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Dies Academicus, Hamburg 2018

Fraunhofer ISIT

Power Quality Compensation for Smart Grids by Model-based Predictive Control

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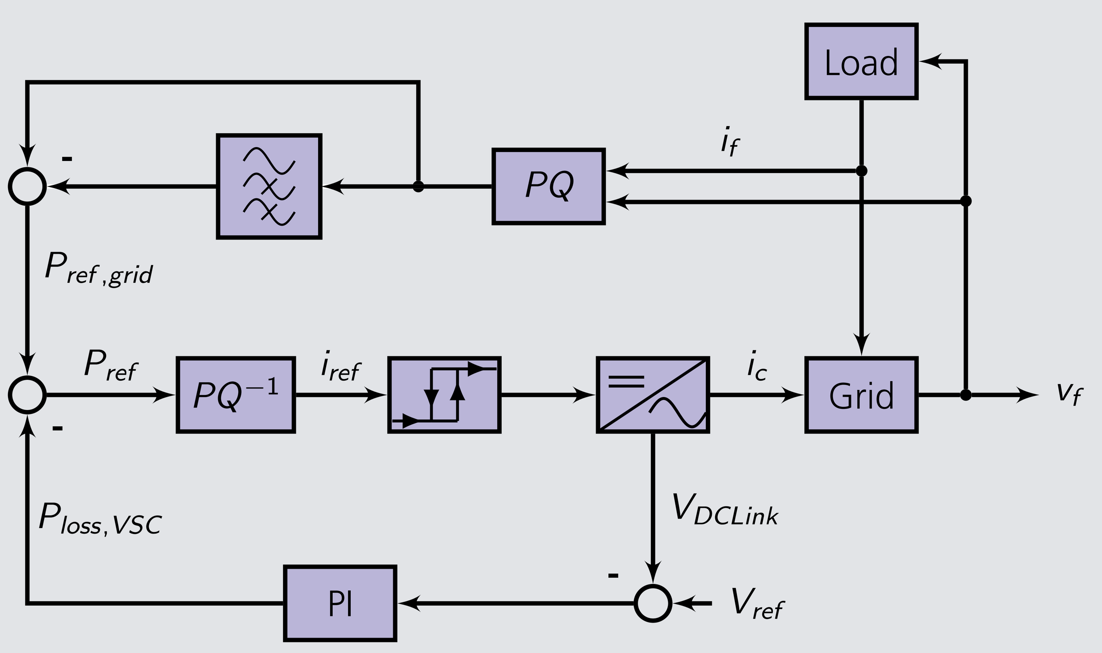
INTRODUCTION

- High order harmonics in the electrical grid introduced by switching converters need to be compensated to avoid damage and energy loss
- Classic active power filter (APF) controllers are capable of compensating harmonics, but are not flexible under variable load scenarios
- A state-of-the-art method to compensate harmonics relies on the instantaneous reference frame (IRP) theory
- A novel approach: "Linear State Signal Shaping Model Predictive Control" (LS^{3}MPC), could be utilized to compensate harmonics using shape classes, without the need to design filters for different load scenarios

APPLICATION PROBLEM

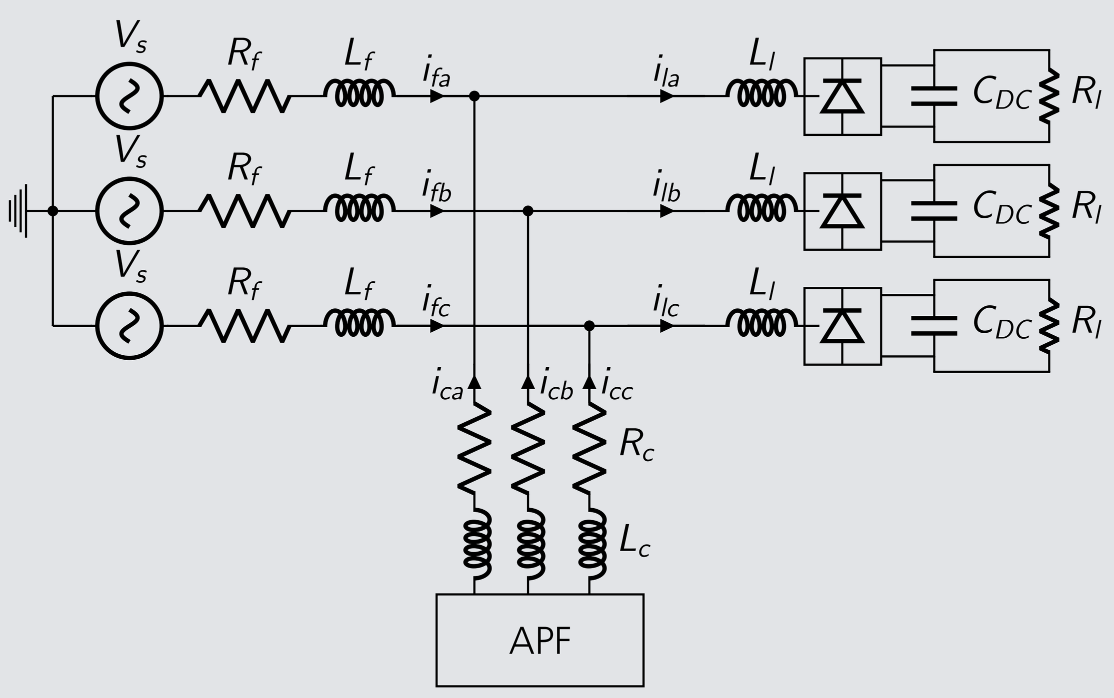
- Could the LS^{3}MPC improve the grid quality compared to a classic IRP APF controller?
- A simulation is set up to evaluate both controller types under different load scenarios

CLASSIC IRP CONTROLLER



- Clarke and p-q transformation are used
- A high pass filter extracts harmonics
- A hysteresis band controller steers the voltage source converter

3-PHASE GRID MODEL



Active power filter in shunt configuration

WHITE-BOX MODELING

Linear state space model of the grid

$$\dot{\mathbf{x}}(t) = \mathbf{A}\mathbf{x}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{E}\mathbf{d}(t)$$

where

$$\mathbf{x}(t) = \begin{pmatrix} v_l & \frac{di_c}{dt} & \frac{di_l}{dt} \end{pmatrix}^\mathsf{T} \in \mathbb{R}^3 \qquad u(t) = \frac{d^2 i_c}{dt^2}, \quad d(t) = \frac{d^2 i_l}{dt^2}$$

and

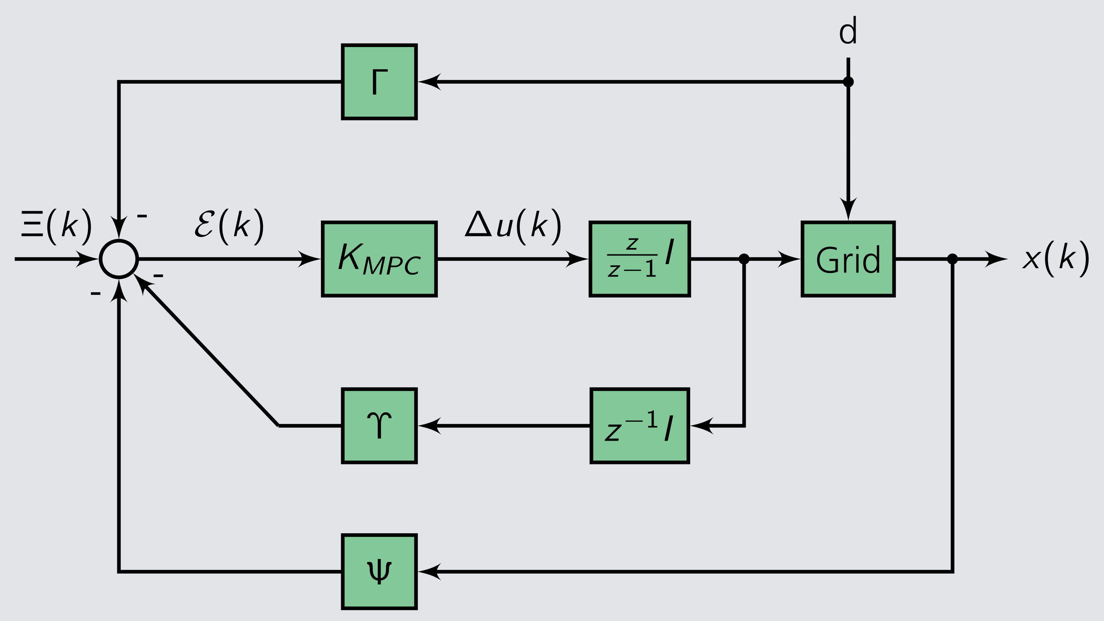
$$\mathbf{A} \in \mathbb{R}^{3\times 3}, \quad \mathbf{B} \in \mathbb{R}^{3\times 1}, \quad \mathbf{E} \in \mathbb{R}^{3\times 1}.$$

PREDICTIVE CONTROLLER

The MPC minimizes the cost function

$$J = \|\mathbf{X}(k) - \Xi(k)\|^2_{\mathbf{Q}} + \|\mathbf{U}(k)\|^2_{\mathbf{R}}.$$

Solved by constrained sparse quadratic programming (QP), with close loop behavior:



LINEAR SHAPE CLASS

The shape of a sine wave is described by the homogeneous ODE

$$\frac{d^2x(t)^2}{dt} + \omega^2 x(t) = 0$$

and approximated in discrete time with

$$\frac{\left(2+\omega^2 t_s^2\right)x(k) - 5x(k+1) + 4x(k+2) - x(k+3)}{t_s^2} = 0.$$

From this difference equation the *linear shape class*[3] V is given as

$$\mathbf{V} = \begin{pmatrix} 2+(\omega t_s)^2 & 5 & 4 & -1 \end{pmatrix} \in \mathbb{R}^{1\times 4}.$$

The state error weight matrix Q is built using V by transferring the control goal to the optimization problem

$$\min_{\mathbf{X}(k)} (\mathbf{V}\mathbf{X}(k))^2,$$

where

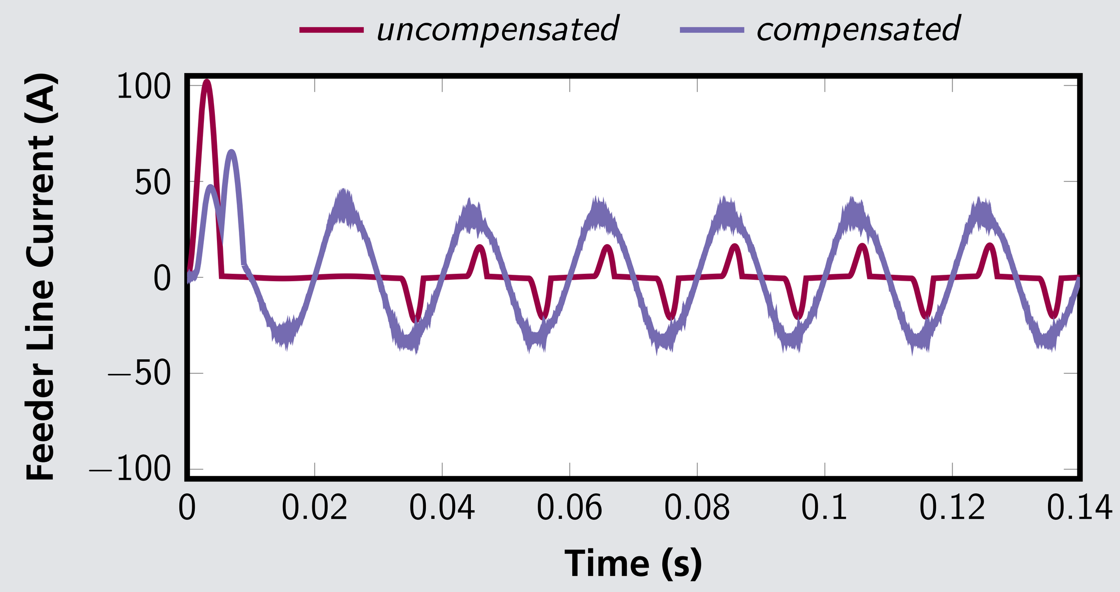
$$\mathbf{X}(k) = \begin{pmatrix} x(k) & x(k+1) & x(k+2) & x(k+3) \end{pmatrix}^\mathsf{T},$$

for all times k.

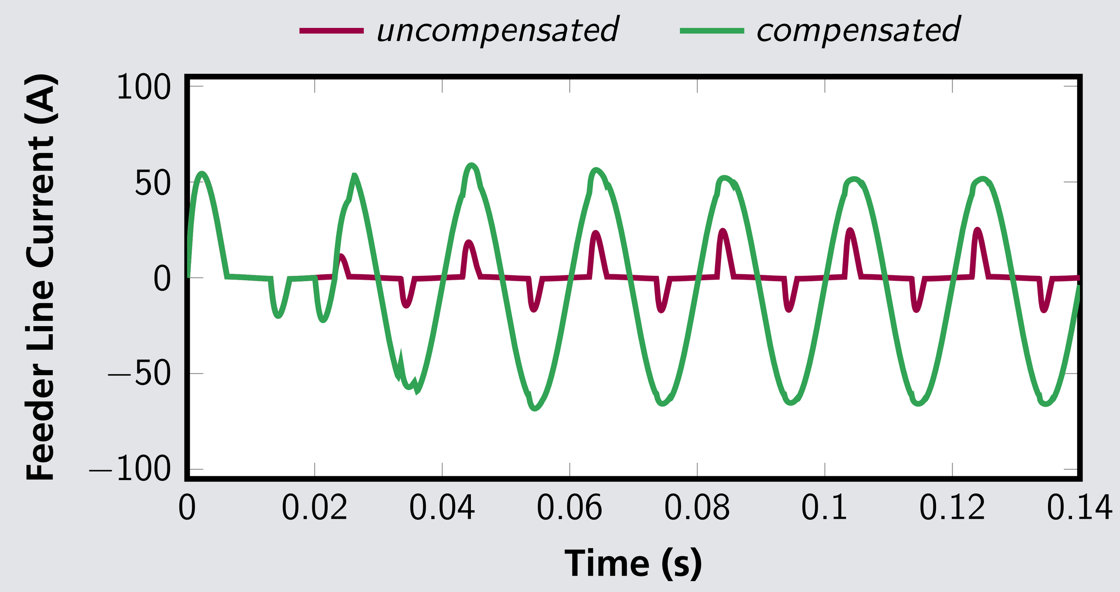
[3]Cateriano Yáñez, C., Pangalos, G., and Lichtenberg, G. (2018). An approach to linear state signal shaping by quadratic model predictive control. In *European Control Conference (ECC) 2018*

SIMULATION STUDIES

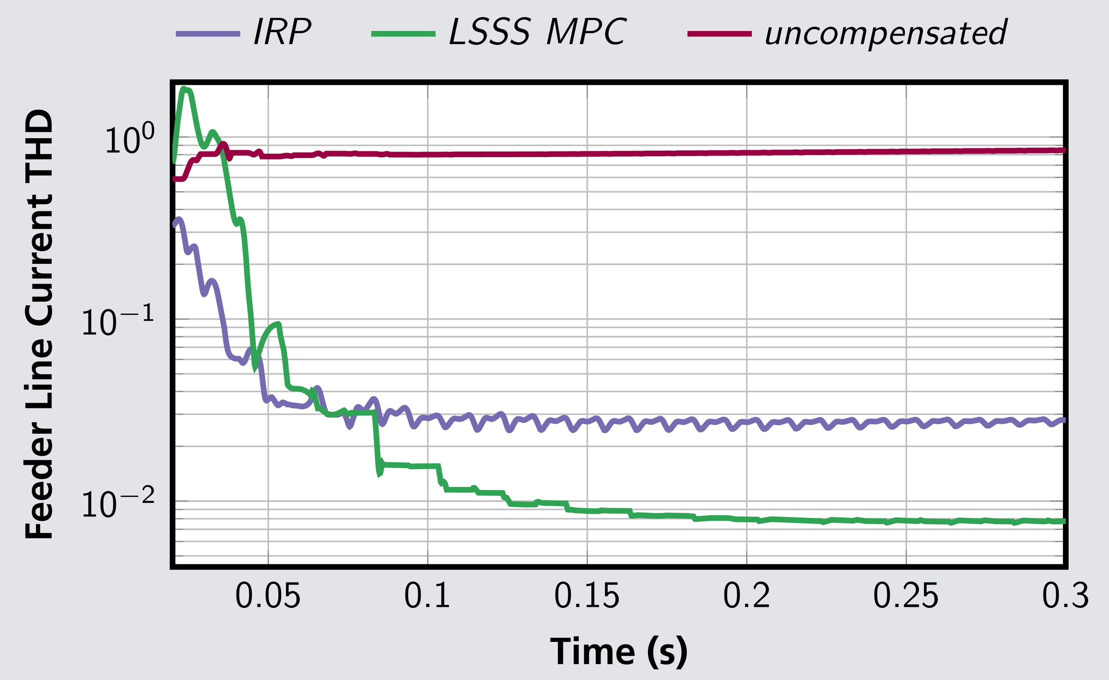
IRP APF harmonic current compensation:



LS^{3}MPC harmonic current compensation:



Total harmonic distortion (THD):



Results for different load scenarios:

Load scenario	THD (v_f) IRP	THD (v_f) LS^{3}MPC	THD (i_f) IRP	THD (i_f) LS^{3}MPC
100 Ω	0.65%	0.17%	4.35%	0.78%
9 Ω	0.45%	0.35%	0.75%	1.57%
2 Ω	1.15%	0.35%	3.75%	1.33%

CONCLUSION

- The LS^{3}MPC approach has the potential to successfully control an APF
- Classic IRP controllers rely on high pass filter design to achieve good compensation results in a given load scenario
- The LS^{3}MPC is capable of adapting to a wider variety of load scenarios