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Control Allocation of the Currents in the Modular Multilevel Converter

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Introduction to the Modular Multilevel Converter (MMC)

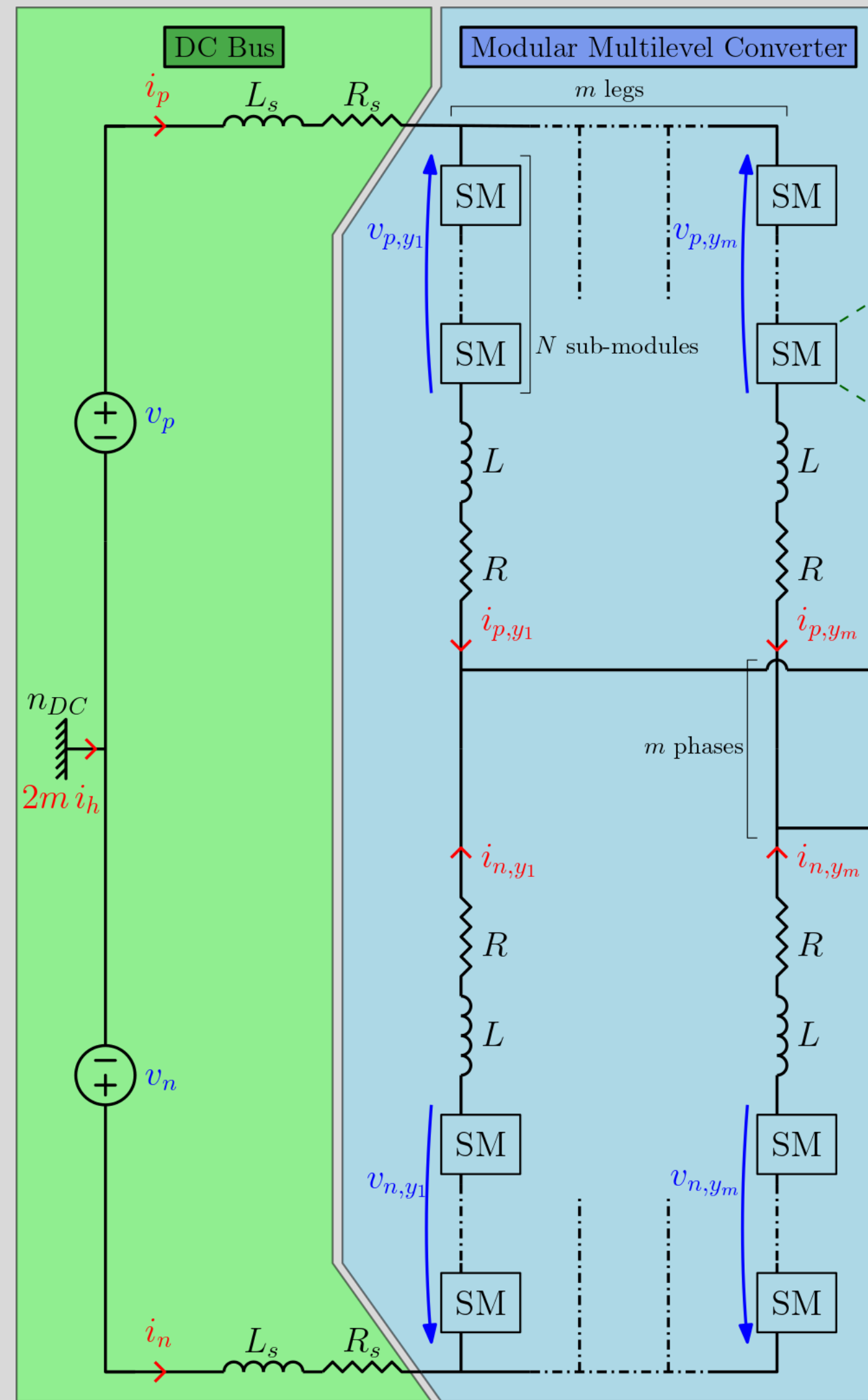


Fig. 1 - Electrical diagram of the MMC with m phases and N SMs per arm.

The modular multilevel converter (MMC), a DC/AC converter, is becoming increasingly popular in HVDC networks for several reasons. First, the multilevel nature of the converter gives it the advantages associated with being able to impose several voltage levels across the arms of the converter, which improves the harmonic quality of the electrical waveforms on the AC side of the converter. The second feature that makes it advantageous is its modularity. A submodule (SM) is an elementary switching cell of the MMC. The MMC will then be built from a stack of these submodules, the higher the electrical power to be converted, the more this topology will include submodules of the same type without needing semiconductors with a larger operating range. The interest of such a modularity is multiple, it allows to use the same converter topology for a very important power range, from kilowatt to gigawatt. Moreover, its industrialization is relatively simple because it is sufficient to produce the same submodule to address a large number of power levels. The research work presented here addresses the control of this converter.

Introduction to the control problem

In order to manage the power converted between the DC source and the AC network, it is necessary to control the AC currents. The MMC is such that in the topology shown in Fig. 1, one can consider that the voltage at the terminals of each arm is a variable source independently of the other arms. In the three-phase topology of Fig. 2 it reads:

- 6 Control variables: $v_{p,a}, v_{p,b}, v_{p,c}, v_{n,a}, v_{n,b}, v_{n,c}$
- 3 Output variables: i_a, i_b, i_c

This means that there are more input variables than output variables. Moreover when the behavior of the system is analyzed, one can notice that more than one arm voltage influence a given output current.

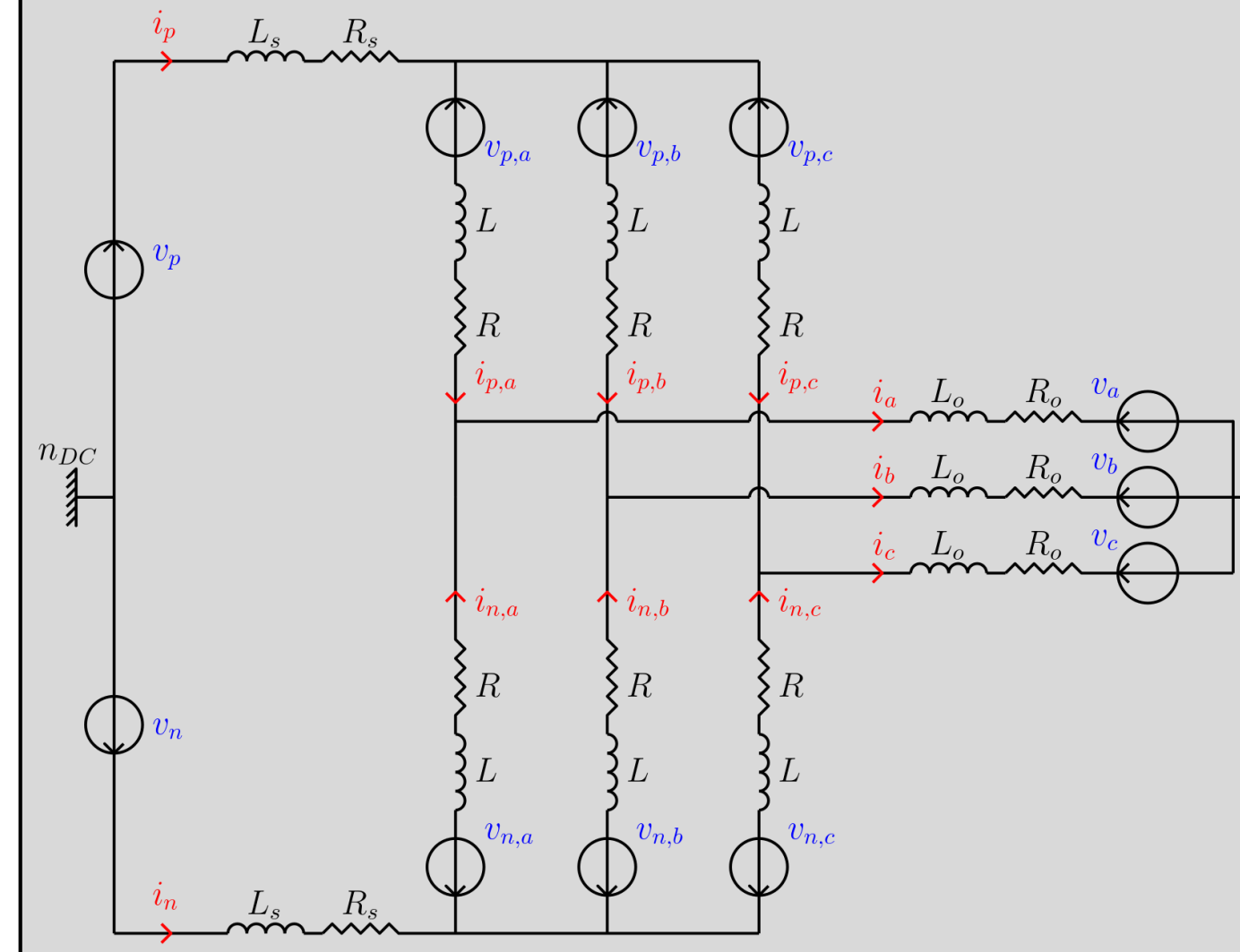


Fig. 2 - Electrical diagram of the MMC with 3 phases.

Thus, the considered system is redundant and can be qualified as **overactuated**. There are more degrees of freedom than constraints for the control: a choice has to be made in real time in order to use, at best, the arm voltages.

Control Allocation (CA) methods thus appear as being well suited to deal with the control of this converter since they are tailored for **overactuated** systems.

Research work flow and method

1 - Modelling

Scalable Control-Oriented Model

The converter being modular in the number of submodules, which provides the capacity of being adaptive to an important number of electrical systems, it is imagined a modularity in the number of phases for an even more generalized usage of the MMC. The first step is to develop a current control law for the MMC, therefore a control-oriented model is derived. **This model is generalized to a wide range of MMCs and is scalable to any number of phases in the AC network [1,2].**

To put it in a nutshell, stemming from relevant assumptions, the model is in the form of the following state-space model:

$$\begin{cases} \dot{X} = AX + BU + E \\ Y = CX \end{cases}$$

2 - Design

Control Allocation (CA) Design

The second step is the formulation of the **Control Allocation** for the currents flowing through the converter during the operation.

Open Loop Behavior

$$\dot{Y} = CAX + CBU + CE$$

Desired Closed Loop Behavior

$$\dot{Y}^* = A_M Y + B_M Y^{ref}$$

Control to Ensure Desired Behavior
(CB) $U = A_M Y + B_M Y^{ref} - C(AX + E)$
 $M \cdot U = a_d$

3 - Development

CA Optimization Algorithm

The third step lies in the derivation of the optimization of the control in real time while taking into account the control limits.

Online Control Optimization

$$\begin{cases} \min J = \|e\|_l^l \\ u. c. : \\ e = M \cdot U - a_d \\ U_{min} \leq U \leq U_{max} \end{cases}$$

A deviation e to the control allocation equation is introduced to account for cases where a_d has a too large magnitude and U is willing to exceed its boundaries. Since U must stay within its limits, a deviation e to the verification of $M \cdot U = a_d$ is allowed so that the optimization problem remains feasible. **Simplex, Interior-Point and Active-Set optimization algorithms are implemented in real time.**

4 - Validation

Hardware-In-the-Loop Testing

The last step has for objective to validate the proposed control algorithm using online optimization. In order to do so, a **Hardware-In-the-Loop (HIL)** testing procedure is designed.

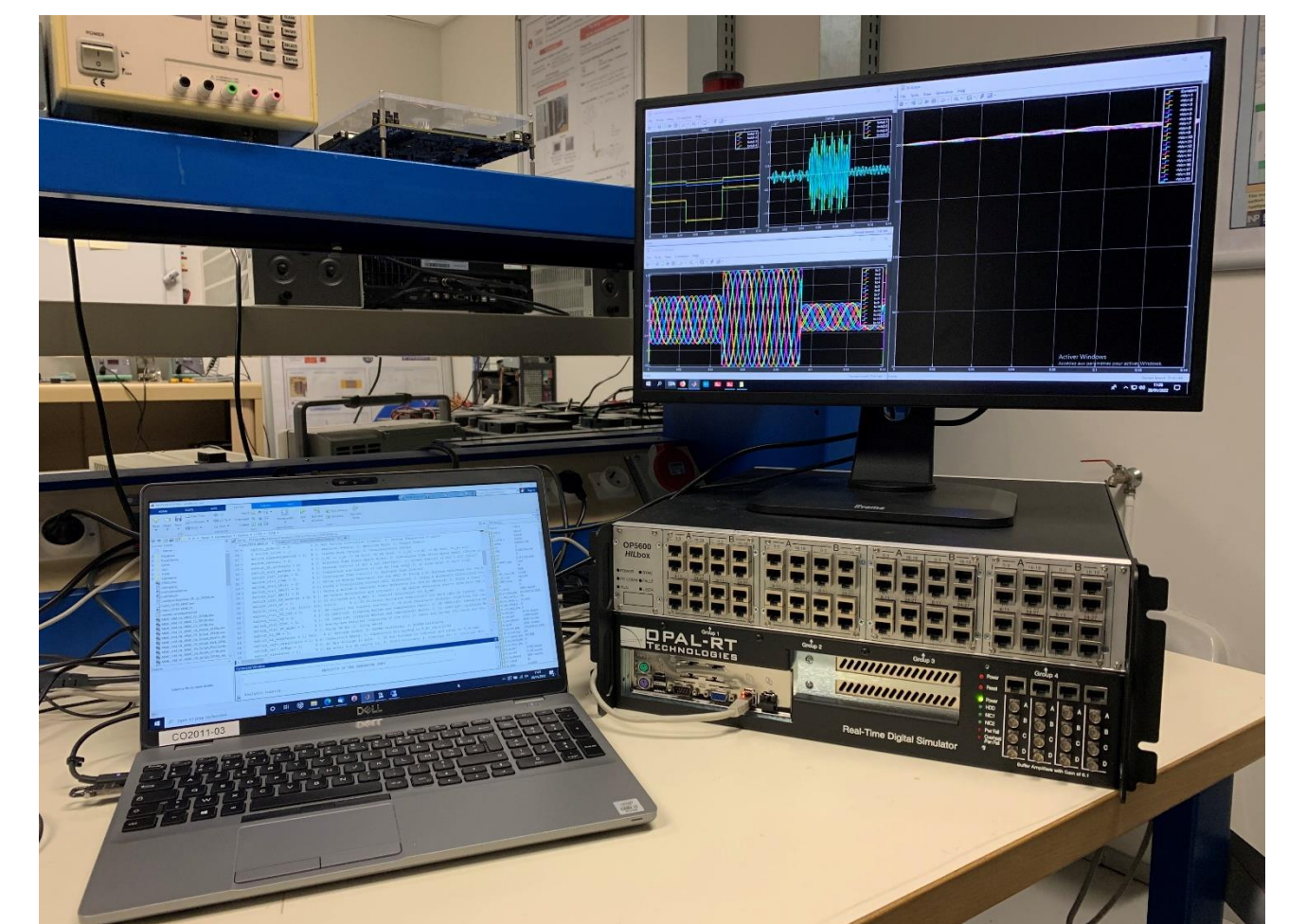
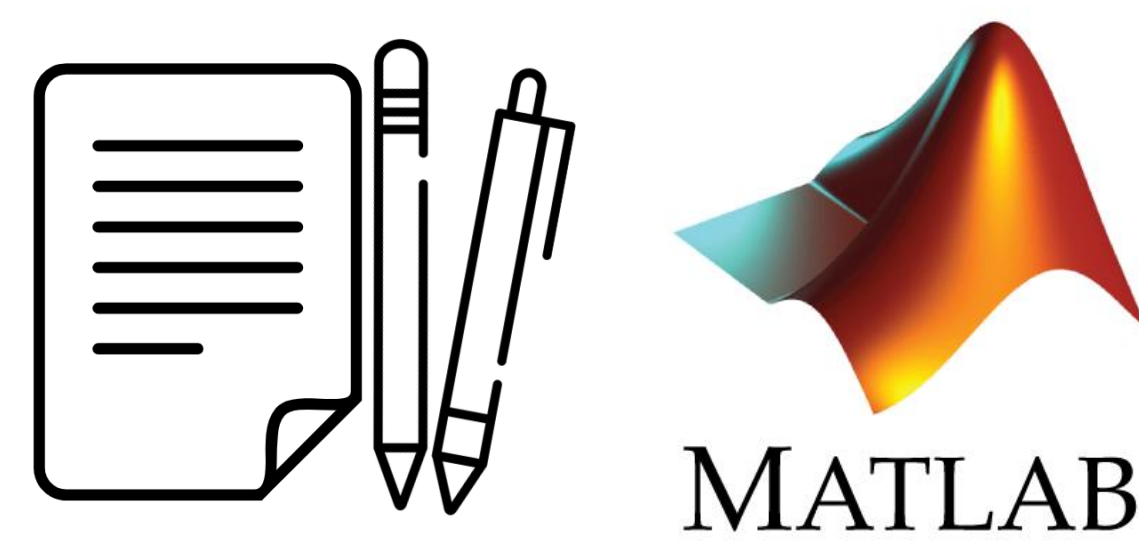


Fig. 3 - Hardware-In-the-Loop test setup with the Opal-RT 5600 HIL box at the LAPLACE laboratory.

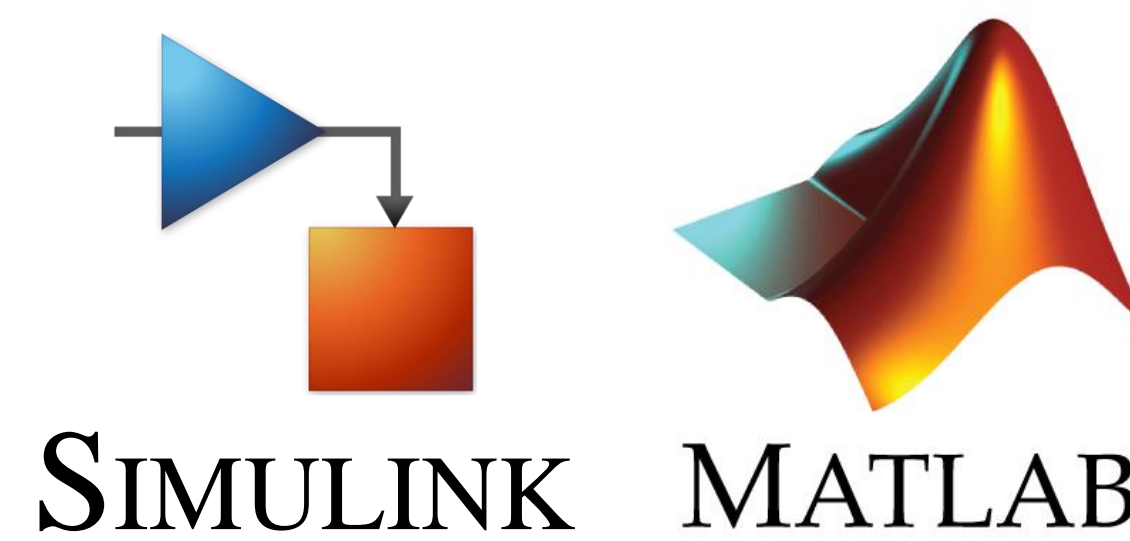
Tools



Tools



Tools



Tools



Results

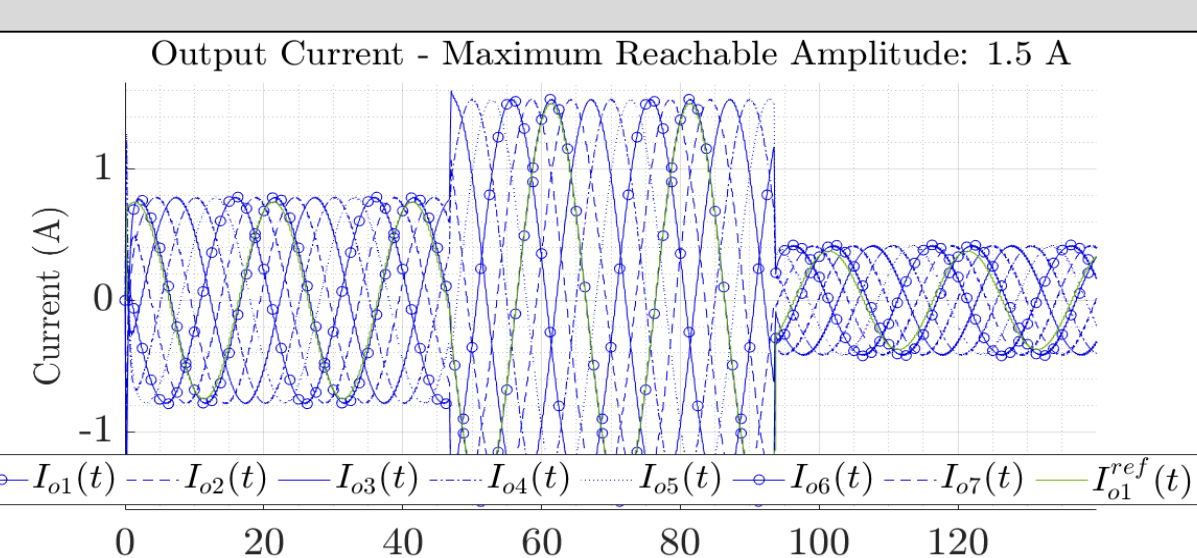


Fig. 4 - Closed-loop response of the system in the 7-phase case using Active-Set (time scale is in ms).

Results show a very good overall performance:

- Static error smaller than 37 mA (2.5%)
- Settling time of 1 ms, in line with the design

Therefore, the developed control allocation meets the requirements and is validated.

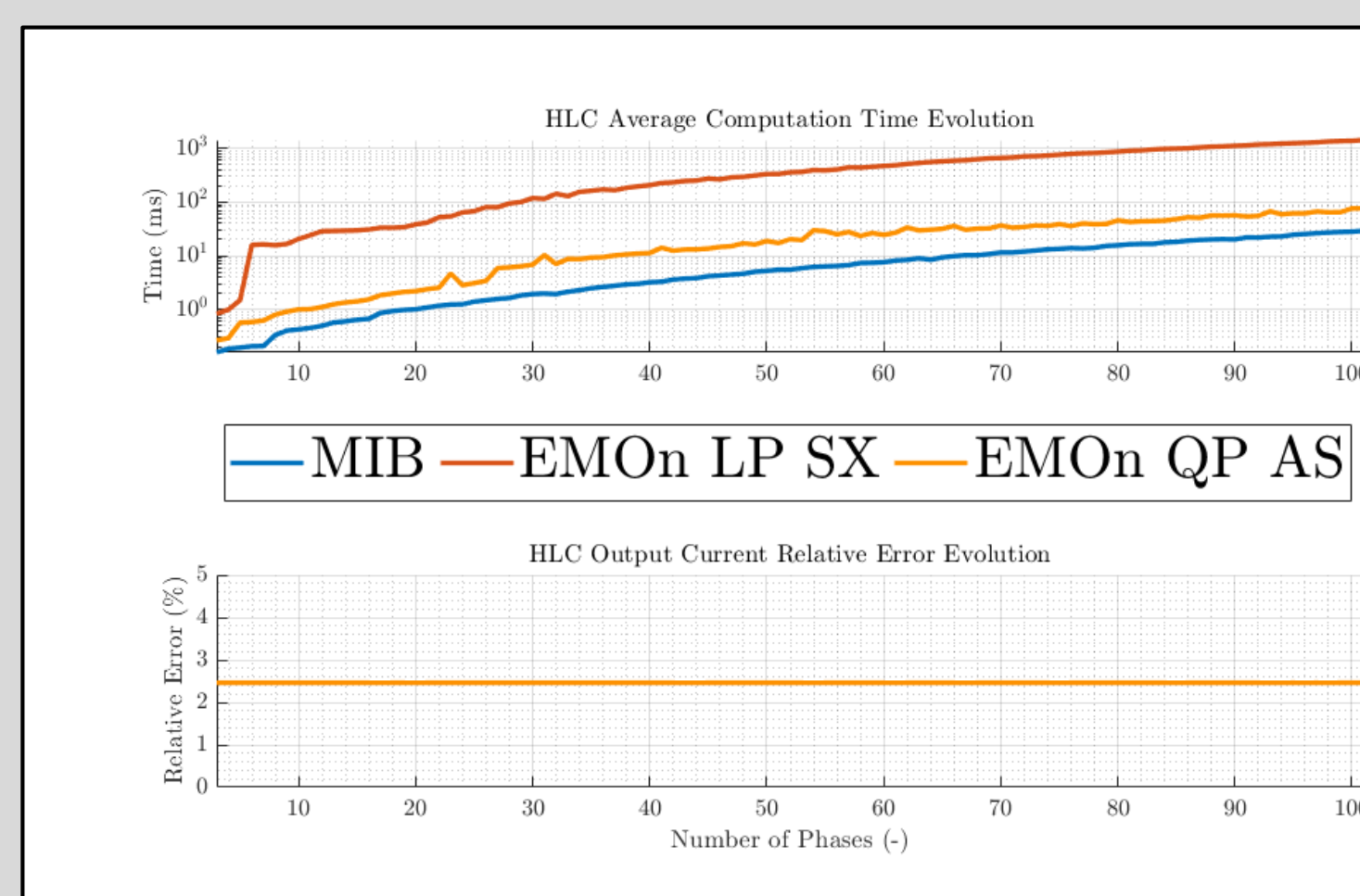


Fig. 5 - Evolution of the control allocation characteristics versus the number of phases.

The validation done for the 7-phase case (Fig. 4) is extended from 3 to 101 phases in order to verify the **scalability property** of the control allocation method. This phase sweep HIL test is not only done for the Active-Set (Quadratic Programming - QP) algorithm but also for the Simplex (Linear Programming - LP) and the Model Inversion Based (MIB) Control Allocation methods.

Fig. 4 shows two figures, on the top one the control average computation time is displayed versus the number of phases, and on the bottom one the output current control error is plotted versus the number of phases. Results show that:

- Control computation time increases quadratically with the number of phases. Active-Set (QP) is the fastest optimization algorithm.
- As the number of phases increases, current control error remains the same (2.5%).

Conclusion

It is now possible to develop current control algorithms for MMCs - of any number of phases and submodules, whatever the nature of the AC load and the presence or absence of a common mode current - using the same online optimization control allocation algorithm that is scalable without having to undergo changes in the code. **As the control allocation scales up, control performance remains the same.**