WP4: Energy Optimization Final Report

ETH

Imperial College London

ABB

Politechnika Krakowska im. Tadeusza Kościuszki

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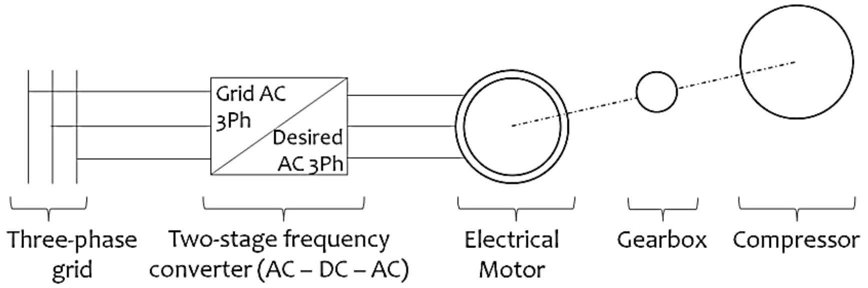
The energy solutions of tomorrow

ETH

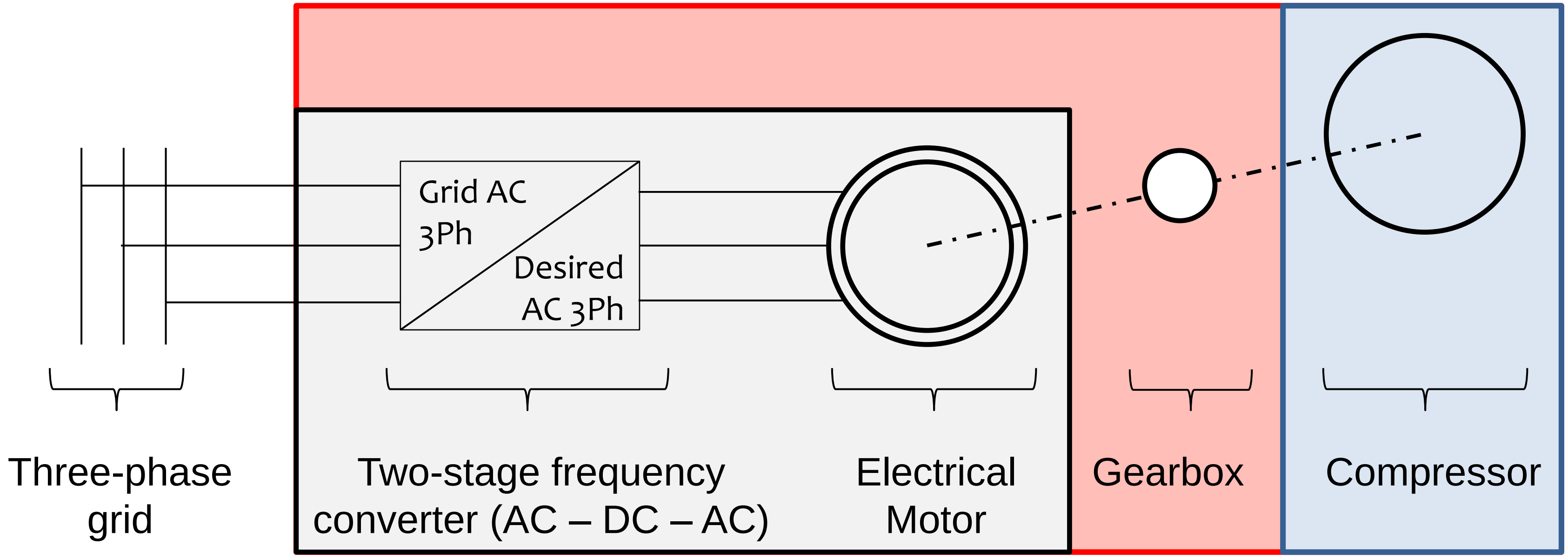
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

WP4 Energy Optimization
Objectives

- Developing robust advanced control techniques for electrical drives, taking account of optimal efficiency
  - Identification of accurate models that consider previously unaccounted effects such as iron losses and machine saturation
  - Finding the best control policy to improve efficiency for a single machine given the requirements from the process (e.g. torque and speed)
  - Robust control techniques to account for variations in model parameters for constrained control problems
- Implementing a practical case study of the control algorithms
  - Developing a two-motor test rig to emulate process machinery (e.g. a compressor)
  - Demonstrations of real-time control, especially for compressors and variable speed drives



WP4 Energy Optimization Objectives



Optimization of electrical drives

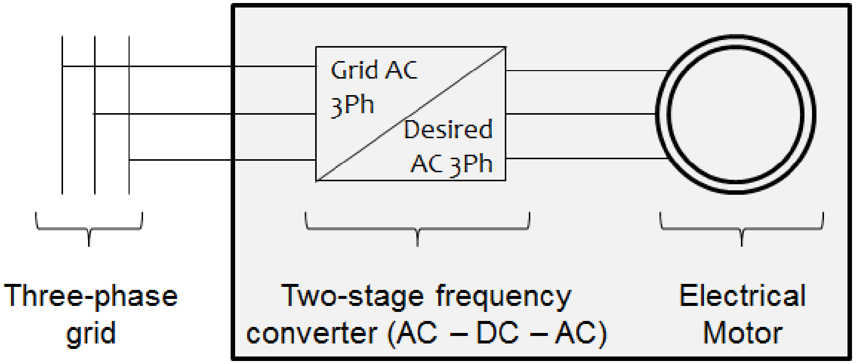
Electrical drive & compressor interaction

Politechnika Krakowska im. Tadeusza Kościuszki

WP4: Optimization of electrical drives

Giampaolo Torrisi, ETH

- TASK
  Loss modelling of electrical drives and Model Predictive Control of compressors
- OUTCOMES
  - Development of accurate loss models and optimization schemes for electrical motors accounting for copper and iron losses and eddy currents
  - Design of robust control algorithm to take into account uncertainties and performance bounds
  - Design of controllers for compressors
    - » PI control, back-stepping control and Model Predictive Control
    - » Active surge control of electrically driven centrifugal compressors



WP4: Other activity
Giampaolo Torrisi, ETH

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SECONDMENTS

- Secondments at ABB Corporate Research Centre in Krakow (i) for experiments and model identification on a centrifugal compressor, and (ii) for efficiency improvement and drive system operation

PAPERS

- Torrisi, G., Mariéthoz, S., and Smith , R., 2014, Identification of magnetic characteristics of induction motors based on the Jiles-Atherton model, *EPE’14-ECCE*, 26-28 August 2014, Lappeenranta, Finland
- Torrisi, G., Mariéthoz, S., Smith , R.S., and Morari, M., 2015, Comparison of the efficiency of different magnetization strategies for a variable speed induction machine drive, submitted to 17th Conference on Power Electronics and Applications, *EPE'15-ECCE* Europe, accepted.
- Torrisi, G., Jaramillo, V-H., Ottewill, J.R., Mariéthoz, S., Morari, M., and Smith, R.S., Active surge control of electrically driven centrifugal compressors, *European Control Conference* ’15, accepted.

TRAINING

- Convex Optimization, Mixed-Integer Optimization
- Model Predictive Control
- Coding knowledge for electric engineering experiments
- Professional Skills Course from Imperial College
- German language courses

WP4: Dynamic control and analysis of uncertain systems, Bart van Parys, ETH

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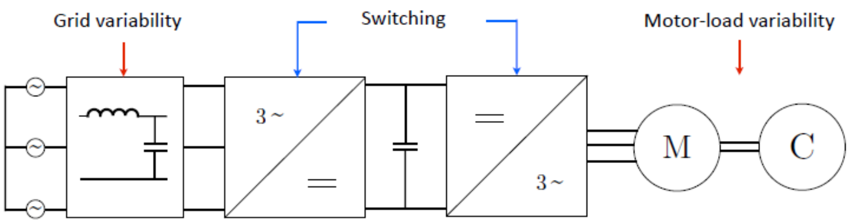
TASK

Robust control formulations for tackling two problems:

- Synthesis of near-optimal controllers,
- Analysis of suboptimality of controllers.



Abstraction

Consider a **infinite horizon** problem :

$$V_\infty(x) := \inf_\pi \mathbb{E}\left[\sum_{t=0}^{\infty} \beta^t \left(\mathrm{x}_t^T Q \mathrm{x}_t + \mathrm{u}_t^T R \mathrm{u}_t\right)\right]$$

subject to:

$$\mathrm{x}_{t+1} = A\mathrm{x}_t + B\mathrm{u}_t + G\mathrm{w}_t,$$
$$(\mathrm{x}_t, \mathrm{u}_t) \in Z, \ \mathrm{x}_0 = x$$

The *robustness* model :

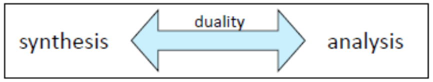
- **Additive noise**, known moments and support,
- worst-case constraint satisfaction.

The cost model :

- discounted **quadratic** stage cost.

INTRACTABLE

Mathematical idea via analogy



1. Synthesis, affine *primal* restriction

$$p := \inf \ \langle c, u\rangle, \ u: \text{ affine}$$
$$\text{st} \ \ Au = b, \ u \in \mathcal{K}$$

2. Analysis, affine *dual* restriction

$$d := \sup \ \langle y, b\rangle, \ (y, s): \text{ affine}$$
$$\text{st} \ \ A^\star y + s = c, \ s \in \mathcal{K}^\star$$

where $p \geq d$.

Both synthesis and analysis are **computationally tractable.**

OUTCOMES

- Find a control policy (i.e. a switching pattern) that is a trade-off between:
  - » Tracking performance, robust against grid and motor-load variability
  - » Energy consumption, consisting of conduction and switching losses

WP4: Other activity
Bart van Parys, ETH

PAPERS

- Van Parys, B., Goulart, P.J., and Morari., M., 2012, Performance bounds for min-max uncertain constrained systems, *IFAC Conference on Nonlinear Model Predictive Control 2012* (NMPC'12), August 23-27, 2012, Noordwijkerhout, the Netherlands.
- Van Parys, B., Goulart, P.J., Morari, M., 2012, Infinite-horizon performance bounds for constrained stochastic systems, *51st IEEE Conference on Decision and Control*, Dec 10-13 2012, Maui, Hawaii, pp 2171-2176 .
- Van Parys, B., Goulart, P.J., and Morari., M., 2013, Infinite horizon performance bounds for uncertain constrained systems, *IEEE Transactions on Automatic Control*, 58, 2803-2817.

TRAINING

- Convex Optimization and Probability Theory
- Model Predictive Control
- Professional Skills Course from Imperial College


WP4: Electrical drive & compressor interaction , Victor Jaramillo (ABB-PL) Alejandro Fernando Gómez (TU-KRAK)

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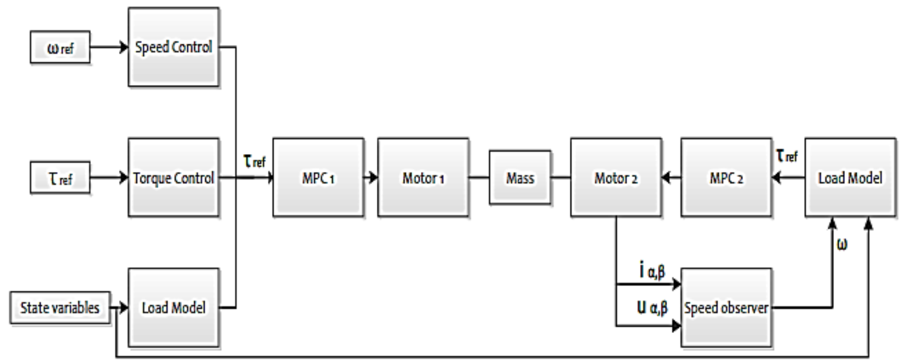
- TASKS
  Compressor modeling for real-time applications

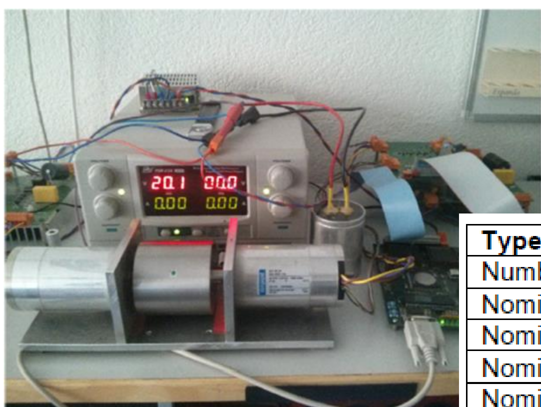
- OUTCOMES
  - ETH test rig was used to emulate a compressor system
    - » two-coupled-machine system, one is a drive, the other emulates a mechanical load



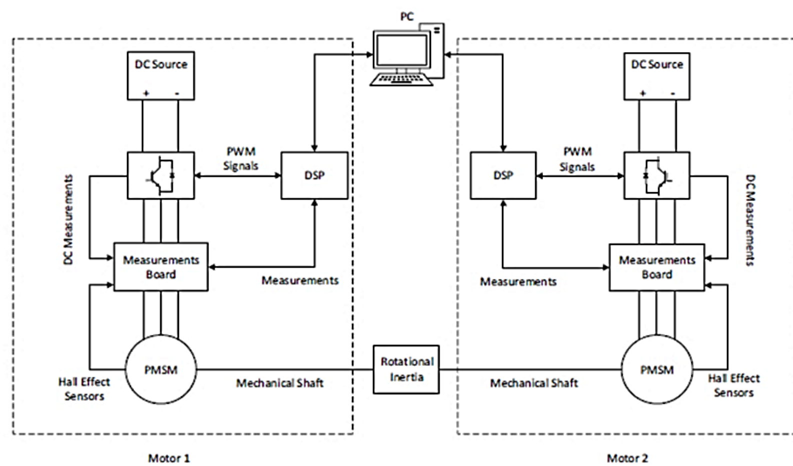
    - » A compressor model relating pressure ratio, mass flow rate, torque and speed implemented in the mechanical system emulator
  - Design of controllers
    - » PI control, back-stepping control and Model Predictive Control

WP4: Case study at ETH

- Giampaolo Torrisi (ETH), Victor Jaramillo (ABB-PL), and Alejandro Fernando Gómez (TU-KRAK)
- An experimental test rig to validate the theoretical results
  - The test bench of two motors whose shafts are connected to each other
  - Each of the motors is controlled by a DSP board, programmable in C. The data acquisition system measures input voltages and currents
  - It provides a framework for compressor emulation



Type	Unit	Value
Number of pole pairs	-	*4*
Nominal voltage	V DC	*48*
Nominal speed	Rpm	*4000*
Nominal torque	N m	*0.36*
Nominal current	A	*4.5*
Nominal output power	W	*150*
No-load speed	Rpm	*6800*
Rotor moment of inertia	Kg m^2	*19 10^{-6}*



WP4 Achievements

INTENDED OUTCOME	METHODOLOGY DEVELOPED	MEASURE OF SUCCESS
Developing advanced control techniques for electrical drives, taking account of optimal efficiency. This requires improved modelling of previously unaccounted effects Given a single machine and the mechanical requirements from the process, we look for the best control policy to improve efficiency Consider a case study as practical implementation of the control algorithms, in particular a two-motor test rig in which a process can be emulated (e.g. a compressor) . The case study is particularly suited for compressors and variable speed drives	Accurate estimation of copper and iron losses are necessary but unavailable from the constructor. Hence we derive a procedure to build the model of losses The estimate of iron losses is considerable in magnitude, thus we consider them in control strategies Robust control algorithms take into account uncertaintes and performance bounds Testing controllers for electric drives connected to compressors can be done on scaled test benches The compressor is emulated by a software which replicates the dynamics of a real compressor	Accounting for the iron losses allow us to achieve up to 20% power losses reduction on the tested 1HP induction motor. This is achieved by advanced control techniques The efficiency increases accordingly up to 3%. This reduces sensibly the stress on the motor and increases the machine rating Control techniques for compressor reduce the risk of instabilities during the operations. This is achieved through combined backstepping control and Model Predictive Control techniques. Recycle valves, usually present in modern plants, can be successfully considered