STABILITY ANALYSIS AND DAMPING OF GRID-_CONVERTER INTERACTIONS

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SCOPE AND BENEFITS
The ever-increasing penetration of electronic power converters poses new challenges to the stability and power quality of electric power grids. Dynamic interactions between the power grid and converters may lead to the instability, resonances, or abnormal harmonics ranging from a few Hz to multiple kHz. The tutorial aims to provide a design-oriented analysis of grid-converter interactions, which will not only reveal the root causes of different instability phenomena, but also enable to synthesize damping controllers for active stabilization and harmonic mitigation.

This full-day tutorial will begin with an in-depth discussion on the small-signal modeling and practical design of the cascade control system for grid-connected converters. The control loops include the vector current control (CC), the phase-locked loop (PLL), and the direct voltage control (DVC). The model representations in the synchronous reference (dq-) frame and in the stationary (αβ-) frame, and their mathematical relationships will be discussed.

Then, the influences of converter control loops on the grid-converter interactions will be revealed with physical insights. The critical effect of the control delay on the interaction between the CC (with LCL filter) and the grid impedance will be elaborated. The stability impacts of the PLL and the DVC will also be characterized.

Next, the state-space modeling and modal analysis of large-scale converter-based power systems will be discussed. The implementation of this approach for the stability analysis and the control design optimization will be elaborated with a practical case, i.e. a High-Voltage Direct Current (HVDC) connected offshore wind farm.

Lastly, two promising control techniques for stabilizing the system, i.e. the grid-forming control and the passivity-based control, will be presented. The passivity-based control is designed in the frequency-domain, which shapes converters with a grid-neutral dynamic behavior, while the grid-forming control makes converters mimic synchronous machines, whose self-synchronizing capability enables converter operate with very weak grids. The practical implementations of these two control methods will be discussed with examples.

CONTENTS

Monday, 17 September 2018 - Tutorial day (Location: RTU, Riga, Latvia)

08:00 - 09:30          Registration for full day and morning tutorials
09:30 - 11:00          Part 1: Control Fundamentals and Small-Signal Models
1) Introduction
   a. Overview of grid-converter interactions
   b. Instability phenomena
2) Vector current control (CC) with L-filter
   a. Complex transfer functions and transfer matrices
   b. Frequency translation between the $dq$- and $\alpha\beta$-frame model
   c. PI/PR current controller design
3) Grid synchronization with Phase-Locked Loop (PLL)
   a. Principle of Synchronous Reference Frame (SRF)-PLL
   b. Controller design of SRF-PLL
4) Direct Voltage Control (DVC)
   a. Multiple-Input Multiple-Output (MIMO) model
   b. Controller design of DVC
   c. Mathematical relationships between the $dq$- and $\alpha\beta$-frame MIMO models

11:00 - 11:30 Coffee break

11.30 - 13:00 Part 2: Impedance-Based Analysis of Single Grid Converter
1) Impedance-based stability analysis
   a. Basic principle
   b. Generalized Nyquist Stability criterion for MIMO systems
2) Stability of CC with LCL resonance
   a. Single-loop CC of LCL-filter
   b. Effect of digital computational and modulation delay
   c. Harmonic current control
3) Dynamic impact of PLL
   a. MIMO model with PLL effect
   b. PLL bandwidth vs. short-circuit ratio of the grid
4) Stability of DVC

13:00 - 14:00 Lunch break and registration for the afternoon tutorials

14:00 - 15:30 Part 3: Modal Analysis of Converter-Based Power Systems
1) Computer-aided state-space modelling
   a. Mathematical foundations
   b. Implementation/demonstration using Modelica
2) Modal decomposition for harmonic stability analysis
   a. Review of mathematical methods for modal decomposition and analysis
   b. Eigenvector and participation factor analysis
   c. Connection to impedance-based stability analysis
3) Practical case
   a. Modal analysis and control design optimization in an HVDC-connected offshore wind farm

15:30 - 16:00 Coffee break
16:00 - 17:30  Part 4: Control Methods for Active Stabilization

1) Frequency-domain passivity-based control
   a. Basic principle
   b. Passivity-based current control with LCL resonance
   c. Passivity-based harmonic current control

2) Grid-forming control
   a. State of the art
   b. Power synchronization control
   c. Inertia emulation
   d. Current limiting control

WHO SHOULD ATTEND
The intended audience are graduate students, practicing engineers, and researchers with interests in the grid applications of power electronics, e.g. renewable energy generations, microgrids, HVDC/FACTS, and other emerging applications. The tutorial is particularly useful for engineers and researchers on the control design of grid-connected converters, the dynamic modeling and analysis of power electronic based power systems.

Technical Level: The technical level of this tutorial will be intermediate. Yet, beginners with the fundamental knowledge of power electronics and linear systems can also follow.

ABOUT THE INSTRUCTORS
Lennart Harnefors (F’17) received the M.Sc., Licentiate, and Ph.D. degrees in electrical engineering from the Royal Institute of Technology (KTH), Stockholm, Sweden, and the Docent (D.Sc.) degree in industrial automation from Lund University, Lund, Sweden, in 1993, 1995, 1997, and 2000, respectively. Between 1994 and 2005, he was with Mälardalen University, Västerås, Sweden, from 2001 as a Professor of electrical engineering. Between 2001 and 2005, he was, in addition, a part-time Visiting Professor of electrical drives with the Chalmers University of Technology, Goteborg, Sweden.

Since 2005, he has been with ABB, where he is currently a Senior Principal Scientist in Corporate Research, Västerås, Sweden. He is, in addition, a part time Adjunct Professor of power electronics with KTH. He is also the lecture of an Industrial/PhD course on “Stability and Control of Grid-Connected Voltage Source Converters” at Aalborg University. His research interests include control and dynamic analysis of power electronic systems, particularly grid-connected converters, ac drives, and wide-bandgap-transistor switching circuits. Dr. Harnefors is an IEEE Fellow, an Associate Editor for the IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS and the IET ELECTRIC POWER APPLICATIONS.
**Xiongfei Wang** (SM’17) is currently an Associate Professor in power electronics with the Department of Energy Technology, Aalborg University, Denmark. His research interests include the small-signal modeling of power converters, harmonics analysis and control, passive and active power filters, stability of power electronic based power systems. He received the PhD degree in energy technology from Aalborg University, Denmark, in 2013. Since 2017, he is with ABB FACTS as an external consultant. He was the tutorial instructor at IEEE APEC 2016, ECCE 2016, PEDG 2015, and is the lecture of an Industrial/PhD course on “Stability and Control of Grid-Connected Converters” at Aalborg University.

Dr. Wang has contributed over 70 IEEE journal articles, most of which are relevant to the stability and control of grid-connected power electronic systems. In 2016, he was selected into Aalborg University Strategic Talent Management Program for the next-generation research leaders (the only one in the power electronics field). He received 4 IEEE Prize Paper awards, and the Outstanding Reviewer Award of IEEE TRANSACTIONS ON POWER ELECTRONICS. He is the Associate Editor for the IEEE TRANSACTIONS ON POWER ELECTRONICS, the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS, and the IEEE JOURNAL OF EMERGING AND SELECTED TOPICS IN POWER ELECTRONICS, and the Guest Editor on Special Issue: “Grid-Connected Power Electronics Systems” in the IEEE TRANSACTIONS ON INDUSTRY APPLICATIONS. He is the Technical Program Chair for the IEEE eT&D 2017, which is a new industry-focused workshop launched by IEEE PELS and IEEE PES.

**Dr. Mats Larsson** is a Senior Principal Scientist at ABB Corporate Research in Baden, Switzerland, responsible for research on wide-area monitoring and control, HVDC, FACTS and power system stability. He is currently with the Power Systems group in the Automation department, working on issues regarding phasor measurement applications in power systems and regional active network management system for power distribution grids.

Dr. Larsson has been with ABB since 2001, and has led the research on wide-area measurement systems, power system operation and visualization and been leading projects on substation automation and distribution management systems. He has also been involved on the definition and implementation of a control architecture for future HVDC grids. Recent research focuses on the analysis and control of harmonic stability and Dr. Larsson was a main contributor in troubleshooting the harmonic issues in the Bard/Borwin wind farm and HVDC system, and the subsequent development of an active damping concept for the HVDC converter. Dr. Larsson has authored or co-authored more than 60 scientific manuscripts for leading journals and conferences as well as more than 30 granted patents and patent applications. In 2011 he was nominated by the European Patent Office Best Inventor Award, for inventions in the field of synchrophasor based wide-area monitoring.