Model Predictive Control in Medium-Voltage Drives

Tobias Geyer

THE UNIVERSITY OF AUCKLAND
NEW ZEALAND

Department of Electrical and Computer Engineering
The University of Auckland
New Zealand

In collaboration with

ABB

ETH Zürich

Outline

Introduction

- Control problem
- Performance trade-off
- Control and modulation schemes

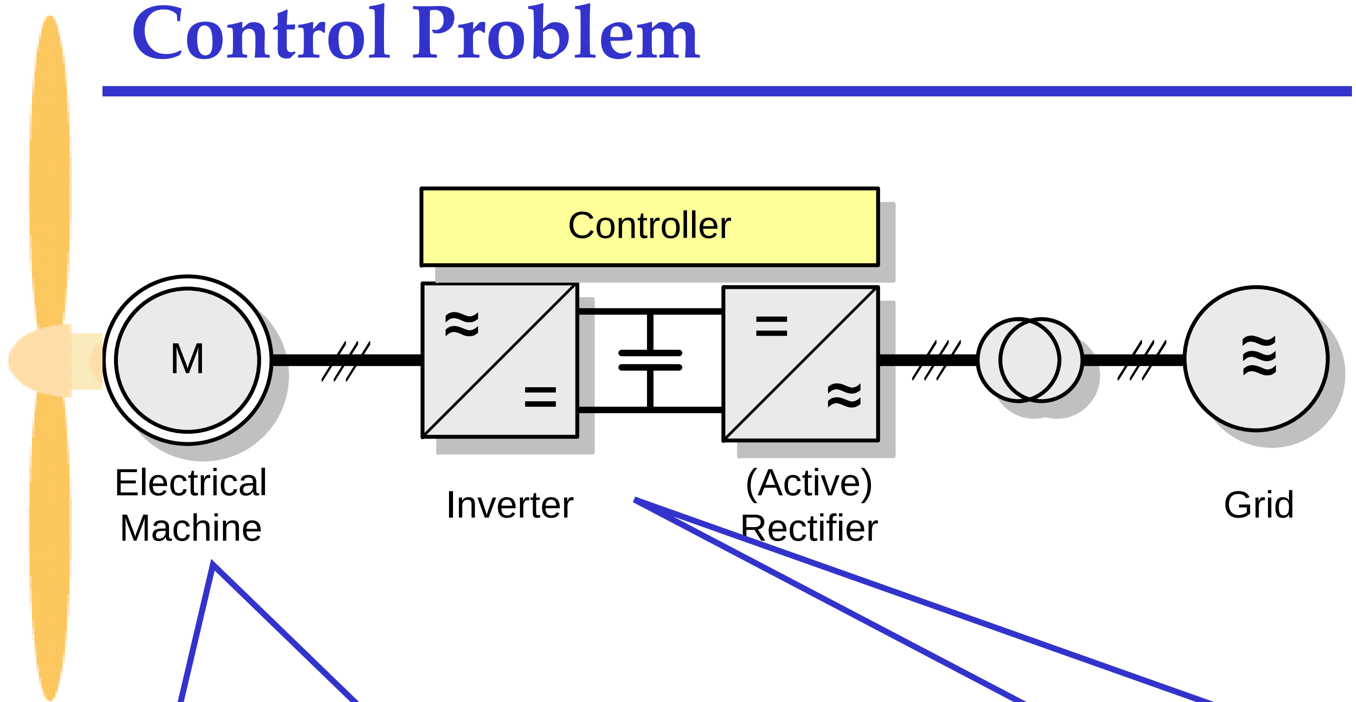
Model Predictive Control

- 1-step predictive control
- Model predictive direct current/torque control
- Computational efficiency

Summary and Outlook

Control Problem

Control Problem



Low **current** distortions => low **thermal** losses

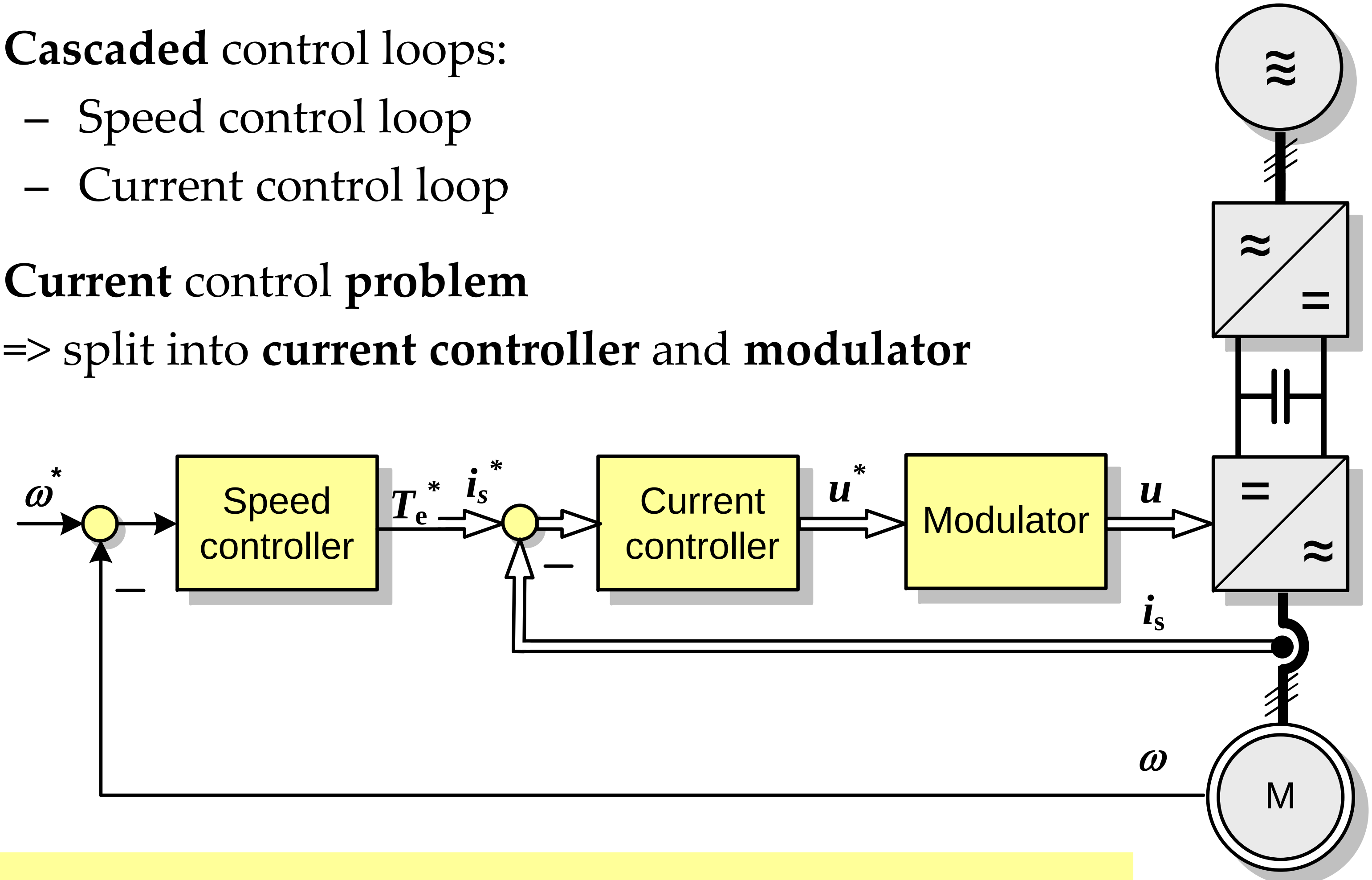
Low switching **losses** => high **efficiency**, low **thermal** losses

Low **torque** distortions => no excitation of mech. **resonances**

Fast torque response => high **dynamic** performance

Control and Modulation

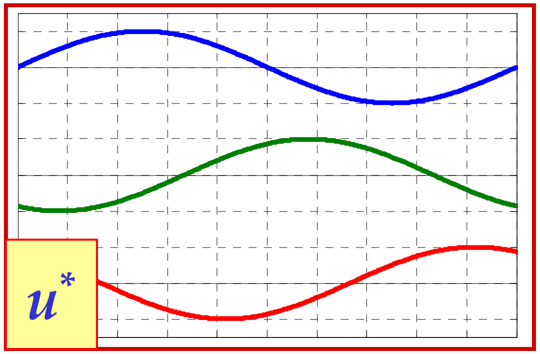
- **Cascaded** control loops:
  - Speed control loop
  - Current control loop
- **Current** control **problem**
  => split into **current controller** and **modulator**

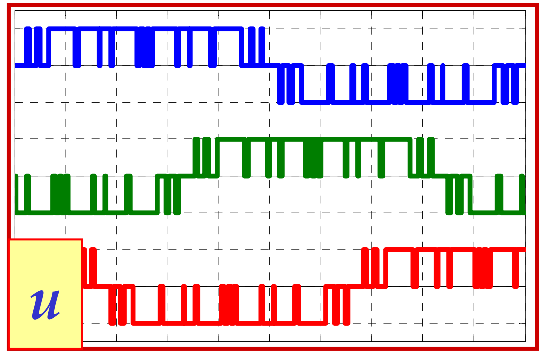


Fundamental **trade-off** between switching **losses** (frequency) and the current / torque **distortion** levels

Performance Trade-Off

Trade-Off (*High* Switching Frequency)



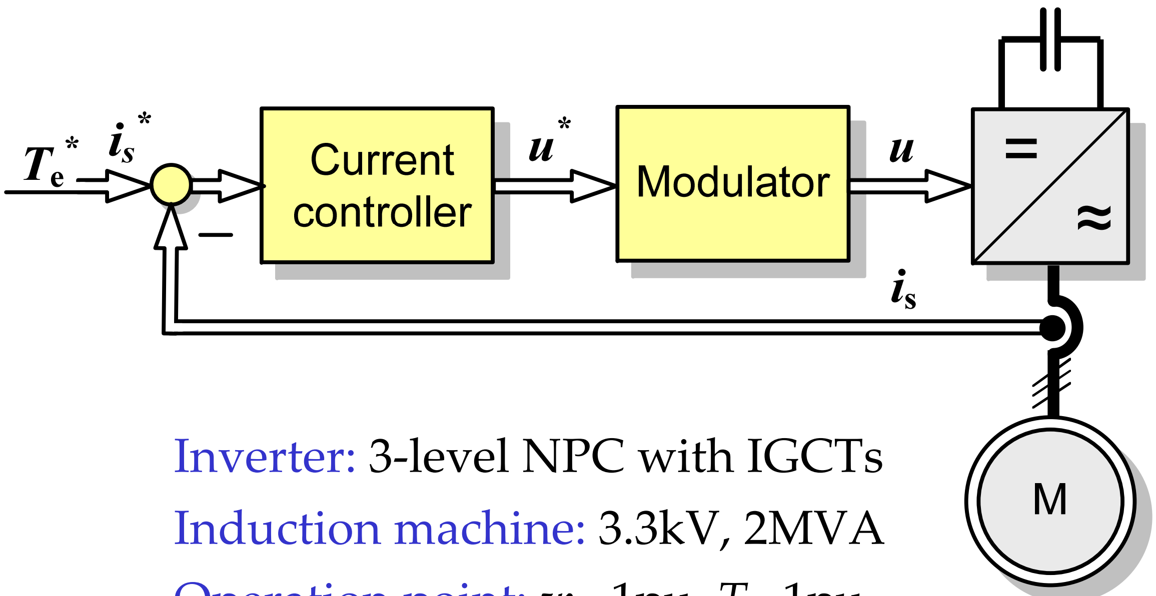


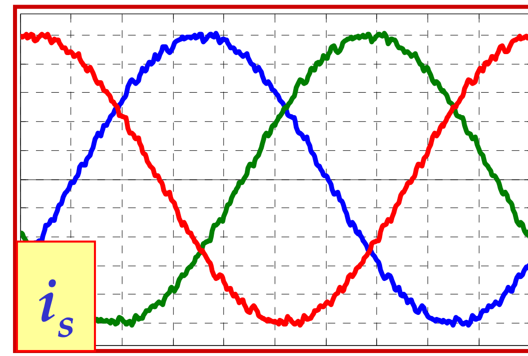
f_{sw}=700Hz

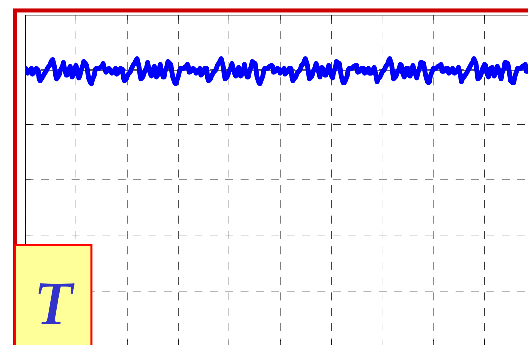
P_{sw}=**16.7**kW,P_{con}=2.7kW

THD_I=2.31%

THD_T=1.93%





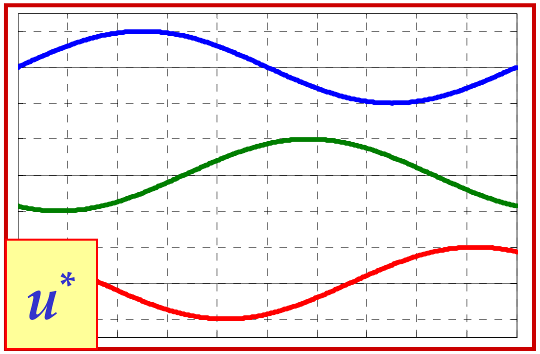


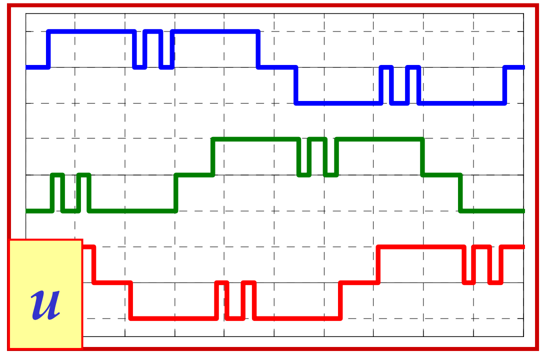
Inverter: 3-level NPC with IGCTs

Induction machine: 3.3kV, 2MVA

Operation point: w_e=1pu, T_e=1pu

Trade-Off (*Low* Switching Frequency)



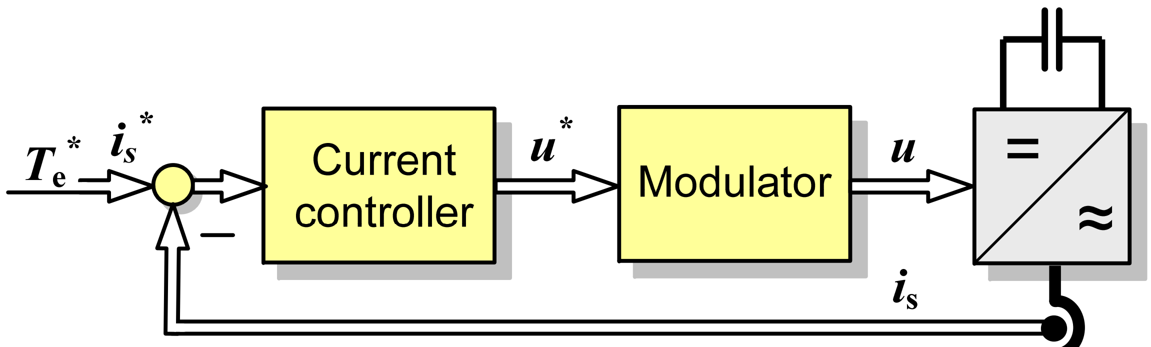


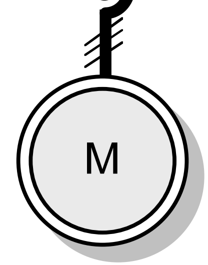
f_{sw}=150Hz

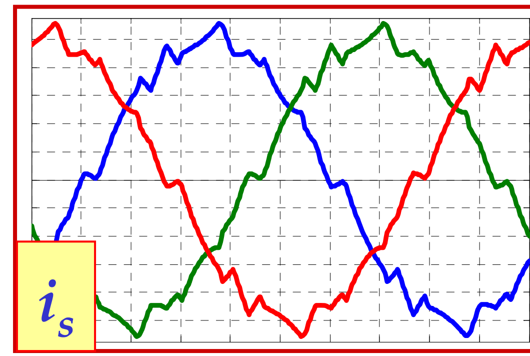
P_{sw}=**3.9**kW, P_{con}=2.8kW

THD_I=6.9%

THD_T=6.0%







Inverter: 3-level NPC with IGCTs

Induction machine: 3.3kV, 2MVA

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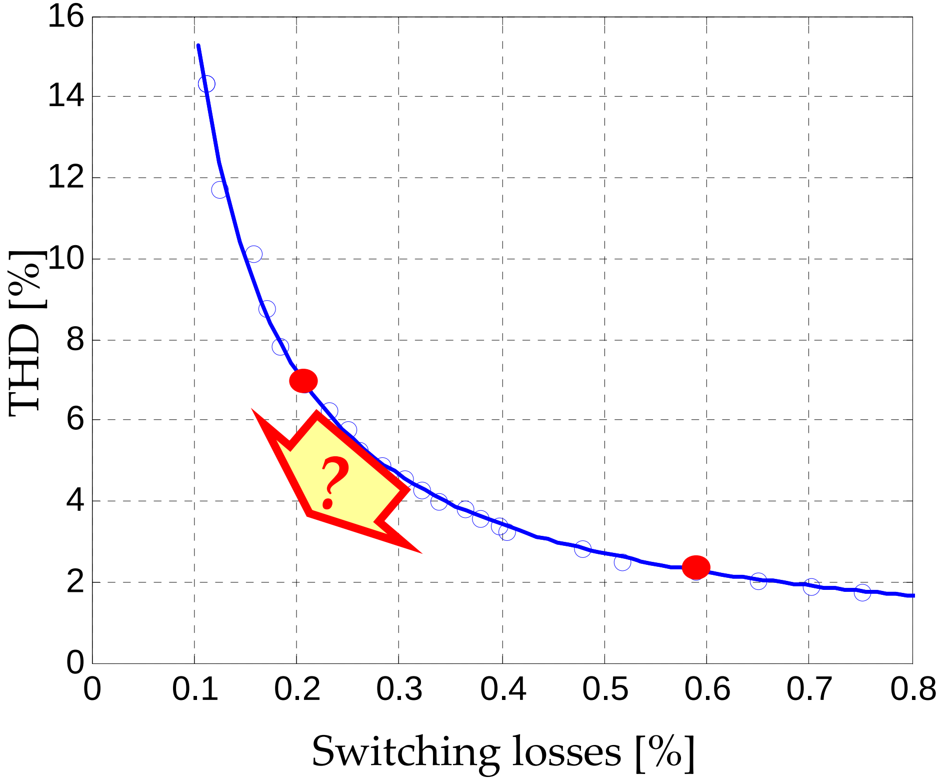
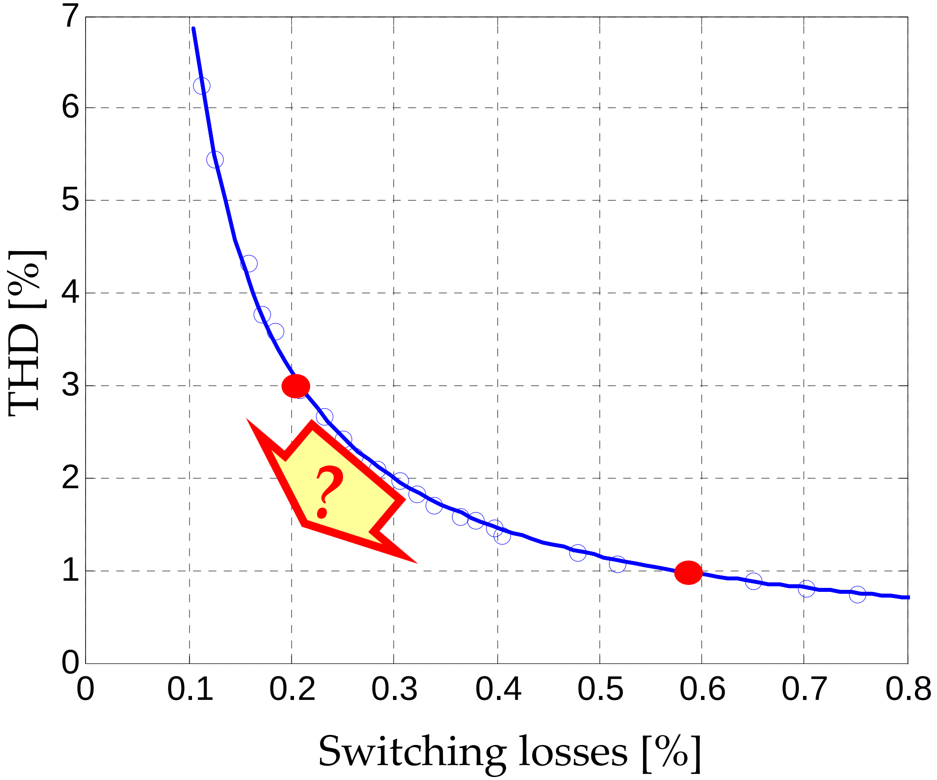
Trade-Off for PWM / SVM

Current THD vs switching losses



$$I_{s,\text{THD}} \cdot P_{\text{sw}} = \text{const}$$

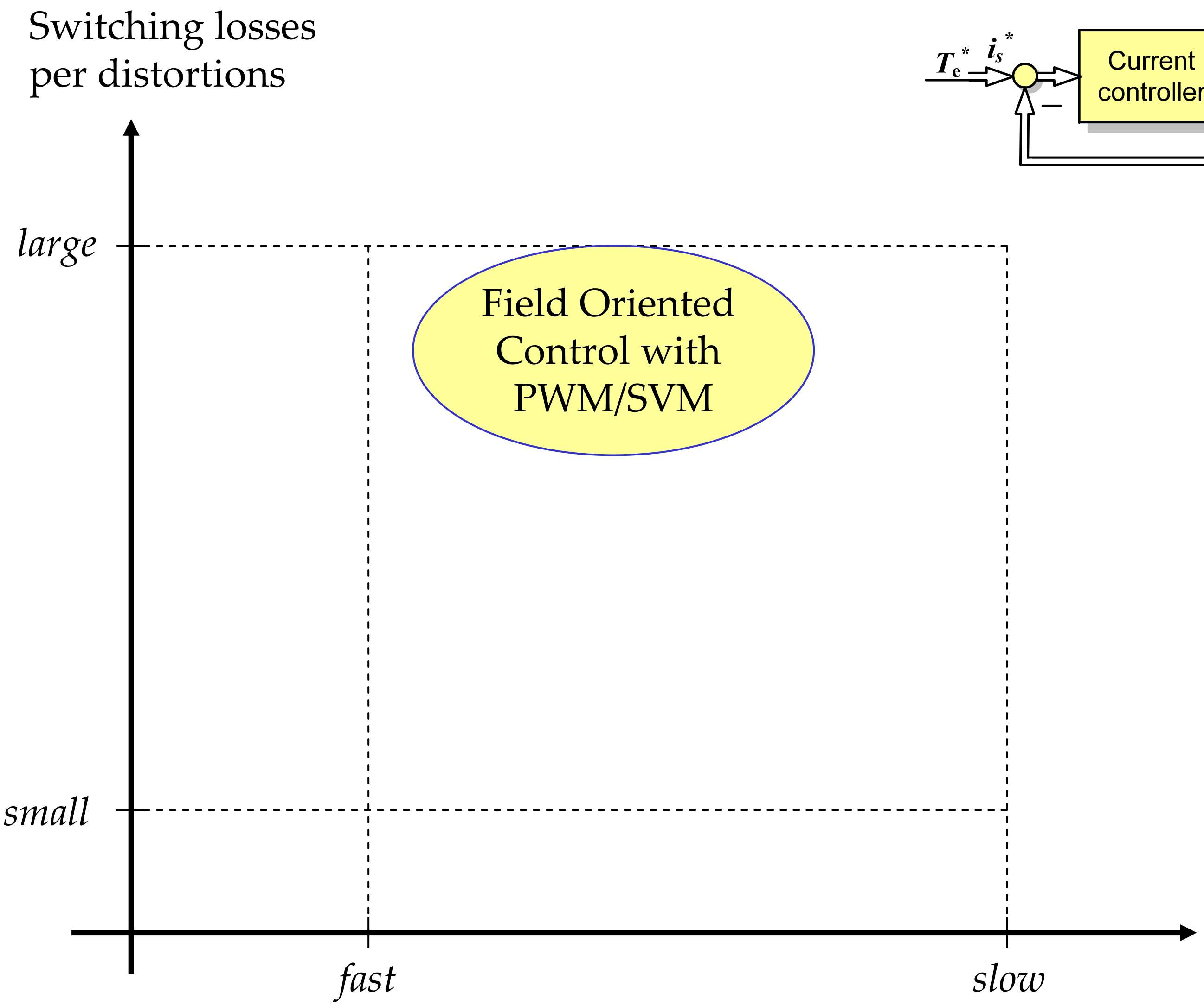
Torque THD vs switching losses

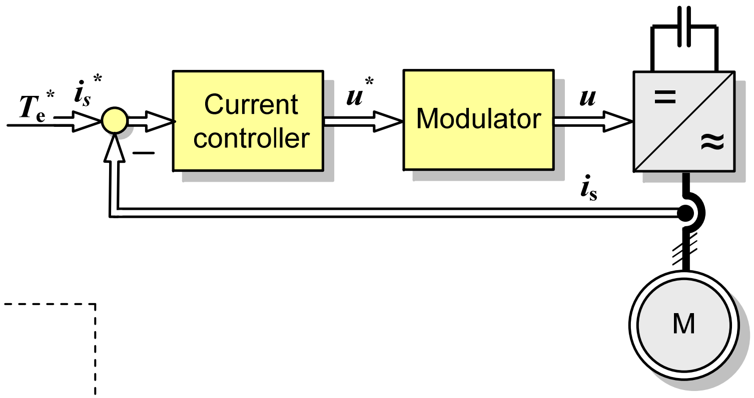


$$T_{e,\text{THD}} \cdot P_{\text{sw}} = \text{const}$$

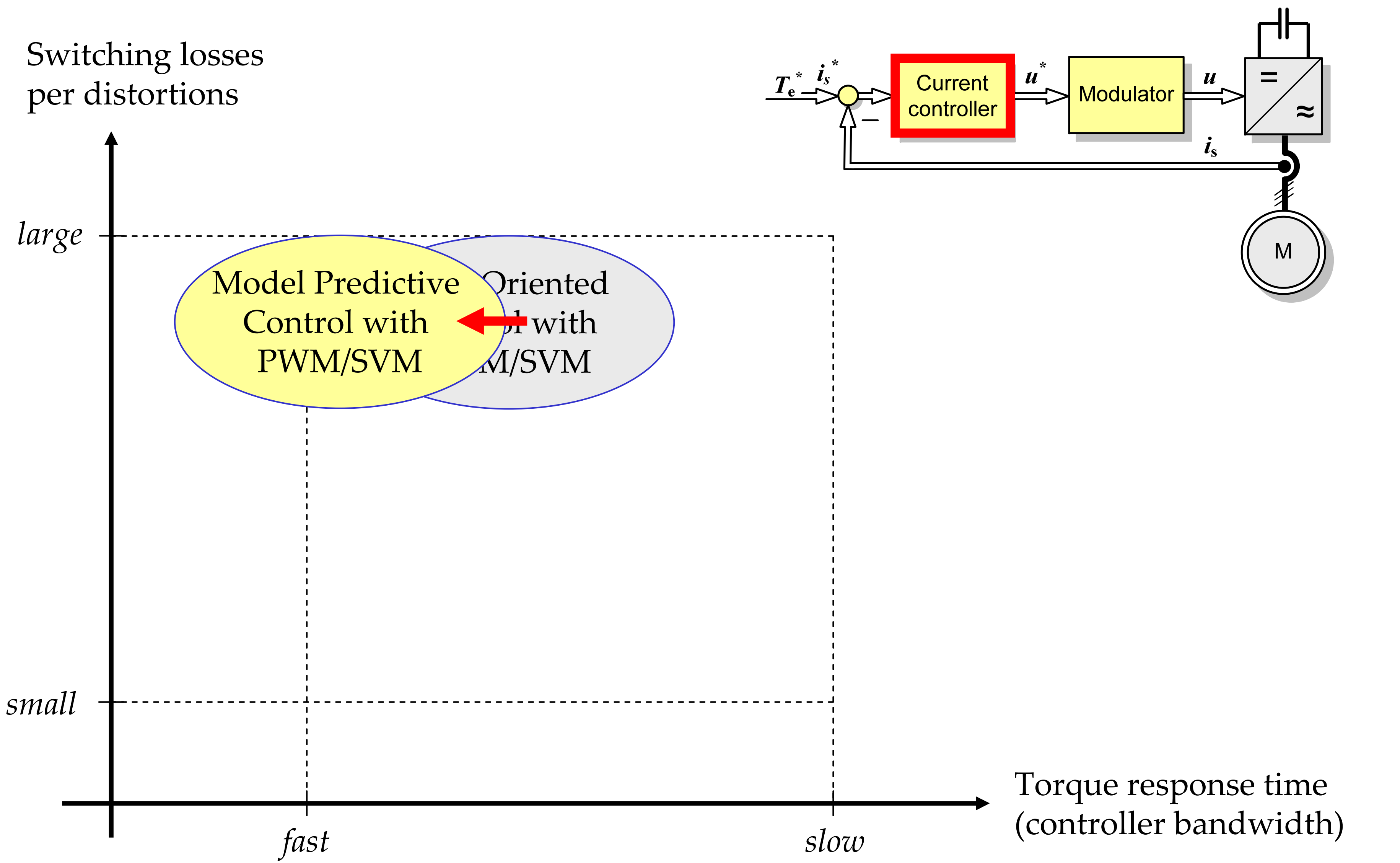
Control and Modulation Schemes

Control and Modulation





Control and Modulation



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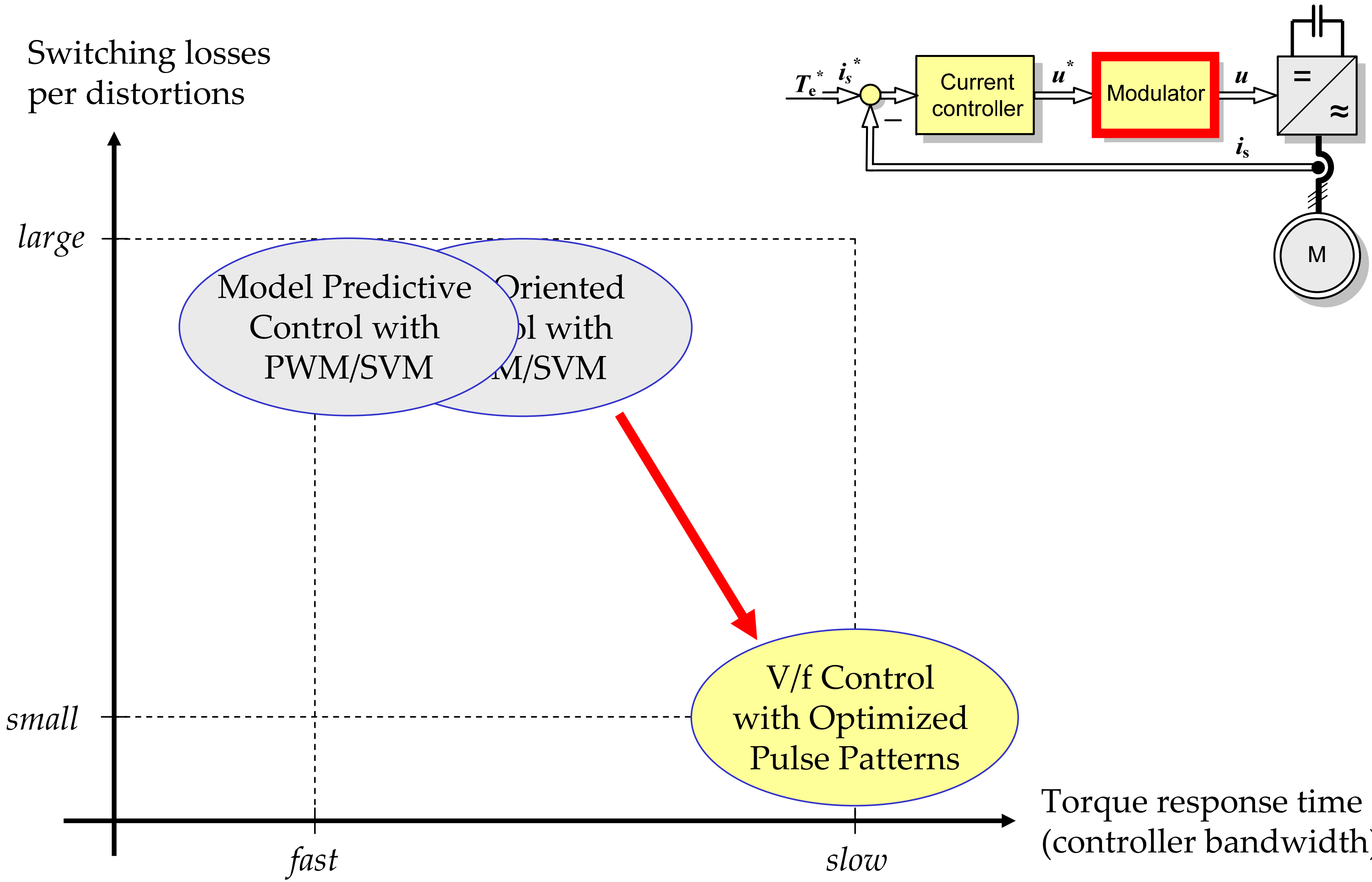

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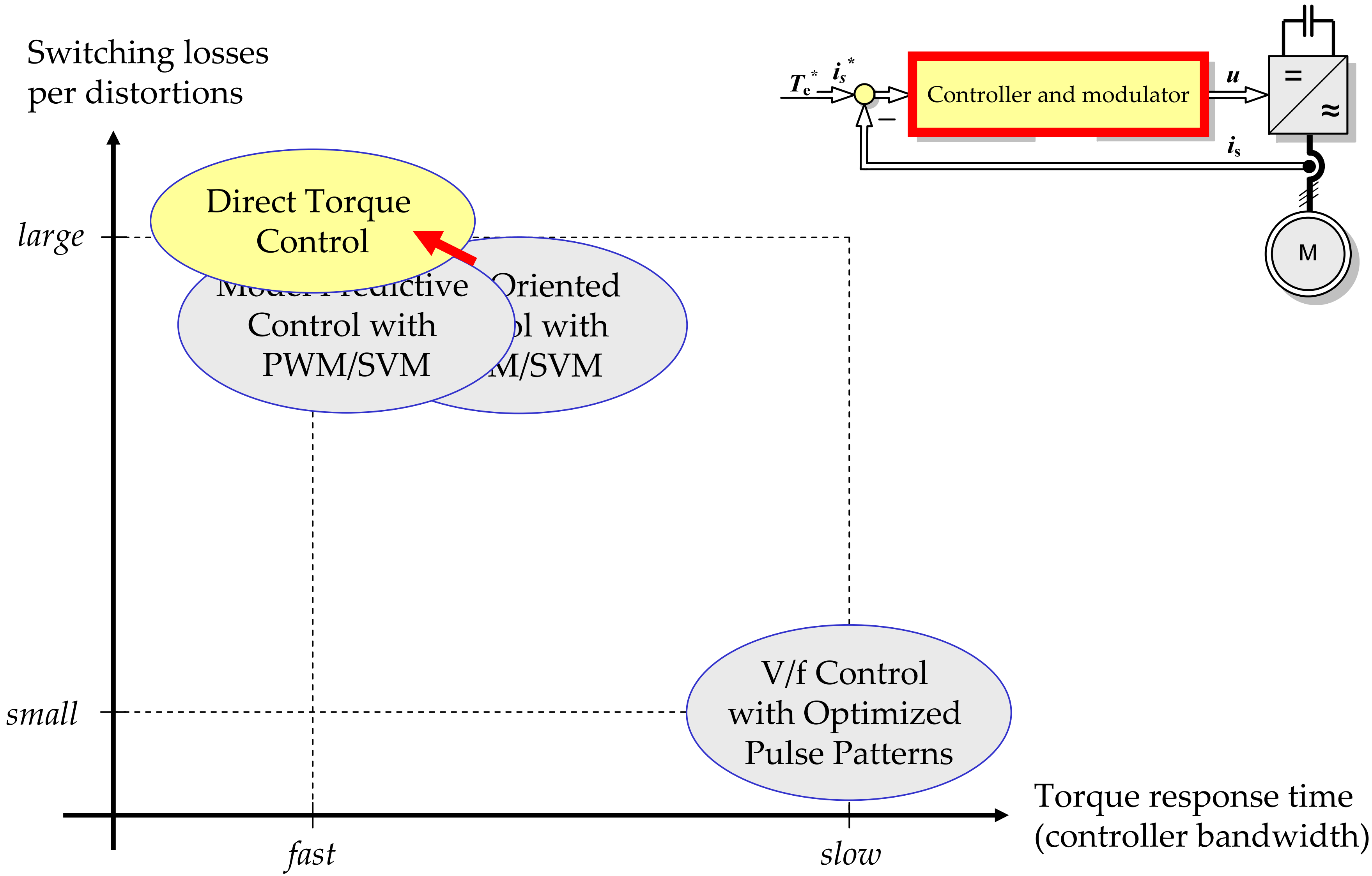

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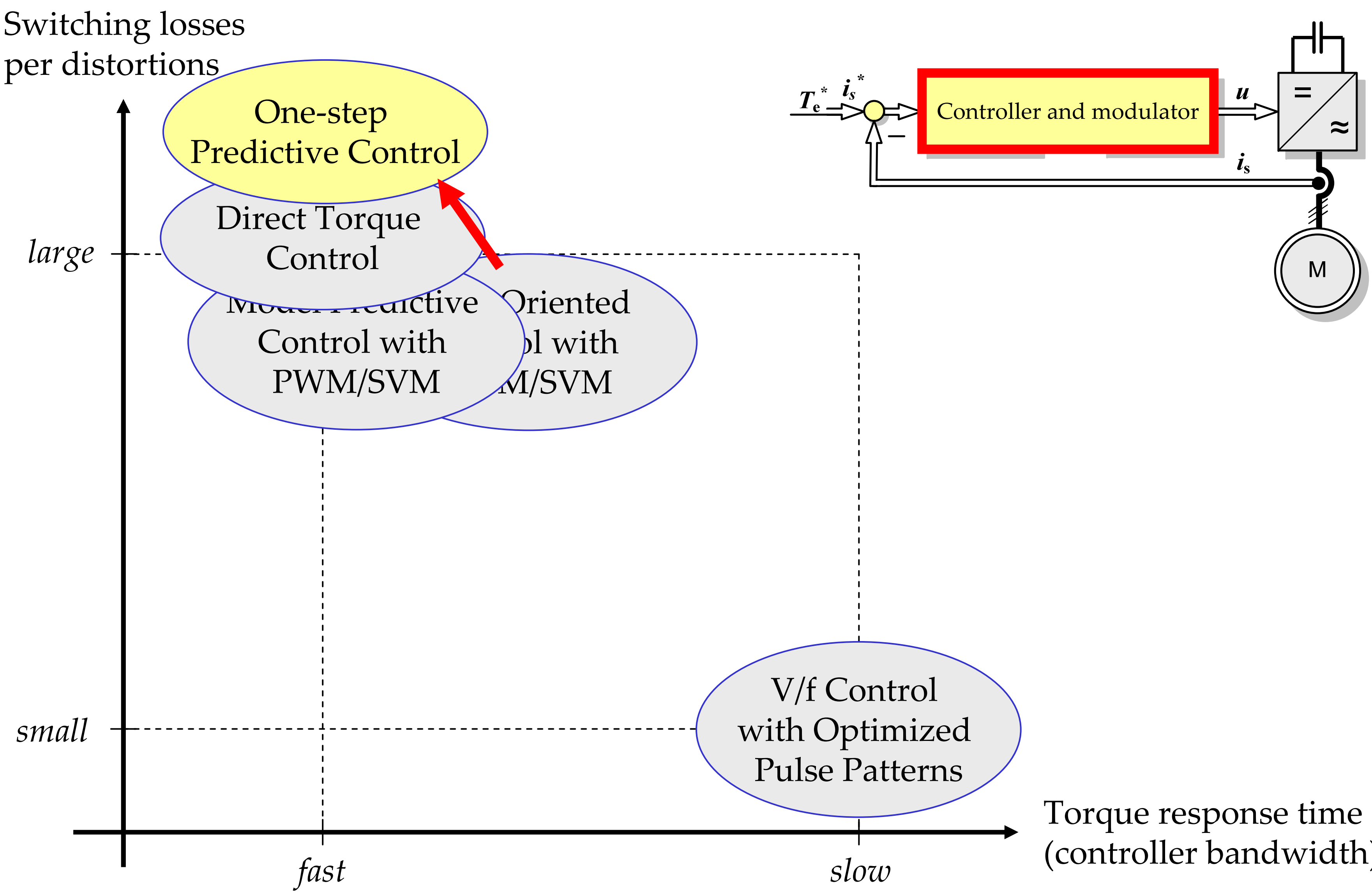
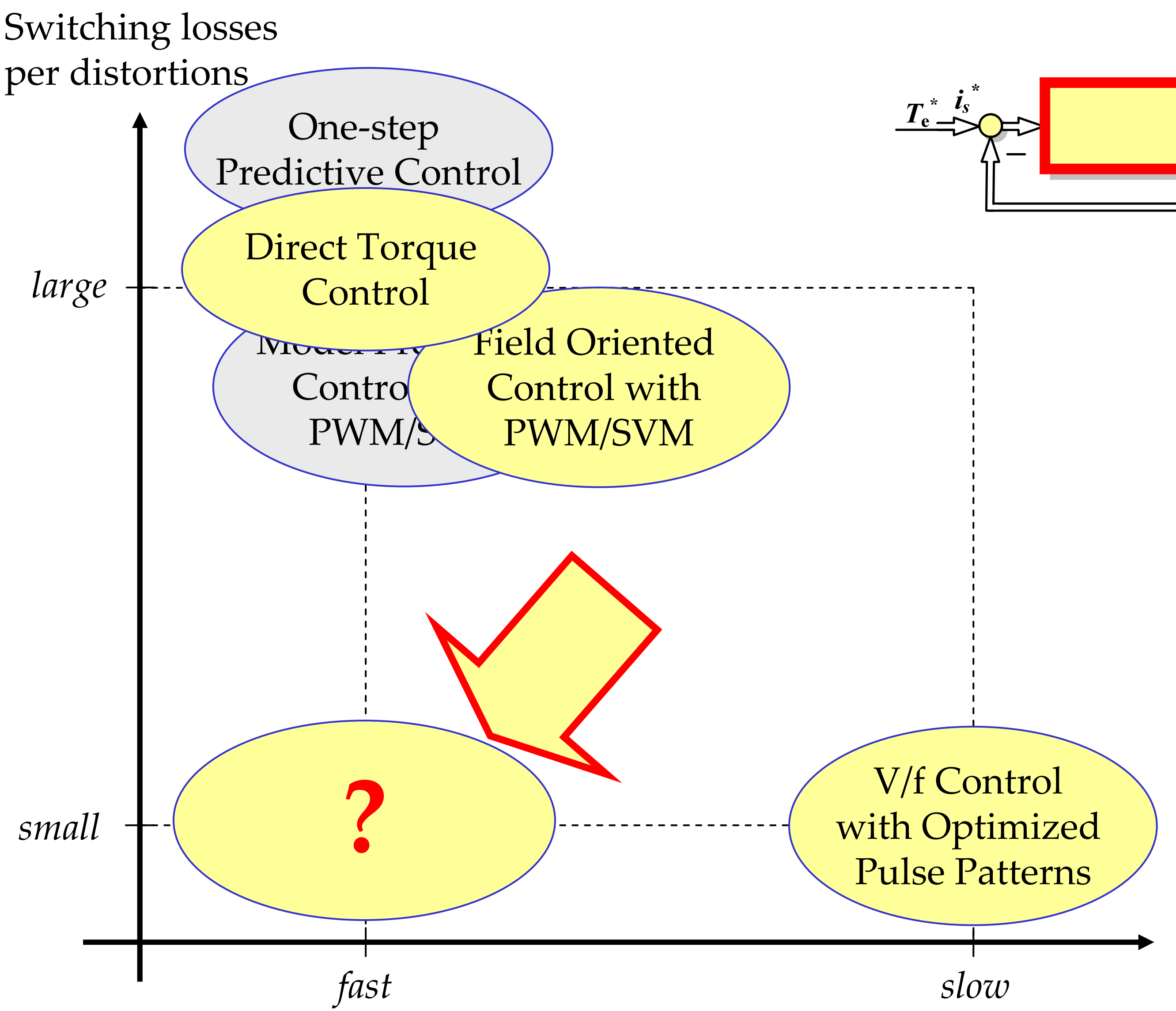
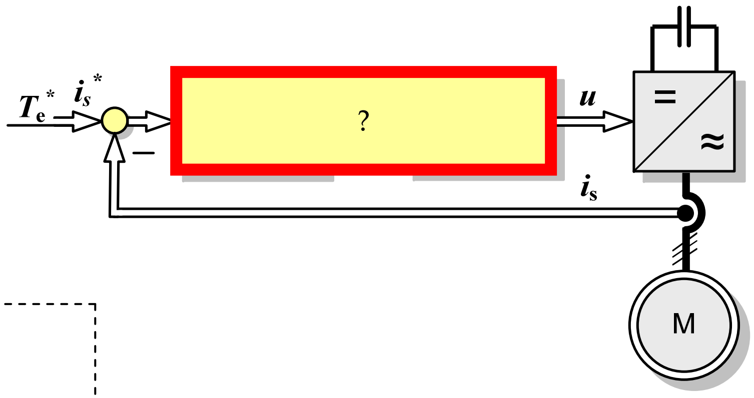
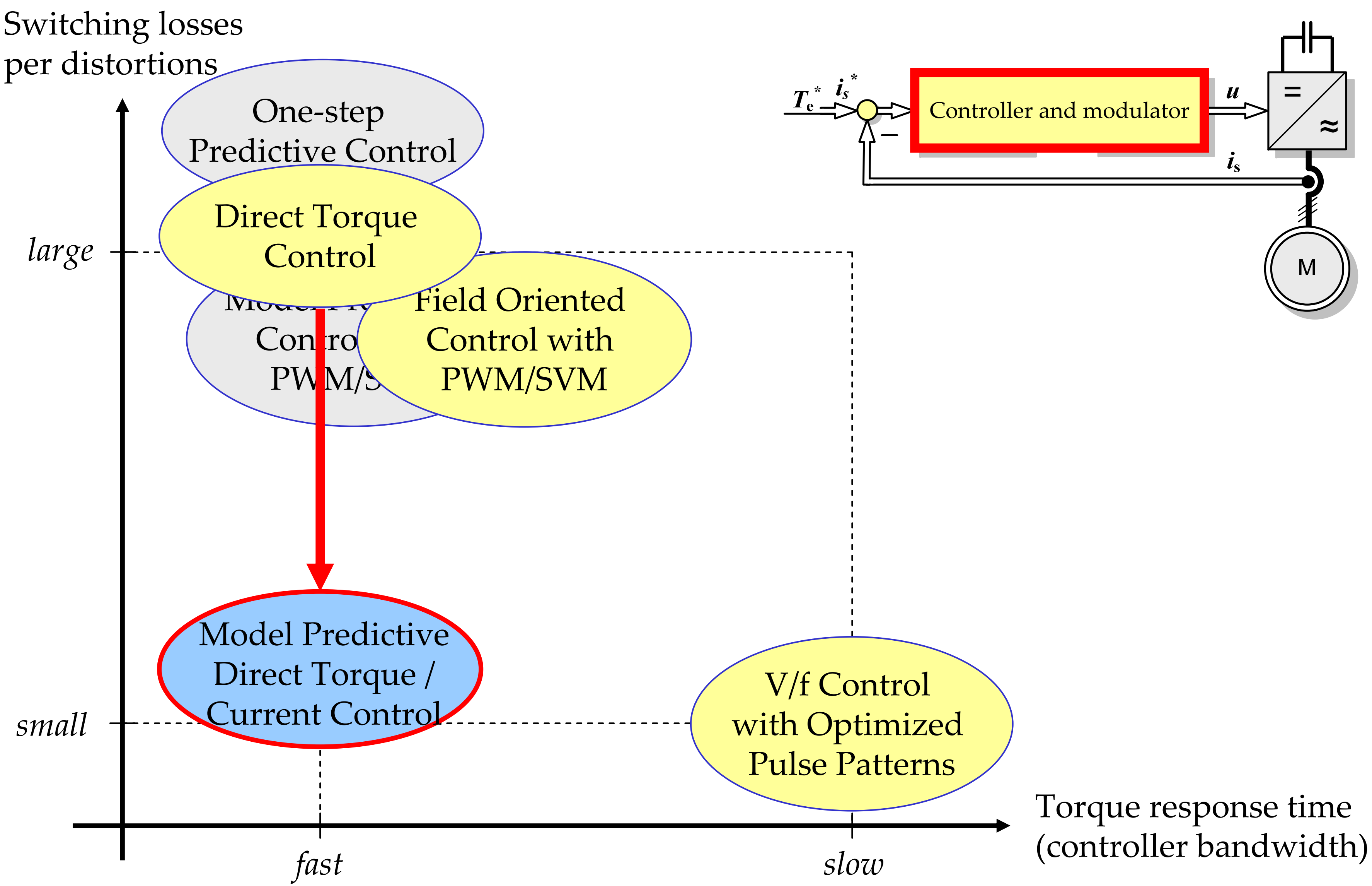


Control and Modulation: Goal





Control and Modulation: New Methods



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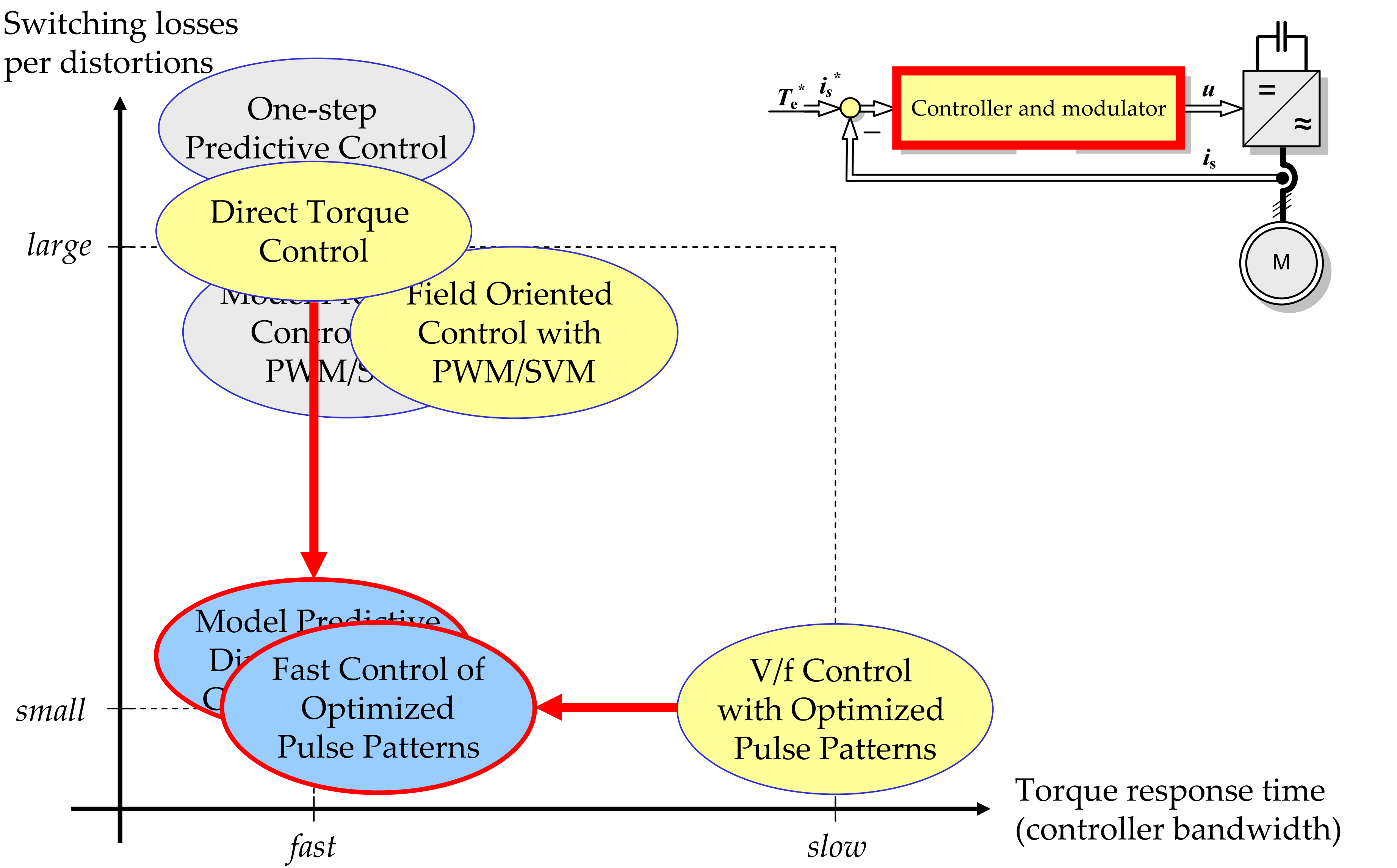


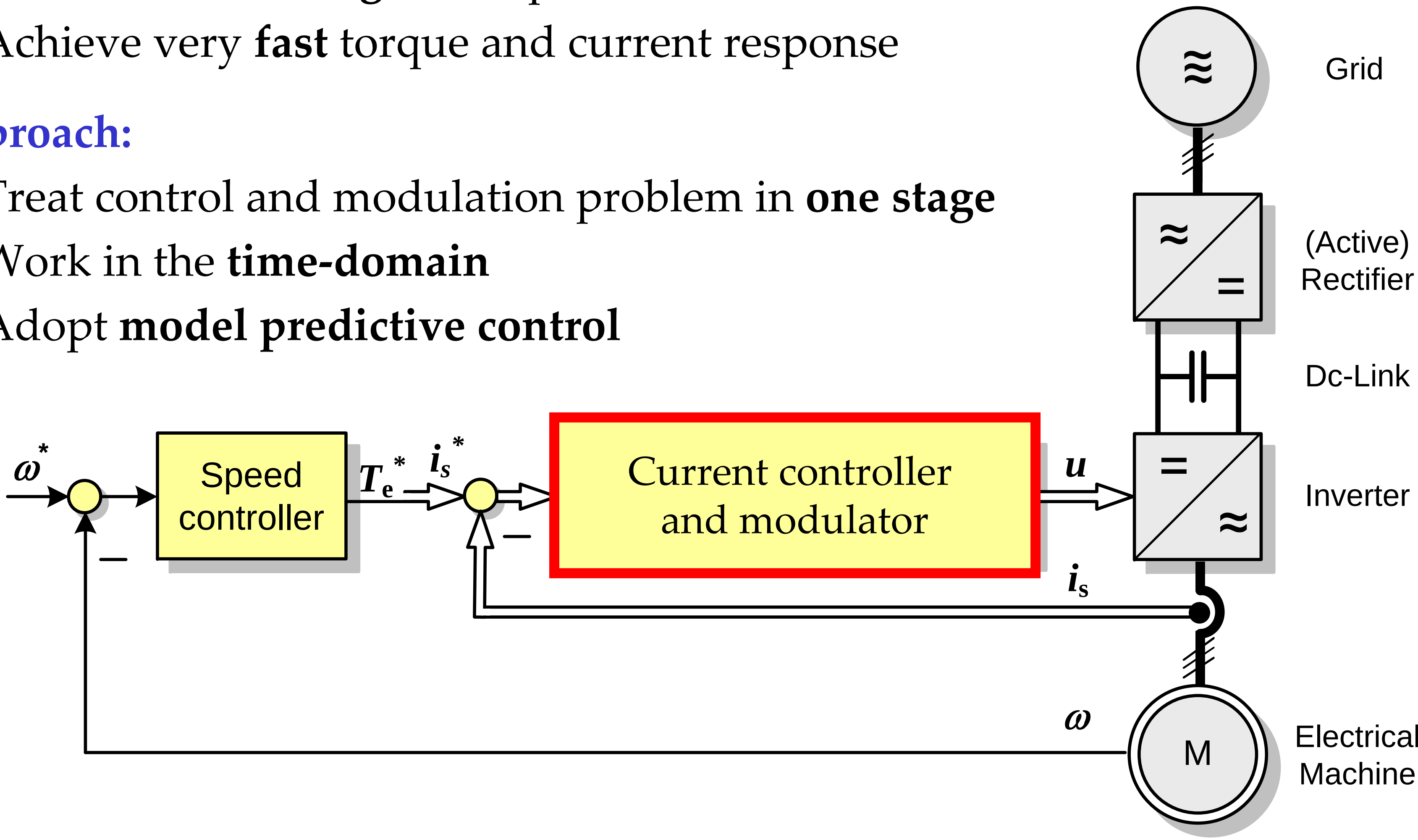
Control and Modulation: New Methods

Goal: Fully utilize capability of drive hardware

- Minimize **switching losses** per **distortions**
- Achieve very **fast** torque and current response

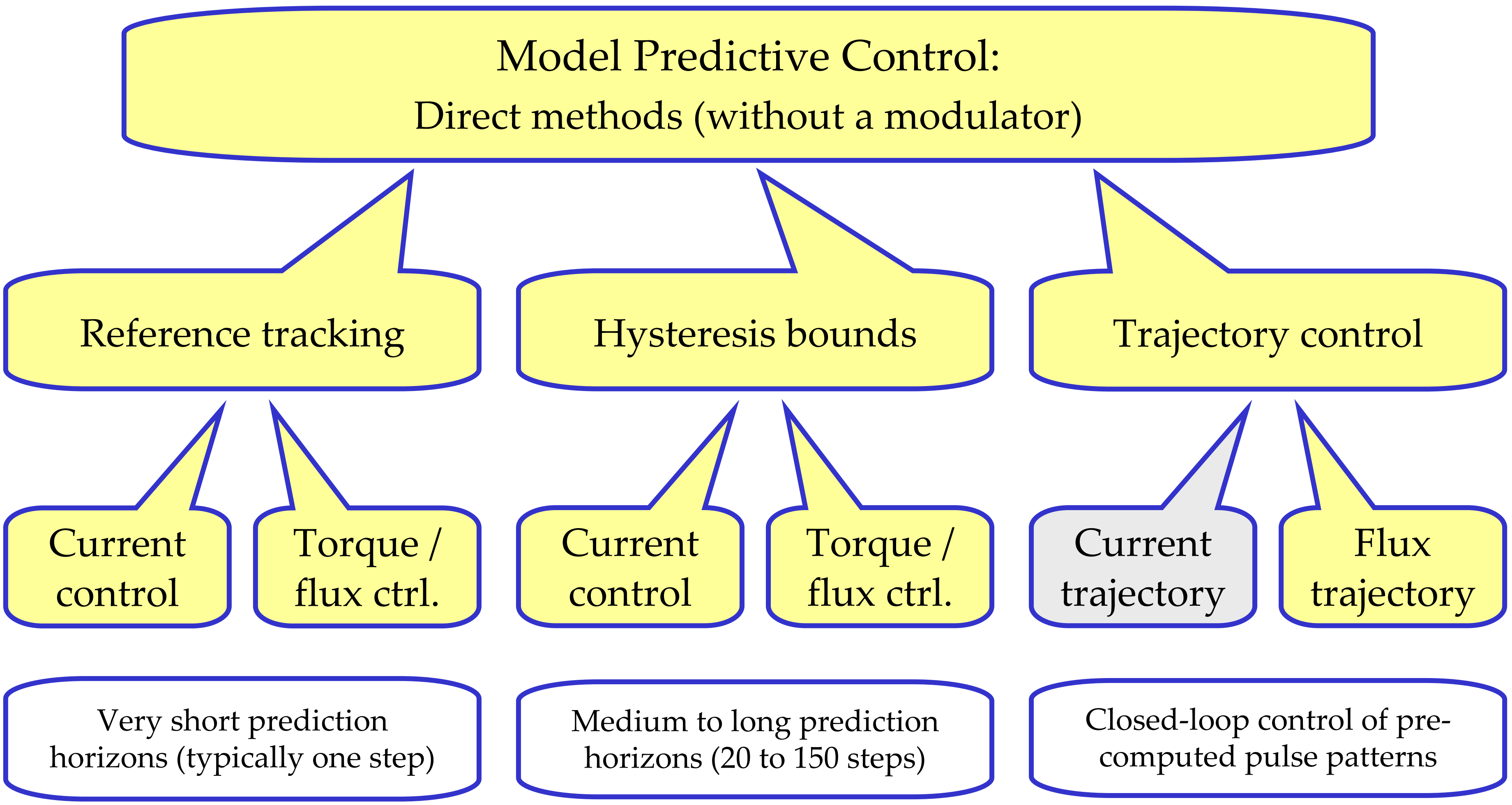
Approach:

- Treat control and modulation problem in **one stage**
- Work in the **time-domain**
- Adopt **model predictive control**



Model Predictive Control
for MV Electrical Drives

Classification of MPC Schemes for Electrical Drives



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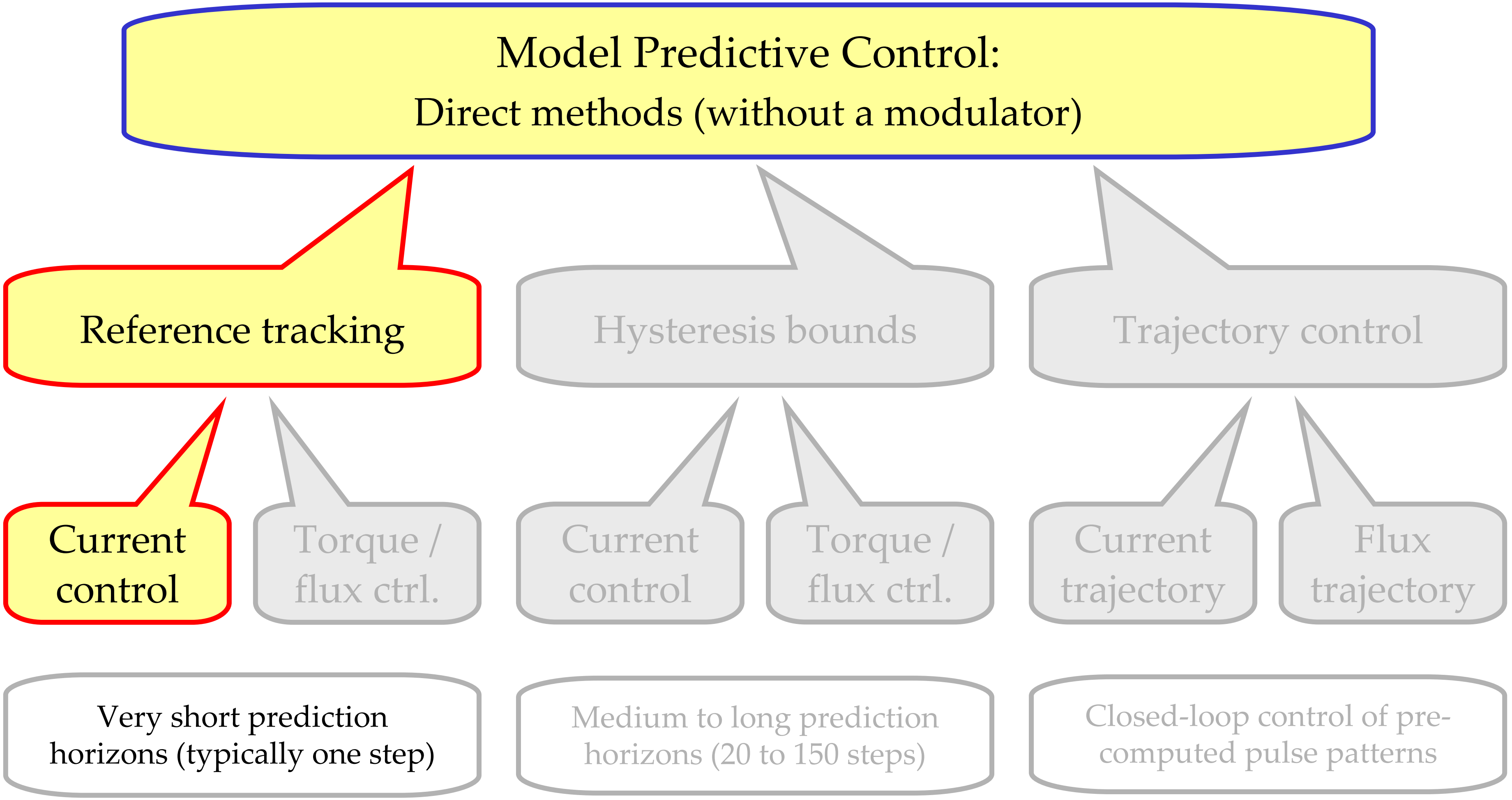
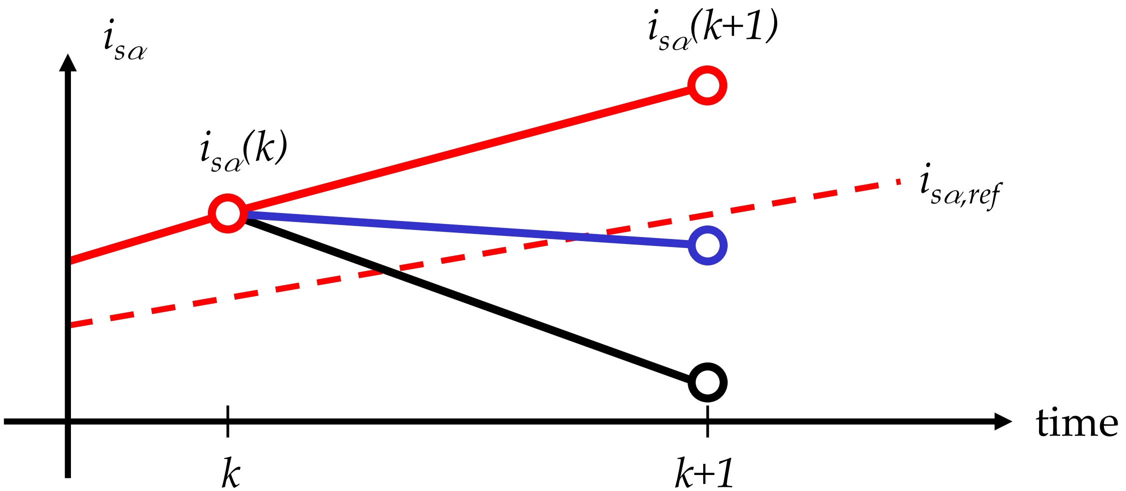
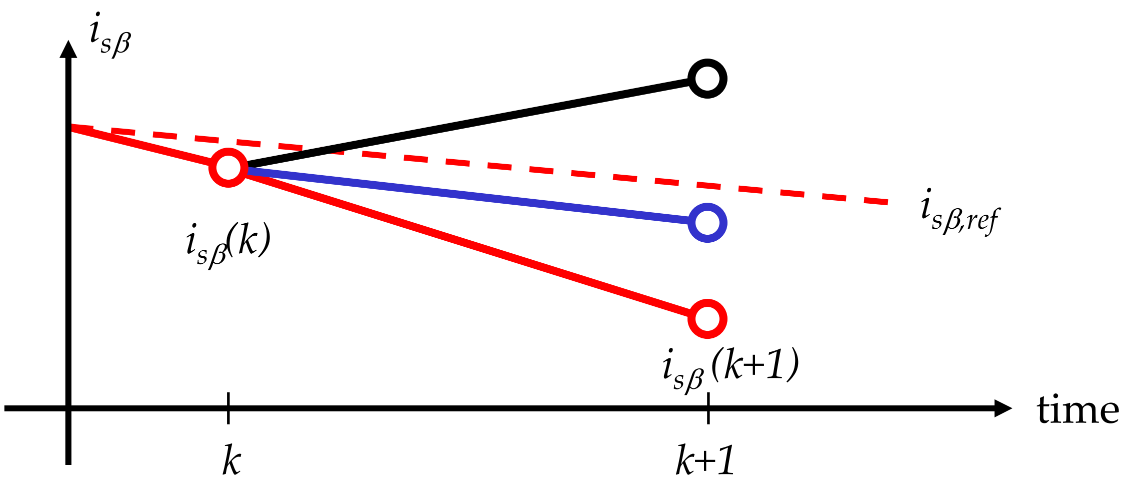


One-Step Predictive *Current* Control





Algorithm

- Enumerate all 27 switch transitions
- Predict currents at k+1
- Choose switch transition with minimal current error at k+1

One-Step Predictive *Current* Control

Performance Index: $J^*(x(k)) := \min_{u_k} \underbrace{||i_e(k+1)||_1}_{\text{Deviation from current reference}} + \lambda_n \underbrace{||\Delta u(k)||_1}_{\text{Penalty on switching effort}}$

Constraints

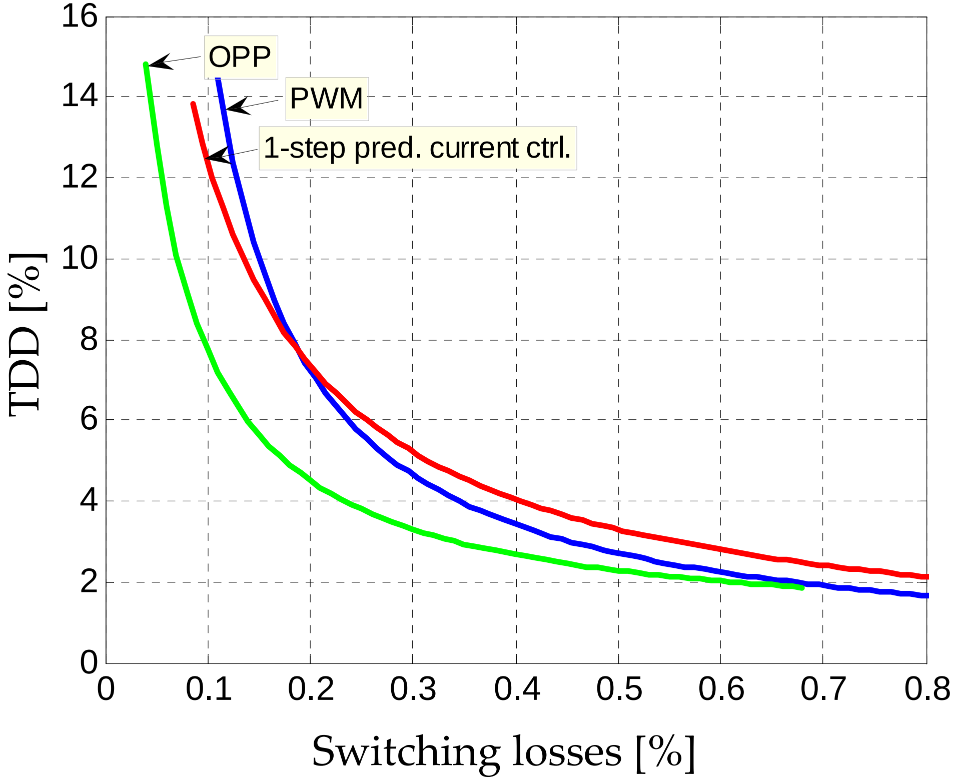
$$\begin{cases} i_s(k+1) = A_1 i_s(k) + A_2 \psi_r(k) + B u(k), & \text{Model of machine} \\ u(k) \in \{-1, 0, 1\}^3, & \text{Discrete-valued switch positions} \\ u(k) \in \mathcal{U}(u(k-1)) & \text{Restrictions on switch transitions} \end{cases}$$

Main features:

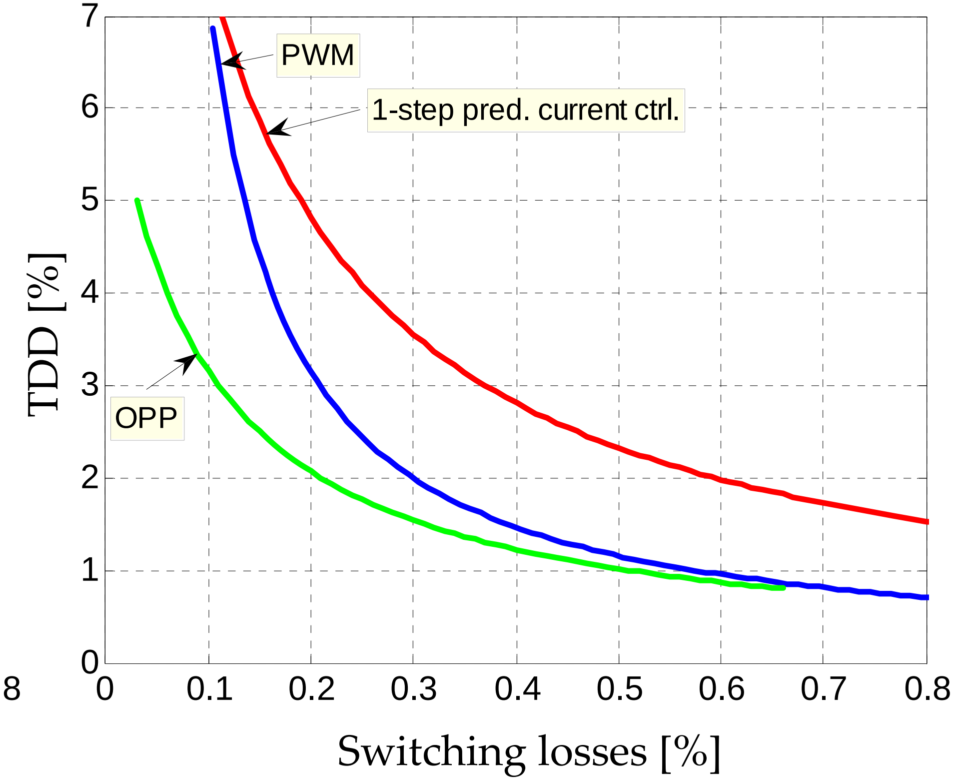
- prediction **horizon** is one
- machine **model**
- **minimization** of switching effort (e.g. frequency)
- λ_n => trade-off between tracking accuracy and switching
- conceptually and computationally **very simple**

One-step Predictive *Current* Control

Current TDD vs switching losses

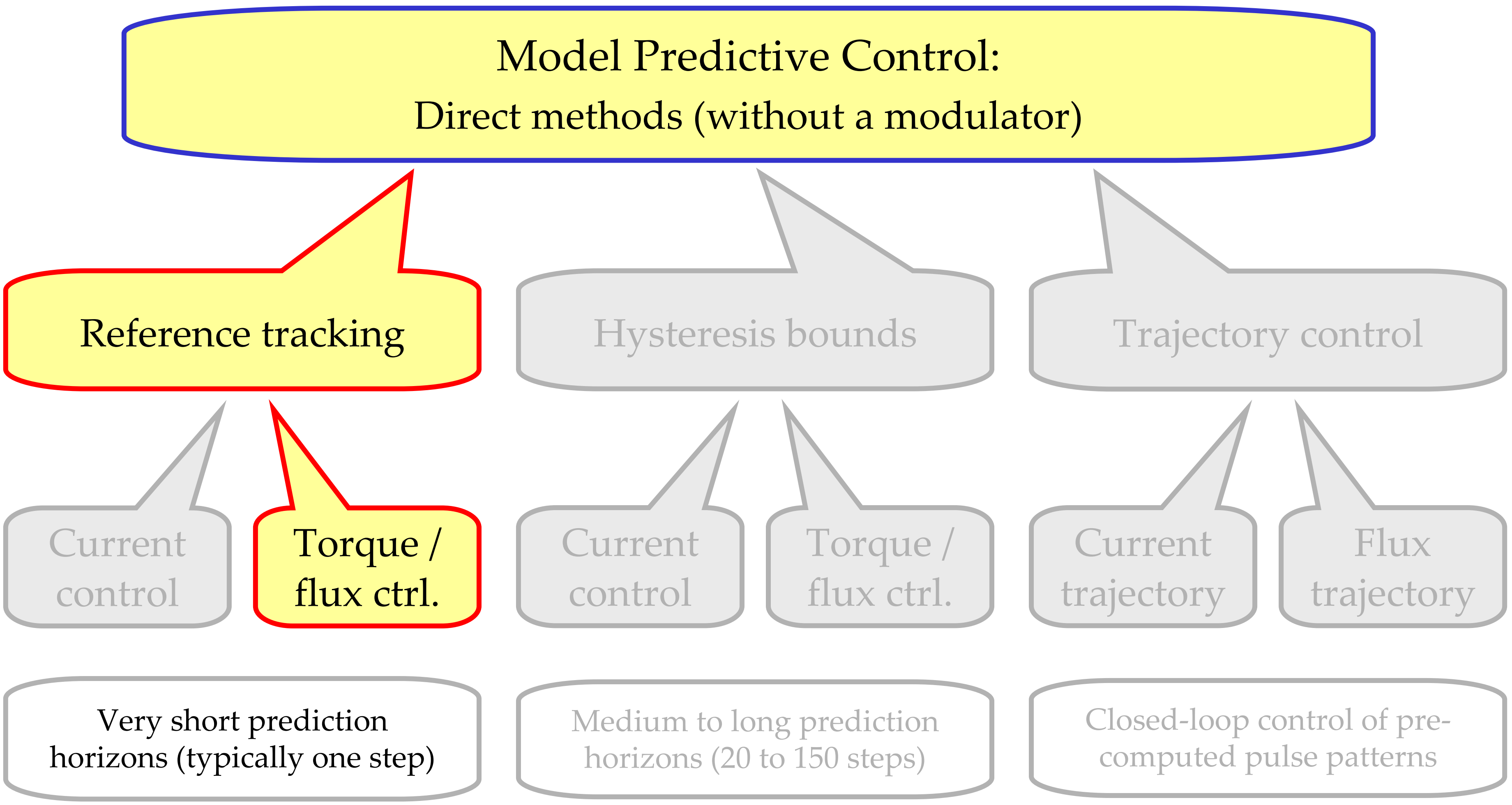


Torque TDD vs switching losses



- Current THD similar to PWM
- Torque THD significantly worse than PWM

Classification of MPC Schemes for Electrical Drives



One-step Predictive *Torque* Control

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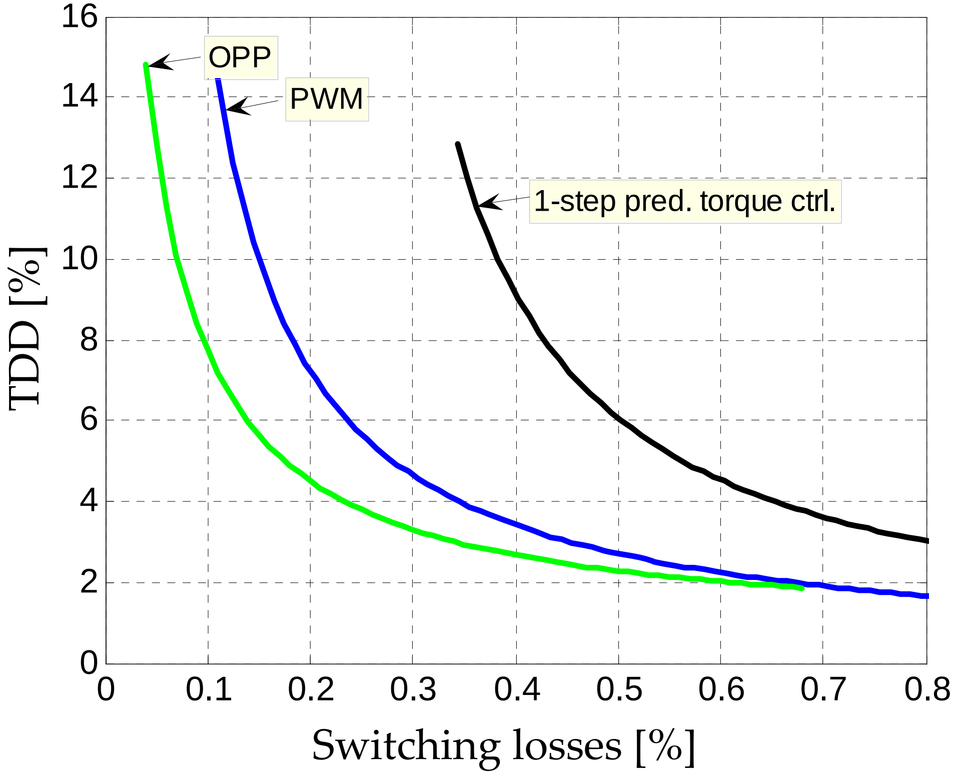

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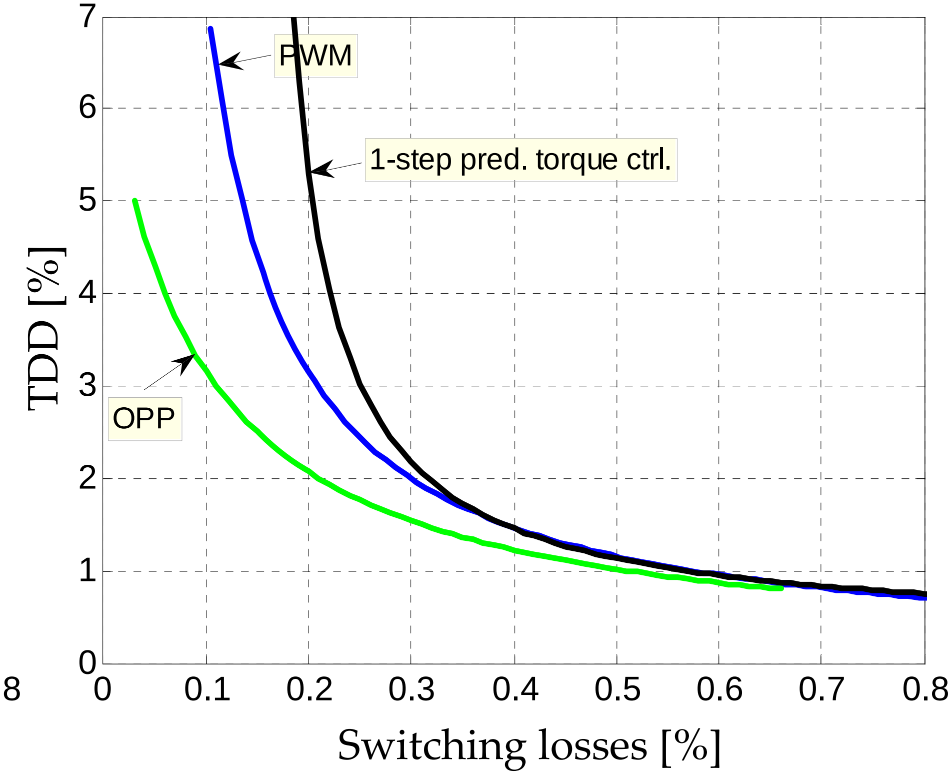

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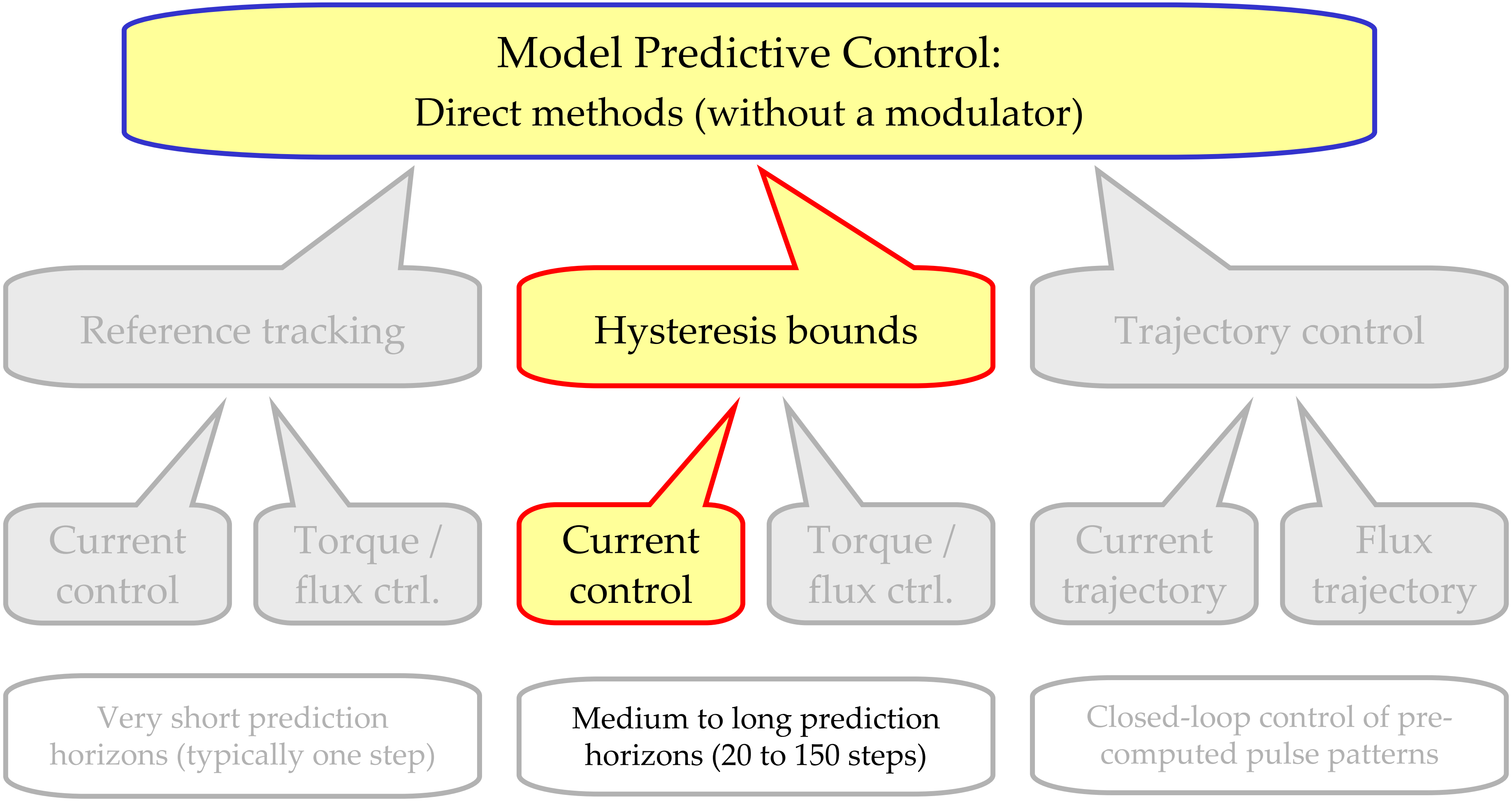


Model Predictive Direct *Current* Control: *Step 1*

Predict current trajectories for (all) possible **switching sequences**

Key ingredients:

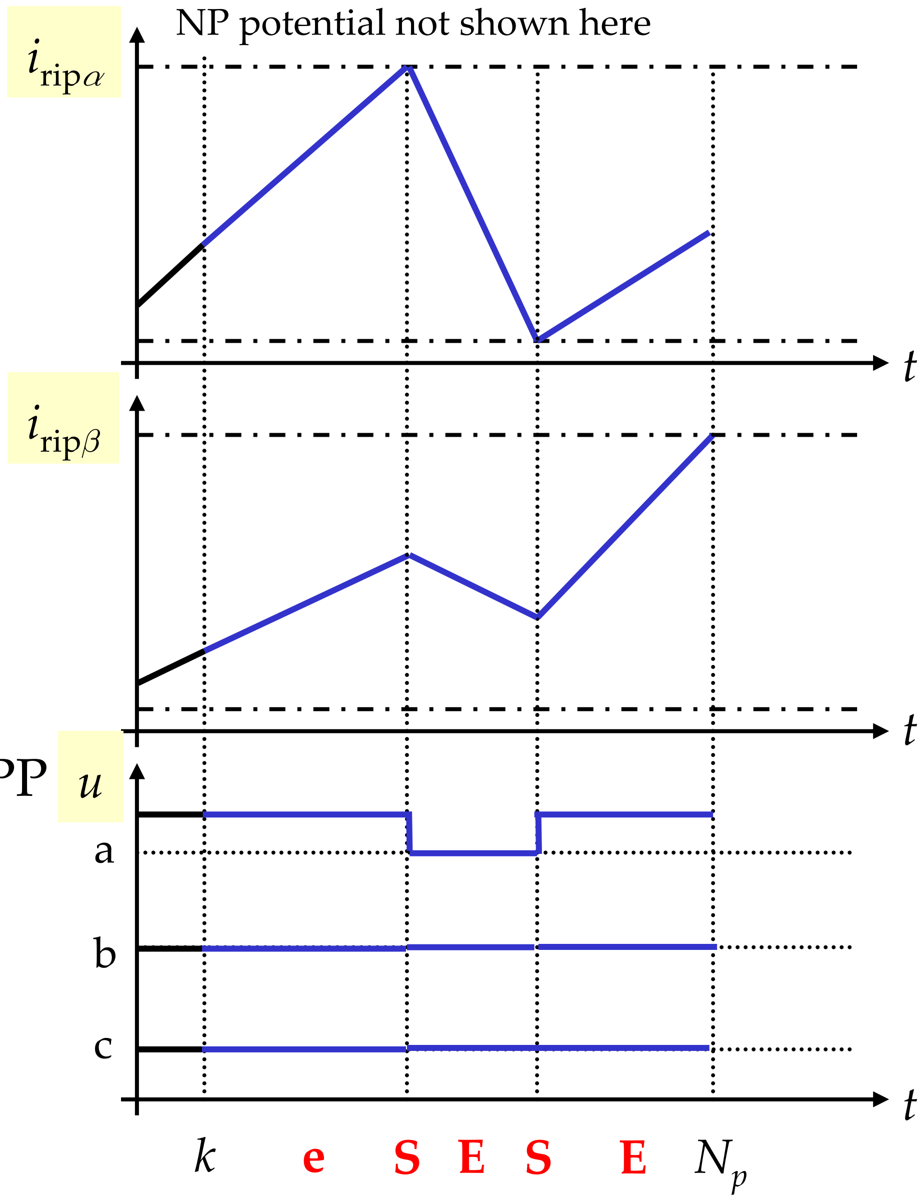
- Drive model
- Extrapolation

Switching horizon, e.g. '**eSESE**'

- **S**: consider all switch transitions
- **E**: extrapolate/extend currents and NPP
- **e**: optional 'E'

Prediction horizon N_p

Typically 50..150 time-steps



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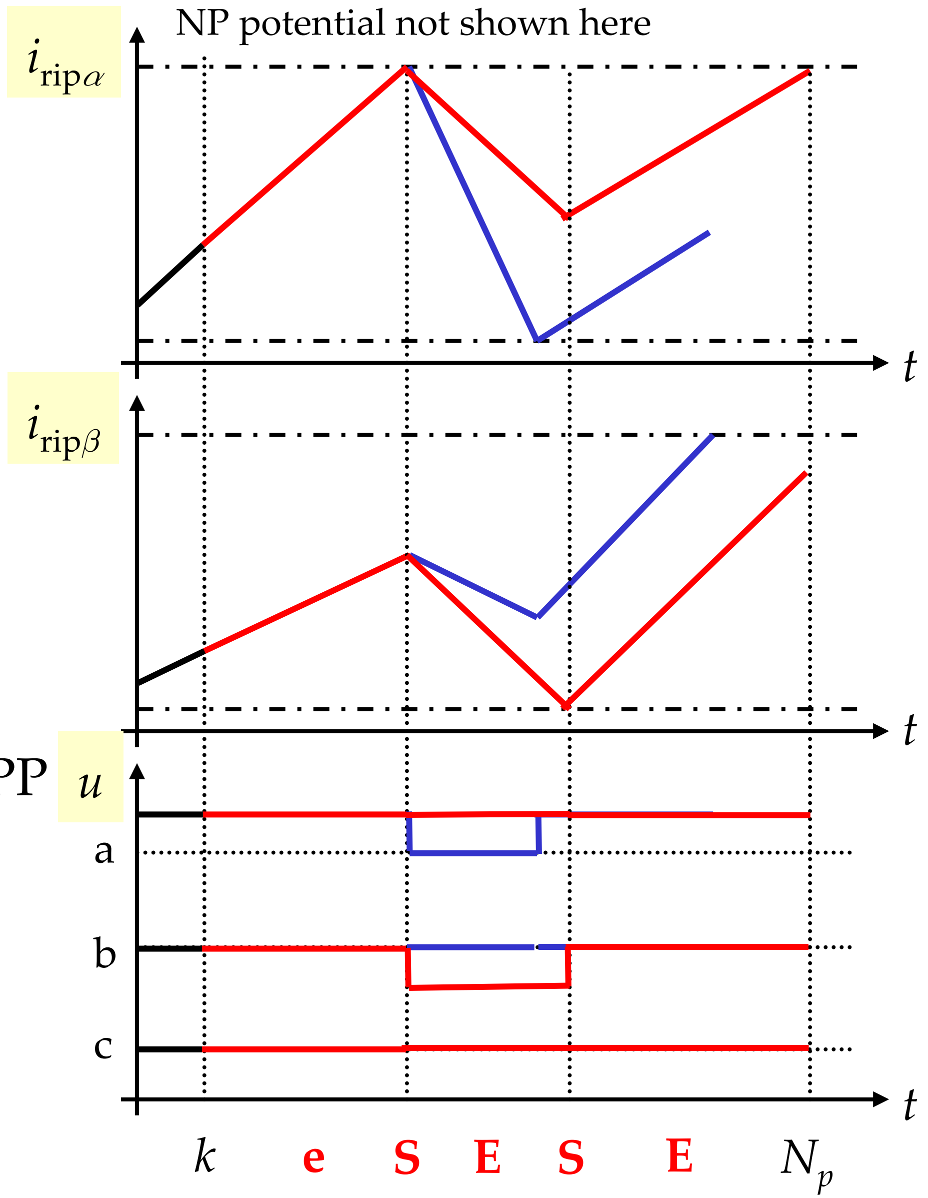
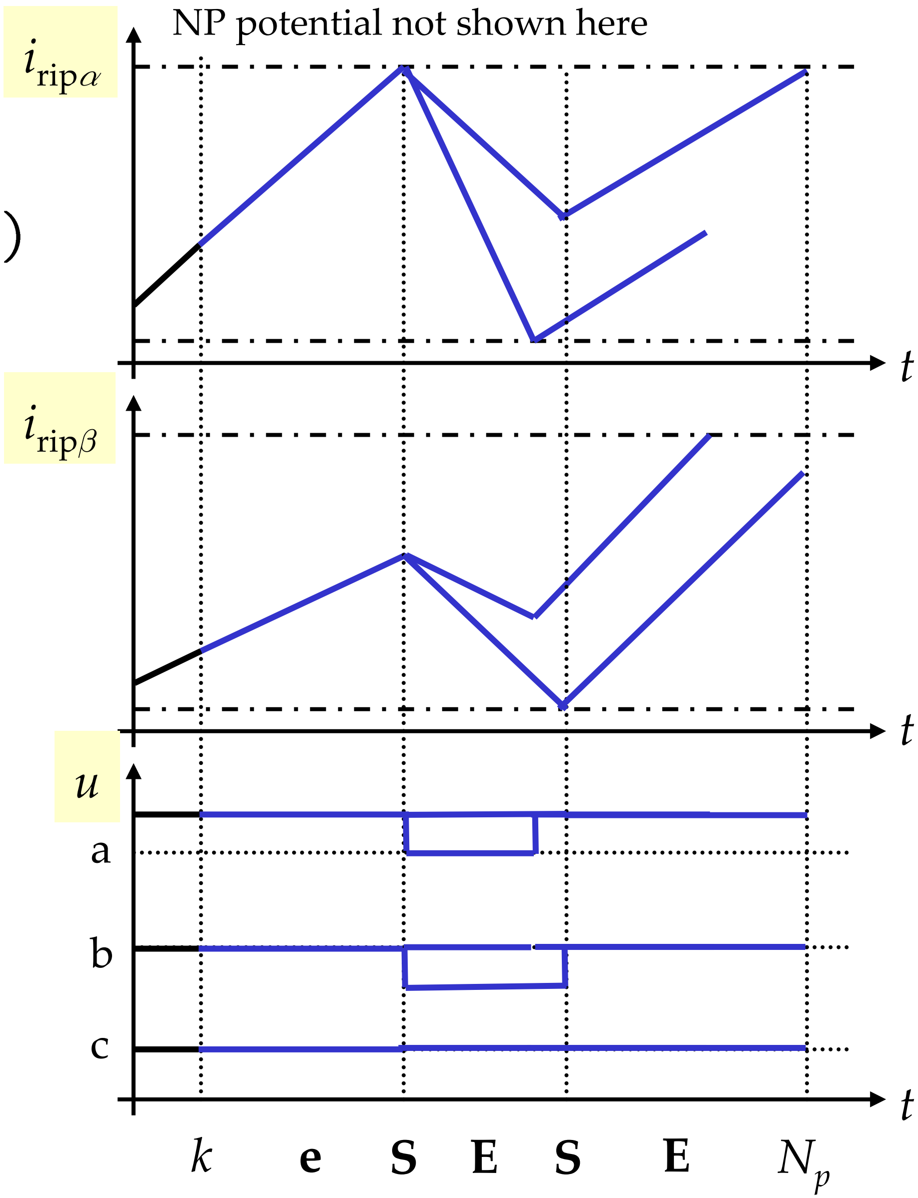


Model Predictive Direct *Current* Control: *Step 2*

Evaluate and **minimize sw. losses**

$$J^*(x) := \min_U \frac{1}{N_p} \sum_{k=0}^{N_p-1} E_{\text{loss}}(x_k, u_k)$$

=> Optimal **switching sequence** U



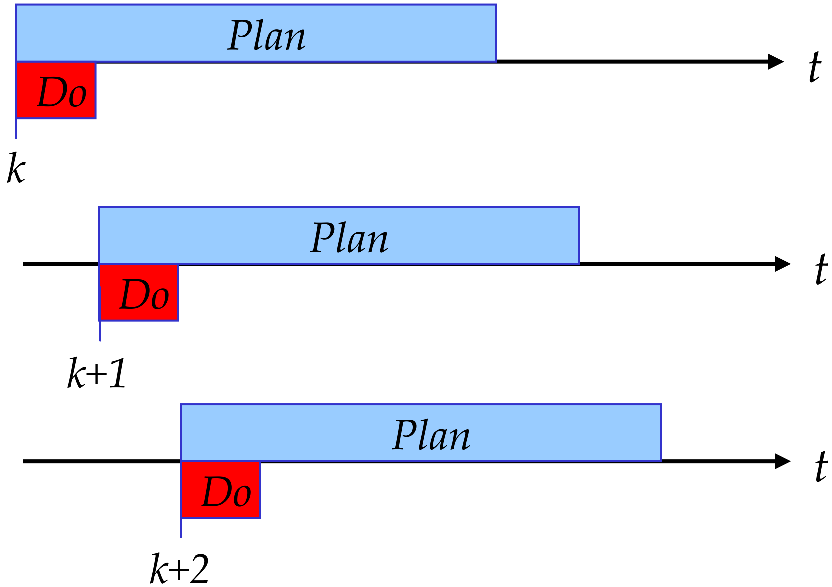
Model Predictive Direct *Current* Control: *Steps 2 & 3*

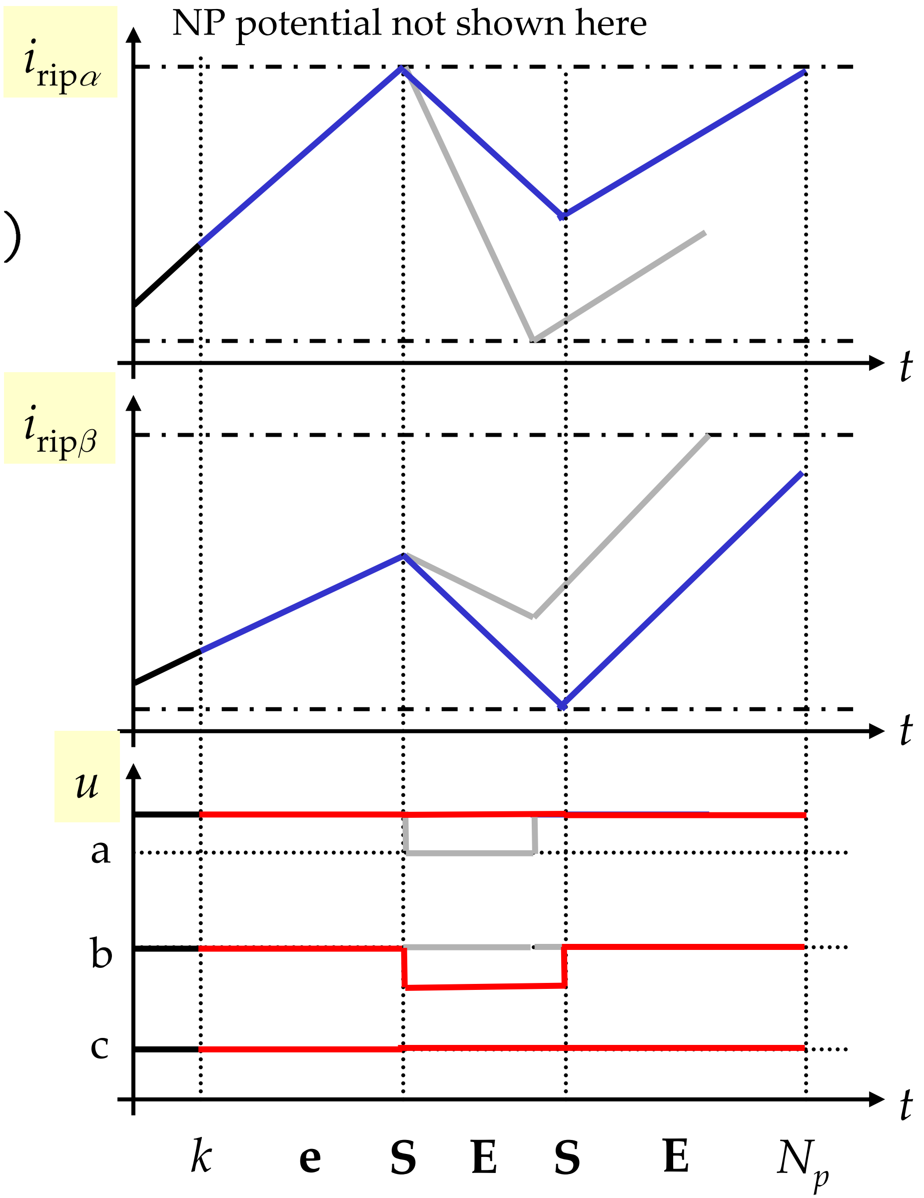
Evaluate and **minimize sw. losses**

$$J^*(x) := \min_U \frac{1}{N_p} \sum_{k=0}^{N_p-1} E_{\text{loss}}(x_k, u_k)$$

=> Optimal **switching sequence** U

Apply only the **first element** of U





Model Predictive Direct *Current* Control

Performance Index: $J^*(x) := \min_U \underbrace{\frac{1}{N_p} \sum_{k=0}^{N_p-1} E_{\text{loss}}(x_k, u_k)}_{\text{Short-term avg. switching losses (power)}}$

Constraints

$\forall k = 0, \dots, N-1$

$$\begin{cases} x_{k+1} = f(x_k, u_k), & \text{Model of machine and inverter} \\ y_k = g(x_k), & \text{Outputs (currents and NP)} \\ y_k \in \mathcal{Y}, & \text{Bounds on currents and NP} \\ u_k \in \{-1, 0, 1\}^3, & \text{Discrete-valued switch positions} \\ u_k \in \mathcal{U}(u_{k-1}) & \text{Restrictions on switch transitions} \end{cases}$$

Main features:

- short **switching** horizon but long **prediction** horizon
- **models** of machine, inverter and losses
- **minimization** of switching losses
- **receding horizon** policy
- **tailored** online solution approach

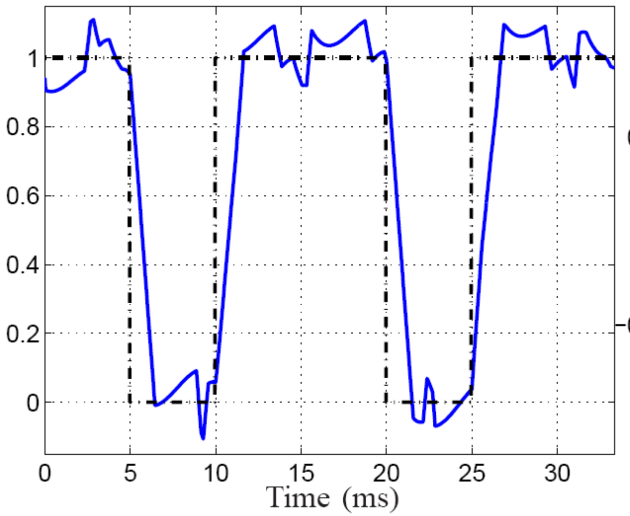
Performance during Transients

3-level NPC inverter with 2MVA induction machine

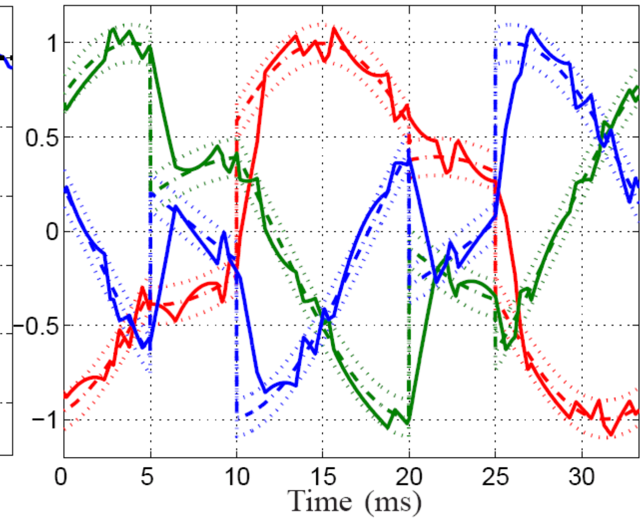
Speed: w_e=0.6 pu

Torque: reference steps between T=1 and 0 pu

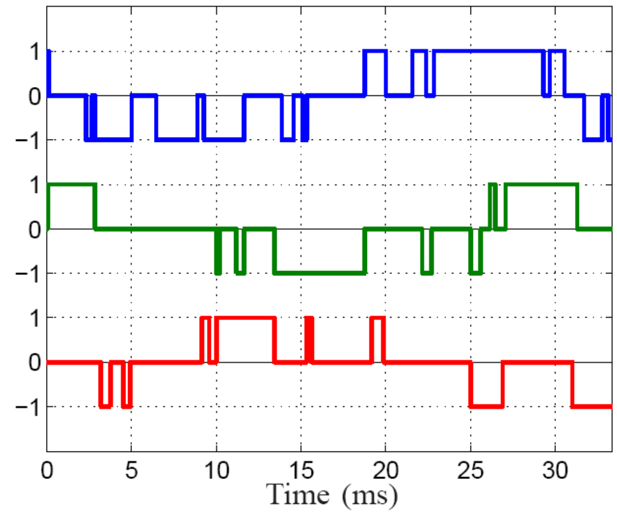
Torque



Stator currents



Switch positions



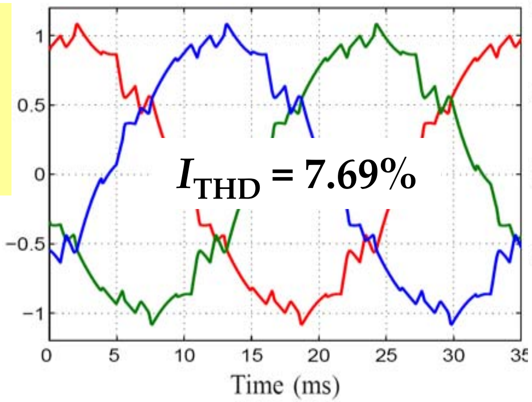
Torque (current) response time of **2 ms**

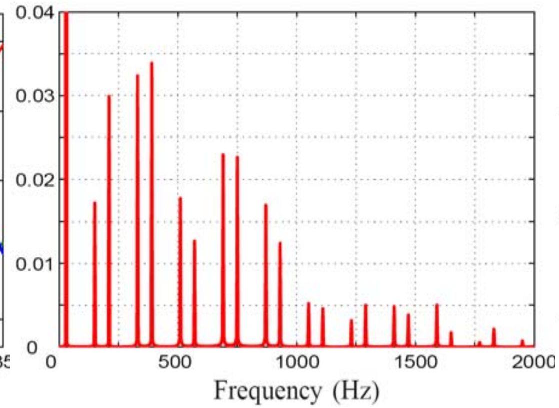
Performance at Steady-State

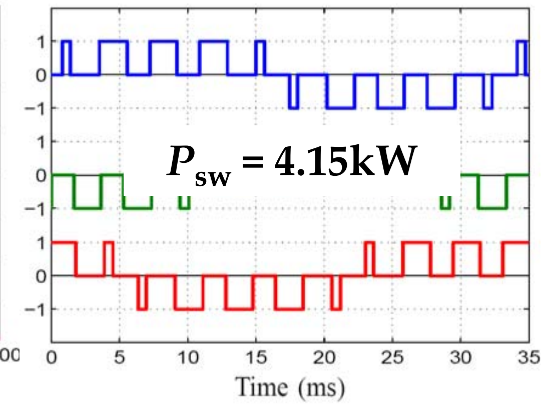
3-level NPC inverter with 2MVA ind. machine
w_e=0.6 pu, T_e=1 pu

	Current	Current spectrum	Switch positions

FOC with PWM and f_c=270 Hz

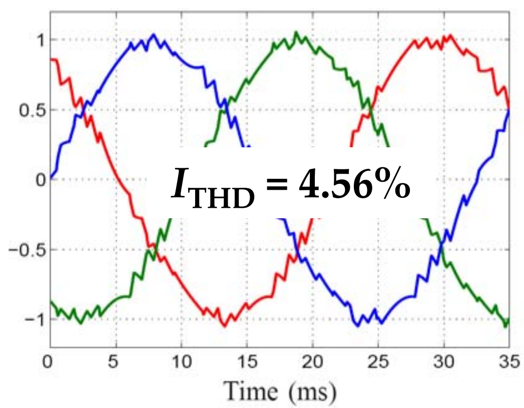


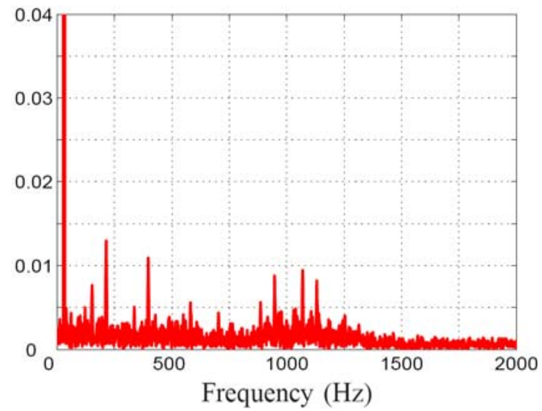


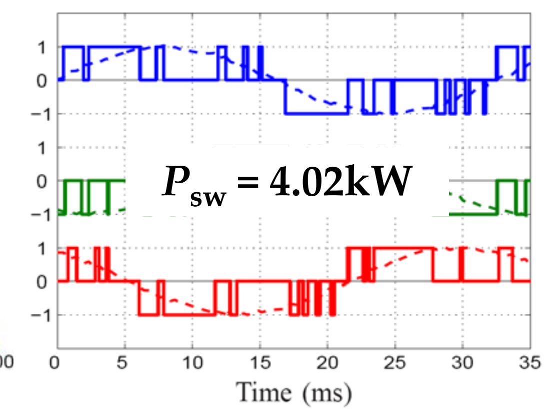


MPDCC ‘e(SE)³’

N_p =70





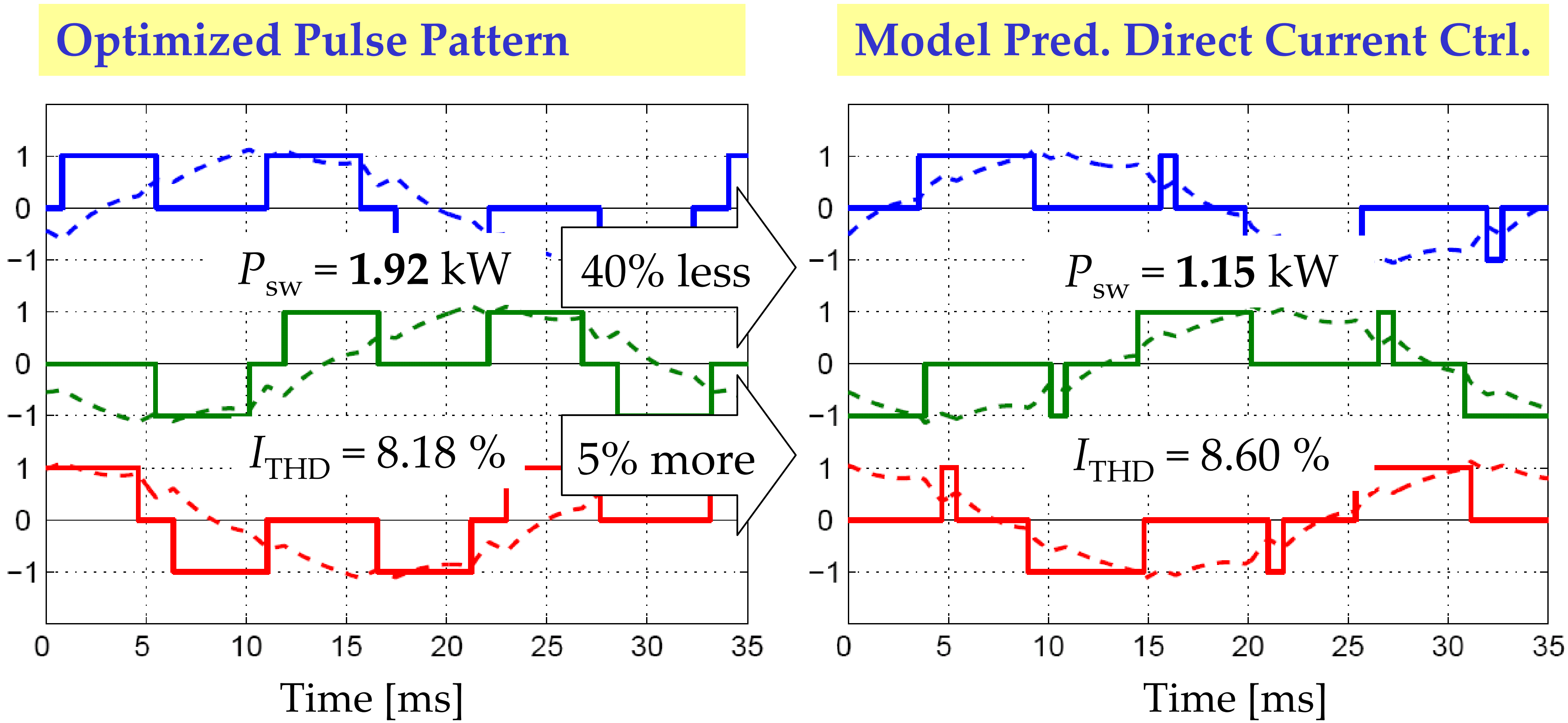


Current THD reduced by **40%** (for the same switching losses)

Similar to **optimal pulse patterns**

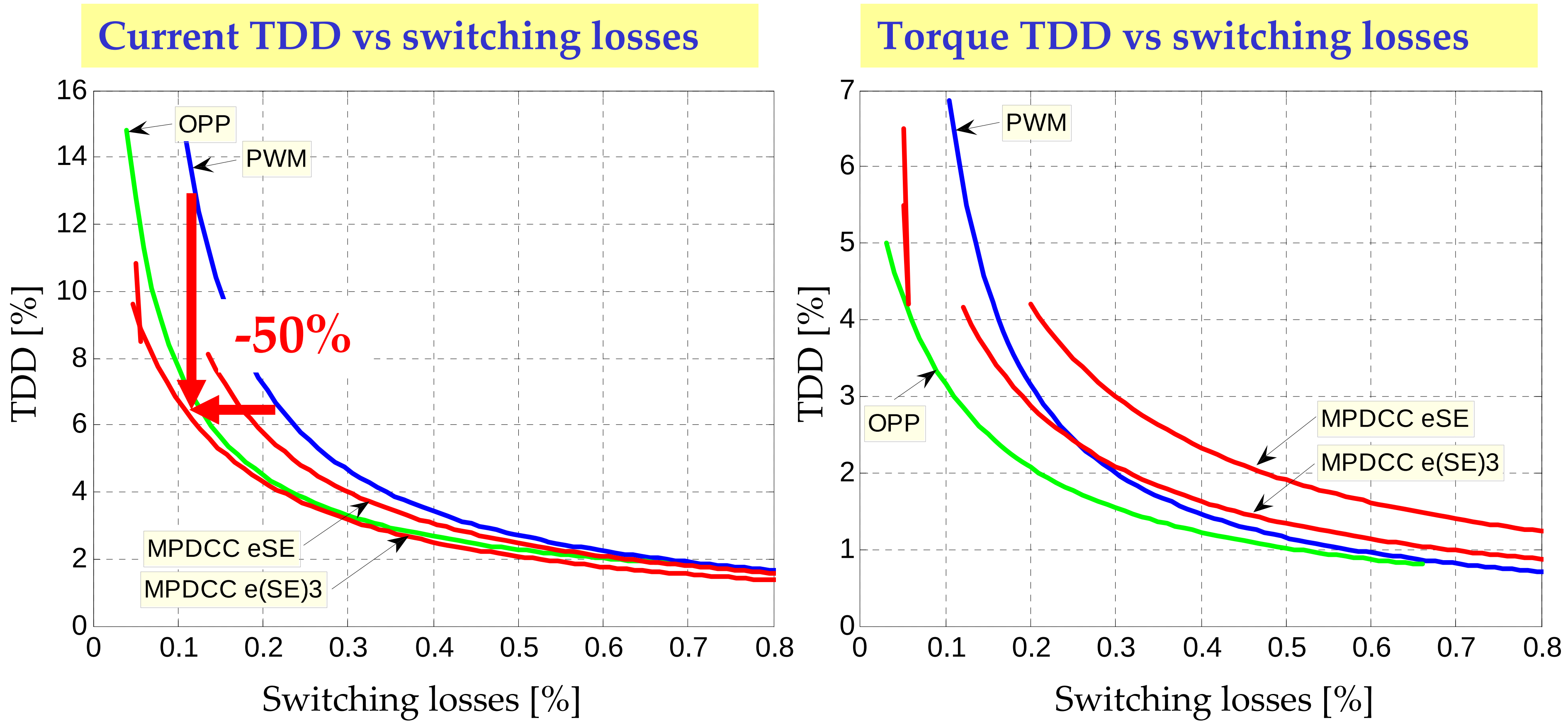
MPDCC outperforming OPP

3-level NPC inverter with 2MVA ind. machine
w_e=0.6 pu, T_e=1 pu



- OPPs: for a given switching *frequency*, minimize the current THD
- MPDCC: for a given current THD, minimize the switching *losses*

Model Predictive Direct *Current* Control

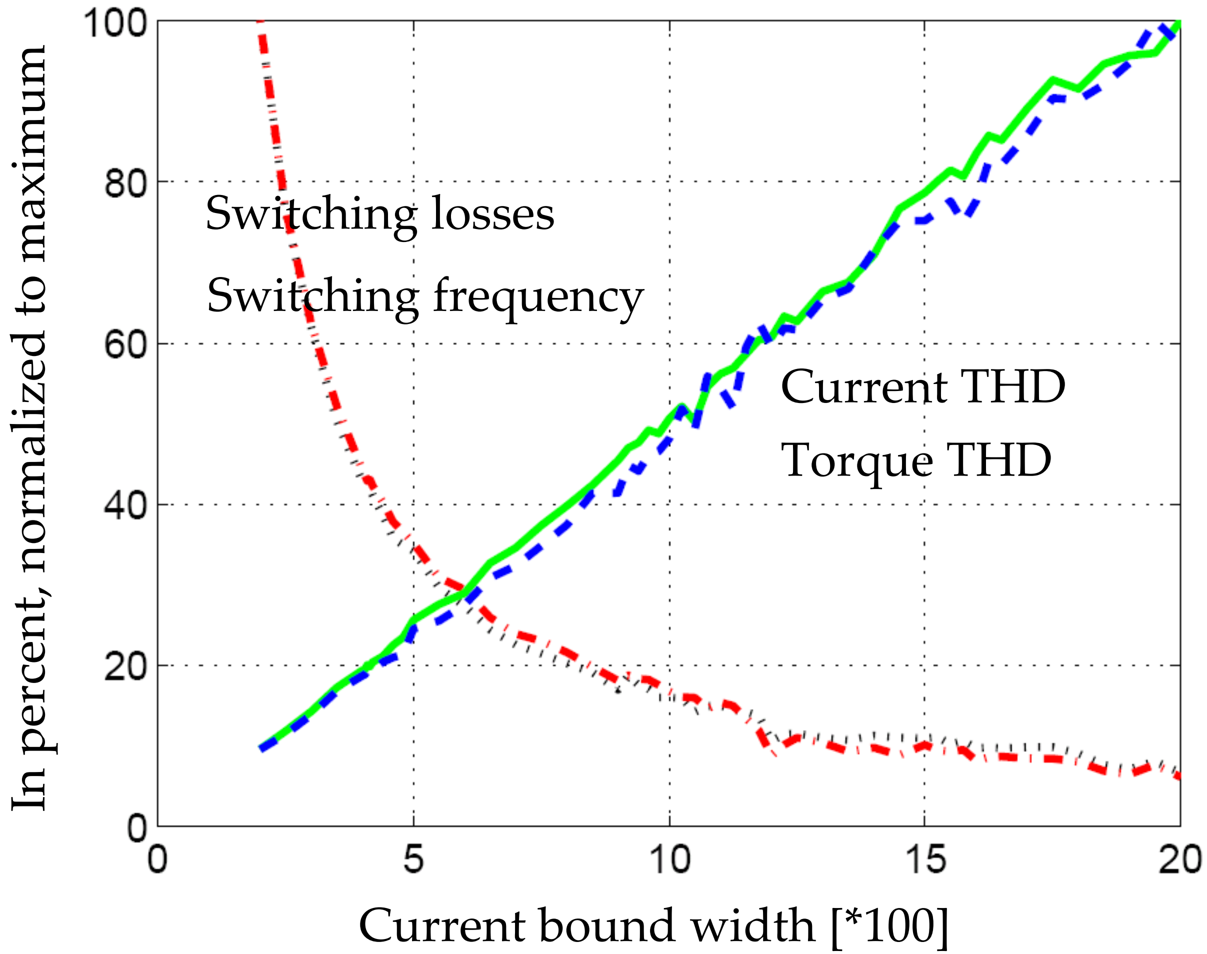


Long switching horizon eSESESE (50-150 steps):

- Current THD: better than with optimized pulse patterns
- Torque THD: similar to PWM

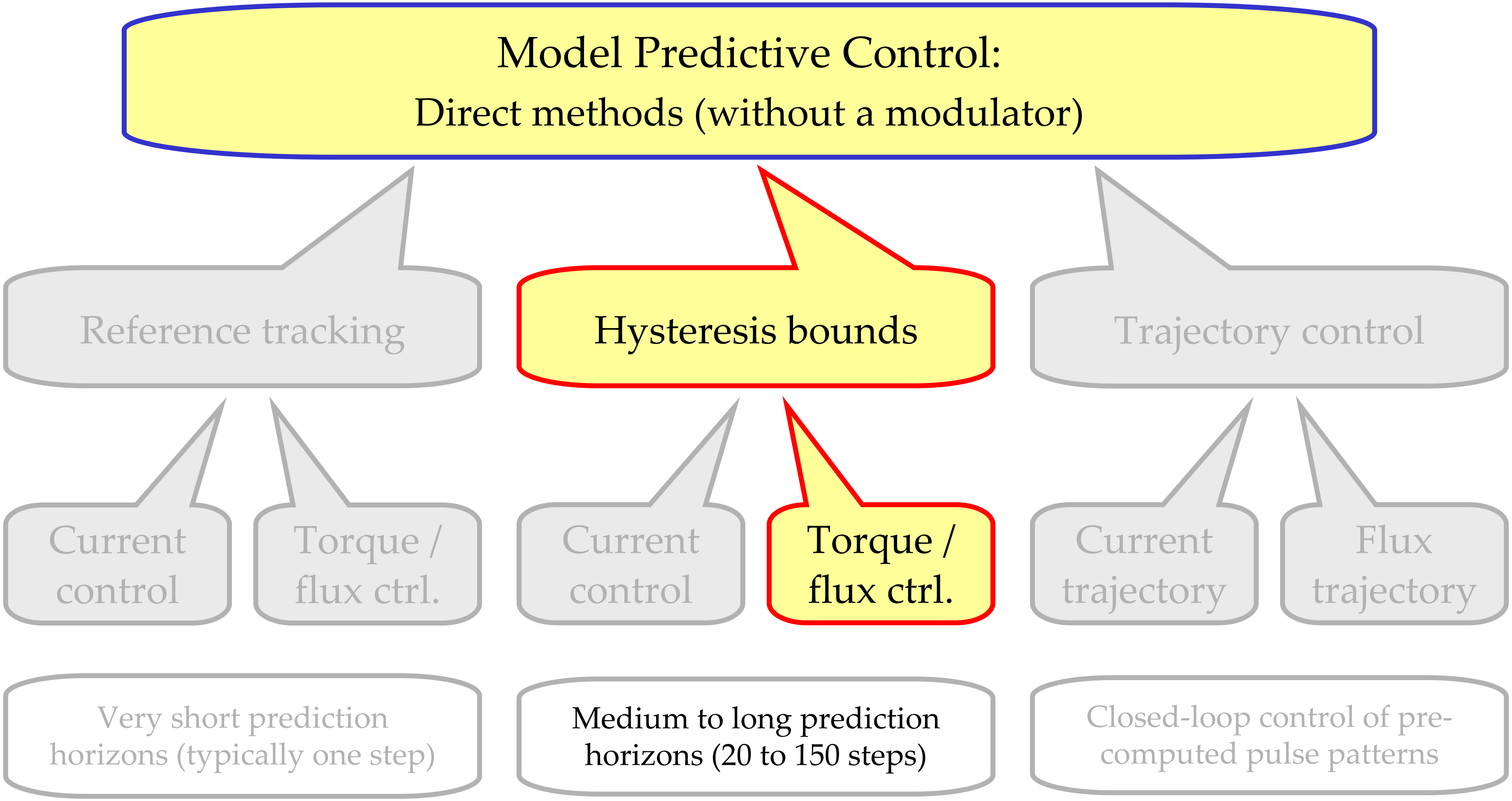
Tuning

3-level NPC inverter with 2MVA IM
w_e=0.6 pu, T_e=1 pu, MPDCC with 'eSE'

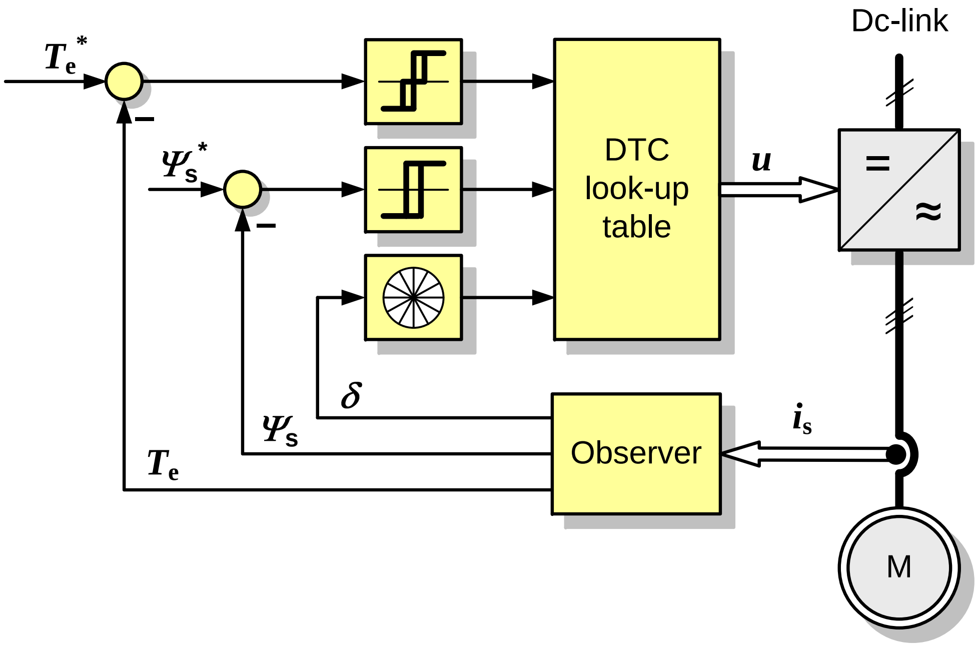


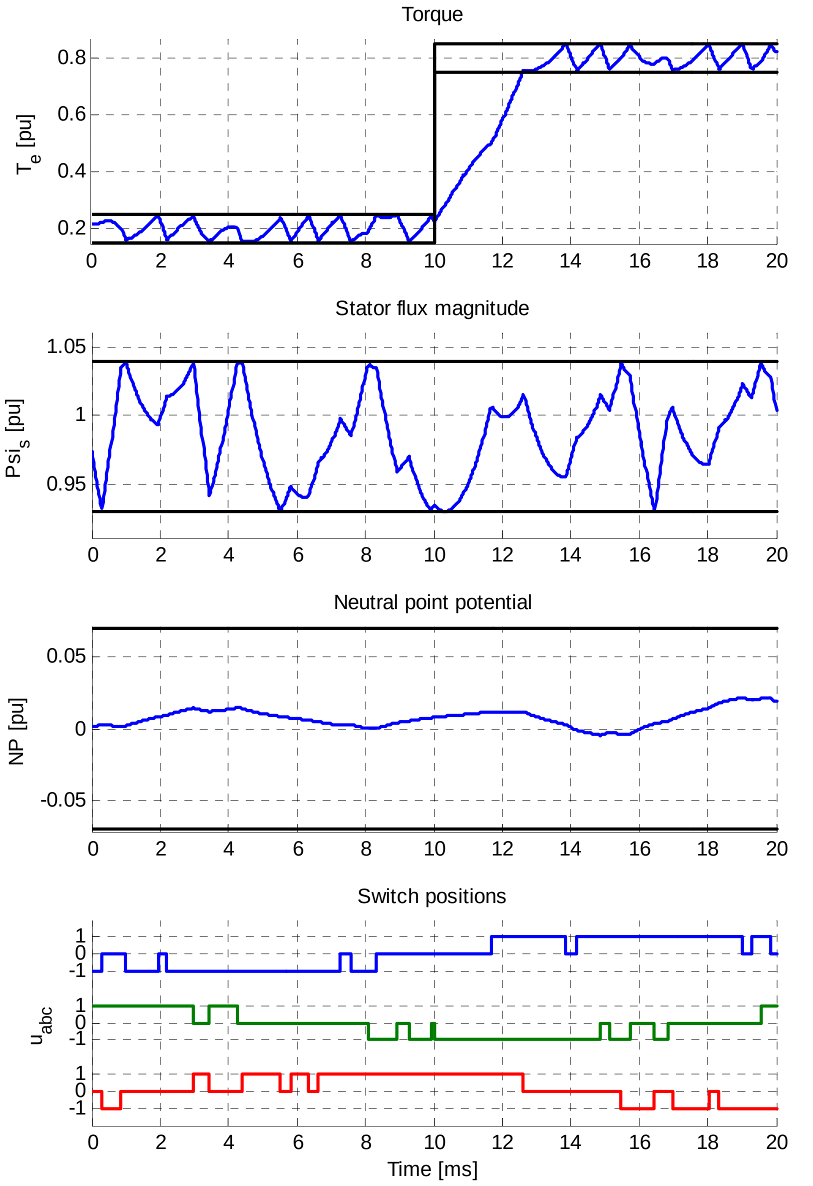
- Current and torque **distortions**: **linear** function of bound width
- **Switching frequency** (and losses): **hyperbolic** function of bound width

Classification of MPC Schemes for Electrical Drives



Direct Torque Control





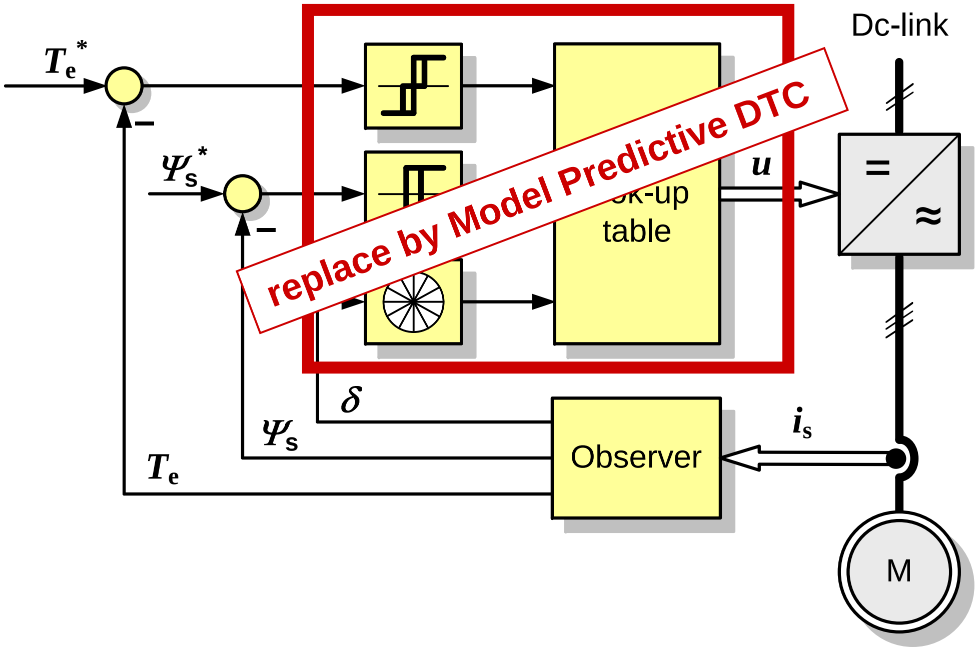
Control objectives:

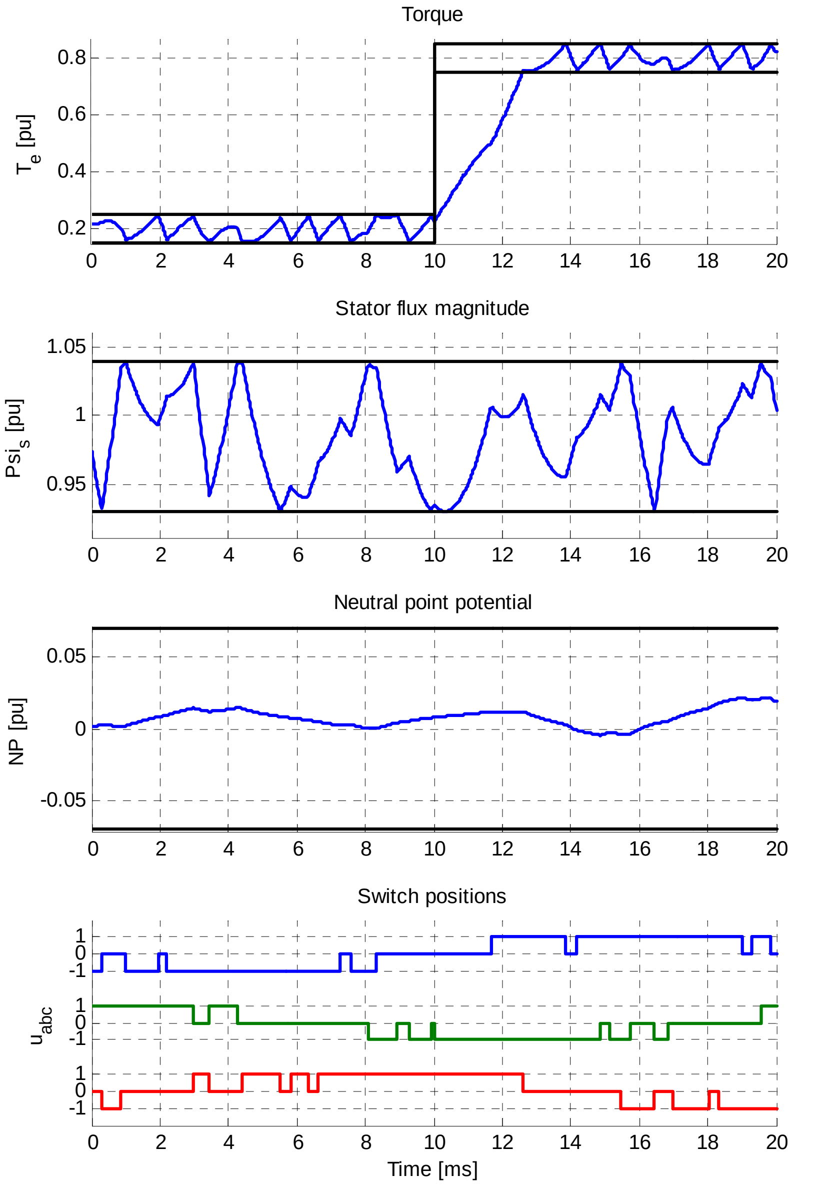
- Keep **torque**, **stator flux** and **neutral point potential** within given bounds
- Minimize the **switching losses**

Control variable:

- Discrete inverter **switch positions**

Model Predictive Direct *Torque* Control



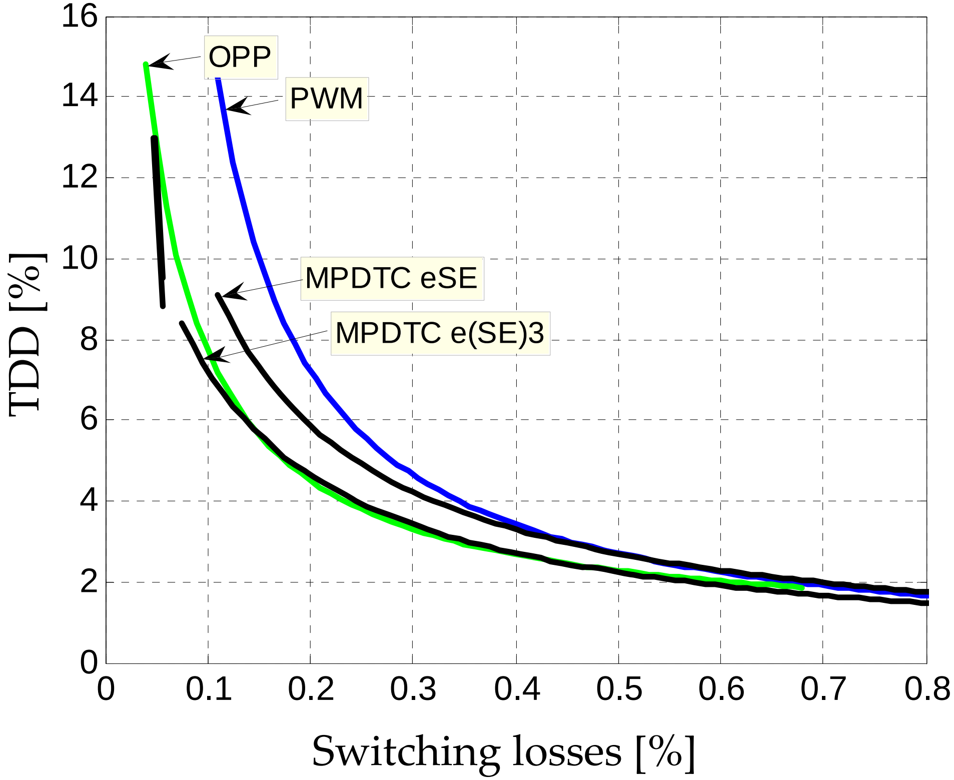


Challenging control problem:

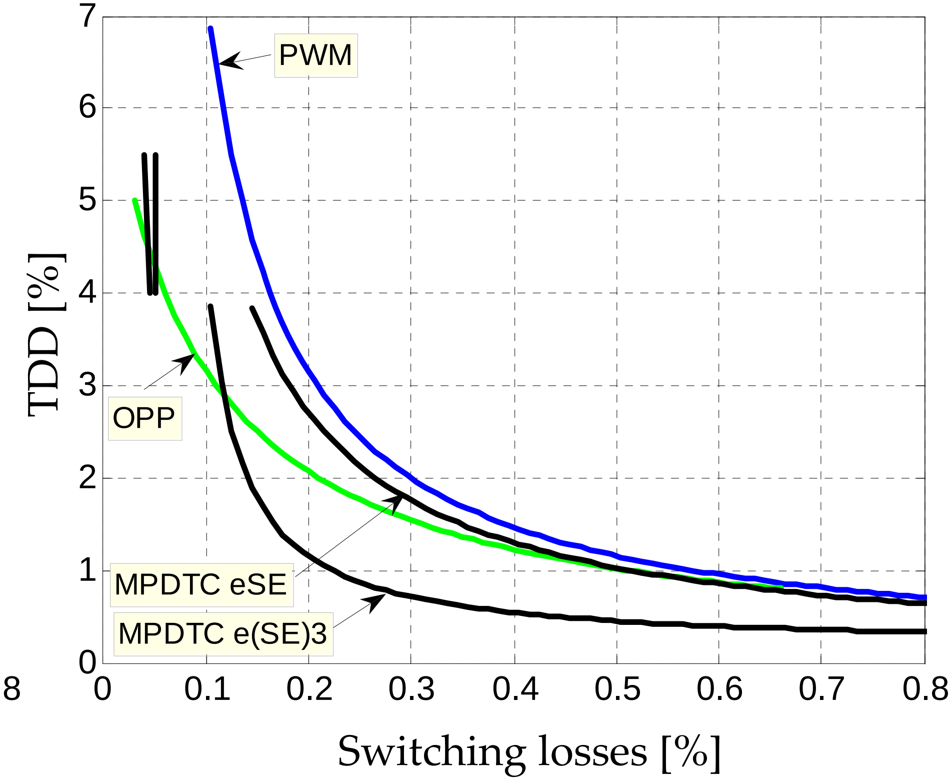
- **Nonlinear**
- **Hybrid**
- MIMO
- Sampling interval T_s = **25us**

Model Predictive Direct *Torque* Control

Current TDD vs switching losses



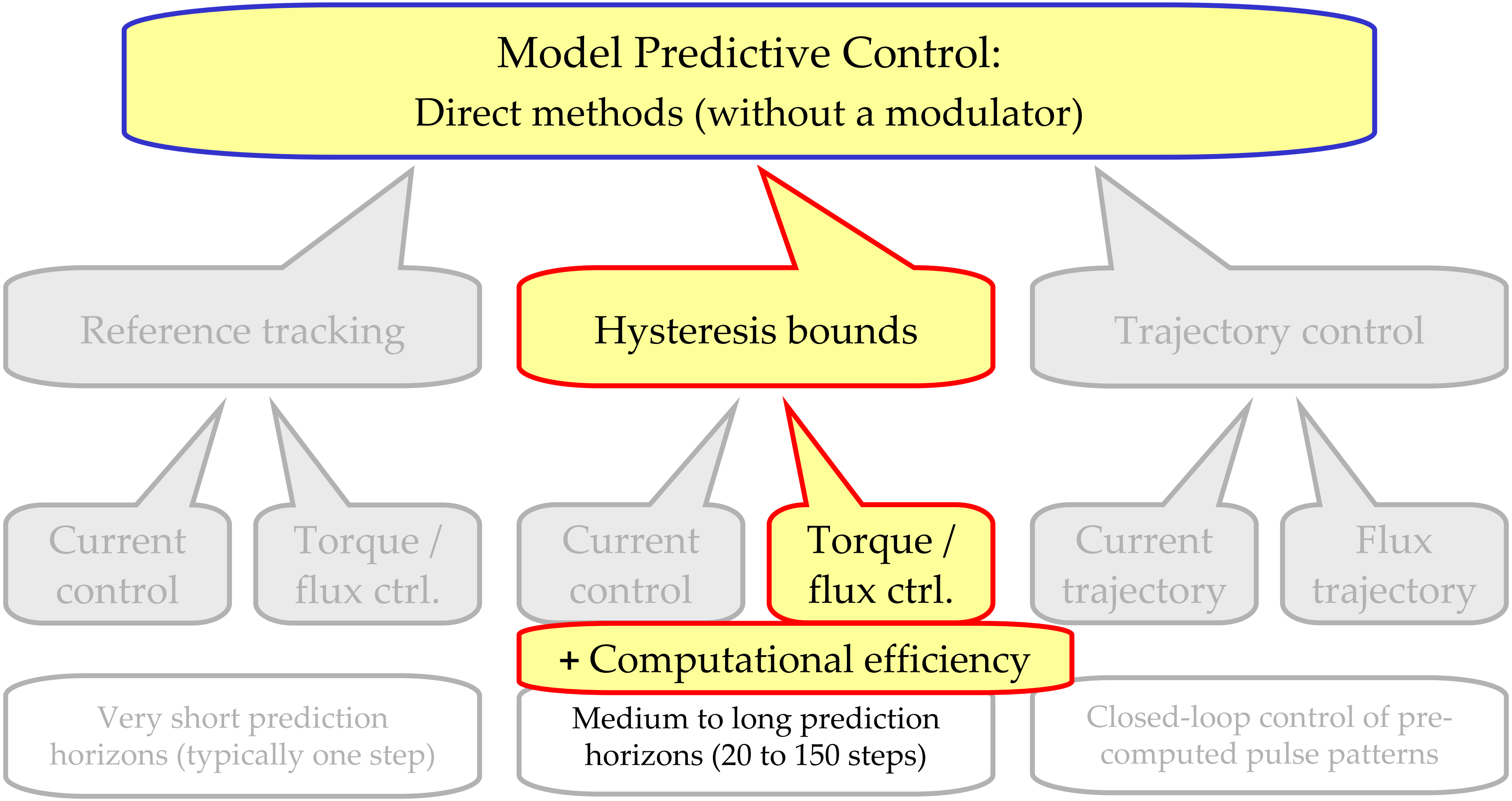
Torque TDD vs switching losses



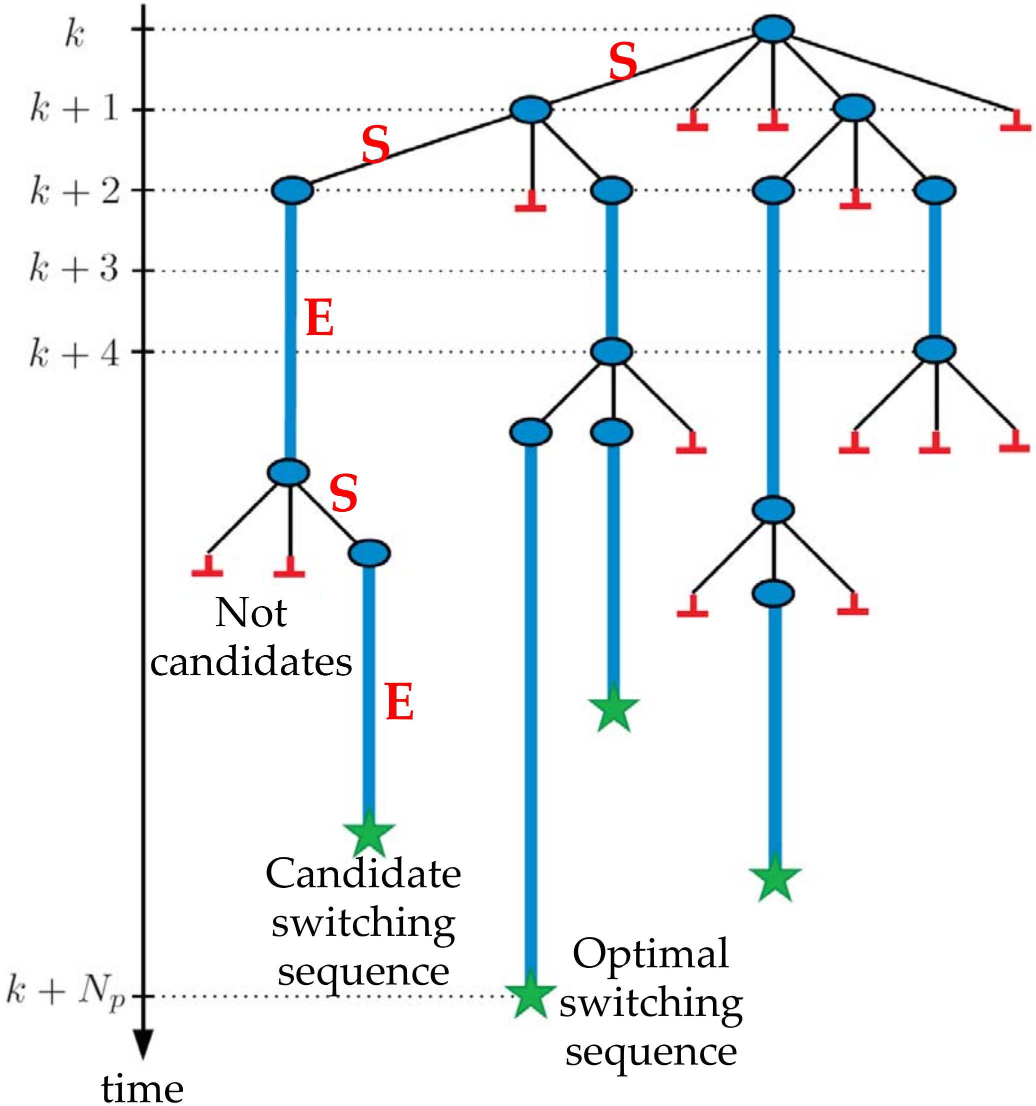
Long switching horizon eSESESE (50-150 steps):

- Current THD: similar to optimized pulse patterns (OPP)
- Torque THD: significantly better than OPP, but at the expense of current THD – points on curves do **not** correspond to each other!

Classification of MPC Schemes for Electrical Drives



Search Tree

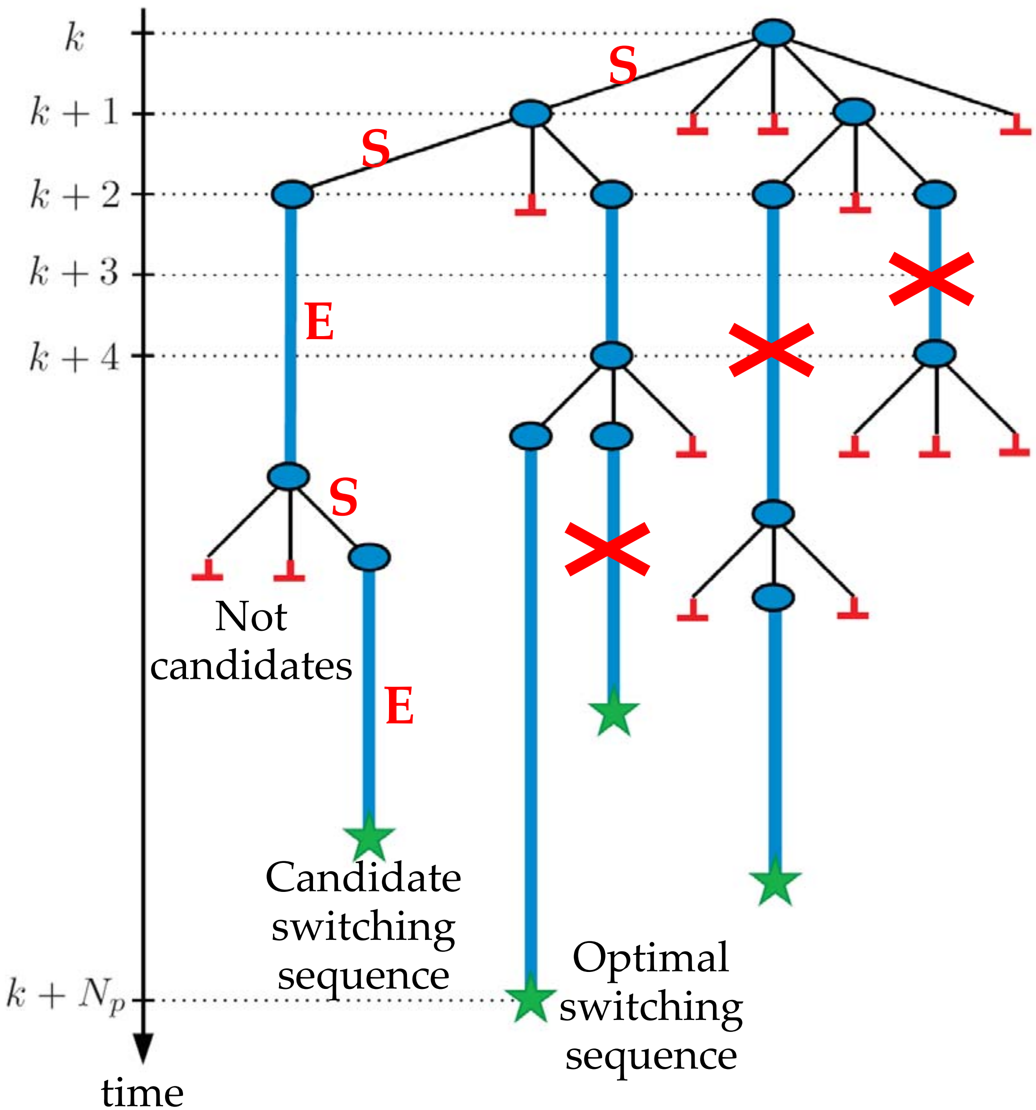


Search tree induced by optimization problem

Computational burden ≈ number of nodes

So far: full enumeration

Search Tree



Search tree induced by optimization problem

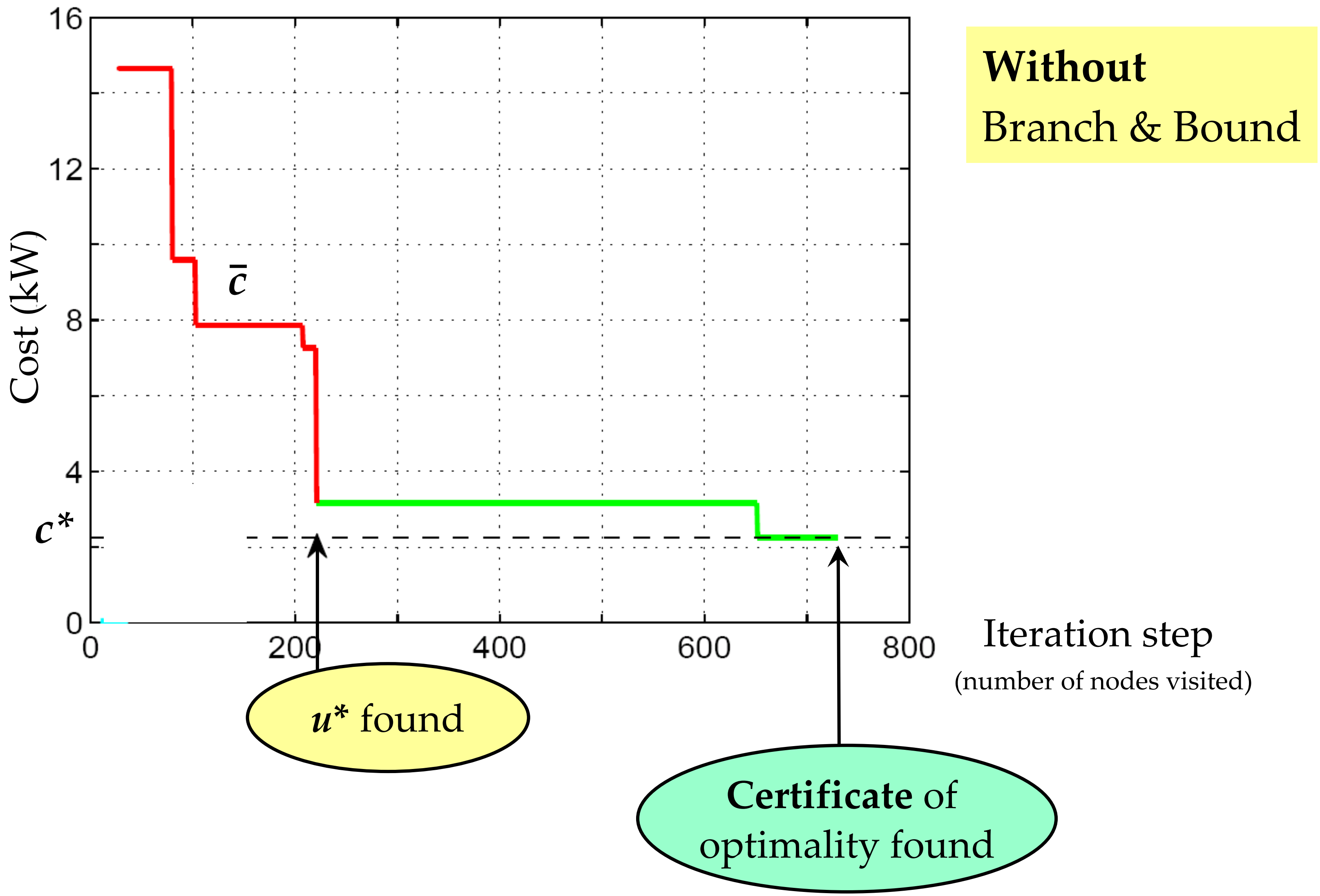
Computational burden ≈ number of nodes

So far: full enumeration

Approaches to reduce **computation time**?

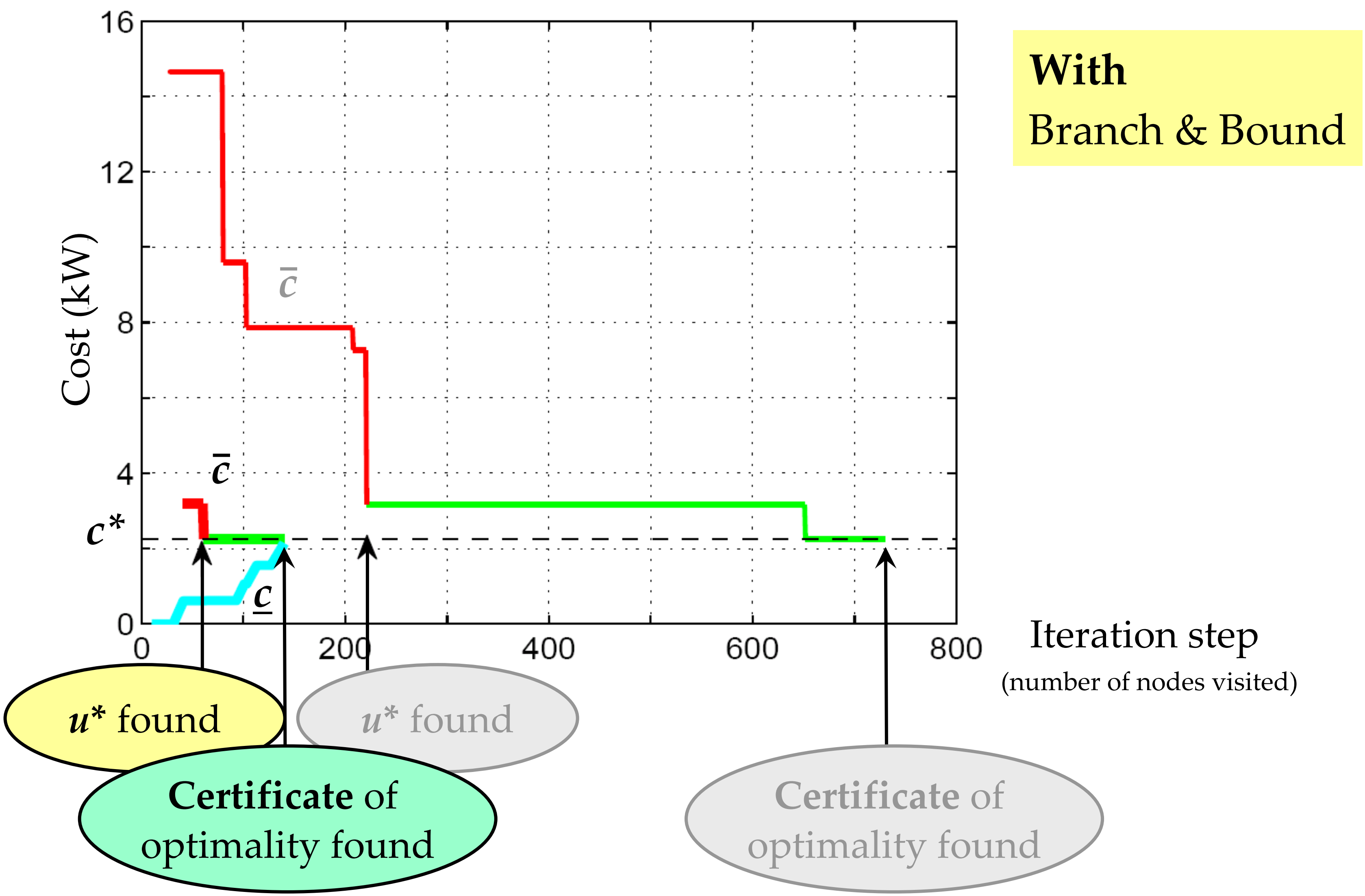
- More efficient **implementation** of algorithm
- More efficient **extension** / extrapolation step
- Reduce number of nodes explored in search tree by using **Branch & Bound**

Evolution of the Optimal Cost during Optimization



Search tree fully explored

Evolution of the Optimal Cost during Optimization



Upper and lower bound converged

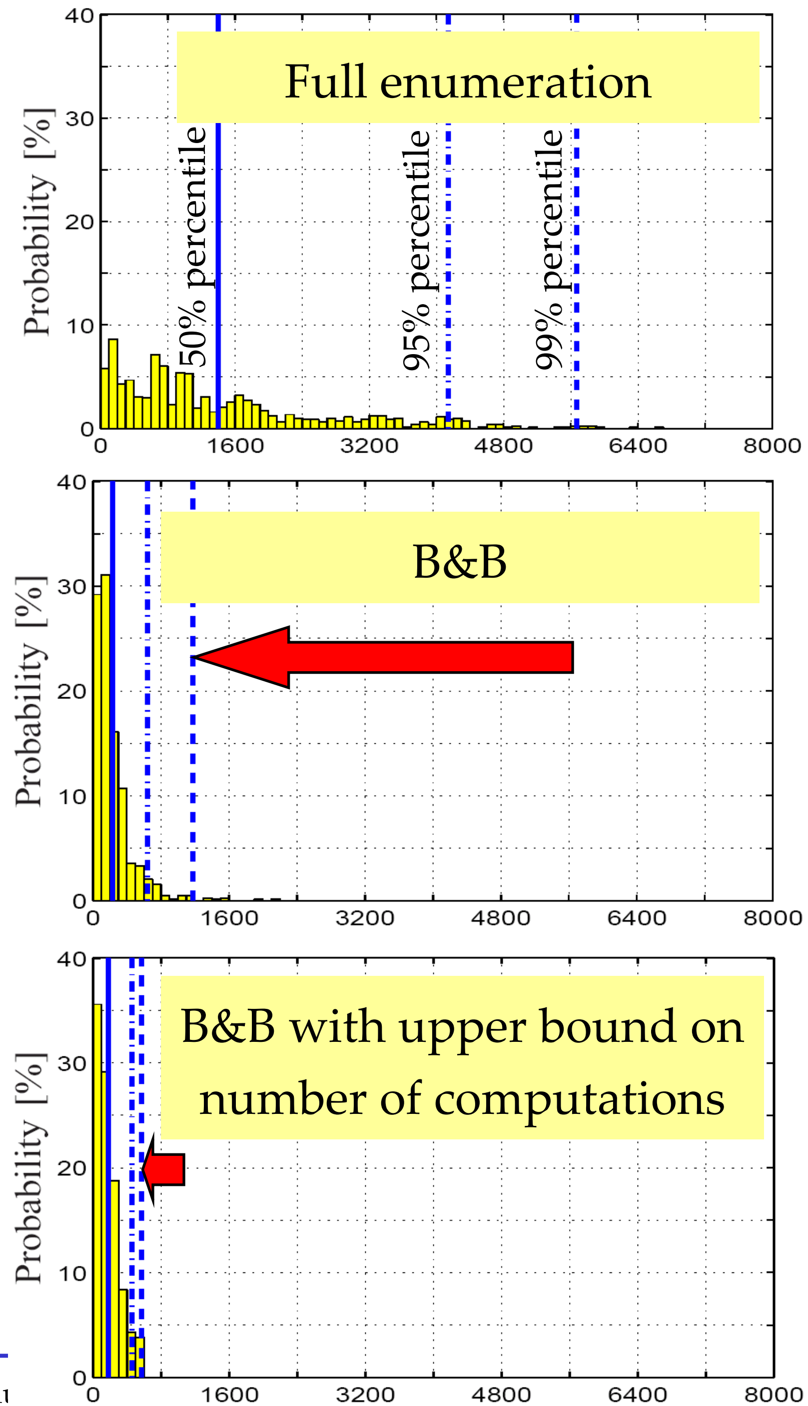
Search tree fully explored

Computational Effort

Example: MPDTC with the switching horizon ′eSSESESE′

Probability distributions:

Number of nodes required to be explored to obtain the **optimal cost** ***c****



Performance vs Computational Burden

Controller settings			Pred. horizon		Nodes explored		u^*	Performance [%]			
Sw. horizon	$N_{\max}$	$j_{\max}$	avg.	max.	avg.	max.	found [%]	P_{sw}	f_{sw}	$I_{s,\mathrm{THD}}$	$T_{e,\mathrm{THD}}$
DTC	–	–	–	–	–	–	–	100	100	100	100
eSSE	–	–	26.6	96	112	277	100	57.3	71.2	103	98.4
eSSE	50	50	22.0	97	43.6	50	92.2	58.3	74.1	104	103
eSSESESE	–	–	98.2	150	3246	7693	100	37.9	48.9	97.0	92.0
eSSESESE	110	600	88.0	152	483	600	92.1	38.6	51.4	97.3	94.0

Short switching horizon (eSSE):

- B&B => computational burden reduced by **factor 5.5**
- Switching losses and THDs merely affected

Benefit: **simplify** implementation for **short** switching horizons

Performance vs Computational Burden

Controller settings			Pred. horizon		Nodes explored		u^*	Performance [%]			
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Short switching horizon (eSSE):

- B&B => computational burden reduced by **factor 5.5**
- Switching losses and THDs merely affected

Benefit: simplify implementation for **short** switching horizons

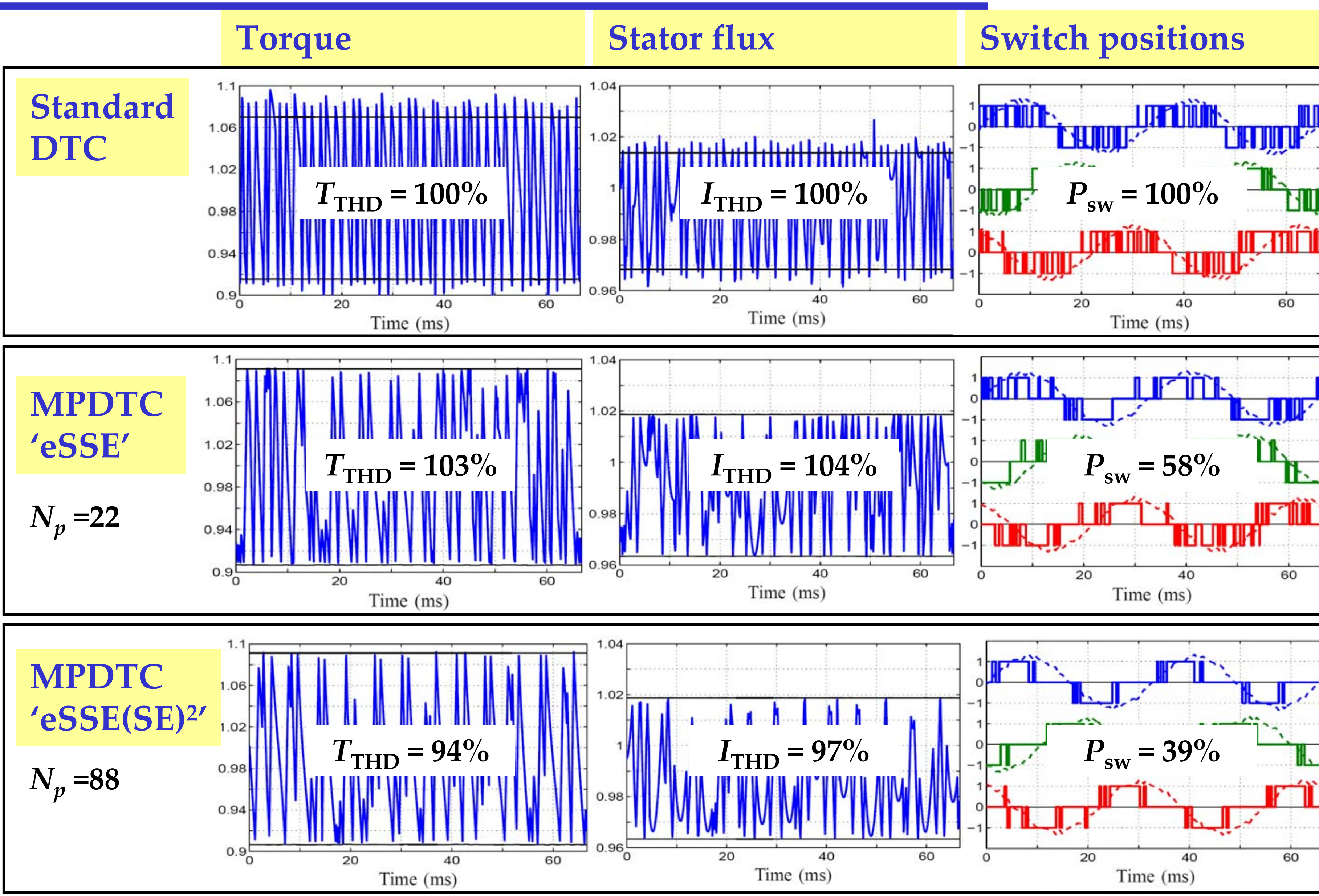
Long switching horizon (eSSESESE):

- B&B => computational burden reduced by **factor 13**
- Switching losses and THDs merely affected

Benefit: enable implementation for **long** switching horizons

Performance Results

ACS 6000, w_e=0.6 pu, T_e=1 pu;
Same torque bounds, flux bounds relaxed by +/- 0.01pu
ABB's simulation environment



Summary and Conclusions

Commercial Benefits

- Higher **rating** of inverter possible
  - **40%** higher power capability (e.g. from 5 MVA to 7 MVA)
  - Hardware remains the same
- **Standard machines** can be used
  - **No derating** of machine required
- For '**complicated**' topologies
  - MPC is **enabling** technology

Fully utilize the drive **hardware**

Summary and Conclusions

Goal: Fully utilize capability of drive hardware

- Minimize **switching losses** per **distortions**
- Achieve very **fast** torque and current response

Approach:

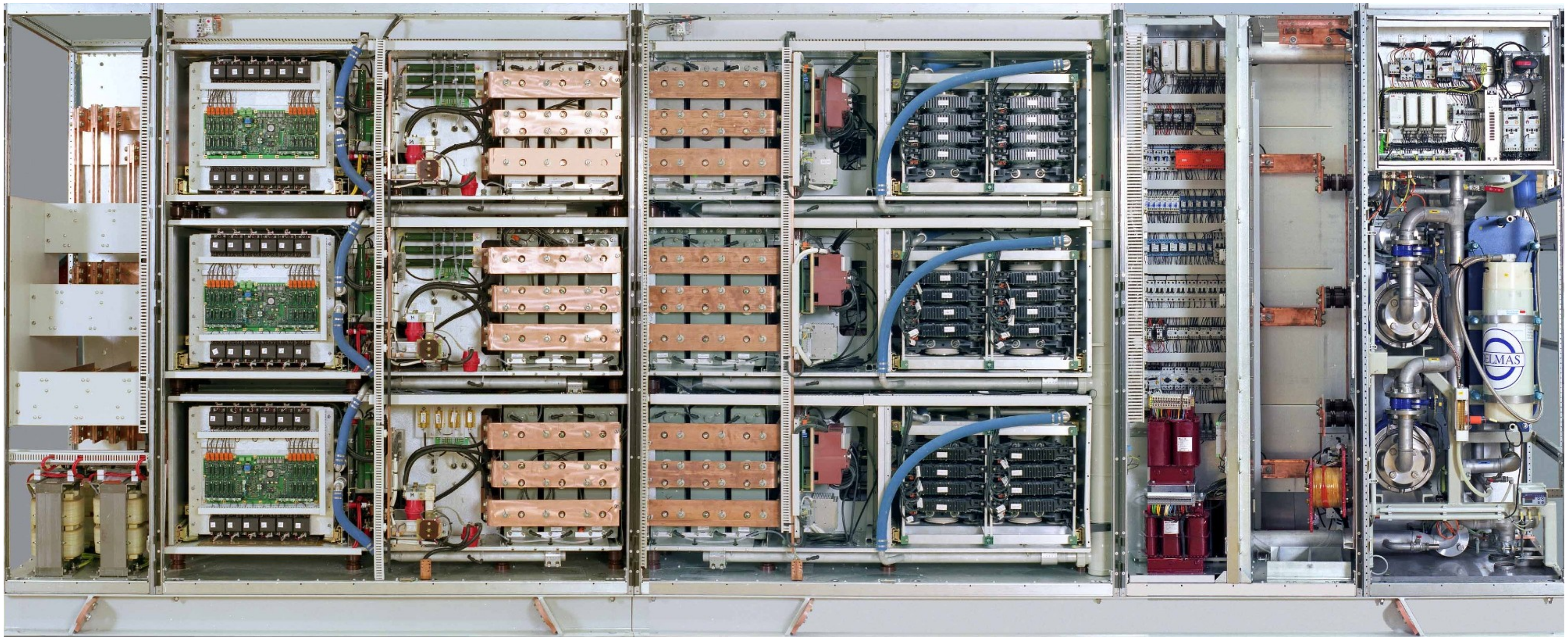
- Treat control and modulation problem in **one stage**
- Work in the **time-domain**
- Adopt **model predictive control**

Results:

- **MPDxC** family
- **MP^{3}C**

For More Information

www.ece.auckland.ac.nz/tgey001



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