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Indirect Model Predictive Control for Capacitor Energy Control in Modular Multilevel Converters

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Motivation

Research questions:

- Which nonlinearities are present in the total capacitor energy dynamics of the MMC?
- What impact do the nonlinearities in MMC dynamics have on the performance and constraint satisfaction of linear MPC controllers?

A linear MPC in a cascaded structure is proposed to mitigate the effects of the nonlinearities.

System Description

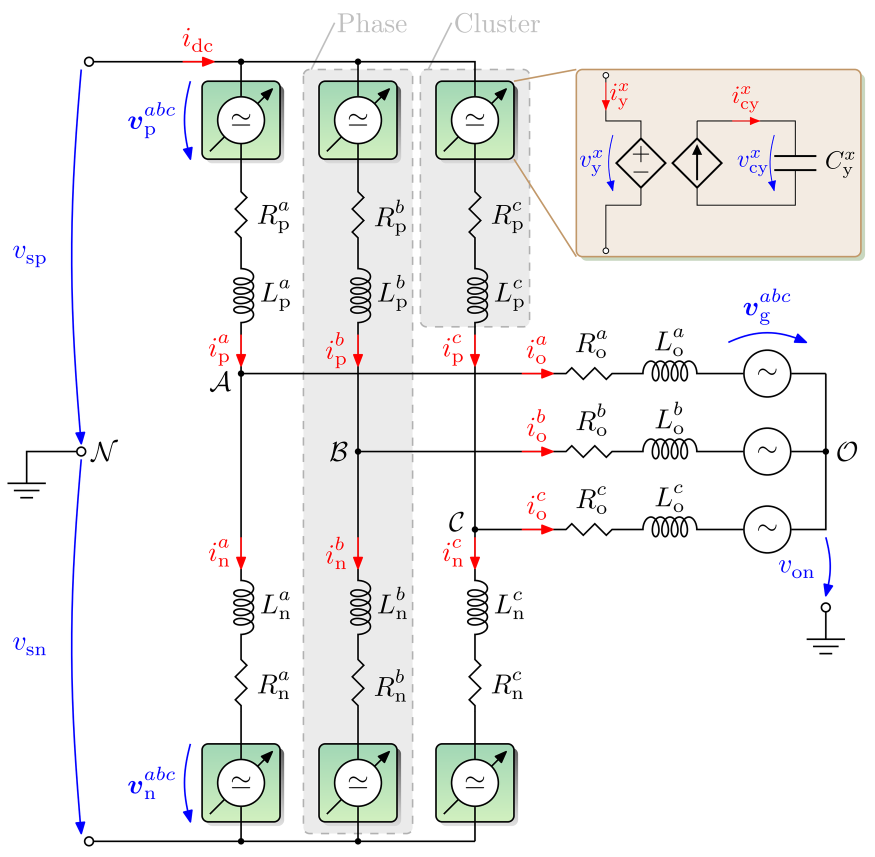


Figure 1. Average value model of the investigated MMC in double-star connection.

Decomposition of cluster currents into grid currents, circulating currents, and dc current.

$$\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\Sigma\Delta}^{\alpha\beta\gamma} = \left(\boldsymbol{L}_{\Sigma\Delta}^{\alpha\beta\gamma}\right)^{-1}\left(-\boldsymbol{R}_{\Sigma\Delta}^{\alpha\beta\gamma}\boldsymbol{i}_{\Sigma\Delta}^{\alpha\beta\gamma} - \boldsymbol{v}_{\Sigma\Delta}^{\alpha\beta\gamma} + \begin{pmatrix}\boldsymbol{0}_3\\ -2\boldsymbol{v}_{\mathrm{g}}^{\alpha\beta\gamma}\end{pmatrix} + \frac{v_{\mathrm{dc}}}{2}\begin{pmatrix}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{1}_3\\ \boldsymbol{0}_3\end{pmatrix} + \begin{pmatrix}\boldsymbol{0}_3\\ -2v_{\mathrm{on}}\boldsymbol{T}_{\mathrm{c}}\boldsymbol{1}_3\end{pmatrix}\right) \tag{1}$$

Nonlinear capacitor energy dynamics.

$$\begin{aligned}\frac{\mathrm{d}}{\mathrm{d}t}e_{\mathrm{c},\Sigma}^{\gamma} =& -\frac{L}{2}\left(\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\Sigma}^{\alpha\beta}\right)^{\top}\boldsymbol{i}_{\Sigma}^{\alpha\beta} - \frac{R}{2}\|\boldsymbol{i}_{\Sigma}^{\alpha\beta}\|^2 - Li_{\Sigma}^{\gamma}\frac{\mathrm{d}}{\mathrm{d}t}i_{\Sigma}^{\gamma} - R\left(i_{\Sigma}^{\gamma}\right)^2\\ &-\frac{2L_{\mathrm{o}}+L}{4}\left(\frac{\mathrm{d}}{\mathrm{d}t}\boldsymbol{i}_{\Delta}^{\alpha\beta}\right)^{\top}\boldsymbol{i}_{\Delta}^{\alpha\beta} - \frac{2R_{\mathrm{o}}+R}{4}\|\boldsymbol{i}_{\Delta}^{\alpha\beta}\|^2 + \frac{1}{2}v_{\mathrm{dc}}i_{\Sigma}^{\gamma} - \frac{1}{4}\left(\boldsymbol{v}_{\mathrm{g}}^{\alpha\beta}\right)^{\top}\boldsymbol{i}_{\Delta}^{\alpha\beta}\end{aligned} \tag{2}$$

Assumptions

Assumption 1 All cluster parameters are identical and a symmetrical three-phase grid is considered.

Assumption 2 The voltage drop across resistors and inductors is small enough to be negligible, i.e., $L_{\kappa}\frac{\mathrm{d}}{\mathrm{d}t}i_{\mathrm{y}}^{x} + R_{\kappa}i_{\mathrm{y}}^{x} \approx 0$.

Linear capacitor energy dynamics under Assumptions 1 and 2.

$$\frac{\mathrm{d}}{\mathrm{d}t}e_{\mathrm{c},\Sigma}^{\gamma} = \tfrac{1}{2}v_{\mathrm{dc}}i_{\Sigma}^{\gamma} - \underbrace{\tfrac{1}{4}\left(\boldsymbol{v}_{\mathrm{g}}^{\alpha\beta}\right)^{\top}\boldsymbol{i}_{\Delta}^{\alpha\beta}}_{=:p_{\mathrm{ac}}} \tag{3}$$

Indirect MPC as QP

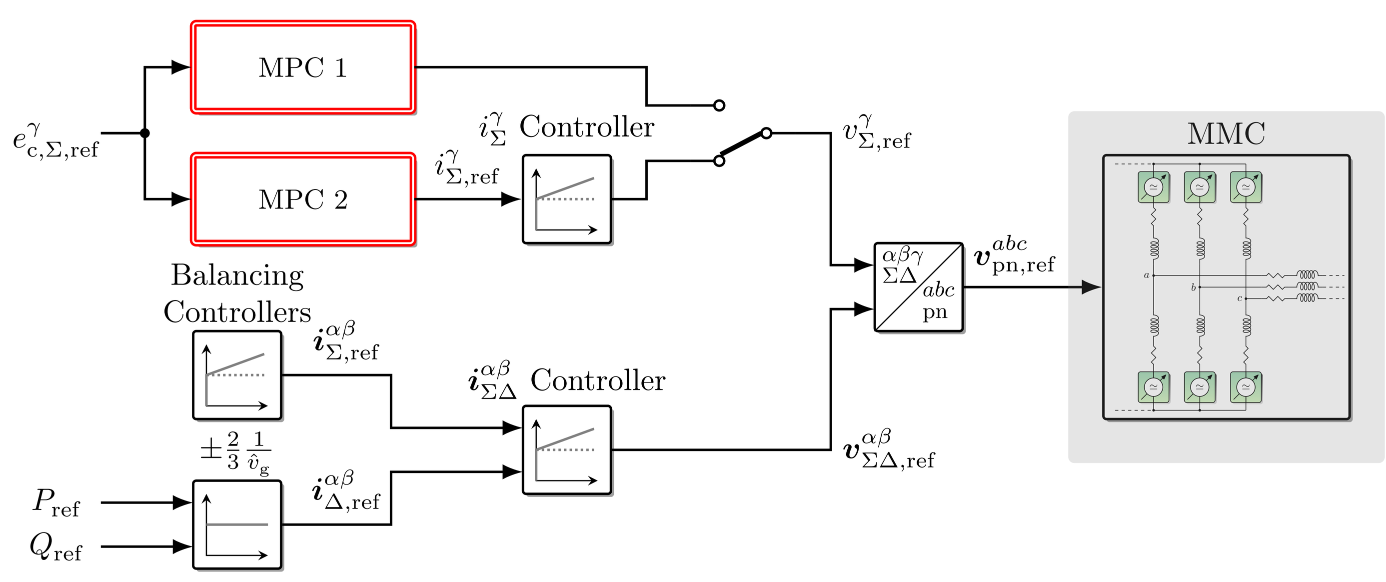


Figure 2. Control structure of the MMC with the proposed MPC variants MPC 1 and MPC 2 highlighted in red.

A generic MPC problem formulation considers discrete linear time-invariant (LTI) systems of the form

$$\begin{aligned}\boldsymbol{x}[k+1] &= \boldsymbol{A}\boldsymbol{x}[k] + \boldsymbol{B}\boldsymbol{u}[k] + \boldsymbol{d}[k],\ \boldsymbol{x}[0] = \boldsymbol{x}_0\\ \boldsymbol{y}[k] &= \boldsymbol{C}\boldsymbol{x}[k],\end{aligned} \tag{4}$$

with the cost function

$$J(k) = \sum_{l=k}^{k+N_{\mathrm{p}}-1}\|\boldsymbol{y}_{\mathrm{ref}}[l+1] - \boldsymbol{y}[l+1]\|_{\boldsymbol{Q}}^2 + \|\Delta\boldsymbol{u}[l]\|_{\boldsymbol{P}}^2 \tag{5}$$

A. MPC in Single-Loop Structure (MPC 1)

The total energy of the capacitors is controlled directly by computing the reference cluster voltage $v_{\Sigma,\mathrm{ref}}^{\gamma}$, see Fig. 2.

$$\begin{aligned}\underbrace{\begin{pmatrix}e_{\mathrm{c},\Sigma}^{\gamma}[k+1]\\ i_{\Sigma}^{\gamma}[k+1]\end{pmatrix}}_{=:\boldsymbol{x}[k+1]} &= \underbrace{\begin{bmatrix}1 & \frac{1}{2}T_s v_{\mathrm{dc}}\\ 0 & 1-T_s\frac{R}{L}\end{bmatrix}}_{=:\boldsymbol{A}}\begin{pmatrix}e_{\mathrm{c},\Sigma}^{\gamma}[k]\\ i_{\Sigma}^{\gamma}[k]\end{pmatrix} + \underbrace{\begin{pmatrix}0\\ -\frac{T_s}{L}\end{pmatrix}}_{=:\boldsymbol{b}}\underbrace{v_{\Sigma,\mathrm{ref}}^{\gamma}[k]}_{=:u[k]} + \underbrace{\begin{pmatrix}T_s p_{\mathrm{ac}}[k]\\ \frac{T_s}{2L}v_{\mathrm{dc}}\end{pmatrix}}_{=:\boldsymbol{d}[k]},\\ y[k] &= \underbrace{\left(1, 0\right)}_{=:\boldsymbol{c}^{\top}}\boldsymbol{x}[k],\end{aligned} \tag{6}$$

B. MPC in Cascaded Structure (MPC 2)

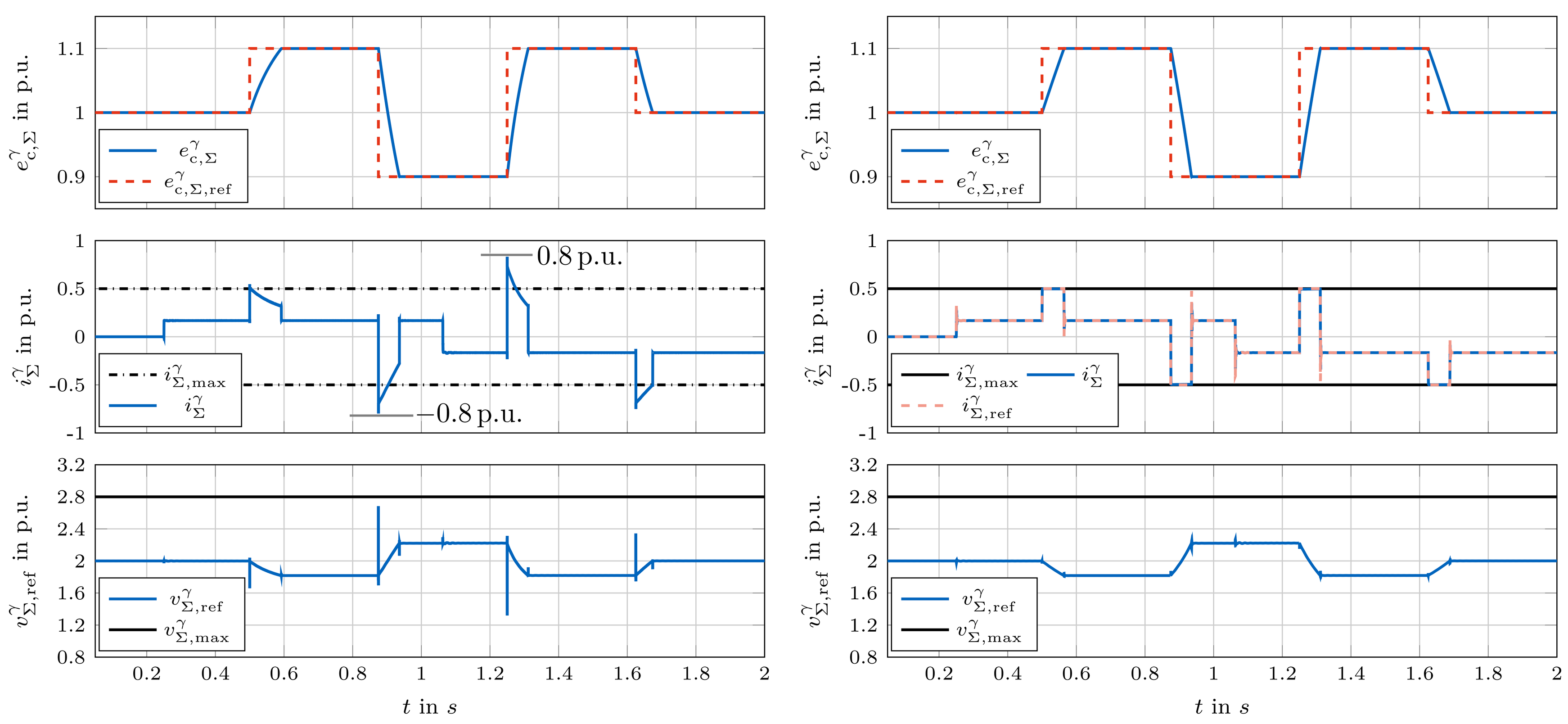
The total energy of the capacitors is controlled by computing a reference current, which is passed to a current controller, see Fig. 2.

$$\begin{aligned}\underbrace{\begin{pmatrix}e_{\mathrm{c},\Sigma}^{\gamma}[k+1]\\ i_{\Sigma}^{\gamma}[k+1]\end{pmatrix}}_{=:\boldsymbol{x}[k+1]} &= \underbrace{\begin{bmatrix}1 & \frac{1}{2}T_s v_{\mathrm{dc}}\\ 0 & 1-\frac{T_s}{T_\sigma}\end{bmatrix}}_{=:\boldsymbol{A}}\begin{pmatrix}e_{\mathrm{c},\Sigma}^{\gamma}[k]\\ i_{\Sigma}^{\gamma}[k]\end{pmatrix} + \underbrace{\begin{pmatrix}0\\ \frac{T_s}{T_\sigma}\end{pmatrix}}_{=:\boldsymbol{b}}\underbrace{i_{\Sigma,\mathrm{ref}}^{\gamma}[k]}_{=:u[k]} + \underbrace{\begin{pmatrix}T_s p_{\mathrm{ac}}[k]\\ 0\end{pmatrix}}_{=:\boldsymbol{d}[k]},\\ y[k] &= \underbrace{\left(1, 0\right)}_{=:\boldsymbol{c}}\boldsymbol{x}[k].\end{aligned} \tag{7}$$

Validation and Simulation Results

Table 1. System and control parameters.

Parameter	MMC	p.u.
dc voltage V_{dc}	100 kV	2.5
rated apparent power S_{R}	60 MVA	1
grid voltage $\hat{v}_{\mathrm{g}}$	25 kV	1
grid frequency f_{g}	50 Hz	1
grid side resistance R_{o}	0.1	0.0025
grid side inductance L_{o}	2 mH	0.0157
cluster capacitance C	1 mF	12.566
cluster resistance R_{pn}	0.1	0.025
cluster inductance L_{pn}	1 mH	0.00785
dc current limit $i_{\Sigma,\max}^{\gamma} = -i_{\Sigma,\min}^{\gamma}$	500 A	0.5
sampling interval T_{s}	100 µs	0.0314
prediction horizon steps N_{p}	3	



(a) MPC 1 (b) MPC 2

Figure 3. Performance of MPC 1 and MPC 2 with soft state (dash-dotted black line) and hard input (solid black line) constraints.

Conclusion and Future Work

- The nonlinearities in the energy dynamics are mainly due to the voltage drop over the resistors and inductors
- These lead to constraint violations for linear MPC in a single-loop structure. However, with a cascaded structure, constraints can be met.
- Extend results to include capacitor energy balancing in the energy control
- Investigate nonlinear MPC for capacitor energy control

References

[1] Leonardo Testa, Petros Karamanakos, and Christoph M. Hackl. Indirect model predictive control for capacitor energy control in modular multilevel converters. In *proceedings of the 2025 IECON Annual conference of the IEEE Industrial Electronics Society*, 2025.

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