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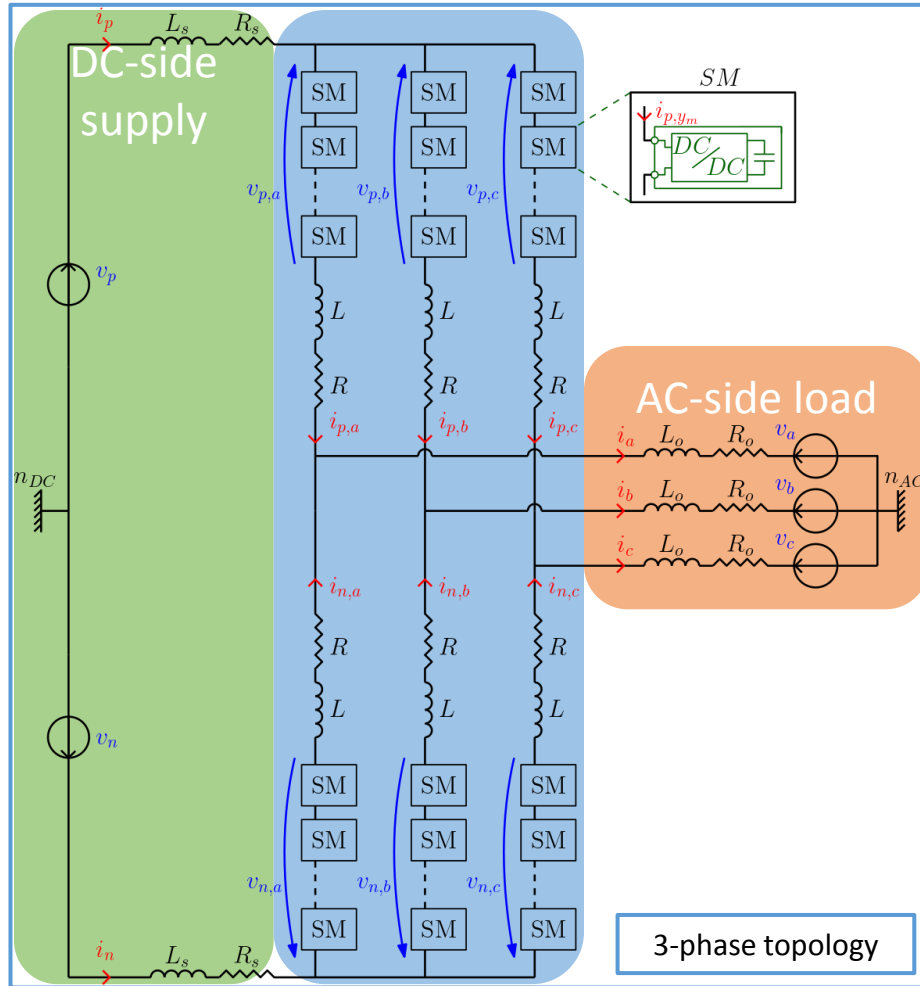


Control Allocation Methods for the Modular Multilevel Converter (MMC)

Grégoire LE GOFF

Control Allocation Workshop – 17 February 2022

The system to be controlled



- DC Voltage is provided to the system from the left
- This converter is made of 2×3 arms
- The converter transforms the DC Current into AC Currents, managing the power flow for DC to AC is necessary in order to ensure a good quality power conversion

➤ Currents must be controlled

- Each arm has N submodules
- Each submodule contains a capacitor which is protecting the switches by maintaining a voltage level

➤ Capacitor voltage must be balanced

Context

Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

A control problem which arises

Context

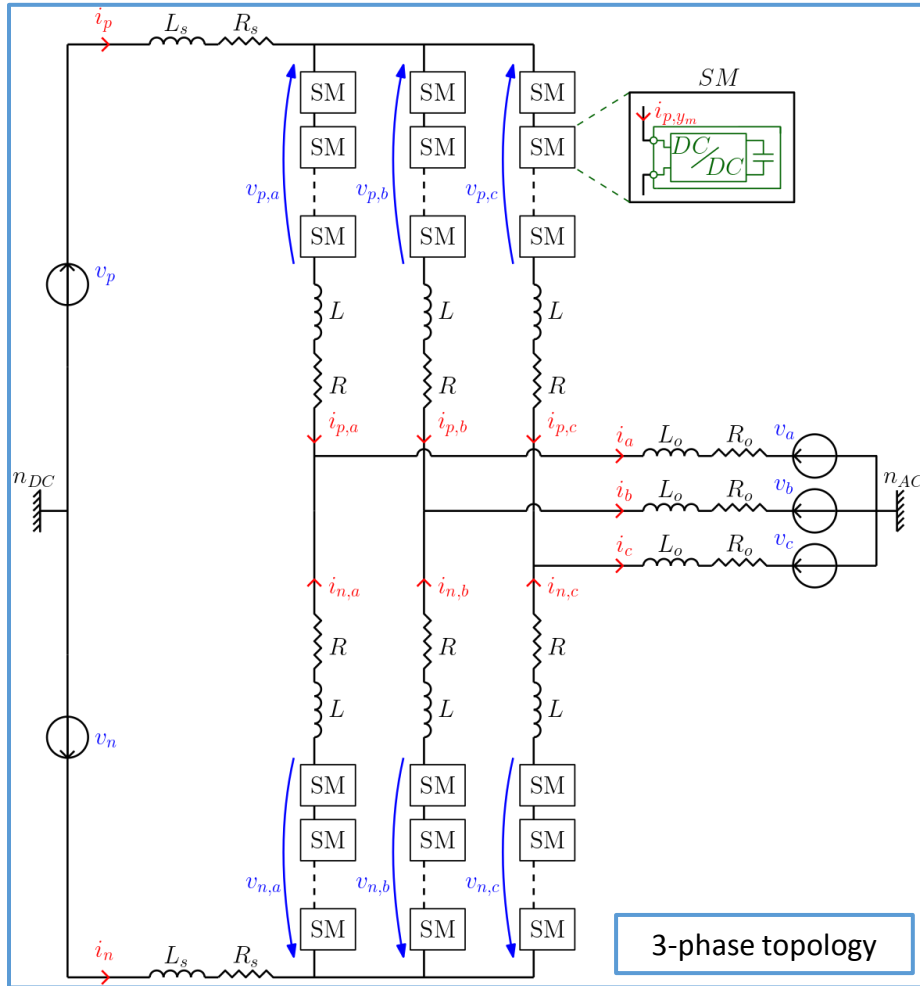
Control-Oriented Model

Control Allocation Methods

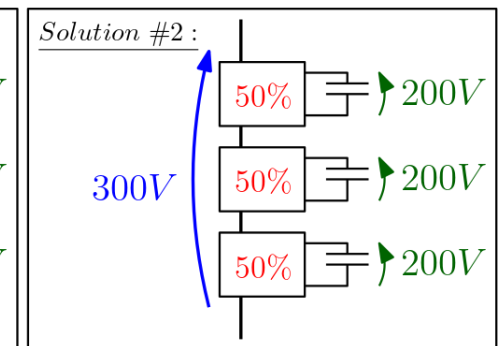
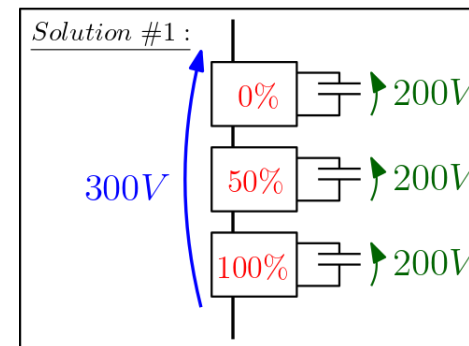
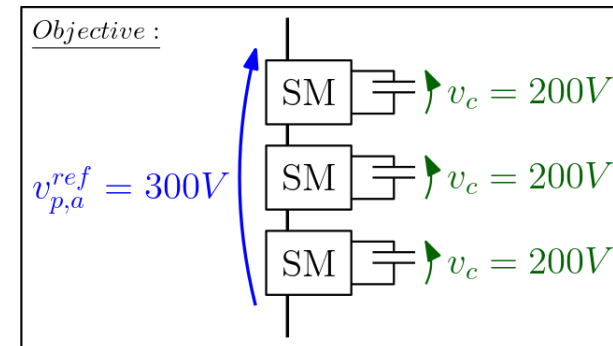
Control Performances Evaluation

Key Points

Conclusion and Perspectives



- Each Submodule (SM) contains a control variable in the form of a duty cycle to be determined
- Several choices of duty cycles are possible to ensure the same reference tracking: a choice must be made in real time



Challenge: Find the best duty cycles configuration in real-time

A family of control methods to address the problem: Control Allocation

Context

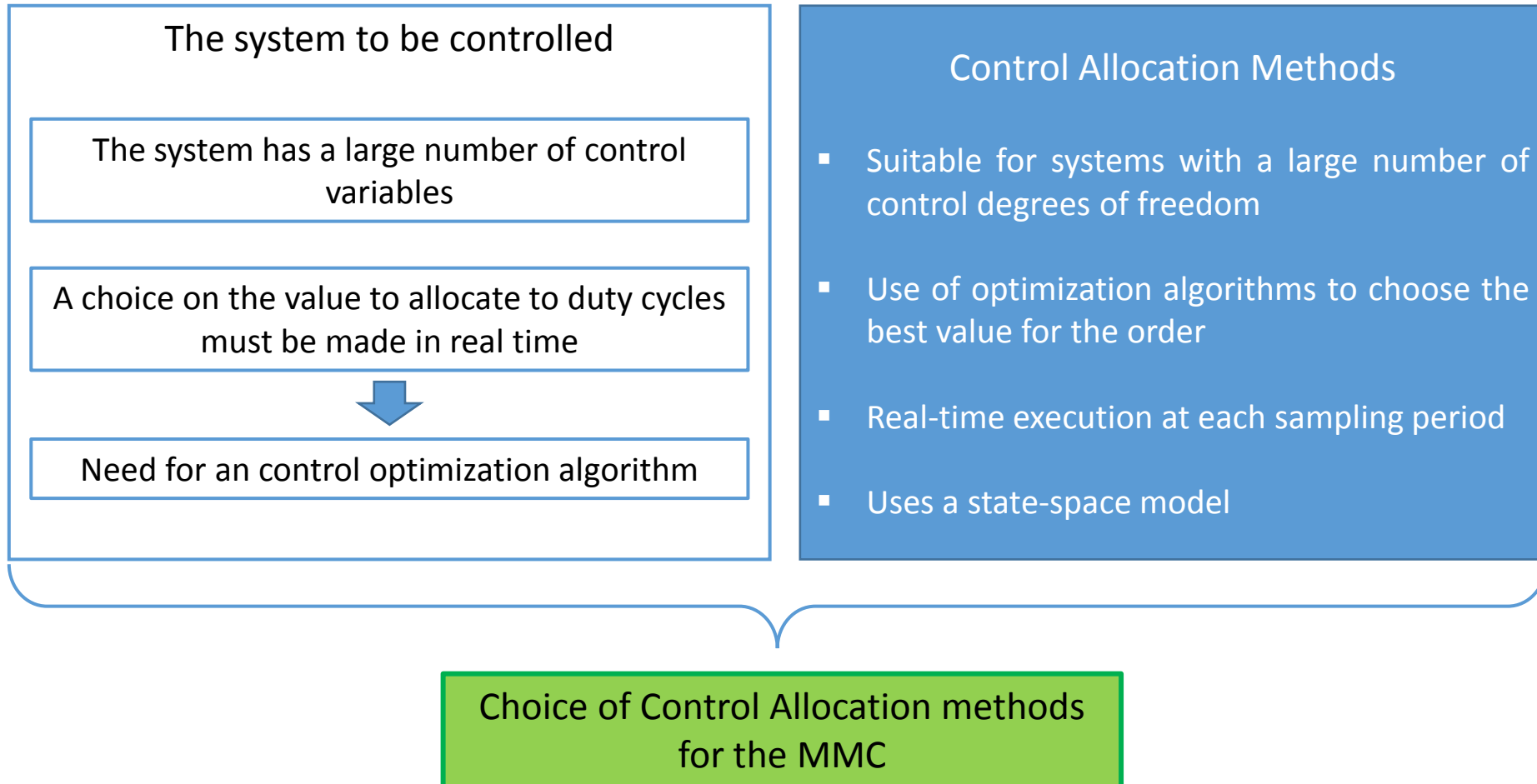
Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

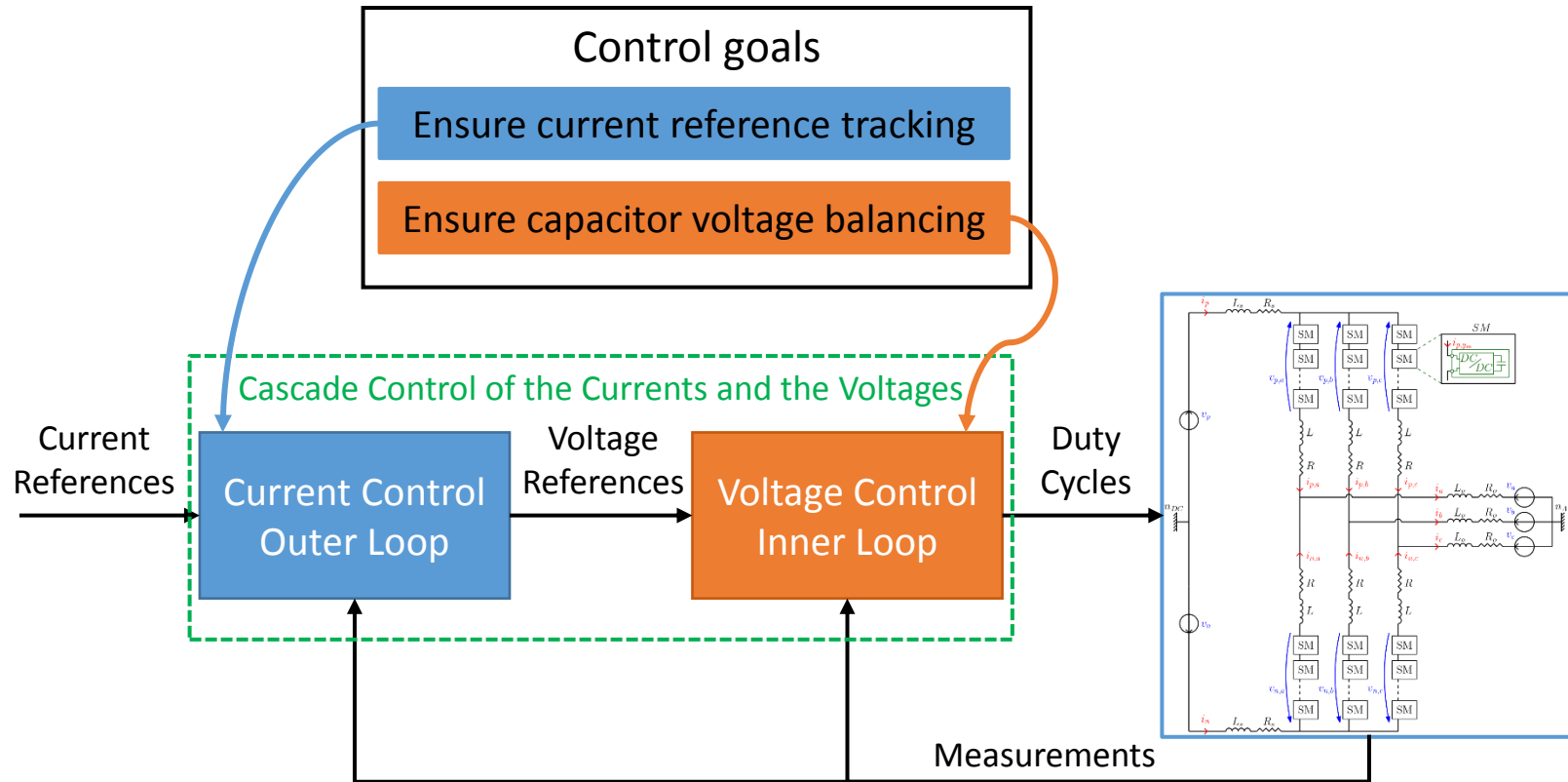
Key Points

Conclusion and Perspectives



Context

Control architecture



Modeling goals:

1. Derive the relationship between duty cycles and voltages
2. Derive the relationship between voltages and currents

Context

Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Control-Oriented Model

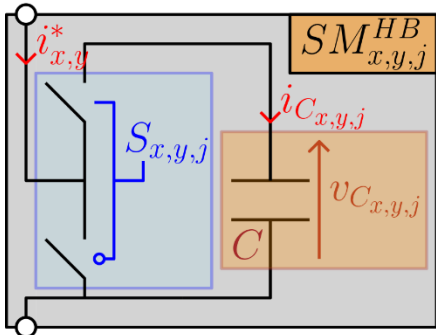
Control-oriented model for capacitor voltage balancing

Submodule physical model

Context

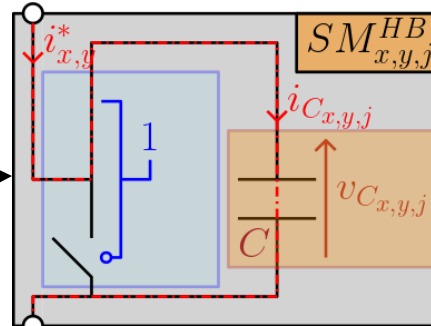
Control-Oriented Model

Focus on the j^{th} submodule of the x^{th} arm of the y^{th} leg. All submodules are the same



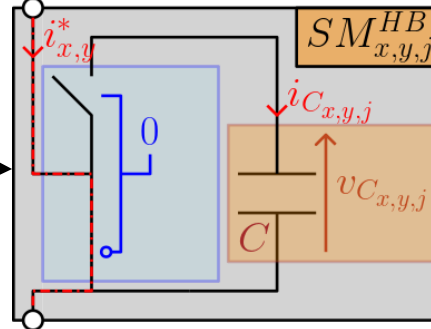
S_{xyj} is the variable controlling the state of the switch

ON state



When $S_{xyj} = 1$, Current i_{xy}^* draws through capacitor and voltage across the cell is $v_{C_{xyj}}$

OFF state



When $S_{xyj} = 0$, No current draws through capacitor and voltage across the cell is null

Submodule functional model

1. $i_{C_{xyj}} = i_{xy}^* \cdot S_{xyj}$
2. $v_{xyj} = v_{C_{xyj}} \cdot S_{xyj}$

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Control-Oriented Model

Context

Control-Oriented Model

Control Allocation Methods

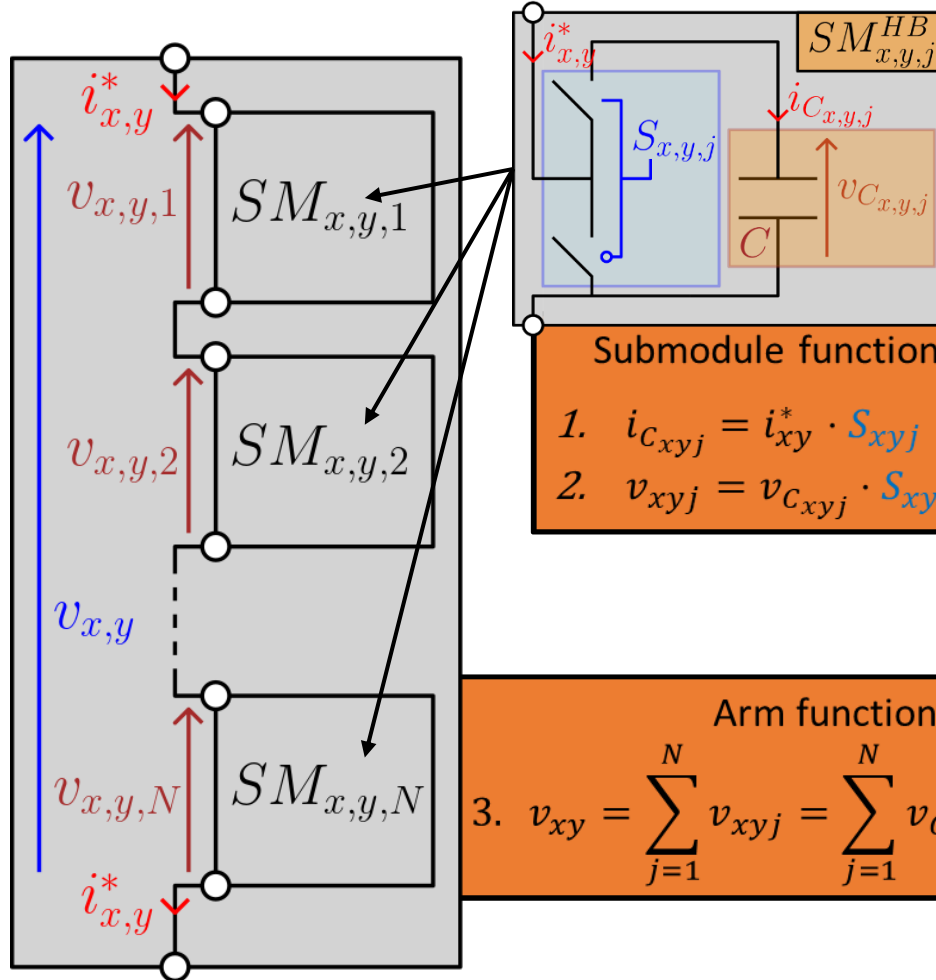
Control Performances Evaluation

Key Points

Conclusion and Perspectives

Control-oriented model for capacitor voltage balancing

Arm physical model



Submodule functional model

1. $i_{C_{xyj}} = i_{xy}^* \cdot S_{xyj} = C \frac{dv_{C_{xyj}}}{dt}$
2. $v_{xyj} = v_{C_{xyj}} \cdot S_{xyj}$

Arm functional model

$$3. v_{xy} = \sum_{j=1}^N v_{xyj} = \sum_{j=1}^N v_{C_{xyj}} \cdot S_{xyj} = v_{C_{xy}}^T \cdot S_{xy}$$

Low-Level functional model for arm #xy among $2 \times m$ arms

$$C \frac{dv_{C_{xy}}}{dt} = i_{xy}^* \cdot S_{xy}$$

$$v_{xy} = v_{C_{xy}}^T \cdot S_{xy}$$

Control-Oriented Model

Control-oriented model for capacitor voltage balancing

Control allocation model

Context

Control-Oriented Model

Low-Level functional model for arm #xy

$$C \frac{dv_{C_{xy}}}{dt} = i_{xy}^* \cdot S_{xy}$$

$$v_{xy} = v_{C_{xy}}^T \cdot S_{xy}$$

Discrete Model

Low-Level functional model for arm #xy

$$v_{C_{xy}}(k+1) - v_{C_{xy}}(k) = \frac{T_s i_{xy}^*(k)}{C} \cdot D_{xy}$$

$$v_{xy}(k) = v_{C_{xy}}^T(k) \cdot D_{xy}$$

Control Allocation Methods

Low-level control goal: Ensuring $v_{C_{xy}}^{ref}(k)$ is reached at time $k+1$ and $v_{xy}^{ref}(k)$ also, thus D_{xy} must be determined to satisfy:

Control Performances Evaluation

Low-Level control objective for arm #xy

$$v_{C_{xy}}^{ref}(k) - v_{C_{xy}}(k) = \frac{T_s i_{xy}^*(k)}{C} \cdot D_{xy}$$

$$v_{xy}^{ref}(k) = v_{C_{xy}}^T(k) \cdot D_{xy}$$

Matrix Form

Low-Level control objective for arm #xy

$$\begin{bmatrix} v_{C_{xy}}^T(k) \\ \frac{T_s i_{xy}^*(k)}{C} \cdot I_N \end{bmatrix} \cdot D_{xy} = \begin{bmatrix} v_{xy}^{ref}(k) \\ v_{C_{xy}}^{ref}(k) - v_{C_{xy}}(k) \end{bmatrix}$$

Key Points

The relationship between duty cycles and voltages is derived

Classic form for Control Allocation

$$M_{LL}^{xy} \cdot U_{LL}^{xy} = a_{d_{LL}}^{xy}$$

$$M_{LL}^{xy} \in \mathcal{M}_{N+1,N}(\mathbb{R}) \quad a_{d_{LL}}^{xy} \in \mathbb{R}^{N+1}$$

Conclusion and Perspectives

Control-Oriented Model

Control-oriented model for current reference tracking

High-level physical model

Context

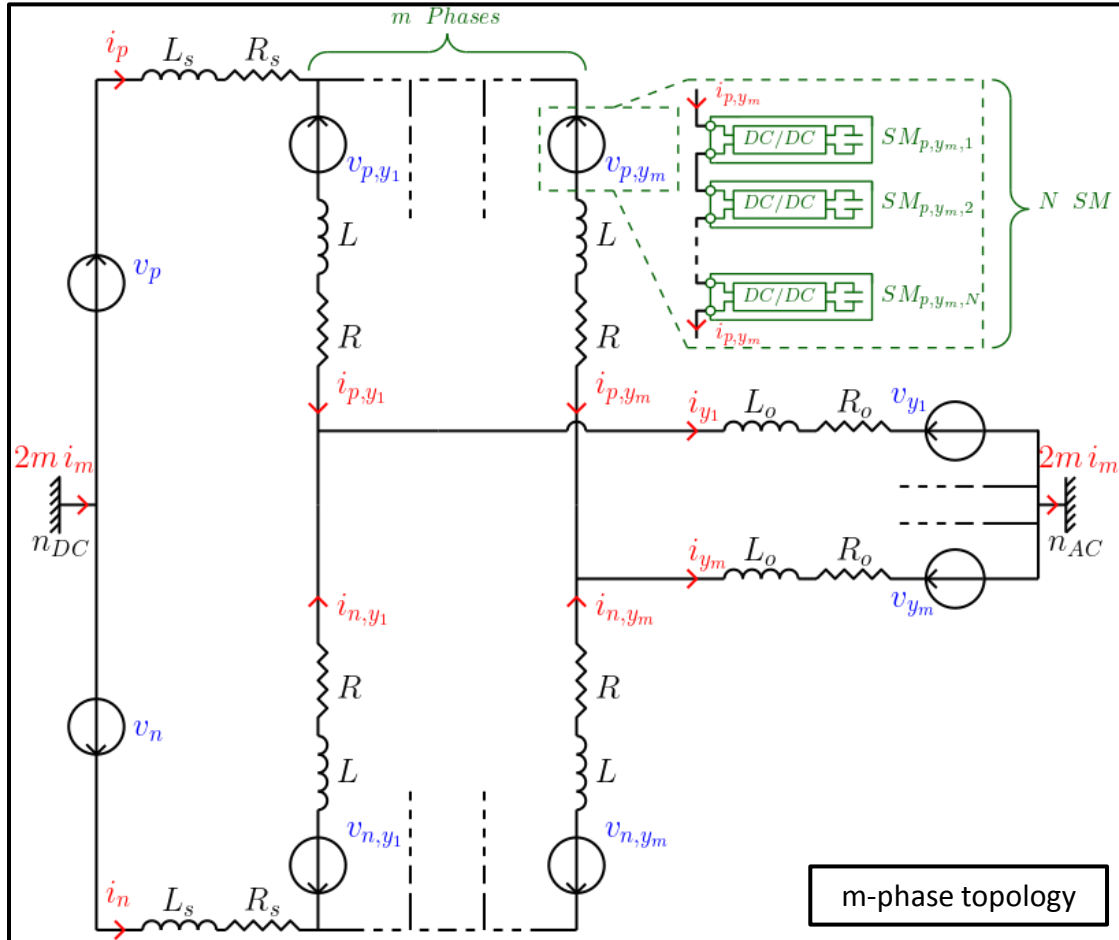
Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives



- From a high-level point of view arms can be seen as controllable voltage sources
- Four different current types can be found flowing within the converter

Possible current types flowing within the converter:

- Common mode current
- DC source current
- Circulating currents
- AC output currents

$$X_{HL} = \begin{bmatrix} I_m \\ I_s \\ I_c \\ I_o \end{bmatrix}$$

Modeling goal: derive the relationship between voltages and currents

Control-Oriented Model

Control-oriented model for current reference tracking

High-level physical model: GPFOCSSM

Context

Control-Oriented Model

Derivations from the Kirchhoff current and voltage laws



$$\begin{cases} \dot{X}_{HL} = A_{HL}X_{HL} + B_{HL}U_{HL} + E_{HL} \\ Y_{HL} = C_{HL}X_{HL} \end{cases}$$

State

Control

$$X_{HL} = \begin{bmatrix} I_m \\ I_s \\ I_c \\ I_o \end{bmatrix}$$

$$\begin{cases} U_{HL} = [V_{py} \quad V_{ny}]^T \\ V_{py} = [v_{p,y_1} \quad v_{p,y_2} \quad \dots \quad v_{p,y_m}]^T \\ V_{ny} = [v_{n,y_1} \quad v_{n,y_2} \quad \dots \quad v_{n,y_m}]^T \end{cases}$$

Control Allocation Methods

GPFOCSSM Model strong feature:
➤ Scalable to any number of phases

Control Performances Evaluation

Key Points

$$A_{HL} = \begin{bmatrix} -R_m^{eq}/L_m^{eq} & 0 & 0 & 0 \\ 0 & -R_s^{eq}/L_s^{eq} & 0 & 0 \\ 0 & 0 & -(R_c^{eq}/L_c^{eq})\mathbb{I}_m & 0 \\ 0 & 0 & 0 & -(R_o^{eq}/L_o^{eq})\mathbb{I}_m \end{bmatrix} \text{ with } \begin{cases} \mathbb{I}_m: \text{size } m \text{ identity matrix} \\ X_m^{eq} = X + 2X_o + mX_s \\ X_s^{eq} = X + mX_s \\ X_c^{eq} = X \\ X_o^{eq} = X + 2X_o \end{cases}$$

$$B_{HL} = \begin{bmatrix} -N_\Sigma(m)/(2L_m^{eq}) & -N_\Sigma(m)/(2L_m^{eq}) \\ -N_\Sigma(m)/(2L_s^{eq}) & +N_\Sigma(m)/(2L_s^{eq}) \\ -N_\Delta(m)/(2L_c^{eq}) & +N_\Delta(m)/(2L_c^{eq}) \\ -N_\Delta(m)/(2L_o^{eq}) & -N_\Delta(m)/(2L_o^{eq}) \end{bmatrix} \text{ with } \begin{cases} N_\Sigma(m) = \frac{1}{m} [1 \quad \dots \quad 1] \\ N_\Delta(m) = \frac{1}{m} (m \cdot \mathbb{I}_m - \mathbb{J}_m) \\ \mathbb{J}_m = \begin{bmatrix} 1 & \dots & 1 \\ \vdots & \ddots & \vdots \\ 1 & \dots & 1 \end{bmatrix} \end{cases} m \text{ et extension: } \mathbb{J}_{n,m} = [1]_{n,m}$$

Conclusion and Perspectives

Control-Oriented Model

Control-oriented model for current reference tracking

High-level physical model: GPFOCSSM

Context

Control-Oriented Model

High-level current model

$$\begin{cases} \dot{\mathbf{X}}_{HL} = \mathbf{A}_{HL}\mathbf{X}_{HL} + \mathbf{B}_{HL}\mathbf{U}_{HL} + \mathbf{E}_{HL} \\ \mathbf{Y}_{HL} = \mathbf{C}_{HL}\mathbf{X}_{HL} \end{cases}$$

Discrete Model

High-level current model

$$\begin{cases} \mathbf{X}_{HL}(k+1) = \mathbf{F}_{HL}\mathbf{X}_{HL}(k) + \mathbf{G}_{HL}\mathbf{U}_{HL}(k) + \mathbf{H}_{HL}\mathbf{E}_{HL}(k) \\ \mathbf{Y}_{HL}(k) = \mathbf{C}_{HL}\mathbf{X}_{HL}(k) \end{cases}$$

High-level control goal: Ensuring that \mathbf{Y}_{HL} follows the dynamic behavior specified by $\mathbf{Y}_{HL}(k+1) = \mathbf{F}_{HL}^+\mathbf{Y}_{HL}(k) + \mathbf{G}_{HL}^+\mathbf{Y}_{HL}^{ref}(k)$

Control Allocation Methods

Control Performances Evaluation

Key Points

High-level control objective

$$\mathbf{F}_{HL}^+\mathbf{Y}_{HL}(k) + \mathbf{G}_{HL}^+\mathbf{Y}_{HL}^{ref}(k) = \mathbf{C}_{HL}\mathbf{F}_{HL}\mathbf{X}_{HL}(k) + \mathbf{C}_{HL}\mathbf{G}_{HL}\mathbf{U}_{HL}(k) + \mathbf{C}_{HL}\mathbf{H}_{HL}\mathbf{E}_{HL}(k)$$

$$\Leftrightarrow (\mathbf{C}_{HL}\mathbf{G}_{HL})\mathbf{U}_{HL}(k) = [\mathbf{F}_{HL}^+\mathbf{Y}_{HL}(k) + \mathbf{G}_{HL}^+\mathbf{Y}_{HL}^{ref}(k) - \mathbf{C}_{HL}(\mathbf{F}_{HL}\mathbf{X}_{HL}(k) + \mathbf{H}_{HL}\mathbf{E}_{HL}(k))]$$

The relationship between voltages and currents is derived

Classic form for Control Allocation

$$\mathbf{M}_{HL} \cdot \mathbf{U}_{HL} = \mathbf{a}_{dHL}$$

$$\mathbf{M}_{HL} \in \mathcal{M}_{2m}(\mathbb{R}) \quad \mathbf{a}_{dHL} \in \mathbb{R}^{2m}$$

Conclusion and Perspectives

Control-Oriented Model

Context

Control-Oriented Model

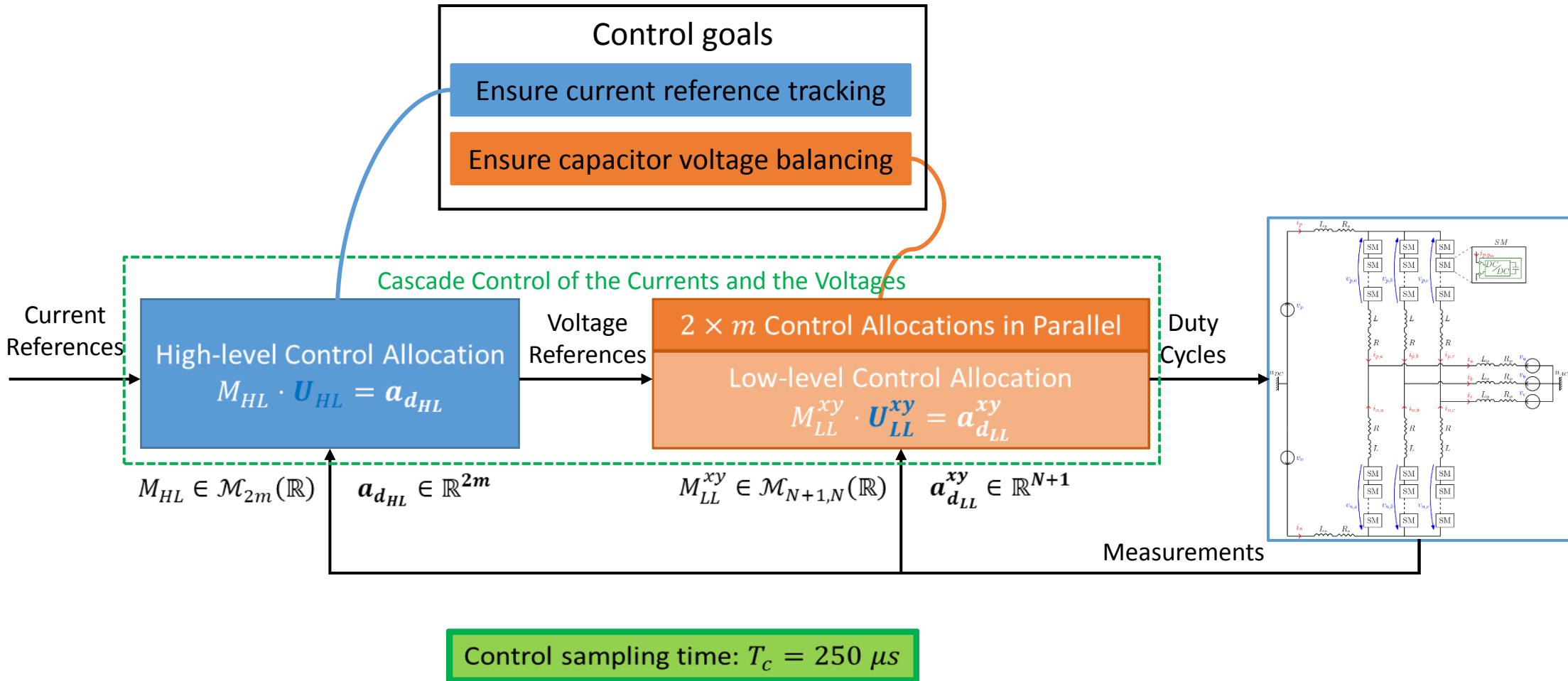
Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Control architecture



Control Allocation Methods

Control sampling time: $T_c = 250 \mu s$

Control Allocation main method families

Model Inversion Based

Principle:

Directly inverting $MU = a_d$ to compute U , taking the constraints $U_{min} \leq U \leq U_{max}$ into account afterwards

Characteristics:

- Suboptimal solutions when U saturates its boundaries
- Easy to implement
- Very fast computation in real-time

Error Minimization Online

Principle:

Minimizing a norm of $e = MU - a_d$ to compute U under the constraints $U_{min} \leq U \leq U_{max}$

Characteristics:

- Optimal solutions even when U saturates its boundaries
- Medium difficulty to implement
- Slowest computation in real-time

Error Minimization Offline

Principle:

Same than for Error Minimization Online but the optimization is done offline and a real-time update law is designed to ensure that U converges to the optimum

Characteristics:

- Optimal solutions even when U saturates its boundaries
- Complex to implement
- Fast computation in real-time

Context

Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

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Control Allocation Methods

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Best trade-off between complexity, optimum and computation time are the **Error Minimization Online (EMOn)** methods

Context

Control-Oriented Model

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Control Performances Evaluation

Key Points

Conclusion and Perspectives

$$M \cdot U = a_d$$

$$e = M \cdot U - a_d$$

Control sampling time: $T_c = 250 \mu s$

Optimization formulation for EMOn Control Allocation

Context

Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Linear Programming (LP)

Quadratic Programming (QP)

CA Form

$$\begin{cases} \min_{U,e} J = |e| = \sum_{i=1}^{n_a} |e_i| \\ u.c.: \\ e = M \cdot U - a_d \\ U_{min} \leq U \leq U_{max} \end{cases}$$

Adapting Formulation

LP Form

$$\begin{cases} \min_x J = c^T x \\ u.c.: \\ Ax = b \\ x_{max} \geq x \geq 0 \end{cases}$$

1. Optimization problem is formulated
2. Formulation is adapted to suit LP algorithms
3. Solving is done **online is less than 250 μs**
4. Algorithms used: **Simplex, Interior-Point**

1. Optimization problem is formulated
2. Formulation is adapted to suit QP algorithms
3. Solving is done **online is less than 250 μs**
4. Algorithms used: **Interior-Point, Active-Set**

CA Form

$$\begin{cases} \min_{U,e} J = \|e\|^2 = \sum_{i=1}^{n_a} e_i^2 \\ u.c.: \\ e = M \cdot U - a_d \\ U_{min} \leq U \leq U_{max} \end{cases}$$

Adapting Formulation

QP Form

$$\begin{cases} \min_x J = \frac{1}{2} x^T H x + c^T x \\ u.c.: \\ Ax = b \\ x_{max} \geq x \geq x_{min} \end{cases}$$

$$x^T = [\bar{U} \quad e^+ \quad e^-] \in \mathbb{R}^{n_U+2n_a}$$

$$c^T = [\mathbb{0}_{1,n_U} \quad [1 \dots 1]] \in \mathbb{R}^{n_U+2n_a}$$

$$A = [M \quad -\mathbb{I}_{n_a} \quad \mathbb{I}_{n_a}] \in \mathcal{M}_{n_a, n_U+2n_a}(\mathbb{R})$$

$$b = [a_d - M \cdot U_{min}] \in \mathbb{R}^{n_a}$$

$$x_{max}^T = [U_{max} - U_{min} \quad e_{max} \quad e_{max}] \in \mathbb{R}^{n_U+2n_a}$$

$$x^T = [U \quad e] \in \mathbb{R}^{n_U+n_a}$$

$$c^T = \mathbb{0}_{1, n_U+n_a} \in \mathbb{R}^{n_U+n_a}$$

$$H = \text{diag}([\mathbb{0}_{1, n_U} \quad [1 \dots 1]]) \in \mathcal{M}_{n_U+n_a}(\mathbb{R})$$

$$A = [M \quad -\mathbb{I}_{n_a}] \in \mathcal{M}_{n_a, n_U+n_a}(\mathbb{R})$$

$$b = [a_d] \in \mathbb{R}^{n_a}$$

$$x_{max}^T = [U_{max} \quad e_{max}] \in \mathbb{R}^{n_U+n_a}$$

$$x_{min}^T = [U_{min} \quad -e_{max}] \in \mathbb{R}^{n_U+n_a}$$

Control Allocation Methods

Context

Control-Oriented Model

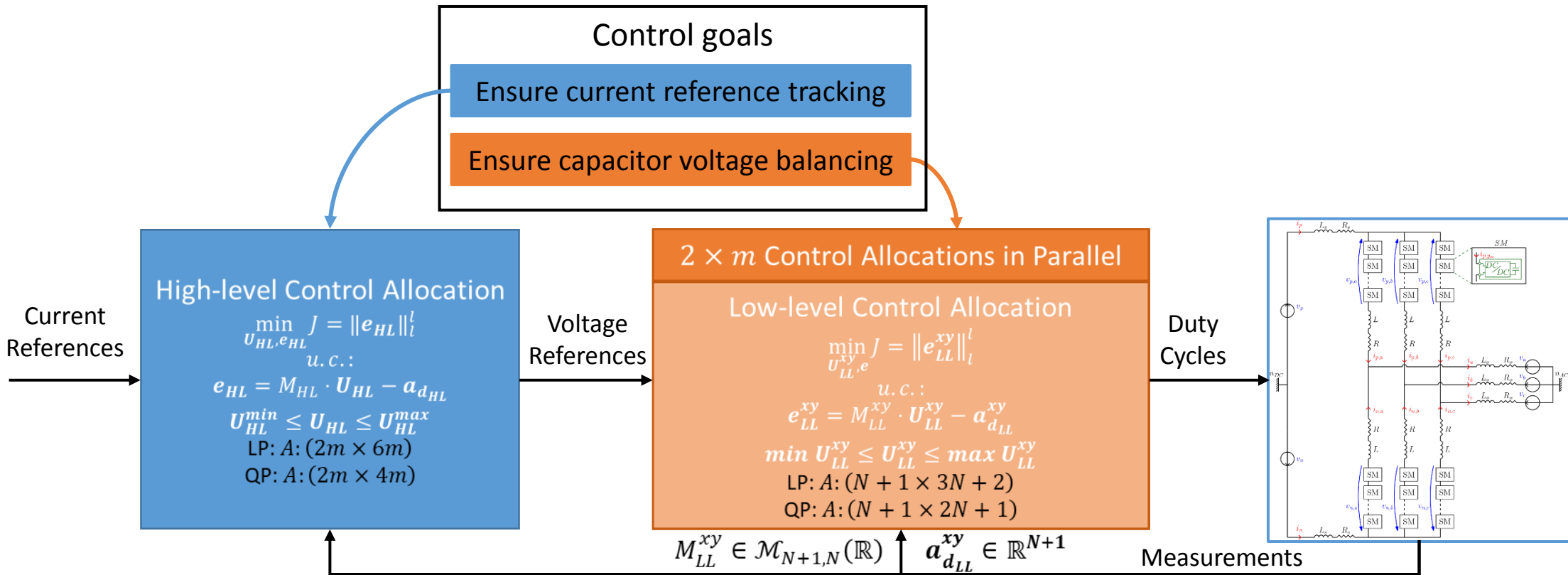
Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Control architecture



- The control architecture is **scalable** to any size MMC
- The entire control architecture has to optimize the control online in less than $T_c = 250 \mu s$

Control Performances Evaluation

Control performances test procedure

Context

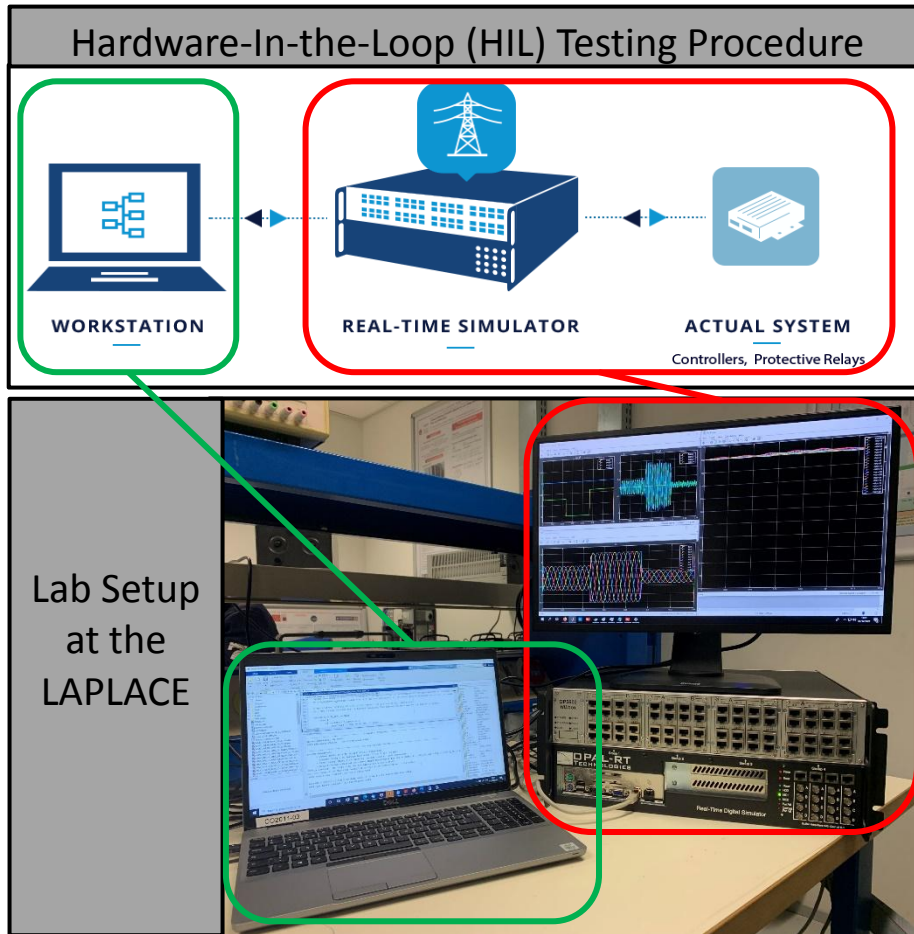
Control-Oriented Model

Control Allocation Methods

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Meaning	Value
Number of submodules per arm	$N = 7$
Number of phases	$m = 7$
DC Bus Voltage	$V_{DC} = 1.4 \text{ kV}$
Capacitor	$C = 2 \text{ mF}$
Capacitor nominal voltage	$V_C = 200 \text{ V}$
Arm impedance	$R = 10 \text{ m}\Omega \quad L = 5 \text{ mH}$
DC Bus impedance	$R_s = 50 \text{ m}\Omega \quad L_s = 2 \text{ mH}$
AC load impedance	$R_o = 40 \text{ }\Omega \quad L_o = 5 \text{ mH}$
Switching frequency	$f_s = 4 \text{ kHz} \quad (T_s = 250 \text{ }\mu\text{s})$
CPU Type	Intel Xeon, 3 GHz, 11.6 Gb cache, 64 Gb RAM
HIL time step	$T_{step} = 25 \text{ }\mu\text{s}$
Control sampling time	$T_c = T_s = 250 \text{ }\mu\text{s}$
Current pole placement	$p_{cc} = -3142 \text{ rad/s} \quad (f_{bw} = 500 \text{ Hz})$

Capacitor voltage balancing

Low-level Control Performances

Context

Control-Oriented Model

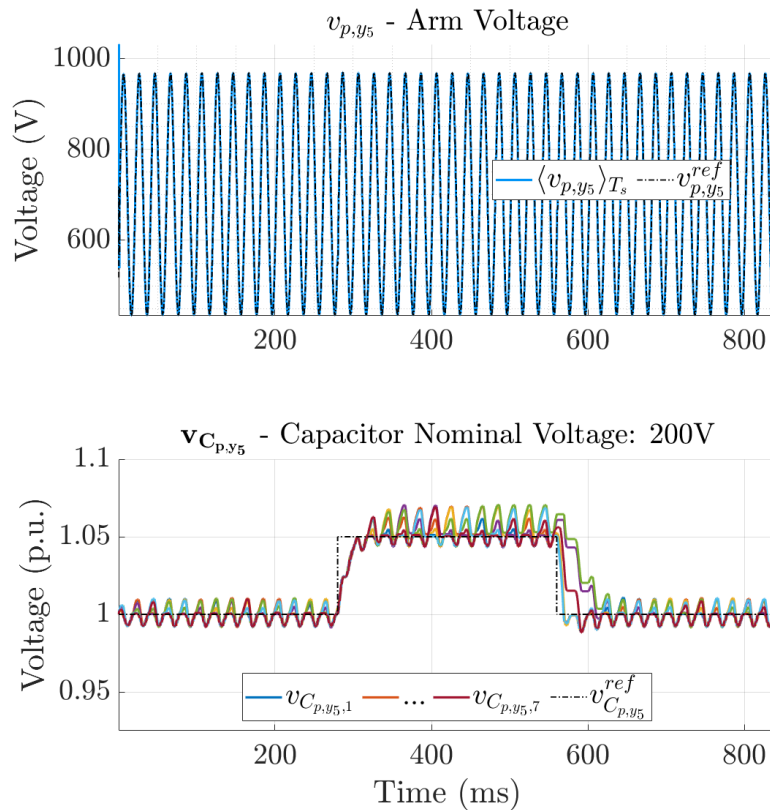
Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Using Linear Programming Interior-Point



- Control allocation ensures the arm voltage reference tracking
- It also guarantees a good capacitor balancing performance
- Ripple is normal since capacitor voltage depends on a current having AC components

➤ The low-level control with **online optimization** ensures capacitor voltage balancing with good performances

Control Performances Evaluation

Capacitor voltage balancing

Low-level Control Performances

Context

Control-Oriented Model

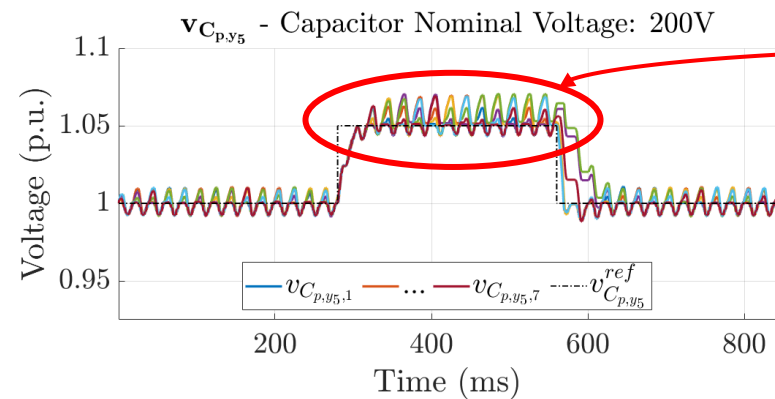
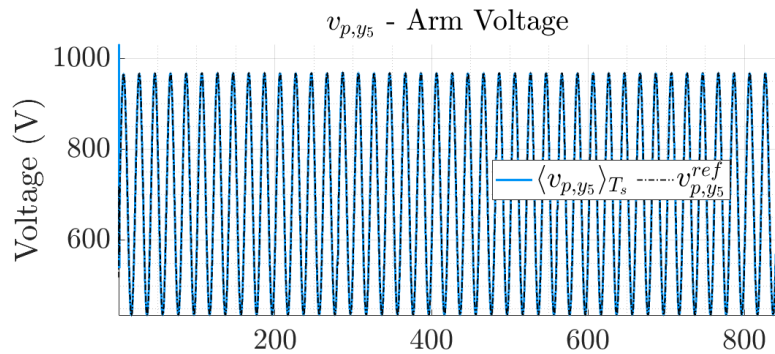
Control Allocation Methods

Control Performances Evaluation

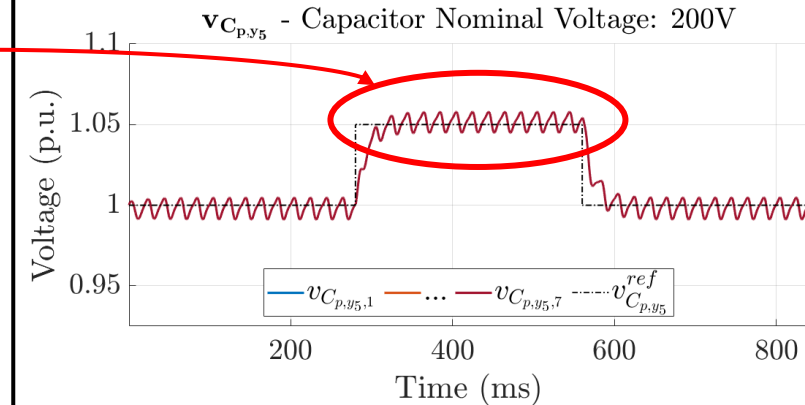
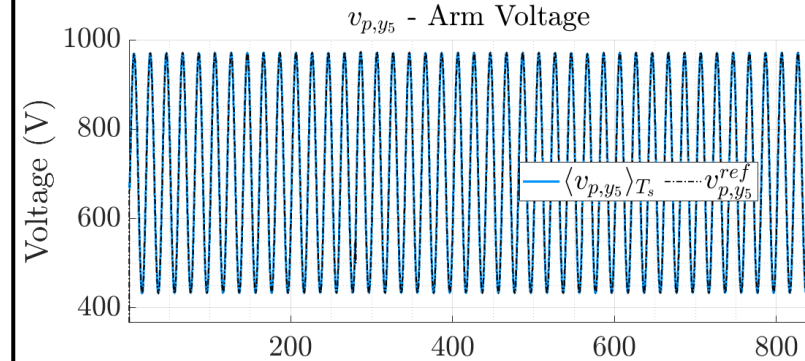
Key Points

Conclusion and Perspectives

Using Linear Programming Interior-Point



Using Quadratic Programming Interior-Point



➤ The use of QP will choose a control U so that its contribution to the generation of the control objective a_d uniformly distributes the deviations of the errors e .

Current reference tracking

High-level Control Performances

Context

Control-Oriented Model

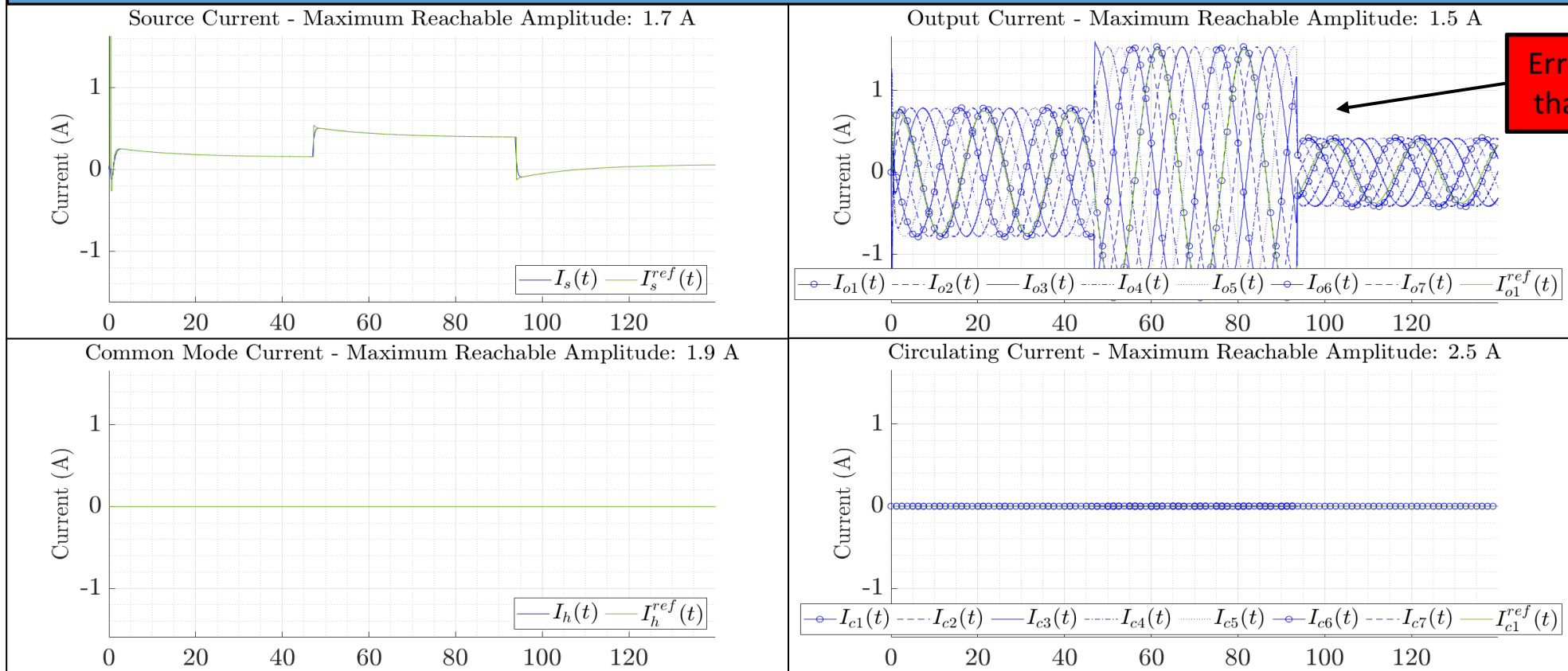
Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

Four Current Types Control Performances Using Quadratic Programming Active-Set



➤ The high-level control with **online optimization** ensures current reference tracking with good performances

Control Performances Evaluation

Current reference tracking

High-level Control Performances

Context

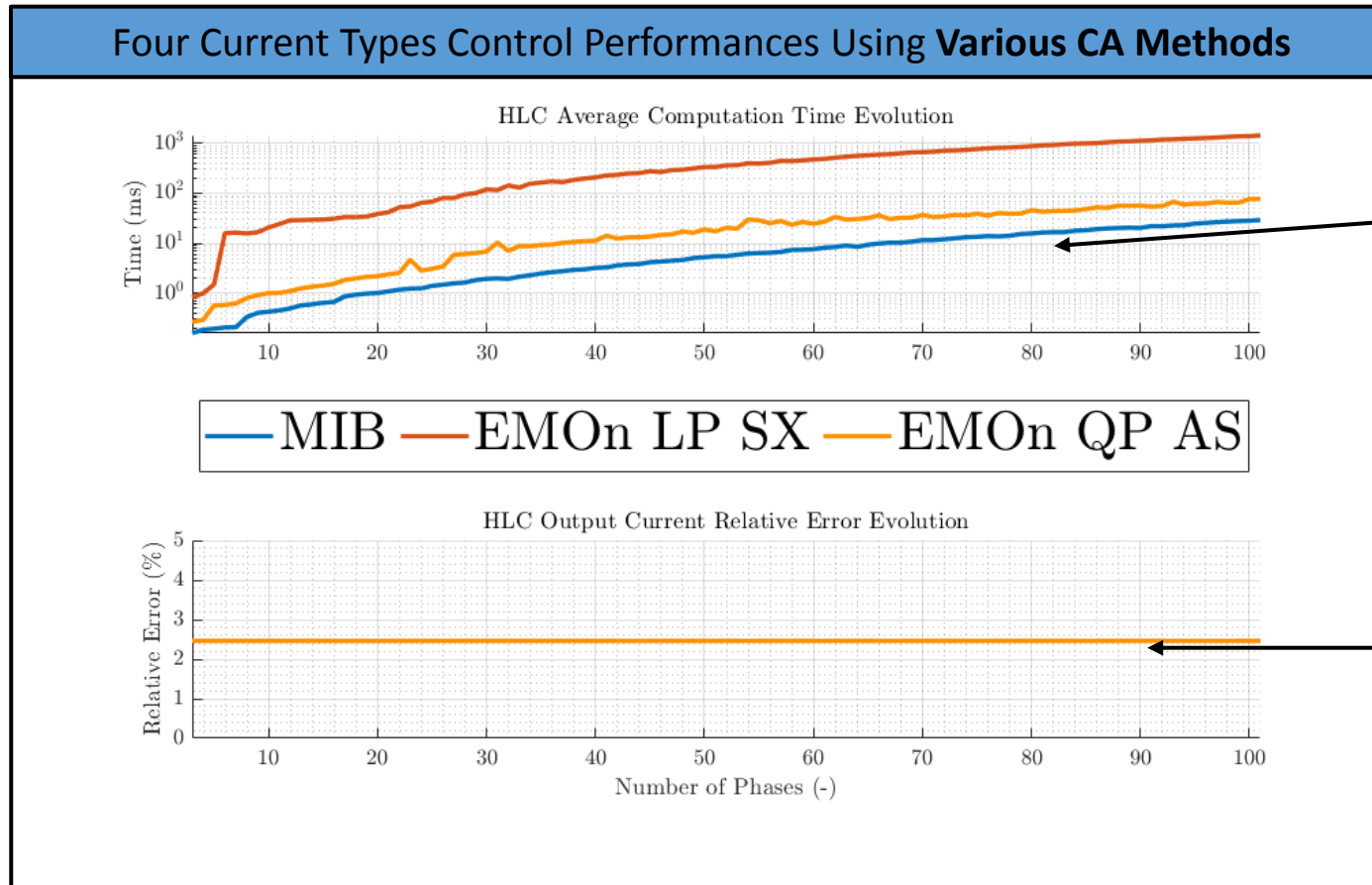
Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

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Conclusion and Perspectives



Computation time of the high-level control increases quadratically with the number of phases, meaning that using this control method will need greater computational resources as one addresses the control of great polyphase systems

Highlights not only the scalability of the control algorithm but also the scalability of the control performance: error remains constant as the number of phases increases

➤ The high-level control with **online optimization** is scalable as well as its performances

Key Points

Context

Control-Oriented Model

Control Allocation Methods

Control Performances Evaluation

Key Points

Conclusion and Perspectives

- Control-oriented **models that are scalable to any MMC** are derived, enabling the design of generic control laws that are scalable to any MMC
- Control allocation methods for the MMC are developed, a HIL testing procedure showed that they **ensure good control quality for the two control objectives**
- Closed-loop test also highlights the fact that **Quadratic Programming will use the control variables in a more balanced way than Linear Programming**
- **Control allocation algorithms scalable to any MMC** are designed and show that control **performances are scalable** to higher size MMC

Conclusion and Perspectives

Context

Control-Oriented Model

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Conclusion and Perspectives

- Control-oriented **models that are scalable to any MMC** are derived, enabling the design of generic control laws that are scalable to any MMC
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- Closed-loop test also highlights the fact that **Quadratic Programming will use the control variables in a more balanced way than Linear Programming**
- **Control allocation algorithms scalable to any MMC** are designed and show that control **performances are scalable** to higher size MMC

Perspectives

- Improve the current control performances
- Deeper analysis of the different control allocation algorithms that are already implemented