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

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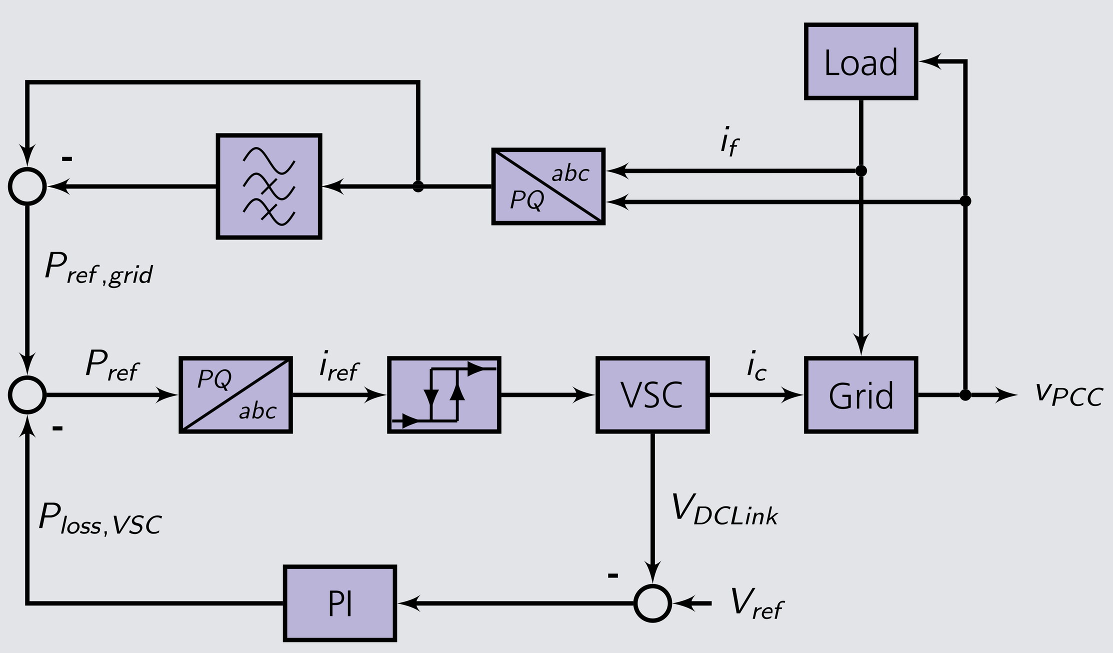
INTRODUCTION

- **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

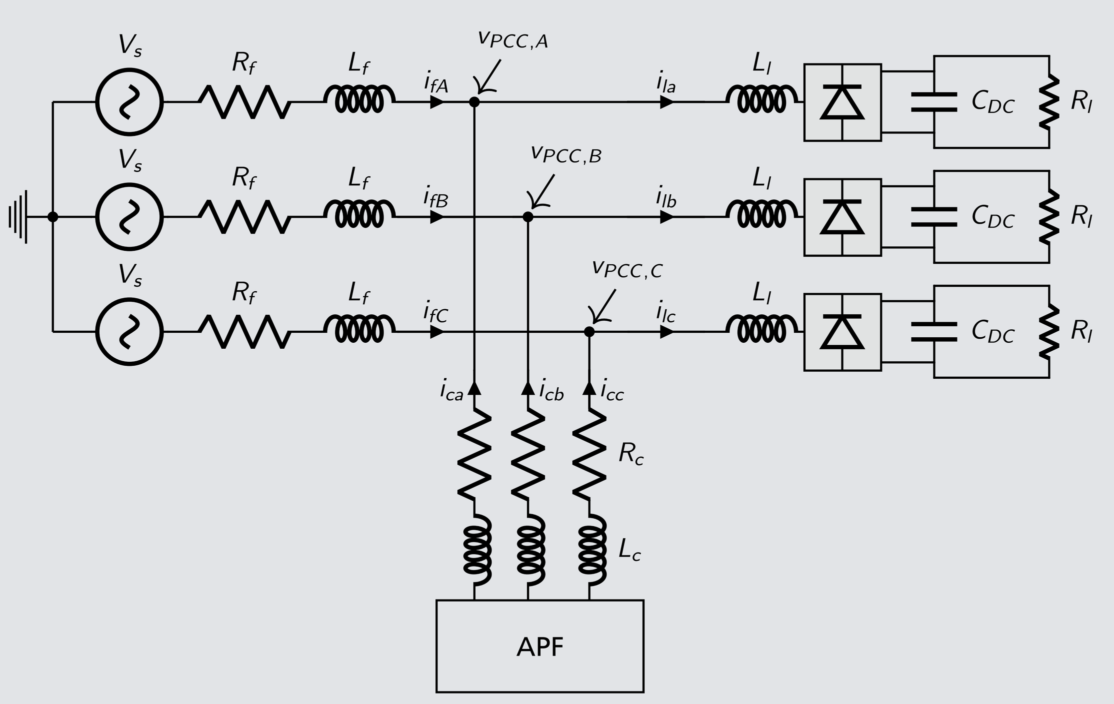
- **Could the LS^{3}MPC improve the grid quality compared to a classic IRP APF controller?**
- **A simulation is set up to evaluate both controller types under different load scenarios**

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 per phase

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

where

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

and

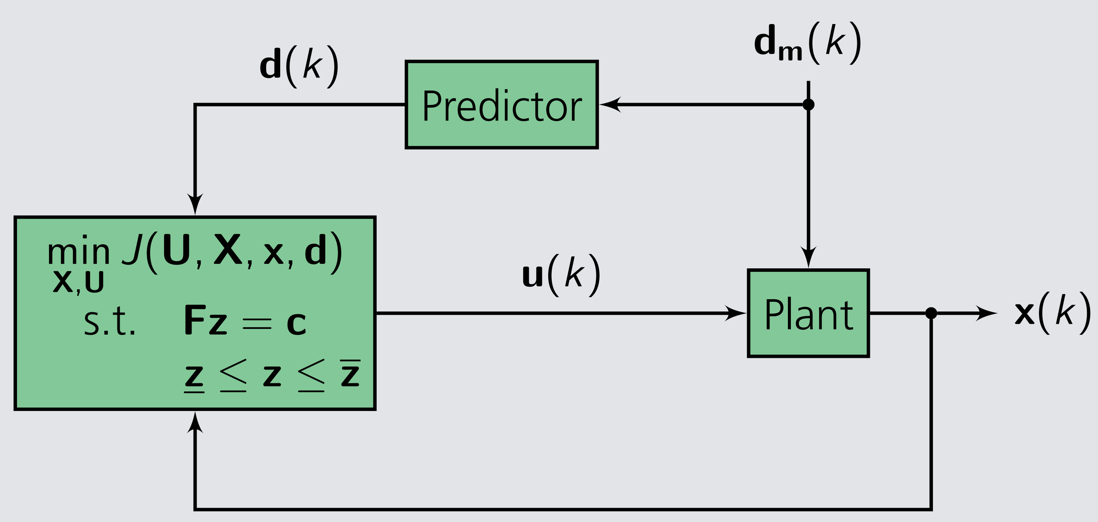
$$\mathbf{A} \in \mathbb{R}^{2\times2}, \quad \mathbf{B} \in \mathbb{R}^{2\times1}, \quad \mathbf{E} \in \mathbb{R}^{2\times2}.$$

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

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

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*[3] V is given as

$$\mathbf{V} = \begin{pmatrix} 1 & (\omega t_s)^2 - 2 & 1 \end{pmatrix} \in \mathbb{R}^{1\times3}.$$

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

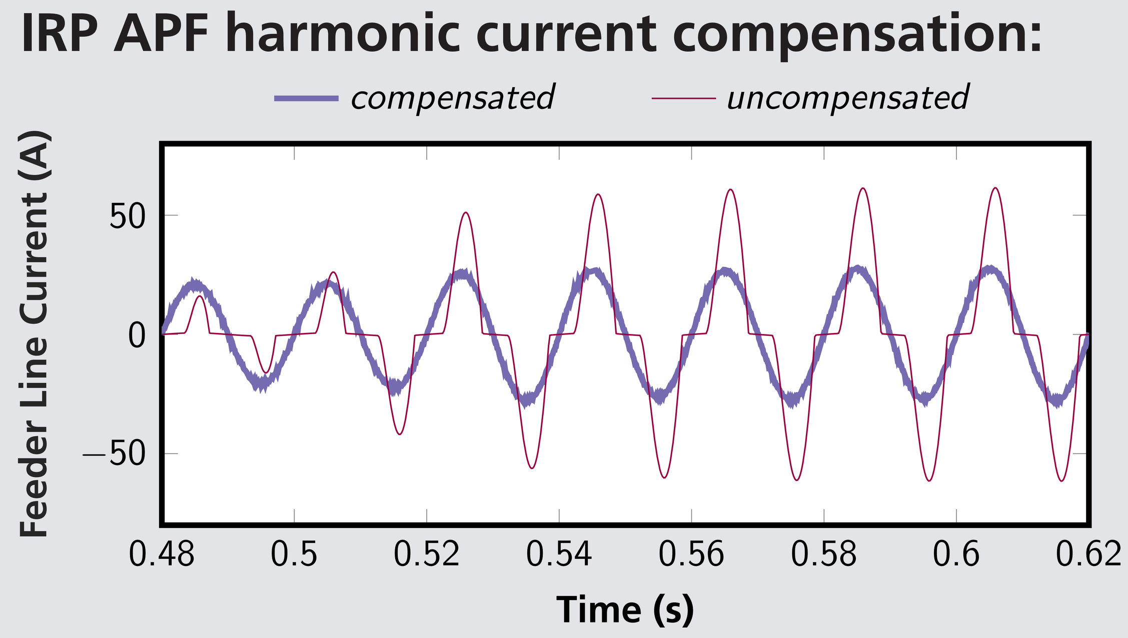
$$\mathbf{X}(k) = \begin{pmatrix} x(k-1) & x(k) & x(k+1) \end{pmatrix}^\top,$$

for all times k.

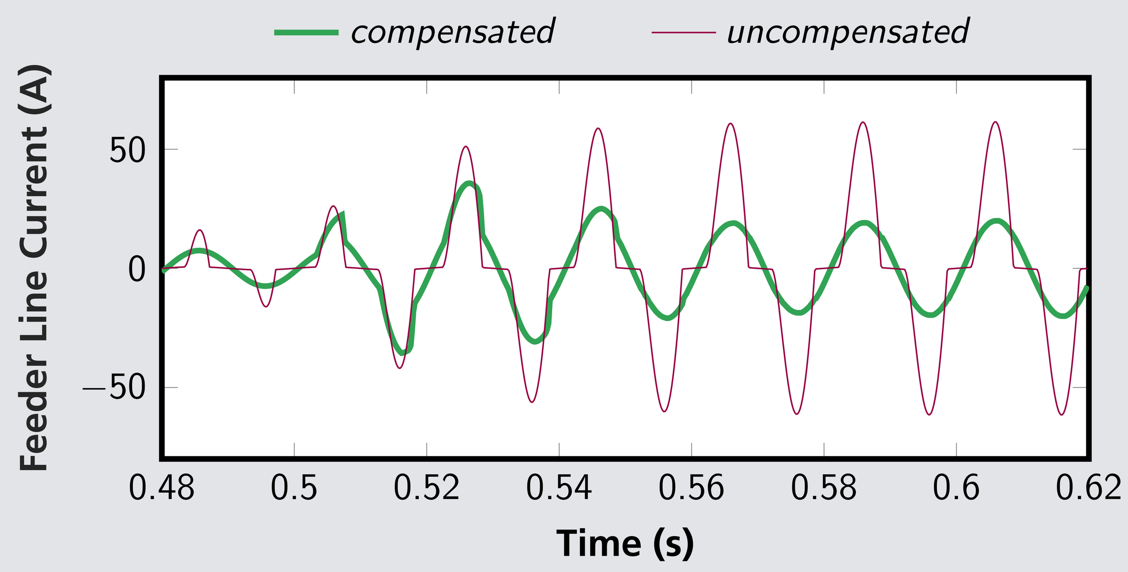
[3]Cateriano Yáñez, C., Pangalos, G., and Lichtenberg, G. (2018). An approach to linear state signal shaping by quadratic model predictive control. In *European Control Conference (ECC) 2018*

SIMULATION STUDIES

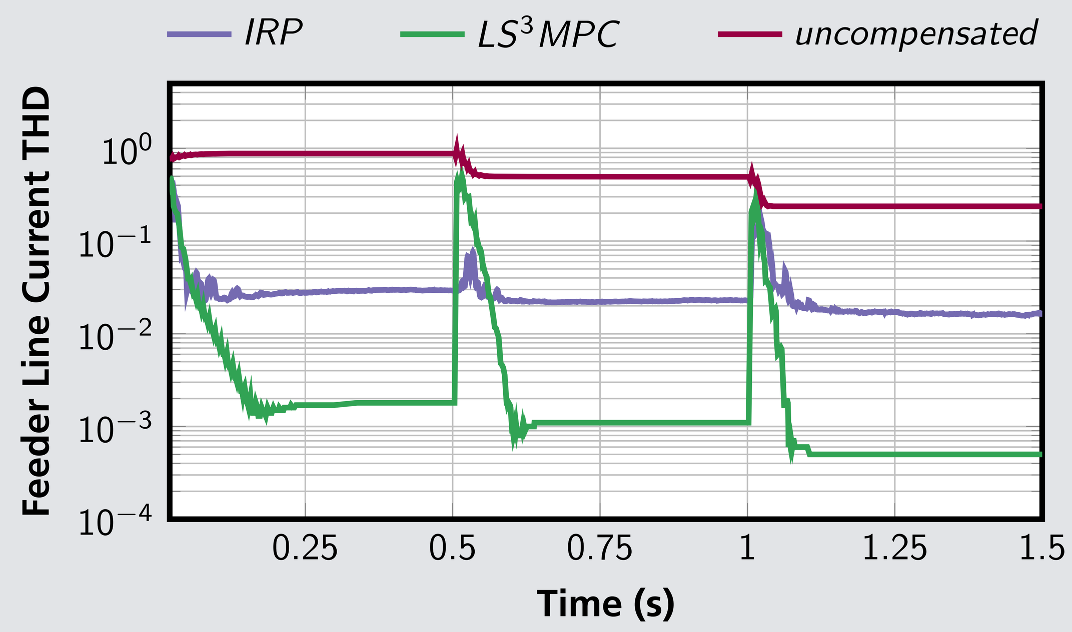
IRP APF harmonic current compensation:



LS^{3}MPC harmonic current compensation:



Total harmonic distortion (THD):



Results for different load scenarios:

Load scenario	THD (v_{PCC}) IRP	THD (v_{PCC}) LS^{3}MPC	THD (i_f) IRP	THD (i_f) LS^{3}MPC
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 LS^{3}MPC can successfully improve the THD compensation of an APF**
- **Classic IRP rely on high pass filter design for a given load scenario, while LS^{3}MPC can inherently adapt to a wider variety**
- **Current research on LS^{3}MPC focuses on enabling reactive power compensation**