EPE'23 ECCE Europe – Call for Tutorials

The Essence of Solid-State Transformers

Fundamentals, Design Challenges, R&D Overview, Comparative Evaluation, Outlook

Name(s) and Affiliation(s) of the Lecturer(s):

Prof. Dr. Johann W. KOLAR
Power Electronic Systems Laboratory
ETH Zürich
Physikstrasse 3
8092 Zürich, Switzerland
kolar@lem.ee.ethz.ch

Dr. Jonas HUBER
Power Electronic Systems Laboratory
ETH Zürich
Physikstrasse 3
8092 Zürich, Switzerland
huber@lem.ee.ethz.ch
Tel: +41 44 633 83 58

Summary:

This seminar introduces participants to the Solid-State Transformer (SST) concept in a comprehensive and easy-to-follow fashion. After a brief review of transformer basics, the SST concept history, and the various intended SST application areas, main SST technology concepts and key design aspects are discussed. These include, e.g., medium-frequency (MF) power conversion, power electronic interfaces connected to medium voltage (MV), key SST topologies, MF transformer design, and isolation coordination.

The second half of the tutorial then showcases latest SST concepts and demonstrator systems from University and Industry R&D activities to establish an overview on the state of the art and the most relevant developments. Based on recent industrial SST realizations, we then discuss benefits and challenges for SST applications in datacenter power supply systems and high-power EV charging by providing a comparative evaluation against alternative approaches (e.g., solutions based on low-frequency transformers and highly efficient low-voltage SiC converters).

Based on this comparative evaluation, the remaining challenges, the most promising SST and Power-Electronic-Building-Block-(PEBB)-based realization concepts and their application potentials, and finally the future research vectors are identified. The tutorial closes with an outlook on future performance targets beyond efficiency/power density, i.e., compatibility with future sustainable circular economy concepts.

Target Audience:

The tutorial is tailored to serve the interests of a broad audience with academic or industrial backgrounds.

Timing:

This is a full-day tutorial (09:30 – 13:00 and 14:00 – 17:30).

Topical Outline:

This tutorial takes up an earlier series of tutorials on solid-state transformers (SSTs) that the authors have presented 6-7 years ago at the APEC, ECCE Asia, and PCIM Europe conferences. In the meantime, SST technology has continued to evolve, and new industrial applications and prototypes have been built and described in literature. It is therefore the right time to present an update on these recent developments, while still providing the audience with a complete and solid foundation of solid-state transformer technology.

Part 1 – J. W. Kolar
Introduction & Intended SST Applications

- Historical development of classical transformer technology
- Basic transformer theory and scaling laws
- Strengths/weaknesses of low-frequency transformers
- Historical motivations of the SST concept
- Megatrends and intended applications for SSTs

Part 2 – J. Huber
SST Concepts & Key Design Aspects
This part provides the technical background to appreciate the discussion and application-oriented evaluation of recent SST demonstrators from academia and industry provided in Parts III and IV. Specifically, the following key aspects are discussed, mostly using exemplary realization options from academia and industry:

- Medium-frequency isolation
  - Main isolated DC-DC converter concepts (DCX, DAB)
- Handling of medium voltage
  - Power semiconductors (Si, LV-SiC, HV-SiC)
  - Multilevel bridge-leg configurations (NPC, FCC, MMC)
- Key SST topologies
  - Isolated back-end / front-end multicell, matrix-type, modular multilevel, single-cell
- Medium-frequency transformer design
  - Design approaches (magnetic-core, air-core, realization examples)
  - Mixed-frequency electric field stress
- Isolation coordination

- Protection concepts
- Reliability
- Standardization & EMC
- Construction and testing

Part 3 – J. W. Kolar

Selected Results of Recent University / Industry SST R&D Activities

In the past years, several full-scale SST demonstrator systems have been presented by academia and industry, which are introduced to illustrate the state of the art; highlights include:

- 10 kV SiC power cells for MMC-based SSTs
- Medium-frequency AC bus multi-port concepts
- DC-DC SSTs for future railway electrification

Part 4 – J. Huber

Comparative Evaluation of SSTs for Datacenters and EV Charging

Based on recent industrial SST realizations, we discuss benefits and challenges for SST applications in datacenter power supply systems and high-power EV charging. Specifically, we provide an application-specific comparative evaluation against alternative approaches (e.g., solutions based on low-frequency transformers and highly efficient low-voltage SiC converters).

Part 5 – J. W. Kolar

Summary & Research Vectors

The tutorial's last part identifies the remaining key challenges for the further adoption of SST technology that need to be addressed by future research and which include:

- System-level & application-specific technology evaluation
- Robustness, reliability, availability
- Protection of MV-connected power electronics against, e.g., lightning strike surges
- Cost (CAPEX, OPEX)

The tutorial closes with an overview on the corresponding research vectors and an outlook on future performance targets beyond efficiency/power density, i.e., compatibility with future sustainable circular economy concepts.

About the Lecturers:

Johann W. Kolar (M'89–F'10) is a Fellow of the IEEE, an International Member of the US NAE and a Full Professor and Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich. He has proposed numerous novel converter concepts incl. the Vienna Rectifier, has spearheaded the development of x-million rpm motors and has pioneered fully automated multi-objective power electronics design procedures. He has graduated 80+ Ph.D. students, has published 900+ research papers, 4 book chapters, and has filed 200+ patents. He has served as IEEE PELS Distinguished Lecturer from 2012 - 2016. He has received 40+ IEEE Transactions and Conference Prize Paper Awards, the 2014 IEEE Power Electronics Society R. David Middlebrook Achievement Award, the 2016 IEEE PEMC Council Award, the 2016 IEEE William E. Newell Power Electronics Award, the 2021 EPE Outstanding Achievement Award and 2 ETH Zurich Golden Owl Awards for excellence in teaching. The focus of his current research is on ultra-compact/efficient WBG PFC rectifier and inverter systems, ultra-high BW switch-mode power amplifiers, multi-port converters, Solid-State Transformers, multi-functional actuators, ultra-high speed / motor-integrated drives, bearingless motors, ANN-based multi-objective design optimization and Life Cycle Assessment of power electronics systems.

Jonas Huber (S'11–M'16—SM'22) received the MSc (with distinction) degree and the PhD degree from the Swiss Federal Institute of Technology (ETH) Zurich, Switzerland, in 2012 and 2016, respectively. Since 2012, he has been with the Power Electronic Systems Laboratory, ETH Zurich and became a Post-Doctoral Fellow, focusing his research interests on the field of solid-state transformers, specifically on the analysis, optimization, and design of high-power multi-cell converter systems, reliability considerations, control strategies, and applicability aspects. From 2017, he was with ABB Switzerland Ltd. as an R&D Engineer designing high-power DC-DC converter systems for traction applications, and later with a Swiss utility company as a Business Development Manager. He then returned to the Power Electronic Systems Laboratory as a Senior Researcher in 2020, extending his research scope to all types of WBG-semiconductor-based ultra-compact, ultra-efficient or highly dynamic converter systems. Since 2015, he has co-presented 9 tutorials at major IEEE conferences (e.g., ECCE, APEC).