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Title

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

Presenters

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Abstract

This intermediate level seminar first introduces participants to state-of-the-art variable speed drive (VSD) systems and gives a short overview of the realization requirements and regulations detailed in corresponding product standards. Next, three-phase PWM inverter topologies with different types of explicit LC output filters, i.e. continuous sinusoidal output voltage, are discussed, which allow the full utilization of ultra-fast switching wide bandgap (WBG) SiC and GaN power semiconductors. The systems do not require shielded motor cables, ensure low motor losses and/or applicability of conventional low-cost motor technology and are preventing dv/dt-related motor insulation stresses, as well as bearing currents and reflections on long motor cables. Different filter structures and the filter design procedure are shown and examples of high switching frequency industrial drive systems with output filters are shown. Furthermore, advanced inverter bridge-leg topologies, including multi- level arrangements with series and/or parallel interleaving are evaluated concerning losses and output filter volume. In this context, a multi-level/cell GaN bridge-leg power module employing 650V GaN power semiconductors, operating at 4.8MHz effective switching frequency and integrating an ultra-compact output filter, is de- scribed.

Subsequently, new three-phase voltage DC-link or current DC-link inverter concepts featuring buck-boost functionality and inherently generating a continuous output voltage waveform are presented. The systems allow operation in a wide DC input voltage and/or AC output voltage/motor speed range and are therefore ideally suited for battery powered or distributed DC-link VSD applications. The new converter topologies are derived starting from conventional inverter structures and are grouped into phase-modular and phase-integrated concepts. Continuous and discontinuous modulation schemes are explained and evaluated for both converter groups and a synergetic coupling of the control of the input and output stages of the systems resulting in low overall switching losses is described. Furthermore, measurement results of high power density laboratory demonstrators of the systems employing latest SiC MOSFETs or monolithic bidirectional GaN e-FET technology are presented.

Final considerations of the seminar are on the fast and accurate measurement of the switching and conduction losses of WBG power semiconductors, and of the low- and high-frequency losses of ceramic capacitors and magnetic core materials as basis for an inverter and/or output filter design. Furthermore, the advantages and challenges of a future embedding of the inverter into the motor are discussed and topics of latest research on next-generation VSD systems at the Power Electronic Systems Laboratory of ETH Zurich arepresented.

Content Outline

The **first** half of the seminar covers concepts allowing the full utilization of ultra-fast switching wide bandgap (WBG) power semiconductors (GaN and SiC) in multi-kW three-phase VSD inverter topologies, which inevitably requires LC output filters. Different bridge-leg topologies and filter structures as well as a detailed filter design procedure are main topics.
The **second** half presents new voltage or current DC-link inverter topologies which feature buck-boost functionality and inherently generate a continuous sinusoidal output voltage, and are therefore of special interest for WBG inverters with widely varying input voltage/battery or fuel-cell power supply and/or for covering a wide output voltage/motor speed range. The detailed theoretical considerations of the systems are substantiated with experimental results of ultra-compact laboratory demonstrators including EMI measurements.
Final considerations are on the fast and highly accurate experimental evaluation of WBG power semiconductors, ceramic capacitors and magnetic core materials, as required for the design of next generation very high switching frequency and highly compact WBG inverter systems. Furthermore, the advantages and challenges of a physical integration of the motor and inverter are highlighted and topics of latest research on next-generation VSD systems at the Power Electronic Systems Laboratory of ETH Zurich are presented.

The subtopics discussed in the main parts of the seminar are listed in the following in combination with the scheduled duration.

Part 1 (30min)

State of the Art Medium Power VSD Systems

- Overall Structure
- Product Standard Summary
- Next Generation VSD Requirements

Challenges of WBG Power Semiconductor Application

- High dv/dt Insulation Stress, Reflections on Long Motor Cables, Bearing Currents
- EMI Equivalent Circuit and EMI Measurement
- Conducted EMI Path incl. Input Stage and Shielded Motor Cable
- Radiated EMI
- Input Side EMI Filter / Output Filter

Part 2 (30min)

Inverter with Output Filter

- Passive and Active dv/dt Filter
- Staggered and Resonant Transition Switching
- Passive DM and Full Sinewave (CM+DM) Filtering
  - DC Bus Referenced Filter & Adv. Modulation
  - Ground Referenced CM Filter Stage
- Active CM EMI Filter (incl. Low CM Voltage Modulation)

- Filter Design Procedure (Design Space etc.)
- Examples of Commercial Drive Systems with Output Filter
  - Superjunction MOSFET Inverter in TCM Operation
  - 650V 100kHz GaN Inverter
  - 900V 100kHz GaN Inverter
- DC-Side filter

Part 3 (30min)

Advanced Inverter Topologies / Bridge Leg Structures

Double-Bridge Inverter
Parallel and Series (FCC) Interleaving
Quasi-Two-Level Operation of Multi-Level Inverter
Hybrid NPC Inverter
Multi-Level FOM
Quasi-Analog MHz-Switching Integrated Filter Multi-Level Bridge-Leg GaN Power Module
Exotic Concepts (9-Switch Inverter, Star-Point DC Source Inverter)

Coffee Break (30min)

Part 4 (30min)

Buck-Boost Inverter Topologies

Z-Source and Cuk Approach

Topologies with Continuous Output Voltage / Integrated Filter Property

Boost Converter and 1/3 VSI with Output Filter (incl. Origin of Concepts & Unfolder Alternatives)
Y-Inverter
2/3 CSI & Monolithic Bidirectional GaN Switch

Part 5 (30min)

Component Measurements

Transient Calorimetric Loss Measurement Concept
Measurements of WBG Power Semiconductor / Ceramic Capacitors / Magnetic Cores
Measurement Results

Part 6 (30min)

Conclusions / Future Developments / Discussion

Integration of Motor and Inverter – IMD / IMMD
Evaluation of WBG vs. Si Power Semiconductors
Thermal Management of Motor and Inverter
Topics of current Research on Next-Generation VSD Systems @ ETH Zurich

Presenters' Biography

Johann W. Kolar received his M.Sc. and Ph.D. degree (summa cum laude/promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria, in 1997 and 1999, respectively. Since 1984, he has been working as an independent researcher and international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drive systems. He has proposed numerous novel PWM converter topologies, modulation and control concepts and has supervised 70+ Ph.D. students. He has published 880+ scientific papers in international journals and conference proceedings, 4 book chapters, and has filed 190+ patents. The focus of his current research is on ultra- compact and ultra-efficient SiC and GaN converter systems, solid-state transformers, advanced variable speed three-phase motor drives, integrated modular motor drives, ultra-high speed motors, bearingless motors/ actuators, and design automation in power electronics/mechatronics. Dr. Kolar has received 29 IEEE Transactions and Conference Prize Paper Awards, the 2014 IEEE Middlebrook Award, the 2016 IEEE William E. Newell Power Electronics Award, the 2016 IEEE PEMC Council Award and two ETH Zurich Golden Owl Awards for excellence in teaching. He initiated and/or is the founder of four ETH Spin-off companies. He is a member of the steering committees of several leading international conferences in the field and has served from 2001 through 2013 as an associate editor of the IEEE Transactions on Power Electronics. Since 2002 he also is an associate editor of the Journal of Power Electronics of the Korean Institute of Power Electronics and a member of the Editorial Advisory Board of the IEEJ Transactions on Electrical and Electronic Engineering.

Mattia Guacci received the B.Sc. degree (summa cum laude) and M.Sc. degree (summa cum laude) in Electronic Engineering from the University of Udine, Italy in July 2013 and in October 2015, respectively. In 2014 he was with Metasystems SpA in Reggio nell'Emilia, Italy working on on-board battery chargers for electric vehicles. In November 2015 he joined the Power Electronic Systems (PES) Laboratory of the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland as a scientific assistant investigating innovative inverter topologies. In September 2016 he started his Ph.D. at PES focusing on advanced power electronics concepts for future aircraft and electric vehicle applications. Mattia Guacci has authored 12 scientific papers in international journals and conference proceedings and has received 1 IEEE Prize Paper Award.

Michael Antivachis received the B.Sc. degree in electrical engineering from National Technical University of Athens (NTUA) in 2014 and the M.Sc. degree in energy science and technology from ETH Zürich in 2016. Since June 2016 he is with the Power Electronic Systems Laboratory of ETH Zurich as a Ph.D. candidate. His research interests include high-speed motor drive systems for commercial applications, efficient inverter topologies in a small form factor employing wide-bandgap power devices and low EMI emission profile converters.

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, co-supervising Ph.D. students and leading industry research projects. During this time he gained a substantiated knowledge in power electronics, e.g. in the design of compact and efficient PFC rectifier systems with soft-switching TCM modulation, the realization of ultra-compact inverter systems for the Google Little Box Challenge employing latest power semiconductor technology (SiC and GaN), the design of future variable speed motor drive systems with PCB-integrated power semiconductors for electric cars, the realization of a high temperature automotive inverter system or the design of lightweight rotating transformers used for the power transfer in advanced high speed spindles applied for ultrasonic assisted grinding.

In 2010, he founded the company Enertronics GmbH, a consulting company in the field of power electronics system engineering and prototyping. The collaborations with leading international companies allowed him to set up a wide network of industry partners and to gain deep insight into industry demands, which is mandatory for the technology transfer from academia to industry.

Since January 2016 Dr. Bortis is heading the research group Advanced Mechatronic Systems at PES, which concentrates on ultra-high speed motors, magnetic bearings and bearingless drives, new linear-rotary actuator and machine concepts with integrated power electronics. In this context, multi-objective optimizations concerning weight/volume/efficiency/costs, the analysis of interactions of power electronics and electric machines, and EMI are given special attention. Targeted applications include advanced industry automation and manufacturing, e.g. highly dynamic and precise positioning systems, medical and pharmaceutical systems, e.g. ultra-high purity and blood pumps, and future mobility concepts, including motors and actuators for hybrid and electric vehicles, more electric aircraft and satellites. Dr. Bortis has published more than 90 scientific papers in international journals and conference proceedings. He has filed 32 patents and has received 6 IEEE Conference Prize Paper Awards.