Modeling and control of wind turbine systems with open switch converter faults

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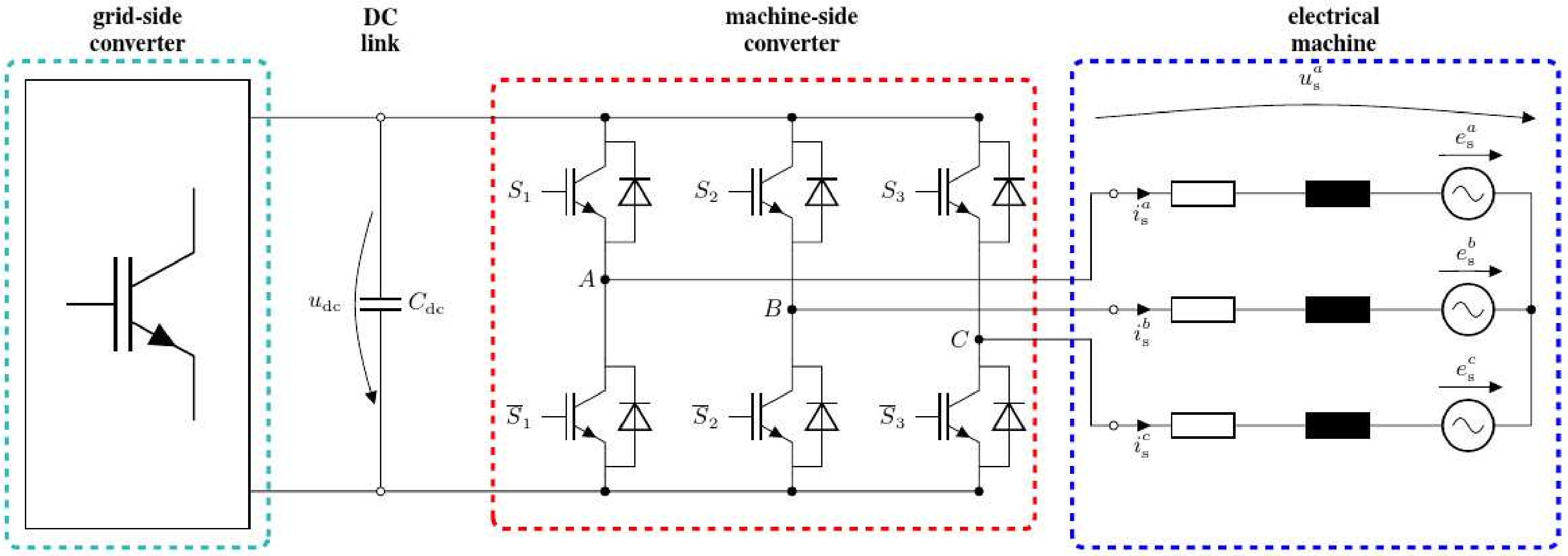
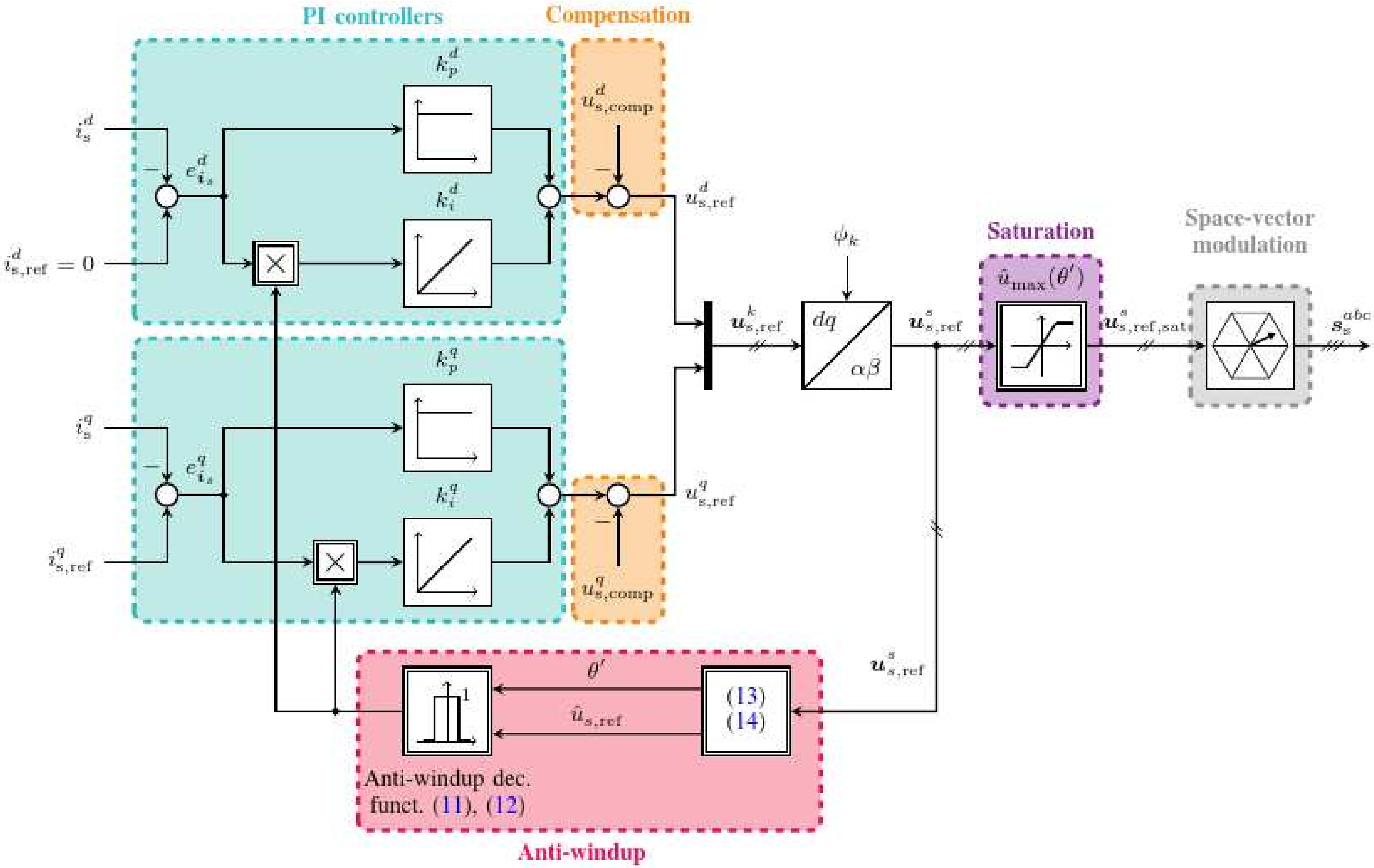
Outline

- **Problem statement**
  - Electrical system
  - Conventional field-oriented control (FOC)
  - Simulation results
- **Modeling**
  - Voltage source inverter (VSI) with open switch fault in S1
  - Models for all possible open switch faults
- **Control**
  - Improved Anti-Windup
  - Flat-top modulation
  - d-current injection
- **Implementation**
  - Block diagramm
  - Laboratory setup
  - Measurement results

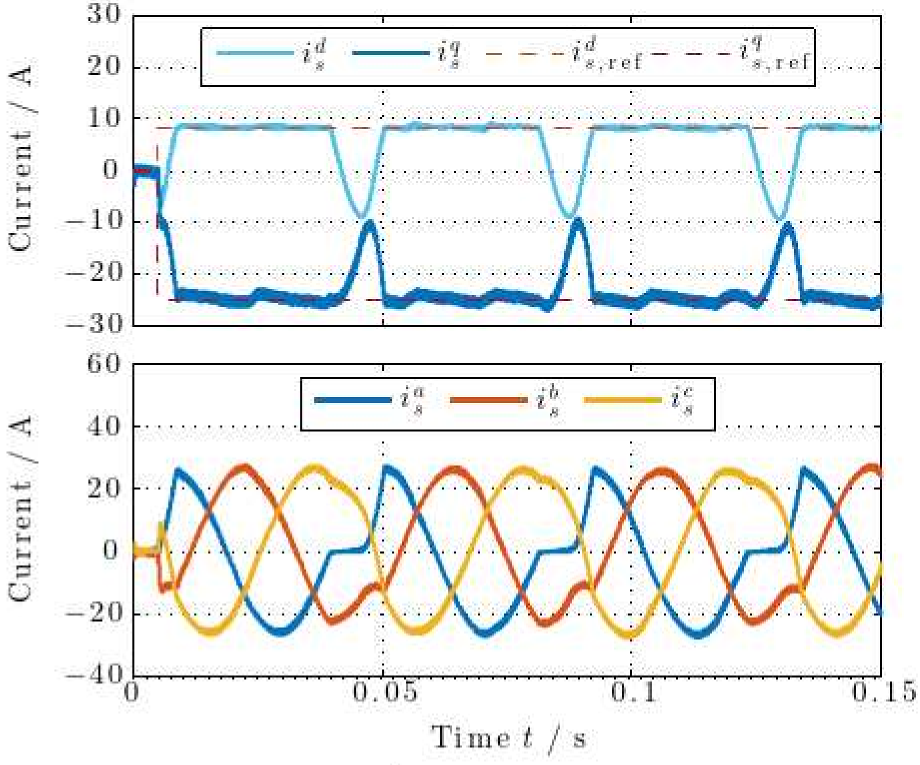
Problem statement: Electrical System



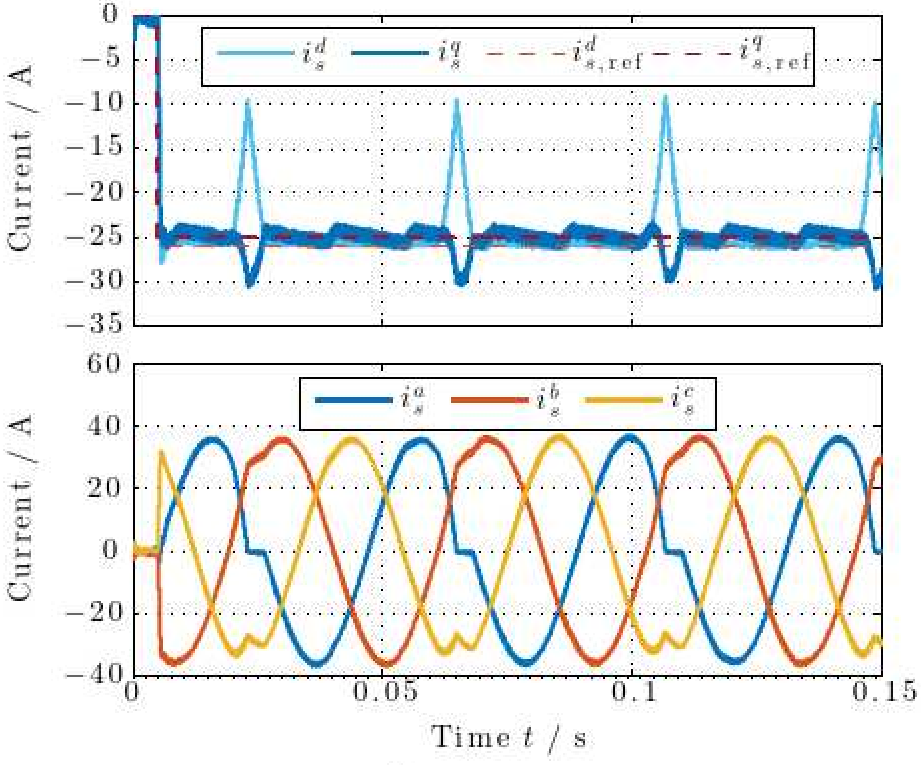
Problem statement: Conventional FOC



Problem statement: Simulation results

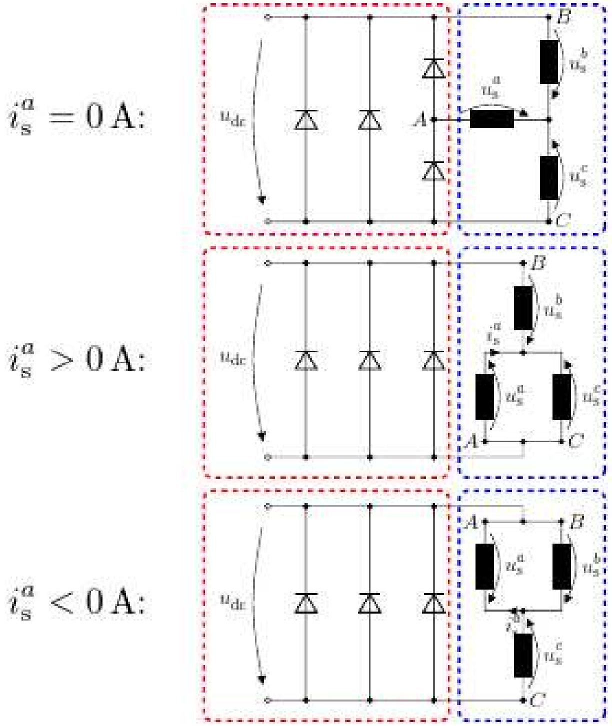


(a) $\varphi_0 = 150^\circ$: $\mathrm{THD}_{i_s^a} = 31.4\,\%$.

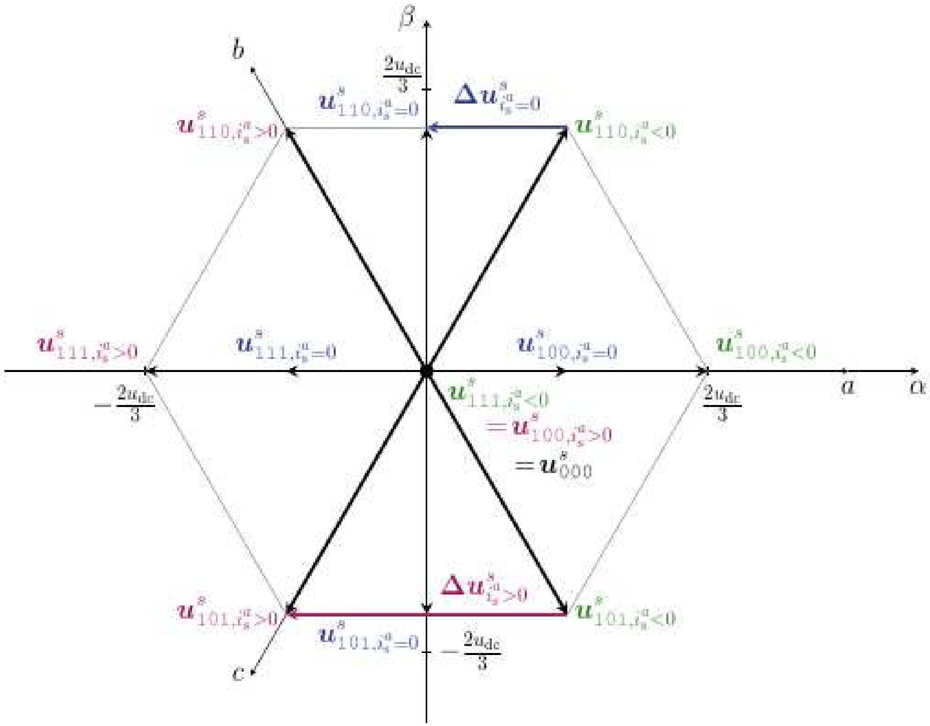


(b) $\varphi_0 = 210^\circ$: $\mathrm{THD}_{i_s^a} = 12.2\,\%$.

Modeling: VSI with open switch fault in S1

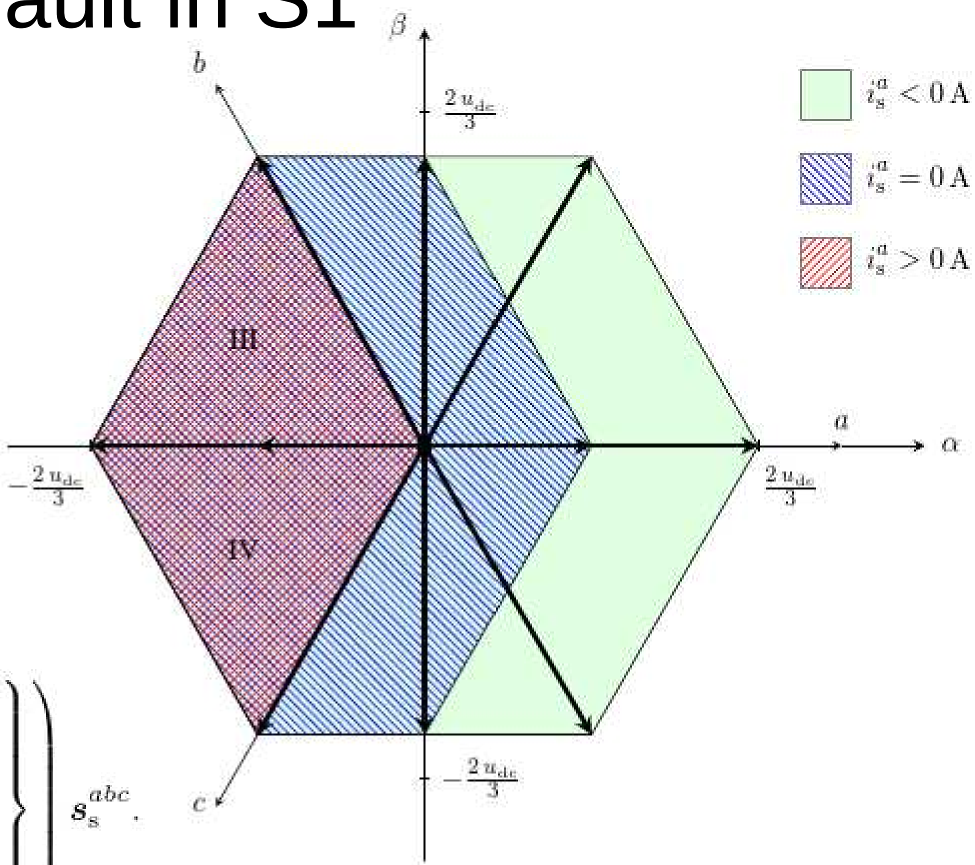


(a) Electrical equivalent circuit for $\boldsymbol{s}_s^{abc} = (1,\ 1,\ 0)^\top$.



(b) Voltage hexagon with *shifted* voltage vectors for all possible $\boldsymbol{s}_s^{abc}$.

Modeling: VSI with fault in S1



$$\boldsymbol{u}_s^{abc} = \frac{u_{dc}}{3} \underbrace{\left(\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix} + \begin{cases} \boldsymbol{O}_{3\times 3}, & \text{if } i_s^a < 0\,\mathrm{A} \\ \begin{bmatrix} -1 & 0 & 0 \\ \frac{1}{2} & 0 & 0 \\ \frac{1}{2} & 0 & 0 \end{bmatrix}, & \text{if } i_s^a = 0\,\mathrm{A} \\ \begin{bmatrix} -2 & 0 & 0 \\ 1 & 0 & 0 \\ 1 & 0 & 0 \end{bmatrix}, & \text{if } i_s^a > 0\,\mathrm{A} \end{cases} \right)}_{=:\boldsymbol{S}_{S_1}(i_s^a)} \boldsymbol{s}_s^{abc},$$

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Modeling: Faults in other switches

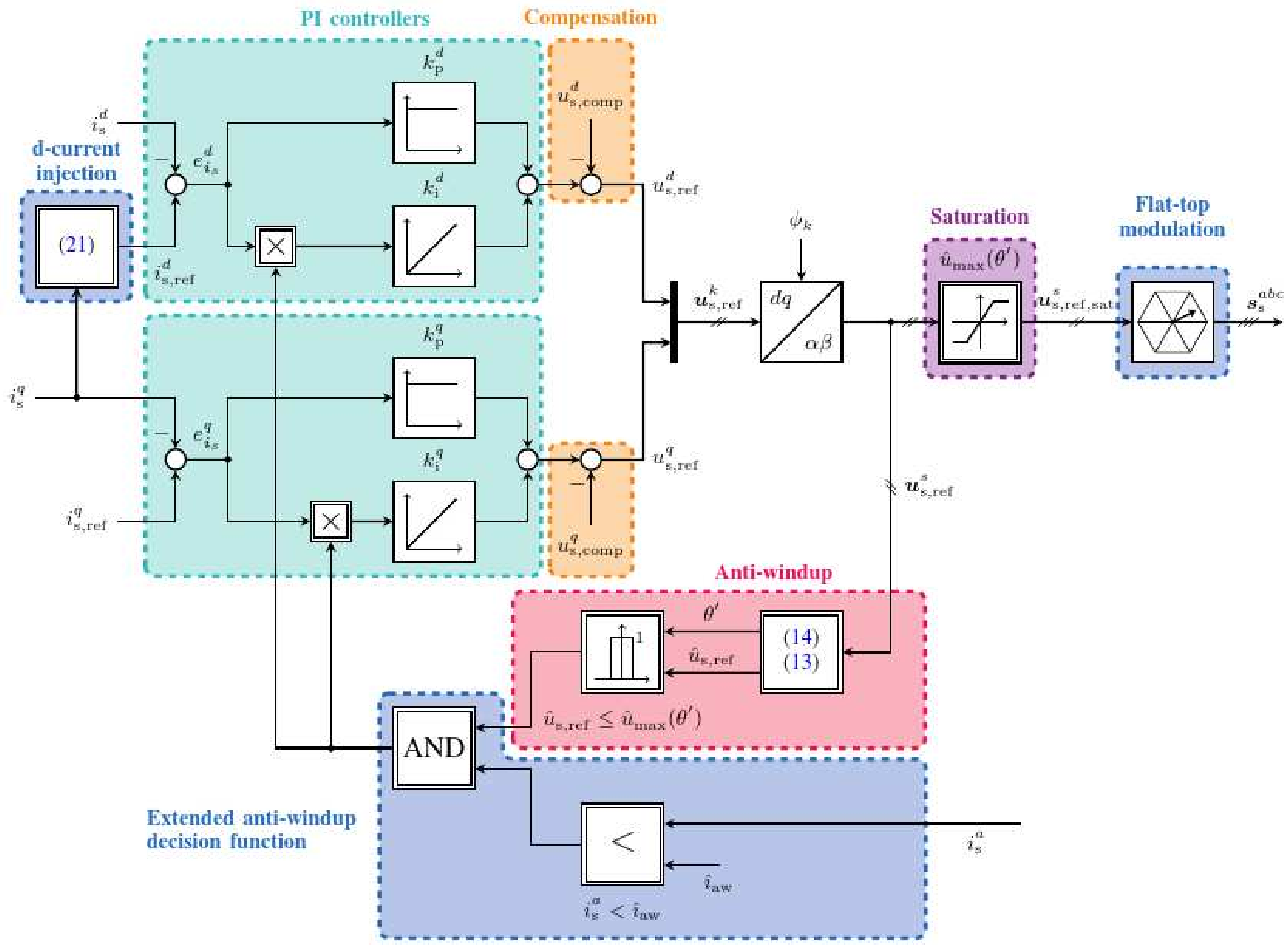
Converter output phase voltage $\boldsymbol{u}_{\mathrm{s}}^{abc} = \frac{u_{\mathrm{dc}}}{3} \boldsymbol{S}_y(i_{\mathrm{s}}^{x})\, \boldsymbol{s}_{\mathrm{s}}^{abc}$ for faults in the *upper* switches

	$y = S_1,\ x = a$	$y = S_2,\ x = b$	$y = S_3,\ x = c$
$\boldsymbol{S}_y\left(i_{\mathrm{s}}^{x} < 0\,\mathrm{A}\right)$	$\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & -1 & -1 \\ -1 & 2 & -1 \\ -1 & -1 & 2 \end{bmatrix}$
$\boldsymbol{S}_y\left(i_{\mathrm{s}}^{x} = 0\,\mathrm{A}\right)$	$\begin{bmatrix} 1 & -1 & -1 \\ -\frac{1}{2} & 2 & -1 \\ -\frac{1}{2} & -1 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & -\frac{1}{2} & -1 \\ -1 & 1 & -1 \\ -1 & -\frac{1}{2} & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & -1 & -\frac{1}{2} \\ -1 & 2 & -\frac{1}{2} \\ -1 & -1 & 1 \end{bmatrix}$
$\boldsymbol{S}_y\left(i_{\mathrm{s}}^{x} > 0\,\mathrm{A}\right)$	$\begin{bmatrix} 0 & -1 & -1 \\ 0 & 2 & -1 \\ 0 & -1 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & 0 & -1 \\ -1 & 0 & -1 \\ -1 & 0 & 2 \end{bmatrix}$	$\begin{bmatrix} 2 & -1 & 0 \\ -1 & 2 & 0 \\ -1 & -1 & 0 \end{bmatrix}$

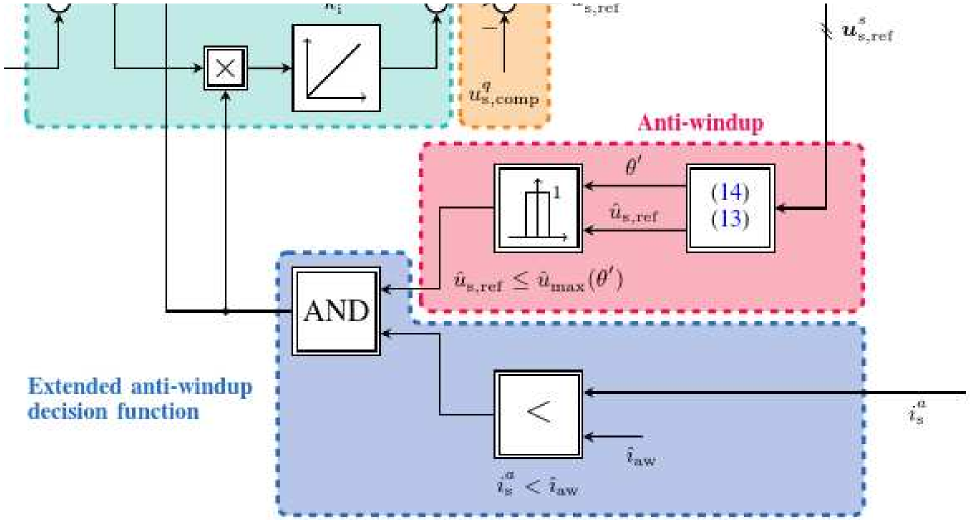
Converter output phase voltage $\boldsymbol{u}_{\mathrm{s}}^{abc} = \frac{u_{\mathrm{dc}}}{3} \boldsymbol{S}_z(i_{\mathrm{s}}^{x})\, \overline{\boldsymbol{s}}_{\mathrm{s}}^{abc}$ for faults in the *lower* switches

	$z = \overline{S}_1,\ x = a$	$z = \overline{S}_2,\ x = b$	$z = \overline{S}_3,\ x = c$
$\boldsymbol{S}_z\left(i_{\mathrm{s}}^{x} < 0\,\mathrm{A}\right)$	$\begin{bmatrix} 0 & 1 & 1 \\ 0 & -2 & 1 \\ 0 & 1 & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & 0 & 1 \\ 1 & 0 & 1 \\ 1 & 0 & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & 1 & 0 \\ 1 & -2 & 0 \\ 1 & 1 & 0 \end{bmatrix}$
$\boldsymbol{S}_z\left(i_{\mathrm{s}}^{x} = 0\,\mathrm{A}\right)$	$\begin{bmatrix} -1 & 1 & 1 \\ \frac{1}{2} & -2 & 1 \\ \frac{1}{2} & 1 & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & \frac{1}{2} & 1 \\ 1 & -1 & 1 \\ 1 & \frac{1}{2} & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & 1 & \frac{1}{2} \\ 1 & -2 & \frac{1}{2} \\ 1 & 1 & -1 \end{bmatrix}$
$\boldsymbol{S}_z\left(i_{\mathrm{s}}^{x} > 0\,\mathrm{A}\right)$	$\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$	$\begin{bmatrix} -2 & 1 & 1 \\ 1 & -2 & 1 \\ 1 & 1 & -2 \end{bmatrix}$

Control: Fault-tolerant control system



Control: Extended anti-windup strategy



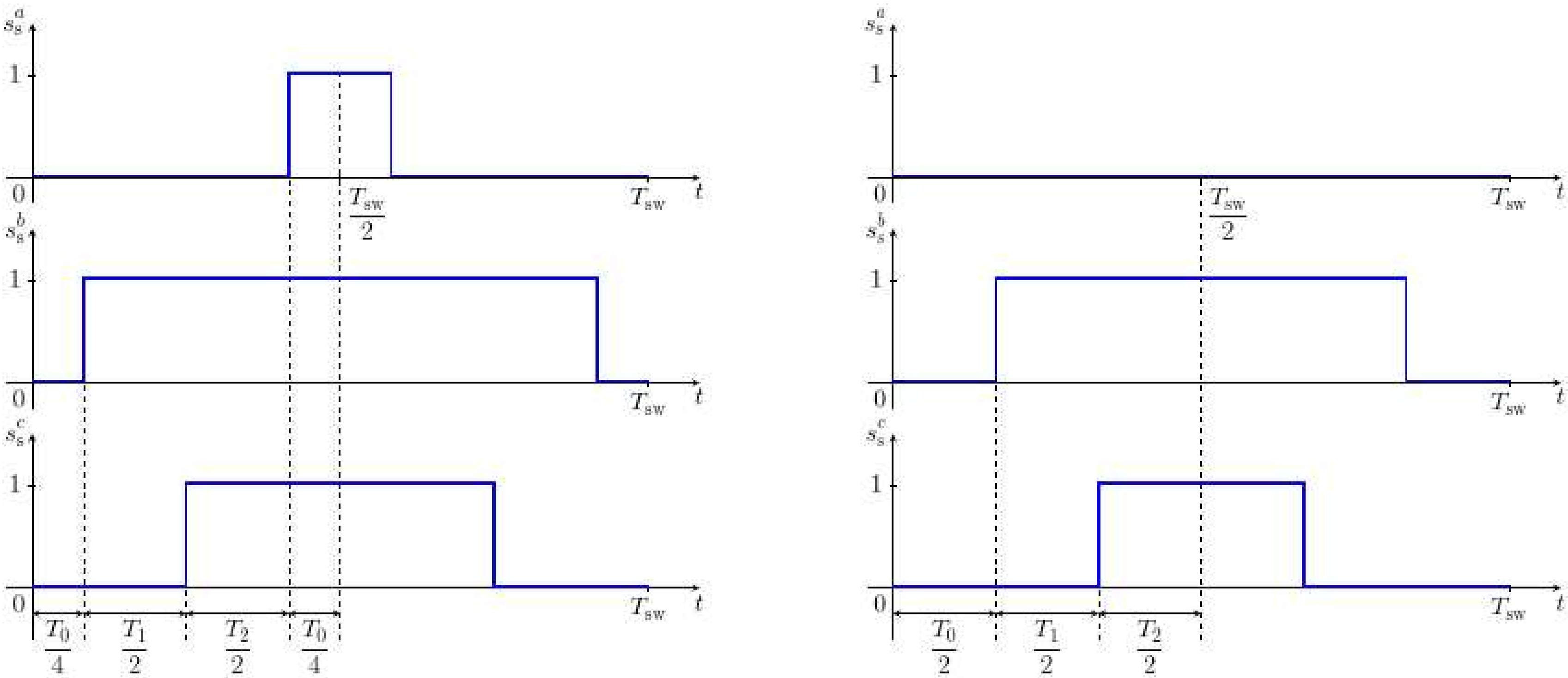
$$\hat{u}_{s,ref} := \sqrt{\left(u^{\alpha}_{s,ref}\right)^2 + \left(u^{\beta}_{s,ref}\right)^2} \quad \text{where}$$

$$\boldsymbol{u}^{s}_{s,ref} := \begin{pmatrix} u^{\alpha}_{s,ref} \\ u^{\beta}_{s,ref} \end{pmatrix} := \boldsymbol{T}_p(\phi_k) \underbrace{\left(\boldsymbol{u}^{k}_{s,PI} - \boldsymbol{u}^{k}_{s,comp}\right)}_{=:\boldsymbol{u}^{k}_{s,ref}}, \qquad (13)$$

$$\hat{u}_{max}(u_{dc}, \theta') := \underbrace{\frac{\sqrt{3}}{\sin(\theta') + \sqrt{3}\cos(\theta')}}_{\frac{\sqrt{3}}{2} \leq \cdot \leq 1} \cdot \tfrac{2}{3} u_{dc} \leq \tfrac{2}{3} u_{dc}$$

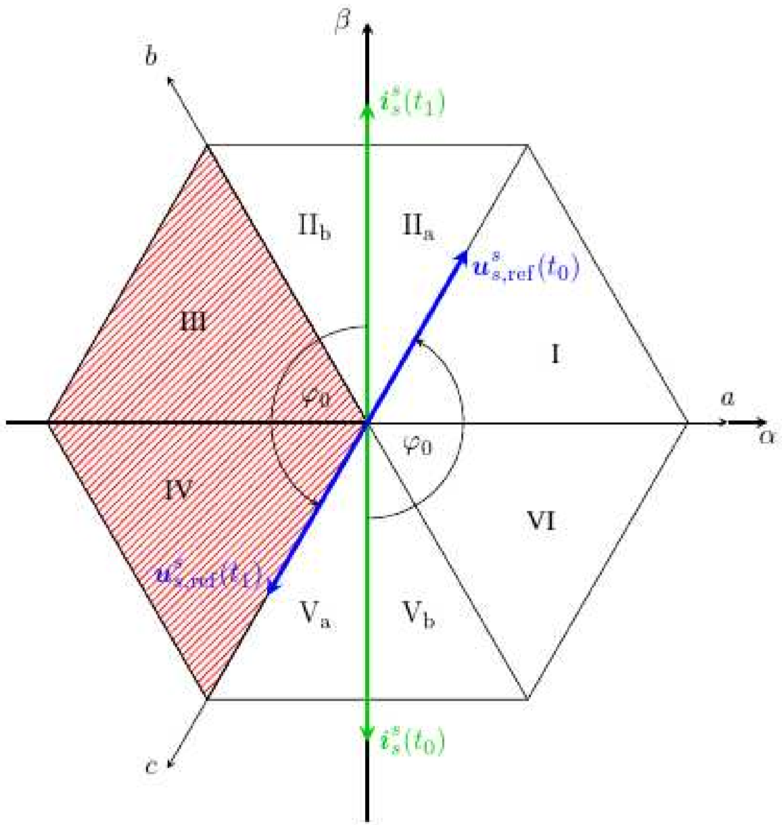
$$\text{where} \quad \theta' := \text{mod}\Big(\underbrace{\text{atan2}(u^{\beta}_{s,ref}, u^{\alpha}_{s,ref})}_{=:\theta}, \tfrac{\pi}{3}\Big) \in \left[0, \tfrac{\pi}{3}\right), \qquad (14)$$

Control: SVM vs. Flat-top modulation



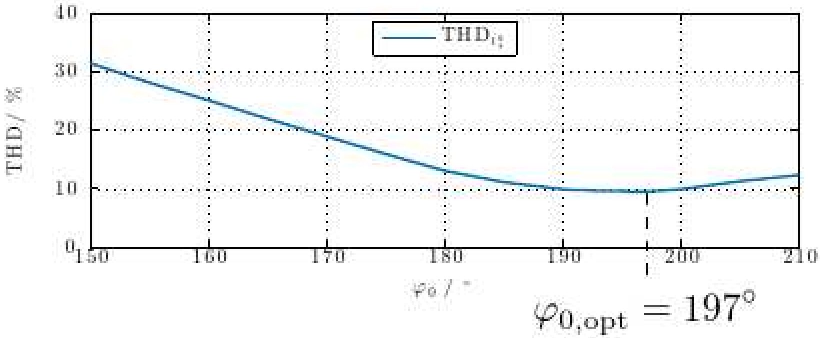
(a) Standard SVM. (b) Flat-top modulation.

Control: Affected voltage sectors

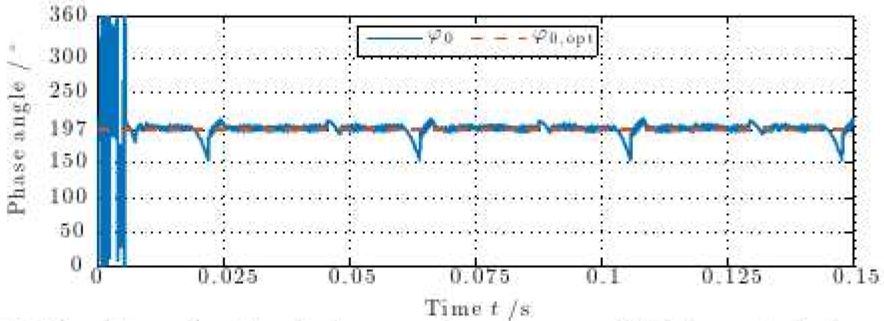


(a) $\varphi_0 = 150^\circ$. (b) $\varphi_0 = 210^\circ$.

Control: Optimal current injection angle



(a) $\mathrm{THD}_{i_s^a}$ for different phase angles φ_0.

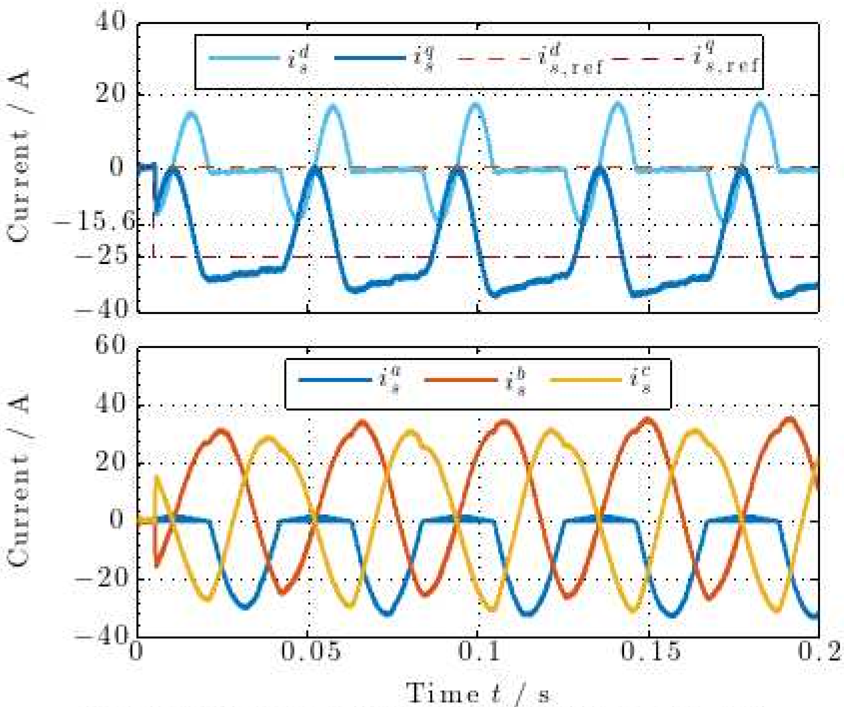


(b) Tracking of optimal phase angle $\varphi_{0,\mathrm{opt}} = 197°$ by actual phase angle φ_0.

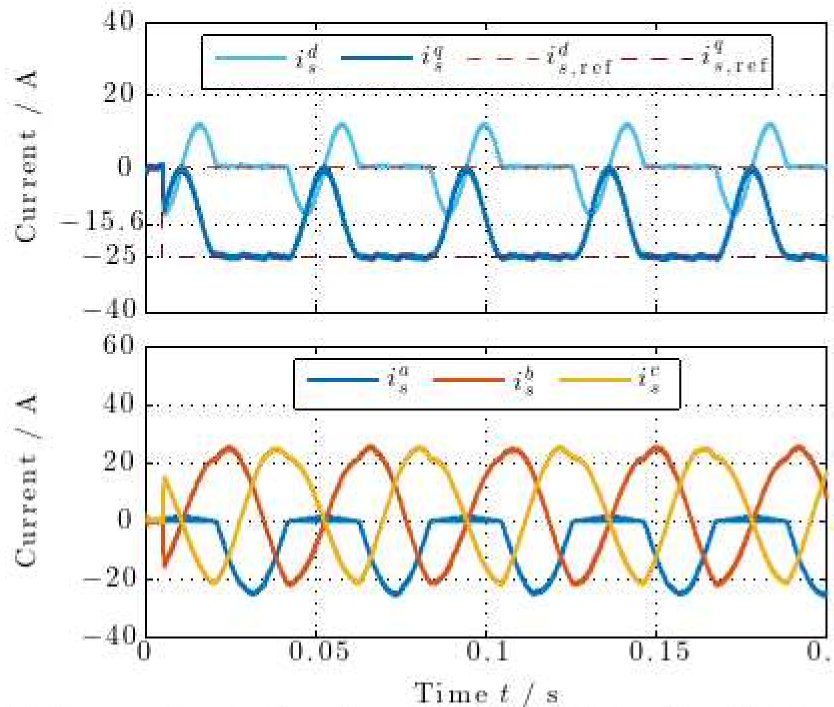
$$i^d_{\mathrm{s,ref}}(i^q_{\mathrm{s}}) = -\frac{n_{\mathrm{p}}\omega_{\mathrm{m}}\hat{\psi}_{\mathrm{pm}}}{2\big(n_{\mathrm{p}}\omega_{\mathrm{m}}L_{\mathrm{s}} - R_{\mathrm{s}}\tan(\varphi_0)\big)} + \sqrt{\frac{(n_{\mathrm{p}}\omega_{\mathrm{m}}\hat{\psi}_{\mathrm{pm}})^2}{4\big(n_{\mathrm{p}}\omega_{\mathrm{m}}L_{\mathrm{s}} - R_{\mathrm{s}}\tan(\varphi_0)\big)^2} - (i^q_{\mathrm{s}})^2 + \frac{n_{\mathrm{p}}\omega_{\mathrm{m}}\hat{\psi}_{\mathrm{pm}}\, i^q_{\mathrm{s}}\tan(\varphi_0)}{\big(n_{\mathrm{p}}\omega_{\mathrm{m}}L_{\mathrm{s}} - R_{\mathrm{s}}\tan(\varphi_0)\big)}}$$

$$\overset{[R_{\mathrm{s}}\approx 0]}{=} -\frac{\hat{\psi}_{\mathrm{pm}}}{2\,L_{\mathrm{s}}} + \sqrt{\Big(\frac{\hat{\psi}_{\mathrm{pm}}}{2\,L_{\mathrm{s}}}\Big)^2 - (i^q_{\mathrm{s}})^2 + \frac{\hat{\psi}_{\mathrm{pm}}}{L_{\mathrm{s}}}\, i^q_{\mathrm{s}}\tan(\varphi_0)}.$$

Simulation results: Conventional FOC vs. Improved Anti-Windup

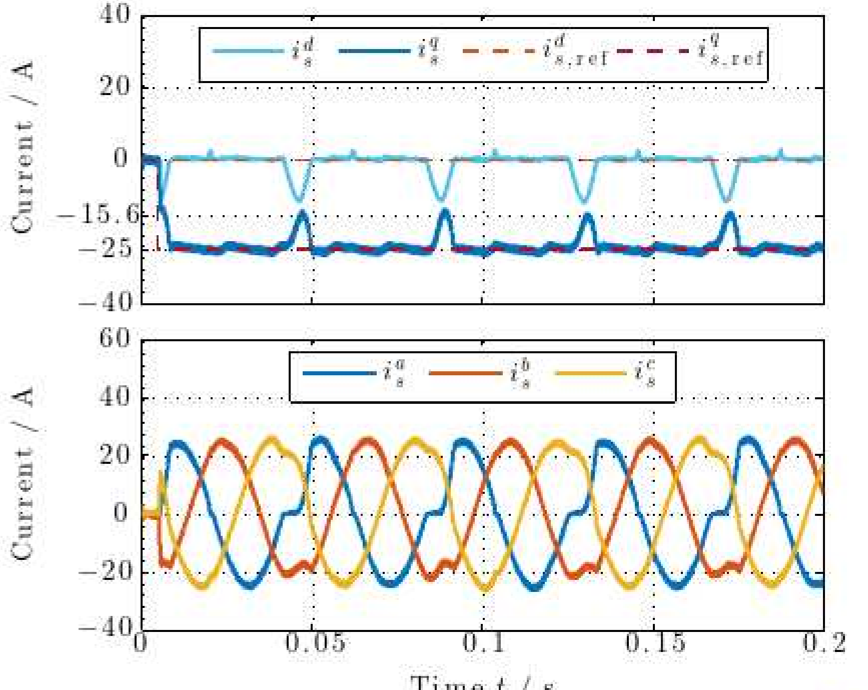


(a) Standard control performance: $\mathrm{THD}_{i_s^a} = 41.8\,\%$.

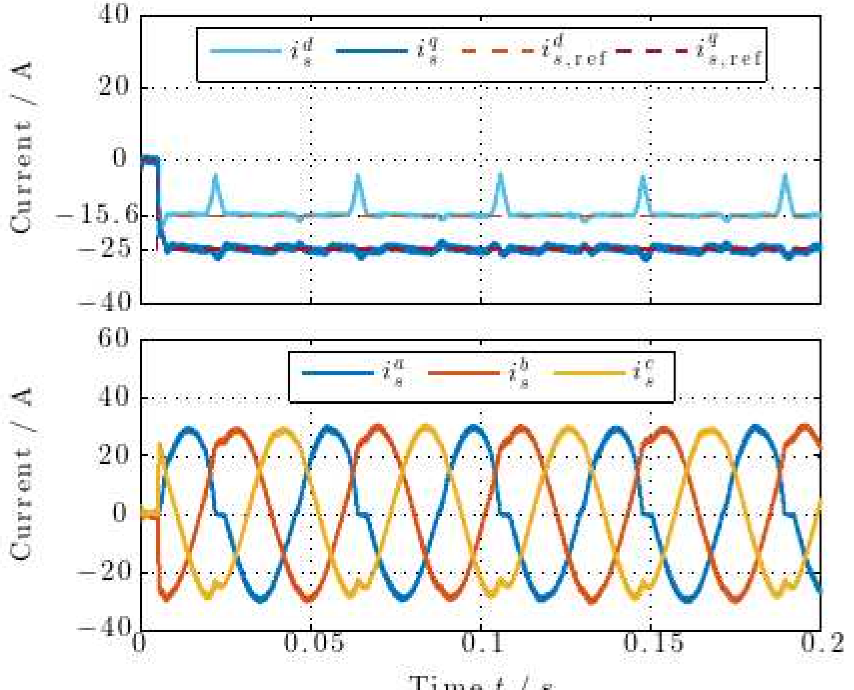


(b) Improved control performance (in particular for i_s^q) due to extended anti-windup (18): $\mathrm{THD}_{i_s^a} = 41.4\,\%$.

Simulation results: Flat-top modulation and d-current injection

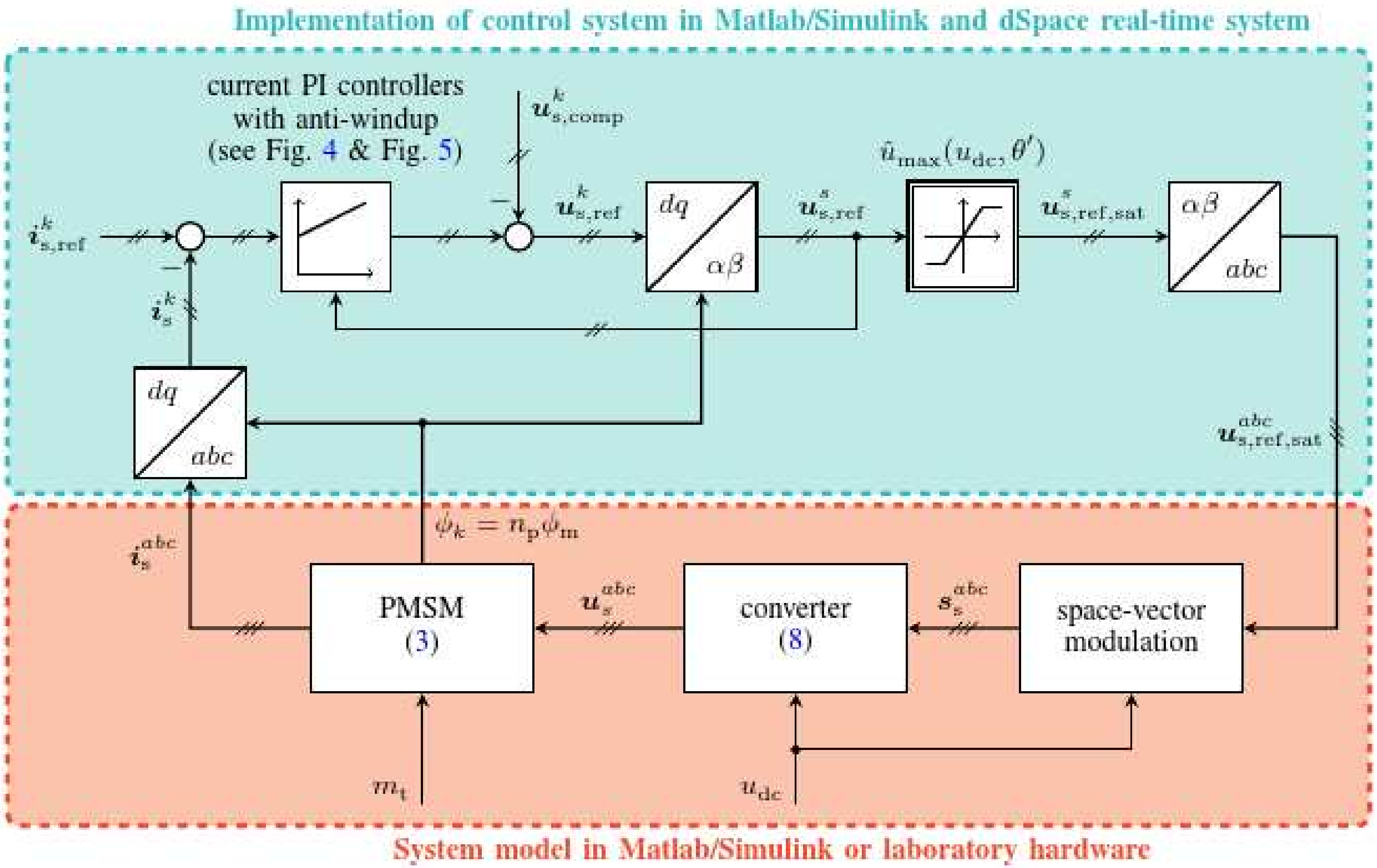


(c) Improved control performance due to extended anti-windup (18) and modified SVM (flat-top modulation): $\text{THD}_{i_s^a} = 19.5\,\%$.



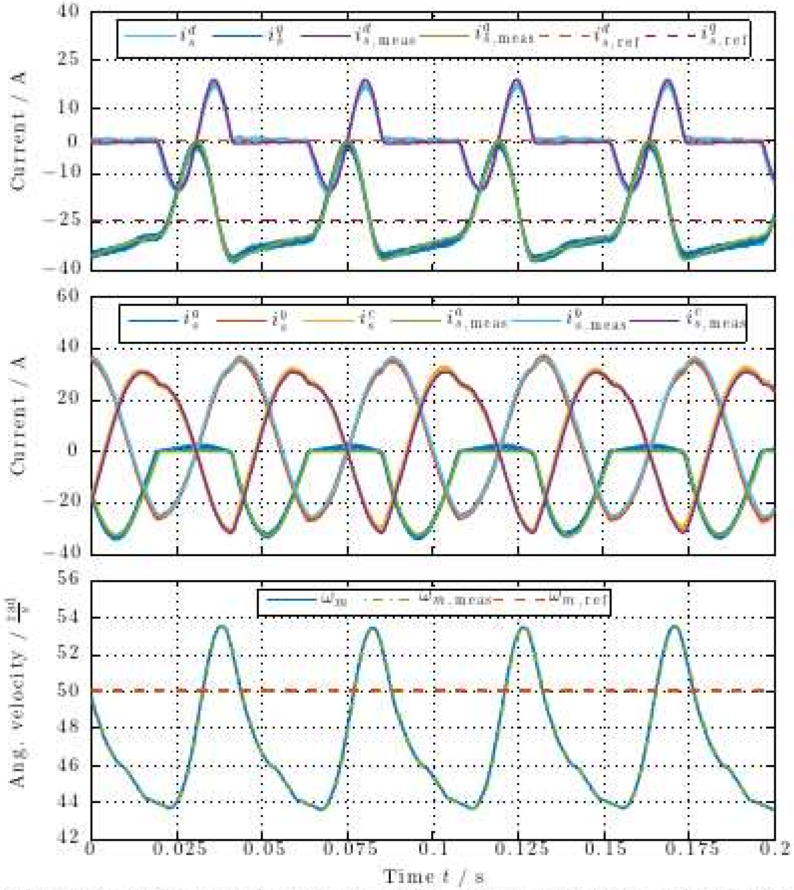
(d) Improved control performance due to extended anti-windup (18), modified SVM (flat-top modulation) and d-current injection: $\text{THD}_{i_s^a} = 9.4\,\%$.

Implementation: Block diagram

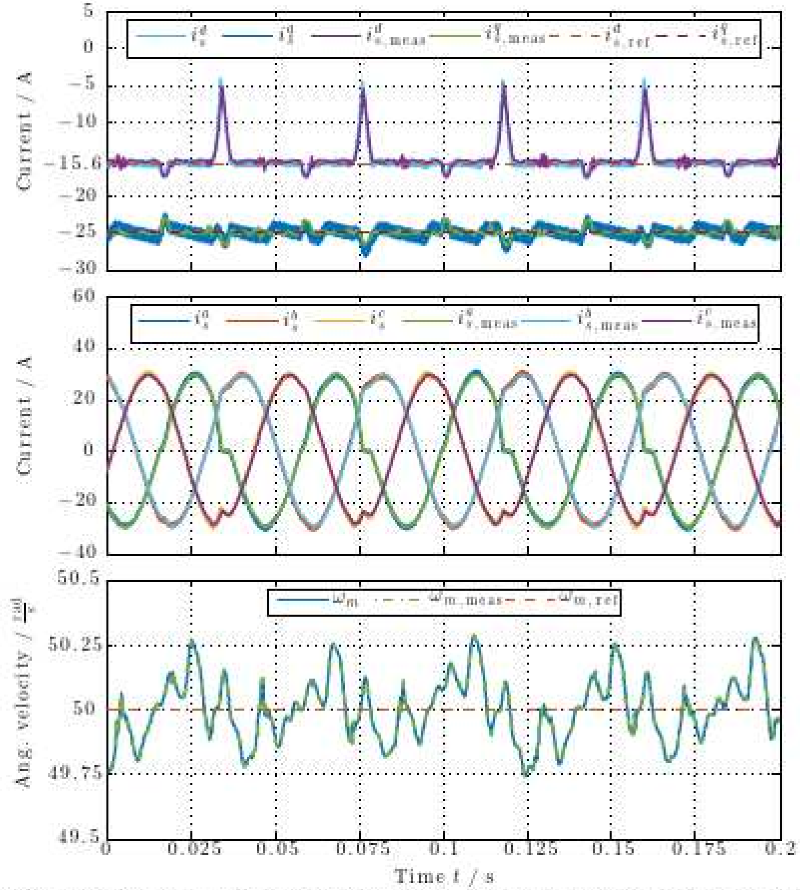


Implementation: Laboratory Setup

Implementation: Measurement results

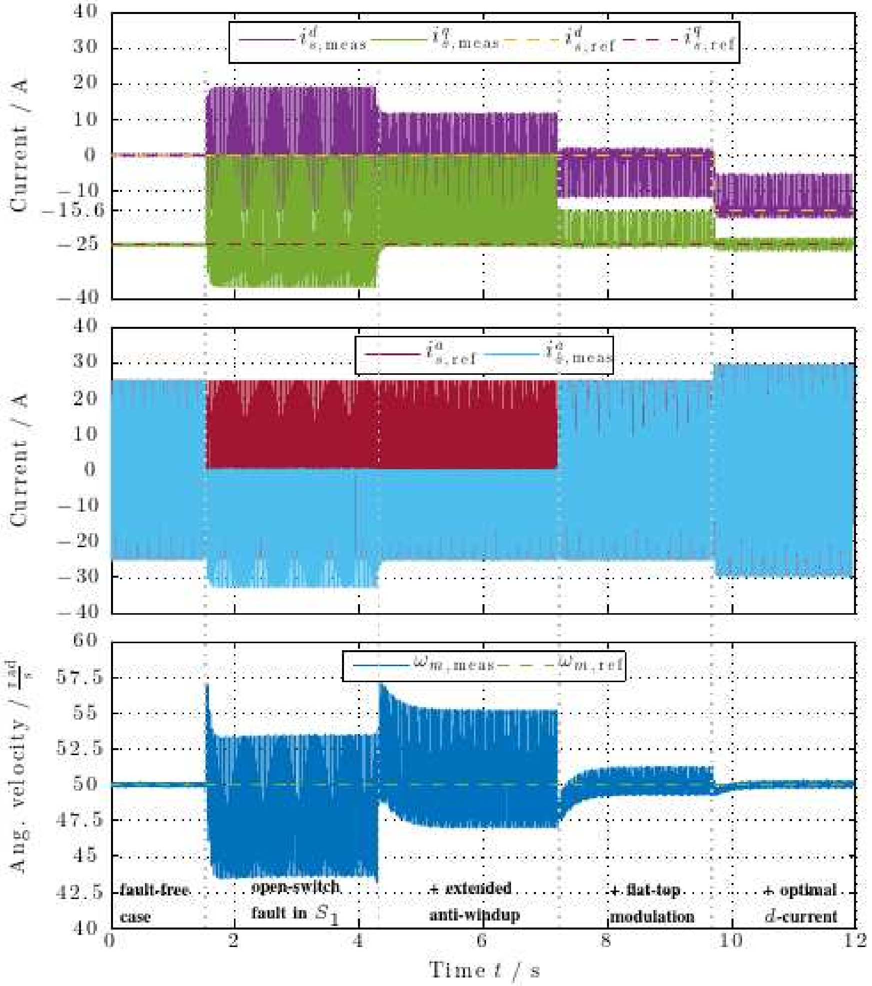


(a) Experiment (E_1): Comparison of simulation and measurement results for standard control system: $\mathrm{THD}_{i_s^a} = 41.8\,\%$ (simulation) vs. $\mathrm{THD}_{i_s^a,\mathrm{meas}} = 45.4\,\%$ (measurement).



(b) Experiment (E_2): Comparison of simulation and measurement results for fault-tolerant control system: $\mathrm{THD}_{i_s^a} = 9.4\,\%$ (simulation) vs. $\mathrm{THD}_{i_s^a,\mathrm{meas}} = 10.6\,\%$ (measurement).

Implementation: Measurement results



Implementation: Key data

Description	Symbol	Value and unit
Simulation parameters		
ODE-Solver (fixed-step)		Runge-Kutta (ode4)
sampling time	h	$1\,\mu\mathrm{s}$
Converter		
DC-link voltage	u_{dc}	$565\,\mathrm{V}$
switching frequency	f_{sw}	$8\,\mathrm{kHz}$
Permanent-magnet synchronous machine (generator, isotropic)		
stator resistance	R_{s}	$0.11\,\Omega$
stator inductance	L_{s}	$3.35\,\mathrm{mH}$
PM-flux linkage	$\hat{\psi}_{\mathrm{pm}}$	$0.377\,\mathrm{V\,s}$
number of pole pairs	n_{p}	3
machine inertia	Θ_{PMSM}	$163 \cdot 10^{-4}\,\mathrm{kg\,m^2}$
Reluctance synchronous machine (anisotropic)		
stator resistance	R_{s}	$0.4\,\Omega$
stator inductances	$L_{\mathrm{s}}^{d} \neq L_{\mathrm{s}}^{q}$	nonlinear (see [33, Fig. 2])
number of pole pairs	n_{p}	2
machine inertia	Θ_{RSM}	$189 \cdot 10^{-4}\,\mathrm{kg\,m^2}$
Current control system of PMSM		
PI controller gains	$k_{\mathrm{p}}^{d} = k_{\mathrm{p}}^{q}$	$8.93\,\frac{\mathrm{V}}{\mathrm{A}}$
	$k_{\mathrm{i}}^{d} = k_{\mathrm{i}}^{q}$	$293.3\,\frac{\mathrm{V}}{\mathrm{A\,s}}$
maximum anti-windup current	$\hat{\imath}_{\mathrm{aw}}$	$-1\,\mathrm{A}$