Advanced Nonlinear Control and Stability Analysis of Power-Electronics Systems and Networks

IEEE IECON 2010 Tutorial Proposal

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A. Significance and Objectives:

Optimal compromise between stability margin and performance of switching power converters (SPCs) is an ongoing challenge. It has now attained newer heights due to traditional applications such as VRMs/POL converters that are of-late demanding significant performance improvements and due to newer DPS/network applications (ranging from Microgrids and FutureGens based on Alternative Energy Sources, More-Electric-Aircrafts (MEA) for aerospace applications, to Advanced Naval Electric Power Systems (AEPS) for electric ships), which demand performance and stability, not only for individual converters but for the network as a whole.

The obvious question is why are traditional approaches based primarily on averaged models alone not enough? This is because linear/nonlinear averaged models cannot account for the “global dynamics” of a SPC/SPC network and their predictions are limited to averaged dynamics under “periodic switching conditions”. Consequently, the associated stability tools and control techniques are limited in their capabilities as well. Thus, there is need for a generalized approach that is powerful enough to account for the global dynamics of standalone/integrated/networked SPCs under saturated, quasi-saturated and unsaturated (periodic switching) operating conditions.

Based on the research advancements made in the last decade, including recent breakthroughs by the author, the author will delineate (using fundamental concepts and several practical applications) this generalized global stability approach, how it can integrate existing averaged model concepts as well as methodologies based on nonlinear maps, and how it can lead to advanced hybrid and distributed controllers. Specifically, the focus of the tutorial will be on two key areas:

- **Reaching Condition Analyses**: The first part of the tutorial focuses on concepts and methodologies to investigate the dynamics of the SPCs (ranging from basic to integrated as well as complex homogeneous and heterogeneous networked converters) in the saturated and quasi-saturated conditions. The resultant analytically simple but extremely powerful conditions predict transient stability of the system and its orbital existence (i.e., convergence of error/state trajectories from arbitrary initial conditions to equilibrium).

- **Equilibrium Stability**: The second part of the tutorial focuses on the steady-state stability (asymptotic as well as bounded) of a SPC once its state trajectories have reached equilibrium/near-equilibrium operating condition. Using advanced bifurcation analysis methods based on nonlinear maps, first of all, simple analytical criterion will be developed for equilibrium stability. Subsequently, an assessment will be made regarding the predictions of these new nonlinear techniques as compared to those...
predicted by nonlinear averaged models as well as more traditional small-signal analyses methodologies based on linearized averaged models.

- **Novel Sequence-based Control:** The author has developed, based on extensive research, a new class of controls for SPCs that i) integrate modulation and control, ii) achieve significant improvement in SPC dynamics by controlling modes (e.g. asymptotic, sliding modes) on the fly, iii) preclude in many cases the need for soft start, iv) provide global stability (i.e. reaching convergence as well as steady-state stability). This will be the focus of the third part of the tutorial presentation. A recently developed switching transition control using photonically-modulated wide-bandgap power semiconductor devices will also be outlined. A related but important emphasis in this section of the oral presentation will be on demonstrating the mechanism for extending this novel control scheme to standalone as well as networked SPCs using fundamentally different control-over-communication framework approach.

B. Intended Audience:

This tutorial is intended for academicians (graduate students and faculty) and researchers in power electronics as well as industry and professional engineers working towards development of controllers for power electronic applications that require higher stability margins and better dynamic performances. The tutorial will be designed in such a manner that basic knowledge of power converter dynamics along with elementary undergraduate level mathematical background will be sufficient to understand the material presented.

C. Tutorial Outline:

1. **Introduction (30 minutes)**
   a. Global stability and dynamics of SPCs: concepts and needs;
   b. Limitations of existing methodologies.

2. **Reaching condition analyses (60 minutes)**
   a. Reaching condition and its relation to dynamics response and transient stability;
   b. State-of-the art and their shortcomings;
   c. Conditions for reachability and orbital existence using composite Lyapunov functions applied to SPC models leading to determination of different modes of convergences from arbitrary initial conditions;
   d. Applications and results for practical SPCs including i) basic single-module dc/dc boost, buck, and Cuk converters, ii) parallel dc/dc boost and buck converters, iii) cascaded converters consisting of a dc/dc boost converter followed by a dc/dc buck converter, iv) full bridge isolated dc/dc converter, v) multi-phase voltage-source inverter with linear or nonlinear loads, and vi) network of interconnected multi-phase power converters connected in homogenous and heterogeneous configurations.

3. **Equilibrium Stability (30 minutes)**
   a. Overview of existing approaches and their scope and limitations;
   b. Advanced bifurcation analyses techniques;
c. Development of stability criteria under equilibrium conditions using bifurcation analyses and nonlinear maps;
d. Comparisons of stability criteria predictions outlined in “c” with those derived using linearized average models;
e. Applications and results encompassing standalone converters with extension to integrated and parallel converters.

4. Optimal Sequence based Control (60 minutes)
   a. Outline of the new hybrid and sequence-based control concept for control of sequence and switching transitions
   b. Delineation of the approach for standalone and networked SPCs by integration of control and communication
   c. Illustrating the impact of network delay and how to design networked control of SPC under stability bound and communication network capacity constraints.
   d. Demonstration of superior performance under stability bound with multiple examples

5. Conclusions (20 minutes)
   a. Review of key concepts and scope of the new global stability approach, its applicability, and tangible benefits;
   b. How can one extend the global stability approach for complex SPC systems by partitioning the system;
   c. Design of new class of advanced hybrid switching-sequence and switching-transition based controllers with faster and robust dynamic response for standalone and networked power electronics.

D. Duration of Tutorial:

The intended duration of the tutorial is 3 hours 20 minutes. However, the duration can be modified as desired by the program committee.

2. LEAD INSTRUCTOR:

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3. AUTHOR BIO:

   Sudip K. Mazumder is the Director of Laboratory for Energy and Switching-Electronics Systems (LESES) and an Associate Professor in the Department of Electrical and Computer Engineering at the University of Illinois, Chicago. He received his Ph.D. from
Virginia Tech and M.S. from RPI. He has over 15 years of professional experience and has held R&D and design positions in leading industrial organizations. His current areas of interests are stability and stabilization of interactive power-electronics networks, renewable and alternative energy systems, and photonic and wide-bandgap devices and applied technologies.

Dr. Mazumder received the 2008 and 2006 Faculty Research Awards from the University of Illinois, Chicago for Outstanding Research Performance and Scholarly Activities. For his work, closely related to this Tutorial, he received the ONR Young Investigator Award and NSF CAREER Award in 2005 and 2003, respectively and the Prize Paper Award from the IEEE Transactions on Power Electronics in 2002. Dr. Mazumder was the Editor-in-Chief for International Journal of Power Management Electronics between 2006 and 2009. He is also an Associate Editor for the IEEE Transactions on Industrial Electronics since 2003, Associate Editor for the IEEE Transactions on Aerospace and Electronics Systems since 2008. He has published over 100 refereed and invited journal and conference papers, has 3 US patents, and is a reviewer for 6 international journals. He has been invited by IEEE, ASME, leading industries and universities, and national laboratories for keynote, plenary, and invited lectures and presentations. Dr. Mazumder is the Co-Chair for IEEE Power Electronics Society Technical Committee on Sustainable Energy Systems and the Vice Chair, IEEE Power Electronics Society Technical Subcommittee on Distributed Generation and Renewable Energy. He is the Chair for Student/Industry Coordination Activities, IEEE Energy Conversion Congress and Exposition (ECCE), for 2009 and 2010.