T. Besselmann, S. Almér, J. Ferreau, 2015-04-01

Nonlinear Model Predictive Torque Control of Load Commutated Inverter-fed Synchronous Machines

Power and productivity for a better world™ ABB

Outline

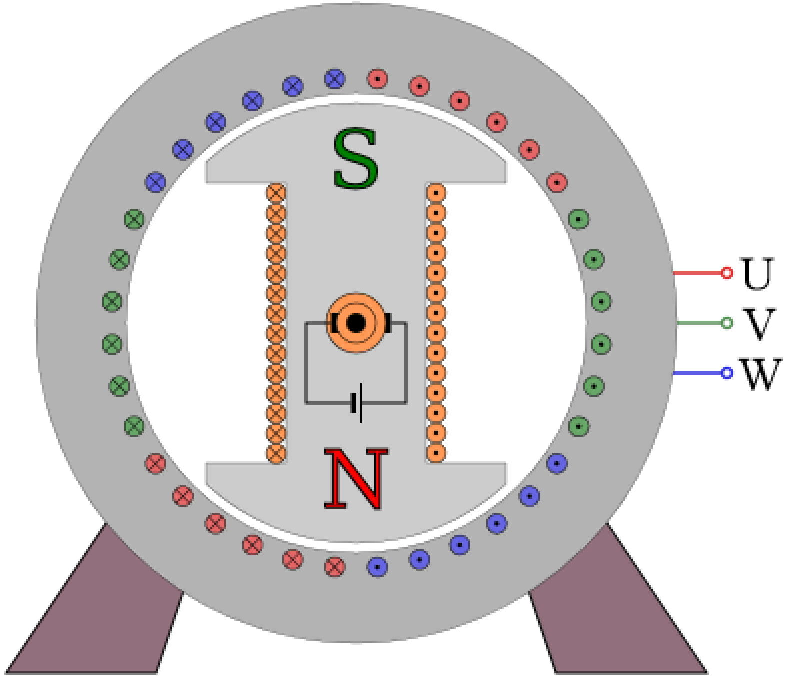
- LCI and synchronous machine
- Dynamic model
  - MPC formulation
- Solution
  - ACADO Toolkit
- Simulation results
- Experimental results

20 MW Synchronous Machine at CESI

Synchronous Machines

Properties:

- Rotor runs with same frequency as stator field
  → Synchronous
- High efficiency (95…99 %)
- Small inertia
- Excitation → More complex



Introduction
What is an adjustable speed drive (ASD)

- Equipment to control the speed and / or torque of a electrical motor.

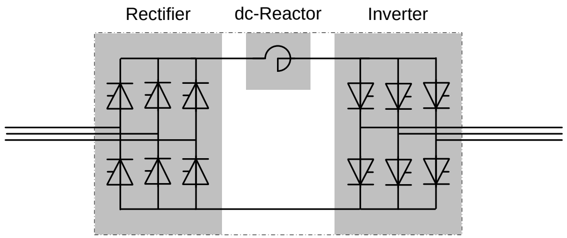
- There are also other common names, such as:
  - VFD (Variable Frequency Drive)
  - AFD (Adjustable Frequency Drive)
  - VSD (Variable Speed Drive)

Overview of MV drives configurations - see IEC61800-4

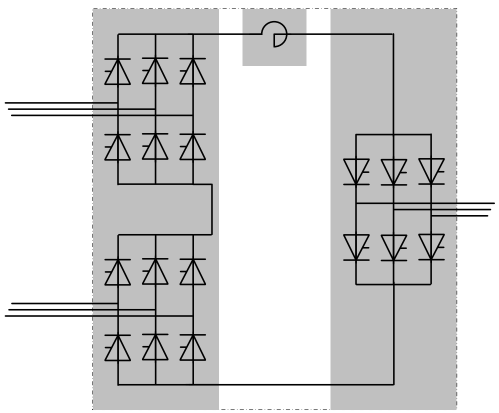
- Direct Converters
  - Circulating current-free cycloconverter
  - Circulating current cycloconverter
- Indirect Converters
  - **Load Commutated Converter (LCI)**
    - **Synchronous Motor**
    - Induction Motor
  - **Current Source Inverter (CSI)**
    - Basic Structure with line commutated line side converter
    - Dual Source Inverter
  - **Voltage Source Inverter (VSI, 2Q** or 4Q models)
    - 2-level
    - **3-level NPC (Neutral Point Clamped)**
    - Multi level – FSC (Floating Symmetrical Capacitor)
    - **Multi level – Multi Secondary Transformer**

Commonly used in industrial applications

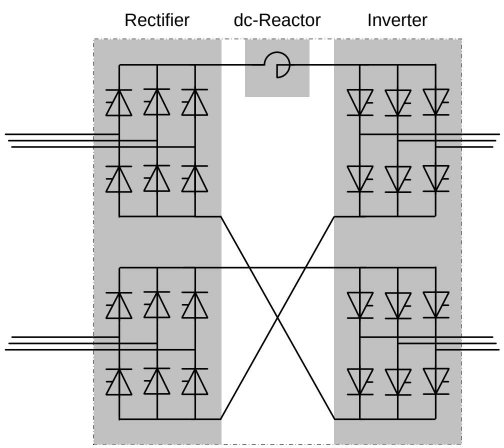
Typical LCI configurations



6/6 - pulse configuration



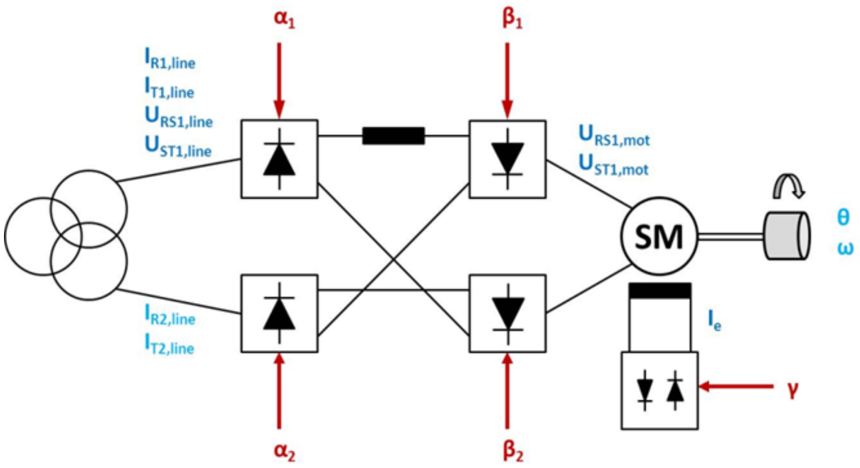
12/6 - pulse configuration



12/12 - pulse configuration

ABB Megadrive LCI

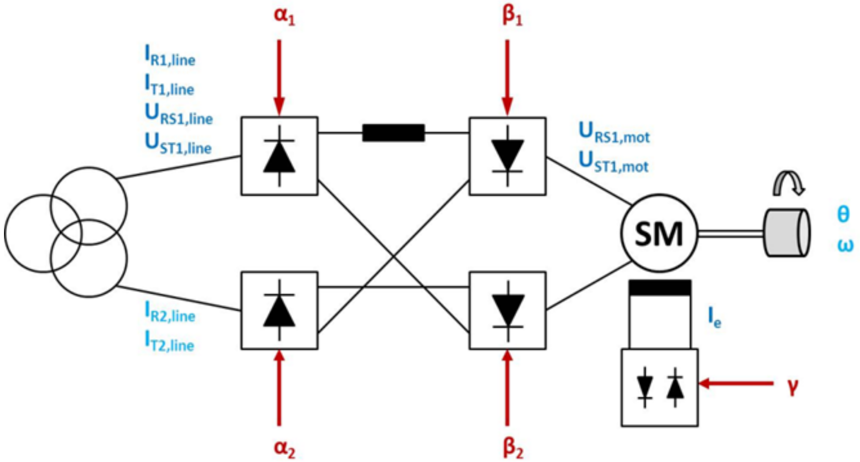
Load commutated inverter and synchronous machine



The system: High power variable speed drive (up to 70 MW)

- Load commutated inverter (LCI)
  - Double six-pulse diode bridges
  - Rectifier connected to grid
  - DC link inductor
  - Inverter connected to machine
- Synchronous machine
  - Field excitation, damper windings

Load commutated inverter and synchronous machine



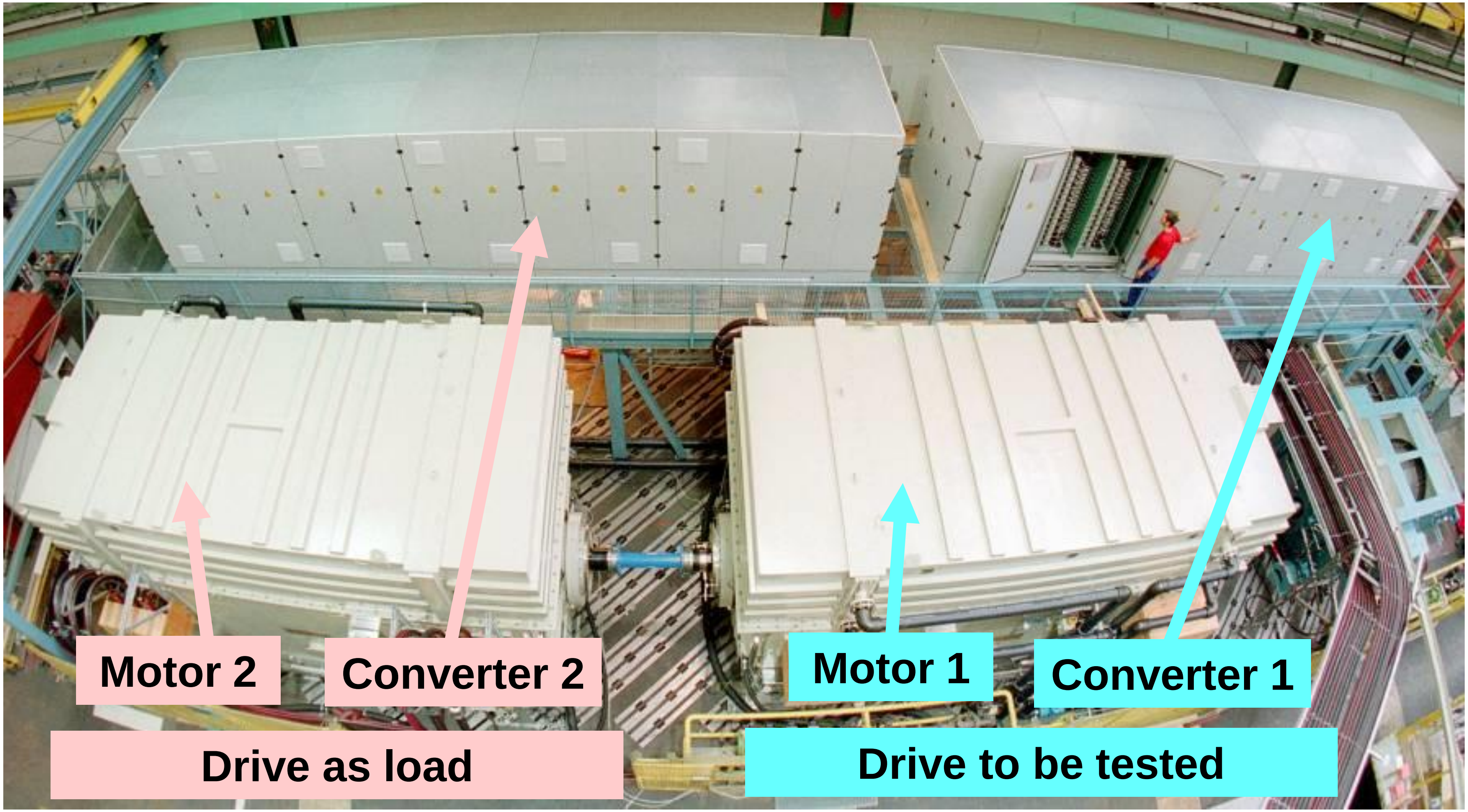
The system: High power variable speed drive (up to 70 MW)

- Control input
  - Rectifier firing angle α
  - Inverter firing angle β
- Control objective
  - Steer torque to reference

MEGADRIVE-LCI Fields of Industries & Applications

Industries	Applications
Cement, Mining and Minerals	Fans and pumps
Chemical, Oil and Gas	Compressors and extruders
Marine	Propulsion systems
Metals	Blast furnace blowers and wire rod mills, fans and pumps
Pulp and Paper	Fans and pumps
Power Generation	Starters for gas turbines and hydro pumped-storage power plants, boiler feed-water pumps
Water and Waste Water	Pumps
Other Applications	Test stands and wind tunnels

VSD system test   Example of 48 MW B2B test



Delivered three 48 MW / 3600 rpm export compressor drives for Ormen Lange, 2005

Google

Load commutated inverter and synchronous machine

Kolsness ***: Revenue of 16 billion USD in 2013***

LCI stops; revenue stops

- **Motivation:**
  - Gas compression plant
  - Weak grid conditions (remote area in Norway)
  - **Safety critical**
  - Existing controller (PI) based on inner/outer loop design
    - Inverter angle β controls machine
    - Rectifier angle α controls DC link
  - MPC controls α and β "simultaneously"
    - Increased robustness to line voltage drops

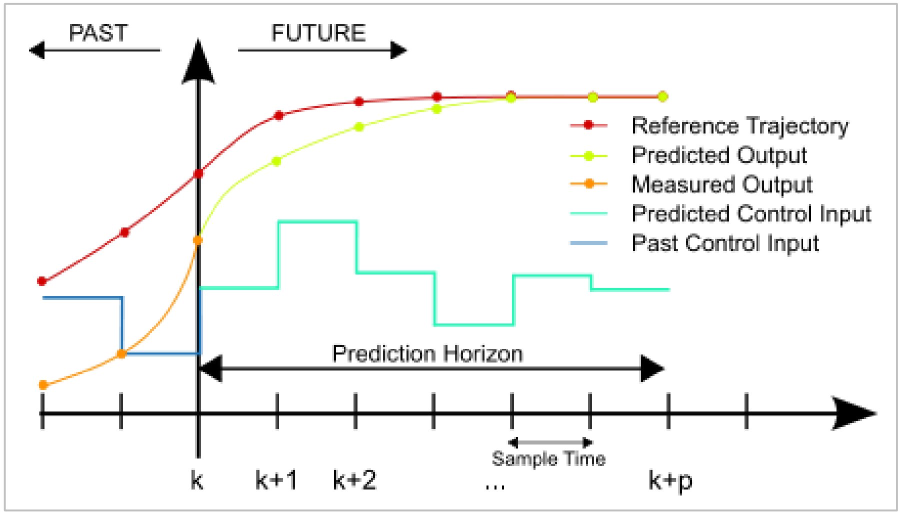
Nonlinear Model Predictive Control

MPC in a Nutshell

- Predict the states and outputs of the system over a finite time horizon by means of a model in dependence of the control inputs.

- Determine the control inputs by solving an optimization problem.

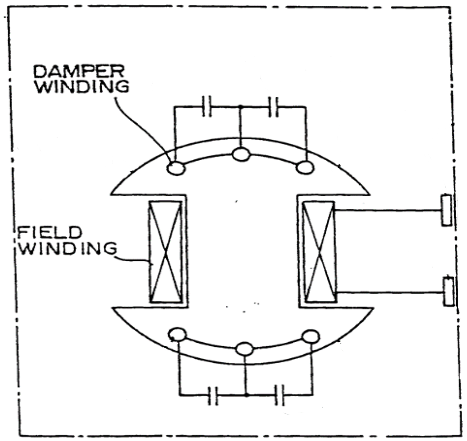
- Implement only the current control inputs and repeat optimizing at the next step.

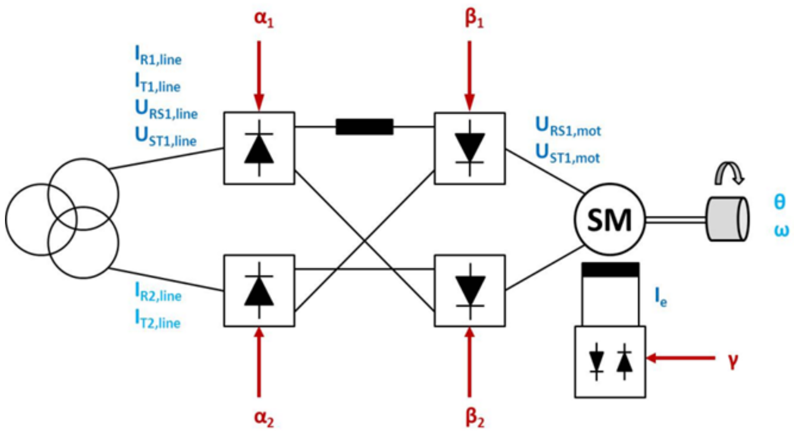


$$\min_{u(\cdot)} \int_{t_0}^{t_0+t_p} \left\| y(t) - y^{\text{ref}}(t) \right\|_Q^2 + \left\| u(t) - u^{\text{ref}}(t) \right\|_R^2 \, dt$$

$$\begin{aligned}
\text{s. t.} \quad x(t_0) &= w_0 \,, \\
\dot{x}(t) &= f(x(t), u(t), p) && \forall\, t \in [t_0, t_0 + t_\text{p}] \,, \\
y(t) &= h(x(t), u(t), p) && \forall\, t \in [t_0, t_0 + t_\text{p}] \,, \\
\underline{u}(t) \leq\ & u(t) \leq \overline{u}(t) && \forall\, t \in [t_0, t_0 + t_\text{p}] \,, \\
\underline{x}(t) \leq\ & x(t) \leq \overline{x}(t) && \forall\, t \in [t_0, t_0 + t_\text{p}] \,.
\end{aligned}$$

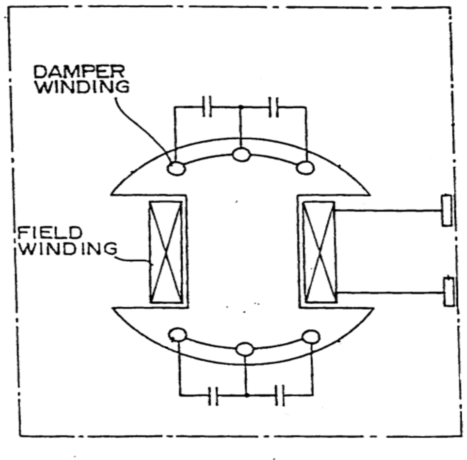
Dynamic model

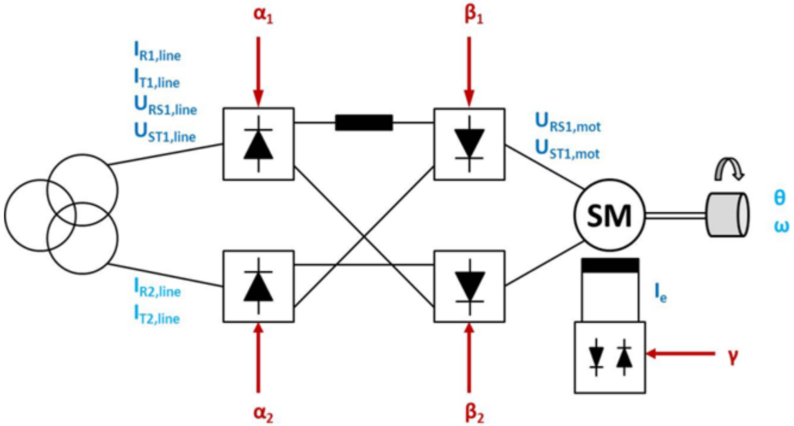




- **State**
  - i_{DC} : DC link current
  - ψ_f : Excitation flux
  - ψ_d, ψ_q : Damper winding fluxes
- **Control input**
  - α, β Rectifier and inverter firing angle

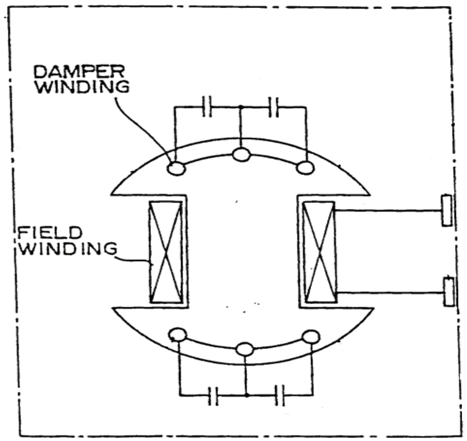
Dynamic model

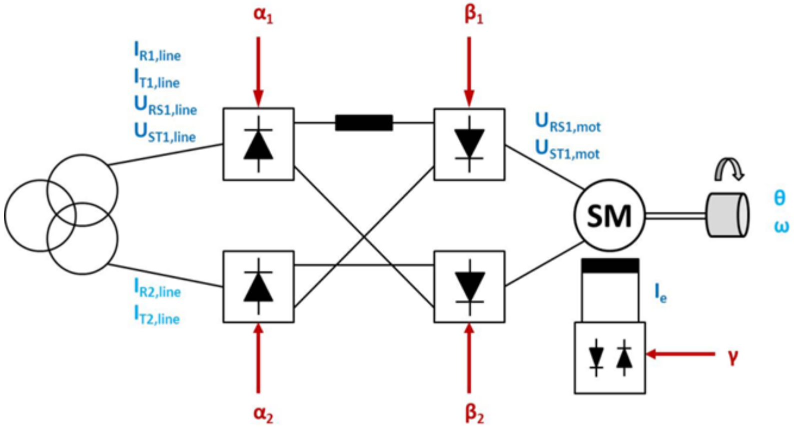




- **State**
  - i_{DC} : DC link current
  - ψ_f : Excitation flux $\leftarrow$ **Controlled by external controller**
  - ψ_d, ψ_q : Damper winding fluxes
- **Control input**
  - α, β Rectifier and inverter firing angle

Dynamic model





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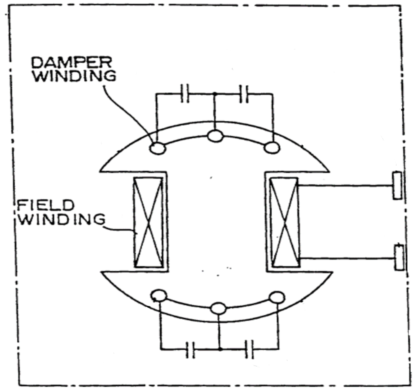
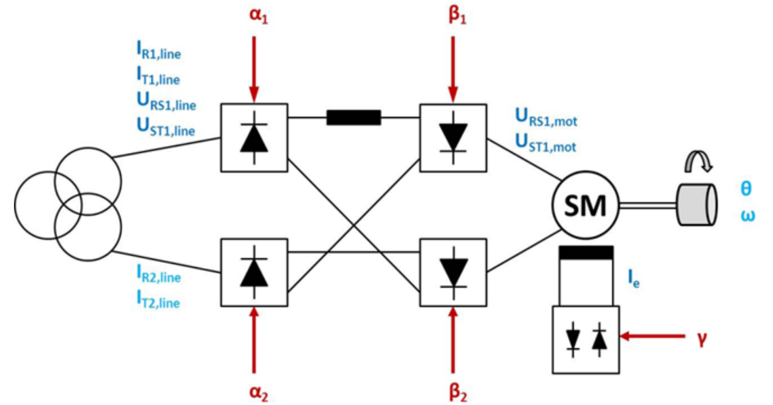
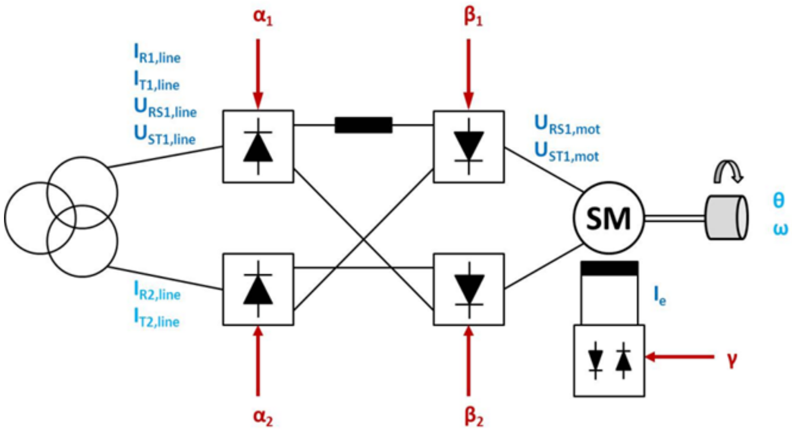
Dynamic model





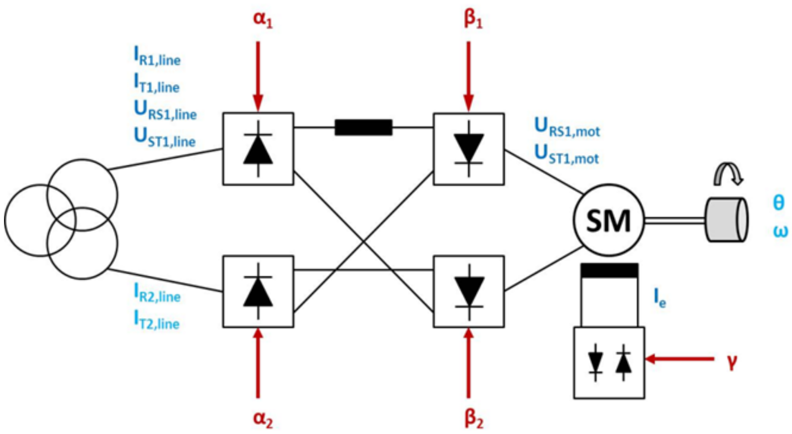
- **State**
  - i_{DC} : DC link current
  - ψ_d, ψ_q : Damper winding fluxes
- **Control input**
  - α, β Rectifier and inverter firing angle
- **Parameters** (slowly varying)
  - ψ_f : Excitation flux
  - ω : Mechanical shaft speed
  - U_L : Line voltage amplitude

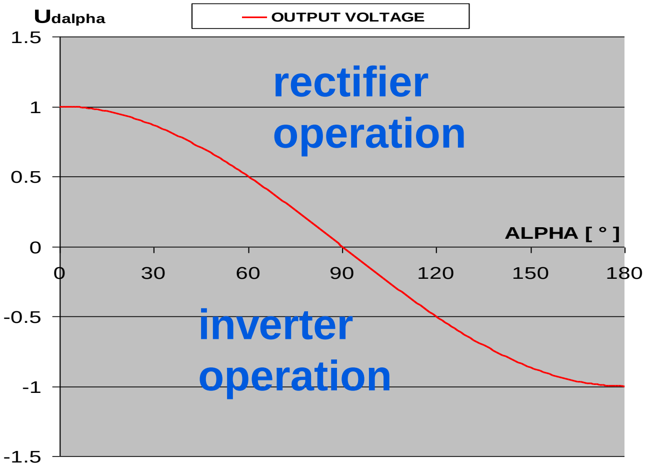
Dynamic model



- **Machine (damper winding) dynamics**
  - Let $\Psi := [\psi_d, \psi_q]^T, \mathrm{I_s} := [\mathrm{i_d}, \mathrm{i_q}]$
  - $\frac{d}{dt}\Psi = A\Psi + BI_s + F\psi_f$
- Averaged approximation of inverter $\mathrm{I_s} \approx i_{DC}\begin{bmatrix}\cos(\beta)\\ \sin(\beta)\end{bmatrix}$
  - $\frac{d}{dt}\Psi = A\Psi + B i_{DC}\begin{bmatrix}\cos(\beta)\\ \sin(\beta)\end{bmatrix} + F\psi_f$

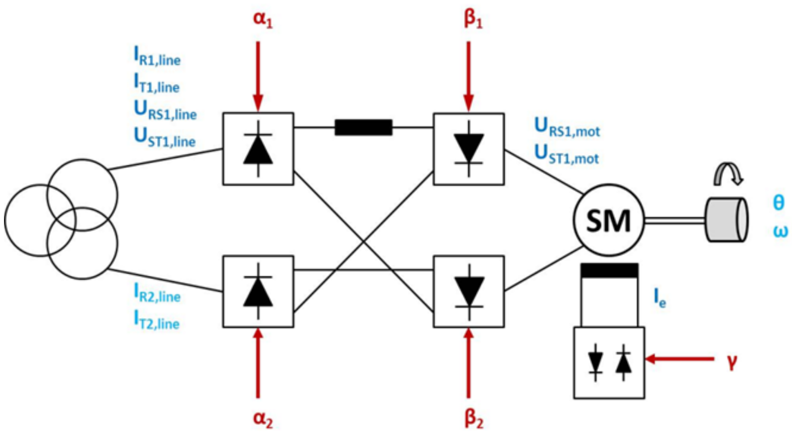
Dynamic model

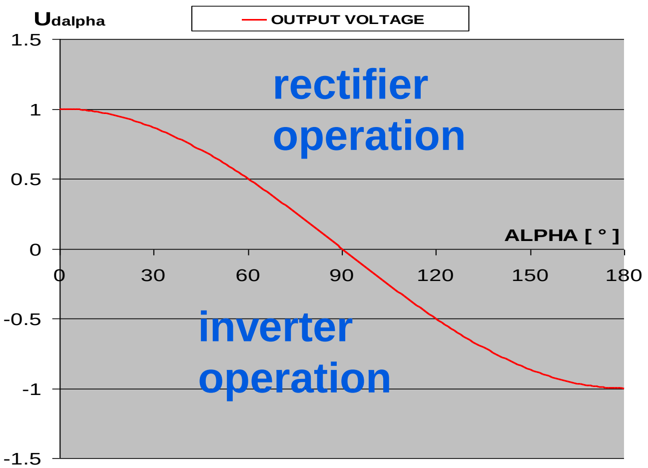




- **DC current dynamics**:
  - $\frac{d}{dt} i_{DC} = \frac{1}{L_{DC}}(-R_{DC} i_{DC} + u_{inv} - u_{rec})$
- Average approximation of inverter and rectifier
  - $u_{rec} = U_L \cos(\alpha)$
  - $u_{inv} = U_M \cos(\beta)$

Dynamic model





- **DC current dynamics**:
  - $\frac{d}{dt} i_{DC} = \frac{1}{L_{DC}}(-R_{DC} i_{DC} + U_L \cos(\alpha) - \boldsymbol{U_M} \cos(\beta))$
- Average approximation of inverter and rectifier
  - $u_{rec} = U_L \cos(\alpha)$
  - $u_{inv} = U_M \cos(\beta)$
  - $\boldsymbol{U_M} = \sqrt{u_d^2 + u_q^2}$ stator voltage amplitude

Dynamic model

- **Machine stator voltage**
  - Let $U_s \coloneqq [u_d, u_q]^T, I_s ;= [i_d, i_q]^T, \Psi_s \coloneqq [\psi_d, \psi_q]^T$
  - $U_s = RI_s + \frac{d}{dt}\Psi_s + \omega S \Psi_s$ (1) Voltage equations
  - $\Psi_s = M_1 I_s + M_2 \Psi + M_3 \psi_f$ (2) Flux linkage equations
  - Put (2) into (1) and approximate:
    - $\frac{d}{dt}\psi_f = 0$, $\frac{d}{dt} I_s = 0$

$$U_s = \Gamma_1(\omega) I_s + \Gamma_2(\omega)\Psi + \Gamma_3(\omega)\psi_f$$

- **Stator voltage as function of state**
  - $U_s = \Gamma_1(\omega) i_{DC} \begin{bmatrix} \cos(\beta) \\ \sin(\beta) \end{bmatrix} + \Gamma_2(\omega)\Psi + \Gamma_3(\omega)\psi_f$

Dynamic model; summary

$$f(x,u) \quad \begin{cases} \frac{d}{dt}\Psi = A\Psi + B i_{DC}\begin{bmatrix}\cos(\beta)\\ \sin(\beta)\end{bmatrix} + F\psi_f \\ \frac{d}{dt} i_{DC} = \frac{1}{L_{DC}}(-R_{DC}i_{DC} + U_L\cos(\alpha) - U_M\cos(\beta)) \\ U_M = \ \left||U_s|\right| \\ .\ U_s = \Gamma(\omega)i_{DC}\begin{bmatrix}\cos(\beta)\\ \sin(\beta)\end{bmatrix} + \Gamma_2(\omega)\Psi + \Gamma_3(\omega)\psi_f \end{cases}$$

Dynamic equations

$$j(x,u) \quad \left\{ \ T = \psi_d i_q - \psi_q i_d \right.$$

Torque equation

- Three states, two inputs

Nonlinear Model Predictive Control

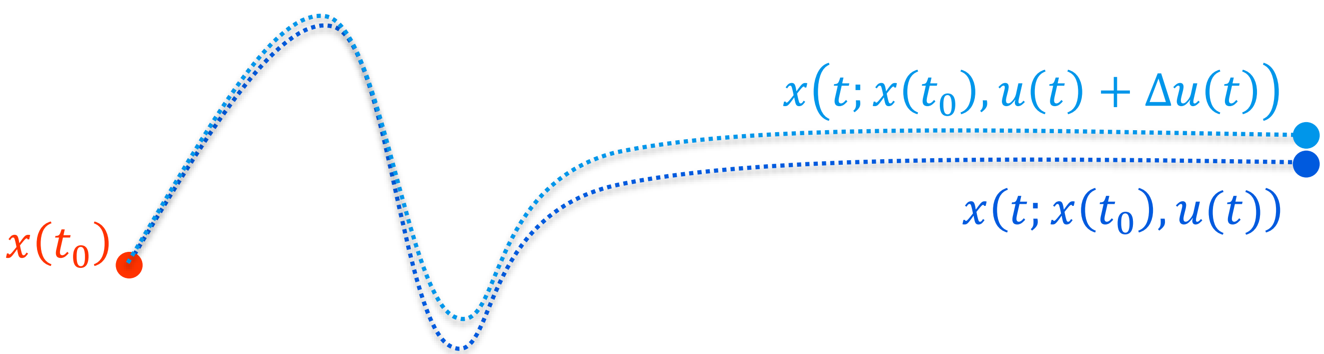
- ACADO Toolkit solves **optimal control problems** of the following form:

$$
\begin{aligned}
\min_{x(\cdot),u(\cdot)} \int_{t_0}^{t_0+t_p} & J\big(x(t),u(t)\big)\,dt \\
s.t.\quad x(t_0) &= w_0 \\
\dot{x}(t) &= f\big(x(t),u(t)\big) \quad \forall\, t \in \left[t_0, t_0+t_p\right] \\
0 &\geq c\big(x(t),u(t)\big) \quad \forall\, t \in \left[t_0, t_0+t_p\right] \\
0 &\geq \tilde{c}\Big(x\big(t_0+t_p\big)\Big)
\end{aligned}
$$

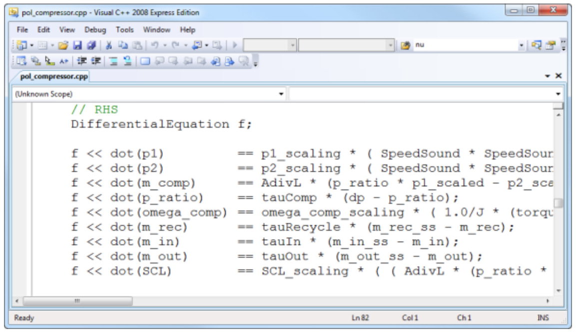
- ACADO: Open source software from KU Löwen, Belgium
  - **`www.acadotoolkit.org`**

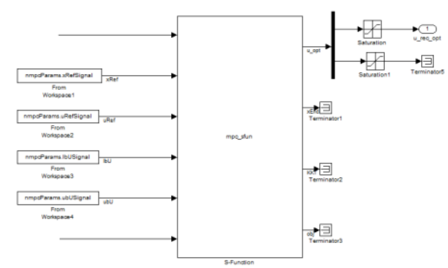
Principle of ACADO
Sequential approach

- Sequential approach; **shooting method:**
  - **Integrate dynamic system** along prediction horizon $[t_0, t_0 + t_p]$ and obtain corresponding sensitivities
  - Solve resulting NLP with SQP method



Practical use of ACADO
Code Generation Workflow





1. Formulate NMPC problem using the ACADO Toolkit **(www.acadotoolkit.org)**
2. Compile/run to auto-generate highly efficient, customized, and self-contained NMPC algorithm
3. Compile NMPC algorithm into Simulink S-function
4. Compile and download Simulink application to AC 800PEC

Simulation results
Simulation set-up

High fidelity Simulink model of LCI:

- Simulation model used by business unit
- Real costumer project: 12/12p LCI, 12 MW

Simulation scenario:

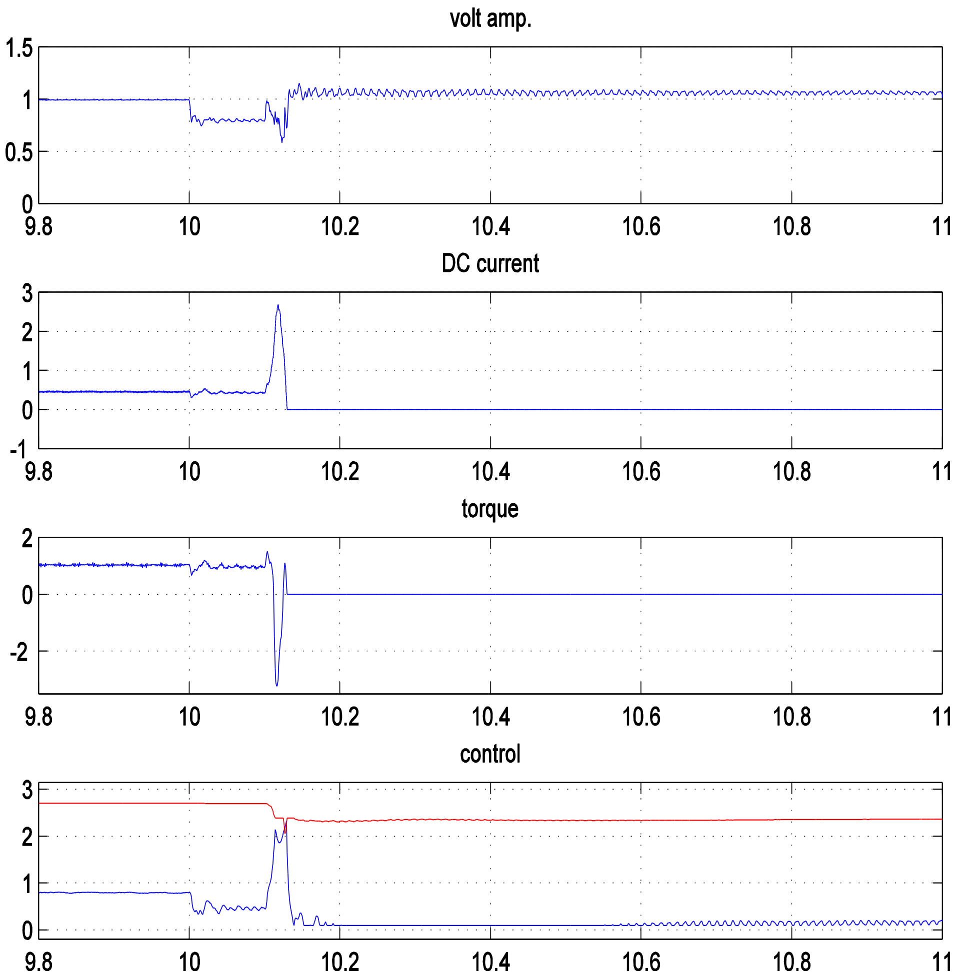
- System at steady-state with nominal torque and speed
- Simulate grid voltage drops

Control objectives:

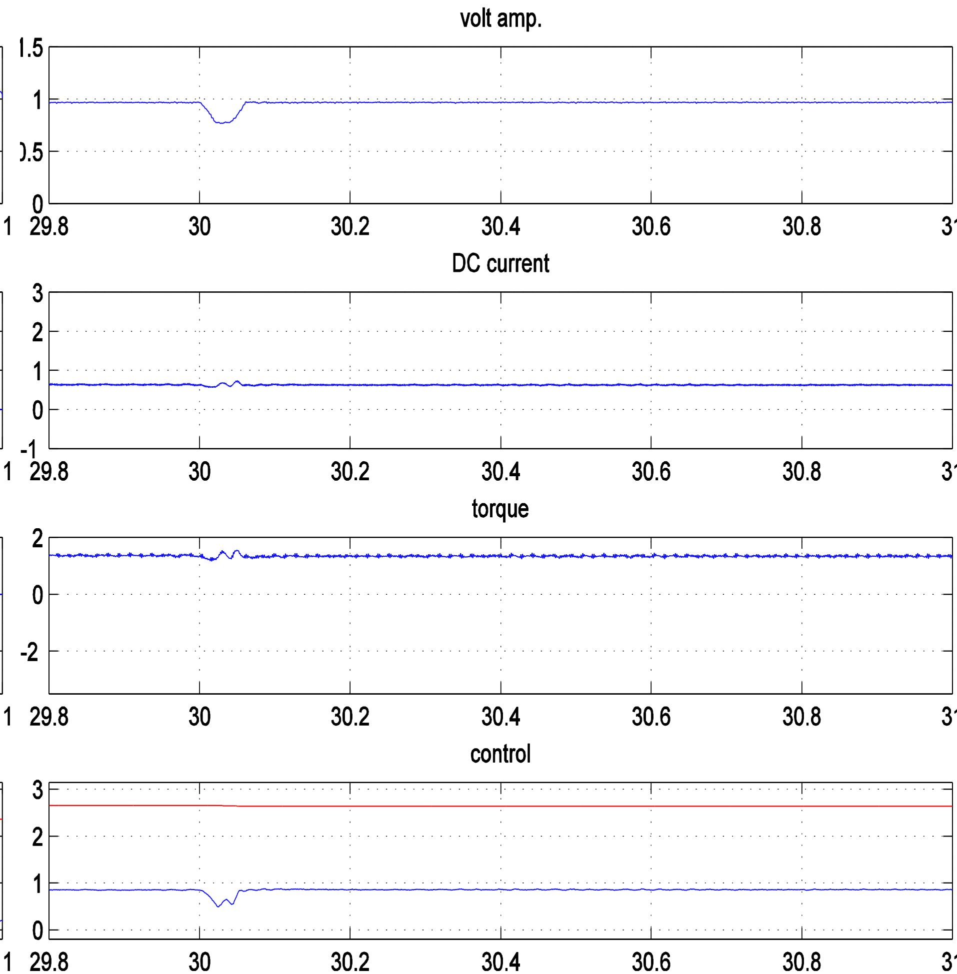
- Can controller keep up the torque (ride-through)?

Voltage drop 1 p.u. → 0.8 p.u

PI

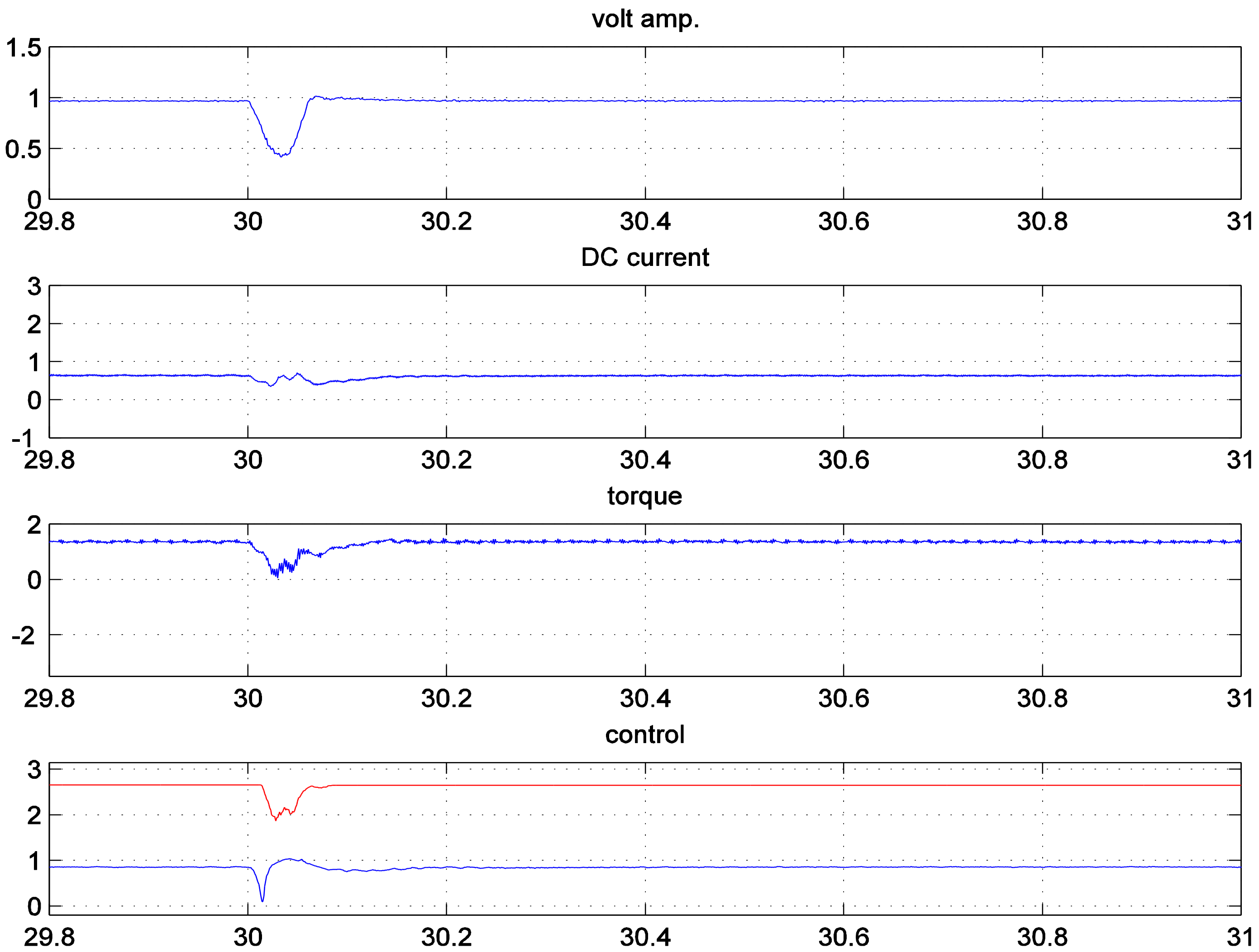


MPC



Voltage drop 1 p.u. → 0.5 p.u.

MPC



Experimental results
Experimental set-up

Low voltage LCI and sync. machine

- 400 V voltage
- 11.6 kW power
- DC motor acts as load

Experimental results
Control platform

Control platform: AC 800PEC

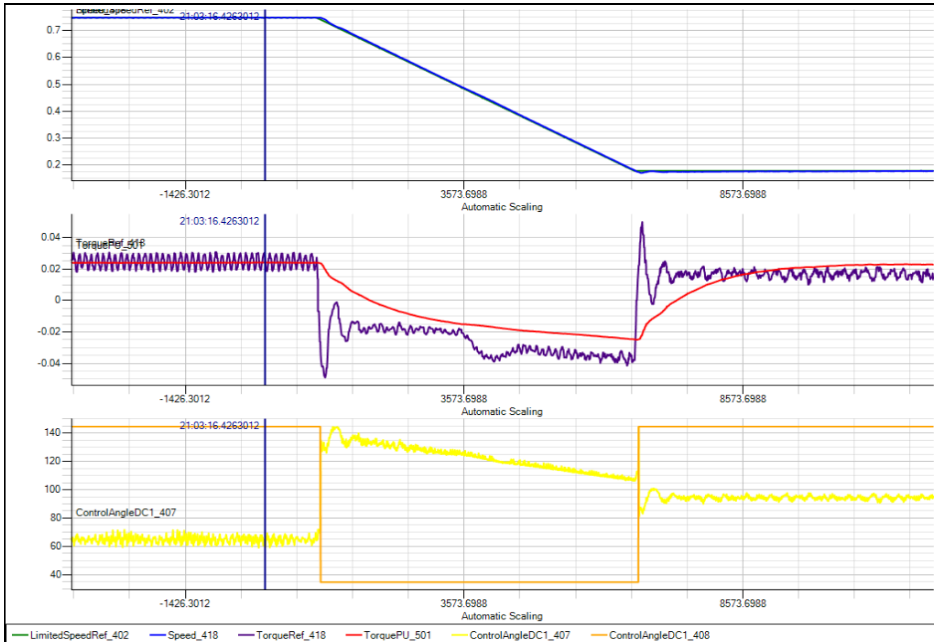
- Standard control platform at ABB
- PowerPC single core @ 600 MHz
- 64 Mb SDRAM
- 16 MB Flash
- Virtex II FPGA

”PEC 800”

Sampling time 1 ms

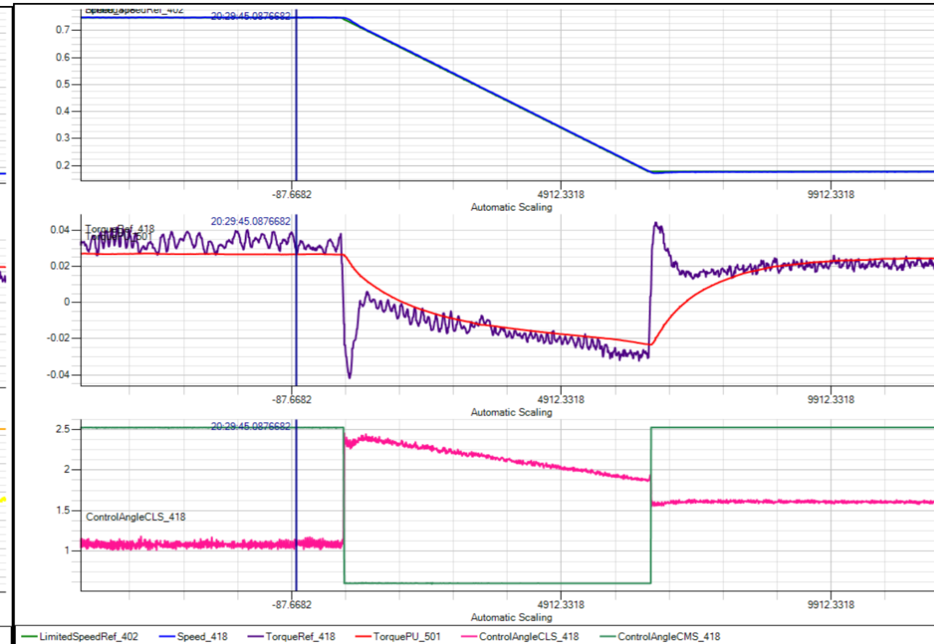
PI

MPC



Signal	Value for Cursor1	Value for Cursor2
LimitedSpeedRef_402	0.75	0.180000007152557
Speed_418	0.749378284551648	0.179388093780071
TorqueRef_418	0.0259352018580397	0.0169345262703585
TorquePU_501	0.0242846816141975	0.0232106616241291
ControlAngleDC1_407	64.1571375016941	93.5190567139984
ControlAngleDC1_408	145	145

Date	4/15/2014
Cursor 1	21:03:12.9543012
Cursor 2	21:03:28.4183012
Range	00:00:15.4640000



Signal	Value for Cursor1	Value for Cursor2
LimitedSpeedRef_402	0.75	0.180000007152557
Speed_418	0.75096304691701	0.179904438592612
TorqueRef_418	0.0318515063578005	0.020984044257957
TorquePU_501	0.0273483983709588	0.0247165696409433
ControlAngleCLS_418	1.08409436570504	1.60346014361915
ControlAngleCMS_418	2.52813912982166	2.53051266941921

Date	4/15/2014
Cursor 1	20:29:41.0876682
Cursor 2	20:29:57.0796682
Range	00:00:15.9920000

- MPC response to torque reference changes similar to PI
- MPC **also handles voltage disturbance**

Conclusion

- LCI and synchronous machine
- Nonlinear MPC
  - Continuous optimization variables
- Solution using ACADO
  - Solution in 1 ms

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