Model Predictive Control in Medium-Voltage Drives

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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 torque distortions => no excitation of mech. resonances
- Fast torque response => high dynamic performance

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

\[ f_{sw} = 700 \text{Hz} \]
\[ P_{sw} = 16.7 \text{kW}, P_{con} = 2.7 \text{kW} \]
\[ \text{THD}_I = 2.31\% \]
\[ \text{THD}_T = 1.93\% \]

Inverter: 3-level NPC with IGCTs
Induction machine: 3.3kV, 2MVA
Operation point: \( w_e = 1 \text{pu}, T_e = 1 \text{pu} \)
Trade-Off (*Low Switching Frequency*)

$f_{sw}=150\text{Hz}$

$P_{sw}=3.9\text{ kW}, P_{con}=2.8\text{ kW}$

$\text{THD}_I=6.9\%$

$\text{THD}_T=6.0\%$

Inverter: 3-level NPC with IGCTs

Induction machine: 3.3kV, 2MVA

Operation point: $w_e=1\text{pu}, T_e=1\text{pu}$
Trade-Off for PWM / SVM

Current THD vs switching losses

Torque THD vs switching losses

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

\[ T_{e,THD} \cdot P_{sw} = \text{const} \]
Control and Modulation Schemes
Control and Modulation

Switching losses per distortions

large

small

fast

slow

Torque response time (controller bandwidth)

Field Oriented Control with PWM/SVM

Current controller

Modulator

$u^*$

$u$

$T_e^*$

$i_s^*$

$i_s$
Control and Modulation

Switching losses per distortions

large

Model Predictive Control with PWM/SVM

Oriented Control with PWM/SVM

small

fast

slow

Torque response time (controller bandwidth)

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Control and Modulation

Switching losses per distortions

- Large
- Small

Fast

Model Predictive Control with PWM/SVM

Field Oriented Control with PWM/SVM

V/f Control with Optimized Pulse Patterns

Torque response time (controller bandwidth)

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Control and Modulation

Switching losses per distortions

- Large Direct Torque Control
- Model Predictive Oriented Control with PWM/SVM

V/f Control with Optimized Pulse Patterns

Torque response time (controller bandwidth)

- Fast
- Slow

Controller and modulator

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Control and Modulation

Switching losses per distortions

- One-step Predictive Control
- Direct Torque Control
- Model Predictive Control with PWM/SVM
- Field Oriented Control with PWM/SVM
- V/f Control with Optimized Pulse Patterns

Torque response time (controller bandwidth)

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Control and Modulation: Goal

Switching losses per distortions

- One-step Predictive Control
- Direct Torque Control
- Model Predictive Control with PWM/SVM
- Field Oriented Control with PWM/SVM

V/f Control with Optimized Pulse Patterns

Torque response time (controller bandwidth)

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Control and Modulation: New Methods

- One-step Predictive Control
- Direct Torque Control
- Model Predictive Direct Torque / Current Control
- Field Oriented Control with PWM/SVM
- V/f Control with Optimized Pulse Patterns

Switching losses per distortions: large
Torque response time (controller bandwidth): fast, slow

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Control and Modulation: New Methods

Switching losses per distortions

- One-step Predictive Control
- Field Oriented Control with PWM/SVM
- Direct Torque Control
- Model Predictive Direct Torque Control with PWM/SVM
- Fast Control of Optimized Pulse Patterns
- V/f Control with Optimized Pulse Patterns

Torque response time (controller bandwidth)

Controller and modulator

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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

Model Predictive Control: Direct methods (without a modulator)

- Reference tracking
  - Current control
  - Very short prediction horizons (typically one step)

- Hysteresis bounds
  - Torque / flux ctrl.
  - Medium to long prediction horizons (20 to 150 steps)

- Trajectory control
  - Current trajectory
  - Closed-loop control of pre-computed pulse patterns
  - Flux trajectory
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One-Step Predictive \textit{Current} Control

\begin{algorithm}
\begin{itemize}
\item Enumerate all 27 switch transitions
\item Predict currents at $k+1$
\item Choose switch transition with minimal current error at $k+1$
\end{itemize}
\end{algorithm}
One-Step Predictive Current Control

Performance Index: \( J^*(x(k)) := \min_{u_k} ||i_e(k + 1)||_1 + \lambda_n ||\Delta u(k)||_1 \)

- Deviation from current reference
- Penalty on switching effort

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

Main features:
- prediction **horizon** is one
- machine **model**
- **minimization** of switching effort (e.g. frequency)
- \( \lambda_n \) => trade-off between tracking accuracy and switching
- conceptually and computationally **very simple**
Current TDD vs switching losses

- Current THD similar to PWM
- Torque THD significantly worse than PWM
Classification of MPC Schemes for Electrical Drives

Model Predictive Control: Direct methods (without a modulator)

Reference tracking
- Current control
- Torque / flux ctrl.

Hysteresis bounds
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- Torque / flux ctrl.

Trajectory control
- Current trajectory
- Flux trajectory

Very short prediction horizons (typically one step)

Medium to long prediction horizons (20 to 150 steps)

Closed-loop control of pre-computed pulse patterns
One-step Predictive Torque Control

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Trajectory control
- Current trajectory
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  - Closed-loop control of pre-computed pulse patterns

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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
Model Predictive Direct Current Control: Step 1

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

**Key ingredients:**
- Drive model
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**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
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 \( U \)

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\[ i_{\text{rip}a}, i_{\text{rip}b} \]

NP potential not shown here

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Model Predictive Direct Current Control

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

Short-term avg. switching losses (power)

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

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

**Speed:** $\omega_e = 0.6 \text{ pu}$

**Torque:** reference steps between $T=1$ and 0 pu

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**Torque**

![Torque Graph]

**Stator currents**

![Stator Currents Graph]

**Switch positions**

![Switch Positions Graph]

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**Torque (current) response time of 2 ms**
Performance at Steady-State

3-level NPC inverter with 2MVA ind. machine
\( \omega_e = 0.6 \ \text{pu}, \ T_e = 1 \ \text{pu} \)

Current

FOC with PWM and \( f_c = 270 \ \text{Hz} \)

\( I_{\text{THD}} = 7.69\% \)

\( P_{\text{sw}} = 4.15\text{kW} \)

Current spectrum

Switch positions

MPDCC ‘e(SE)^3’

\( N_p = 70 \)

\( I_{\text{THD}} = 4.56\% \)

\( P_{\text{sw}} = 4.02\text{kW} \)

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

Similar to optimal pulse patterns
MPDCC outperforming OPP

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

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

\[ P_{sw} = 1.92 \text{ kW} \quad 40\% \text{ less} \]
\[ I_{THD} = 8.18\% \quad 5\% \text{ more} \]

\[ P_{sw} = 1.15 \text{ kW} \]
\[ I_{THD} = 8.60\% \]
Model Predictive Direct Current Control

Current TDD vs switching losses

Torque TDD vs switching losses

Long switching horizon eSESESESE (50-150 steps):
- Current THD: better than with optimized pulse patterns
- Torque THD: similar to PWM
Tuning

3-level NPC inverter with 2MVA IM
\( w_c = 0.6 \text{ pu}, \ T_c = 1 \text{ pu}, \ \text{MPDCC with ‘eSE’} \)

- 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

Model Predictive Control:
Direct methods (without a modulator)

Reference tracking

Current control

Very short prediction horizons (typically one step)

Hysteresis bounds

Torque / flux ctrl.

Medium to long prediction horizons (20 to 150 steps)

Trajectory control

Current trajectory

Closed-loop control of pre-computed pulse patterns

Flux trajectory

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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 $T_s = 25\mu s$

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Long switching horizon eSESESESE (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

Model Predictive Control:
Direct methods (without a modulator)

- Reference tracking
- Current control
- Very short prediction horizons (typically one step)

- Torque / flux ctrl.
- Trajectory control
- Current trajectory
- Medium to long prediction horizons (20 to 150 steps)

- Hysteresis bounds
- + Computational efficiency
- Closed-loop control of pre-computed pulse patterns

- Torque / flux ctrl.
- Current control
- Medium to long prediction horizons (20 to 150 steps)

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Search Tree

Search tree induced by optimization problem

Computational burden \( \approx \) number of nodes

So far: full enumeration

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Search Tree

Search tree induced by optimization problem

Computational burden $\approx$ 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

Without Branch & Bound

Search tree fully explored
Evolution of the Optimal Cost during Optimization

With Branch & Bound

* $\bar{c}$
* $c^*$
* $\bar{c}$

$u^*$ found

Certificate of optimality found

Upper and lower bound converged

Search tree fully explored

Iteration step (number of nodes visited)
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

<table>
<thead>
<tr>
<th>Controller settings</th>
<th>Pred. horizon</th>
<th>Nodes explored</th>
<th>$u^*$ found [%]</th>
<th>Performance [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sp. horizon</td>
<td>$N_{\text{max}}$</td>
<td>$j_{\text{max}}$</td>
<td>avg.</td>
<td>max.</td>
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<tr>
<td>DTC</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>eSSE</td>
<td>-</td>
<td>-</td>
<td>26.6</td>
<td>96</td>
</tr>
<tr>
<td>eSSE</td>
<td>50</td>
<td>50</td>
<td>22.0</td>
<td>97</td>
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<tr>
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<td>-</td>
<td>-</td>
<td>98.2</td>
<td>150</td>
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<tr>
<td>eSSESESE</td>
<td>110</td>
<td>600</td>
<td>88.0</td>
<td>152</td>
</tr>
</tbody>
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**Short switching horizon (eSSE):**
- B&B $\Rightarrow$ computational burden reduced by **factor 5.5**
- Switching losses and THDs merely affected

**Benefit:** simplify implementation for **short** switching horizons
Performance vs Computational Burden

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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, $w_r=0.6 \text{ pu}$, $T_e=1 \text{ pu}$;
Same torque bounds, flux bounds relaxed by $+/-.01\text{pu}$
ABB’s simulation environment

### Torque

<table>
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<th>MPDTC ‘eSSE’</th>
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<td>$T_{THD} = 100%$</td>
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### Stator flux

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### Switch positions

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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
Selected Literature