Model Predictive Control of Power Converters: An Introduction

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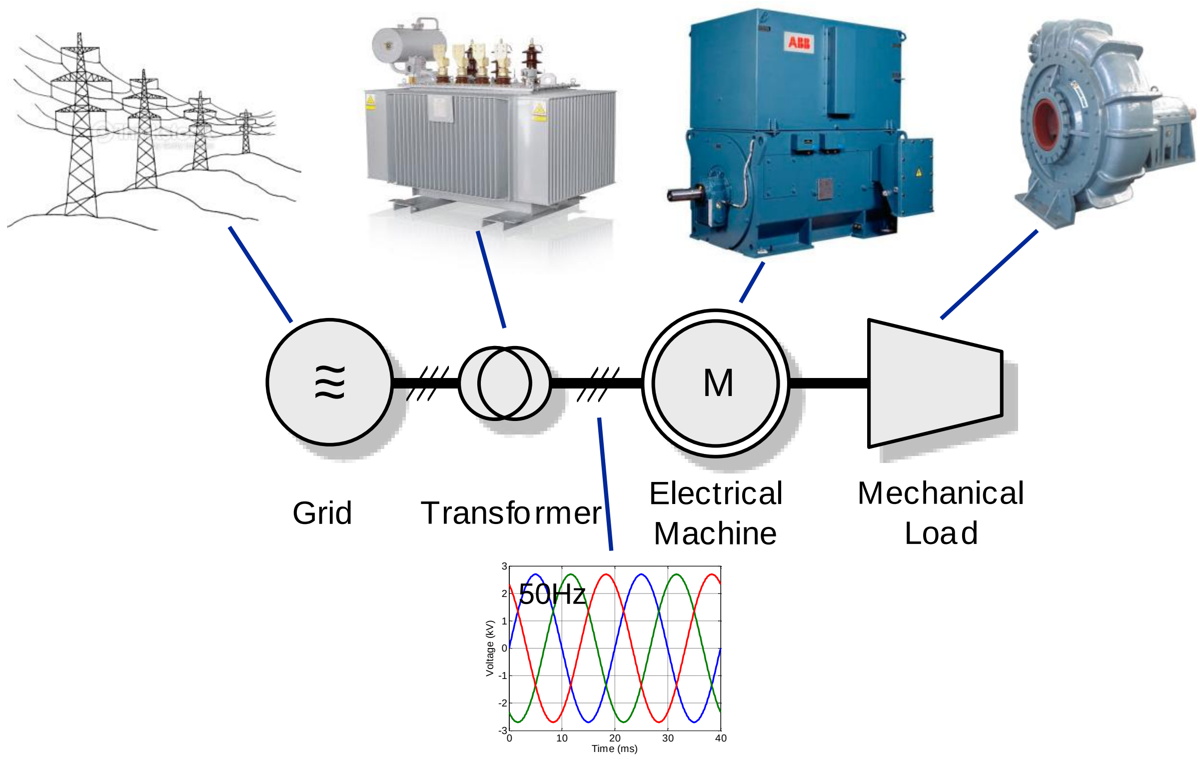
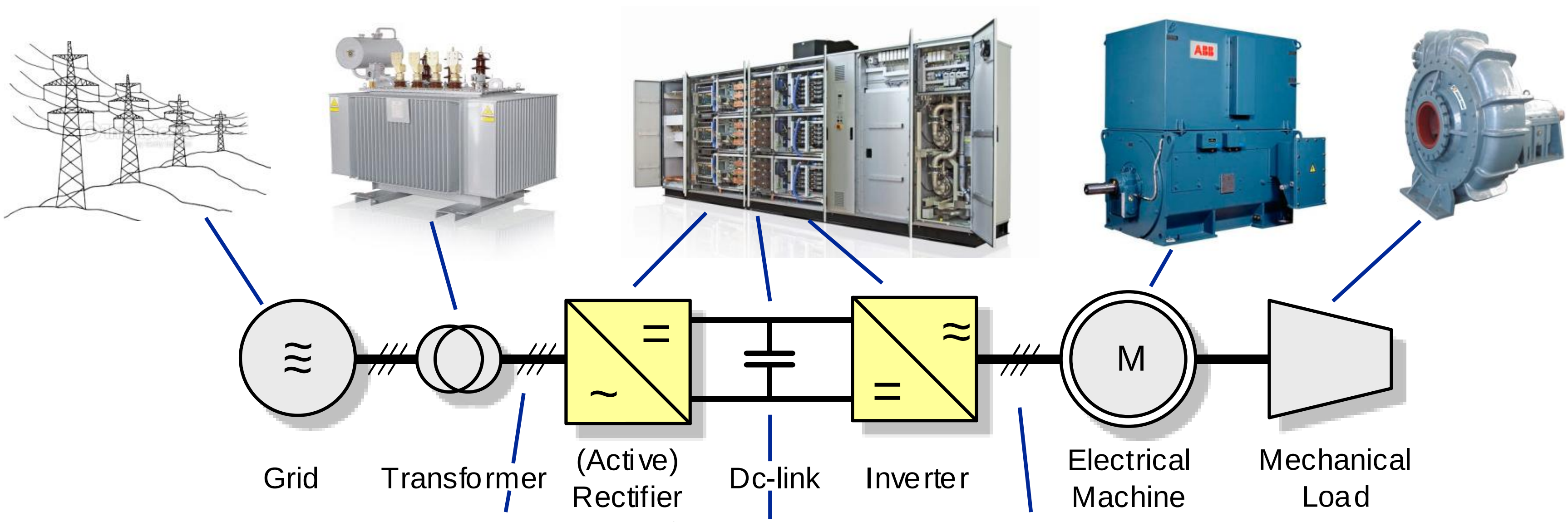
Introduction
Direct Grid-Connected Machine

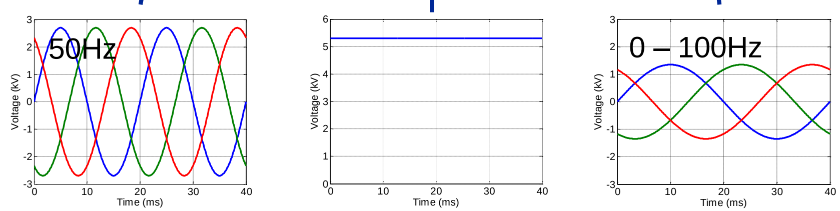


Purposes:

- Electro-mechanical **power conversion**

Introduction
Variable Speed Drive

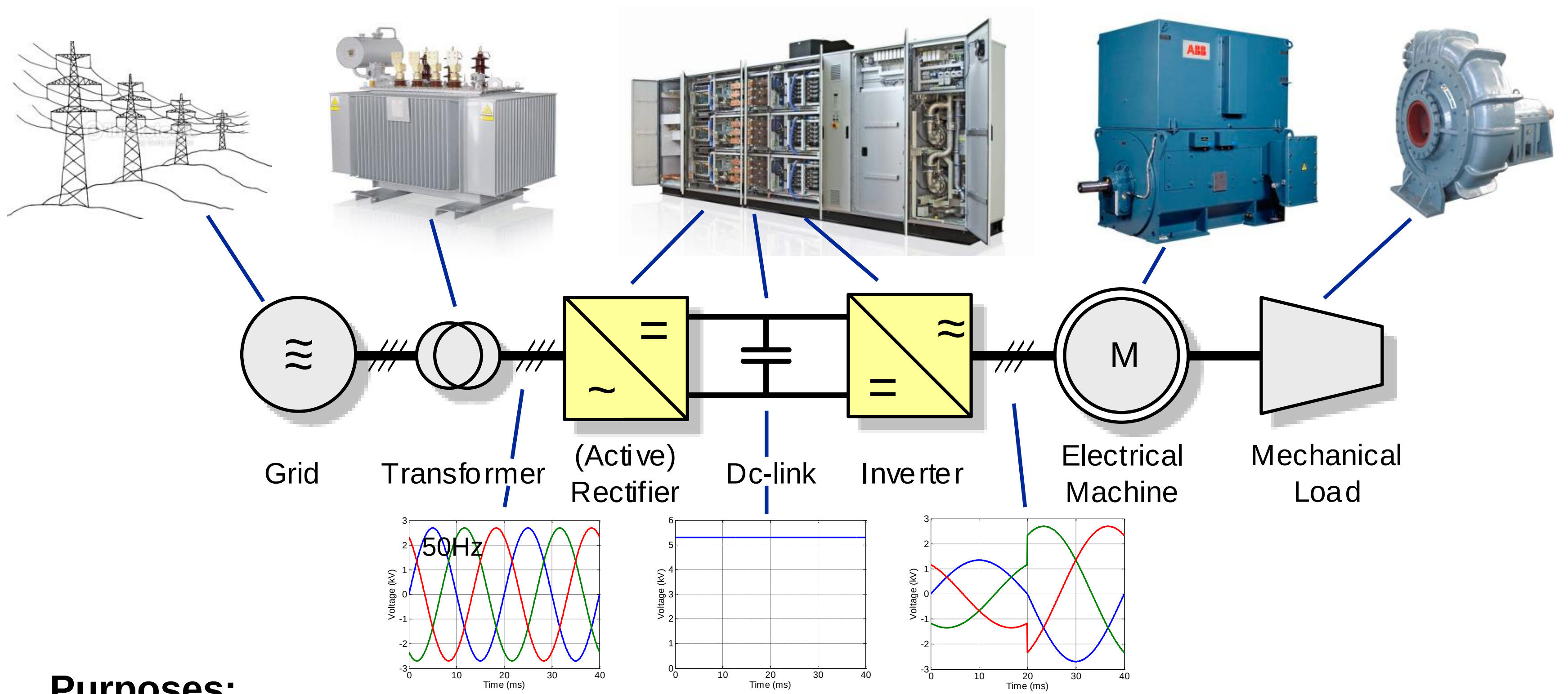




Purposes:

- Electro-mechanical **power conversion**
- **Decoupling** of the machine from the grid => variable speed operation

Introduction
Variable Speed Drive

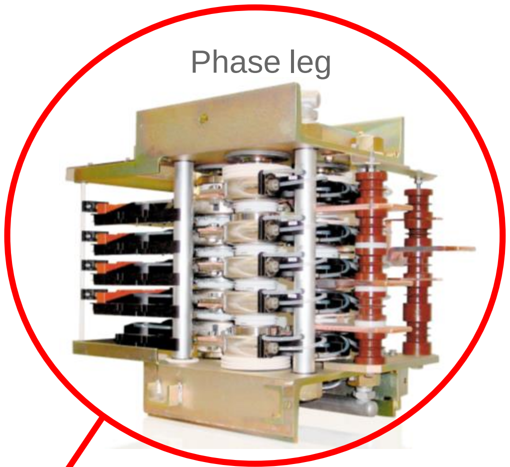


Purposes:

- Electro-mechanical **power conversion**
- **Decoupling** of the machine from the grid => variable speed operation
- Dynamic **control** of the machine currents => fast torque and speed response

Power conversion between the **ac grid** and the **ac machine** via a **dc-link**

Introduction
Medium-Voltage Three-Level Drive



9 MVA frame at 3.3 kV

- Dimensions: 6.23m wide, 1.07m deep and 2.48m tall
- Weight: 6’470kg
- Highly modular

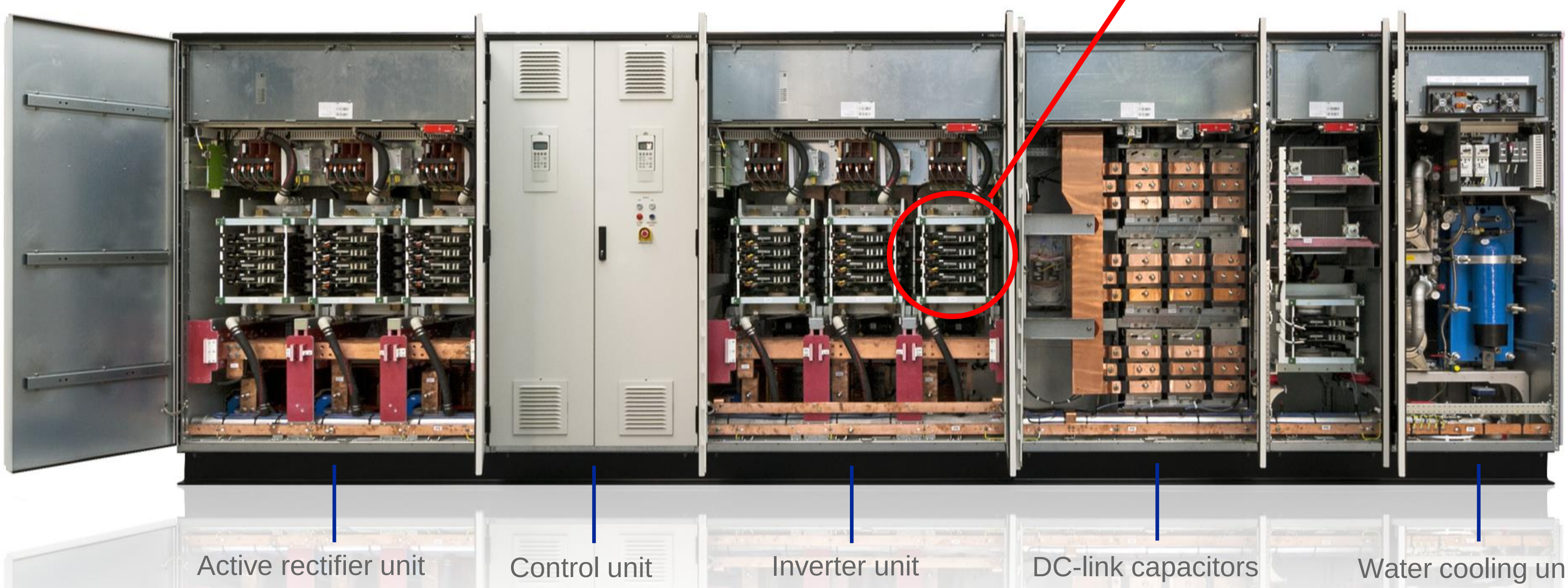
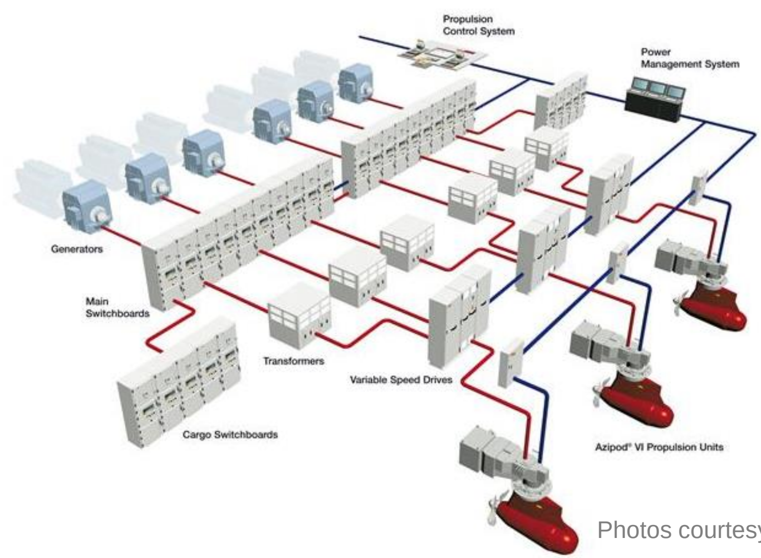


Photo courtesy of ABB Ltd.

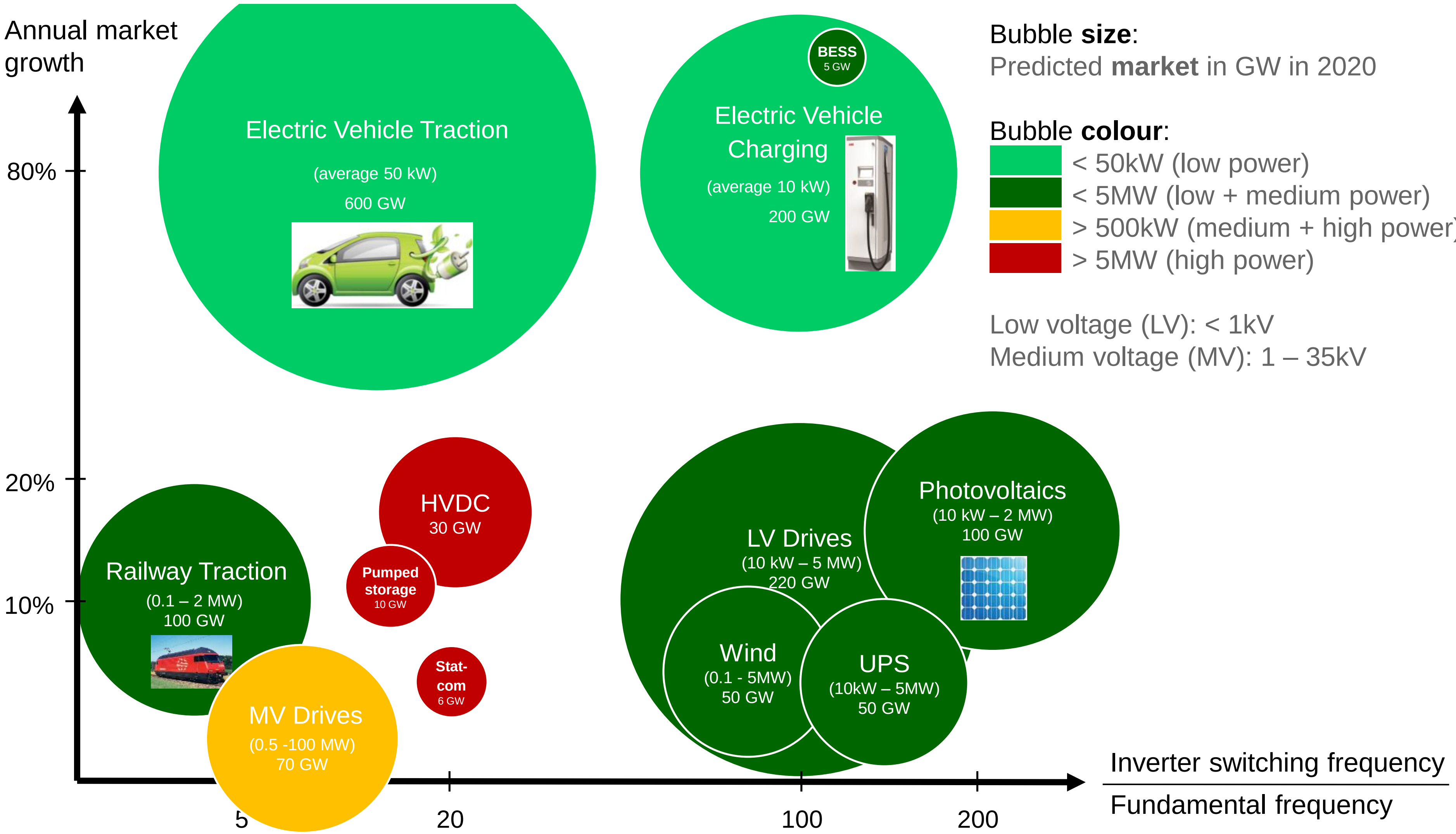
Introduction
Oasis of the Seas (2009)

- Diesel-electric propulsion system using azipods
- 3 x 20MW synchronous motors are mounted to the vessel's hull
- 10-15% fuel saving
- Improved maneuverability



Photos courtesy of ABB Ltd.

Introduction
Power Electronics Market (10kW – 10GW)



Market data provided by Peter Steimer, ARC Advisory Group and IHS Market Research, 2015

Introduction
High Power Electronics

Characteristics:

- Semiconductor switches rated at kV and kA

  => Operation at (very) low switching frequencies

- Low ohmic resistance

  => Little passive damping of system resonances

Trends:

- Higher power and voltage ratings

  => Evolution from 2-level converter to multilevel topologies

- Strict limits on harmonic distortions

  => Harmonic standards for grid-connected converters

  => Retrofitting of MV motors

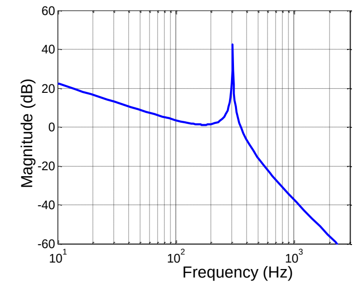
- Competitive market with new competitors

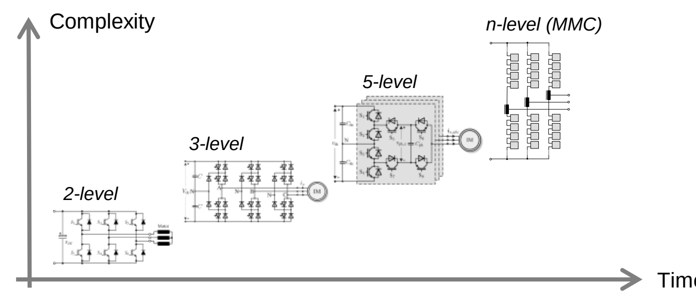
  => Shift from project to product business

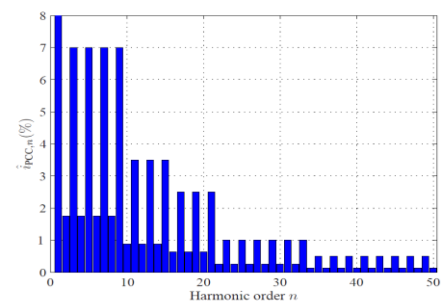
  => Need to fully utilize the power electronics hardware

- Powerful control hardware

  => Possibility to solve optimization problems in real time

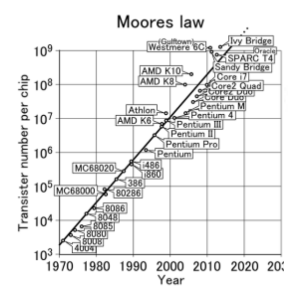






Current distortion limits at PCC according to IEEE 519 standard (assuming short circuit ratio of 20)

ABB SIEMENS Rockwell Automation TMEiC We drive industry



FPGA

Model Predictive Control of Power Converters
Outline

Introduction

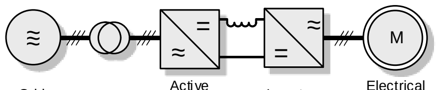
- *Variable speed drives and power electronics market*

Control and modulation

- *Linear control and carrier-based PWM*

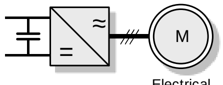
Coordinated control

- *Model predictive control of a line commutated inverter drive*



Fast control of optimized pulse patterns

- *Optimized pulse pattern, control method and experimental results*



Conclusions and outlook

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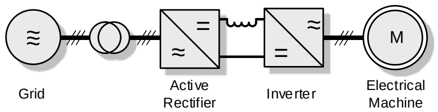

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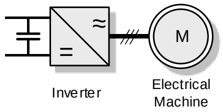
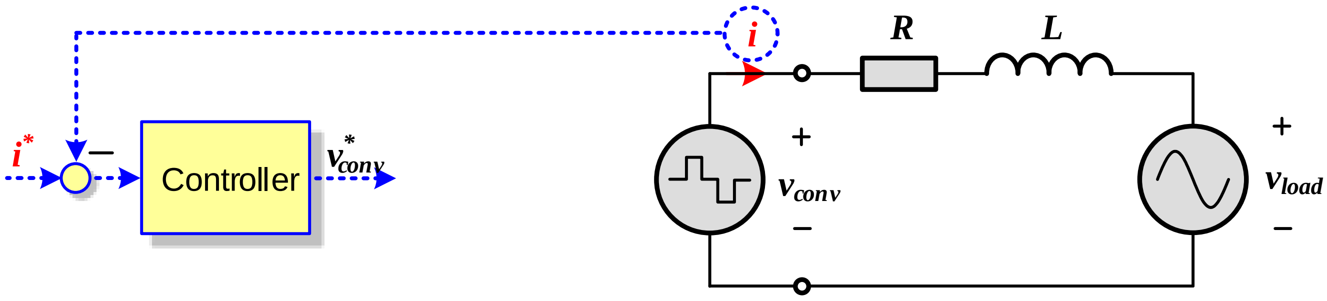


Conclusions and outlook

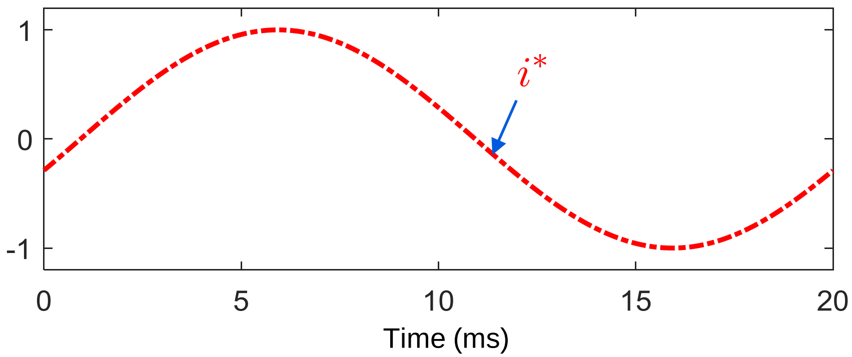
Introduction to Control and Modulation
A Simple Control Problem

Single-phase converter with active *RL* load

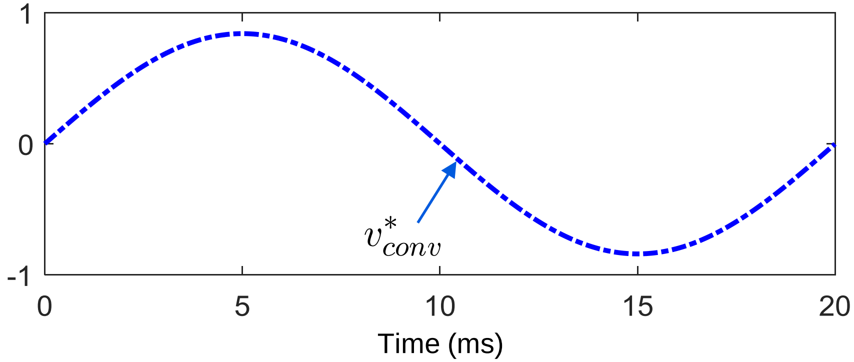


Control objective:

Regulate the load current i along its reference i^*



by manipulating the reference converter voltage v^*_{conv}



Control problem: manipulate the plant input such that the output **follows its reference**, the plant is **stabilized** and an acceptable **performance** is achieved (despite **disturbances**)

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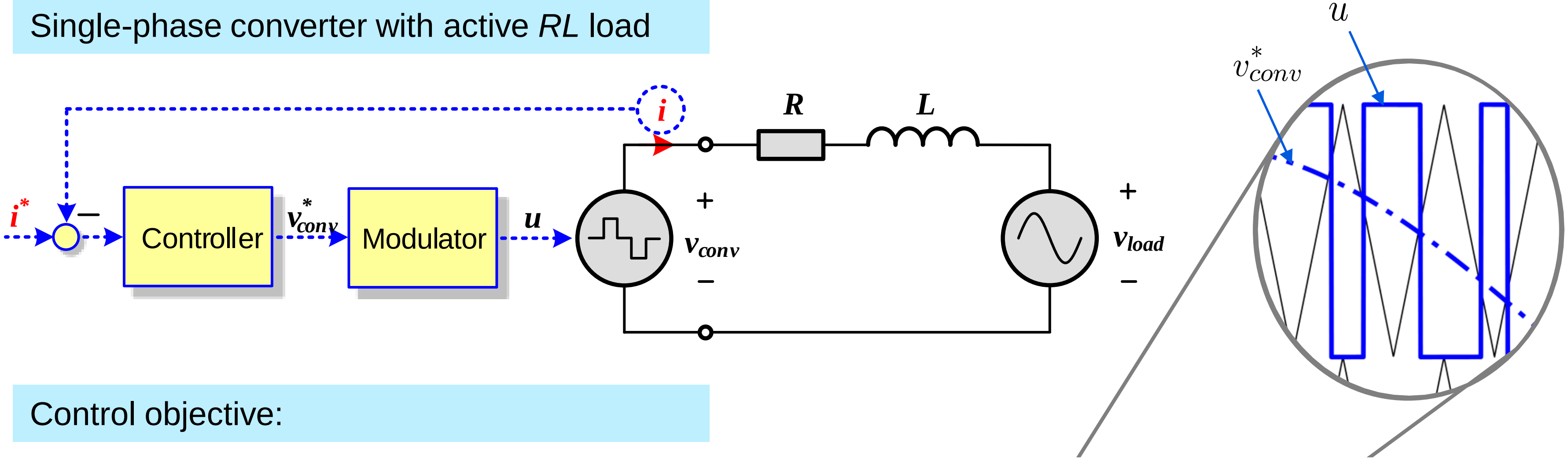

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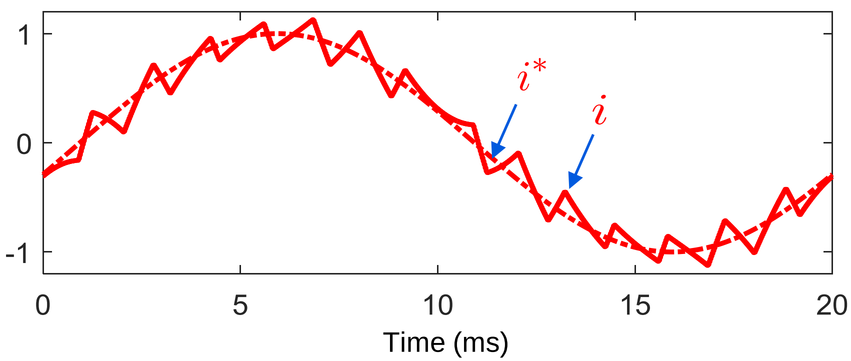
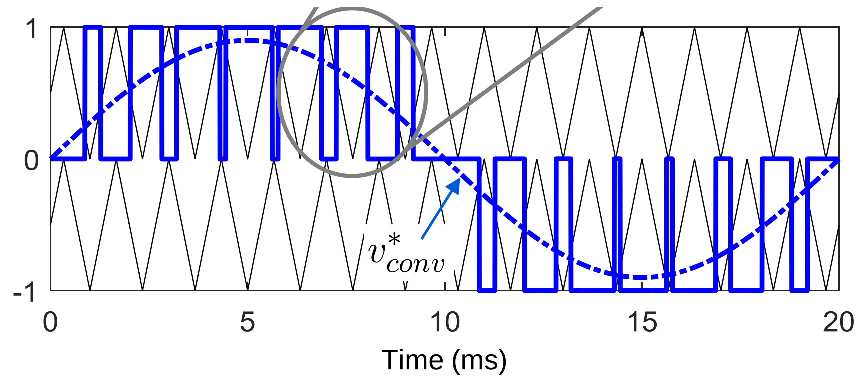


by manipulating the switch position $u \in \mathbb{Z}$



… using carrier-based pulse width modulation

A **pulse width modulator** translates the real-valued input reference v^*_{conv} into **switching commands** *u*

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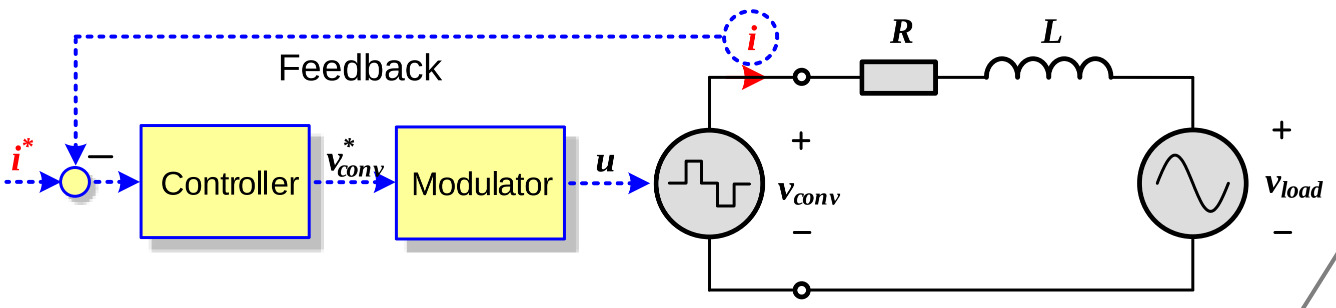

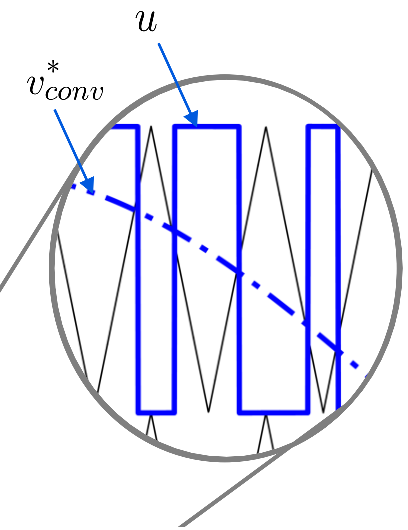

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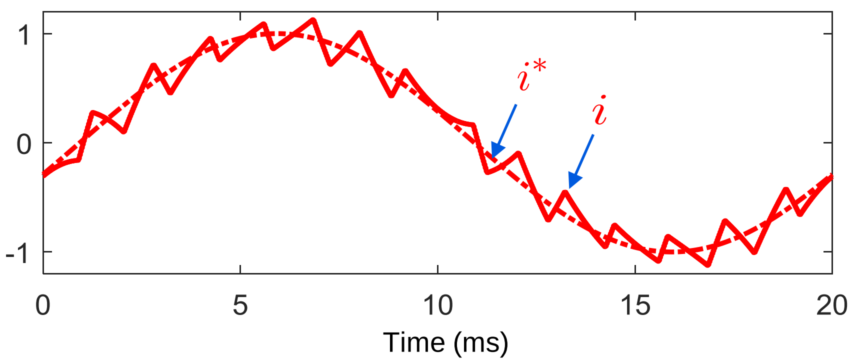

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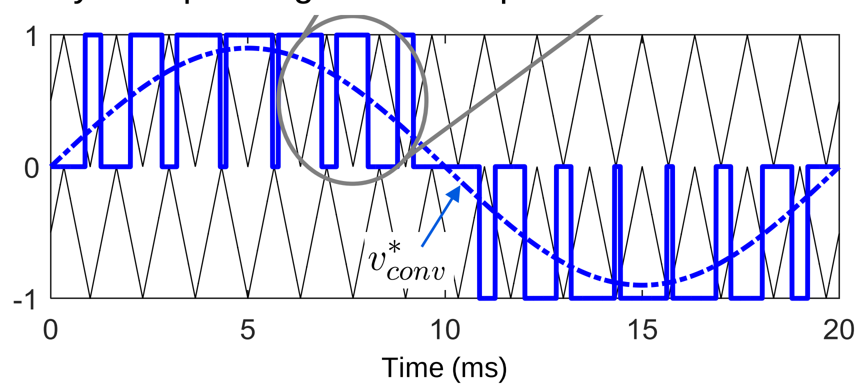

… using carrier-based pulse width modulation

Feedback loop: stabilization of unstable processes, disturbances rejection, reduced parameter sensitivity, …

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A Simple Control Problem

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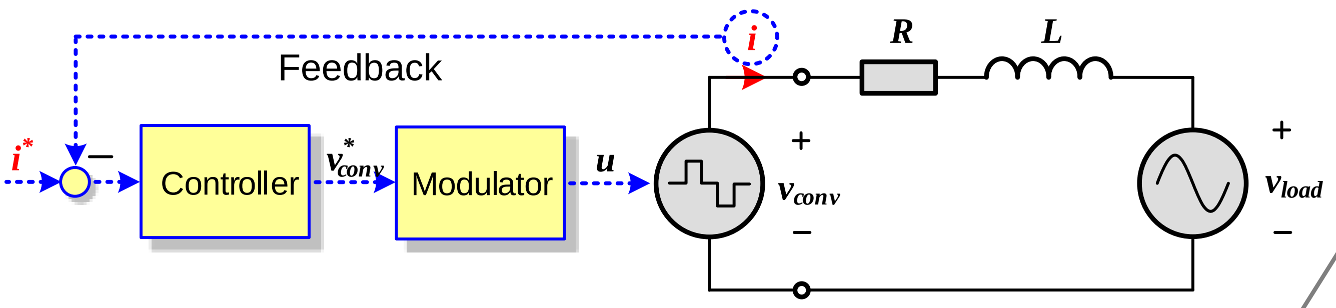

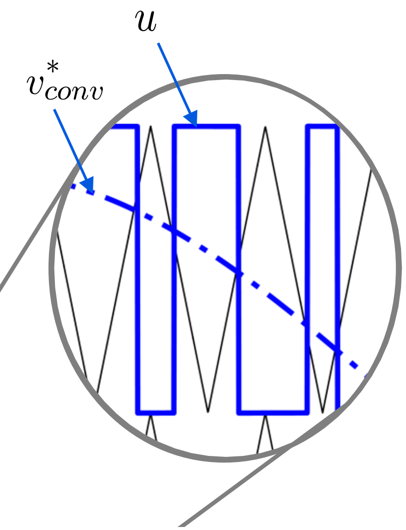

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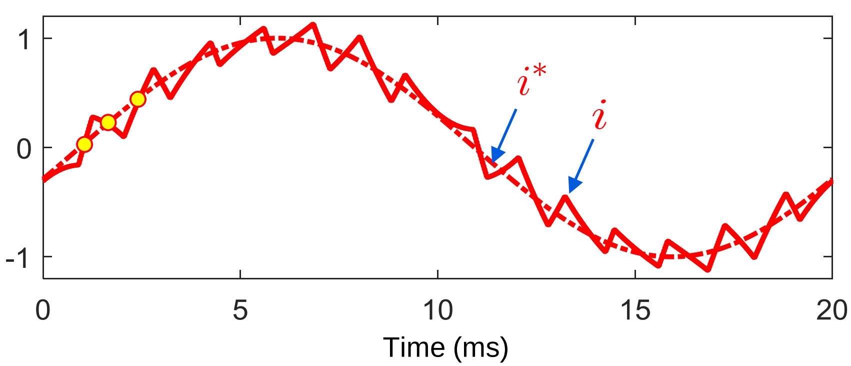

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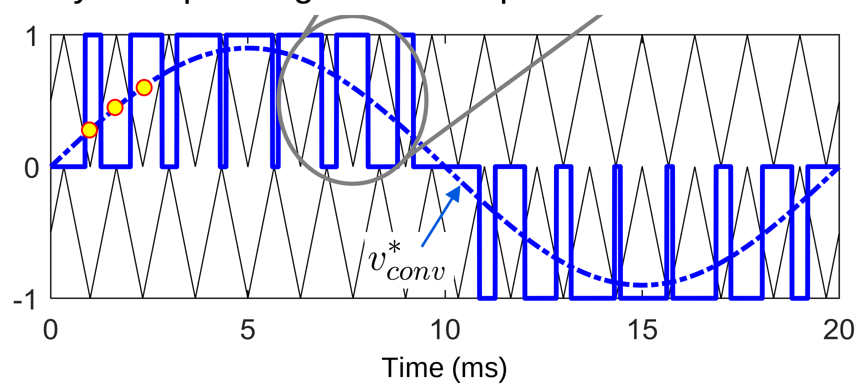


… using carrier-based pulse width modulation

Carrier-based PWM and appropriate sampling **hides the switching behavior**

This directly extends to three-phase systems and general loads (such as electrical machines and the grid)

Introduction to Control and Modulation
Power Electronics Characteristics and Control Challenges

System characteristics:

- Components are mostly **linear**
- Some **nonlinearities** exist
  => Saturation of magnetic material, electromagnetic torque, nonlinear loads, etc
- Multiple inputs, multiple outputs
- Actuators are operated in the **on/off** mode
  => (Non)linear system with integer inputs

Technical challenges:

- Fast dynamic response / high bandwidth
  *=> Sampling intervals between **25µs** and 1ms*
- Low **harmonic distortions**
- Operation at switching frequencies below **250Hz**
- Operation within the safe operating area
  => Constraints

Model characteristics:

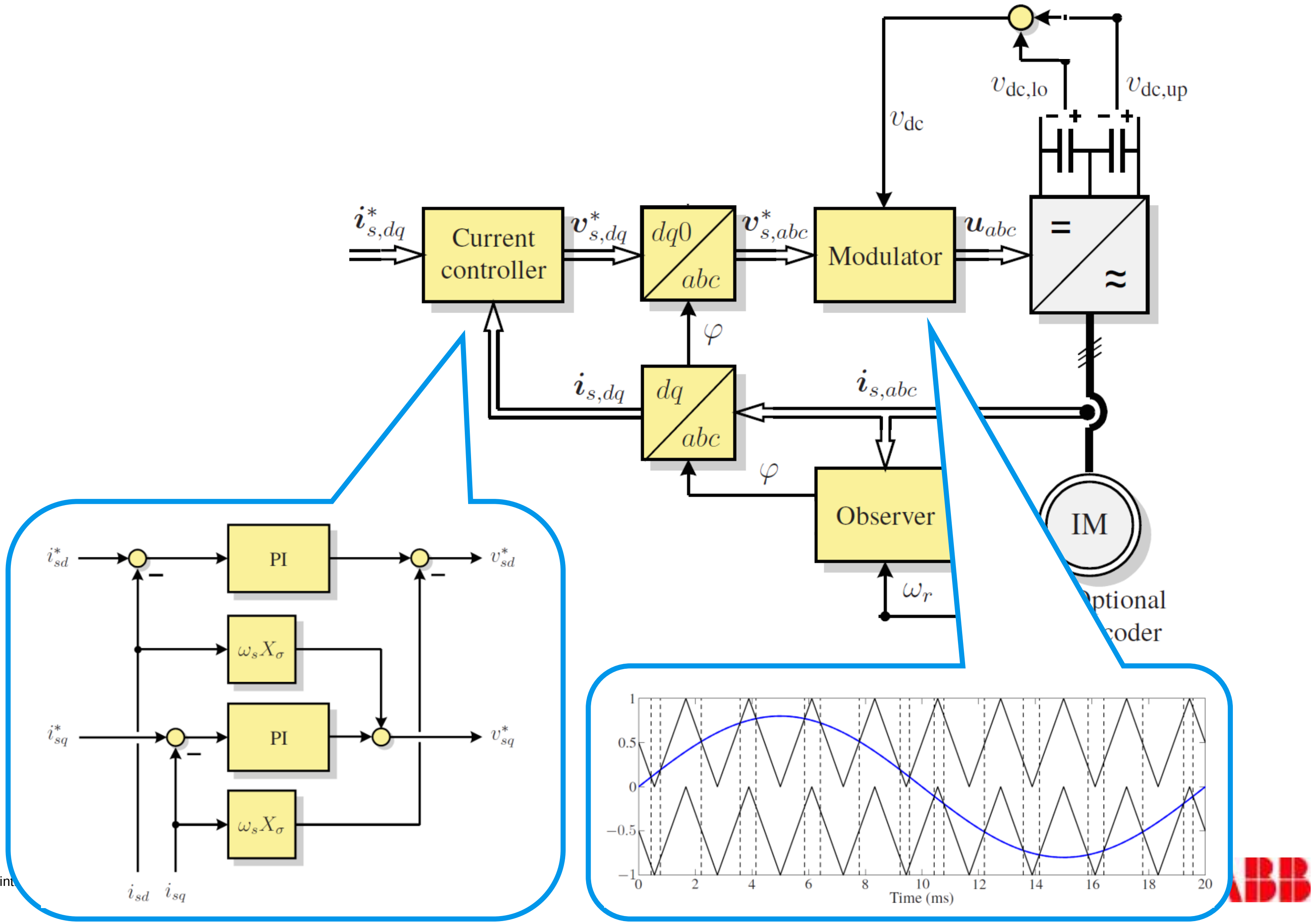
- **Accurately** known (except for grids and UPS)
- Typically less than 10 **state** variables
- Typically three **manipulated** variables

=> Modelling based on first principles

Commercial challenges:

- Control method should be **general**
  => Applicable to a wide range of products
- Control method should be **simple**
  => Can be maintained and modified by R&D teams and commissioned by field engineers

Introduction to Control and Modulation
Direct Rotor Field-Oriented Control



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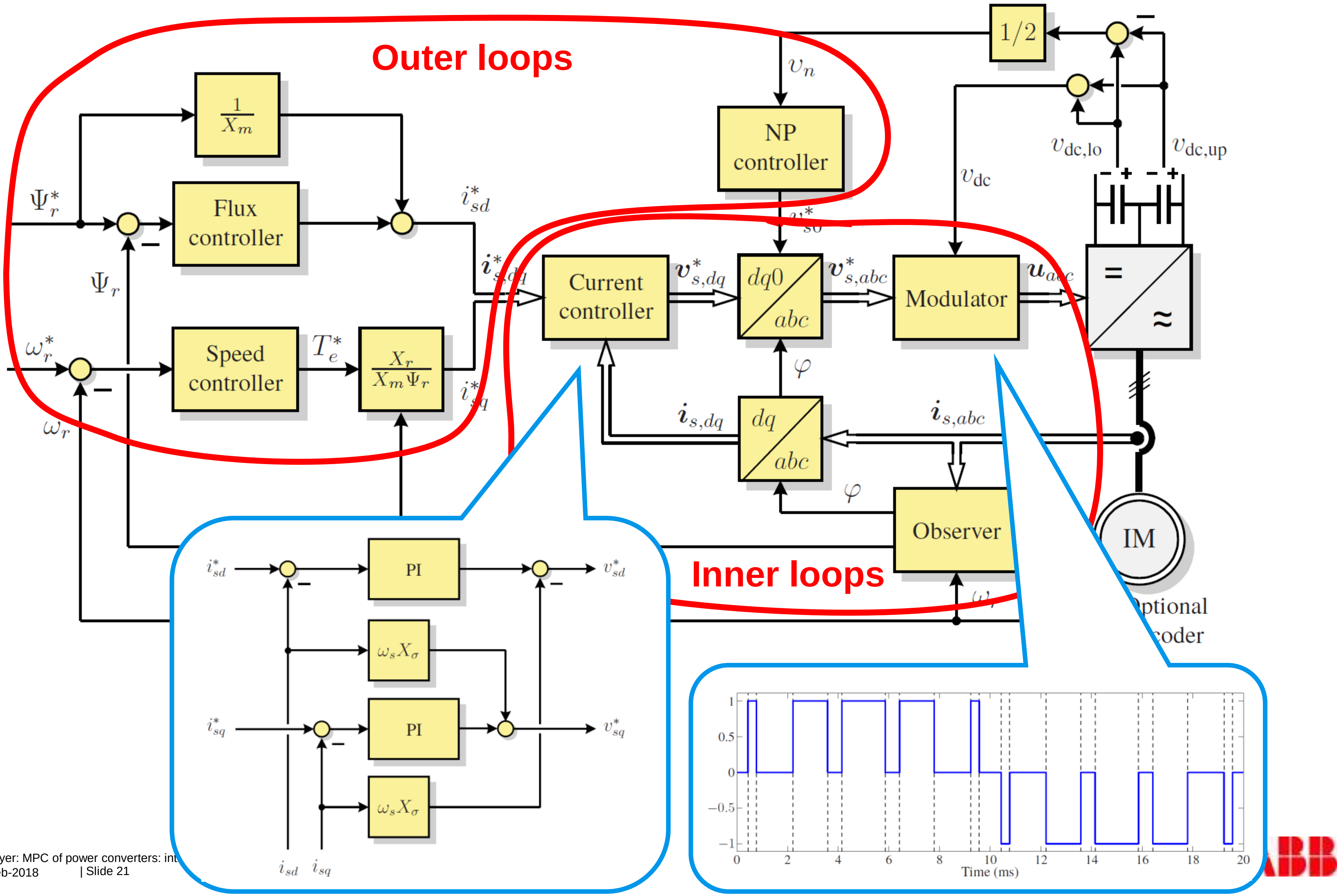


Introduction to Control and Modulation
The Commonly used Control Approach

- Split the MIMO control problem into **several** (cascaded) **SISO** control problems

  => Enables "simple" controller design based on PI controllers with feedforward terms

- Split the inner control problem into a current controller and a **modulator**

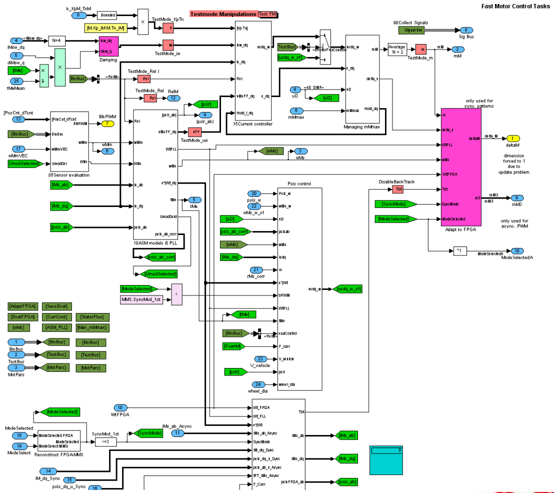
  => Hides the switching characteristic from the controller
  (provided that the current ripple is zero at the sampling instants)

- Work in a **rotating** coordinate system

  => Turns ac quantities into dc quantities during steady-state operation

Drawbacks:

- **SISO control loops** are poorly **decoupled** during transients
- **Cascaded** control loops limit the **bandwidth**
- **Carrier-based** PWM works poorly at low pulse numbers
- Controllers have to be "**slowed down**" during transients to avoid violations of the **safe operating** area



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Coordinated control

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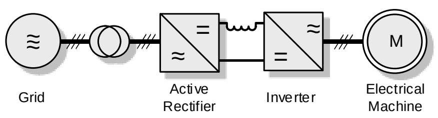

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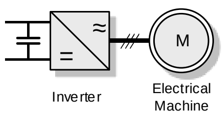
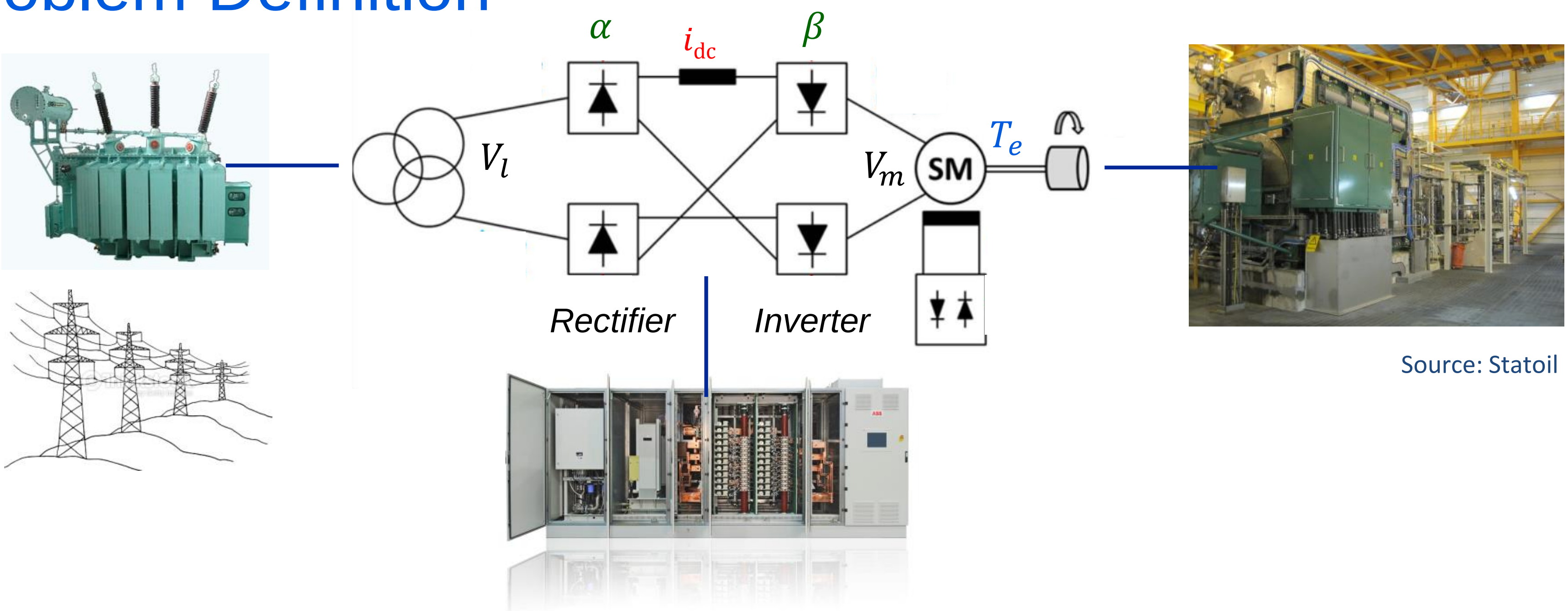


Conclusions and outlook

Coordinated Control: Load Commutated Inverter Drive
Problem Definition



Source: Statoil

System:

- Load commutated inverter (LCI) with synchronous machine

Model:

- Dc-link dynamic: $L_{\text{dc}} \frac{d}{dt} i_{\text{dc}} = V_l \cos(\alpha) - V_m \cos(\beta)$
- Electromagnetic torque: $T_e = -i_{\text{dc}} \cos(\beta)$

Control objective:

- Regulate the torque T_e and the dc-link current i_{dc} to their references by manipulating the firing angles α and β while respecting constraints

Constraints:

- $0 \leq i_{\text{dc}} \leq i_{\text{dc max}}$
- $\alpha_{\min} \leq \alpha \leq \alpha_{\max} \quad \beta_{\min} \leq \beta \leq \beta_{\max}$

T. Besselmann, S. Van de moortel, S. Almer, P. Jörg and J. Ferreau: "Model predictive control in the multi-megawatt range", Trans. on Ind. Electronics, July 2016

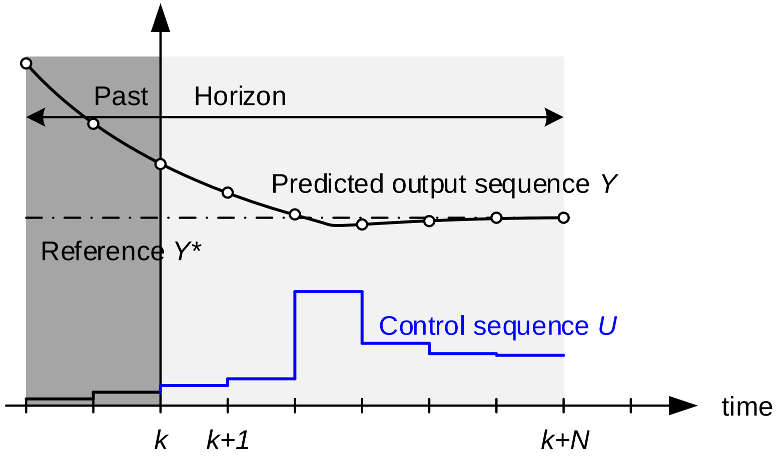
Coordinated Control: Load Commutated Inverter Drive
Model Predictive Control

Concept: Use a mathematical model of the process to predict its future evolution over a horizon (taking into account constraints) and choose the "best" control input by solving a mathematical optimization problem. At the next step, obtain new measurements and re-plan over a shifted horizon.

Key Features:

- **Internal model:** describes the dynamic system behaviour
  => basis for predictions, makes the controller 'smart'

$$\boldsymbol{x}(k+1) = f\big(\boldsymbol{x}(k), \boldsymbol{u}(k)\big)$$
$$\boldsymbol{y}(k) = g\big(\boldsymbol{x}(k)\big)$$



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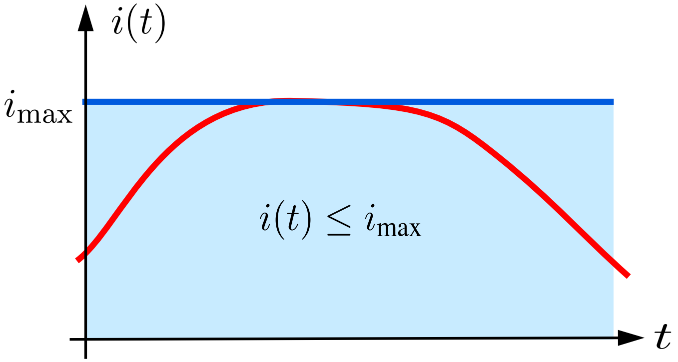

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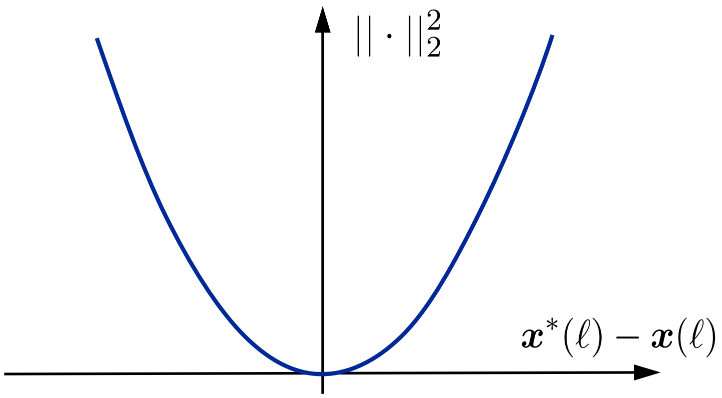

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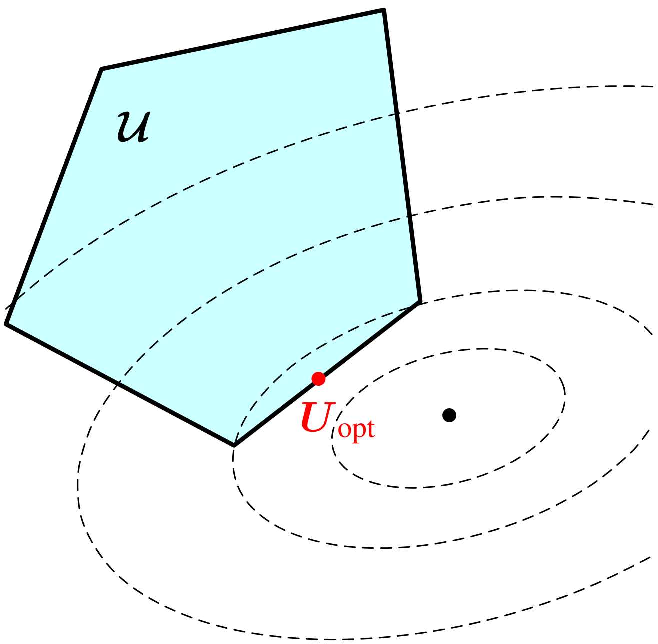

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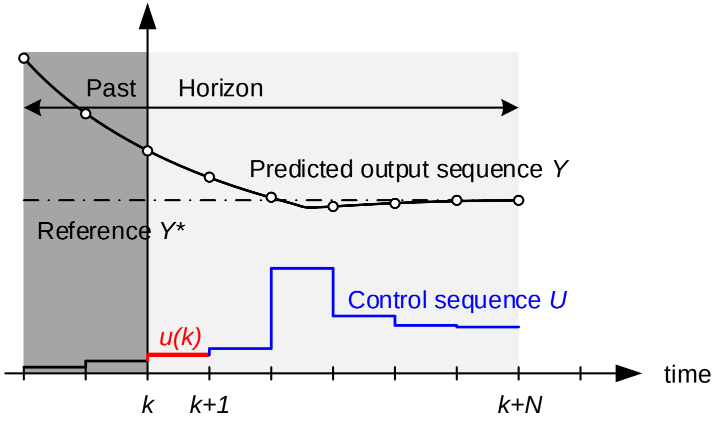
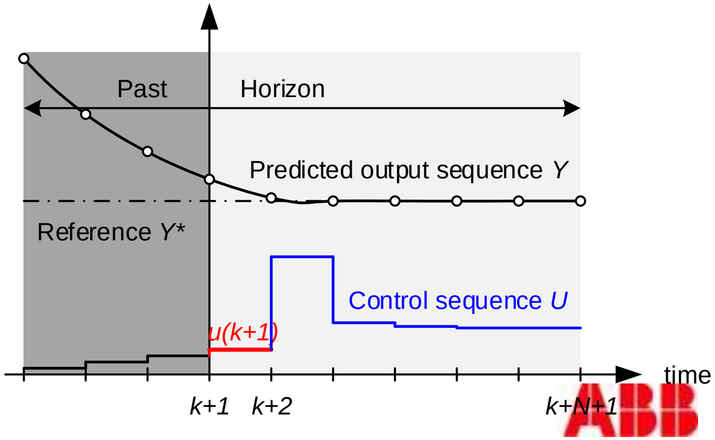
  => *feedback and robustness*





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MPC directly addresses systems with **multiple inputs, multiple outputs, constraints** and **switching**

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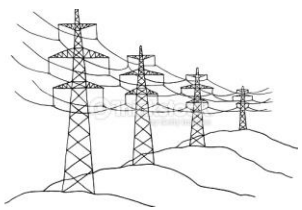
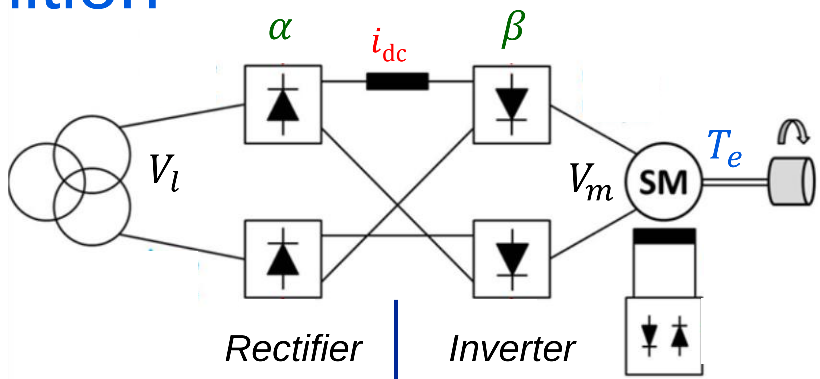
Problem Definition





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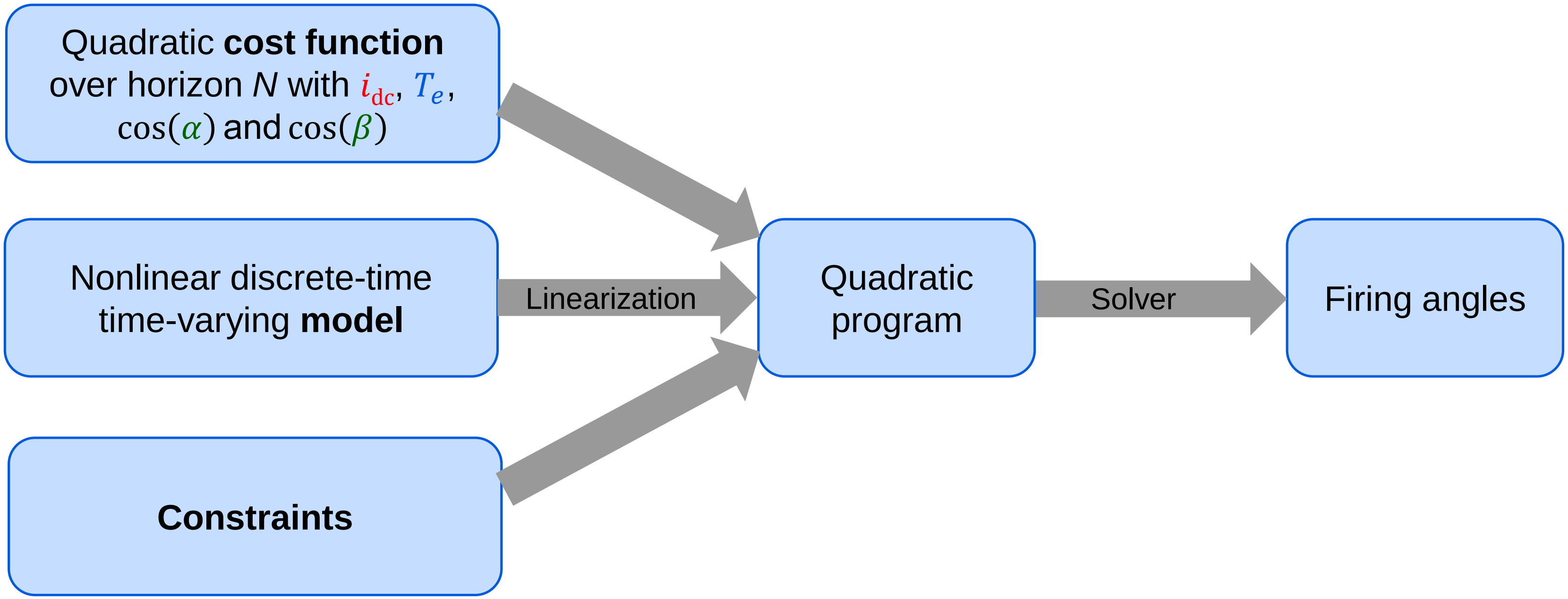
Coordinated Control: Load Commutated Inverter Drive
Model Predictive Control Formulation

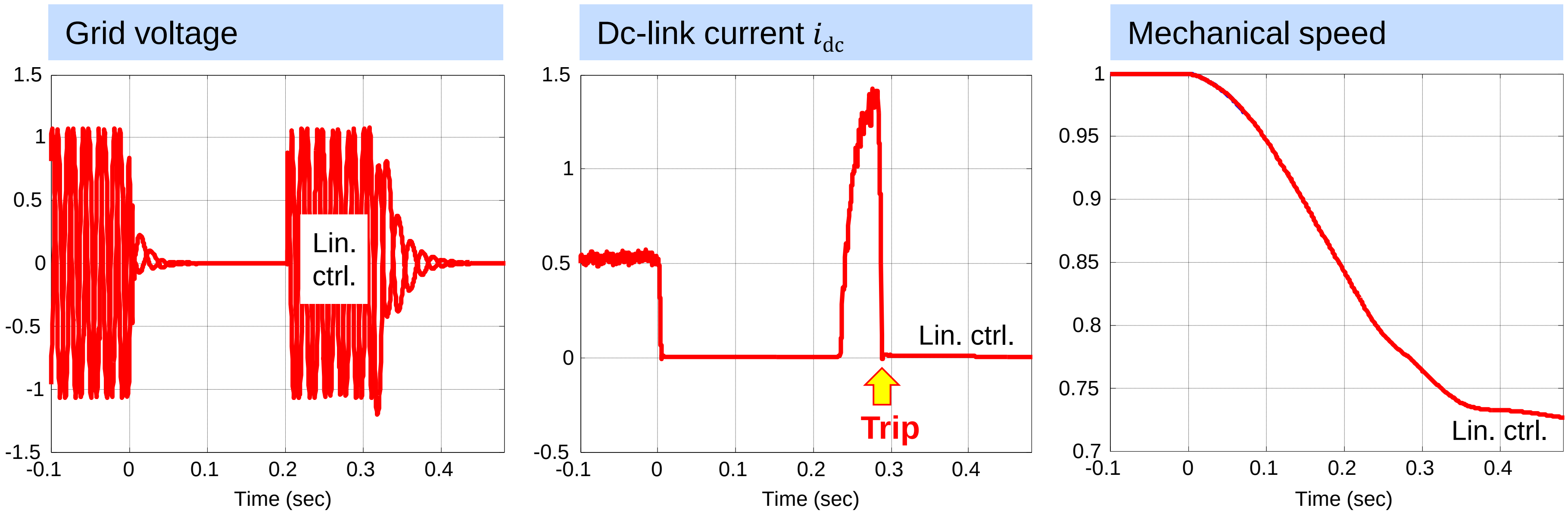


Control platform: PEC 3 (dual core PowerPC with 1.2 GHz)

Sampling interval: 1ms

T. Besselmann, S. Van de moortel, S. Almer, P. Jörg and J. Ferreau: “Model predictive control in the multi-megawatt range”, Trans. on Ind. Electronics, July 2016

Coordinated Control: Load Commutated Inverter Drive
Experimental Results on LV drive



Low-voltage ride through:

- **Linear** controller (separate PI control loops for rectifier and inverter) **trips** when restoring power (i_{dc} too high)

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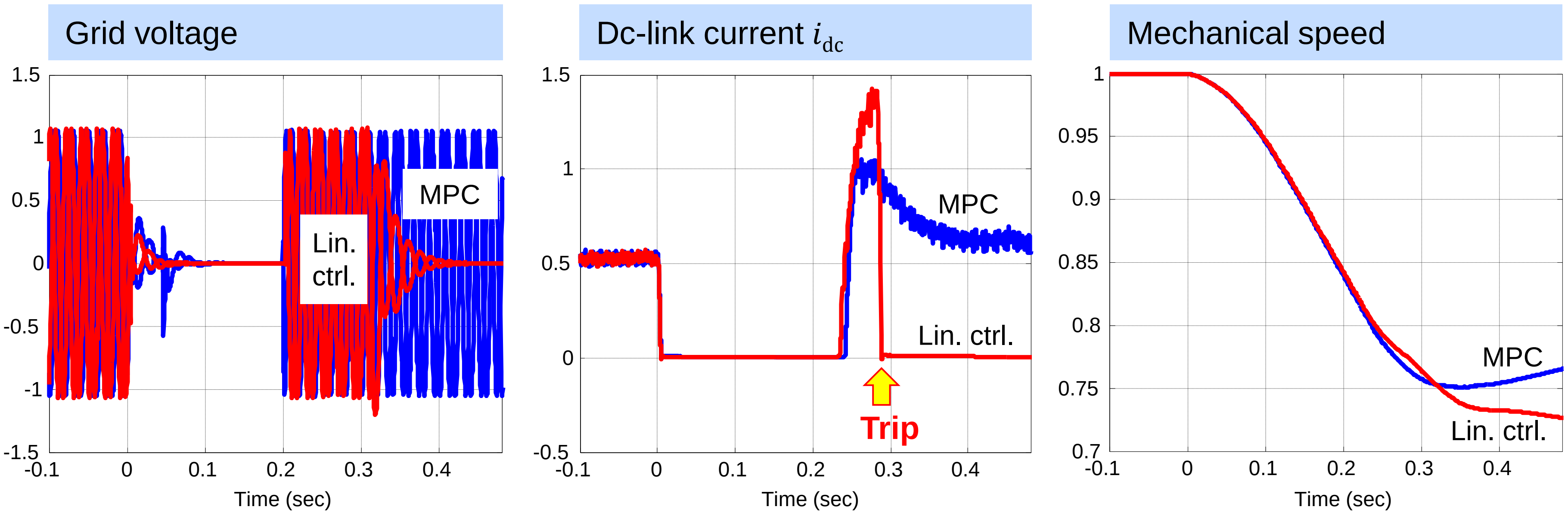


Low-voltage ride through:

- **Linear** controller (separate PI control loops for rectifier and inverter) **trips** when restoring power (i_{dc} too high)
- **MPC** rides through and respects the constraints

T. Besselmann, S. Van de moortel, S. Almer, P. Jörg and J. Ferreau: "Model predictive control in the multi-megawatt range", Trans. on Ind. Electronics, July 2016

Coordinated Control: Load Commutated Inverter Drive
Pilot Installations (since Mid 2015)

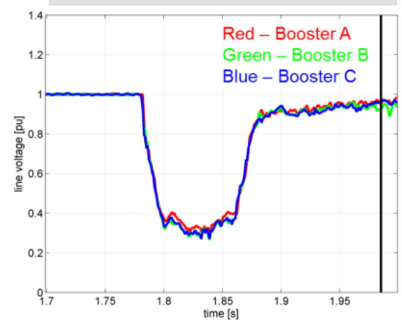
Kollsnes, Norway

- Processes about **40%** of Norway's gas export
- Grid voltage disturbances
- Trips very costly (0.5M$ per hour)
- Six compressor strings with 41.2 MW LCIs
- Two (out of six) LCIs are controlled by MPC

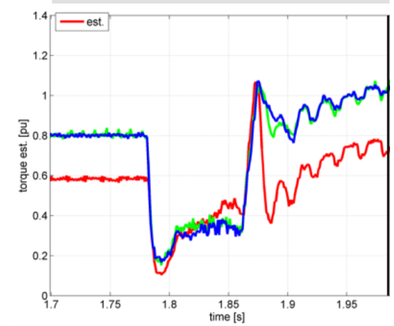
Kårstø, Norway

- Europe's biggest export port for natural gas liquids
- Three 7.5 MW LCIs in booster compressors are controlled by MPC
- Low-voltage ride through

Grid voltage



Torque



Commercial benefits

- Improved low-voltage **ride through** => higher **availability**
- Lower **reactive power** => Increased **efficiency**

T. Besselmann, S. Van de moortel, S. Almer, P. Jörg and J. Ferreau: “Model predictive control in the multi-megawatt range”, Trans. on Ind. Electronics, July 2016

Coordinated Control
Assessment

Advantages of Model Predictive Control

- Safety and operational **constraints** can be imposed and met
- Control of **multiple** variables
- **Established** control framework

=> Improved performance and resilience during **transients**, **disturbances** and **faults**

- Better low-voltage **ride-through**
- Faster **transients** without tripping
- Operation closer to the **physical limits** / less conservative **hardware design**

Limitations

- Solving the **optimization problem** in real time can be challenging

Enhanced **availability** and **reliability** => commercially **attractive**

Model Predictive Control of Power Converters
Outline

Introduction

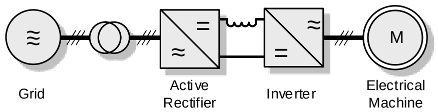
- *Variable speed drives and power electronics market*

Control and modulation

- *Linear control and carrier-based PWM*

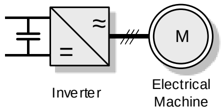
Coordinated control

- *Model predictive control of a line commutated inverter drive*



Fast control of optimized pulse patterns

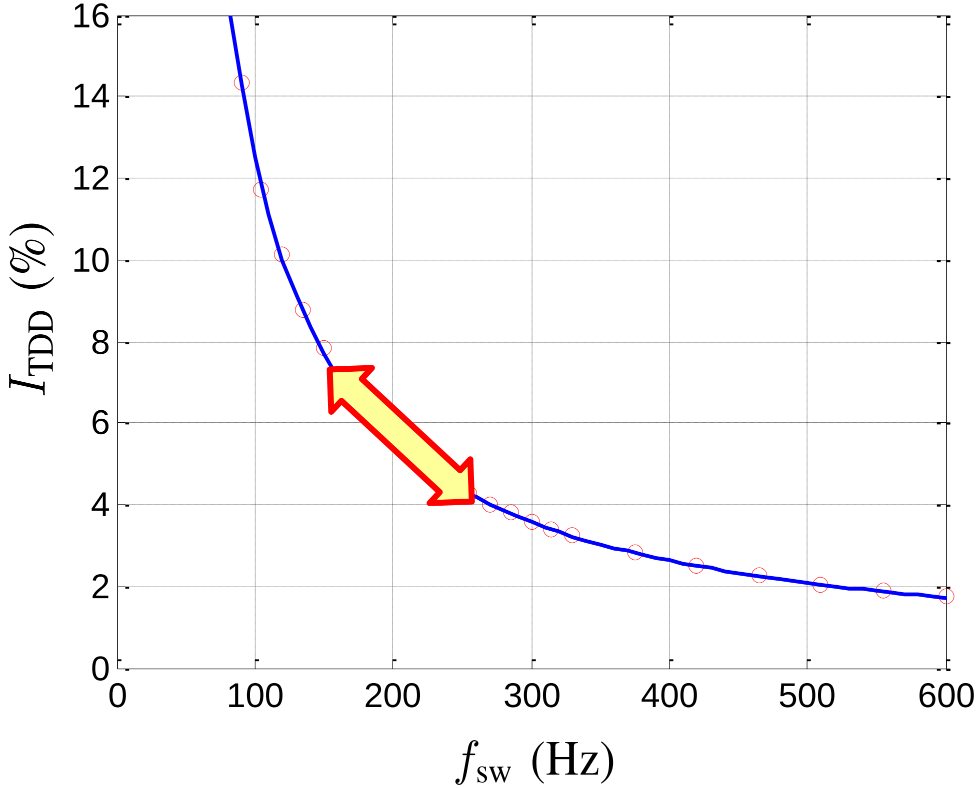
- *Optimized pulse pattern, control method and experimental results*



Conclusions and outlook

Fast Control of Optimized Pulse Patterns
Performance Trade-Off of Modulation

Current distortions vs switching frequency



$$I_{\text{TDD}} \cdot f_{\text{sw}} = \text{const}$$

Total Demand Distortion (TDD) of the current:

$$I_{\text{TDD}} = \frac{1}{\sqrt{2} I_{s,\text{nom}}} \sqrt{\sum_{n \neq 1} (\hat{i}_{s,n})^2}$$

Simulation setup:

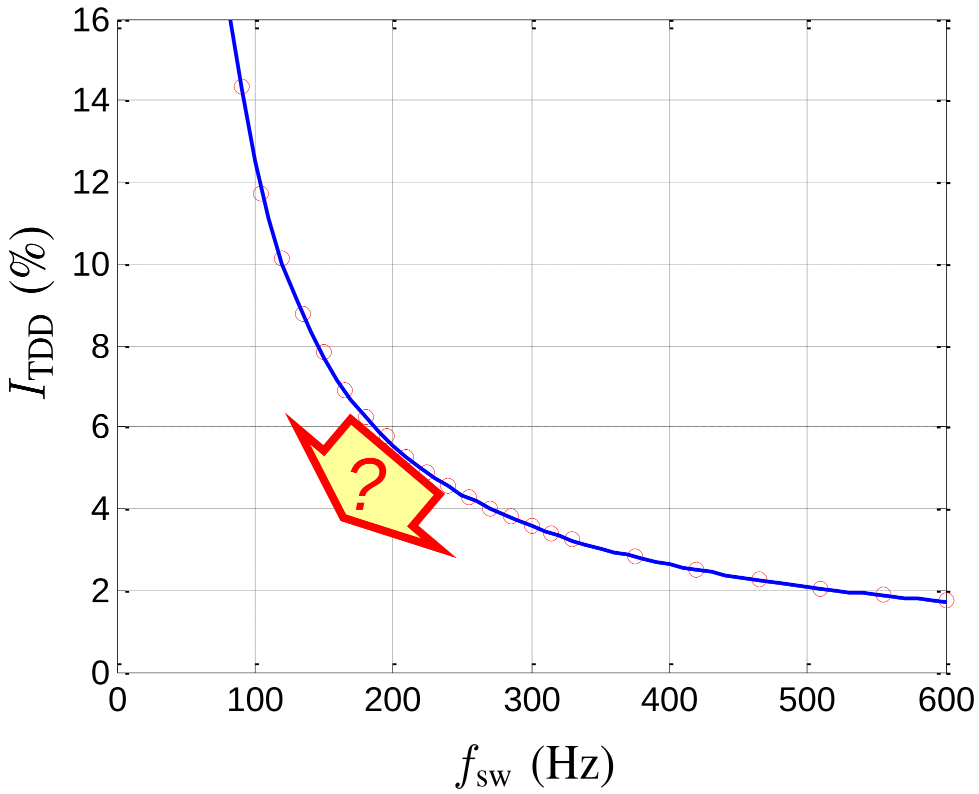
- SVM with f_c = 150 .. 1200Hz
- fundamental frequency f_1 = 30Hz
- 3-level converter
- induction machine with L_{sig} = 0.25 pu

Similar statements hold true for the

- switching losses and the
- electromagnetic torque

Fast Control of Optimized Pulse Patterns
Performance Trade-Off of Modulation

Current distortions vs switching frequency



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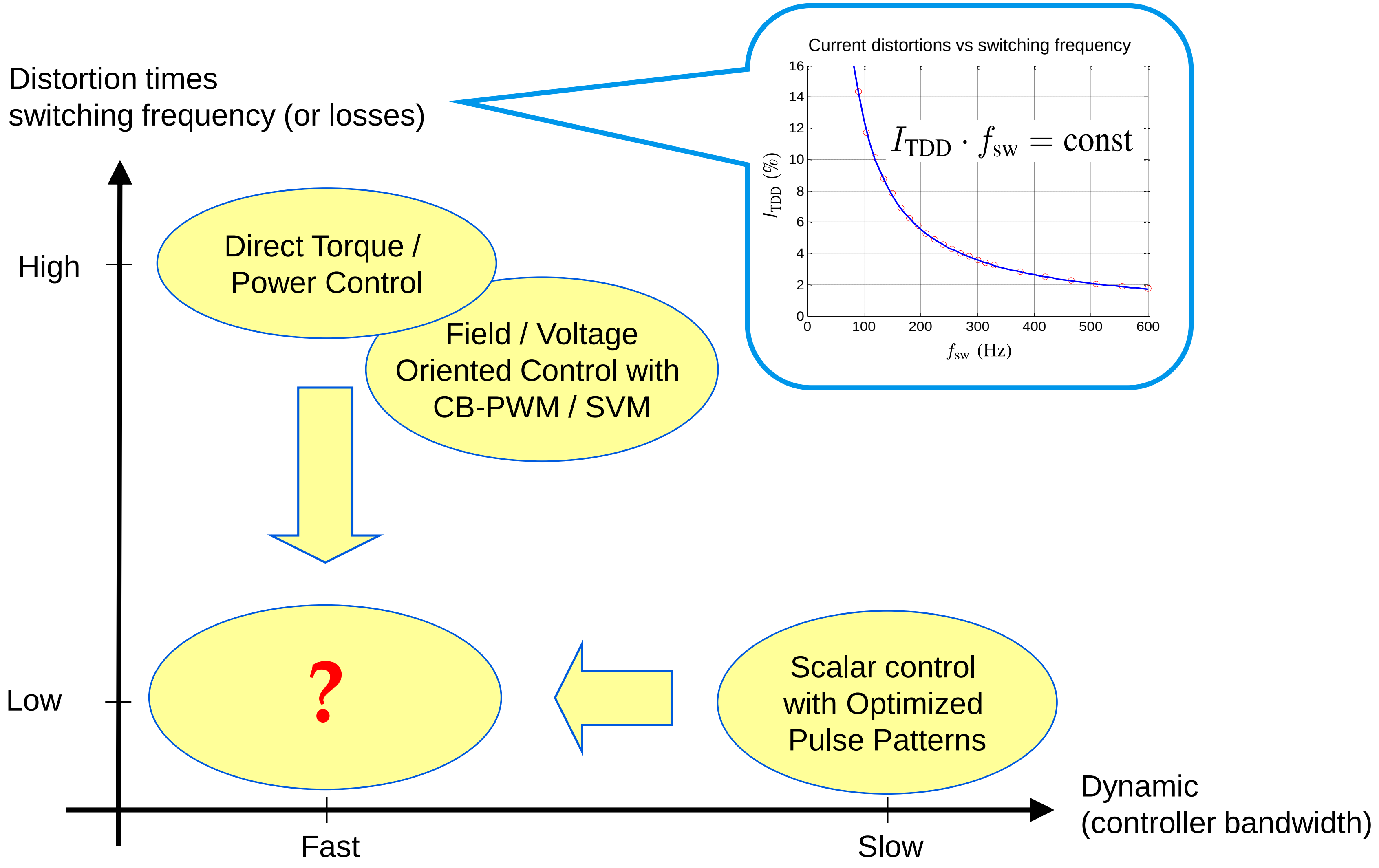
Fast Control of Optimized Pulse Patterns
Classic Control and Modulation Schemes



T. Geyer: "A comparison of control and modulation schemes for medium-voltage drives: emerging predictive control concepts versus PWM-based schemes", Trans. on Ind. Appl., May/June 2011

Fast Control of Optimized Pulse Patterns
Optimization Problem and Example

Computation of **optimal** pulse patterns

Given:
- The desired voltage amplitude
  => modulation index m
- The desired switching frequency
  => number of switching angles d

Compute the optimal switching angles α_i that minimize the current distortions

$$\underset{\alpha_i}{\text{minimize}} \sum_{n=5,7,\ldots} \left(\frac{1}{n^2} \sum_{i=1}^{d} \Delta u_i \cos(n\alpha_i) \right)^2$$

$$\text{subject to } \frac{4}{\pi} \sum_{i=1}^{d} \Delta u_i \cos(\alpha_i) = m$$

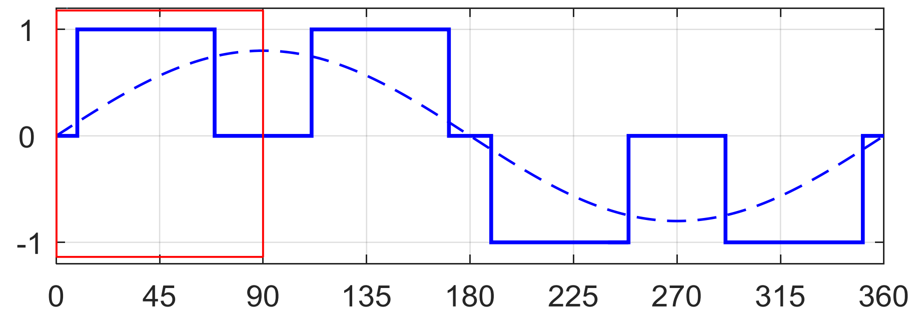
$$0 \le \alpha_1 \le \alpha_2 \le \ldots \le \alpha_d \le \frac{\pi}{2}$$

=> Nonlinear optimization problem

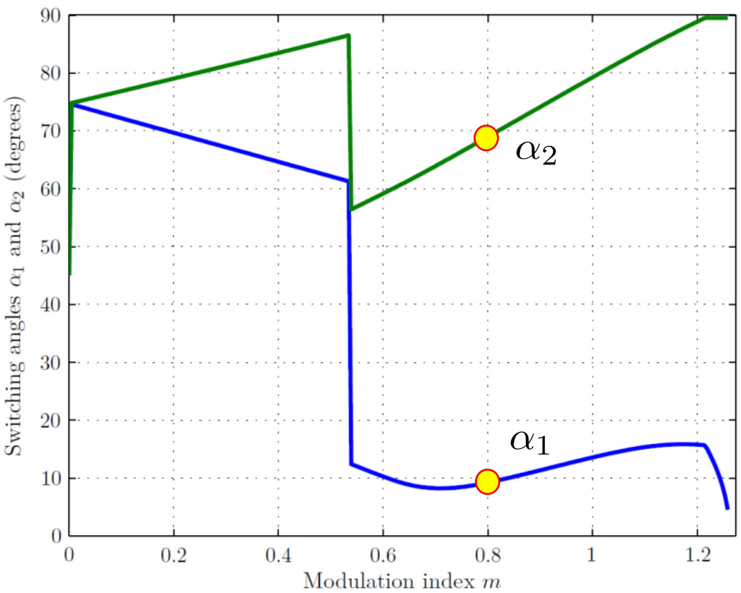
G. S. Buja: "Optimum output waveforms in PWM inverters," IEEE Trans. Ind. Appl., Nov./Dec. 1980

Example for 3-level converter

Switching pattern (with *d*=2):

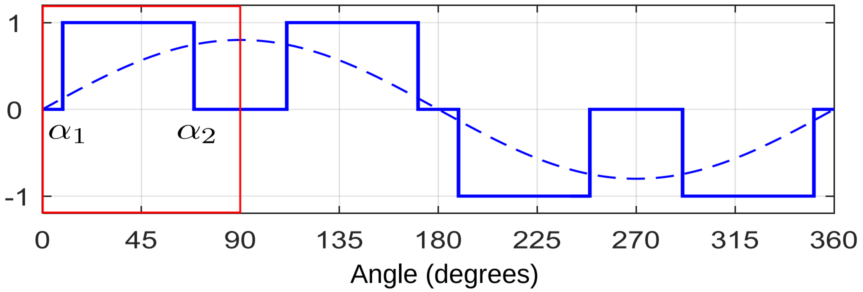


Set of witching angles:



Fast Control of Optimized Pulse Patterns
Optimization Problem for Two Switching Angles

Switching pattern



Optimization problem

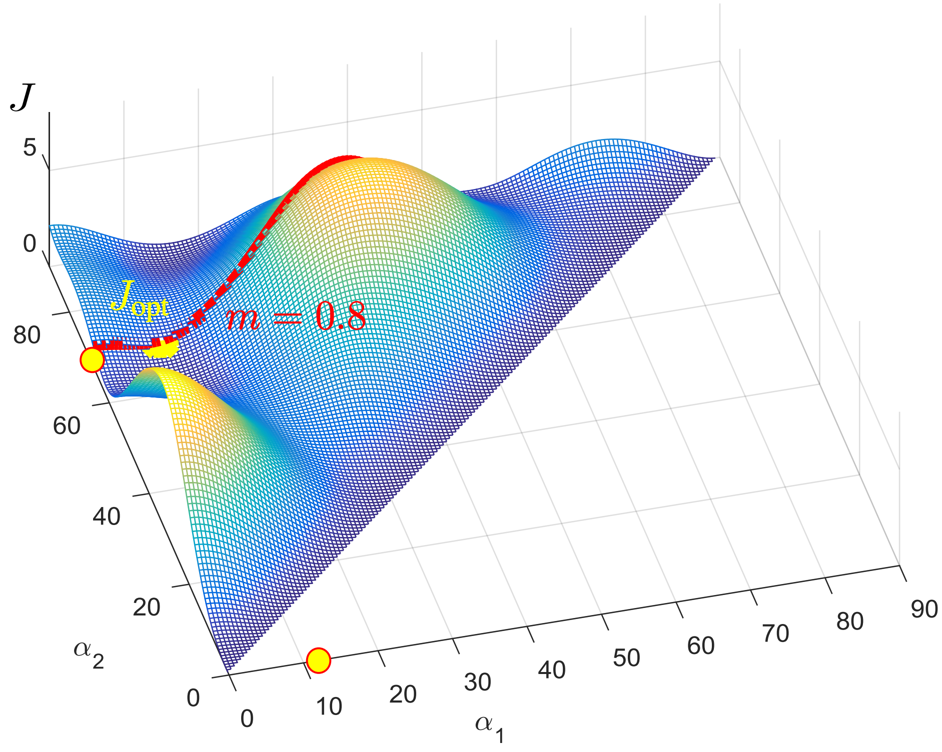
$$J_{\text{opt}} = \min_{\alpha_1,\alpha_2} \sum_{n=5,7,\dots} \left(\frac{\cos(n\alpha_1) - \cos(n\alpha_2)}{n^2} \right)^2$$

$$\text{subj. to } \frac{4}{\pi}\Big(\cos(\alpha_1) - \cos(\alpha_2)\Big) = m$$

$$0 \le \alpha_1 \le \alpha_2 \le \frac{\pi}{2}$$

- Minimize the sum of the squared **amplitudes** of the three-phase current **harmonics** (assuming an inductive load)
- Impose the desired modulation index *m* (**voltage**)

Cost function $J(\alpha_1, \alpha_2)$

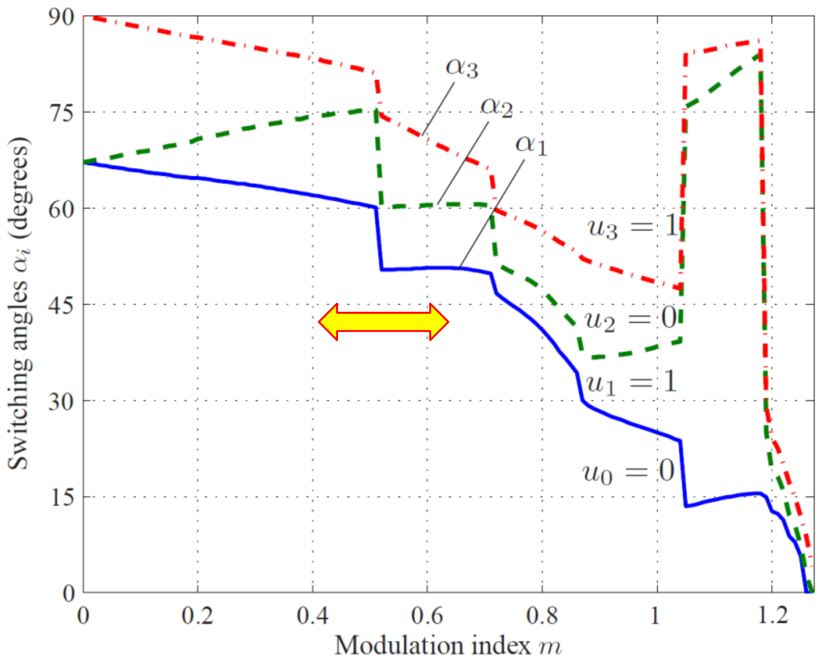


ABB

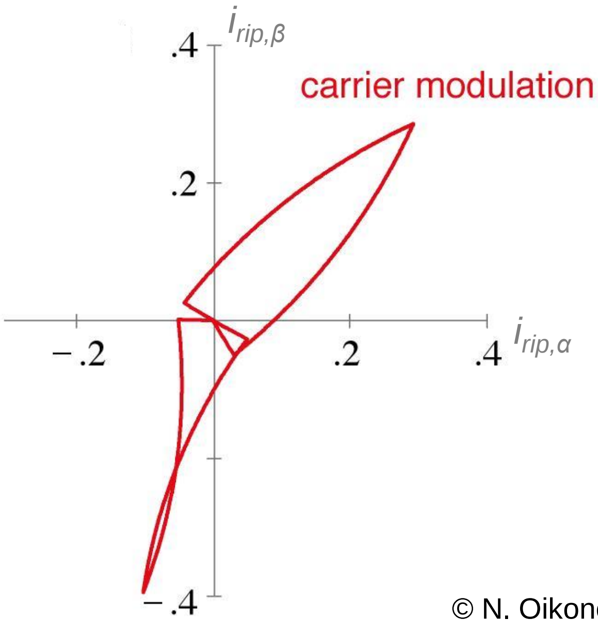
Fast Control of Optimized Pulse Patterns
Difficulties Arising for Linear Controllers

Linear controllers sample the converter current at **regular** sampling instants and manipulate the **modulation index** *m*

The switching angles are discontinuous in *m*



The current ripple is zero at equidistant time instants



Enforce **smooth** switching angles

=> Suboptimal pulse pattern

Fast Control of Optimized Pulse Patterns
Difficulties Arising for Linear Controllers

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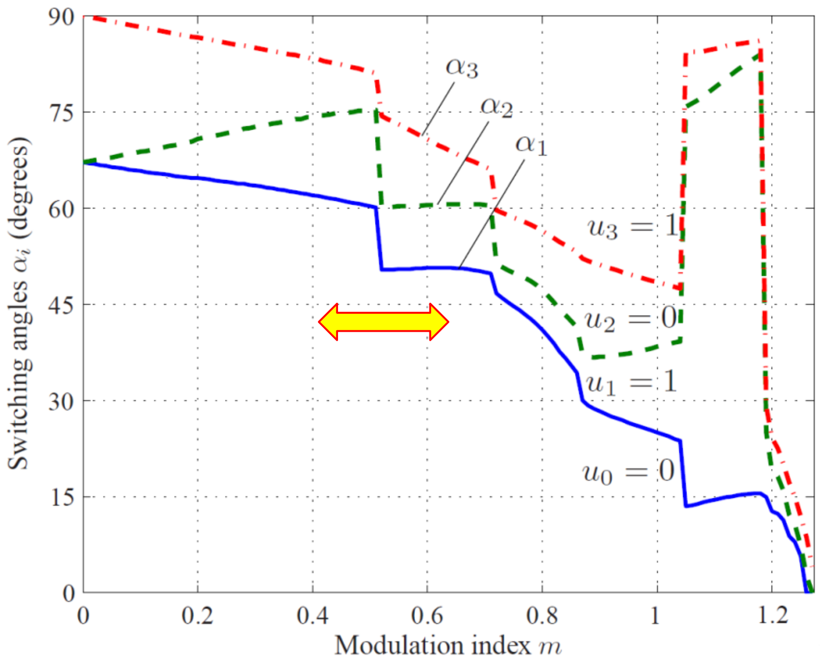
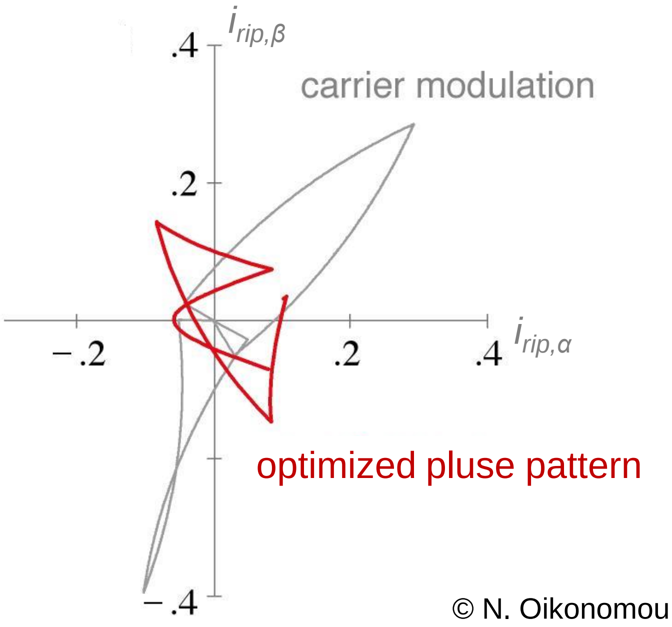


The current ripple is (in general) never zero



Enforce **smooth** switching angles

=> Suboptimal pulse pattern

Use **slow** controllers

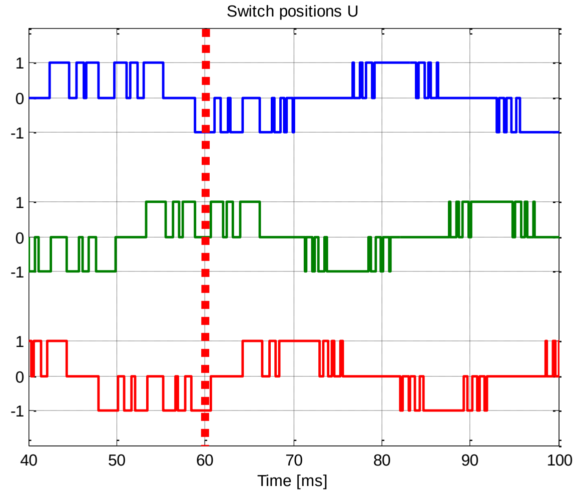
=> Poor disturbance rejection / response in transients

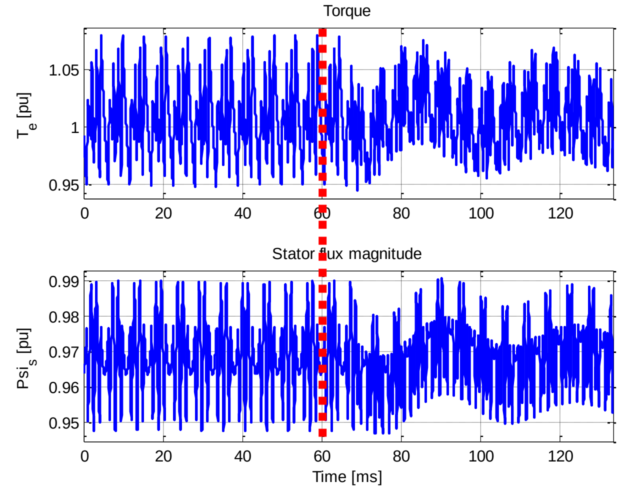
Fast Control of Optimized Pulse Patterns
Transition Between OPPs

Without control:

Change in OPP at constant output voltage

=> **Oscillation** in torque and flux magnitude



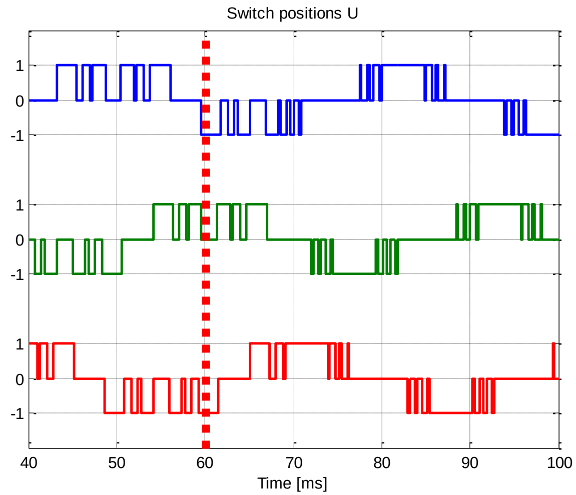


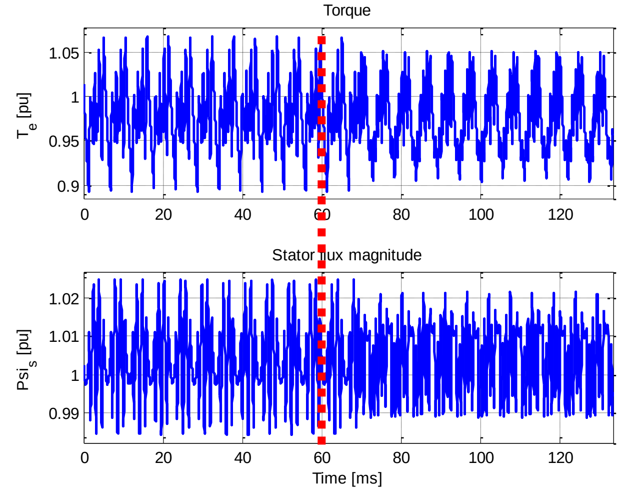
Pulse number 5 ⇨ **Pulse number 6**

With control:

Very small modifications of the switching instants is required

=> **Seamless transition** from one OPP to another





Need fast **closed-loop control** of OPPs

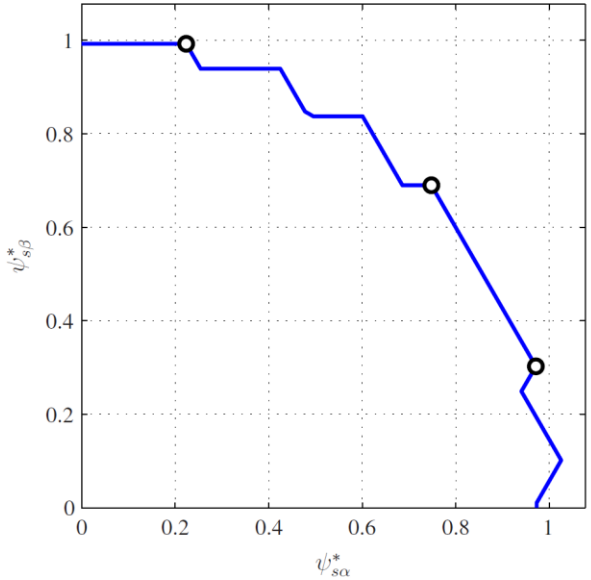
ABB

Fast Control of Optimized Pulse Patterns
Control Principle

Stator flux trajectory

Stator flux: $\boldsymbol{\psi}_s(t) = \boldsymbol{\psi}_s(0) + \frac{v_{\text{dc}}}{2} \int_0^t \boldsymbol{u}_{\text{OPP}}(\tau) \mathrm{d}\tau$

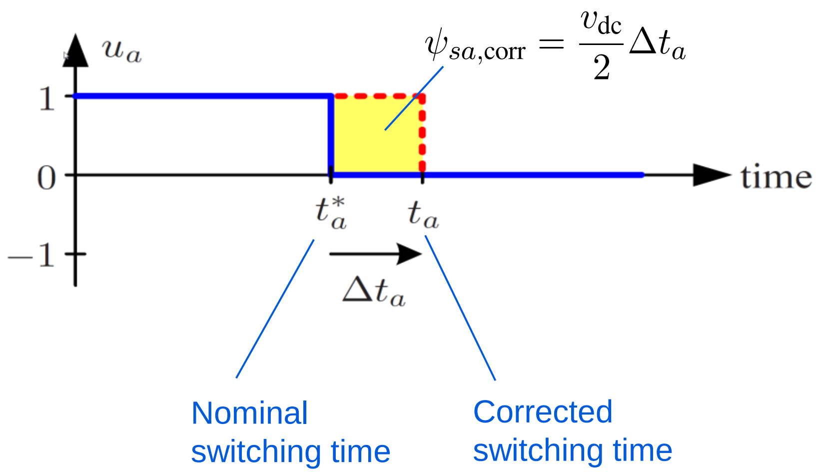
=> Integrate the optimal pulse pattern to derive the optimal stator flux trajectory



Stator flux reference trajectory is **optimal** (minimizes the current distortions) => **Tracking**

Stator flux correction

- Manipulate the time-instants of the switching transitions to correct the stator flux
- Example: switching transition in phase a

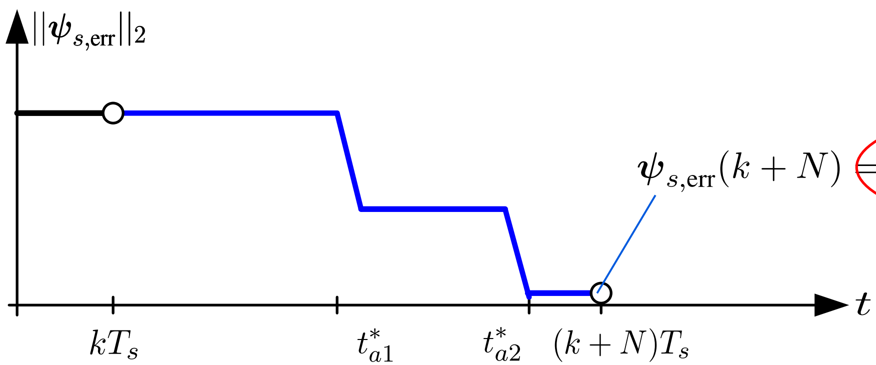


Achieve **fast** closed-loop **control**

J. Holtz and N. Oikonomou: "Synchronous optimal pulse width modulation and stator flux trajectory control for medium-voltage drives," Trans. on Ind. Appl., Mar./Apr. 2007

Fast Control of Optimized Pulse Patterns
Control Problem Formulation

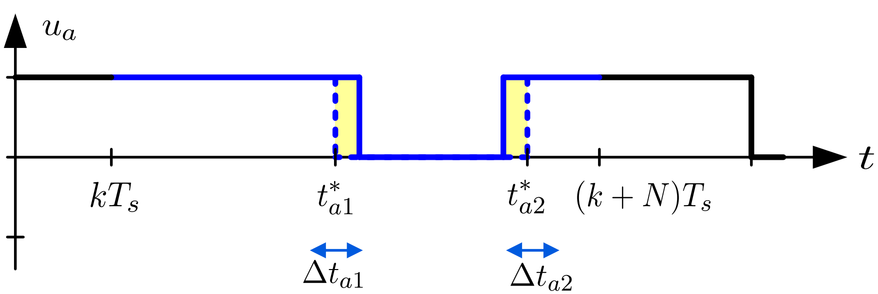
Stator flux error (controlled var.): $\psi_{s,\text{err}} = \psi_s^* - \psi_s$ (in $\alpha\beta$)



$$\psi_{s,\text{err}}(k+N) = \psi_{s,\text{err}}(k) - \sum_{\ell=0}^{N-1} \psi_{s,\text{corr}}(k+\ell)$$

$$= -\frac{v_{\text{dc}}}{2} \boldsymbol{K}_{\alpha\beta} \begin{bmatrix} \sum_i^{n_a} \Delta u_{ai} \Delta t_{ai} \\ \sum_i^{n_b} \Delta u_{bi} \Delta t_{bi} \\ \sum_i^{n_c} \Delta u_{ci} \Delta t_{ci} \end{bmatrix}$$

Switching time modifications (manipulated var.): Δt



… similarly in phases *b* and *c*

Model predictive pulse pattern control (**MP³C**) of the switching time modifications $\Delta t \in \mathbb{R}^n$

T. Geyer, N. Oikonomou, G. Papafotiou and F.D. Kieferndorf: "Model predictive pulse pattern control", Trans. on Ind. Appl., Mar./Apr. 2012.

Fast Control of Optimized Pulse Patterns
Optimization Problem

Optimization problem

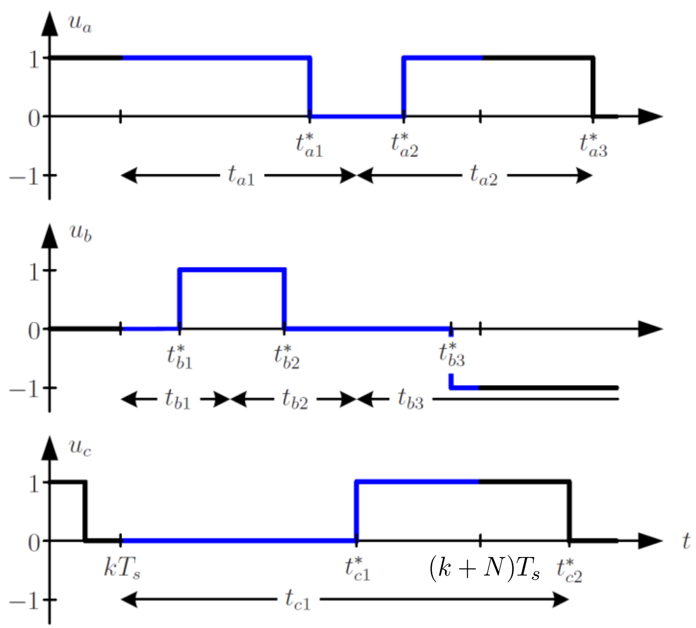
$$\underset{\Delta \boldsymbol{t}}{\text{minimize}} \ ||\boldsymbol{\psi}_{s,\text{err}} - \boldsymbol{\psi}_{s,\text{corr}}(\Delta \boldsymbol{t})||_2^2 + \Delta \boldsymbol{t}^T \boldsymbol{Q} \Delta \boldsymbol{t}$$

$$\text{subject to} \ kT_s \le t_{a1} \le t_{a2} \le \ldots \le t_{an_a} \le t^*_{a(n_a+1)}$$

$$kT_s \le t_{b1} \le t_{b2} \le \ldots \le t_{bn_b} \le t^*_{b(n_b+1)}$$

$$kT_s \le t_{c1} \le t_{c2} \le \ldots \le t_{cn_c} \le t^*_{c(n_c+1)}$$

Example:



Solution approaches

- This is a quadratic program (**QP**) in $\Delta \boldsymbol{t} \in \mathbb{R}^n$

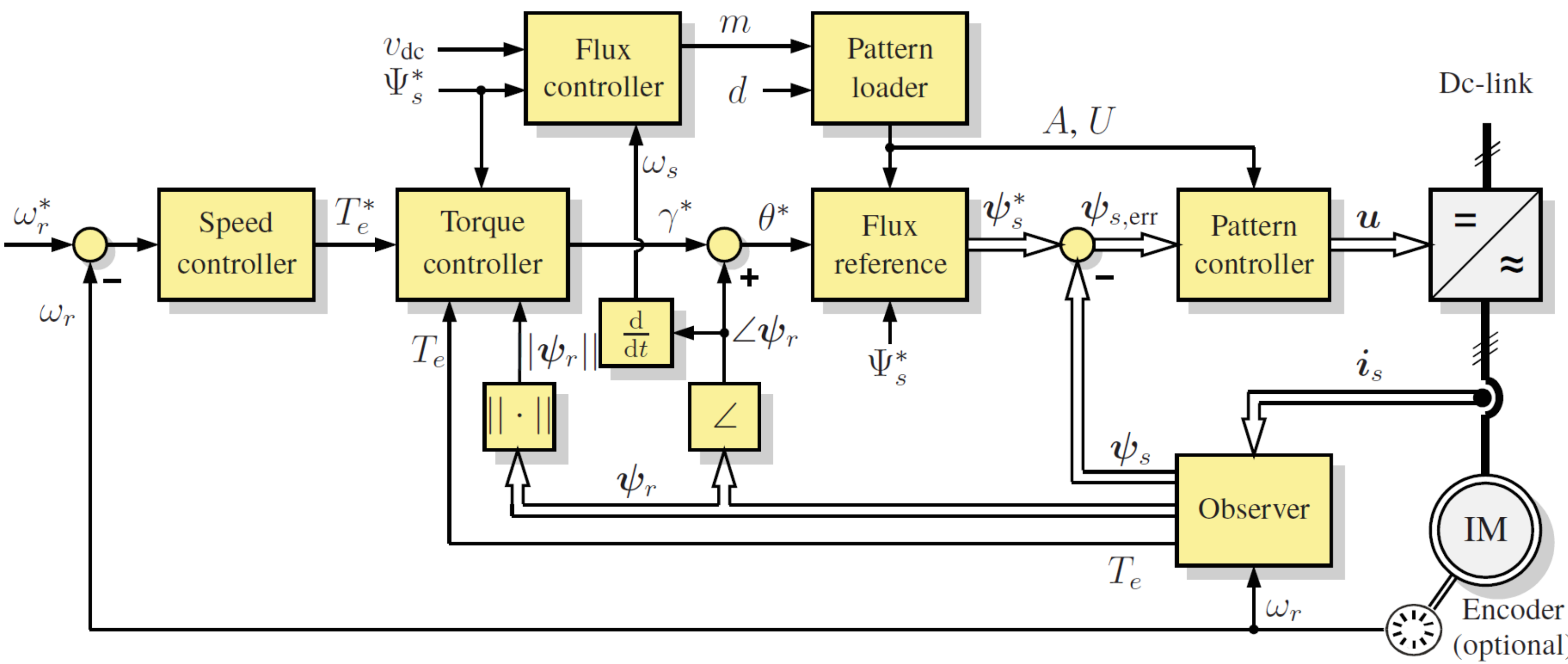
  => Solve with an active set or a gradient method

- Or simplify the QP to a **deadbeat** control problem
  - by setting $\boldsymbol{Q} = 0$ and
  - by choosing the minimal horizon *N* (such that the prediction interval includes at least one switching transition per phase)

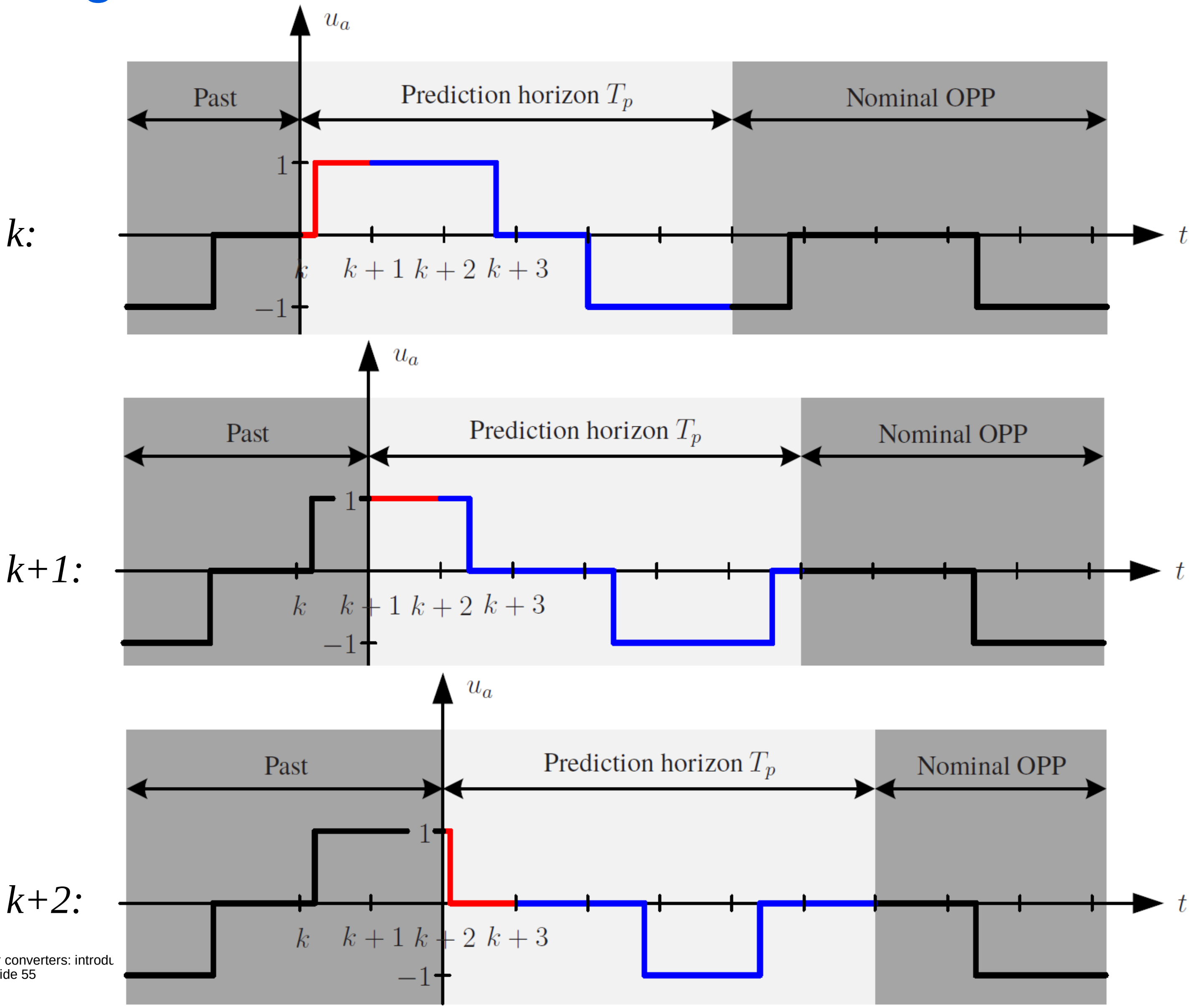
- In case of very large flux error: insert additional switching transitions

T. Geyer, N. Oikonomou, G. Papafotiou and F.D. Kieferndorf: "Model predictive pulse pattern control", IEEE Trans. Ind. Appl., Mar./Apr. 2012

Fast Control of Optimized Pulse Patterns
Block Diagram



Fast Control of Optimized Pulse Patterns
Receding Horizon Policy



Fast Control of Optimized Pulse Patterns
Medium-Voltage Lab

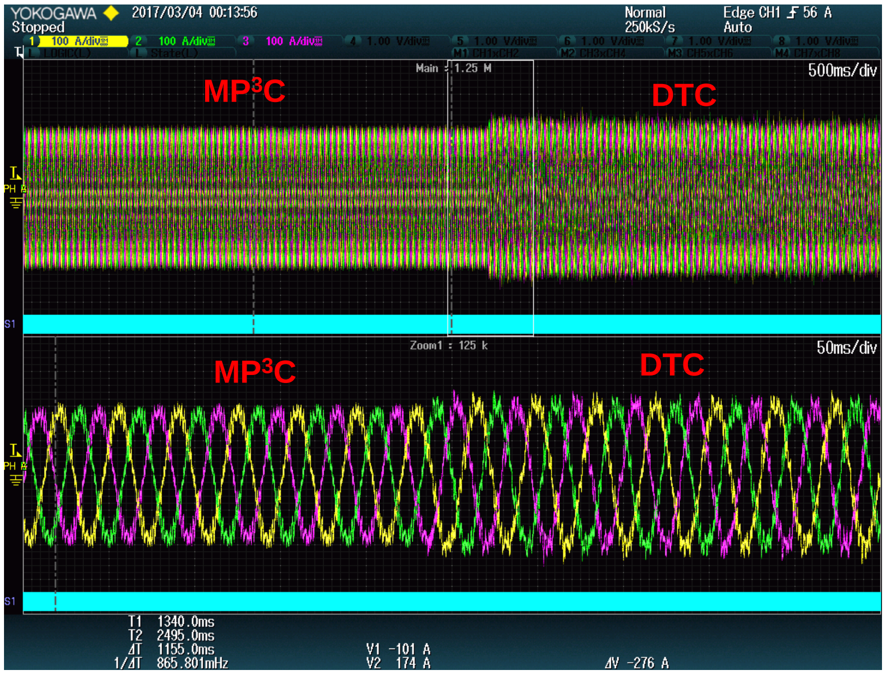
2 MVA induction machine:

Three-level back-to-back converter:

Fast Control of Optimized Pulse Patterns
Experimental Results

Steady-state operation:

55% speed, 60% torque



Up to **50% lower** current distortions for the same switching frequency (or vice versa)

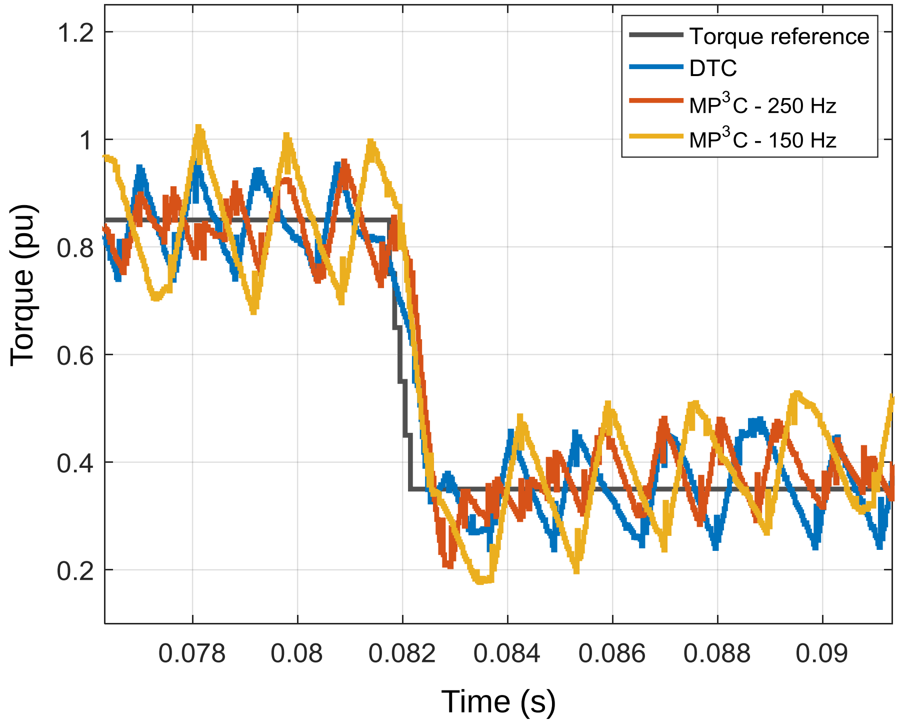
=> Machine-friendly operation, lower switching frequencies, higher power

Lab results from Vedrana Spudic

Fast Control of Optimized Pulse Patterns
Experimental Results

Torque transients:

40% speed, reference step from 85% to 35% torque



Dynamic performance similar to that of Direct Torque Control (**DTC**)

Lab results from Vedrana Spudic

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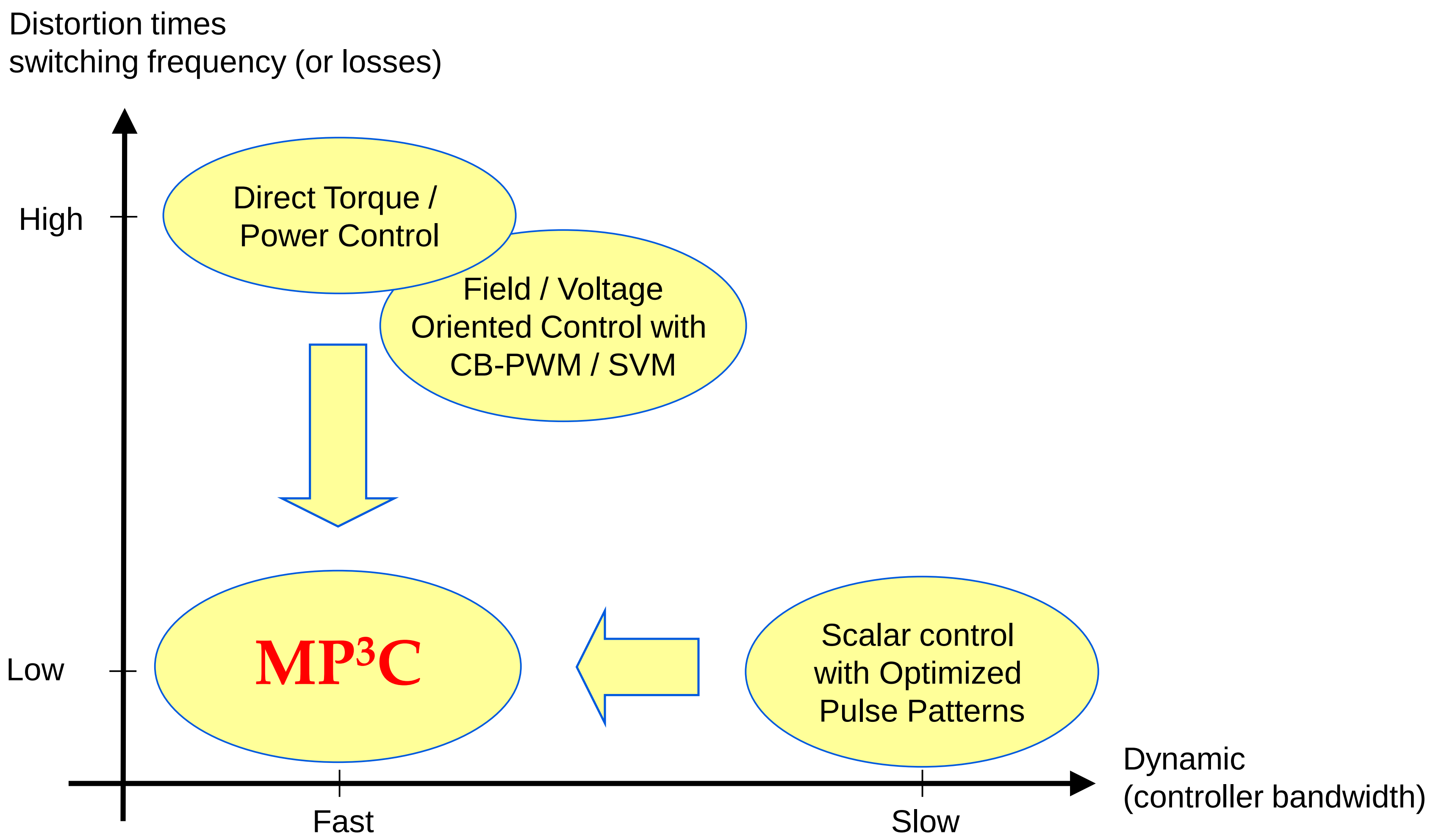
Fast Control of Optimized Pulse Patterns
Model Predictive Pulse Pattern Control (MP³C)

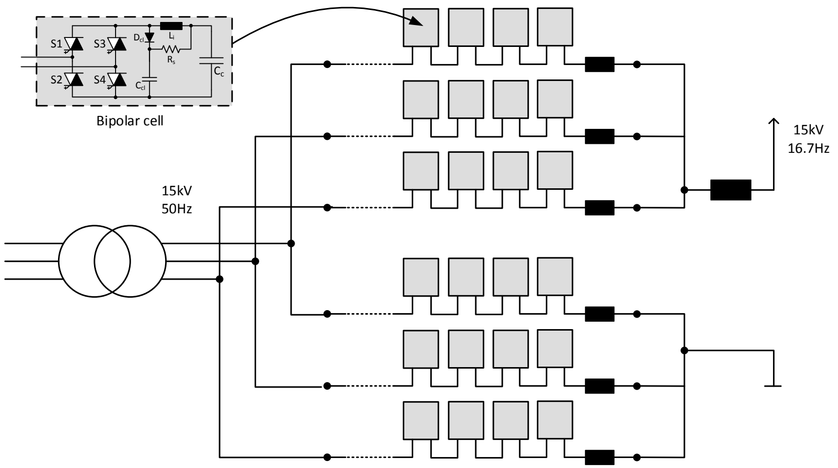


Fast Control of Optimized Pulse Patterns
Assessment

Advantages

- Simple and general method *=> can be applied across a wide range of products (grid-side, modular multilevel converter)*
- Large part of the problem is solved offline *=> optimized pulse pattern*
- Minimize harmonic distortions / shape spectrum *=> minimize harmonic losses in load, minimize filter and meet grid codes*
- Modulation up to the maximal converter voltage and low current ripple *=> power boost of the converter*
- Various extensions exist *=> pulse insertion, balancing of neutral point potentials, etc.*

Example: Modular multilevel converter



Limitations

- Performance deteriorates in the presence of asymmetries *=> grid imbalances or non-uniform phase voltage steps*

Significant **cost** reductions

=> Commercially **attractive** for high-power converters

Model Predictive Control of Power Converters
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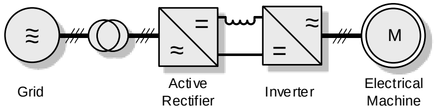
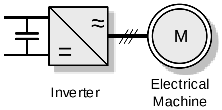


Fast control of optimized pulse patterns

- *Optimized pulse pattern, control method and experimental results*



Conclusions and outlook

Control of High Power Electronics
Conclusions

Commercial benefits of modern control methods:

- Minimization of the **cost per MVA** of the power electronic system
- Superior performance during **transients** and faults
- Operation within the **safe operating area**
- Reduced effort to **design** and **adapt** the controller

=> *Cost savings and boost of competitiveness*

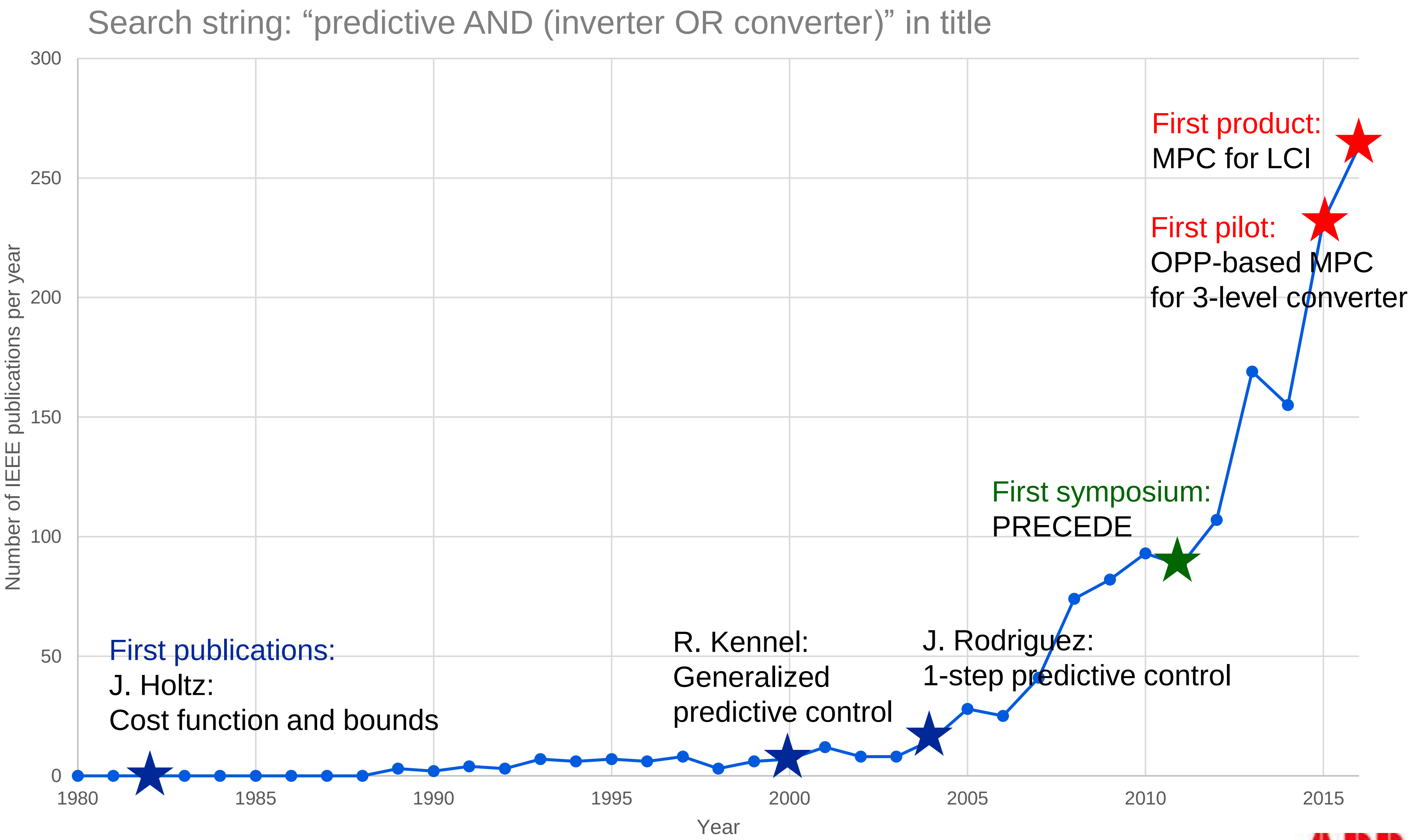
Challenges:

- Built-up of **know-how** and productization
- Conceptual **simplicity**
- Applicability to the whole **product range**

An assessment:

- Control is a potential **differentiator** and **cost saver** for industry
- Lack of **computational power** is typically not the limiting factor
- **Predictive control** for power electronics is rapidly emerging

Control of High Power Electronics
Milestones in “Predictive Control in Power Electronics”



Control of High Power Electronics
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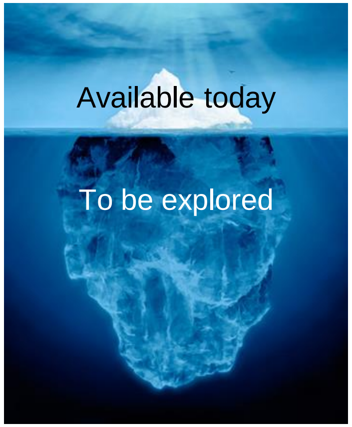
- Lack of **computational power** is typically not the limiting factor
- **Predictive control** for power electronics is rapidly emerging
- Few MPC methods have been proposed that are suitable for **high** power electronics

=> Look beyond FCS-MPC



Modern control for power electronics is still at an early stage

Acknowledgements

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- Georgios Papafotiou
- Nikolaos Oikonomou
- Wim van der Merwe
- Christian Stulz
- Christof Gutscher
- Eduardo Rohr
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- Tobias Thurnherr

ETH Zurich, Switzerland:

- Manfred Morari

Stellenbosch University, South Africa:

- Toit Mouton

Tampere University, Finland:

- Petros Karamanakos

University of Paderborn, Germany:

- Daniel E. Quevedo

Univ. of Auckland, New Zealand:

- Udaya Madawala

TU Munich, Germany:

- Ralph Kennel

Univ. of Technology Sydney, Australia:

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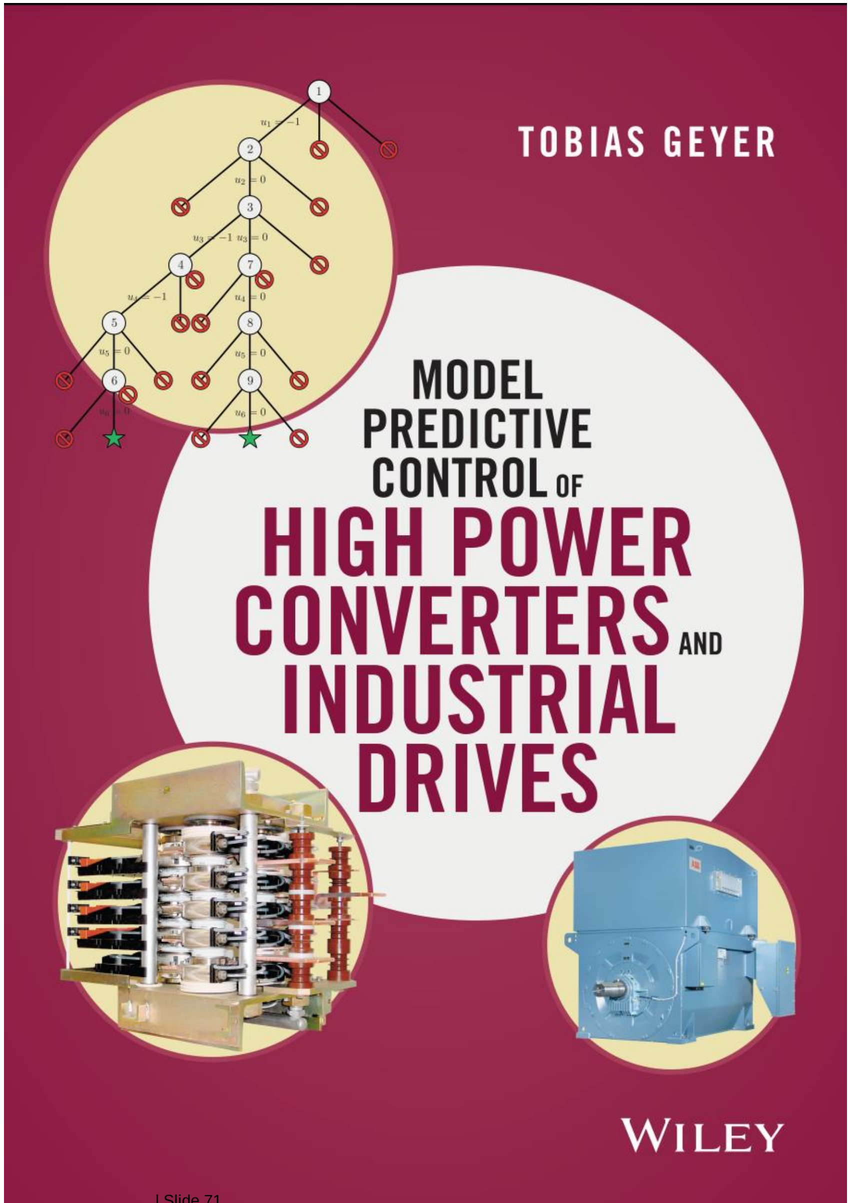
MPC of High Power Electronics and Industrial Drives



Five main parts:

- **Introduction:** MPC, machines, semiconductors, topologies, MV inverters, requirements, CB-PWM, OPPs, field oriented control, direct torque control
- **Direct MPC with reference tracking (FCS-MPC):** predictive current control, predictive torque control, integer quadratic programming formulation, sphere decoding, performance evaluation for NPC inverter drive system without and with LC filter
- **Direct MPC with bounds:** model predictive direct torque control, extension methods, performance evaluation for 3L and 5L inverter drive systems, state-feedback control law, deadlocks, branch and bound methods, model predictive direct current control, model predictive direct power control
- **MPC based on PWM:** model predictive pulse pattern control, pulse insertion, performance evaluation for NPC inverter drive system, experimental results for 5L inverter drive system, MPC of an MMC using CB-PWM
- **Summary and conclusions:** performance comparison of direct MPC schemes, assessment, summary and discussion, outlook

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