Hochschule
München
University of
Applied Sciences

Laboratory for
Mechatronic
and Renewable
Energy Systems
(LMRES)

A generic Lyapunov-based Observer for Double-Star-Chopper-Cell/Bridge-Cell Modular-Multilevel-Cascade-Converters

Leonardo Testa, Oliver Kalmbach and Christoph M. Hackl
leonardo.testa@hm.edu

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■ Introduction

1 System description

2 Proposed Lyapunov-based observer

3 Simulation

4 Conclusion

Outline I

- Introduction

Introduction

Modular Multilevel Cascade Converter

- High number of capacitors
- Capacitor voltage must be measured (voltage balancing) [1]
- Many sensors necessary (costs, communication effort, . . .)

Observer

- Sensor reduction (Cost savings) [2]
- Reduced communication effort [3]
- Reliability (less components) [4]
- Fault detection [5]

Outline I

1 System description

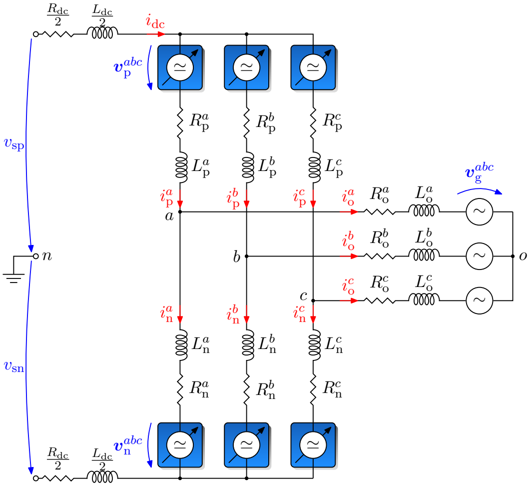
System description

Switching model

Current and capacitor voltage dynamics:

$$\frac{\mathrm{d}}{\mathrm{d}t}\underbrace{\begin{pmatrix}\boldsymbol{i}_{\Sigma\Delta}^{\alpha\beta\gamma}\\ \boldsymbol{v}_{\mathrm{cpn}}^{abc}\end{pmatrix}}_{=:\boldsymbol{x}} = \underbrace{\begin{bmatrix}\boldsymbol{A}_i(\boldsymbol{S}) & \boldsymbol{A}_{iv}(\boldsymbol{S})\\ \boldsymbol{A}_{vi}(\boldsymbol{S}) & \boldsymbol{A}_v\end{bmatrix}}_{=:\boldsymbol{A}(\boldsymbol{S})}\begin{pmatrix}\boldsymbol{i}_{\Sigma\Delta}^{\alpha\beta\gamma}\\ \boldsymbol{v}_{\mathrm{cpn}}^{abc}\end{pmatrix} + \underbrace{\begin{pmatrix}\boldsymbol{d}^{\alpha\beta\gamma}\\ \boldsymbol{0}\end{pmatrix}}_{=:\boldsymbol{d}}$$

- $\boldsymbol{i}_{\Sigma\Delta}^{\alpha\beta\gamma}$: Transformed sigma/delta currents
- $\boldsymbol{v}_{\mathrm{cpn}}^{abc}$: Capacitor voltage of each cell
- $\boldsymbol{S}$: Switching matrix



System description

Average model

Switching signals not accessible in the DSP

Moving average
$$\overline{x}(t) := \frac{1}{T_\mathrm{p}} \int_{t-T_\mathrm{p}}^{t} x(\tau)\,\mathrm{d}\tau$$

Averaged model of system
$$\frac{\mathrm{d}}{\mathrm{d}t} \underbrace{\begin{pmatrix} \overline{\boldsymbol{i}}_{\Sigma\Delta}^{\alpha\beta\gamma} \\ \overline{\boldsymbol{v}}_{\mathrm{c,pn}}^{abc} \end{pmatrix}}_{=:\overline{\boldsymbol{x}}} \approx \underbrace{\begin{bmatrix} \boldsymbol{A}_i(\overline{\boldsymbol{S}}) & \boldsymbol{A}_{iv}(\overline{\boldsymbol{S}}) \\ \boldsymbol{A}_{vi}(\overline{\boldsymbol{S}}) & \boldsymbol{A}_v \end{bmatrix}}_{=:\boldsymbol{A}(\overline{\boldsymbol{S}})} \begin{pmatrix} \overline{\boldsymbol{i}}_{\Sigma\Delta}^{\alpha\beta\gamma} \\ \overline{\boldsymbol{v}}_{\mathrm{c,pn}}^{abc} \end{pmatrix} + \underbrace{\begin{pmatrix} \overline{\boldsymbol{d}}^{\alpha\beta\gamma} \\ \boldsymbol{0} \end{pmatrix}}_{=:\overline{\boldsymbol{d}}}$$

Assumption: Ripples of $\overline{\boldsymbol{i}}_{\Sigma\Delta}^{\alpha\beta\gamma}$ and $\overline{\boldsymbol{v}}_{\mathrm{c,pn}}^{abc}$ are small over T_p (small ripple analysis)

Outline I

2 Proposed Lyapunov-based observer

Proposed Lyapunov-based observer

Approach

General form of observer

$$\frac{\mathrm{d}}{\mathrm{d}t}\widehat{\boldsymbol{x}} = \widehat{\boldsymbol{A}}\widehat{\boldsymbol{x}} + \widehat{\boldsymbol{d}} + \boldsymbol{W}\boldsymbol{e},$$

where

$$\widehat{\boldsymbol{A}} = \boldsymbol{A}(\boldsymbol{S}) \quad \text{or} \quad \widehat{\boldsymbol{A}} = \boldsymbol{A}(\overline{\boldsymbol{S}})$$

and with

$$\boldsymbol{e} := \begin{pmatrix} \boldsymbol{e}_i \\ \boldsymbol{e}_v \end{pmatrix} := \boldsymbol{x} - \widehat{\boldsymbol{x}}, \qquad \boldsymbol{W} := \begin{bmatrix} \boldsymbol{W}_i & \boldsymbol{O} \\ \boldsymbol{W}_v & \boldsymbol{O} \end{bmatrix}$$

Assumptions:

- $\widehat{\boldsymbol{d}} = \boldsymbol{d}$ Output voltage is measured, common mode voltage is neglected
- $\widehat{\boldsymbol{A}} = \boldsymbol{A}$ All system parameters are known

Proposed Lyapunov-based observer

Error dynamics

Dynamics of estimation error

$$\tfrac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e} = \boldsymbol{A}\boldsymbol{e} - \boldsymbol{W}\boldsymbol{e}$$

Lyapunov candidate

$$V(\boldsymbol{e}) = \boldsymbol{e}^\top \boldsymbol{P}\boldsymbol{e}, \quad \text{with } \boldsymbol{P}^\top = \boldsymbol{P} := \begin{bmatrix} \boldsymbol{P}_i & \boldsymbol{P}_{iv} \\ \boldsymbol{P}_{iv}^\top & \boldsymbol{P}_v \end{bmatrix} \succ 0$$

it applies that

$$V(\boldsymbol{e}) > 0 \; \forall \; \boldsymbol{e} \neq \boldsymbol{0}$$

Proposed Lyapunov-based observer

Sketch of stability proof

Time derivative of $V(\boldsymbol{e})$

$$\frac{\mathrm{d}}{\mathrm{d}t}V(\boldsymbol{e}) = \boldsymbol{e}^\top \boldsymbol{P}\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e} + \frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{e}^\top \boldsymbol{P}\boldsymbol{e}$$

$$\vdots$$

$$\leq -\boldsymbol{e}_i^\top \Big[\boldsymbol{Q}_i - \varepsilon_i\Big]\boldsymbol{e}_i - \boldsymbol{e}_v^\top \Big[\boldsymbol{Q}_v - \varepsilon_v\Big]\boldsymbol{e}_v < 0$$

- $\boldsymbol{Q}_i$ and $\boldsymbol{Q}_v$ are the Lyapunov identities [6]
- $\boldsymbol{Q}_v \succ \varepsilon_v := 2\|\boldsymbol{P}_{iv}^\top \boldsymbol{A}_{iv}\|$
- $\boldsymbol{Q}_i \succ \varepsilon_i := 2\|\boldsymbol{P}_{iv}\boldsymbol{P}_v^{-1}\big(\boldsymbol{A}_{iv}^\top \boldsymbol{P}_i + \boldsymbol{A}_v \boldsymbol{P}_{iv}^\top + \boldsymbol{P}_{iv}\boldsymbol{K}_i\big)\|$

Proposed Lyapunov-based observer

Upper bound of the estimation error convergence time

Upper bound for the error norm

$$\|\boldsymbol{e}(t)\| \leq \sqrt{\frac{\lambda_{\max}(\boldsymbol{P})}{\lambda_{\min}(\boldsymbol{P})}}\, \|\boldsymbol{e}(0)\| \, \exp\left(-\frac{1}{2}\,\frac{\lambda_{\min}(\boldsymbol{Q})-\varepsilon}{\lambda_{\max}(\boldsymbol{P})}\, t\right)$$

- $\lambda(\boldsymbol{P}), \lambda(\boldsymbol{Q}) > 0$
- $\varepsilon := \max(\varepsilon_i, \varepsilon_v)$
- $\lambda_{\min}(\boldsymbol{Q}) > \varepsilon$

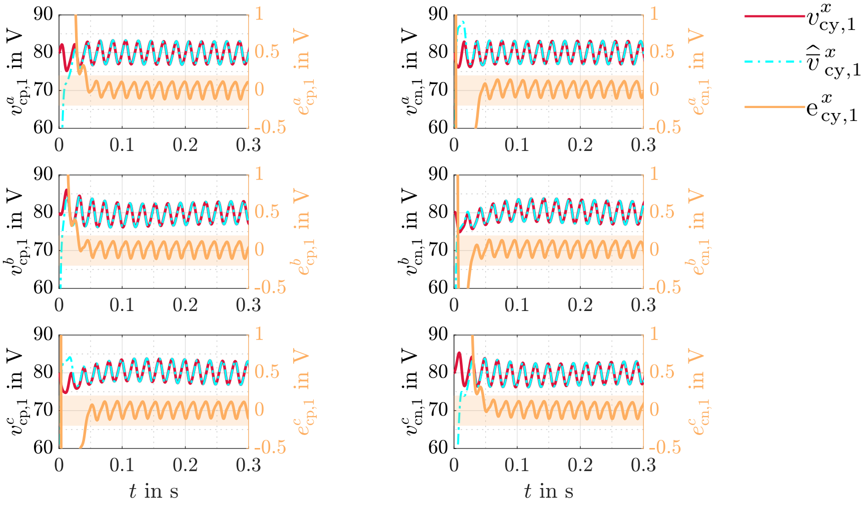
→ exponential decay of estimation error

Outline I

3 Simulation

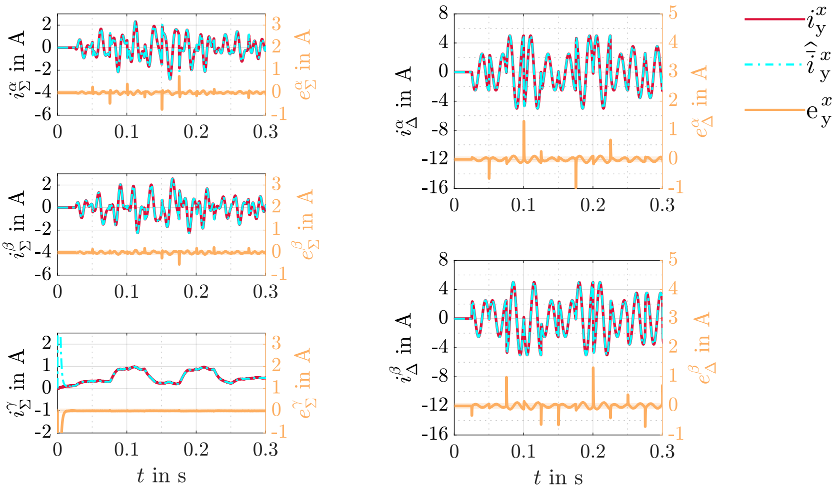
Simulation

Voltage estimation and estimation error in steady state



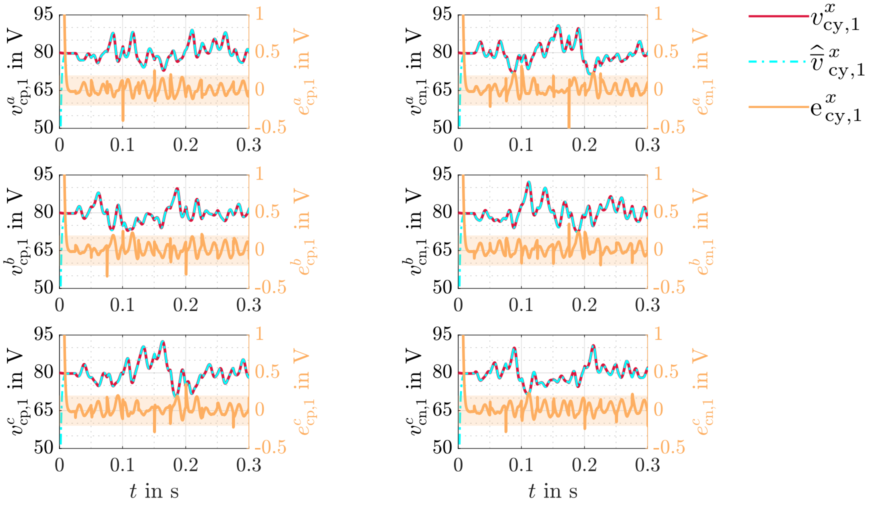
Simulation

Current estimation and estimation error in transient state



Simulation

Voltage estimation and estimation error in transient state



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4 Conclusion

Conclusion

To take home

- Exponentially stable observer derived
- Observability proven implicitely
- Based on an averaged MMCC model (Implementation on DSP feasible)
- Only 5 current measurements and duty cycles required

Future work

- Optimal choice of observer parameters
- Use of observed quantities in feedback control
- Robustness analysis and experimental validation

References I

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[3] Guilherme S. da Silva, Rodrigo P. Vieira, and Cassiano Rech. Discrete-Time Sliding-Mode Observer for Capacitor Voltage Control in Modular Multilevel Converters. *IEEE Transactions on Industrial Electronics*, 65(1):876–886.

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[5] Shuai Shao, Patrick W. Wheeler, Jon C. Clare, and Alan J. Watson. Fault Detection for Modular Multilevel Converters Based on Sliding Mode Observer. *IEEE Transactions on Power Electronics*, 28(11):4867–4872, 2013.

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