Advanced SiC/GaN 3-Φ PWM Inverter Systems for VSD Applications

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Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

April 15, 2019
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J.W. Kolar, M. Guacci, M. Antivachis, D. Bortis

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April 15, 2019
## Departments

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## Students ETH in total

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<td>4’500</td>
<td>Doctoral Students</td>
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21 Nobel Prizes
509 Professors
5800 T&R Staff
2 Campuses
136 Labs
35% Int. Students
90 Nationalities
36 Languages
150th Anniv. in 2005

509
21
36
35%
ITET – Research in E-Energy

- Power Electronic Systems
- Advanced Mechatronic Systems
- Power Semiconductors
- Power Systems
- High Power Electronics
- High Voltage Technology

► Balance of Fundamental and Application Oriented Research

High Power Electronics Systems

ITET - Research in E-Energy

ETH Zürich
Power Electronic Systems Laboratory

Industry Relations
R. Coccia / B. Seiler

Johann W. Kolar

Adv. Mechatronic Systems
D. Bortis

AC-DC Converter
M. Heller
J. Azurza
P. Czyz
M. Heller

AC-AC Converter
J. Azurza
P. Czyz
M. Haider

DC-DC Converter
F. Krismer
P. Bezerra
T. Guillod
G. Knabben
J. Schäfer

DC-AC Converter
D. Bortis
M. Antivachis
J. Böhler
M. Guacci

Multi-Domain Modeling
F. Krismer
P. Papamanolis

Measurement Technology
P. Niklaus

Advanced Mechatronics
D. Bortis
E. Hubmann

Magnetic Levitation
D. Bortis
Th. Holenstein
P. Püntener
S. Miric

Secretariat
M. Kohn / Y. Schnyder

Administration
P. Maurantonio

Computer Systems
M. Eisenstat

Electronics Laboratory
P. Seitz

19 Ph.D. Students
2 Sen. Researchers

ETH zürich

CPES

Leading Univ. in Europe
Outline

- Introduction
- SiC/GaN Application Challenge
- Inverters with Output Filter
- Adv. Inverter Topologies
- Conclusions
Introduction

State-of-the-Art
Future Requirements
Applications of Drive Systems

- Industry Automation / Robotics
- Material Machining / Processing – Drilling, Milling, etc.
- Pumps / Fans / Compressors
- Transportation
- etc., etc.

.... Everywhere!

60% of El. Energy Used in Industry Consumed by VSDs
**State-of-the-Art**

- **Mains Interface / 3-Φ PWM Inverter / Motor — Separated**
  - Large Installation Space / $$$
  - Complicated / Expert Installation / $$$

- **Conducted EMI / Radiated EMI / Bearing Currents / Reflections on Long Motor Cables**
  - Shielded Motor Cables / $$$
  - Inverter Output Filters (Add. Vol.) / $$$

**Source:** FLUKE

![Diagram of Drive Input and Motor and Drive Train](image-url)

- **High Performance @ High Level of Complexity / High Costs (!)**
Future Requirements (1)

- "Non-Expert" Install. / Low-Cost Motors → "Sinus-Inverter"
- Wide Applicability / Wide Voltage & Speed Range → Matching of Supply & Motor Voltage
- High Availability

- Single-Stage Energy Conversion → No Add. Converter for Voltage Adaption

Source: magazine.fev.com

Future Requirements (1)
Future Requirements (2)

- **Red. Inverter Volume / Weight** → Matching of Low High-Speed Motor Volume
- **Lower Cooling Requirement** → Low Inverter Losses & HF Motor Losses
- **High Speed Machines** → High Output Frequency Range

→ Main “Enablers” — SiC/GaN Power Semiconductors & Adv. Inverter Topologies
Enabling Technologies & Challenges

WBG Semiconductors
Advanced Inverter Topologies
SiC/GaN

- Very Low On-State Resistance → Low (Partial Load) Conduction Losses
- Very Low Switching Losses → High Switching Frequencies
- Small Chip Area → Compact Realization

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

Challenges in Packaging / Thermal Management / Gate Drive / PCB Layout
- Extremely High Sw. Speed \((dv/dt)\) → Motor Isol. Stress / Reflections / Bearing Curr. / EMI
**Si vs. SiC**

- **Si-IGBT** $\Rightarrow$ $dv/dt = 2...6$ kV/us (Inverter for Var. Speed Drives / IEC 61800-3)
- **SiC** $\Rightarrow$ $dv/dt = 20...60$ kV/us

Source: M. Bakran / ECPE 2019

### Si-IGBT / Hybrid-Pack 2

*Turn-off @ $T_J = 25^\circ$C*

- $E_{off} = 45900$ μJ
- $\Rightarrow$ 8 kV/μs at 400V

### SiC-MOSFET / (scaled for low inductance)

*Turn-off @ $T_J = 25^\circ$C*

- $E_{off} = 4672$ μJ
- $\Rightarrow$ 44 kV/μs at 400 V

→ **Extremely High dv/dt** → **Motor Isol. Stress / Reflections / Bearing Curr. / EMI**
$\frac{dv}{dt}$ - Challenges
Motor Insulation Destruction

- Partial Discharge Due to Insul. Imperfections (Ionisation & Transient Space Charge Distrib.)
- Partial Discharge Inception Voltage (PDIV) Dependent on $dv/dt$

$dv/dt$-Limits Specified by Standards
$dv/dt$-Filtering or Full Sinewave Filtering
Surge Voltage Reflections

- Short Rise Time of Inv. Output Voltage
- Impedance Mismatch of Cable & Motor → Reflect. @ Motor Terminals / High Insul. Stress
- Long Motor Cable $l_c \geq \frac{1}{2} t_r v$

→ $dv/dt$-Filtering or Full Sinewave Filtering / Termination & Matching Networks etc.
Motor Bearing Currents

- Switching Frequency CM Inverter Output Voltage → Motor Shaft Voltage
- Electrical Discharge in Bearing (“EDM”)

**SiC vs. Si Inverter EMI Spectrum**

- SiC Enables Higher \( dv/dt \)  \( \rightarrow \) Factor 10
- SiC Enables Higher Switching Frequencies  \( \rightarrow \) Factor 10
- EMI Envelope Shifted to Higher Frequencies

\[ f_S = 10\text{kHz} \quad \& \quad 5 \text{kV/us for (Si IGBT)} \]
\[ f_S = 100\text{kHz} \quad \& \quad 50 \text{kV/us for (SiC MOSFET)} \]

\[ V_{DC} = 800\text{V} \quad \text{DC/DC @ } D = 50\% \]

\[ f_{c1} = (\pi t_{\text{on}})^{-1} \]
\[ f_{c2} = (\pi t_{\text{i}})^{-1} \]

\( f_{\text{S}} \)

\( V(t) \)

\( V_{\text{DC}} \)

\( 0 \text{V} \)

\( T \)

\( t_{\text{on}} \)

\( t_{\text{i}} \)

\( t_{\text{r}} \)

\[ V_{\text{DC}} = 800\text{V} \quad \text{DC/DC @ } D = 50\% \]

\( f_{c1} = (\pi t_{\text{on}})^{-1} \]

\( f_{c2} = (\pi t_{\text{i}})^{-1} \]

\[ V \text{- Amplitude (dB\( \mu \text{V}) \]  

\[ f \text{- Frequency (Hz)} \]

\( \rightarrow \) Higher Influence of Filter Component Parasitics and Couplings

\( \rightarrow \) \( dv/dt \)-Filtering or Full Sinewave Filtering, Shielded Motor Cables

Source/Idea: M. Schutten / GE
**DM & CM Conducted / Radiated EMI**

- **DM Conducted EMI Pathway**

- **CM Conducted EMI Pathway (Motor Side)**

- **EMI Standards (Cond. & Rad.)** \(\rightarrow\) **Shielded Motor Cables** OR **Full Sinewave Filtering**
3-Φ DM/CM EMI Measurement & Separation

- EMI Measurement @ Inverter Output
- DM/CM Splitting for Specific Filter Design

- Cap. Coupled Interface Circuit as Replacement for LISN (Var. Output Frequ.)
Inverter Output Filters

dv/dt-Filters
Motor Cable Termination
Staggered Switching
Active CM Filtering
Passive $dv/dt$-Filter & Cable Termination

- $f_c > f_s$ → Reduction of High $dv/dt$ of Inverter Output Voltage to 3...5kV/us

Termination of Cable with Characteristic Impedance & Damping (No $dv/dt$-Limit)

- Limited Applicability @ High Output / Sw. Frequencies (Losses) → Full Sinewave Filter
Active \( \frac{dv}{dt} \)-Filtering

- Active Control of the \( \frac{dv}{dt} \)-Filter Transient Behavior \( \rightarrow \) 2-Step Transition
- Influence of Motor Current \( \rightarrow \) Adaption of Sw. Scheme
- DC- Connection Optional

- Ideally No Damping Resistors
- Increase of Sw. Losses \( \rightarrow \) Low Sw. Frequ. OR High Sw. Speed Semiconductors

Lappeenranta Univ., 2009 / VACON
Staggered/Resonant Switching

- Staggered Sw. Parallel Bridge Legs → Non-Resonant Multi-Step Transition

- 2-Step Switching / Resonant Transition (cf. Active dv/dt Filter)

Active CM Voltage Filters

- Series Compensation of CM Voltage & DM dv/dt-Filtering

- Aux. Bridge Leg → Zero CM Voltage for Active Inv. Sw. States & DM dv/dt-Filtering

- Residual CM Voltage Due to Transf. & Sw. Imperfections / Complexity & Missing Zero State

Source: X. Chen et al., 2007
Source: T.A. Lipo et al., 1999
Inverter Output Filters

Sinewave Filters
“SineFormer” Output Filter

- $f_c << f_S$ DM and CM (!) Output Filter Stage → Sin. Output Voltage / No Sw. Frequ. CM Voltage
- No Shielded Motor Cables Required
- Reduction of Mains-Side EMI

Source: TDK

- Large Weight & Volume → $\approx 2$ kVA/dm$^3$ ($f_S = 4...8$ kHz, $f_0 = 0...100$ Hz)
- Filter Cap. Starpoint Connected to PE Not DC- (Allows Retrofitting)
Full Sinewave Filtering @ ZVS/TCM Operation

- ZVS of Inverter Bridge Legs (No Use of Integral Diode of Si MOSFETs)
- High Sw. Frequency & TCM → Low Filter Inductor Volume

Widely Varying Switching Frequency → Voltage Headroom and/or Multiple Bridge-Legs
Rel. High Current Stress on the Power Transistors
Full Sinewave Filtering @ CCM Operation (1)

- **DC- Ref. LC-Filter** → Max. Ind. Current Ripple @ $d=0.5$
- **DCCMM** — Max. DC-Offset $M_0$ Shifting Phase Voltages Towards $d=0$ OR $d=1$
- **GTHM** — Max. 3rd Harm. $M_3$ for Red. of Sw. Frequ. Harmonic Power

- **GTHM** — Results in Add. Cap. Reactive Power → Limited for Higher Frequencies
Full Sinewave Filtering @ CCM Operation (2)

- Massive Red. of Current Ripple @ Lower Modulation Index
- DCCMM — Adv. for $M = 0...0.5$
- GTHM — Adv. for $M = 0.5...1.0$

- GTHM — Results in Add. Cap. Reactive Power → Limited for Higher Frequencies
**Buck+Boost Inverter**

- Z-Source Inverter etc.
- VSI & DC/DC Front-End
- Double-Bridge VSI
- Phase-Modular Buck+Boost Inverter
- CSI & DC/DC Front-End
“Outside-the-Box” Topologies

- **Z-Source Inverter → Shoot-Through States Utilized for Boost Function**
- **Higher Component Stress Eff. Limits Boost Operation to ≈120% \( U_{in} \)**

**3-Φ Back-End DC/AC Cuk-Converter**

*Source: F.Z. Peng / 2003
J. Rabkowski / 2007
T.A. Lipo et al. /2002 & K.D.T Ngo / 1984*

*Integration Typ. Results in Higher Comp. Stresses & Complexity / Lower Performance*
Boost Converter DC-Link Voltage Adaption

- Inverter-Integr. DC/DC Boost Conv. → Higher DC-Link Voltage / Lower Motor Current
- Access to Motor Star Point & Specific Motor Design Required
- No Add. Components

Explicit Front-End DC/DC Boost Stage

Source: www.rick-gerber.com
Source: J. Pforr et al. / 2009
Source: R.W. Erickson et al. / 1986

→ Analyze Coupling of the Control of Both Converter Stages → “Synergetic Control”
Front-End DC/DC Boost Converter

- “Synergetic Control” @ High Output Voltage
- 2 (!) Inverter Phases Clamped → Low Switching Losses / High Efficiency
- Conv. PWM Inverter / Clamped Boost-Stage Operation @ Low Output Voltage

Preferable for Low Dynamics Drive Systems
**Double-Bridge Inverter (1)**

- Alternative to Front-End DC/DC Converter → **Eff. Doubles DC-Link Voltage**
- 2\textsuperscript{nd} Bridge Switching with Output Freq. → **“Unfolder” Operation**
- Avoids Volume and Losses of Boost Stage → **Eff. Single-Stage Conversion**
- Only Three Inductive Components

- Requires Open Winding Motor & Higher Number of Gate Drives
Double-Bridge Inverter (2)

- Hardware Demonstrator

\[ U_{FC} = 40V \]
\[ P = 1.0kW \]
\[ f_s = 350kHz \] (200V EPC GaN, 2 per Switch)
\[ f_o = 5kHz \]

● Requires Open Winding Motor & Higher Number of Gate Drives
Double-Bridge Inverter (3)

Hardware Demonstrator

$U_{FC} = 40V$
$P = 1.0kW$
$f_s = 350kHz$ (200V EPC GaN, 2 per Switch)
$f_o = 5kHz$

- Requires Open Winding Motor & Higher Number of Gate Drives
Phase-Modular Topologies

Boost+Buck Modules
Buck+Boost Modules
**General Remarks**

- **Usually DC Link Voltage Midpoint Considered as AC Output Ref. Point**
- **Open Machine Starpoint → Introduce CM Voltage Shift → Neg. DC Rail as Reference**

---

Source: Cuk (1982)

**Fig. 7.** New three-phase switching amplifier. Three bidirectional dc-dc converters, with their own modulators, driven by a set of three-phase sine waves, constitute three phase voltages around the differential load.

**Fig. 8.** (a) Line-to-ground and (b) line-to-line voltages generated by the new three phase power amplifier. The dc component of the line-to-ground voltages automatically disappears in line-to-line voltages which are pure ac.

**→ Realization of 3-Φ Inverter Using 3 DC/DC Converter (Phase) Modules — S. Cuk/1982**
**Phase-Modular Boost+Buck / Buck+Boost Inverter**

- **Wide Voltage Conv. Range** → Battery or Fuel-Cell Supply & Adaption to Motor Voltage
- **Continuous Output Voltage** → Explicit / Integr. LC Output Filter

→ **Preference for Low Number of Ind. Components** → Buck+Boost Concept — “Y-Inverter”
Y-Inverter Lighthouse Project

- Three-Phase Continuous Output / Low EMI!
- Buck+Boost Operation / Wide Input &/or Output Range
- Industrial Drive
- Standard Bridge Legs / Building Blocks
- ZVS Operation / Extreme Power Density
- No Shielded Cables / No Insul. Stress
- 1.2kV SiC MOSFETs

Project Scope → Hardware Demonstrator / Exp. Analysis / Comparative Evaluation
**Y-Inverter (1)**

- **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 (2)**

- **Modulation Schemes**

  - *Sinusoidal Modulation* ➔ Variable Output Voltage DC Offset for Low Mod. Index
  - *3rd Harmonic Injection* OR Phase Clamping as Alternative Concepts

![Diagram of Y-Inverter](image)

- **Adv. of Reduced Voltage Against DC- & Reduction of Sw. Losses**
Y-Inverter (3)

- Control Structure

"Democratic Control" → Seamless Transition Between Buck & Boost Operation
**Y-Inverter Prototype (a)**

- **Demonstrator Specifications**
  - **Wide Input Voltage Range** → $400...750\text{V}_{\text{DC}}$
  - **Max. Input Current** → $\pm 15\text{A}$

- **Max. Output Power** → $6...11\text{ kW}$
- **Output Frequency Range** → $0...500\text{Hz}$
- **Output Voltage Ripple** → $3.2\text{V}$ Peak-to-Peak (incl. Add. Output Filter)
Y-Inverter Prototype (b)

- DC Voltage Range 400...750V\(_{DC}\)
- Max. Input Current ± 15A
- Output Voltage 0...230V\(_{rms}\) (Phase)
- Output Frequency 0...500Hz
- Sw. Frequency 100kHz
- 3x SiC (75m\(\Omega\))/1200V per Switch
- IMS Carrying Buck/Boost-Stage Semicond. & Comm. Caps & 2\(^{nd}\) Filter Ind.

Dimensions \(\rightarrow\) 160 x 110 x 42 mm\(^3\) (15kW/dm\(^3\), 245W/in\(^3\))
**Y-Inverter Prototype (c)**

- **Measurement Results**

  \[
  U_{DC} = 400V
  \]

  \[
  U_{AC} = 400V_{\text{rms}} \quad \text{(Motor Line-to-Line Voltage)}
  \]

  \[
  f_0 = 50Hz
  \]

  \[
  f_S = 100kHz \ / \ \text{DPWM}
  \]

  \[
  P = 6.5kW
  \]

  ![Graphs showing measurement results]

  - **Line-to-Line Output Voltage Ripple < 3.2V**
**Y-Inverter Prototype (d)**

- **Demonstrator Performance**  - Efficiency over Output Power @ Given Input Voltage

\[ U_{DC} = 400V / 600V \]
\[ U_{AC} = 230V_{rms} \text{ (Motor Phase Voltage, rms)} \]
\[ f_S = 100kHz \]

\[ U_{DC} = 400V / 600V \]
\[ U_{AC} = 230V_{rms} \text{ (Motor Phase Voltage, rms)} \]
\[ f_S = 100kHz \]

\[ \eta = 98.27\% \]

→ **Multi-Level Bridge Leg Structure for Ind. Comp. Volume Reduction**
**Alternative Topology**

- *Phase Modules Based on 2-Switch Buck+Boost Topology*

![Diagram of 2-Switch Buck+Boost Topology]

- Lower Number of Switches / Higher Component Stresses → *Low Power Applications*
DC/DC Buck Stage & Current Source Inverter

Monolithic Bidir. GaN Switches Synergetic Control

NEW ARRIVAL
**Current Source Inverter (CSI) Topologies**

- **Phase Modular Concept** → Y-Inverter (Buck-Stage / Current Link / Boost-Stage)
- **3-Φ Integrated Concept** → Buck-Stage & Current DC Link Inverter

→ **Low Number of Ind. Components** & **Utilization of Bidir. GaN Semicond. Technology**
**3-Φ -Integrated Buck-Boost CSI (1)**

- Basic Topology Proposed in 1984 / Ph.D. Thesis of K.D.T Ngo
- Bidir./Bipolar Switches → Positive DC-Side Voltage for Both Directions of Power Flow

**Monol. GaN Switches** → Factor 4 Improvement in Chip Area Comp. to Discrete Realiz.
**Also Beneficial for Matrix Converter Topologies**
3-Φ - **Integrated Buck-Boost CSI (2)**

- **Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates / Full Controllability**
- **Buck-Stage for Const. DC Current / PWM CSI for Output Voltage Control**

“Synergetic Control” of Buck & Inverter Stage for Red. of Sw. Losses
3-Φ –Integrated Buck-Boost CSI (3)

- Monolithic Bidir. Bipolar GaN Switches Featuring 2 Gates / Full Controllability
- “Synergetic” Variable DC Current Control of Buck Stage & Inverter Stage Clamping

Experimental Analysis in Progress (Upcoming Publication @ PEDG 2019)
Further Concepts

Integrated Modular Motor Drive
Integrated Modular Motor Drive

- Machine/Inverter Fault-Tolerant VSD
- Motor Integr. Low-Voltage Inverter Modules
- Very-High Power Density / Efficiency
- Supply of 3-Φ Winding Sets / Low C Buffer Cap.

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

Evaluate Machine Concept (PMSM vs. SRM etc.) / Wdg Topologies / Filter Req. / etc.
Conclusions
Conclusions

Future Need for „SWISS Knife“-Type Systems

- Wide Input / Output Voltage Range
- Continuous / Sinusoidal Output Voltage
- Electromagnetically „Quiet“ - No Shielded Cables
- On-Line Monitoring / Industry 4.0
- “Plug & Play” / Non-Expert Installation
- SMART Motors

Enabling Technologies

- SiC / GaN
- Adv. (Multi-Level) Topologies incl. PFC Rectifier
- “Synergetic” Control
- Monolithic Bidirectional GaN
- Intelligent Power Modules
- Integration of Switch / Gate Drive / Sensing / Monitoring
- Adv. Modeling / Simulation / Optimization

System Level → Integr. of Storage, Distrib. DC Bus, Hybrid Hydr./Pneum./El. Drives etc.
Thank You!