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

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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

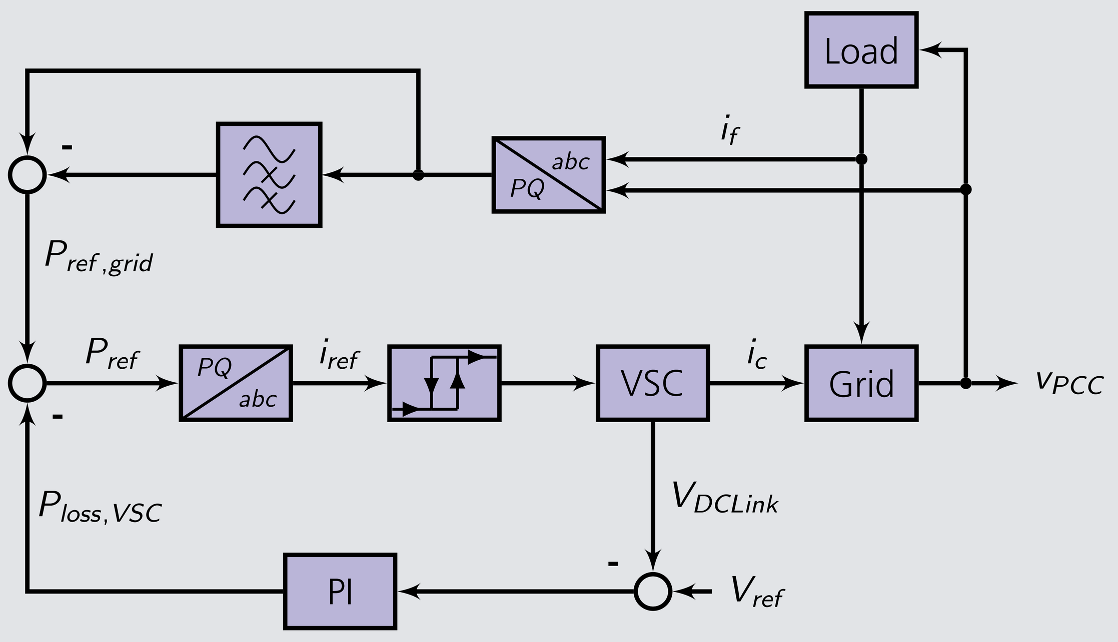
APPLICATION PROBLEM

A novel approach: Linear State Signal Shaping Model Predictive Control (LS^{3}MPC), has been developed to compensate harmonics using shape classes

- Can the LS^{3}MPC improve the grid quality compared to a classic APF controller?
- Can the LS^{3}MPC adapt under variable load scenarios?

CLASSIC IRP CONTROLLER

The instantaneous reactive power (IRP) theory is a state-of-the-art classic APF control approach.



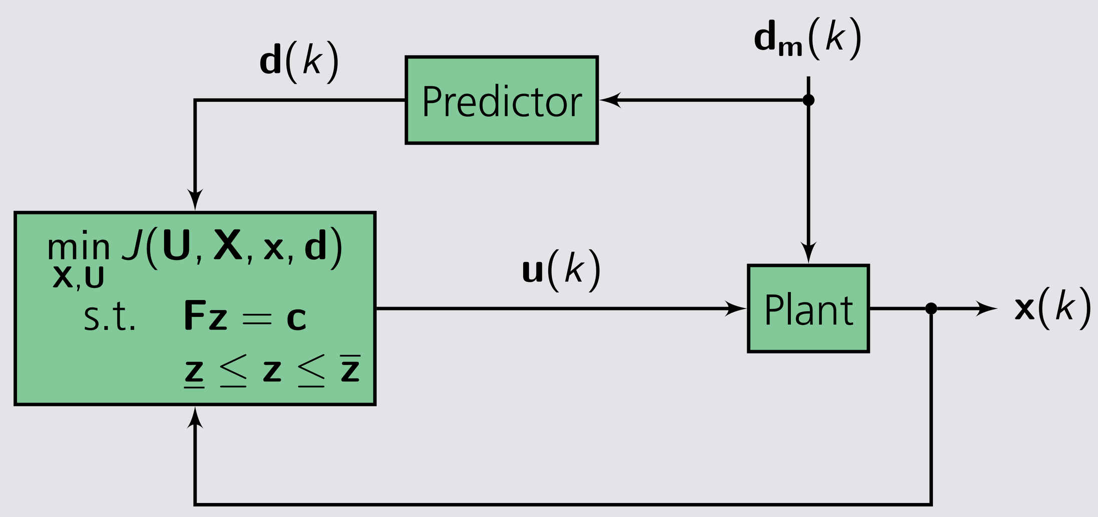
- Clarke and p-q transformation are used
- A high pass filter extracts harmonics
- A hysteresis band controller steers the voltage source converter

PREDICTIVE CONTROLLER

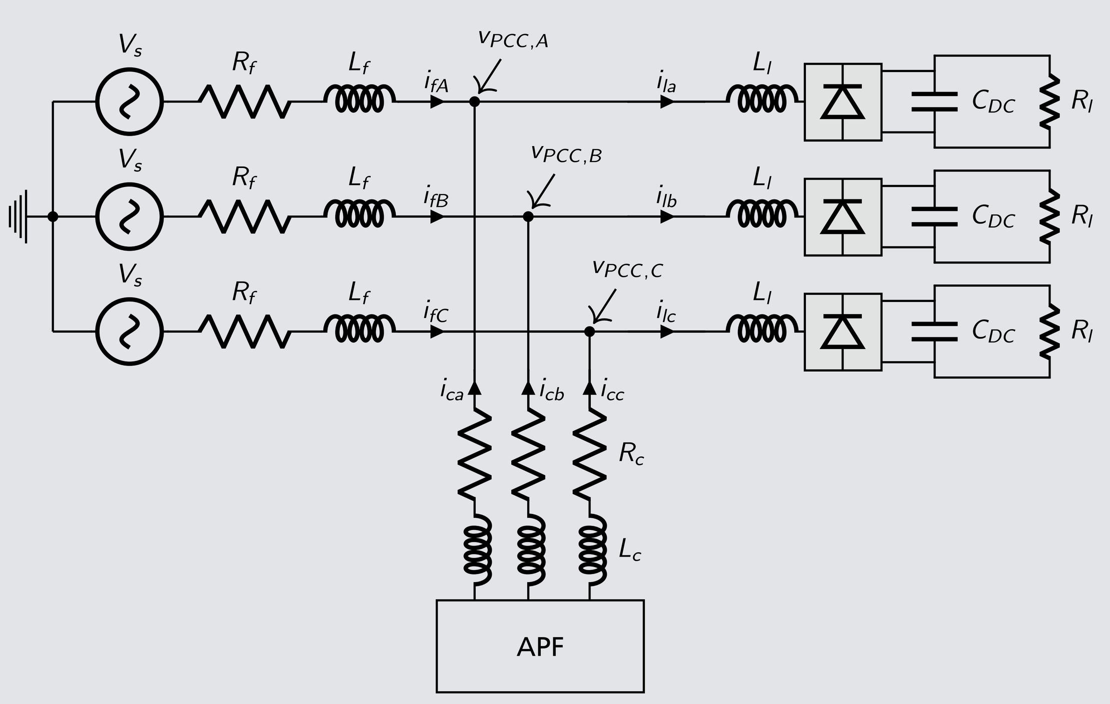
The MPC minimizes the cost function

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

The optimization problem is solved by formulating it as a constrained sparse quadratic programming (QP) problem, with the following close loop behavior:



3-PHASE GRID MODEL



Active power filter in shunt configuration

WHITE-BOX MODELING

Linear state space model per phase

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

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

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

LINEAR SHAPE CLASS

A sine wave shape is given by the 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* $\mathbf{V}$ 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 $\mathbf{Q}$ is built using $\mathbf{V}$ by transferring the control goal to the optimization problem

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

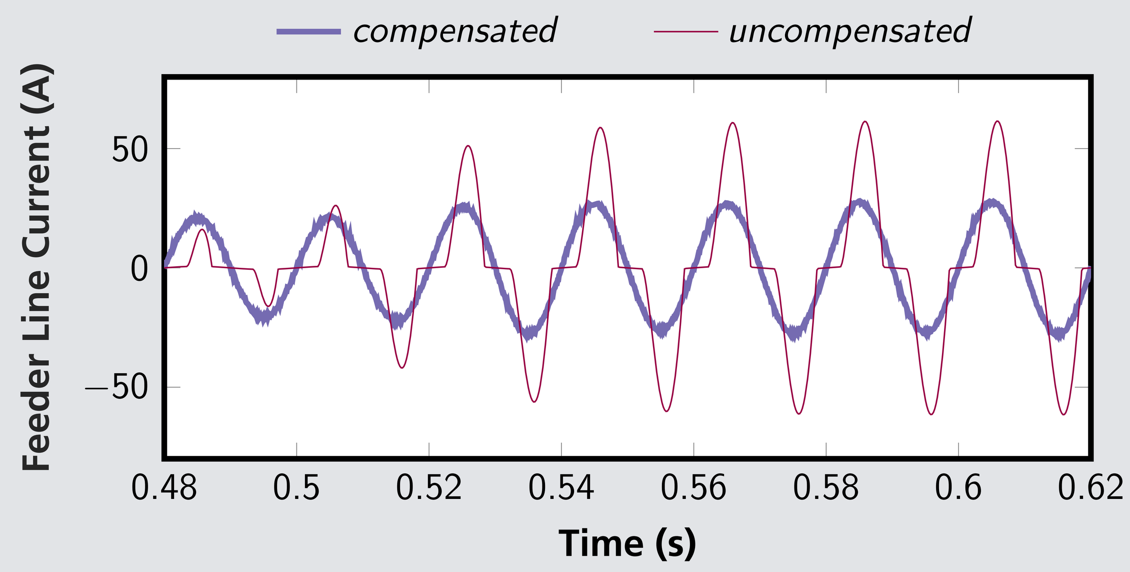
where

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

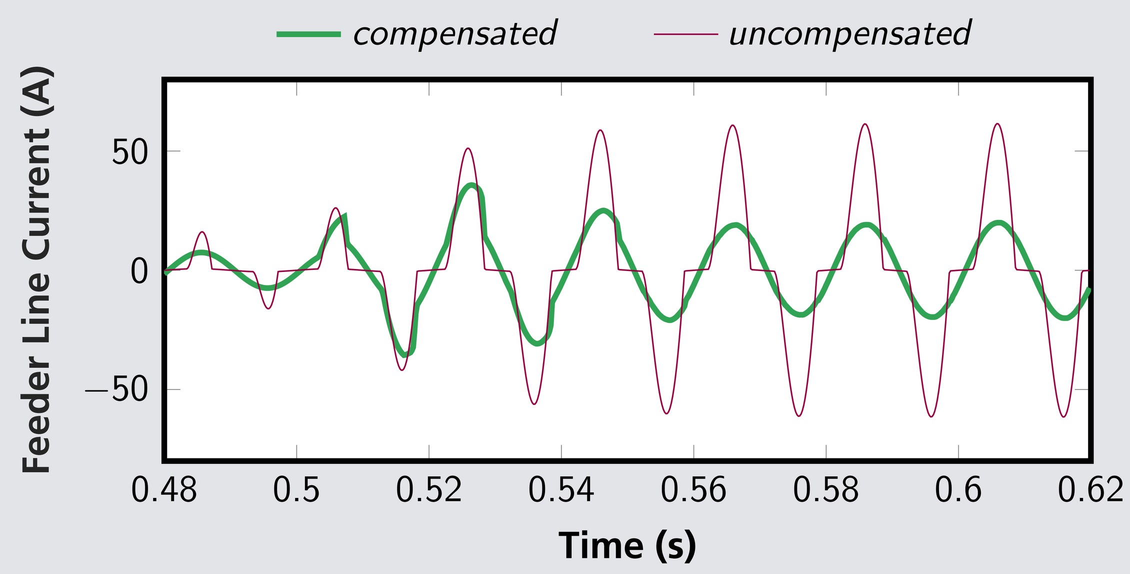
for all times k.

SIMULATION STUDIES

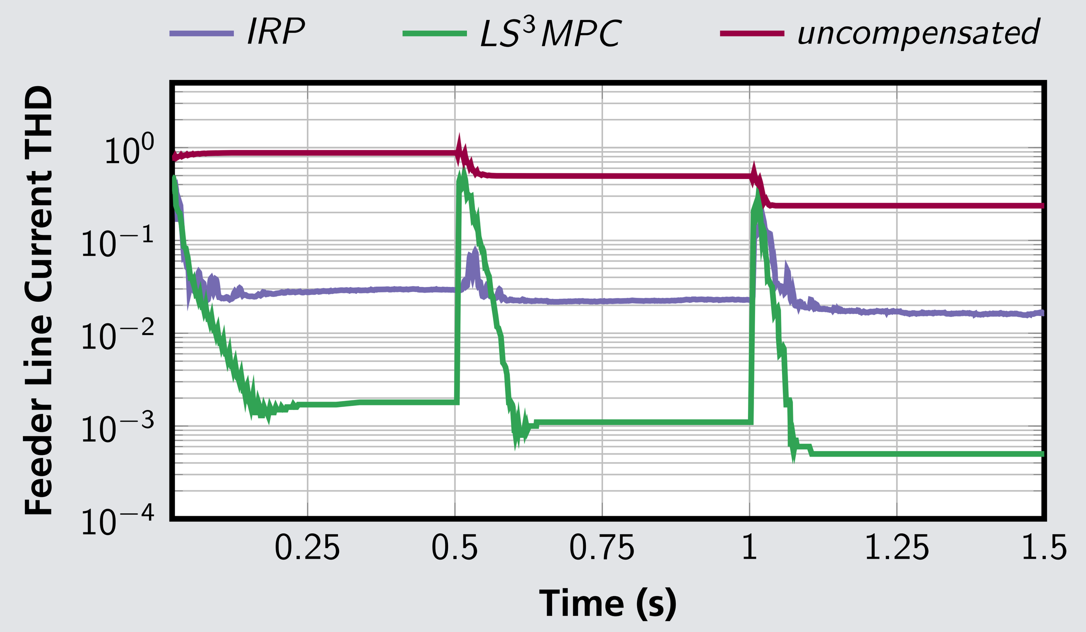
IRP APF harmonic current compensation:



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%	2.92%	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
- The LS^{3}MPC can inherently adapt to a wider variety of load scenarios
- Current research on LS^{3}MPC focuses on enabling reactive power compensation

PUBLICATIONS

- 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*
- Weihe, K., Cateriano Yáñez, C., Pangalos, G., and Lichtenberg, G. (2018). Comparison of Linear State Signal Shaping Model Predictive Control with Classical Concepts for Active Power Filter Design. In *Simultech 2018*