High-Performance Model Predictive Control of Power Electronic Systems

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

Prof. Dr. Tobias GEYER
ABB System Drives
ABB Switzerland Ltd.

5300 Turgi, Switzerland
t.geyer@ieee.org

Associate Prof. Dr. Petros KARAMANAKOS
Tampere University
Faculty of Information Technology
and Communication Sciences
33101 Tampere, Finland
p.karamanakos@ieee.org

Scope and Benefits:

Power electronic systems are often underutilized with conventional control solutions and are being operated in a suboptimal manner. An attractive control alternative is model predictive control (MPC) due to its numerous advantages, such as explicit inclusion of design criteria and restrictions, design versatility, and inherent robustness. Thanks to these features, MPC can bring significant benefits by improving performance metrics (e.g., current distortion, power losses, settling time), and/or reducing the hardware requirements (or, equivalently, by fully utilizing the existing hardware).

Motivated by the above, the objective of this tutorial is to show the *performance* improvement that can be achieved with control algorithms designed in the framework of MPC. To this aim, different MPC methods (control problem formulations) will be discussed and analyzed. Moreover, it will be shown how these MPC strategies can bring tangible improvements, such as lower harmonic distortions, hardware reduction, increased efficiency, or increased output power. Furthermore, implementation-related issues will be analyzed, while methods to tackle them will be presented. In doing so, insight into the MPC-based algorithms and the associated challenges will be provided.

Overall, the tutorial aims at providing a balanced mix of theory and application-related material. Special care is taken to ensure that the presented material is intuitively accessible to the power electronics practitioner. This is achieved by augmenting the mathematical formulations by illustrations and simple examples.

By the end of the tutorial, the attendees will:

- understand the standard and emerging MPC methodologies, their design and real-time implementation as well as suitable embedded system architectures to implement them and to solve the underlying optimization problems,

- be able to understand what design options exist that maximize the system performance and how MPC-based controllers are to be designed to outperform conventional control techniques and to push the system performance to its physical limits, and

- appreciate the industrial relevance and benefits of MPC-based controllers.

Contents:

The outline of the tutorial day is as follows:

- **Part 1** — Introduction to MPC (Tobias Geyer, 30 minutes):
  System model, optimal control problem, optimization problem, receding horizon policy, direct and indirect MPC, stability, history

- **Part 2** — Direct MPC with reference tracking and hysteresis bounds (150 minutes):

  Part 2.a — FCS-MPC (Tobias Geyer, 60 minutes): Introduction to finite control set MPC (FCSMPC), short-horizon formulation, long-horizon formulation, sphere decoding, systems with *LC* filters

  Part 2.b — Design guidelines for FCS-MPC (Petros Karamanakos, 60 minutes): Formulation of the optimization problem, analysis of the factors that affect the closed-loop performance, design guidelines that enable maximization of the system performance, performance assessment based on two different case studies

  Part 2.c — MPC with hysteresis bounds (Tobias Geyer, 30 minutes): MPDxC (torque control, MPDTC, current control, MPDCC), refinements and extensions, performance assessment

- **Part 3** — Direct MPC with implicit modulator and indirect MPC (90 minutes):

  Part 3.a — MPC with programmed PWM (Tobias Geyer, 30 minutes): optimized pulse patterns (OPPs), model predictive pulse pattern control (MP3C), industrial success story

  Part 3.b — MPC with variable switching time instants (Petros Karamanakos, 30 minutes): Emulation of continuous and discontinuous PWM, performance assessment based on electrical drives and grid-connected converters with *LCL* filters

  Part 3.c — Indirect MPC with CB-PWM (Petros Karamanakos, 30 minutes):
  Introduction to carrier-based pulse width modulation (CB-PWM), formulation of the constrained optimal control problem, performance assessment

- **Part 4** — Looking beyond and ahead (90 minutes):

  Part 4.a — Implementation aspects (Petros Karamanakos, 30 minutes):
  Delay compensation, realtime solvers, real-time systems

Part 4.b — Emerging topics (Petros Karamanakos, 30 minutes):
Robustness (model-free MPC, disturbance observers), computational complexity, solvers

Part 4.c — Final assessment and outlook (Tobias Geyer, 30 minutes)

Schedule:

The schedule is as follows:

Friday, 9 September 2022 - 2nd Tutorial Day - Full Day

09:30 - 10:00	Part 1
10:00 - 11:00	Part 2.a
11:00 - 11:30	Coffee break
11.30 - 13:00	Parts 2.b – 2.c
13:00 - 14:00	Lunch break (Optional – If ordered)
14:00 - 15:30	Part 3
15:30 - 16:00	Coffee break
16:00 - 17:30	Part 4

Who should attend:

The target audience of this tutorial are researchers from both academia and industry (e.g., university students at, or above, the M.Sc. level, academics, and engineers in industry focusing on research and development) who are interested in an introduction to MPC for power electronics systems and its different approaches.

Technical Level:

The tutorial aims to provide the fundamentals of MPC and the discussed methods, and gradually builds on top of them. Thus, the required knowledge level spans over a wide range, starting from a beginner level. Ideally, the attendees should have a good understanding of the basics of power electronics and electrical machines (voltage source inverters, pulse width modulation, three-phase induction machines) and system modeling (coordinate transformations, linear systems, state-space representation, discrete-time systems). Familiarity with modern control theory (optimal control) and exposure to optimization (integer programming, quadratic programming) are helpful but not a prerequisite.

About the Lecturers:

Tobias Geyer joined ABB's Medium-Voltage Drives in 2020 as R&D platform manager of the ACS6080. He is also an extraordinary Professor at Stellenbosch University, South Africa. Dr. Geyer received the Dipl.-Ing. degree in electrical engineering, the Ph.D. in control engineering and the Habilitation degree in power electronics from ETH Zurich in the years 2000, 2005 and 2017, respectively.

After his Ph.D., he spent three years at GE Global Research, Munich, Germany, three years at the University of Auckland, Auckland, New Zealand, and eight years at ABB's Corporate Research Centre, Baden-Dättwil, Switzerland, where his last position was that of a Senior Principal Scientist for power conversion control.

He is the author of 35 patent families and the book "Model predictive control of high power converters and industrial drives" (Wiley, 2016). He teaches a regular course on model predictive control at ETH Zurich. His research interests include medium-voltage and low-voltage drives, utility-scale power converters, optimized pulse patterns and model predictive control.

Dr. Geyer received the Semikron Innovation Award and the Nagamori Award, both in 2021. He is also the recipient of the 2017 First Place Prize Paper Award in the IEEE Transactions on Power Electronics, the 2014 Third Place Prize Paper Award in the IEEE Transactions on Industry Applications, and of two Prize Paper Awards at conferences.

He is a former Associate Editor for the IEEE Transactions on Industry Applications (from 2011 until 2014) and the IEEE Transactions on Power Electronics (from 2013 until 2019). He was an international program committee vice chair of the IFAC conference on Nonlinear Model Predictive Control in Madison, WI, USA, in 2018. Dr. Geyer is a Distinguished Lecturer of the IEEE Power Electronics Society (from the year 2020 until 2023) and a Fellow of the IEEE.

Petros Karamanakos has been with the Faculty of Information Technology and Communication Sciences, Tampere University, Tampere, Finland, since 2016, where he is currently an Associate Professor. Dr. Karamanakos received the Diploma and the Ph.D. degrees in electrical and computer engineering from the National Technical University of Athens (NTUA), Athens, Greece, in 2007, and 2013, respectively.

From 2010 to 2011 he was with the ABB Corporate Research Center, Baden-Dättwil, Switzerland, where he worked on model predictive control strategies for medium-voltage drives. From 2013 to 2016 he was a PostDoc Research Associate in the Chair of Electrical Drive Systems and Power Electronics, Technische Universität München, Munich, Germany. His main research interests lie at the intersection of optimal control, mathematical programming and power electronics, including model predictive control and optimal modulation for power electronic converters and ac variable speed drives.

Dr. Karamanakos received the 2014 Third Best Paper Award of the IEEE Transactions on Industry Applications and two Prize Paper Awards at conferences. He serves as an Associate Editor of the IEEE Transactions on Industry Applications and of the IEEE Open Journal of Industry Applications. Dr. Karamanakos is a Regional Distinguished Lecturer of the IEEE Power Electronics Society in the years 2022 and 2023 and an IEEE Senior Member.