High-Speed High-Performance Model Predictive Control of Power Electronics Systems

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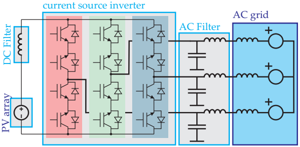
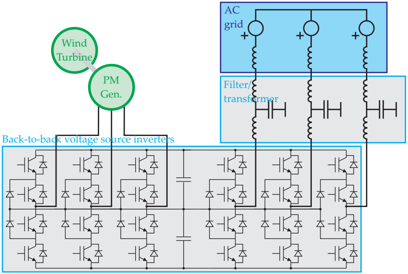
Outline

Application Areas

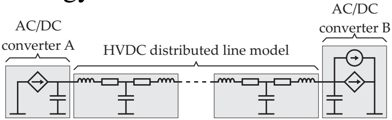
1. Renewable energy generation





- Components: electric drives, frequency/level power converters

2. High-voltage DC electrical energy transmission



- Components: frequency/level power converters

Application Area summary

1. Renewable energy generation,Transmission, Electrical energy storage
2. Transportation, Industry/robotics, Consumer electronics

- Components: electric drives, frequency/level power converters

Power electronics systems

- Broad range of applications
- System made of different types of
  - Electric drives
  - Frequency/level power converters
- Improving performance of these two types of components

$\Rightarrow$ large impact

Control challenges

1. Dynamic performance and constraint satisfaction
2. Systematic control approach
    - MPC
3. Very fast dynamic modes
    - $\Rightarrow$ Fast switching/sampling frequencies (100Hz-1MHz)
    - Fast MPC
4. Semiconductor switches $\Rightarrow$ power losses and operating limitations
    - Constrained power losses and operating frequency
5. Energy conversion $\Rightarrow$ desired high energy efficiency
6. Grid applications $\Rightarrow$ desired high power quality
7. Low-power applications $\Rightarrow$ desired low size and consumption of control system

- System design and control optimization

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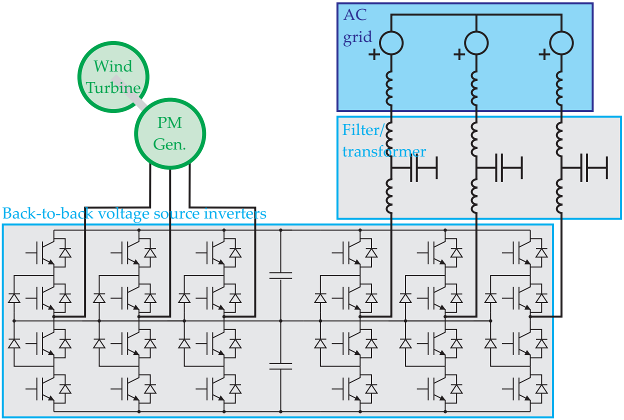
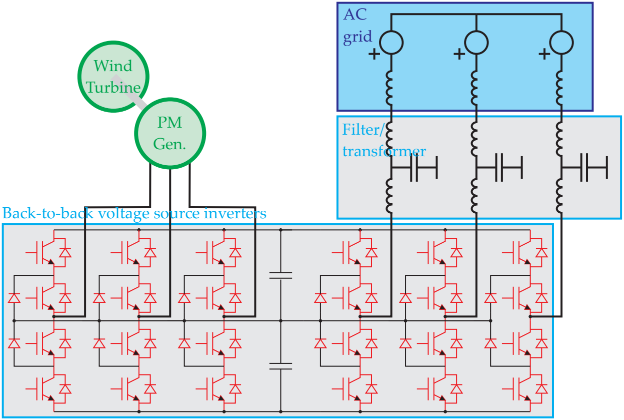
Electric drives — Frequency/level conversion



Power electronics systems

- Controllable semiconductor switches

Electric drives — Frequency/level conversion



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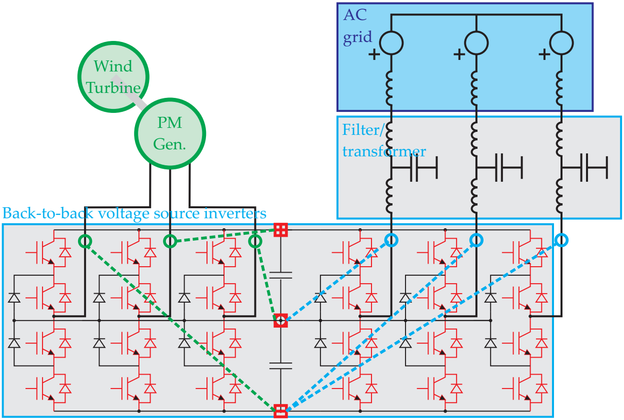
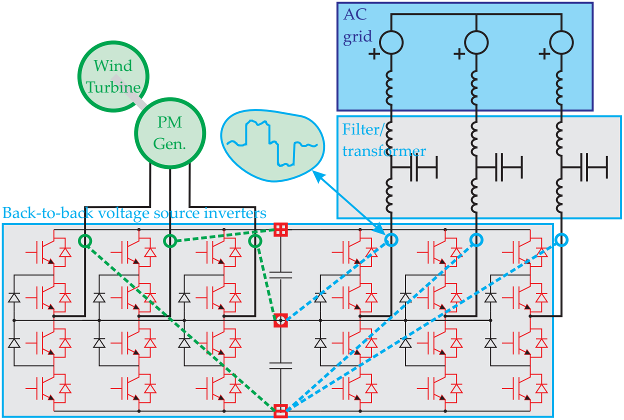


Power electronics systems

- Controllable semiconductor switches
- interconnect different points of circuits

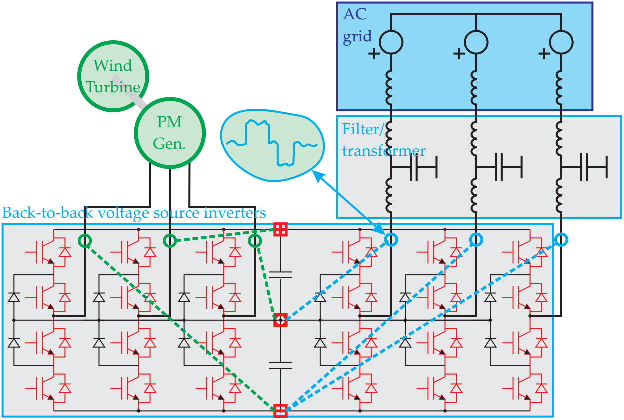
Electric drives — Frequency/level conversion



Power electronics systems

- Controllable semiconductor switches
- interconnect different points of circuits ⇒ switched waveforms

Electric drives — Frequency/level conversion

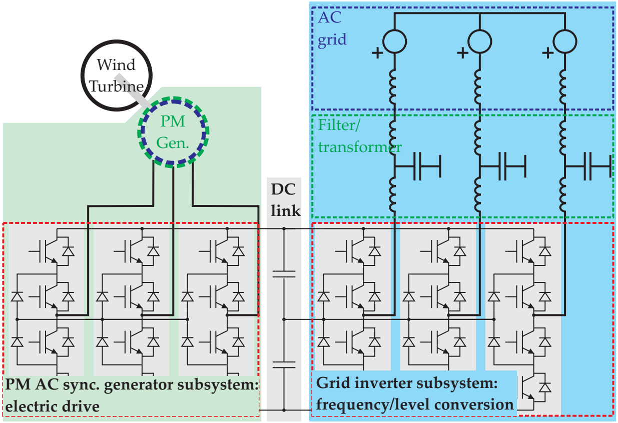


Power electronics systems

- Dynamics ⇒ Complex hybrid systems

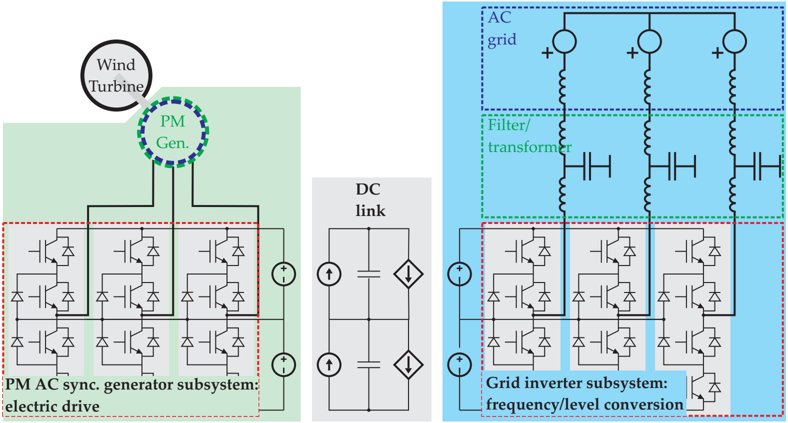
$$\dot{x} = \sum_i s_i \left(F_i x + G_{vi} v\right) \quad s_i \in \{0, 1\} \quad \sum_i s_i = 1$$

Subsystem decomposition



Structured system: modes and objectives

Subsystem decomposition

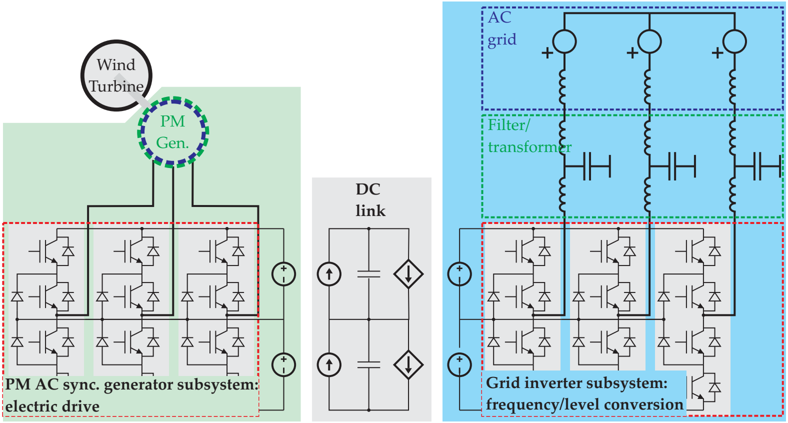


Structured system: modes and objectives

- Linear subsystems with binary inputs ⇒ Much simpler hybrid dynamics

$\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}_{\mathrm{u}}\boldsymbol{u} + \boldsymbol{G}_{\mathrm{w}}\boldsymbol{w} \quad \boldsymbol{u} = \sum_i s_i \boldsymbol{v}_i \quad s_i \in \{0, 1\} \quad \sum_i s_i = 0$

Subsystem decomposition



Structured system: modes and objectives

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  $\dot{x} = Fx + G_u u + G_w w \quad u = \sum_i s_i v_i \quad s_i \in \{0, 1\} \quad \sum_i s_i = 0$

⇒ 2 modelling and control approaches

Modelling approaches

1. Hybrid system approach
   - Linear subsystems with binary input
     $\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{F}_{\mathrm{u}}\boldsymbol{u} + \boldsymbol{F}_{\mathrm{w}}\boldsymbol{w} \quad \boldsymbol{u} = \sum_i s_i \boldsymbol{v}_i \quad \sum_i s_i = 1 \quad s_i \in \{0, 1\}$

2. Model averaging approach ⇒ relaxed binary constraints
   - Linear subsystems with linearly constrained continuous input
     $\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}_{\mathrm{u}}\boldsymbol{u} + \boldsymbol{G}_{\mathrm{w}}\boldsymbol{w} \quad \boldsymbol{u} = \sum_i d_i \boldsymbol{v}_i \quad \sum_i d_i = 1 \quad d_i \in [0, 1]$

Modelling approaches

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   - Linear subsystems with binary input
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   - Accurate model ⇒ loss or distortion minimization
2. Model averaging approach ⇒ relaxed binary constraints
   - Linear subsystems with linearly constrained continuous input
     $\dot{\boldsymbol{x}} = \boldsymbol{F}\boldsymbol{x} + \boldsymbol{G}_{\mathrm{u}}\boldsymbol{u} + \boldsymbol{G}_{\mathrm{w}}\boldsymbol{w} \quad \boldsymbol{u} = \sum_i d_i \boldsymbol{v}_i \quad \sum_i d_i = 1 \quad d_i \in [0, 1]$
   - Model sufficient for control ⇒ MPC of averaged dynamics

Outline

Linear Explicit MPC based on model averaging

- Discretization of averaged dynamics with sampling period T_s
  $\boldsymbol{x}_{k+1} = \boldsymbol{A}\boldsymbol{x}_k + \boldsymbol{B}_\mathrm{u}\boldsymbol{u}_k + \boldsymbol{B}_\mathrm{w}\boldsymbol{w}_k \quad \boldsymbol{u}_k = \sum_i d_{ki}\boldsymbol{v}_{ki} \ \sum_i d_{ki} = 1 \ d_{ki} \in [0,1]$
- Formulation of tracking linear MPC problem

$$\min_{u_k} \sum_{l=k}^{k+N} \|\boldsymbol{x}_l - \boldsymbol{x}_l^\mathrm{e}\|_{\boldsymbol{Q}} + \|\boldsymbol{u}_l - \boldsymbol{u}_l^\mathrm{e}\|_{\boldsymbol{R}} \ \text{track equilibrium point}$$

$$\text{s.t. } \boldsymbol{x}_{l+1} = \boldsymbol{A}\boldsymbol{x}_l + \boldsymbol{B}_\mathrm{u}\boldsymbol{u}_l + \boldsymbol{B}_\mathrm{w}\boldsymbol{w}_l$$

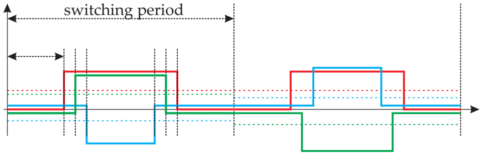
$$\boldsymbol{u}_l = \sum_i d_{li}\boldsymbol{v}_{li} \ \sum_i d_{li} = 1 \ d_{li} \in [0,1]$$

linear input and state constraints

- Can be solved parametrically:
  1. Exactly if shape and orientation of input set does not change
  2. Limitation: length of horizon and dimension of parameter
  3. Yields relaxed variables $d_{ki} \Rightarrow$ need feasible binary solution

Obtain feasible binary solution

- Duty cycle interpretation of d_{ki}
- Apply input vectors $\boldsymbol{v}_{ki}$ with duty cycles d_{ki} over T_s using pulse-width-modulation (PWM)
  $\Rightarrow$ apply $\boldsymbol{v}_{ki}$ during time interval $d_{ki}\, T_\mathrm{s}$



- Approach:
  - Very good dynamic performance
  - Losses and distortion depend on PWM scheme

Linear explicit MPC of 2-level induction motor drive

1. Objective: track torque (currents) and flux

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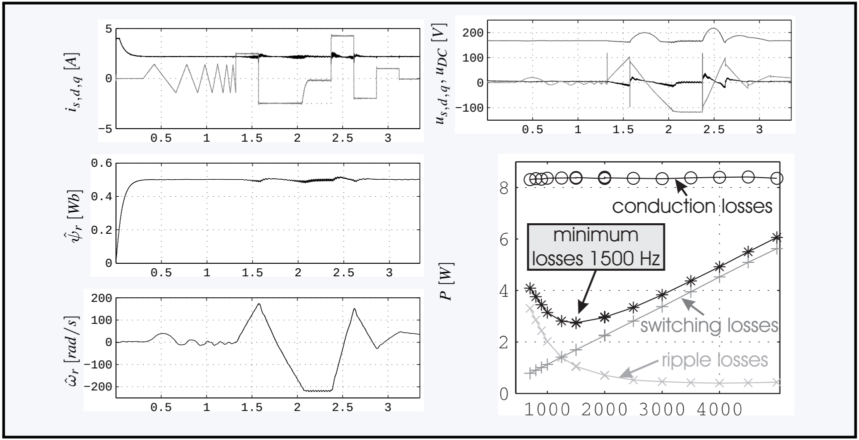
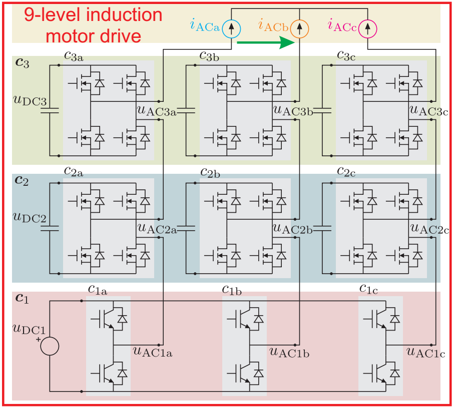
2. State-of-the-art scheme requires 5 kHz for good tracking performance
3. EMPC gives better performance at 1.5 kHz
4. EMPC run-time on low-cost DSP $10\mu s$ (total $30\mu s$)

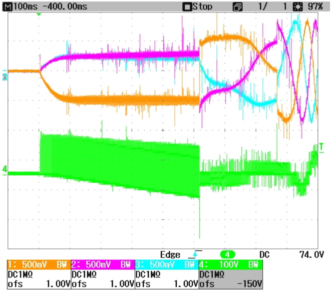
Linear explicit MPC of 2-level induction motor drive

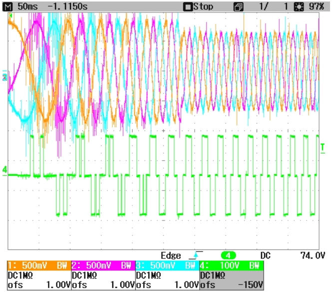
1. Objective: track torque (currents) and flux
2. State-of-the-art scheme requires 5 kHz for good tracking performance
3. EMPC gives better performance at 1.5 kHz
4. EMPC run-time on low-cost DSP 10μs (total 30μs)
5. EMPC $\Rightarrow$ better energy efficiency and dynamic performance



Linear explicit MPC of 9-level induction motor drive

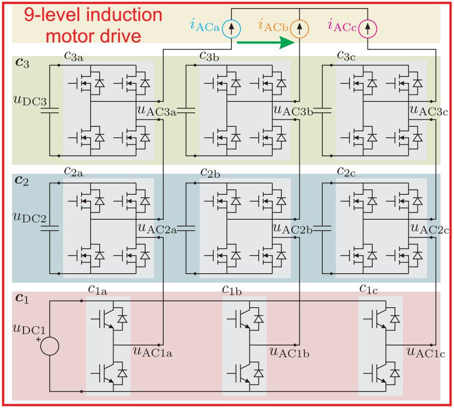


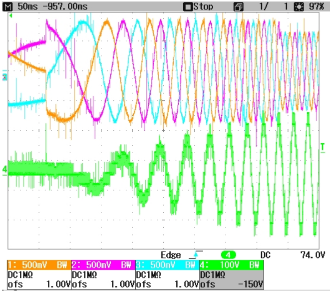


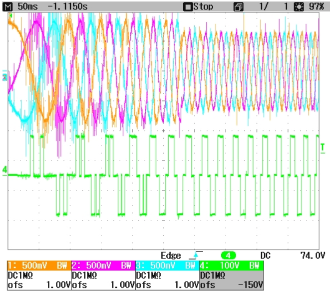


- low-distortion high efficiency drive

Linear explicit MPC of 9-level induction motor drive

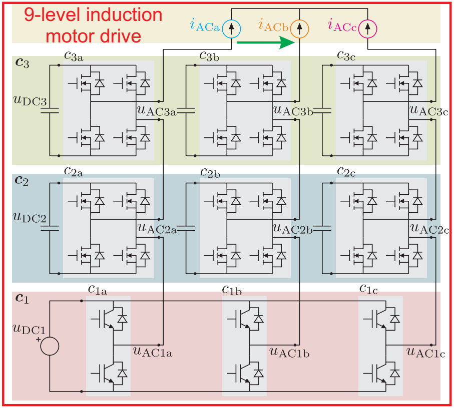


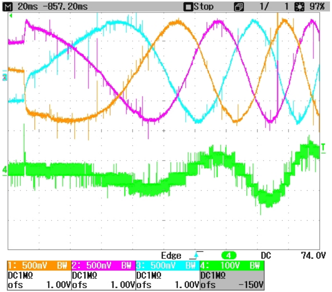


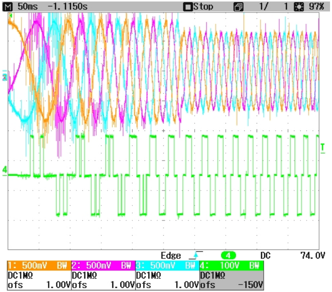


- low-distortion high efficiency drive
- hierarchical approach with linear explicit MPC

Linear explicit MPC of 9-level induction motor drive

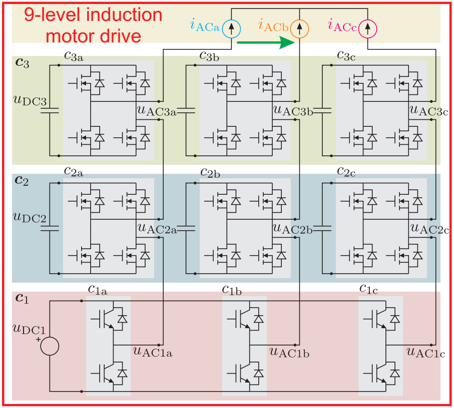


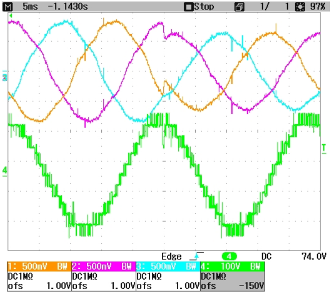


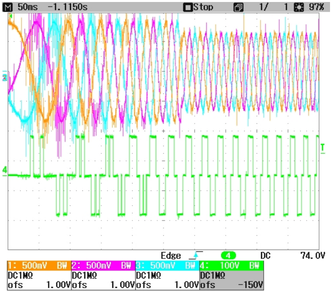


- low-distortion high efficiency drive
- hierarchical approach with linear explicit MPC
- high-dynamic performance
- unified approach

Linear explicit MPC of 9-level induction motor drive







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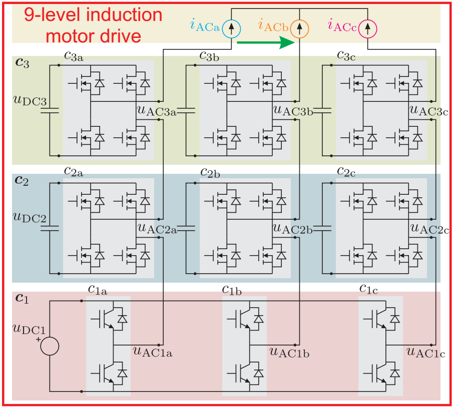

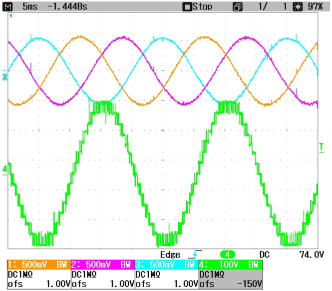

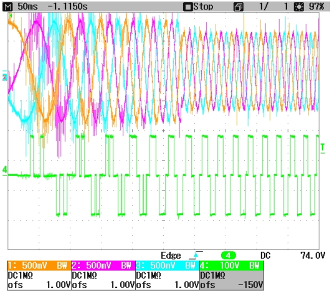

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- Power Electronics Systems' Application Areas
- Control challenges

Modelling power electronics system dynamics

Linear Explicit MPC based on model averaging

Hybrid approach: objective/ status/ future challenges

Conclusions

Hybrid system approach

- Averaging approach gives satisfactory dynamic performance

⇒ Why bothering about hybrid approach?

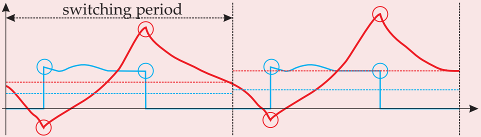
Hybrid system approach

- Averaging approach gives satisfactory dynamic performance

⇒ Why bothering about hybrid approach?

Losses and distortion

- Switching losses in semiconductor devices occur during transitions
- They depend on the switched currents and voltages:



- Conduction losses depend on high frequency currents $\geq f_{\text{switching}}$
- Distortion depends on high frequency currents/voltages $\geq f_{\text{switching}}$
- Averaged model valid only below $f_{\text{switching}}$

⇒ High-frequency model of voltages and currents required to evaluate losses and distortion

Hybrid system approach

- Averaging approach gives satisfactory dynamic performance

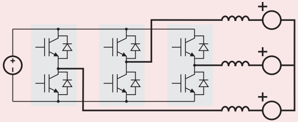
⇒ Why bothering about hybrid approach?

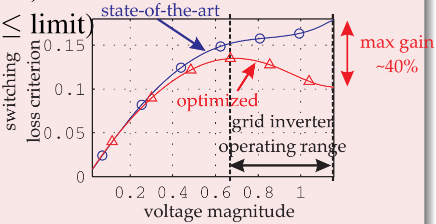
Energy efficiency maximization

- Primary control output defined as an integral over cycle
  - ⇒ infinitely many solutions
- Exploit this property to minimize losses such that

  primary output (e.g. average power) = reference

  other constraints (e.g. distortion $\leq$ limit)



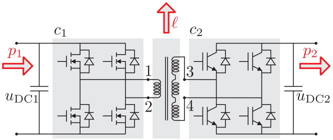


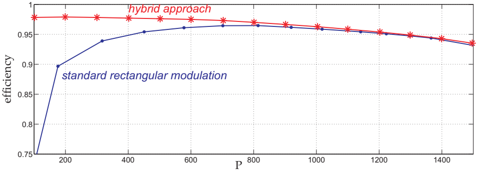
⇒ Hybrid approach can provide significant loss reduction

- Computational complexity ⇒ MIP

Hybrid system approach

- Fairly systematic modelling approach
- Tractable problems
  - too complex for parametric programming
  - too slow for targeted applications
- Can implement particular cases using look-up tables and interpolation





- Broader range of applications

$\Rightarrow$ Efficient Solvers/Schemes/Control Systems

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- Power electronics systems
  - Broad range of applications
  - Many different types of Level/frequency power converters, electric drives
- Structure and modelling approaches
  - ⇒ determine complexity and performance
- Linear explicit MPC based on model averaging
  - improved dynamic performance
  - low complexity compatible with high frequency $\geq$ MHz
- Hybrid approach
  - improved energy efficiency and power quality
  - already some real-time applications
  - remaining computional challenges for broadening applications