nom. Load – 7.5 kW** → **75W Total Semi. Losses** (Only 2.1W per Switch)
- Comparison of best 200V Si and GaN Devices available on the Market

- **Si-MOSFET:** IPT111N20NFD, Optimos 3 (11mOhm)
- **GaN:** EPC2034C (8mOhm)

- GaN achieves 2-3 times Higher Switch. Freq. compared to Si for 99% → 2-3x lower FC Volume
- Overload Capability → 3 x Nominal Load for 3 Seconds

Nominal Load Efficiency (%)
Overload Operation

- **Worst Case Overload Operation at Standstill**
- **3 x Torque/Current (45A_{peak}) for 3s**

  → **Strongly Increased Semicon. Losses**
  → **3 x Flying Cap. Vol. for same FC Voltage Ripple**

- **Conduction Losses dominate Overload Losses** → **Increase Switching Frequency at Overload**
- **3 x Switching Frequency** → **Flying Cap. designed for Nom. Load**
- **Max. Junction Temp. (Si: 175°C/ GaN: 150°C)** → **Proper Cooling Concept needed**
Cooling Concepts

- Si MOSFET → Cooling Through PCB with Copper Inlay
- GaN (Bottom Side mounted) → Directly Attached Copper Piece & TIM to Heatsink

Si: IPT111N20NFD (Optimos 3 FD)
- Bottom: $R_{\text{ΘJB}} = 0.4 \text{ K/W}$

GaN: EPC2034C
- Top: $R_{\text{ΘJC}} = 0.3 \text{ K/W}$
- Bottom: $R_{\text{ΘJB}} = 4 \text{ K/W}$

- Inlay for Si & Copper Plate for GaN
- Minimize Th. Contact betw. GaN Device and Cu Plate → Thermal Capacitor & Heat Spreader
- Determine Thermal Performance → Realization & Dynamic Thermal Model
**Flying Capacitor Cell Realization**

- **Si MOSFET**  →  Cooling Through PCB with Copper Inlay
- **GaN (Bottom Side mounted)**  →  Directly Attached Copper Piece & TIM to Heatsink

**Si:** IPT111N20NFD  
(Optimos 3 FD)

- **Top:** $R_{\theta JC} = 0.3 \, \text{K/W}$
- **Bottom:** $R_{\theta JB} = 0.4 \, \text{K/W}$

**GaN:** EPC2034C

- **Top:** $R_{\theta JC} = 4 \, \text{K/W}$
- **Bottom:** $R_{\theta JB} = 4 \, \text{K/W}$

- **Inlay for Si & Copper Plate for GaN**  →  Thermal Capacitor & Heat Spreader
- **Minimize Th. Contact betw. GaN Device and Cu Plate**  →  Heat Paste, Liquid Gap Filler, Solder Pad
- **Determine Thermal Performance**  →  Realization & Dynamic Thermal Model
Dynamic Thermal Modeling

- **Si MOSFET** → Cooling Through PCB with Copper Inlay
- **GaN (Bottom Side mounted)** → Directly Attached Copper Piece & TIM to Heatsink

Si: IPT111N20NFD (Optimos 3 FD)
Bottom: $R_{\text{JB}} = 0.4 \text{ K/W}$

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Top: $R_{\text{JC}} = 0.3 \text{ K/W}$
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- Inlay for Si & Copper Plate for GaN
- Minimize Th. Contact betw. GaN Device and Cu Plate → Heat Paste, Liquid Gap Filler, Solder Pad
- Determine Thermal Performance → Realization & Dynamic Thermal Model
Dynamic Thermal Model Parametrization

- **Empirical Parametrization**
  - Measure Temp. Profile for different Injected Power Profiles
- **Junction Temp.**
  - Electrically with temperature-dependent $R_{ds,\text{on}}$ (1ms Rate)
- **Case, Cu-Plate & Heat Sink**
  - Optically with Thermal Camera (40ms Rate)

**FLIR A655SC & Close-up Lens**
- 100μm Resolution
- 40ms Update Rate

- **DC Power Injection**
  - Relation between Junction Temp. and $R_{ds,\text{on}}$
- **Pulsed Power Injection**
  - Thermal Resistances
  - Thermal Capacitances
Dynamic Thermal Model

- Normalized Thermal Step Response → Cu-Piece increases Time Constant drastically
- Similar Dyn. & Stat. Th. Behavior for 1xSi & 2xGaN if Cu-Piece same Dim. as Si-Exposed Pad

Si: 0.91 K/W per Device

GaN: 1.81 K/W per Device

- Initial Small Time Constant → Defined by Device Package ($\tau < 10\,\text{ms}$)
- Afterwards Large Time Constant → Defined by Cooling Concept ($\tau_{\text{Si}} = 0.4\,\text{s}, \tau_{\text{GaN}} = 0.65\,\text{s}$)
- Overload Duration $> 4 \cdot \tau_{\text{Semi}}$ → Equals Continuous Overload (Worst Case)
Thermal Cycling vs. Output Frequency (1)

- Max. and Min. Junction Temperature within one Electric Period depending on $f_{\text{out}}$
- Maximum Overload Junction Temperature at Standstill $\rightarrow$ approx. 130°C for Si and GaN

- Immediate Reduction of Th. Cycling at Low Speeds $\rightarrow$ Th. Low-Pass Filter Behavior with $\tau_{\text{Semi}}$
- Residual Th. Cycling at High Speeds due to thermal Behavior of Device Package

- Experimental Verification $\rightarrow$ AC Current & Switched 2L-Operation
Thermal Cycling vs. Output Frequency (2)

- **Switched 2L-Operation**
- **Junction Temperature Profile**
- **Injected Losses**

→ **Measurement and Simulation of Case Temperature**
→ **Determined from Thermal Model**
→ **Calculated from Semiconductor Loss Model**

- **Very Good Agreement between Measured and Simulated Temperature Profiles**
- **Fast Decay of Thermal Cycling Magnitude with increasing Frequency**

![Graphs showing thermal cycling vs. output frequency at 0.1Hz, 1Hz, and 10Hz.]
LC Output Filter with Overload Capability

- **Multi-Level Converter**  → Small Voltage Steps but still high \( \frac{dv}{dt} \)
- **LC Output Filter mitigate**  → CM & Bearing Currents  → EMI Emissions & HF-Machine Losses

- **Multi-Level Converters enable**  → Small Filter Volume  → Overload Capability \((3 \times I_{\text{nom}})\) needed for Filter Inductor

![Diagram of LC Output Filter with Overload Capability](image)
Output Inductor Design

- **Ferrite Core Filter Inductor** → Sudden Drop of Permeability around Saturation
  → Magnetic Design for Overload needed

- **Powder Core Filter Inductor** → Smooth Drop of Permeability till Saturation

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- **Max. FC Voltage Ripple** → Inverter operated with $3 \times f_{sw}$ at Overload
- **Constant Inductor Current Ripple** → Inductance can drop by $x3$ at Overload
  → Powder Core Filter Inductor designed for Nominal Load (!)
Output Inductor Design

Filter Inductor Pareto Optimization for Si 7L FCI

Nom. Ind.: 20.4 μH
OL Ind.: 7.6 μH
Ripple: 80%

Tiny Filter Inductor for a Nominal 7.5kW Integrated Motor Drive → 3-4 x Smaller than Ferrite
Temperature Increase of 5°C at Overload → based on Thermal Capacity
Output Inductor Design

- **Filter Inductor Pareto Optimization for GaN 7L FCI**

Nom. Ind.: 13.4 µH
OL Ind.: 4.9 µH
Ripple: 50%

8.2 cm³

\[ f_{sw} = 60 \text{ kHz} \]

\[ f_{sw} = 180 \text{ kHz} \]

- Tiny Filter Inductor for a Nominal 7.5kW Integrated Motor Drive \(\rightarrow 3-4 \times\) Smaller than Ferrite
- Temperature Increase of 5°C at Overload \(\rightarrow\) based on Thermal Capacity
“X-Concepts”

Phase-Modular Buck+Boost Inverter
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**
**Buck-Boost Y-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
Buck-Boost Y-Inverter

- **Operating Behavior**

- $u_{am} < U_{in} \rightarrow$ Buck Operation
- $u_{am} > U_{in} \rightarrow$ Boost Operation
- Output Voltage Generation Referenced to DC Minus
Y-Inverter VSD

- **Demonstrator Specifications**
  - Wide DC Input Voltage Range → 400...750V\textsubscript{DC}
  - Max. Input Current → ± 15A

- Max. Output Power → 6...11 kW
- Output Frequency Range → 0...500Hz
- Output Voltage Ripple → 3.2V Peak @ Output of Add. LC-Filter
Y-Inverter Demonstrator

- 3x SiC (75mΩ)/1200V per Switch
- Sw. Frequency $\rightarrow$ 100kHz

- Dimensions $\rightarrow$ 160 x 110 x 42 mm$^3$
- 15kW/dm$^3$ (245W/in$^3$)
Y-Inverter - Measurement Results

- Transient Operation

\[ U_{DC} = 400\text{V} \]
\[ U_{AC} = 400\text{V}_{\text{rms}} \text{ (Motor Line-to-Line Voltage)} \]
\[ f_0 = 50\text{Hz} \]
\[ f_s = 100\text{kHz} / \text{DPWM} \]
\[ P = 6.5\text{kW} \]

- Dynamic Behavior V-f Control and Load-Step

- Smooth/Sinusoidal Voltage and Current Waveforms
Three-Phase Integration
CSI & DC/DC Front-End
3-Φ Current Source Inverter Topology Derivation

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

→ Single Inductive Component & Utilization of Monolithic Bidirectional GaN Switches
3-Φ Current Source Inverter (CSI)

- Bidirectional/Bipolar Switches $\rightarrow$ Positive DC-Side Voltage for Both Directions of Power Flow

- Monolithic Bidir. GaN Switches $\rightarrow$ Factor 4 (!) Red. of Chip Area Comp. to Disc. Realization
3-Φ Buck-Boost CSI – Synergetic Control

- “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 → Significant Red. of Sw. Losses (≈ -86% for R-Load)
- Operation with Phase Shift of AC-Side Voltage & Current possible
Conclusions
**Conclusions**

- **“X-Technology”: SiC / GaN Enable Motor-integrated Drive Systems**
  - High $dv/dt$ & Thermal Management are Major Challenges
  - Continuous / Sinusoidal Output Voltage $\rightarrow$ Full-Sinewave Filters

- **“X-Concepts”: Multi-Level Converters and Integrated Filters**
  - Low-Voltage Steps & Scaling of Inductor & FOM
  - ALL SMD Realization $\rightarrow$ Automated Assembly
  - Loss Distribution among many Devices $\rightarrow$ High Overload Capability
  - Filtering Recommended $\rightarrow$ Powder Core
  - Wide Input / Output Voltage Range
  - Electromagnetically „Quiet”
  - Synergetic Control & Monolithic Bidirectional GaN Switch

- **System Level $\rightarrow$ Integration of Storage, Distributed DC Bus Systems / Industry 4.0 etc.**
Thank you!
Dominik Bortis received the M.Sc. and Ph.D. degree in electrical engineering from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2005 and 2008, respectively. In May 2005, he joined the Power Electronic Systems Laboratory (PES), ETH Zurich, as a Ph.D. student. From 2008 to 2011, he has been a Postdoctoral Fellow and from 2011 to 2016 a Research Associate with PES.

Since January 2016 Dr. Bortis is heading the research group Advanced Mechatronic Systems at PES, which concentrates on ultra-high speed motors, bearingless drives, linear-rotary actuator and machine concepts with integrated power electronics. Targeted applications include e.g. highly dynamic positioning systems, medical systems, and future mobility concepts. Dr. Bortis has published 90+ scientific papers in international journals and conference proceedings. He has filed 30+ patents and has received 8 IEEE Conference Prize Paper Awards and 2 First Prize Transaction Paper Award.