Comparative Evaluation of Three-Phase AC-AC PWM Converter Systems

TUTORIAL ANNOUNCMENT

AC-AC converters are being implemented in an increasing number of applications, such as in electric drives requiring a bi-directional power flow and a high input power factor. For such requirements matrix converters are considered to offer significant advantages over conventional concepts in terms of energy conversion efficiency and volume of passive components. However, despite three decades of research, matrix converters are still not widely used in industry. One possible reason for their under utilization is their perceived demanding modulation scheme to guarantee safe operation, and perform rectification and inversion simultaneously.

The main objective of this Tutorial is to introduce the participant to matrix converters as well as voltage and current DC-link based converter systems in a figurative, easy-to-follow way. In a fist step the matrix converter concept is comparatively evaluated for drive applications against competing converter topologies with DC-link energy storage regarding efficiency, desirable torque-speed operating range, EMI filtering effort, and volume of passive components. A particular focus is set on a semiconductor chip area based assessment of different converter topologies which provides a distinct criterion for comparison. The scope of the Tutorial not only includes bidirectional converters but also converter topologies with unidirectional power flow, which allow to reduce the number of power semiconductors and to decrease the overall volume.

The Tutorial aims at providing the participants with different figures-of-merit to select the most suitable converter concept for a given application and to assess the influence of future advancements in power semiconductor technology regarding performance gain of converter systems. The intended audience is researchers and manufacturers interested in an entry-level introduction and a comprehensive evaluation of three-phase AC-AC converters.

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Tutorial Part 1 (09:30 - 11:00)
Introduction and Overview

The Tutorial starts with a review of the basic principle of operation and space vector modulation of voltage and current source converter systems, showing the formation of the input, output, and DC-link quantities. Then, the most basic form of a direct AC-AC converter (i.e., a voltage DC-link back-to-back converter system with suppressed DC-link capacitor, Fundamental Frequency Front-End Converter) is introduced and discussed concerning output voltage formation, output voltage range, and input current behavior. Subsequently, the circuit topology is extended into an Indirect Matrix Converter (IMC) where the modulation is directly following from the voltage and current source rectifier considerations. Zero current and zero voltage commutation of the IMC are discussed and a possible simplification of the IMC is presented which leads to the Sparse Matrix Converter (SMC) topology.

Based on the initial considerations, circuit topologies and a classification of all matrix converter concepts presented in the literature will be discussed. This includes hybrid matrix converters, three-level matrix converters, and full-bridge matrix converters for supplying machines with open-ended windings.

Coffee Break (11:00 - 11:30)

Tutorial Part 2 (11:30 - 13:00)
Converter Dimensioning and Comparison

In the second part of the Tutorial the output voltage and input current space vectors available for the (direct) Conventional Matrix Converter (CMC) are compared to those of the IMC, which immediately identifies the equivalence of switching states for both systems. This relationship is then used to translate the IMC modulation into a CMC switching sequence, which links the knowledge basis of both systems. In order to provide a basis for the system dimensioning, the derivation of a low-complexity analytical expression for the calculation of the IMC and CMC power semiconductors current stresses is presented. Furthermore, the worst-case operating conditions, i.e. the component stresses for providing full torque at stand-still or operation with an output frequency close to the mains frequency, are analyzed. In addition, the optimum partitioning of a given silicon area to the power transistors and power diodes is identified for a given operating range in the torque-speed plane.

Finally, the matrix converter topologies are compared with voltage and current DC-link AC-AC converter systems concerning the input and output current waveform quality, required input and output EMI filters to meet EMC requirements, efficiency, compactness, control dynamics, possibilities for ride-through operation, and semiconductor utilization. For these comparisons, an equal total silicon area is assumed to be employed in all systems. The theoretical considerations are substantiated by measurement results of experimental systems including an

All-SiC current source back-to-back converter and All-SiC IMC, a Si RB-IGBT IMC, and an Ultra-Sparse Matrix Converter with Si and SiC semiconductors.

A possible implementation of a Virtual Converter Evaluation Laboratory (VCEL) is demonstrated highlighting its effectiveness to compare different converter topologies and the need for efficient multi-domain simulation tools. Finally, the results of the comparative assessment based on theoretical calculations and the VCEL are presented which clearly reveal the strengths and the weaknesses of the different topologies. This leaves the participants with an understanding of the most advantageous application areas of the different converter systems.

Lunch Break (13:00 - 14:00)

Tutorial Part 3 (14:00 - 15:30)
Unidirectional AC-AC Converters

There is a wide range of applications where bidirectional power flow is not required, e.g. pumps, fans, and compressors or where braking or generator operation is rarely used or even not allowed like for More Electric Aircraft. Accordingly, starting from the industrially well established voltage DC-link inverter topology with diode bridge rectifier input stage this part of the Tutorial addresses DC-link and matrix converter topologies with sinusoidal input current control but unidirectional mains interfaces.

Firstly, boost-type voltage DC-link rectifier concepts like the Three-Switch Bridgeless PWM Rectifier, the Delta-Switch PWM Rectifier and the Three-Switch Three-Level (Vienna) Rectifier are introduced. Secondly, a Three-Switch Buck Rectifier and Three-Switch Buck+Boost Rectifier with single output or output power splitting are discussed. As alternatives, a hybrid combination of a 12-Pulse Autotransformer Rectifier and Electronic Smoothing Inductors or DC-side boost-type DC-DC converters are presented. Finally, the Nine-Switch Ultra-Sparse Matrix Converter is described and a comparative evaluation of all concepts is provided with a focus on input current quality, realization effort, efficiency, and power density.

Coffee Break (15:30 - 16:00)

Tutorial Part 4 (16:00 - 17:30):
Multi-Domain Simulator Demonstration, Discussion, Questions

In the fourth part of the Tutorial the performance of a fast multi-discipline simulator (GECKO), currently being developed at the Power Electronic Systems (PES) Laboratory of ETH Zurich, is demonstrated, which allows a simultaneous simulation of electrical and thermal quantities as well as a prediction of the conducted EMI of converter systems. *A free copy of the program, including a Virtual Converter Evaluation Laboratory, will be handed to the Tutorial Participants.*
The last quarter of an hour is reserved to answer questions and for plenary discussions.

ABOUT THE INSTRUCTORS

Johann W. Kolar (SM'04) received his Ph.D. degree (summa cum laude / promotio sub auspiciis praesidentis rei publicae) from the University of Technology Vienna, Austria. Since 1984 he has been working as an independent international consultant in close collaboration with the University of Technology Vienna, in the fields of power electronics, industrial electronics and high performance drives. He has proposed numerous novel PWM converter topologies, and modulation and control concepts, e.g., the VIENNA Rectifier and the Three-Phase AC-AC Sparse Matrix Converter. Dr. Kolar has published over 300 scientific papers in international journals and conference proceedings and has filed 75 patents. He was appointed Professor and Head of the Power Electronic Systems Laboratory at the Swiss Federal Institute of Technology (ETH) Zurich on Feb. 1, 2001.

The focus of his current research is on AC-AC and AC-DC converter topologies with low effects on the mains, e.g. for power supply of telecommunication systems, More-Electric-Aircraft and distributed power systems in connection with fuel cells. Further main areas of research are the realization of ultra-compact intelligent converter modules employing latest power semiconductor technology (SiC), novel concepts for cooling and EMI filtering, multi-domain/multi-scale modeling and simulation, physical model based lifetime prediction, pulsed power, bearingless motors, and Power MEMS. He received the Best Transactions Paper Award of the IEEE Industrial Electronics Society in 2005. He also received an Erskine Fellowship from the University of Canterbury, New Zealand, in 2003. In 2006, the European Power Supplies Manufacturers Association (EPSMA) awarded the Power Electronics Systems Laboratory of ETH Zurich as the leading academic research institution in Europe.

Dr. Kolar is a Member of the IEEE and a Member of the IEEJ and of Technical Program Committees of numerous international conferences in the field (e.g. Director of the Power Quality Branch of the International Conference on Power Conversion and Intelligent Motion). From 1997 through 2000 he has been serving as an Associate Editor of the IEEE Transactions on Industrial Electronics and since 2001 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.

Thomas Friedli (S'06) studied electrical engineering at the Swiss Federal Institute of Technology in Zurich (ETH Zurich) and received his M.Sc. Degree in 2005 with Distinction. From 2003 to 2004 he worked as a student trainee for Power-One in the R&D centre for telecom power supplies. During his M.Sc. studies he focused on power electronics, control engineering, signal processing, and hardware development. His Master thesis research involved the design and implementation of a modular three-phase PFC input stage (Delta-Rectifier).

End of 2005, he joined the Power Electronic Systems Laboratory at ETH Zurich as a Ph.D. student. His research activities deal with the further development of current source and matrix converter topologies using silicon carbide power semiconductors and a comparative assessment of different AC-AC converter topologies.