MPC Design for Power Electronics: Perspectives and Challenges

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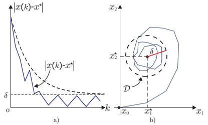
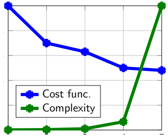




Model Predictive Control

- Model Predictive Control (MPC) is one of the key strategies in contemporary systems control.
- It has a long history[1] and has had a major impact on industrial (process) control applications.
- An attractive feature of MPC lies in its unique capacity to tackle flexible problem formulations.
- MPC can handle general constrained nonlinear systems with multiple inputs and outputs in a unified and clear manner.
- Concepts needed to implement MPC are intuitive and easy to understand → “human based”.

[1] e.g., Dreyfus, *The art and theory of dynamic programming*, 1977.

MPC for Power Electronics

Due to their switching nature, power electronics circuits give rise to a unique set of control engineering challenges.

- Various embodiments of MPC principles have emerged as a promising alternative for power converters and electrical drives.
- MPC can handle converters and drives with multiple switches and states; e.g., current, voltage, power, torque, etc.
- It has the potential to replace involved control architectures, such as cascaded loops, by a unique controller.
- MPC formulations can be extended to suit specific modes of operation, e.g., start-up procedures and fault accommodation.
- Successful designs however, require domain specific knowledge.

This talk

1. revises basic concepts of MPC (apologies)
2. presents some of our work on how to choose design parameters in MPC for power converters
3. points to research challenges

Outline

Basic Ingredients of MPC

1. A (discrete-time) system model to evaluate predictions:[2]

$$x(k+1) = f(x(k), u(k)), \quad k \in \{0, 1, 2, \dots\},$$

   where
   - $x(k)$ is the system state (capacitor voltages, inductor currents),
   - $u(k)$ is the control input (e.g., switch positions)

   The discrete-time model can be obtained from a continuous time model and take into account computational delays.
2. Constraints
3. Cost function
4. Moving horizon optimization

[2] Quevedo, Aguilera, Geyer, *Advanced and Intelligent Control in Power Electronics and Drives*, Springer, 2014.

System constraints

State and input constraints can be incorporated

$$
\begin{aligned}
x(k) &\in \mathbb{X} \subseteq \mathbb{R}^n, \qquad & k &\in \{0, 1, 2, \ldots\},\\
u(k) &\in \mathbb{U} \subseteq \mathbb{R}^m, \qquad & k &\in \{0, 1, 2, \ldots\}.
\end{aligned}
$$

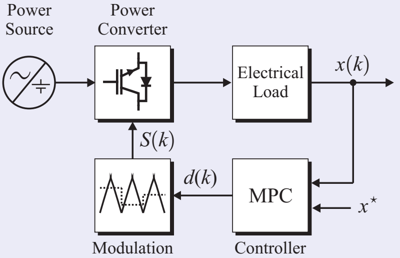
- State constraints: e.g., capacitor voltages or load currents
- Input constraints

Input constraints

$u(k) \in \mathbb{U}$ describes switch positions during the interval $(kh, (k+1)h]$.

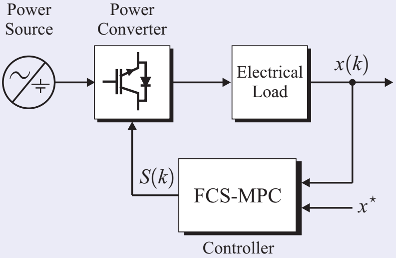
Input constraints

Continuous control set



$$u(k) = d(k) \in \mathbb{U} \triangleq [-1, 1]^m$$

Finite control set



$$u(k) = S(k) \in \mathbb{U} \triangleq \{0, 1\}^m$$

Cost function

A cost function over a finite horizon of length N is minimized at each time instant k and for a given (measured or estimated) plant state $x(k)$.

Performance Measure

$$V(x(k), \vec{u}'(k)) \triangleq F(x'(k+N)) + \sum_{\ell=k}^{k+N-1} L(x'(\ell), u'(\ell)).$$

- The controller uses the current plant state $x(k)$ to examine predictions $x'(\ell)$, which would result if the inputs were set to

$$\vec{u}'(k) \triangleq \{u'(k), u'(k+1), \ldots, u'(k+N-1)\},$$

- The weighting functions $L(\cdot,\cdot)$ and $F(\cdot)$ serve to trade quality of control for actuation effort (e.g., switching losses).

Optimizing control sequence

Constrained minimization of $V(\cdot,\cdot)$ gives the optimizing control sequence at time k and for state $x(k)$:

$$\vec{u}^{\text{opt}}(k) \triangleq \left\{u^{\text{opt}}(k), u^{\text{opt}}(k+1;k), \ldots, u^{\text{opt}}(k+N-1;k)\right\}.$$

In general, plant state predictions, $x'(\ell)$, will differ from actual plant state trajectories, $x(\ell)$. This is due to:

- uncertainties in the parameter values
- use of simplified models
- disturbances

To address these issues, feedback is used!

Moving Horizon Optimization

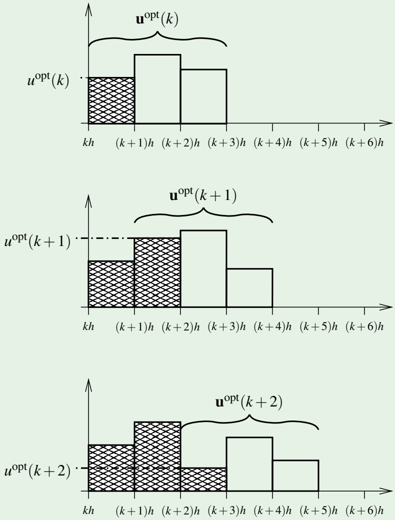
Optimizing control sequence

$$\vec{u}^{\text{opt}}(k) \triangleq \left\{u^{\text{opt}}(k), u^{\text{opt}}(k+1;k), \dots, u^{\text{opt}}(k+N-1;k)\right\}.$$

- To obtain a closed loop control law, commonly only the first element is used:
$$u(k) \longleftarrow u^{\text{opt}}(k).$$
- At the next sampling step, the current state $x(k+1)$ is measured (or estimated) and another optimization is carried out.
- This gives $\vec{u}^{\text{opt}}(k+1)$ and
$$u(k+1) = u^{\text{opt}}(k+1) \neq u^{\text{opt}}(k+1;k).$$

Moving Horizon Optimization

- The constrained minimization of the cost function is carried out at every time step k
- The optimization takes into account the entire horizon
- Only the first element of $\vec{u}^{\text{opt}}(k)$ is used
- The horizon slides forward as k increases



1. System model
2. Constraints
3. Cost function
4. Moving horizon optimization

Choice of Cost Function

In addition to assigning the sampling interval (which, inter alia, determines the system model), the choice of cost function is key.

Design parameters

- weighting functions $F(\cdot)$ and $L(\cdot, \cdot)$,
- references,
- constraint set $\mathbb{U}$,
- horizon length N.

Cost Function Design

$$V(x(k), \vec{u}'(k)) \triangleq F(x'(k+N)) + \sum_{\ell=k}^{k+N-1} L(x'(\ell), u'(\ell)), \quad u'(\ell) \in \mathbb{U}.$$

- The weighting functions $F(\cdot)$ and $L(\cdot,\cdot)$ should take into account the actual control objectives and may also consider stability/performance issues.
- The choice of constraint set has an impact on hardware to be used and resulting performance.
- To design reference trajectories for the system state, one needs to take into account physical/electrical properties.
- The optimization horizon N allows the designer to trade-off performance versus on-line computational effort.

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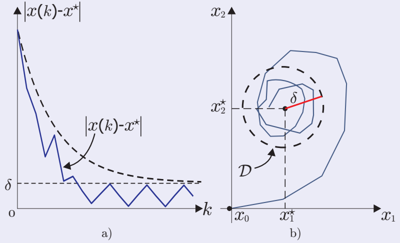
Closed Loop Dynamics

- Due to the switching nature of power converters, characterizing closed loop performance is a highly non-trivial task.
- Lyapunov-stability ideas can be used to design the cost function to ensure that the state trajectory remains bounded.[3]



Convergence of the converter state, $x(k)$, to a neighbourhood of the reference $x^\star$:

1. Practical asymptotic stability
2. $x(k)$ will be confined in $\mathcal{D}$

[3] Aguilera and Quevedo, *IEEE Trans. Ind. Inf.*, Feb. 2015

Quadratic cost, horizon $N = 1$, finite $\mathbb{U}$

$$V(x(k), u'(k)) = \|x(k) - x^\star(k)\|_Q^2 + \|u'(k) - u^\star(k)\|_R^2 + \|x'(k+1) - x^\star(k+1)\|_P^2.$$

Constrained solution (also valid for larger horizons!)

$$u^{\text{opt}}(k) = W^{-1/2} q_{\mathbb{V}}\left(W^{1/2} u_{uc}^{\text{opt}}(k)\right) \in \mathbb{U},$$

$u_{uc}^{\text{opt}}(k)$ is the unconstrained solution and $q_{\mathbb{V}}$ is a vector quantizer.[a]

[a] Quevedo, Goodwin, De Doná, *Int. J. Robust Nonlin. Contr.*, 2004

By denoting the quantization error via $\eta_{\mathbb{V}}(k)$, we obtain:

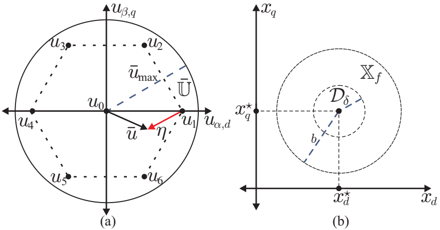
$$u^{\text{opt}}(k) = u_{uc}^{\text{opt}}(k) + W^{-1/2} \eta_{\mathbb{V}}(k),$$

Performance Guarantees

Using the cost as a candidate Lyapunov function and adapting robust control (ISS) ideas, we obtain an

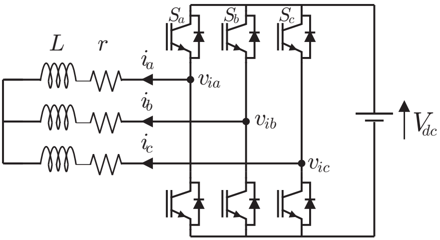
FCS-MPC design procedure

1. Choose Q and R
2. Calculate matrices P and W
3. Assign the (circular) nominal control region $\bar{\mathbb{U}}$.
4. Check an inequality which relates the maximum quantization error to system parameters
5. Calculate regions $\mathbb{X}_f$ and $\mathcal{D}_\delta$.



(a) Finite control set $\mathbb{U}$ and nominal control region $\bar{\mathbb{U}}$.
(b) Terminal region $\mathbb{X}_f$ and bounded set $\mathcal{D}_\delta$.

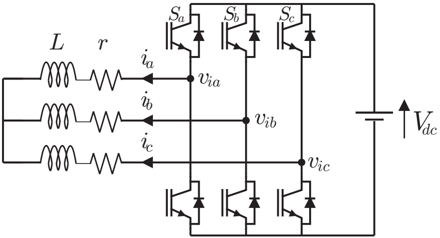
Example: Two-Level Inverter



The switch position are restricted to belong to the finite set

$$\mathbb{S} \triangleq \left\{ \begin{bmatrix}0\\0\\0\end{bmatrix}, \begin{bmatrix}0\\0\\1\end{bmatrix}, \begin{bmatrix}0\\1\\0\end{bmatrix}, \begin{bmatrix}0\\1\\1\end{bmatrix}, \begin{bmatrix}1\\0\\0\end{bmatrix}, \begin{bmatrix}1\\0\\1\end{bmatrix}, \begin{bmatrix}1\\1\\0\end{bmatrix}, \begin{bmatrix}1\\1\\1\end{bmatrix} \right\}.$$

State Space Description



Considering $x = i_{dq}$ and $u = s_{dq}$, a discrete-time model of the 2-level inverter, in the rotating dq frame, is given by:

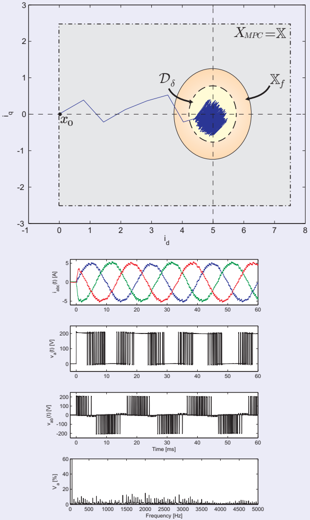
$$x(k+1) = Ax(k) + Bu(k),$$

where

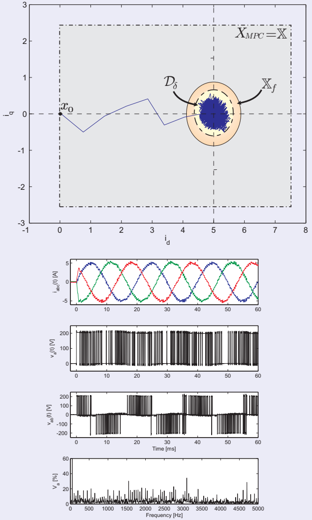
$$A = \begin{bmatrix} 1 - hr/L & \omega h \\ -\omega h & 1 - hr/L \end{bmatrix}, \quad B = \begin{bmatrix} hV_{dc}/L & 0 \\ 0 & hV_{dc}/L \end{bmatrix}.$$

Experimental results; $V_{dc} = 200\,V$, $r = 5\Omega$, $L = 17mH$

$R = 2I_{2\times 2}$



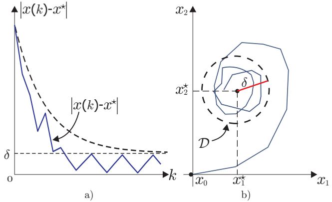
$R = 0.0001\,I_{2\times 2}$



Summary

- When controlling solid-state power converters in discrete-time, in general, voltages and currents will not converge to the desired steady-state values.

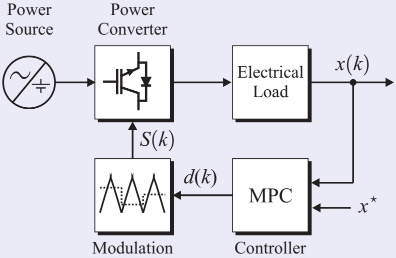
- In some situations, the cost function of Finite Control-Set MPC can be designed to guarantee
  1. practical stability of the power converter
  2. a desired performance level



Outline

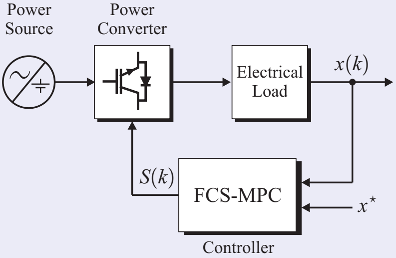
Choice of Constraint Set

Continuous control set



$$u(k) = d(k) \in \mathbb{U} \triangleq [-1, 1]^m$$

Finite control set

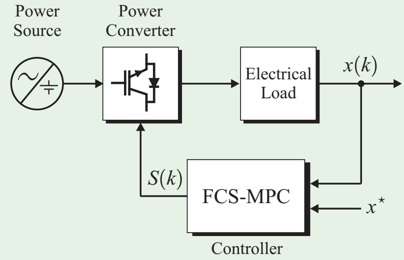


$$u(k) = S(k) \in \mathbb{U} \triangleq \{0, 1\}^m$$

Depending on the constraint set imposed, the resulting controllers have complementary properties.

Finite Control-Set MPC

Finite control set



$$u(k) = S(k) \in \mathbb{U} \triangleq \{0,1\}^m$$

Advantages

- can deal with non-linear converter topologies
- provides fast transients

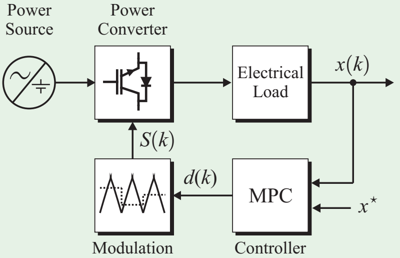
Limitations

- often gives steady state errors and wide-spread spectra[4]

[4] cf., Cortés, Rodríguez, Quevedo, Silva, *IEEE Trans. Power Electron.*, Mar. 2008.

Continuous Control-Set MPC

Continuous control set



$$u(k) = d(k) \in \mathbb{U} \triangleq [-1, 1]^m$$

Advantages

- steady-state performance
- zero-average tracking error
- concentrated spectra

Limitation

- (tractable) convex formulations are limited to linear(izable) models

MPC with Switching Constraint Sets

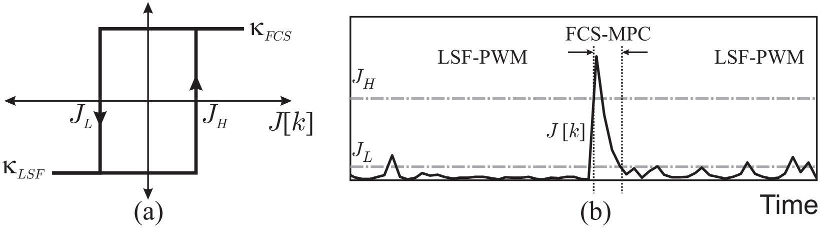
- An MPC formulation which combines the complementary properties of MPC with and without a modulator can be conceived.[5]
- During transients, the proposed method uses horizon-one non-linear Finite Control Set MPC to drive the system towards the desired reference.
- When the system state is close to the reference, the controller switches to linear operation, i.e., a modulator is used.

[5] Aguilera, Lezana, Quevedo, *IEEE Trans. Ind. Inf.*, Aug. 2015

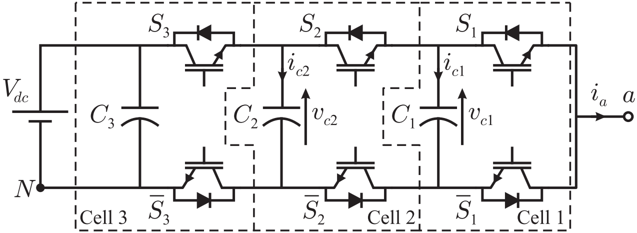
- The constraint set chosen in MPC depends on the value taken by the triggering function

$$J(k) \triangleq \|x(k) - x^{\star}(k)\|_P^2,$$

- To avoid chattering, a hysteresis band is introduced:



Example: Three-cell (four-level) single-phase FCC



States and Inputs

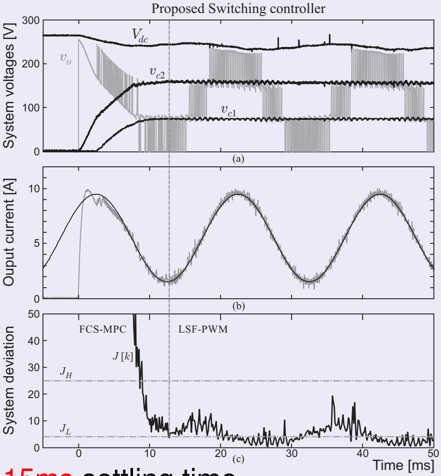
$$x(k) = \begin{bmatrix} v_{c1}(k) \\ v_{c2}(k) \\ i_a(k) \end{bmatrix}, \quad u(k) = \begin{bmatrix} S_1(k) \\ S_2(k) \\ S_3(k) \end{bmatrix}$$

Nonlinear Dynamics

$$x(k+1) = Ax(k) + B(x(k))u(k)$$

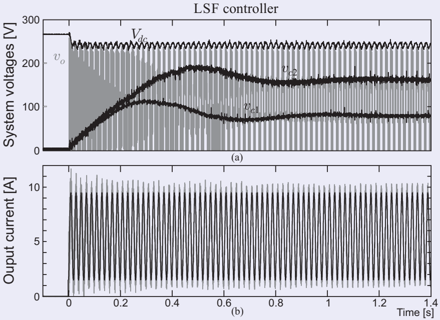
Experimental results: Start-up

Switched MPC



15ms settling time

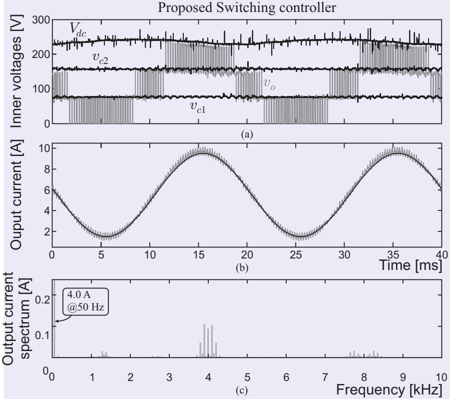
Linear State Feedback controller



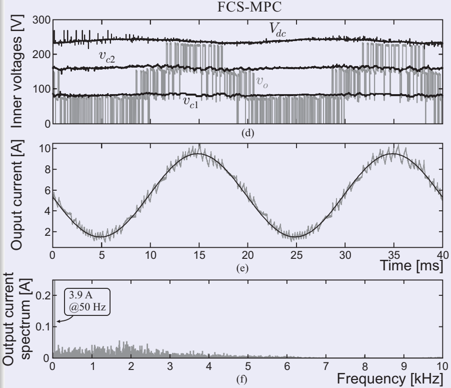
700ms settling time

Steady-state Performance

Switched MPC



Finite Constraint Set MPC



Better steady-state response than Finite Constraint Set MPC

Summary

- In some instances, one may choose the input constraint set used in the MPC formulation.
- The control algorithm described switches between non-linear Finite Control Set MPC and linear state-feedback control.
- This exploits the advantages of both basic control strategies.
- Experiments showed that fast dynamic response can be obtained, even when the system non-linearities are more evident.
- In steady state, the output current tracks the reference, and power semiconductors operate at a constant switching frequency.

Outline

Reference Design

MPC allows one to incorporate references in an explicit manner.

- Especially when using short horizons, reference trajectories for the entire state $x(k)$ should be specified.
- This requires knowledge of possibilities and limitations of the system to be controlled:

1. For AFE converters, careful consideration of energy balancing and dynamic limitations can be used to design compatible references for powers and capacitor voltages.[6]
2. For Modular Multilevel Converters, it is useful to understand the role of internal (circulating) currents.

[6] Quevedo, Aguilera, Pérez, Cortés, Lizana, *IEEE Trans. Power Electron.*, 2012.

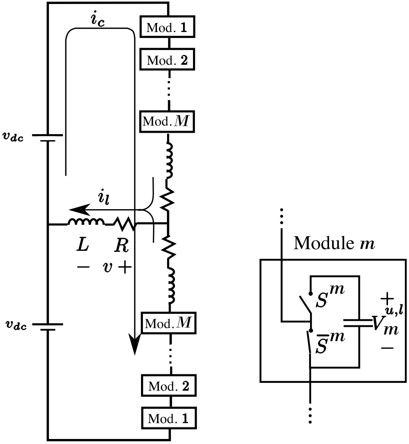
Modular Multilevel Converters (MMCs)

use a DC/AC topology capable to reach high voltages and power.

Control Challenges

- Many input signals (one per module).
- The output current i_l depends on
  1. the circulating current i_c
  2. the capacitor voltages
- Thus, a control is required for i_c and the capacitor voltages.

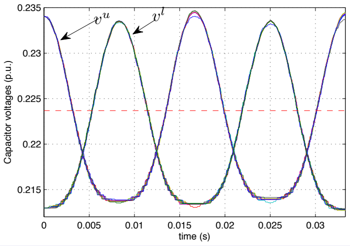
All variables are related; their references have to be carefully designed.



FCS MPC with a quadratic cost and $N = 1$

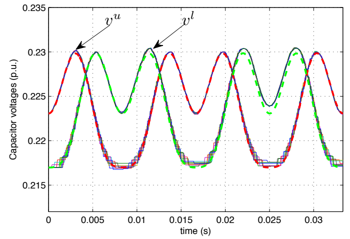
A reduced order model is used for the design of state references (MMC with $M = 8$ modules per arm).[7]

Simplified DC references



- bad reference tracking
- high voltage ripple

Designed references



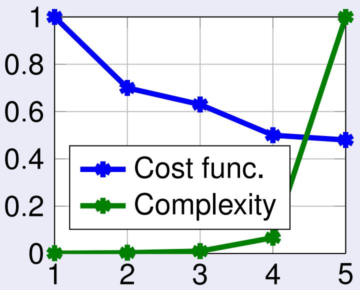
- accurate reference tracking
- optimal voltage ripple

[7] Lopez, Quevedo, Aguilera, Geyer and Oikonomou, *Australian Control Conf.*, 2014.

MPC with larger horizons

- Given the large number of switches in MMCs, MPC with large horizons and using explicit enumeration becomes infeasible.
- In fact, with $M = 8$ optimizing for $N = 5$ would require evaluating $\left(2^{16}\right)^5 \approx 1.2 \times 10^{24}$ switching combinations!

- Sphere decoding[8] can be adapted to the present situation in order to find the optimal solution with only few computations.
- Larger horizons give performance gains.



[8] Geyer and Quevedo, *IEEE Trans. Power Electron.*, 2014, 2015.

Outline

Some research challenges

1. developing methods to quantify stability and performance of more general situations
   - more general cost functions
   - horizons larger than one
   - bilinear systems
2. systematic design methods for references
   - Here domain specific knowledge is key!
3. further focus on computational issues
   - larger horizons for bilinear systems
   - sphere decoding is just one of the available methods (study signal processing and information theory literature!)
   - suboptimal methods / early terminations?

Some research challenges (I am interested in)

- More advanced computational methods
  - distributed computations in multi-core systems
  - time-varying processing resources, e.g., shared computing
  - non-periodic computations
- Networked control
  - wireless opens new possibilities!
  - hot topic in systems control theory and applications (process control, Internet of Things, Industry 4.0, etc.)
  - shared communications lead to communication resource limitations
  - control / communications co-design is difficult

Can (or should?) Model Predictive Control of power electronics and drives benefit from these developments?

Further Reading

1. Quevedo, Aguilera, Geyer, “Predictive Control in Power Electronics and Drives: basic concepts, theory and methods,” in *Advanced and Intelligent Control in Power Electronics and Drives*, pp. 181–226, Springer, 2014.
2. Aguilera and Quevedo, “Predictive Control of Power Converters: Designs with Guaranteed Performance,” *IEEE Transactions on Industrial Informatics*, vol. 11, no. 1, pp. 53–63, Feb. 2015.
3. Aguilera, Lezana, Quevedo, “Switched Model Predictive Control for Improved Transient and Steady-State Performance,” *IEEE Transactions on Industrial Informatics*, pp. 968–977, Aug. 2015.
4. Lopez, Quevedo, Aguilera, Geyer and Oikonomou, “Reference Design for Predictive Control of Modular Multilevel Converters,” *Proceedings of the Australian Control Conference*, 2014.

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