Next Generation Time-Domain Control of Power Electronics Systems using Predictive Switching Sequences

**ECCE 2015 Tutorial**

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ABSTRACT

Significance and Objectives:

This tutorial provides a fundamentally different perspective to control of switching power electronic systems. It is based on controlling the time evolution of the switching states (i.e., switching sequences) as well as controlling the switching transition of the power semiconductor device of the solid state electronic system. The former – i.e., switching-sequence based control (SBC) yields rapid response under transient condition, optimal equilibrium response, and yields seamless transition between the two states of dynamics. The first part of the tutorial will primarily focus on SBC for power electronics systems. By enabling integration of modulation and control, SBC precludes the need for ad-hoc offline modulation synthesis. In other words, an optimal switching sequence for the power converter is generated dynamically without the need for prior determination of a modulation scheme (which generates a pre-determined switching sequence) in typical conventional approaches. One of the distinctions between SBC and conventional model predictive control (MPC) is that SBC ensure optimal determination of the switching sequence of the power converter under stability bound. The tutorial will provide the mechanism to carry out SBC and MPC control syntheses and demonstrate the differences between SBC and MPC. Several device, converter, and network level implementations (e.g., motor drive, multilevel converter, microgrid, parallel inverters, aircraft power system) of the SBC will be provided.

The second part of the tutorial reviews control and modulation methods that fully exploit the performance potential of high-power converters, by ensuring fast control at very low switching frequencies and low harmonic distortions. To achieve this, the control and modulation problem is addressed in one computational stage. To this end, the benefits of deadbeat control methods (such as direct torque control) are combined with the optimal steady-state performance of optimized pulse patterns, by resolving the antagonism between the two. As a result, the current harmonic distortions and the switching losses can be reduced simultaneously, when compared to carrier-based PWM. Indeed, at low switching frequencies, the resulting steady-state behavior is similar to that of optimized pulse patterns. During transients, however, very fast current and torque response times are achieved, similar to deadbeat control. To this end, two control and modulation methods will be presented. First, a direct MPC with long prediction horizons. Using a branch and bound technique, the optimization problem can be solved efficiently for long prediction horizons. Large performance benefits result for converters with LC filters, which do not require an additional active damping loop. This formulation generalizes the well-known finite control set MPC formulation. Second, a fast closed-loop control based on optimized pulse patterns will be provided. Experimental results on a five-level medium-voltage drive will be demonstrated.

Finally, the tutorial will focus on switching transition control (STC). The primary objective of STC is to demonstrate how key power electronic system parameters including $dv/dt$ and $di/dt$ stress, switching loss, electromagnetic noise emission can be controlled dynamically by modulating the dynamics of the power semiconductor devices. Both electrical and newly developed optical control mechanisms to achieve STC will be demonstrated. In the context of the latter, mechanisms for monolithic integration of switching sequence control as well as switching transition control will be outlined and the revolutionary impact of such a novel integration on system performance will be demonstrated with practical applications.
Tutorial Outline:

The comprehensive tutorial is arranged in four parts.

1. Need for next-generation power-electronics control
   1.1. Overview of need
   1.2. Control elements and their current limitations
       1.2.1. Beyond averaged modeling
       1.2.2. Overview of existing equilibrium stability approaches: scope and limitations
       1.2.3. Limitations of conventional control approaches
   1.3. New control propositions based on SBC, MPC: similarities and differences

2. Switching-sequence-based control (SBC)
   2.1. Conditions for orbital existence of power electronics systems
       2.1.1. Demonstrative results
   2.2. SBC control formulation and optimization
       2.2.1. SBC results for standalone, high-frequency-link, and networked power electronics systems

3. Direct MPC with long prediction horizons (DMPC)
   3.1. Control problem formulation and solution approach using branch and bound optimization
       3.1.1. Case study of an NPC inverter drive system with a sine filter, performance evaluation during steady-state operation and transients, and assessment of the performance benefits when compared to short horizons
   3.2. MPC based on optimized pulse patterns
       3.2.1. Real-time implementation issues
       3.2.2. Experimental results for five-level MV drive

4. Outline of switching-transition control (STC)
   4.1. Control of a power electronics system at the semiconductor device level
   4.2. Real-time implementation and results for simultaneous control of system switching loss, \( \frac{dv}{dt} \) and \( \frac{di}{dt} \) stress, and electromagnetic noise of an optically-triggered power electronics system

5. Review of key concepts and conclusions

Intended Audience:

This tutorial is intended for a wide spectrum of researchers and industry professional reflecting the typical distribution of ECCE audience.

Duration of Tutorial:

The intended duration of the tutorial is 4 hours. However, the duration can be modified as desired by the program committee.
Tobias Geyer:

Dr. Geyer received the Dipl.-Ing. and Ph.D. degrees in electrical engineering from ETH Zurich, Zurich, Switzerland, in 2000 and 2005, respectively. From 2006 to 2008, he was with the High Power Electronics Group of GE's Global Research Centre, Munich, Germany. Subsequently, he spent three years at the Department of Electrical and Computer Engineering, The University of Auckland, Auckland, New Zealand, where he developed model predictive control schemes for medium-voltage drives. In 2012, he joined ABB’s Corporate Research Centre, Baden, Switzerland. His research interests are at the intersection of power electronics, modern control theory and mathematical optimization. This includes model predictive control and medium-voltage electrical drives.

Dr. Geyer was a recipient of two Prize Paper Awards at conferences and of the 2014 Third Best Paper Award of the Transactions on Industry Applications. From 2011 until 2014 he served as an Associate Editor of the Industrial Drives Committee for the Transactions on Industry Applications. Since 2013 he has been serving as an Associate Editor for the Transactions on Power Electronics. He has authored and co-authored more than 100 peer-reviewed publications and patent applications.

Sudip K. Mazumder:

Dr. Mazumder is a Professor at the University of Illinois and also the President of NextWatt LLC and also serves as the Director for the Laboratory of Energy and Switching-Electronics Systems. He received his Ph.D. from Virginia Tech in 2001. He has over 23 years of professional experience and has held R&D and design positions in leading industrial organizations. His current areas of interests are optimal switching-sequence based control and stability analysis of power electronic device, converters, and networks; renewable and alternative energy based high-frequency-link conversion systems; and photonic and wide-bandgap devices and applied technologies. He has more than 185 publications, 8 book/book chapters, and 10 patents, and has worked on close to 42 sponsored research projects.

Dr. Mazumder received the following prestigious awards: Inventor of the Year Award (2014) from the University of Illinois, Chicago, University Scholar Award (2013) from the University of Illinois, NSF CAREER Award (2003) and ONR Young-Investigator Award (2005), IEEE PELS Transaction Prize Paper Award (2002), Best Paper Award at IEEE PEDG Conference (2013), Outstanding Paper Award at IEEE AINA Conference (2007), and IEEE Future Energy Challenge Award (2005). He was the first Editor-in-Chief for Advances in Power Electronics and currently served as the Guest Editor-in-Chief for IEEE PELS Transaction apart from serving as an Editorial Board Member for IEEE IES, IEEE TII, IEEE PELS, and IEEE TAES. He also serves on several IEEE PELS Technical Committees and is serving as a Plenary Chair for IEEE ECCE 2015.