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

Carlos Cateriano Yáñez[1,2], Kathrin Weihe[1], Georg Pangalos[2], and Gerwald Lichtenberg[1]

[1]Hamburg University of Applied Sciences, Faculty Life Sciences, Ulmenliet 20, 21033 Hamburg
[2]Fraunhofer ISIT, Application Center Power Electronics for Renewable Energy Systems, Steindamm 94, 20099 Hamburg

{carlos.caterianoyanez, kathrin.weihe, gerwald.lichtenberg}@haw-hamburg.de, georg.pangalos@isit.fraunhofer.de,

MOTIVATION

- **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**

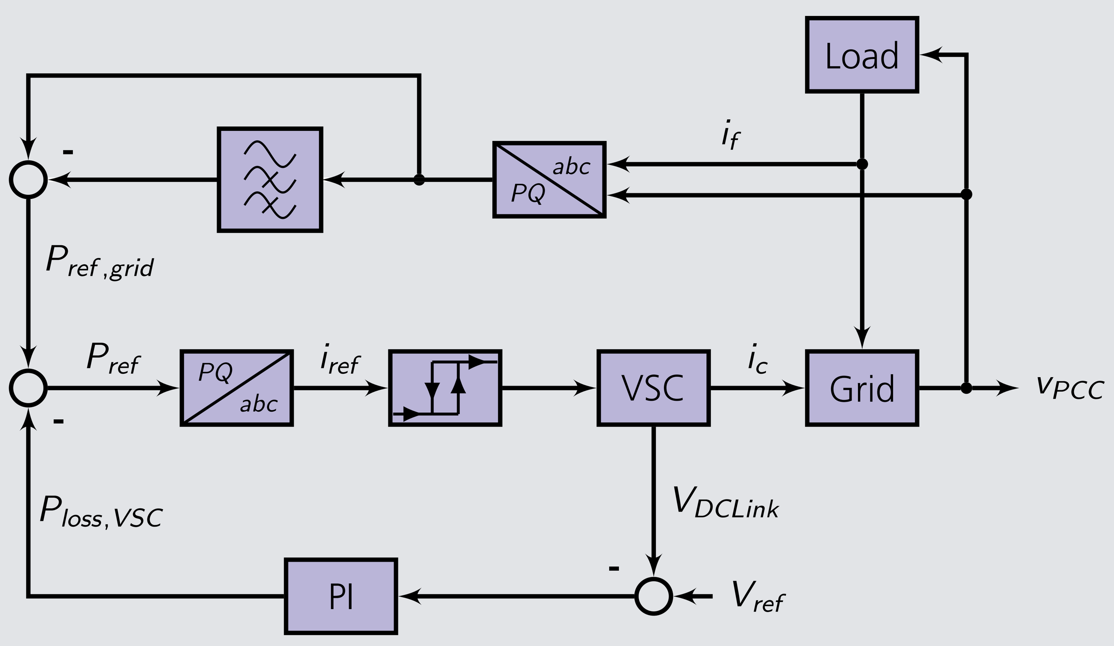
APPLICATION PROBLEM

A novel approach: "Linear State Signal Shaping Model Predictive Control" (LS³MPC), to compensate harmonics using shape classes has been developed

- **Could the LS³MPC improve the grid quality compared to a classic APF controller?**
- **Could the LS³MPC adapt under variable load scenarios?**

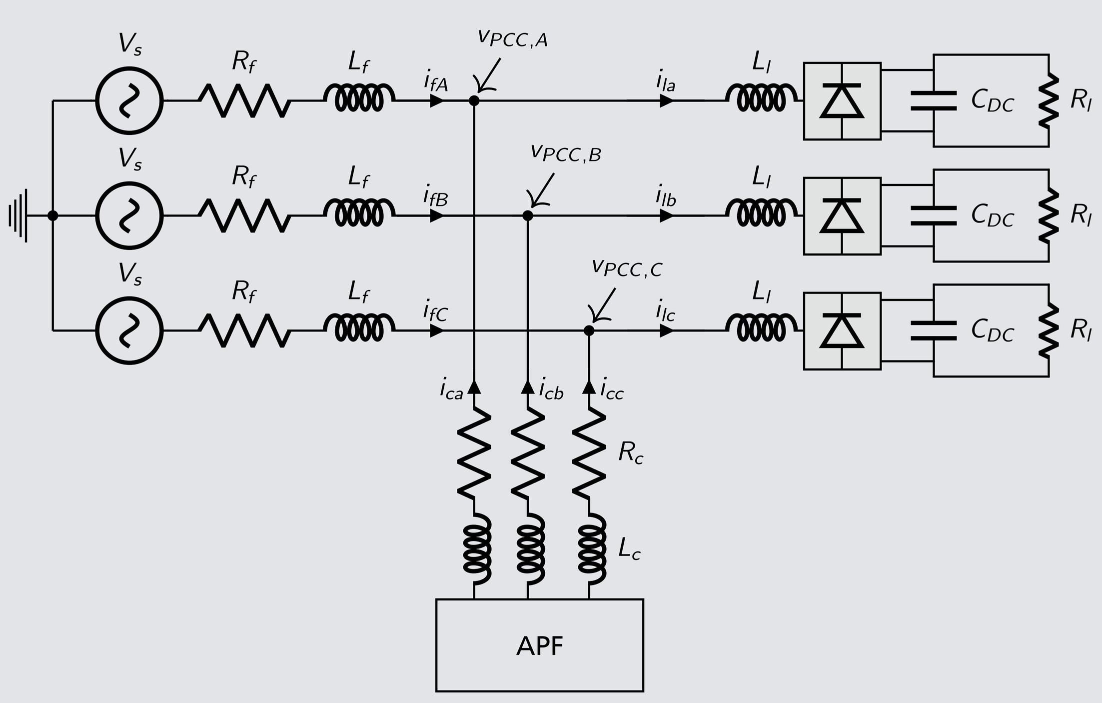
CLASSIC IRP CONTROLLER

A state-of-the-art classic APF controller to compensate harmonics relies on the instantaneous reactive power (IRP) theory



- **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 per phase

$$\mathbf{x}(k+1) = \mathbf{A}\mathbf{x}(k) + \mathbf{B}u(k) + \mathbf{E}\mathbf{d}(k)$$

where

$$\mathbf{x}(k) = \begin{pmatrix} i_f \\ i_c \end{pmatrix} \in \mathbb{R}^2 \qquad u(k) = i_{c0} \in \mathbb{R} \qquad \mathbf{d}(k) = \begin{pmatrix} v_s & i_{l0} \end{pmatrix}^{\mathsf{T}} \in \mathbb{R}^2$$

and

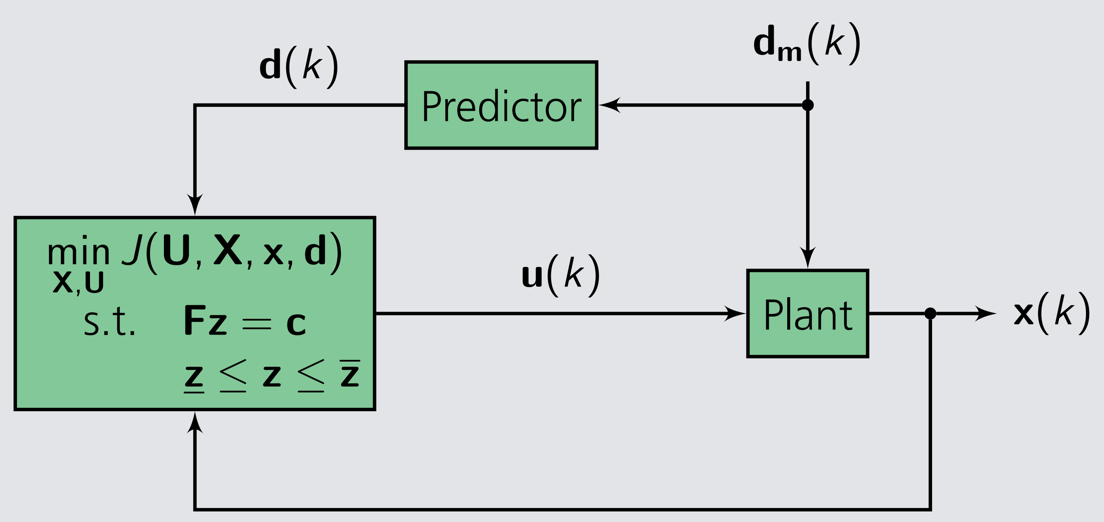
$$\mathbf{A} \in \mathbb{R}^{2\times 2}, \quad \mathbf{B} \in \mathbb{R}^{2\times 1}, \quad \mathbf{E} \in \mathbb{R}^{2\times 2}.$$

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

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

and approximated in discrete time with

$$x(k-1) + \left((\omega t_s)^2 - 2\right)x(k) + x(k+1) = 0.$$

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

$$\mathbf{V} = \begin{pmatrix} 1 & (\omega t_s)^2 - 2 & 1 \end{pmatrix} \in \mathbb{R}^{1\times 3}.$$

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

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

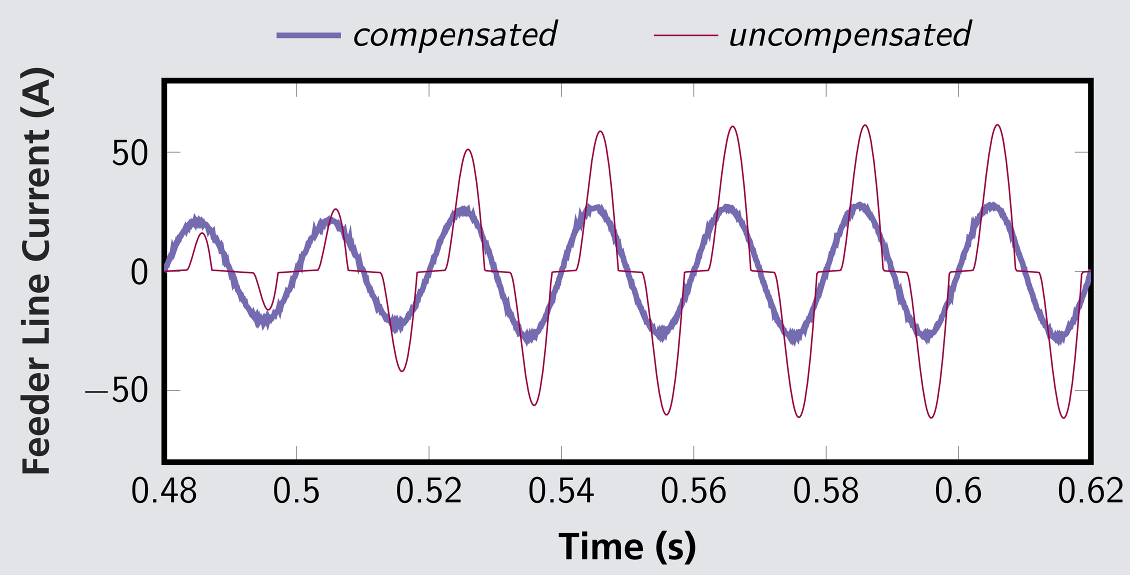
where

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

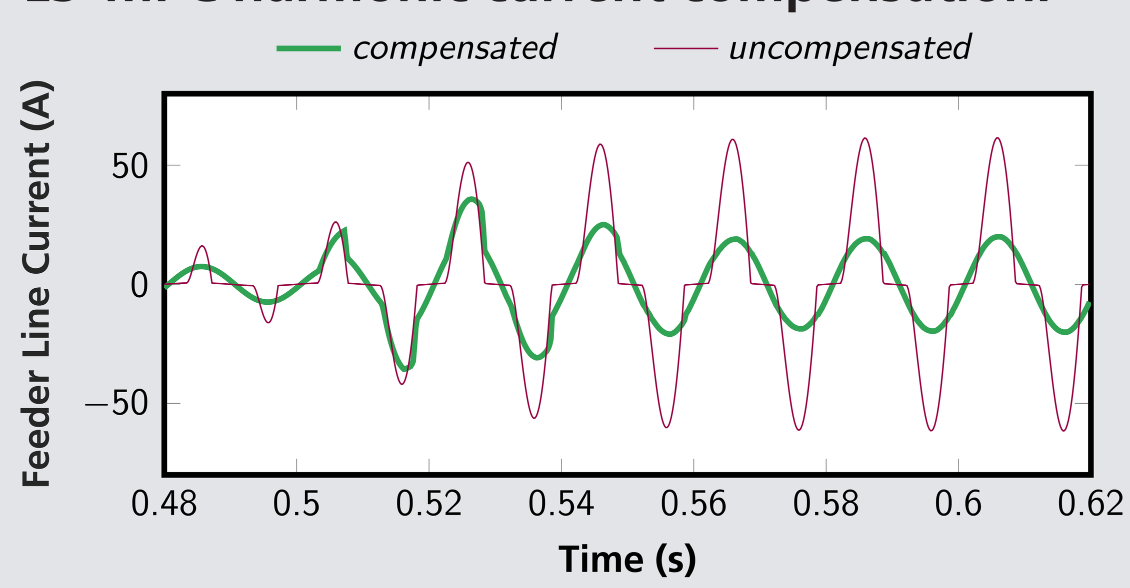
for all times k.

SIMULATION STUDIES

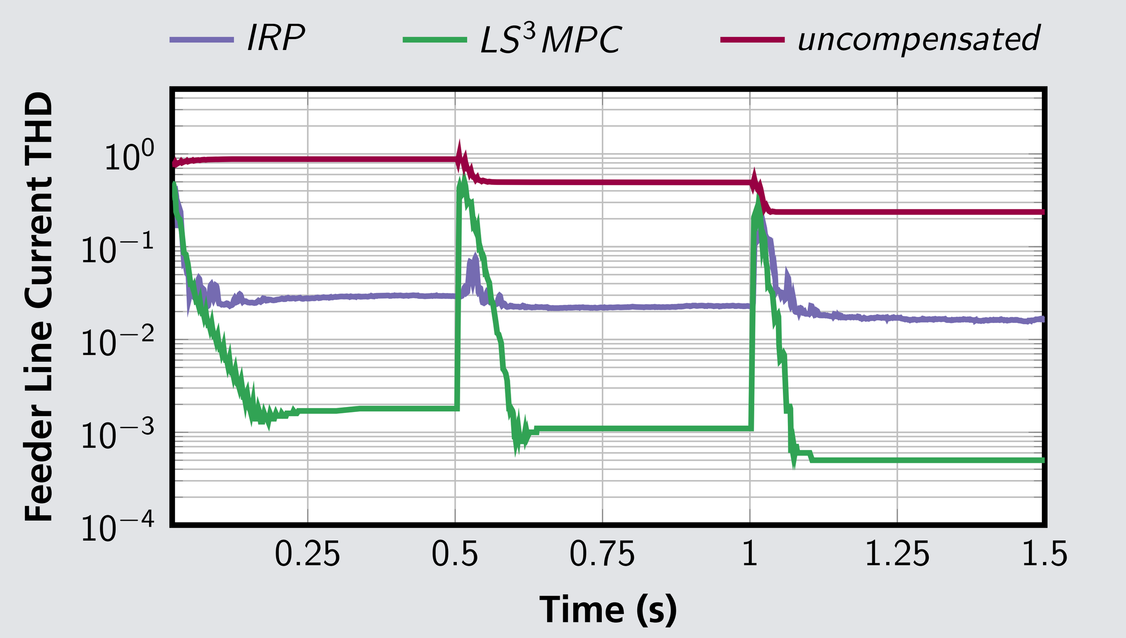
IRP APF harmonic current compensation:



LS³MPC harmonic current compensation:



Total harmonic distortion (THD):



Results for different load scenarios:

Load scenario	THD (v_{PCC})		THD (i_f)	
	IRP	LS³MPC	IRP	LS³MPC
100 Ω	1.07%	0.01%	6.68%	0.18%
9 Ω	0.75%	0.02%	2.72%	0.11%
2 Ω	0.85%	0.07%	2.56%	0.05%

CONCLUSION

- **The LS³MPC can successfully improve the THD compensation of an APF**
- **Classic IRP rely on high pass filter design for a given load scenario, while LS³MPC can inherently adapt to a wider variety**
- **Current research on LS³MPC focuses on enabling reactive power compensation**