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Use of Resonant Terms in a 2DOF Control Scheme for the Current Control of an Active Power Filter

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1. Introduction

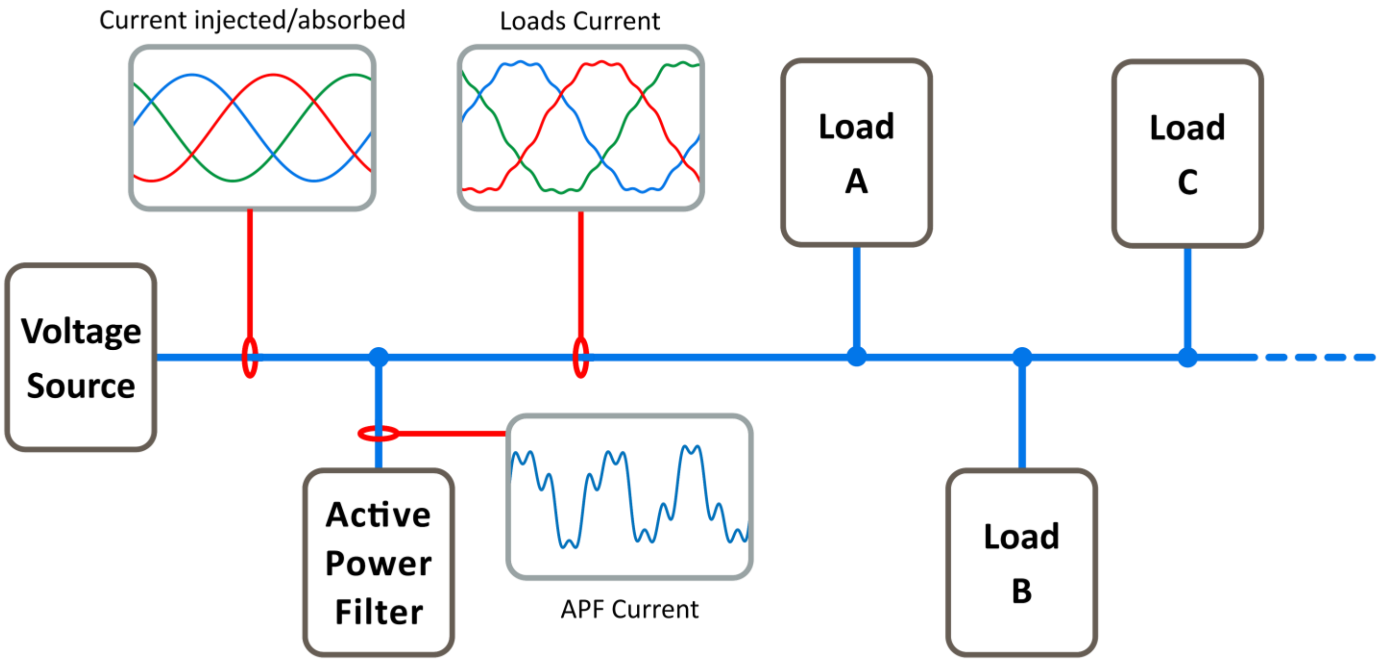
- Number of non-linear and single-phase loads has increased
  - Current harmonics
  - Voltage and current disbalances
- Power quality issues
  - Reduction of the power transferred in the grid
  - EMC issues
- Shunt Active Power Filter (APF)
  - Current disturbances: e.g., Current harmonics and disbalances
  - Reactive Power

1. Introduction

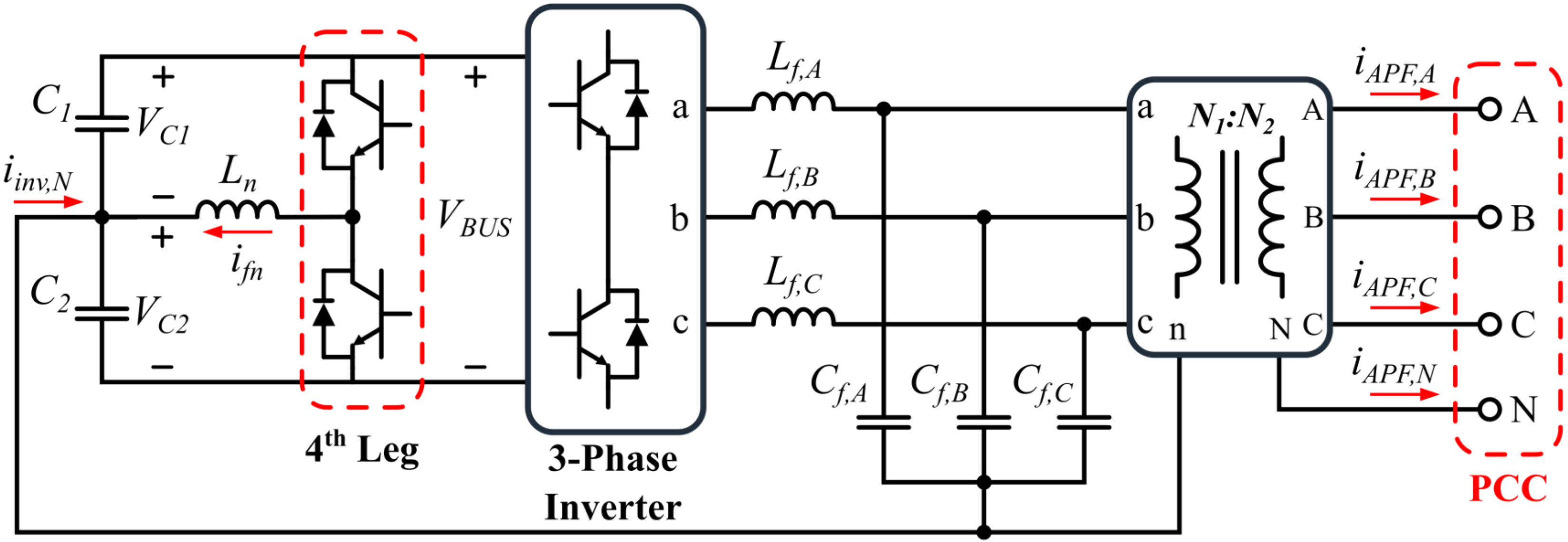
- Operation of the APF: 3 different Stages
  - Extraction of the undesired current components
  - Control of the APF
  - PWM modulation

- Objective: Control stage of an APF with an LCL filter placed at its output
  - Control scheme based on a 2-Degrees-of-Freedom (2DOF) structure
  - Damping of the LCL filter
  - Independent control of each phase of the APF
    - Can be also applied to single-phase systems
    - Use of a Synchronous Reference Frame (SRF) for control purposes is avoided

2. System Description



2. System Description

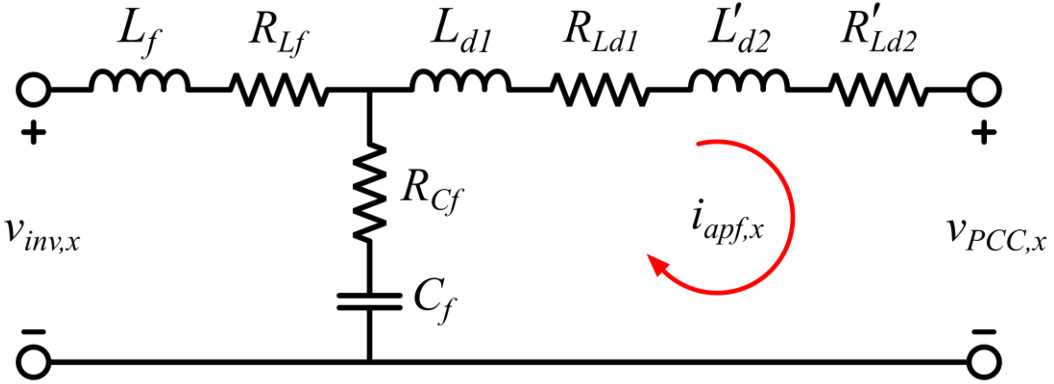


2. System Description

- LCL Filter Model
  - Single-phase model of the LCL filter
    - Neglecting magnetizing inductance of the transformer

$$R'_{d2} = \frac{R_{d2}}{r^2} \qquad L'_{d2} = \frac{L_{d2}}{r^2}$$

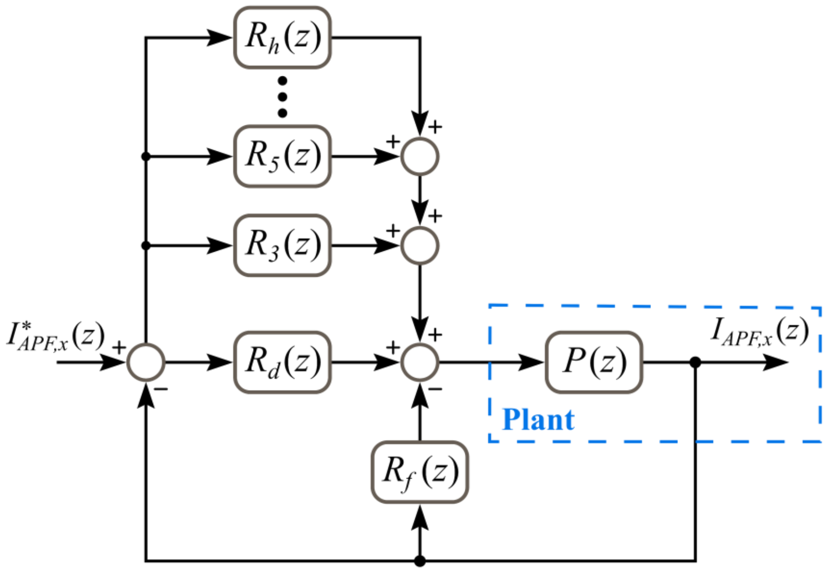
$$P(s) = \frac{I_{apf,x}(s)}{V_{pcc,x}(s)} = \frac{B_1 s + B_0}{s^3 + A_2 s^2 + A_1 s + A_0}$$



$$P(z) = \frac{1}{z} \cdot \frac{b_2 z^2 + b_1 z + b_0}{z^3 + a_2 z^2 + a_1 z + a_0}$$

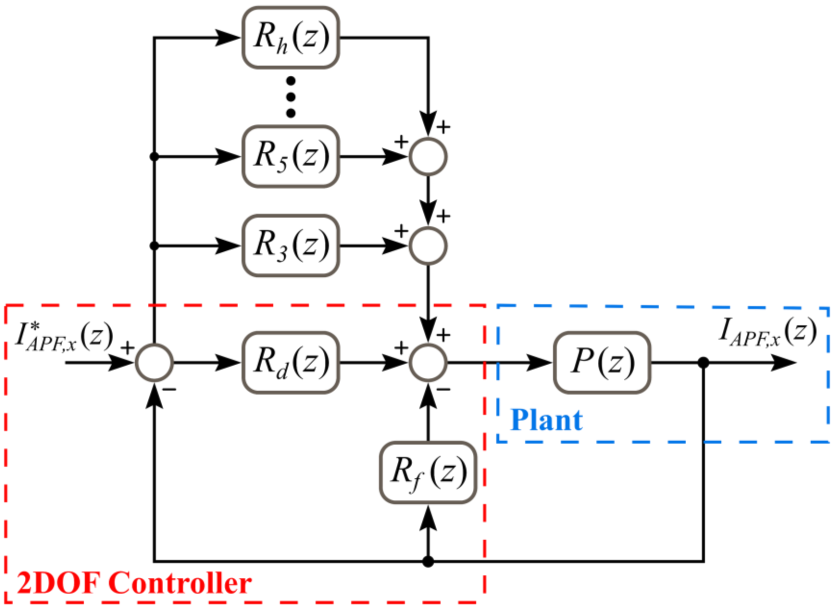
PWM

3. Design of the Control Stage



3. Design of the Control Stage

- 2DOF Controller



$$R_d(z) = R_\omega(z) \cdot R_p(z)$$

$$R_\omega(z) = \frac{R_{\omega,n}(z)}{R_{\omega,d}(z)} = \frac{z-1}{z^2 + c_0 z + 1}$$

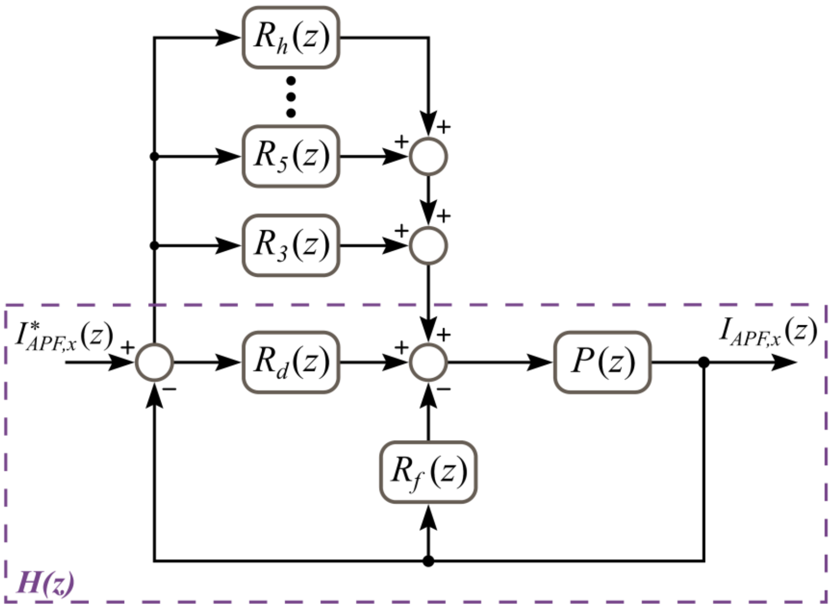
$$c_0 = -2\cos(2\pi f_0 T_s)$$

$$R_p(z) = \frac{R_{p,n}(z)}{R_{p,d}(z)} = \frac{K_1 z - K_0}{z^3 + \rho_2 z^2 + \rho_1 z + \rho_0}$$

$$R_f(z) = \frac{R_{p,n}(z)}{R_{p,d}(z)} = \frac{K_5 z^3 - K_4 z^2 + K_3 z + K_2}{z^3 + \rho_2 z^2 + \rho_1 z + \rho_0}$$

3. Design of the Control Stage

- 2DOF Controller



$$H(z) = \frac{N(z)}{F(z)}$$

$$F(z) = P_d(z)R_{\omega,n}(z)R_{p,n}(z) +$$

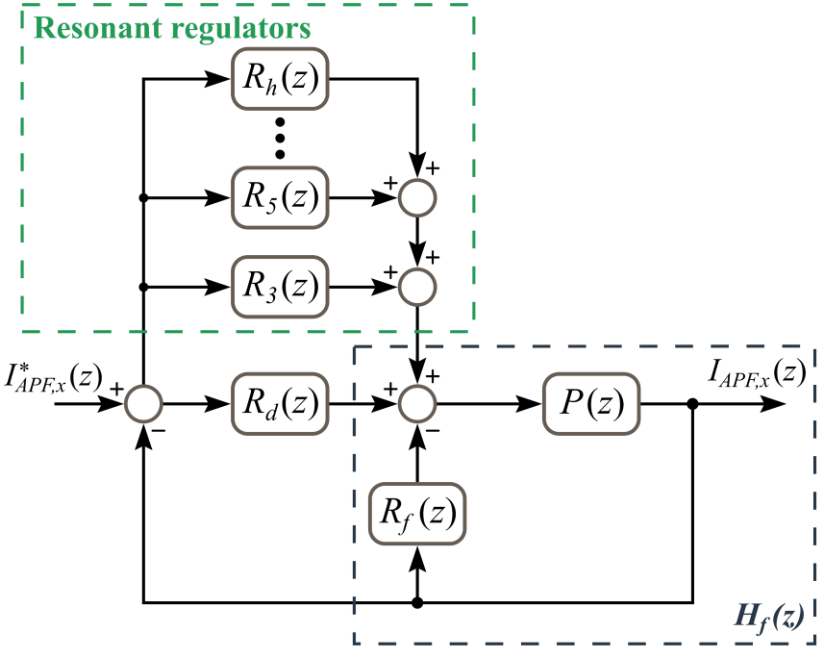
$$+ P_n(z)\left[R_{p,n}(z)R_{\omega,n}(z) + R_{2,n}(z)R_{\omega,d}(z)\right]$$

$$F(z) = (z - p_9) \ldots (z - p_0)$$

System of linear equations

3. Design of the Control Stage

- 2DOF Controller



$$R_h(z) = \frac{1}{z^2 + c_h z + 1} \cdot k_h \frac{z - \beta_h}{z - \alpha_h}$$

$$c_h = -2\cos(2\pi h f_0 T_s)$$

Particular solution:

$$\alpha_h = 0$$

4. Design example

LCL Filter

Parameter	Value	Parameter	Value
$L_f\ (mH)$	2.6	$R_{Lf}\ (m\Omega)$	80
$C_f\ (\mu F)$	46	$R_{Cf}\ (m\Omega)$	50
$L_{d1}\ (mH)$	0.155	$R_{Ld1}\ (m\Omega)$	200
$L_{d2}\ (mH)$	0.274	$R_{Ld1}\ (m\Omega)$	300
r	$\sqrt{3}$	$T_s\ (\mu s)$	100

Location of the Poles

Pole	Location	Pole	Location
p_0	0.966	p_5	0
p_1	0.966	p_6	0
p_2	-0.2826	p_7	0
p_3	0.483	p_8	0
p_4	0.483		

4. Design example

LCL Filter

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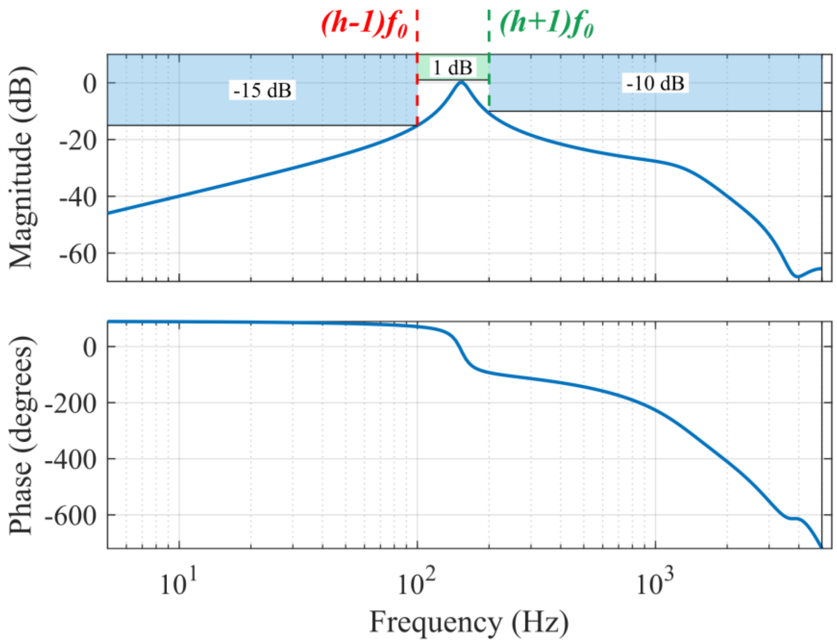
r	$\sqrt{3}$	$T_s\ (\mu s)$	100

Control Parameters

Param.	Value	Param.	Value
c_0	-1.9990	ρ_0	0.1597
ρ_1	0.9207	ρ_2	1.4122
K_0	-3.2085	K_1	3.9929
K_2	-3.2085	K_3	31.4209
K_4	-19.8707	K_5	4.1270

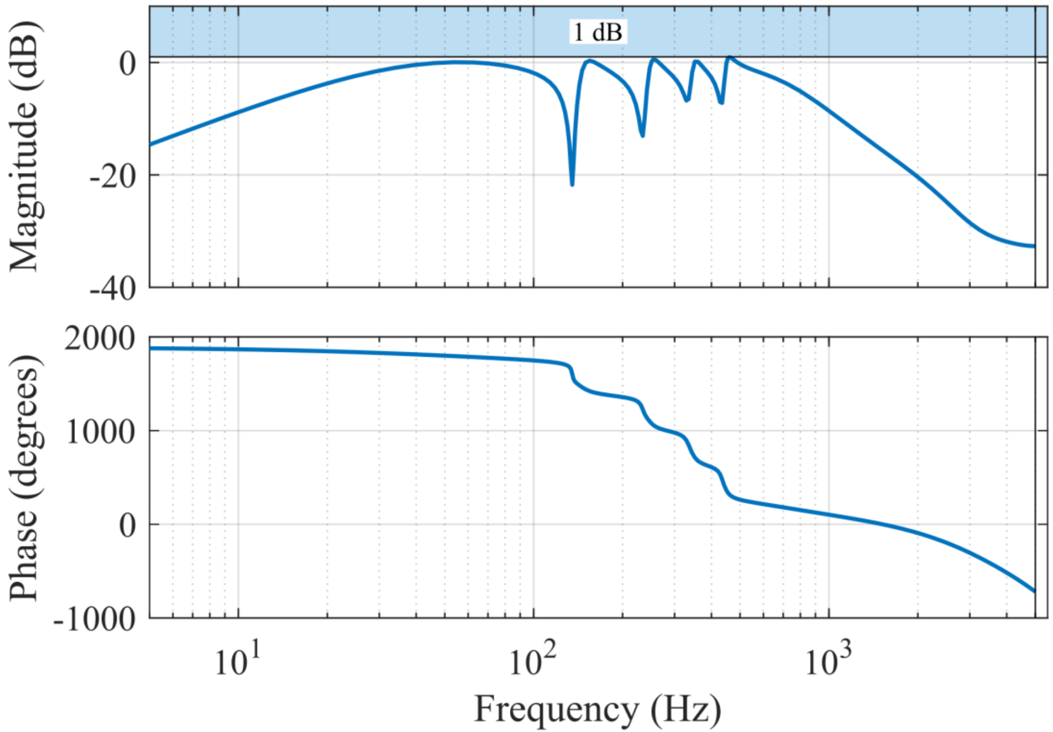
4. Design example



Control Parameters

h	c_h	k_h	β_h
3	-1.9911	0.280	0.800
5	-1.9754	0.260	0.850
7	-1.9518	0.255	0.930
9	-1.9206	0.230	0.975

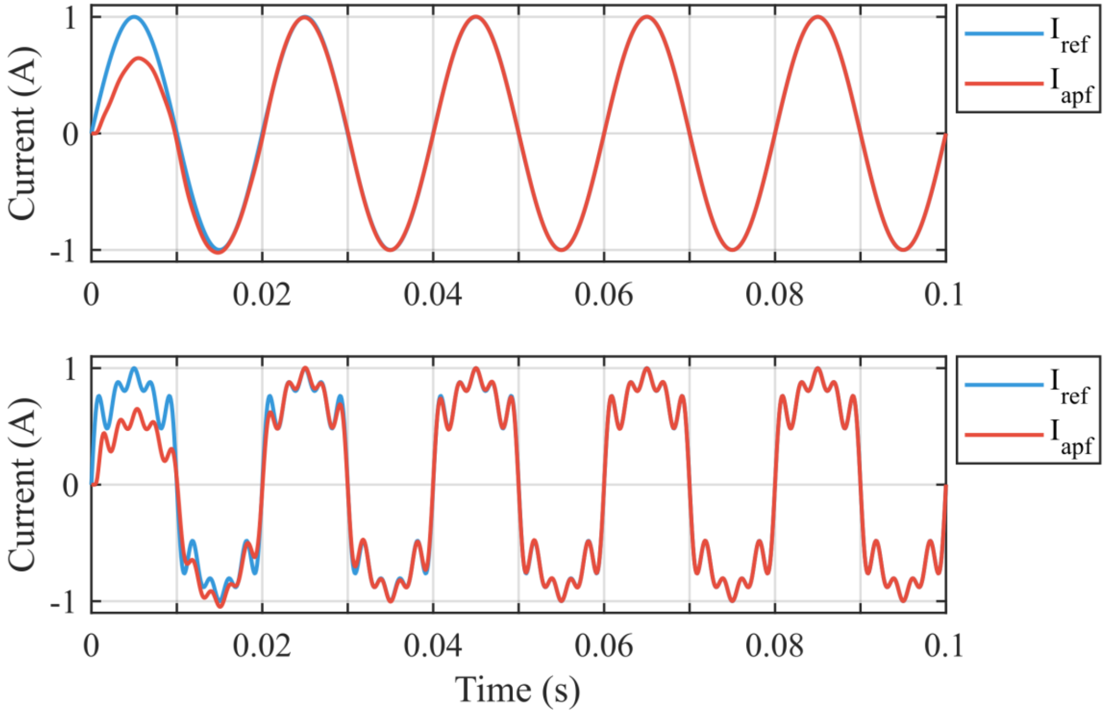
4. Design example



4. Design example

50 Hz
Only

50 Hz
+
Harmonics

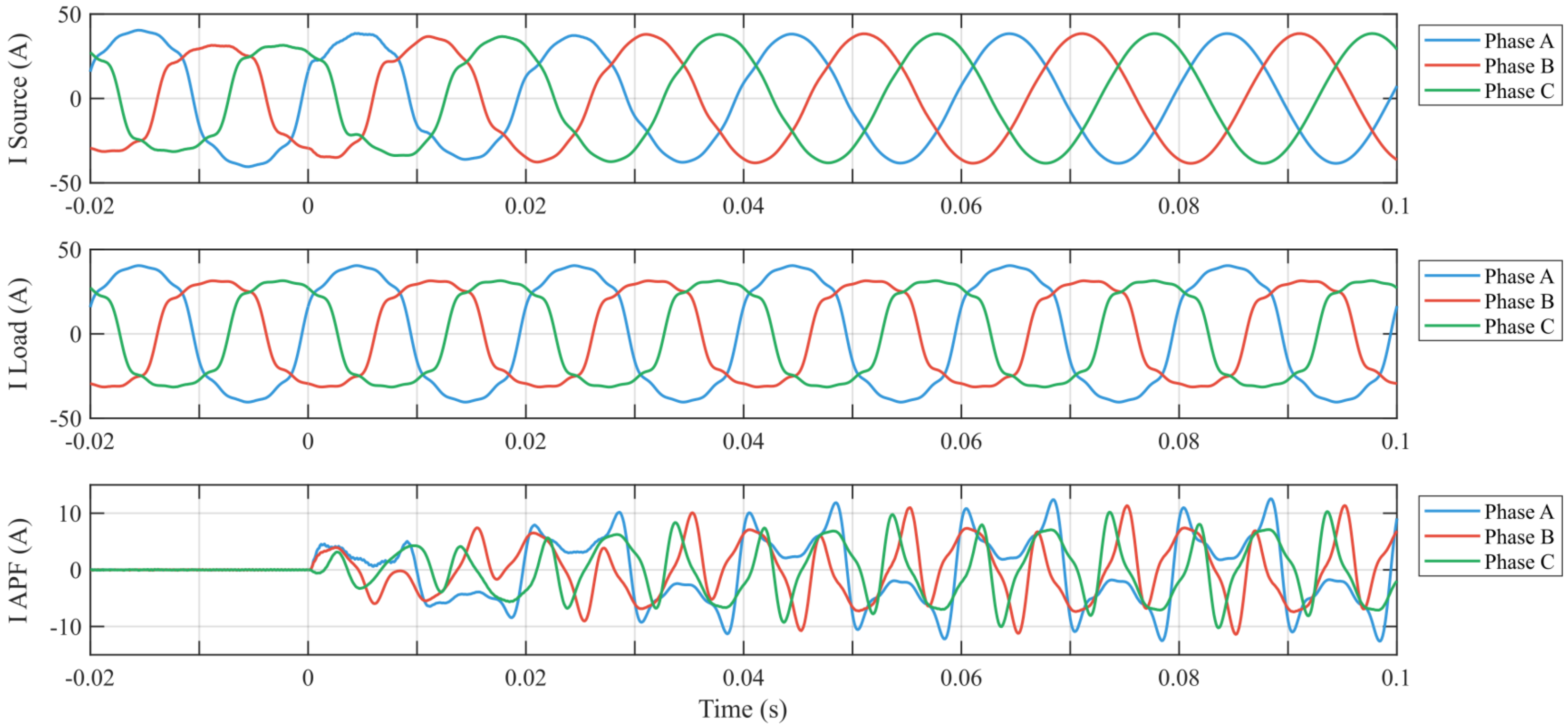


5. Simulation results

- Hardware-In-the-Loop (HIL) Emulation
  - Typhoon HIL 402 & dSPACE MicroLabBox
- Three Loads
  - Load A
    - Positive, negative and zero sequence components
    - 5 A, 4 A and 2 A RMS, respectively
  - Load B
    - Inductive load: L = 20 mH, R = 62 Ω
  - Load C

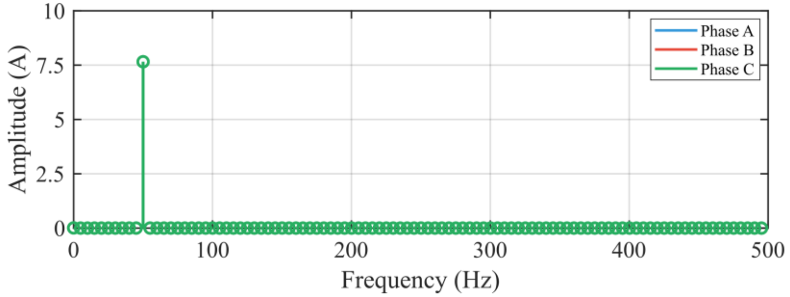
h	*Amplitude*	$\hat{I}_h / \hat{I}_1$ (%)	h	*Amplitude*	$\hat{I}_h / \hat{I}_1$ (%)
1	20	–	7	1.44	7.2
3	4.32	21.6	9	0.76	3.8
5	2.14	10.7			

5. Simulation results

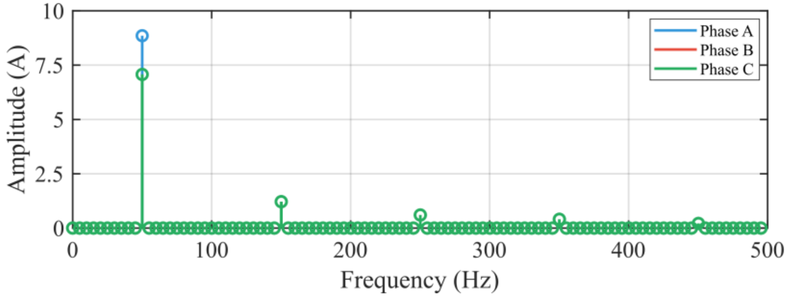


5. Simulation results

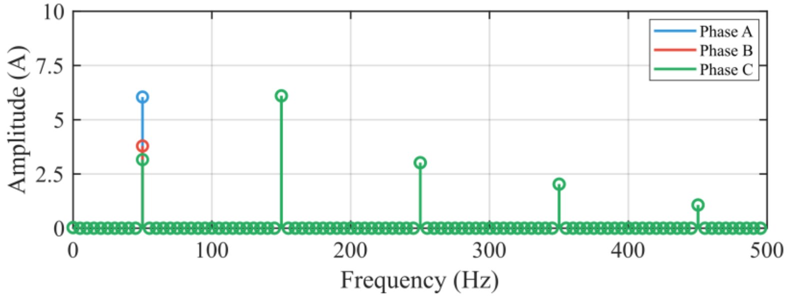
Source



Load



APF



6. Conclusions

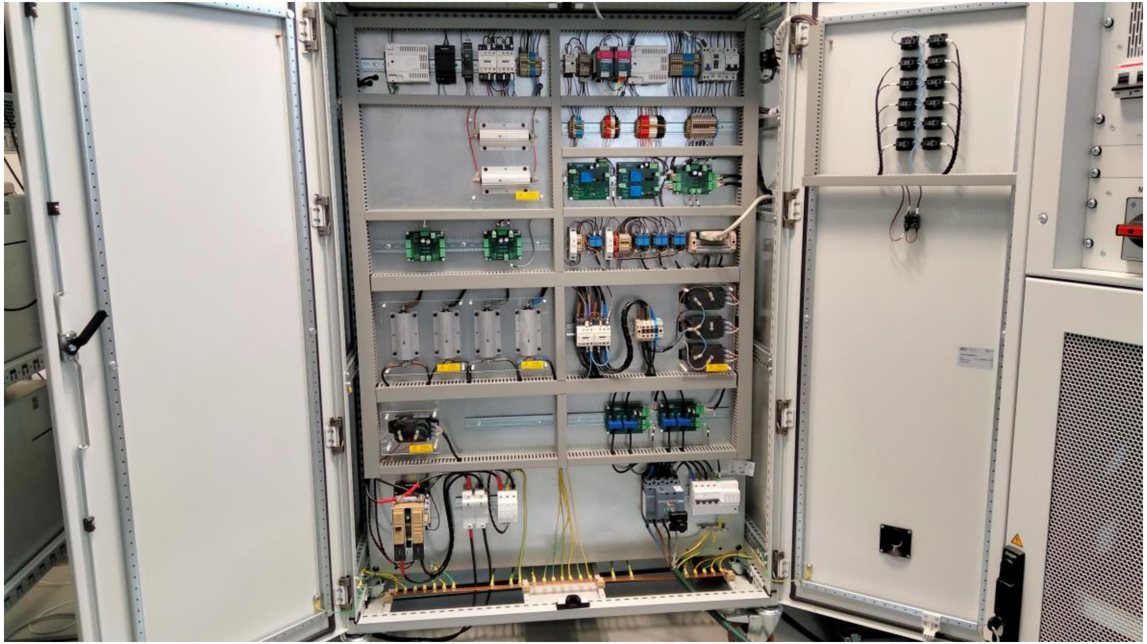
- Current control for a three-phase four-wire APF with an LCL filter
  - Damping of the LCL filter
  - Can be also applied to single-phase systems
- Control scheme based on a 2D0F structure
  - 2DOF controller for tracking the 50 Hz signal
  - Resonant regulators for tracking harmonic components
- Simulation results
  - Fast tracking of the 50 Hz signal (2D0F controller)
  - Proper tracking and compensation of the current harmonics

6. Conclusions

- Future work: Experimental results

6. Conclusions

- Future work: Experimental results



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Thank you for your attention!

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