Control and Modulation Schemes for High-Performance Electrical Drive Systems

Tobias Geyer

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

In collaboration with

ABB  ETH Zürich
Outline

Introduction
• Variable speed drives
• Market drivers and R&D trends
• Control and modulation schemes

Three recent drive developments
• Model predictive DTC: *pred. control fully utilizes the hardware capability*
• ABB’s new 5-level topology: *modern control is the enabling technology*
• 35 MW electrical drive: *fault tolerance maximizes the availability*

Conclusions and outlook
What are Variable Speed Drives?
Variable Speed Drives

Electrical machine + Power electronics + Controller

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

Control of the machine currents => fast torque and speed response

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Variable Speed Drives

Plus auxiliaries: cooling, protection, etc
Variable Speed Drives

Machine side

Grid side

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Key Application Areas of Variable Speed Drives
Power Generation

Purposes of Variable Speed Drive:
- Electro-mechanical power conversion
- Variable speed operation => higher efficiency
- Fast control of the turbine torque

Source: Aalborg University
**Electrification**

Augment *combustion engine* by an *electric drive*:

=> Increase **efficiency**

=> Reduce **emissions** / fuel consumption

=> Simplify mechanical *drive train* (remove clutch, gear box, etc)

**Example:** diesel-electric train engine
Electrification

Augment **combustion engine** by an **electric drive**:

- Increase **efficiency**
- Reduce **emissions** / fuel consumption
- Simplify mechanical **drive train** (remove clutch, gear box, etc)
Summary: Applications of Variable Speed Drives

Power generation
- Wind turbines
- Pumped hydro (storage)

Electrification
- Electric vehicles (HEV, plug-in HEV, EV)
- Diesel-electric train engines
- Off highway vehicles (OHV)
- Ships
- Oil&Gas: LNG, pipeline compression, subsea pumps
- More electric aircraft

Moreover
- Rolling steel mills
- Pumps, fans, blowers, conveyor belts, etc
- Numerous applications with smaller power
Market Drivers and R&D Trends
### Market Drivers:

- Higher **efficiency**
- Lower CO₂ **emissions**
- Lower current and torque **distortions**
- Lower **losses** in the inverter
- **Higher power, voltage, speed**
- **Higher reliability / availability**

### R&D Trends:

- Variable speed drives (electrification)
- Induction machines => (permanent magnet) **synchronous machines**
- **New control and modulation schemes**
- Wide **bandgap** semiconductor devices (SiC etc)
- **Multi-level** topologies
- Redundancy
- **Fault-tolerance**
- Online diagnostics
Control and Modulation Schemes
Semiconductors are operated in **on/off mode** (nonlinear regime)

⇒ Sinusoidal voltage waveforms are **approximated** by **switching pattern**

⇒ Current **distortions** and switching **losses**

But: **Inductive** load acts as **low-pass** filter for currents
Control and Modulation: Requirements

- 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
Trade-Off (High Switching Frequency)

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

\( f_{sw} = 700 \text{Hz} \)
\( P_{sw} = 16.7 \text{kW}, P_{con} = 2.7 \text{kW} \)
\( \text{THD}_I = 2.31\% \)
\( \text{THD}_T = 1.93\% \)
Trade-Off (*Low Switching Frequency*)

- Inverter: 3-level NPC with IGCTs
- Induction machine: 3.3kV, 2MVA
- Operation point: $w_e = 1\text{pu}$, $T_e = 1\text{pu}$

**Parameters:**
- $f_{sw} = 150\text{Hz}$
- $P_{sw} = 3.9\text{kW}$, $P_{con} = 2.8\text{kW}$
- THD$_I = 6.9\%$
- THD$_T = 6.0\%$
Trade-Off for PWM / SVM

Current THD vs switching losses

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

Torque THD vs switching losses

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

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Control and Modulation: Standard Schemes

Switching losses per distortions

- Direct Torque Control
- Field Oriented Control with PWM/SVM
- V/f control with Optimized Pulse Patterns

Switching losses:
- large
- small

Torque response time (controller bandwidth):
- fast
- slow

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Control and Modulation: New Methods

Switching losses per distortions

- **large**
  - Direct Torque Control
  - Field Oriented Control with PWM/SVM

- **small**
  - Model Predictive Direct Torque Control
  - Fast control with Optimized Pulse patterns

Torque response time (controller bandwidth)

- **fast**
  - V/f control with Optimized Pulse Patterns

- **slow**
Control and Modulation: New Methods

**Goal:** Fully utilize capability of drive hardware
- Minimize **switching losses** per **distortions**
- Achieve very **fast** torque response

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

![Control and Modulation Diagram](image-url)
Model Predictive DTC:

fully utilizing hardware capability
ABB’s ACS 6000

Drive:
- 3-level NPC inverter with induction machine
- Up to 9MVA, 3.3kV
- Most **widely used** medium-voltage drive

Applications:
- Large **wind turbines**
- Steel mills
- Large pumps, fans, compressors

Objectives:
- Low **switching losses** in the inverter
- Low current and torque **distortions**
- **Fast** torque and speed control
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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Model Predictive Direct Torque Control

Minimization of cost function

Prediction of trajectories

Observer

DC-link

$T_e^*$

$\Psi_s^*$

$\Psi_s \ \Psi_r$

$\omega$

$u$

$\rightarrow$

$\rightarrow$

$\rightarrow$

MPDTC

$\rightarrow$

$\rightarrow$

$\rightarrow$

$\rightarrow$
Model Predictive DTC: Step 1

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

**Key ingredients:**
- Drive model
- Extrapolation

**Switching horizon**, e.g. ‘eSESE’
- **S**: consider all switch transitions
- **E**: extrapolate/extend torque, flux, NPP
- **e**: optional ‘E’

**Prediction horizon** $N_p$
Typically 50..150 time-steps
Model Predictive DTC: Step 1

Predict output trajectories for (all) possible switching sequences

Key ingredients:
• Drive model
• Extrapolation

Switching horizon, e.g. ‘eSESE’
• S: consider all switch transitions
• E: extrapolate/extend torque, flux, NPP
• e: optional ‘E’

Prediction horizon $N_p$
Typically 50..150 time-steps
Evaluate and **minimize switching 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 DTC: Step 2**

---

**Plan**

**Do**

\( k \)

**Plan**

**Do**

\( k+1 \)

**Plan**

**Do**

\( k+2 \)
Model Predictive DTC Problem Formulation

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

\( E_{\text{loss}}(x_k, u_k) \) Short-term avg. switching (power) losses

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

Main features:  
- short switching horizon but long prediction horizon  
- tailored online solution approach  
- bound width proportional to THD
ACS 6000, \( w_c = 0.6 \text{ pu} \), \( T_c = 0.6 \text{ pu} \); MPDTC with ‘eSSESE’
Comparison: DTC vs MPDTC

ACS 6000, \( w = 0.6 \text{ pu}, T_e = 0.6 \text{ pu}; \)
MPDTC with ‘eSSESSE’
Same torque bounds, flux bounds relaxed by +/-0.01pu
ABB’s simulation environment

DTC

MPDTC
Comparison: DTC vs MPDTC

Results (compared to DTC):
• 60% less switching losses and (!)
• 20% less torque distortions (similar current distortions)
Current THD vs switching losses

Torque THD vs switching losses

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
Commercial Benefits

• Higher **rating** of inverter possible
  – 40% higher power capability (e.g. from 5 MVA to 7 MVA)
  – Hardware remains the same
  – Software (control) allows company to greatly **increase** margin

• **Standard machines** can be used
  – No **derating** of machine required

**Fully utilize the drive hardware**
Experimental Results of MPDTC at 1MW

Trans. on Ind. Electronics 2009

Courtesy of ABB Switzerland
ABB’s new 5-level topology: modern control is enabling technology
ABB’s ACS 2000

Drive:
• 5-level aNPC inverter with induction machine
• Up to 1MVA, 6.9kV

Applications:
• Retrofit
• Direct-to-line grid connection (6.0-6.9kV)
• Large pumps, fans, compressors

Objectives:
• Low current and torque distortions
• Low switching losses in the inverter
• Fast torque and speed control

Solution Approach:
• Fast control based on optimized pulse patterns
• Predictive balancing (derivative of MPDTC)

Commercial Benefit:
• Only viable control scheme available so far
• Product release in a few months
Control and Modulation Scheme

**Upper Level:**
*Fast pred. control* based on optimized pulse patterns of
- torque
- rotor flux magnitude

\[ V = [v_1 \ v_2 \ v_3] \]
\[ t = [t_1 \ t_2 \ t_3] \]

**Lower Level:**
*Predictive balancing* (derivative of MPDTC) of
- neutral point potential
- 3 phase capacitor voltages

\[ U = [u_1 \ u_2 \ u_3 \ u_4] \]
\[ t = [t_1 \ t_2 \ t_3 \ t_4] \]
ACS 2000 (5-level aNPC topology with flying phase capacitors); \(w_r=0.8\text{pu}, \ T_r=1\text{pu}\) step to 0.5pu; fast control based on OPP, predictive balancing with ‘eSESE’
35 MW electrical drive: maximizing the availability
GE’s Steadfast 40

Drive:
• Up to 4 back-back 3-level NPC inverter
• Synchr. machine with brushless exciter
• Up to 35MW, 3.3kV

Applications:
• Large compressor trains (LNG)
Electrification of LNG Compressor Trains

Gas turbine driven
Motor is starter only

LNG super train
Motor is starter/helper

e-LNG
Redundant generators feed multiple motors

Main challenges:

- Very high power
- Torsional resonances / grid side harmonics
- High reliability / availability

=> parallel threads
=> interleaving, active damping
=> fault-tolerance
Interleaving of PWM carriers

Concept of Interleaving:
PWM carriers of converter threads are **phase-shifted** against each other
=> certain **harmonics** can be **cancelled**

**Interleaved** & motoring operation

**Non-interleaved** & generating operation

Switching patterns & thread currents

Resulting line current

Trans. on Ind. Appl. 2009 (best paper award)
Reliability and Availability

Thread exclusion scenario

**Fault** in Thread #1 (in drive with 3 threads)

=> Thread #1 is isolated, shut down and repaired

=> Threads #2 and #3 ramp up currents

**Seamless transition** into **degraded mode** operation

System availability of 99.98% (downtime < 2h/year)

Compare with 94% of Frame 7EA gas turbine
Conclusions and Outlook
Conclusions

- **Market** drivers for electrical drives include
  - **Wind** turbines => higher efficiency
  - **Electrification** => higher efficiency, higher availability
- **Modern control** and **modulation** schemes
  - Fully utilize **hardware** capability (reduce switching **losses** and **distortions**)
    => higher rating, use of standard machines, etc
  - Required for **complex** new **topologies** and drive configurations
- **Fault-tolerance** => higher reliability / availability

**Courtesy of ABB Switzerland**
Outlook

- **Grid-side** converters
  - Drives
  - Modular multi-level topologies
  - Power systems (FACTS, etc)
  - Power quality (AVC, UPS, etc)
  - HVDC light
  - MVDC grid, e.g. for offshore wind turbines

- **Reliability / availability**
  - Redundancy (device, converter, machine, control)
  - Fault tolerance

- **Electrification**
  - Train engines
  - Large drives for the Oil & Gas industry

- **Low(er) power drives**
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S. Schröder, General Electric

For more information:
www.ece.auckland.ac.nz/tgey001
Backup
Evolution of the MPDxC Family

MPDTC with SE, SSE; min. of $f_{sw}$
- PhD thesis 2005
- Trans on Ind El 2009

MPDTC with long horizons and min. $P_{sw}$
- CDC 2009

Test runs > 1MVA
- Trans on Ind El 2009

Implementation

MPDTC with SE, SSE; min. of $f_{sw}$
- PhD thesis 2005
- Trans on Ind El 2009

5-level VSI with high-speed machine
- IECION 2009

MPDCC for 2-level VSI
- ICIT 2010

PMSM
- ECCE 2010

Computationally efficient MPDTC
- ECCE 2010
- Trans on Power El 2011

Benchmarking
- ECCE 2010
- Trans on Ind Appl 2011

MPDCC for multi-level VSI
- ECCE 2010
- Ind Appl Mag 2011

Deadlock avoidance
- MSc thesis 2011

Trajectory ext. methods
- MSc thesis 2010
- APEC 2011

5-level aNPC drive
- Submitted to ECCE 2011

Predictive Balancing
- Implemented, tests ongoing

Benchmarking
- Submitted to ECCE 2011

Grid-side converter with LCL filter
- PhD ongoing, first results submitted to ECCE 2011

Control of harmonics
- IP filed

Analysis and stability
- Submitted to ECCE 2011

Modular multi-level converter
- PhD recently started

Ongoing:
- Control and modulation schemes for high-performance electrical drive systems

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Search Tree

Search tree induced by optimization problem

So far: full enumeration

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Search tree induced by optimization problem

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

Cost (kW)

Iteration step (number of nodes visited)

Search tree fully explored

Certificate of optimality found

\( u^* \) found

\( \bar{c} \)

Without Branch & Bound
Evolution of the Optimal Cost during Optimization

With Branch & Bound

Upper and lower bound converged

Search tree fully explored

Certificate of optimality found

Certificate of optimality found

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 $c^*$

Full enumeration

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<th>Percentile</th>
<th>Probability [%]</th>
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<tr>
<td>50%</td>
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<tr>
<td>95%</td>
<td>20</td>
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<tr>
<td>99%</td>
<td>30</td>
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</tbody>
</table>

B&B

B&B with upper bound on number of computations

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