

Small-Signal Modelling of Modular Multilevel Converters → Internal Stored Energy Control Stability Improvements ←

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Contents

Introduction

MMC Modelling for Time-Invariance

Energy Control for Stability Improvements

Conclusions

Table of Contents



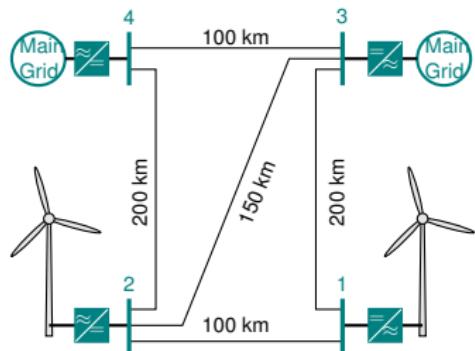
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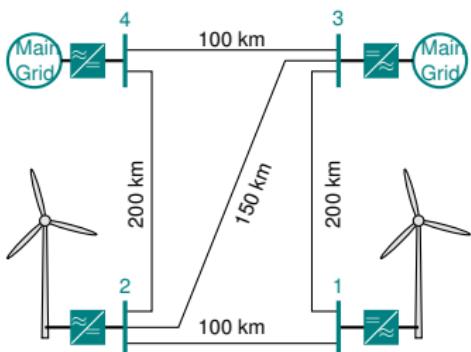
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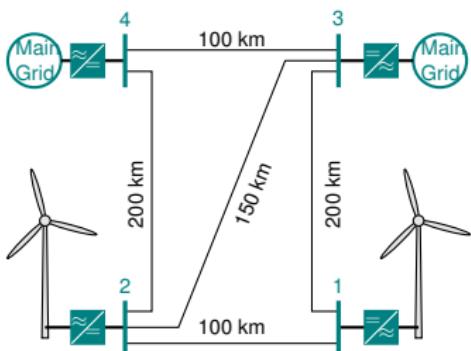
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 - Focus on the Modular Multilevel Converter.



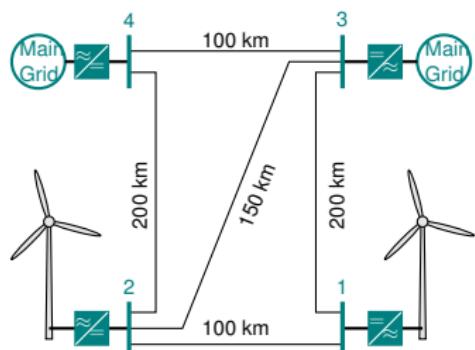
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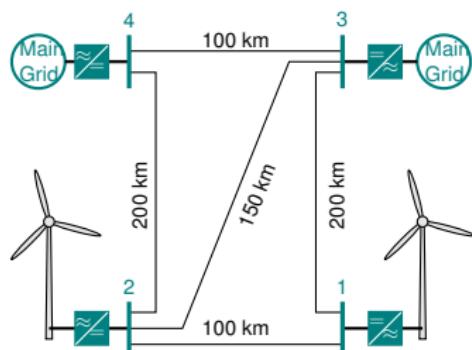
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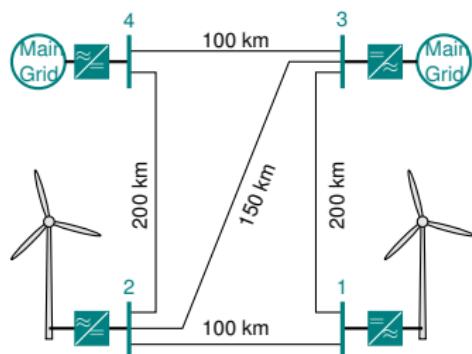
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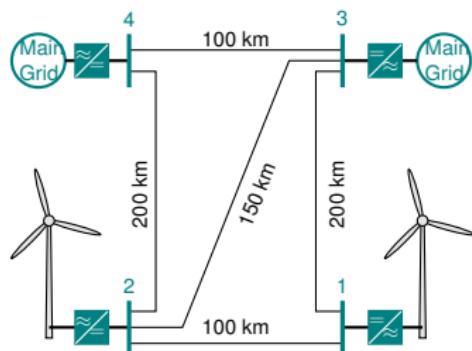
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 - Linear Time Invariant (small-signal) models;
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- **Challenge:** Standard MMC models are Time-Periodic.

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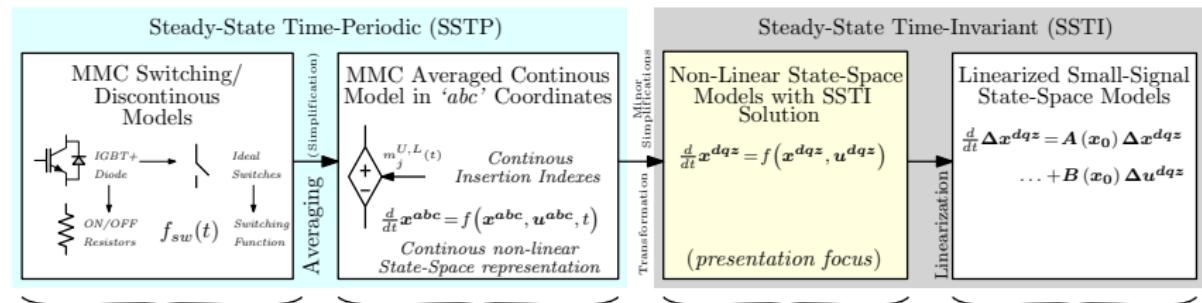
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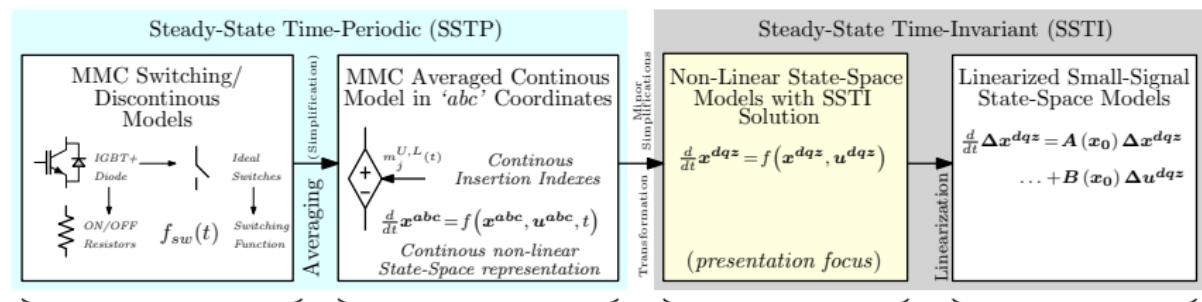
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Overview on modelling approaches



- Explicit representation of sub-modules and switching events
- Suitable for Electro-Magnetic Transient (EMT) simulations
- Assumes ideal capacitor voltage balancing
- Equivalent arm capacitance and continuous time averaged arm voltages
- Suitable for analysis and design of controllers
- Analysis of state-space models in time-periodic framework
- Derived from average model in stationary 'abc' coordinates
- Non-linear system analysis and control design requiring constant variables in steady-state
- Prerequisite for linearization at equilibrium
- Valid for a small region around the linearization point
- Analysis of system dynamics and stability by traditional eigenvalue-based methods

Overview on modelling approaches

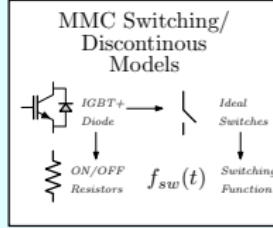


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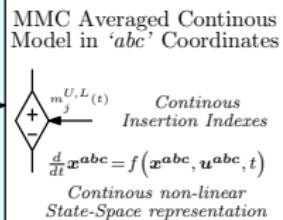
— A time-invariant MMC model cannot be achieved with a single Park transformation

Overview on modelling approaches

Steady-State Time-Periodic (SSTP)



Averaging (Simplification)



Steady-State Time-Invariant (SSTI)

Non-Linear State-Space Models with SSTI Solution

$$\frac{d}{dt}x^{dqz} = f(x^{dqz}, u^{dqz})$$

(presentation focus)

Linearized Small-Signal State-Space Models

$$\begin{aligned} \frac{d}{dt}\Delta x^{dqz} &= A(x_0)\Delta x^{dqz} \\ &\dots + B(x_0)\Delta u^{dqz} \end{aligned}$$

Minor Simplifications

Linearization

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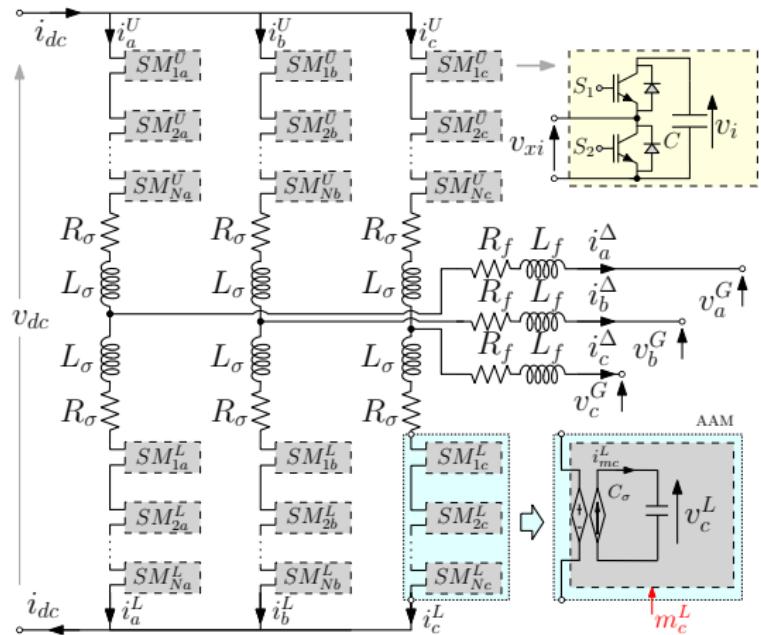
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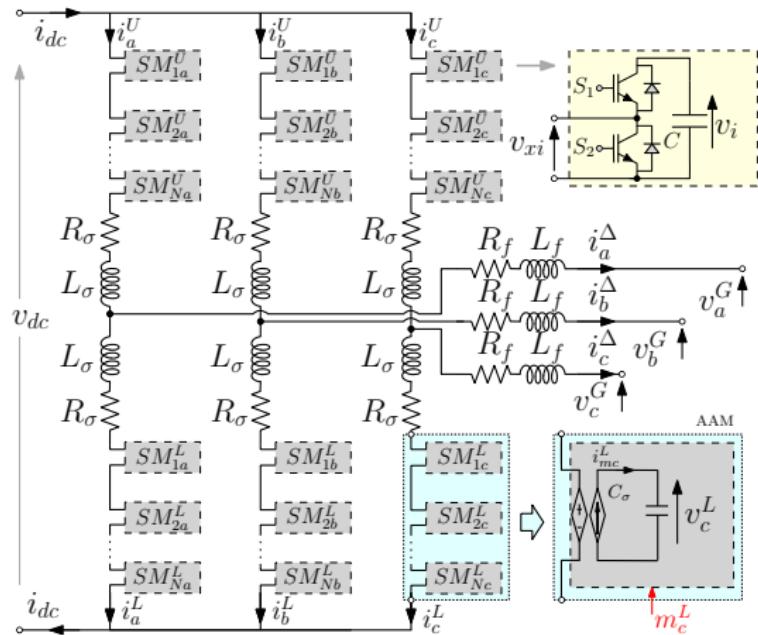
— A time-invariant MMC model cannot be achieved with a single Park transformation

- ...due to the multiple frequency components in its variables at steady-state.

The Modular Multilevel Converter

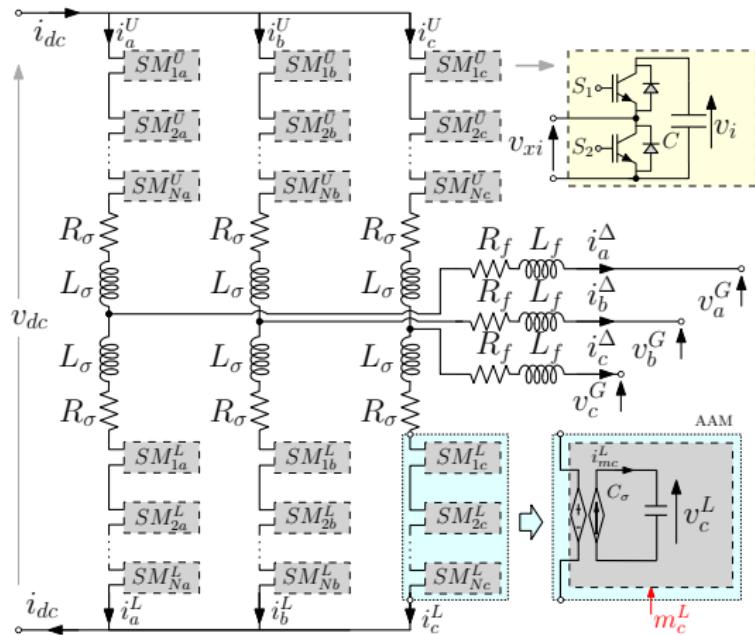


The Modular Multilevel Converter



— Variables in $U-L$ coordinates.

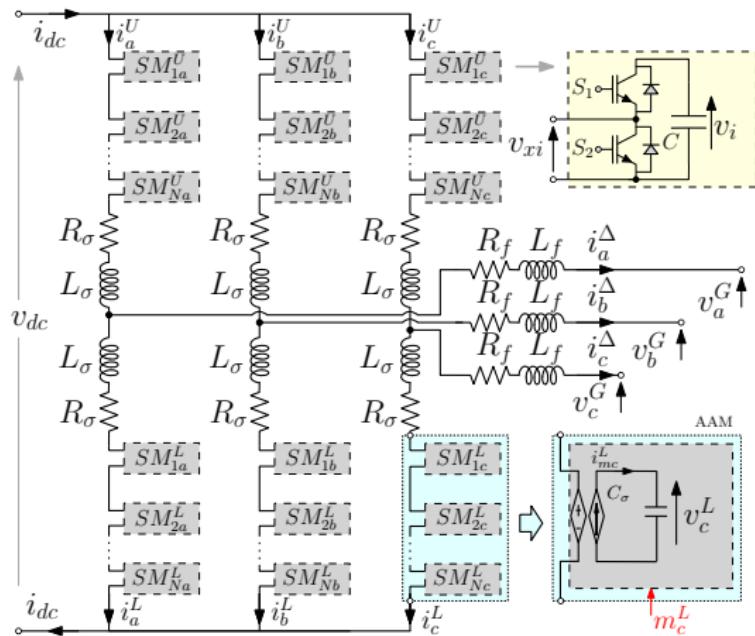
The Modular Multilevel Converter



— Variables in $U-L$ coordinates.

- i_{abc}^U Upper arm currents
- i_{abc}^L Lower arm currents

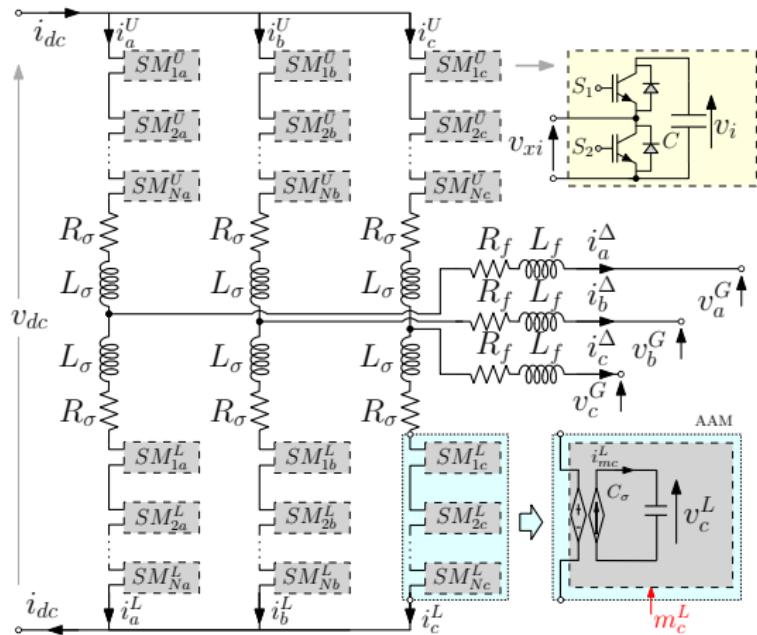
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- i_{abc}^U Upper arm currents
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- v_{abc}^U Upper arm voltage
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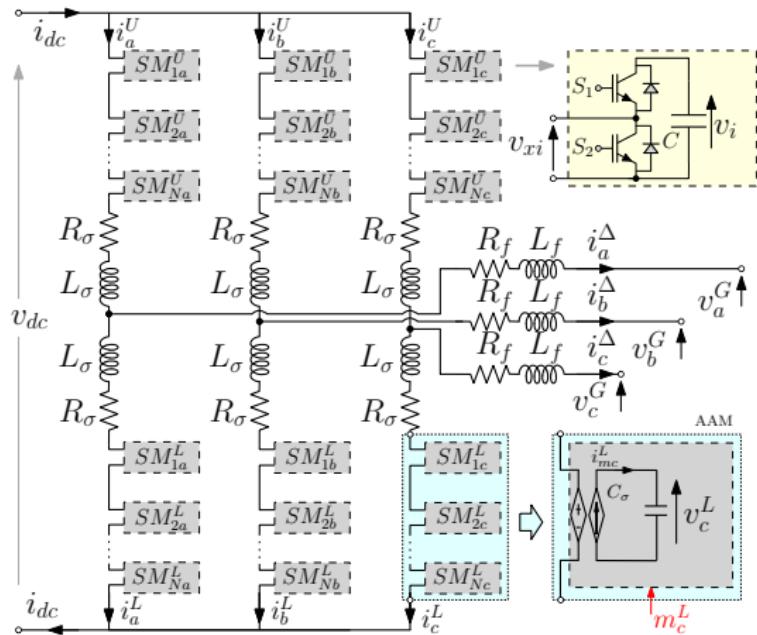
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— Variables in $U-L$ coordinates.

| | |
|-------------|--------------------------|
| i_{abc}^U | Upper arm currents |
| i_{abc}^L | Lower arm currents |
| v_{abc}^U | Upper arm voltage |
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| m_{abc}^U | Upper modulation indices |
| m_{abc}^L | Lower modulation indices |

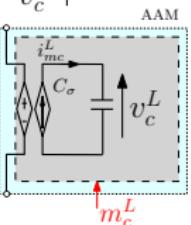
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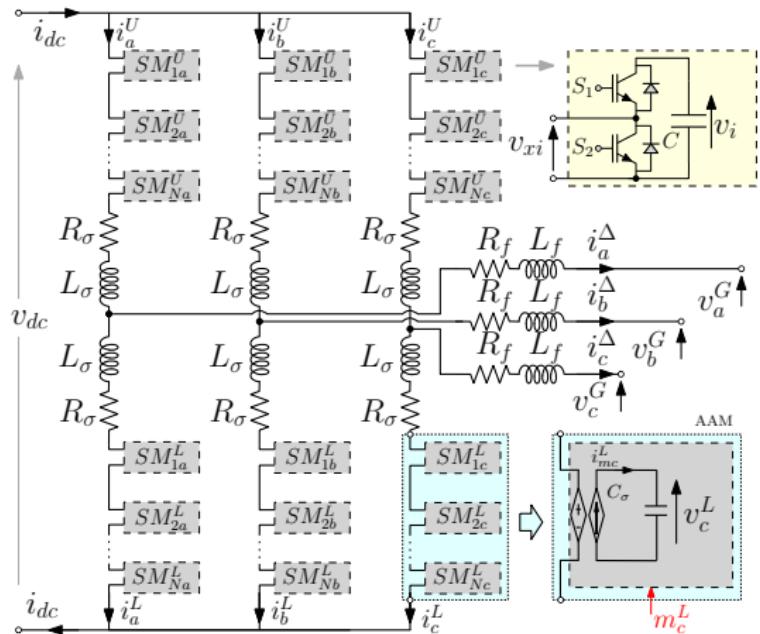
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— Variables in Σ - Δ coordinates.



The Modular Multilevel Converter



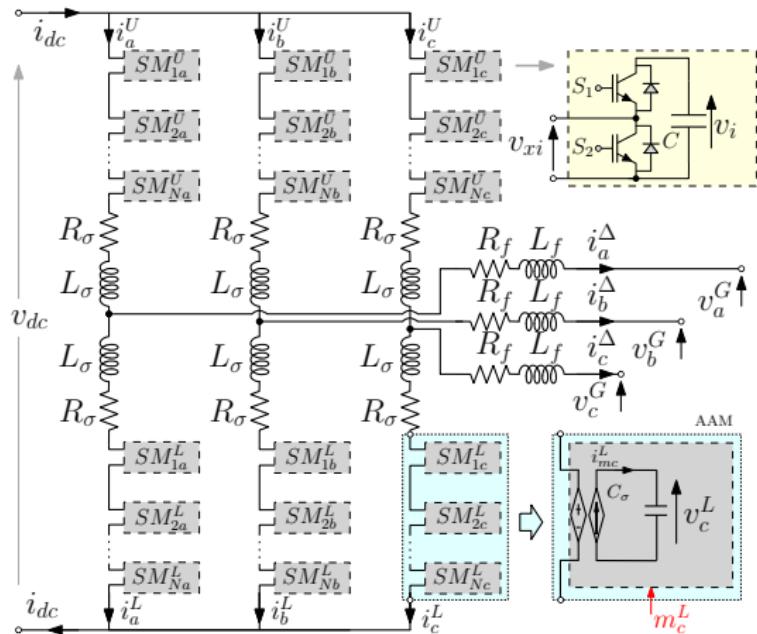
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— Variables in $\Sigma-\Delta$ coordinates.

| | |
|------------------|----------------------|
| i_{abc}^Σ | Circulating currents |
| i_{abc}^Δ | Grid currents |

The Modular Multilevel Converter



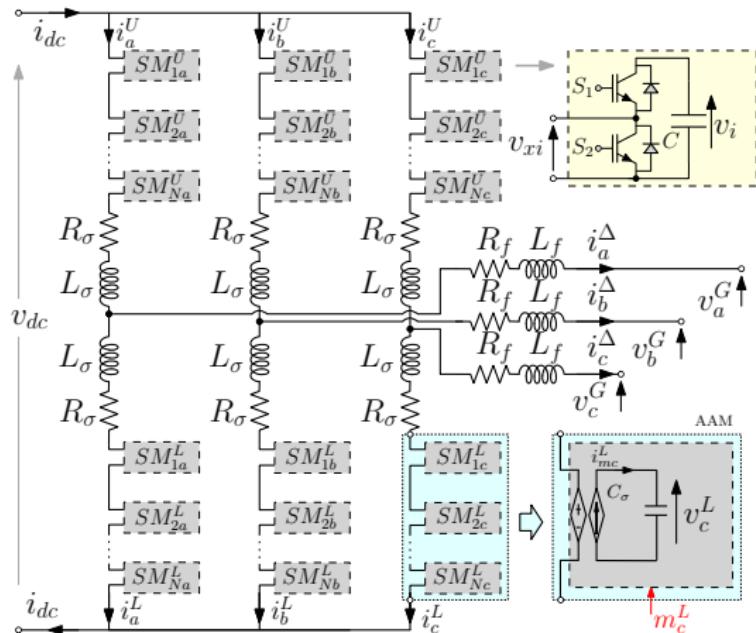
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The Modular Multilevel Converter



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Why the Σ - Δ variable change?



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- Variables in upper-lower ($U-L$) coordinates can oscillate up to **4** main frequencies in steady-state: dc , ω , -2ω and 3ω .

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- In $\Sigma\text{-}\Delta$ coordinates, **2 frequency groups** are naturally formed:

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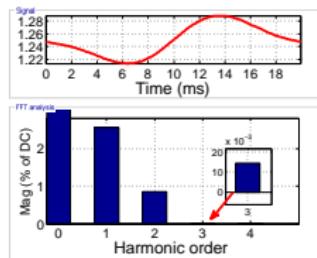
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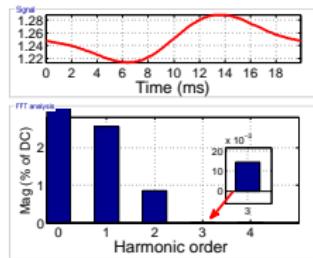
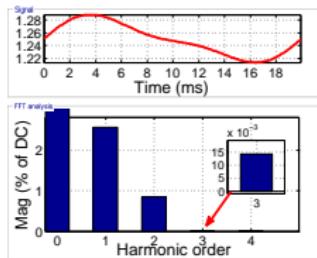
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Upper Arm Voltage v^U

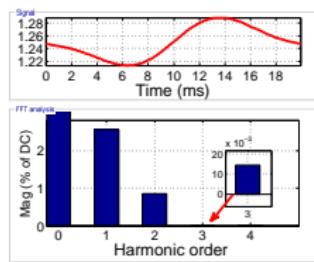
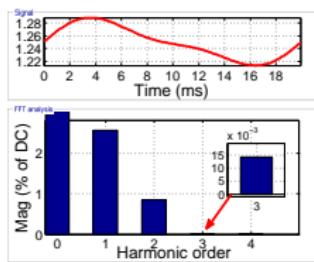
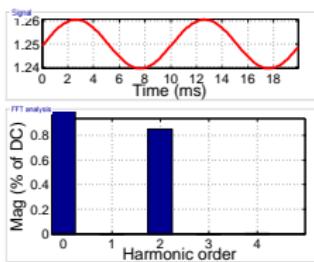
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Upper Arm Voltage v^U Lower Arm Voltage v^L

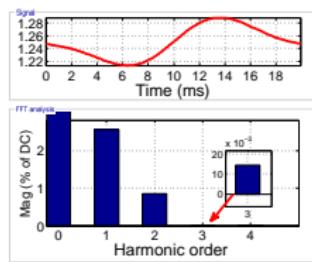
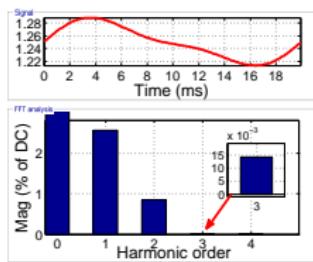
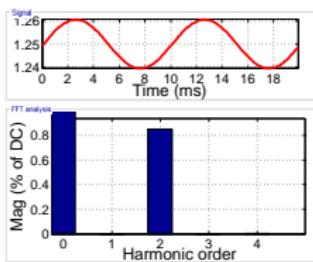
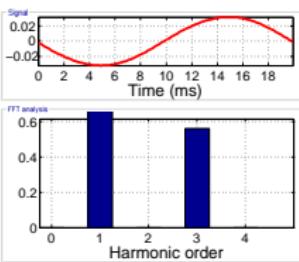
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Upper Arm Voltage v^U Lower Arm Voltage v^L Arm Voltage Sum v^Σ

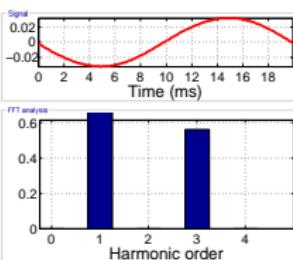
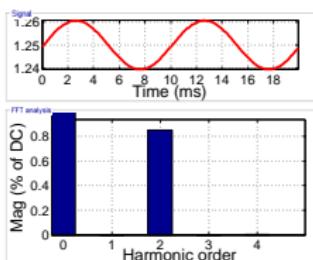
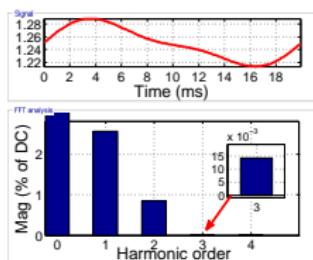
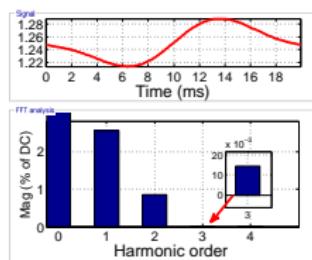
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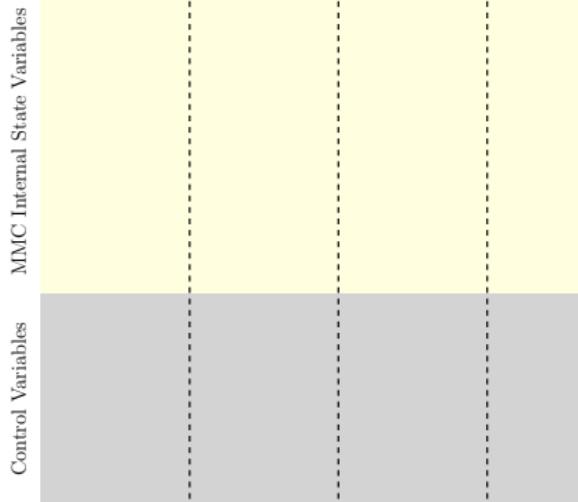
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- Moreover, **one out of the two** main frequencies of each group can be captured by the zero-sequence component of a Park transformation.

Multi-frequency Park transforms + virtual system

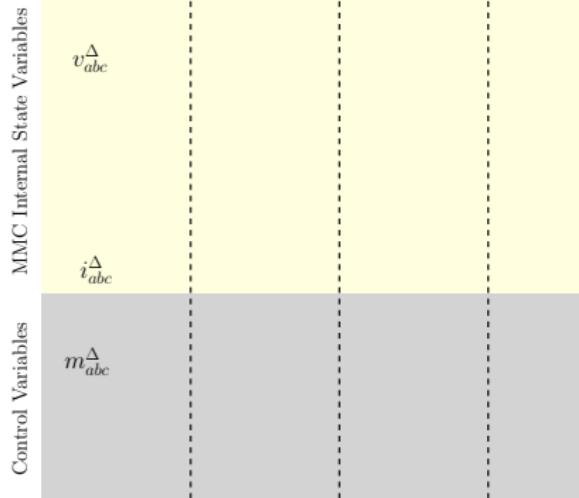
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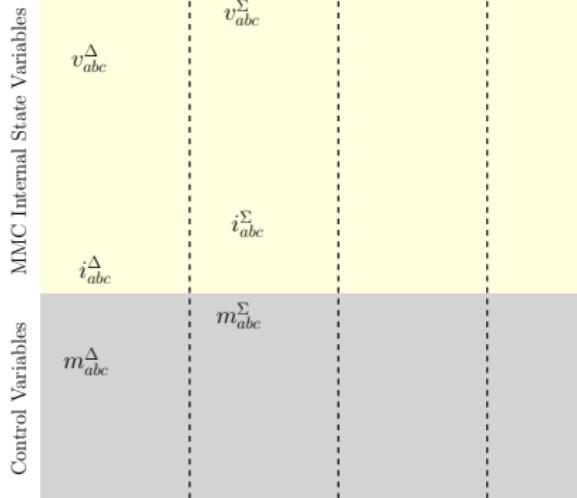
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Multi-frequency Park transforms + virtual system

MMC Internal State Variables

| | $\omega, 3\omega$ | $-2\omega, dc$ | 3ω | dc |
|------------------|-------------------|------------------|------------------|------|
| v_{abc}^Δ | | v_{abc}^Σ | | |
| i_{abc}^Δ | | | i_{abc}^Σ | |
| m_{abc}^Δ | | m_{abc}^Σ | | |

$$C_\sigma \frac{d}{dt} v_{abc}^\Sigma = \hat{x}_{Mabc}^\Sigma(m, i);$$

$$C_\sigma \frac{d}{dt} v_{abc}^\Delta = \hat{x}_{Mabc}^\Delta(m, i);$$

$$L_\sigma \frac{d}{dt} i_{abc}^\Sigma = -R_\sigma i_{abc}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{V}_{Mabc}^\Sigma(m, v);$$

$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{V}_{Mabc}^\Delta(m, v) - v_{Gabc}^\Delta;$$

Multi-frequency Park transforms + virtual system

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|------------------|-------------------|------------------|------------------|------|
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| i_{abc}^Δ | | | i_{abc}^Σ | |
| m_{abc}^Δ | | m_{abc}^Σ | | |

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$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{\mathcal{V}}_{Mabc}^\Delta(m, v) - v_{Gabc}^\Delta;$$

$$\hat{\mathcal{X}}_{Mabc}^\Sigma(m, i) \triangleq m_{abc}^\Sigma \circ i_{abc}^\Sigma + \frac{1}{2} m_{abc}^\Delta \circ i_{abc}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables

| | $\omega, 3\omega$ | $-2\omega, dc$ | 3ω | dc |
|------------------|-------------------|------------------|------------------|------|
| v_{abc}^Δ | | v_{abc}^Σ | | |
| i_{abc}^Δ | | | i_{abc}^Σ | |
| m_{abc}^Δ | | m_{abc}^Σ | | |

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$$L_\sigma \frac{d}{dt} i_{abc}^\Sigma = -R_\sigma i_{abc}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{v}_{Mabc}^\Sigma(m, v);$$

$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{v}_{Mabc}^\Delta(m, v) - v_{Gabc}^\Delta;$$

$$\hat{v}_{Mabc}^\Delta(m, v) \triangleq - \frac{(m_{abc}^\Sigma \circ v_{abc}^\Delta + m_{abc}^\Delta \circ v_{Cabc}^\Sigma)}{4}$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables

| | $\omega, 3\omega$ | $-2\omega, dc$ | 3ω | dc |
|------------------|-------------------|------------------|------------------|------|
| v_{abc}^Δ | | v_{abc}^Σ | | |
| i_{abc}^Δ | | | i_{abc}^Σ | |
| m_{abc}^Δ | | m_{abc}^Σ | | |

$$C_\sigma \frac{d}{dt} v_{abc}^\Sigma = \hat{x}_{Mabc}^\Sigma(m, i);$$

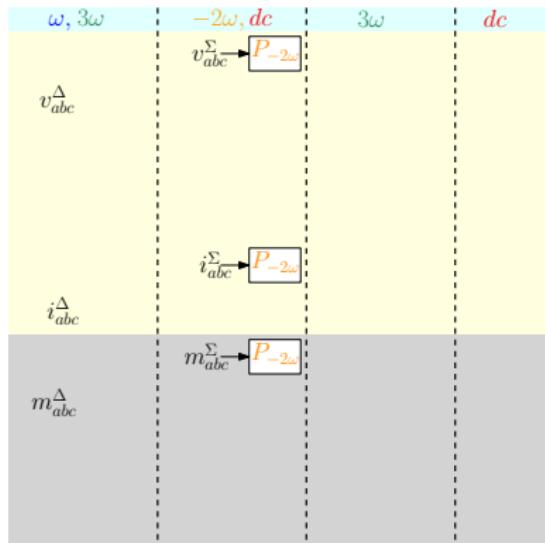
$$C_\sigma \frac{d}{dt} v_{abc}^\Delta = \hat{x}_{Mabc}^\Delta(m, i);$$

$$L_\sigma \frac{d}{dt} i_{abc}^\Sigma = -R_\sigma i_{abc}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{V}_{Mabc}^\Sigma(m, v);$$

$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{V}_{Mabc}^\Delta(m, v) - v_{Gabc}^\Delta;$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{abc}^\Sigma = \hat{x}_{Mabc}^\Sigma(m, i);$$

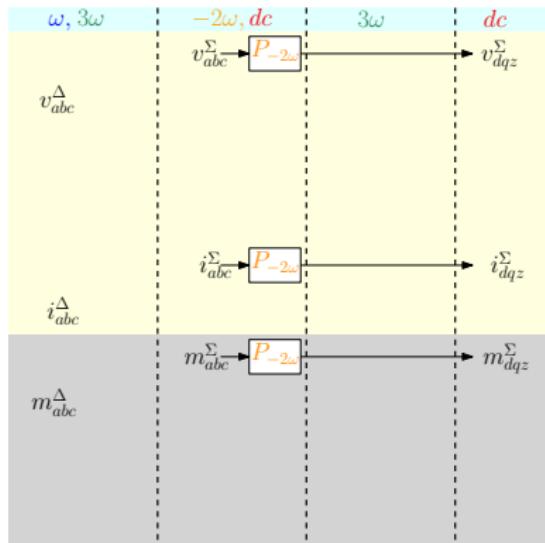
$$C_\sigma \frac{d}{dt} v_{abc}^\Delta = \hat{x}_{Mabc}^\Delta(m, i);$$

$$L_\sigma \frac{d}{dt} i_{abc}^\Sigma = -R_\sigma i_{abc}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{V}_{Mabc}^\Sigma(m, v);$$

$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{V}_{Mabc}^\Delta(m, v) - v_{Gabc}^\Delta;$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} \left[P_{-2\omega}^{-1} v_{dqz}^\Sigma \right] = \hat{x}_{Mabc}^\Sigma;$$

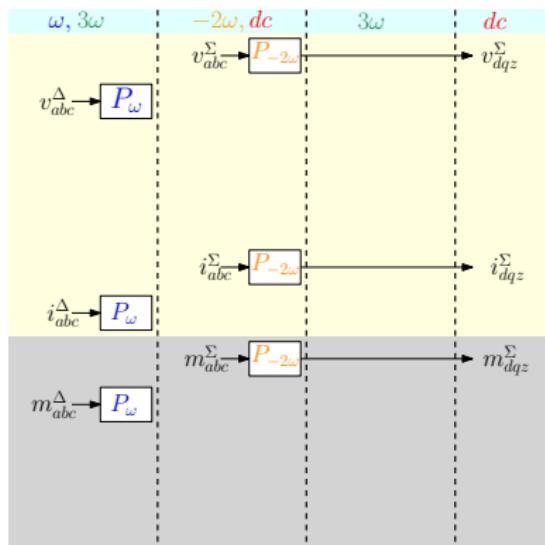
$$C_\sigma \frac{d}{dt} v_{abc}^\Delta = \hat{x}_{Mabc}^\Delta;$$

$$L_\sigma \frac{d}{dt} \left[P_{-2\omega}^{-1} i_{dqz}^\Sigma \right] = -R_\sigma P_{-2\omega}^{-1} i_{dqz}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{V}_{Mabc}^\Sigma;$$

$$L_\delta \frac{d}{dt} i_{abc}^\Delta = -R_\delta i_{abc}^\Delta + \hat{V}_{Mabc}^\Delta - v_{Gabc}^\Delta;$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_{\sigma} \frac{d}{dt} \left[\textcolor{orange}{P_{-2\omega}^{-1}} v_{dqz}^{\Sigma} \right] = \hat{x}_{Mabc}^{\Sigma};$$

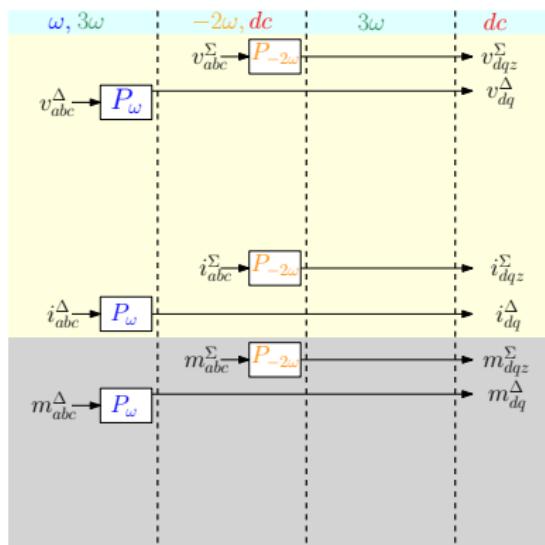
$$C_{\sigma} \frac{d}{dt} v_{abc}^{\Delta} = \hat{x}_{Mabc}^{\Delta};$$

$$L_{\sigma} \frac{d}{dt} \left[\textcolor{orange}{P_{-2\omega}^{-1}} i_{dqz}^{\Sigma} \right] = -R_{\sigma} \textcolor{orange}{P_{-2\omega}^{-1}} i_{dqz}^{\Sigma} + 1_3 \frac{v_{dc}}{2} - \hat{V}_{Mabc}^{\Sigma};$$

$$L_{\delta} \frac{d}{dt} i_{abc}^{\Delta} = -R_{\delta} i_{abc}^{\Delta} + \hat{V}_{Mabc}^{\Delta} - v_{Gabc}^{\Delta};$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables

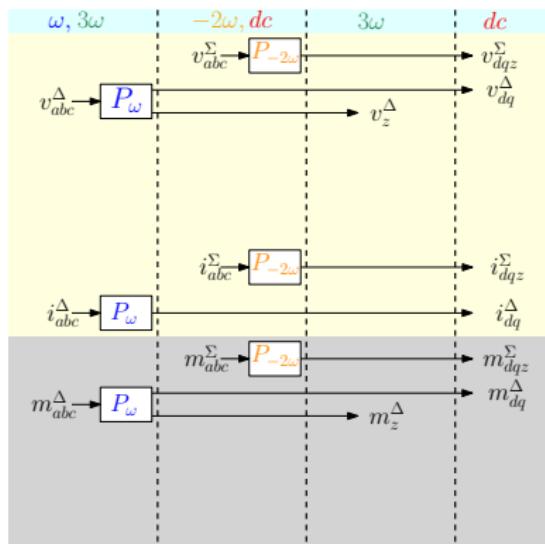


Control Variables

$$\begin{aligned} C_\sigma \frac{d}{dt} \left[\mathcal{P}_{-2\omega}^{-1} v_{dqz}^\Sigma \right] &= \hat{\mathcal{X}}_{Mabc}^\Sigma; \\ C_\sigma \frac{d}{dt} \left[\mathcal{P}_\omega^{-1} v_{dqz}^\Delta \right] &= \hat{\mathcal{X}}_{Mabc}^\Delta; \\ L_\sigma \frac{d}{dt} \left[\mathcal{P}_{-2\omega}^{-1} i_{dqz}^\Sigma \right] &= -R_\sigma \mathcal{P}_{-2\omega}^{-1} i_{dqz}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{\mathcal{V}}_{Mabc}^\Sigma; \\ L_\delta \frac{d}{dt} \left[\mathcal{P}_\omega^{-1} i_{dqz}^\Delta \right] &= -R_\delta \mathcal{P}_\omega^{-1} i_{dqz}^\Delta + \hat{\mathcal{V}}_{Mabc}^\Delta - \mathcal{P}_\omega^{-1} v_{Gdqz}^\Delta; \end{aligned}$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} \left[\mathbf{P}_{-2\omega}^{-1} v_{dqz}^\Sigma \right] = \hat{\mathbf{x}}_{Mabc}^\Sigma;$$

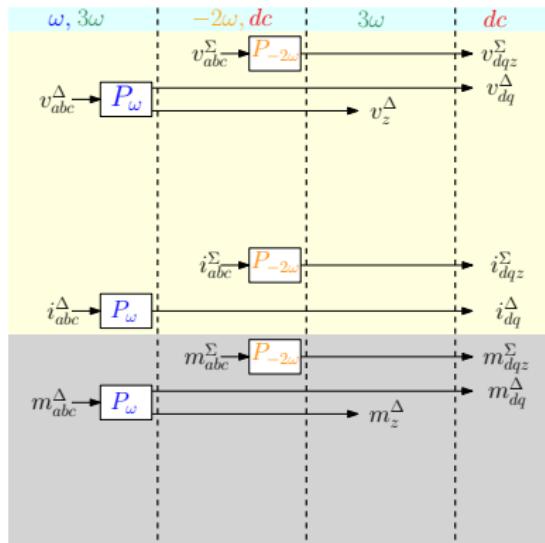
$$C_\sigma \frac{d}{dt} \left[\mathbf{P}_\omega^{-1} v_{dqz}^\Delta \right] = \hat{\mathbf{x}}_{Mabc}^\Delta;$$

$$L_\sigma \frac{d}{dt} \left[\mathbf{P}_{-2\omega}^{-1} i_{dqz}^\Sigma \right] = -R_\sigma \mathbf{P}_{-2\omega}^{-1} i_{dqz}^\Sigma + 1_3 \frac{v_{dc}}{2} - \hat{\mathbf{V}}_{Mabc}^\Sigma;$$

$$L_\delta \frac{d}{dt} \left[\mathbf{P}_\omega^{-1} i_{dqz}^\Delta \right] = -R_\delta \mathbf{P}_\omega^{-1} i_{dqz}^\Delta + \hat{\mathbf{V}}_{Mabc}^\Delta - \mathbf{P}_\omega^{-1} v_{Gdqz}^\Delta;$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\mathcal{X}}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\mathcal{X}}_{M dq}^\Delta$$

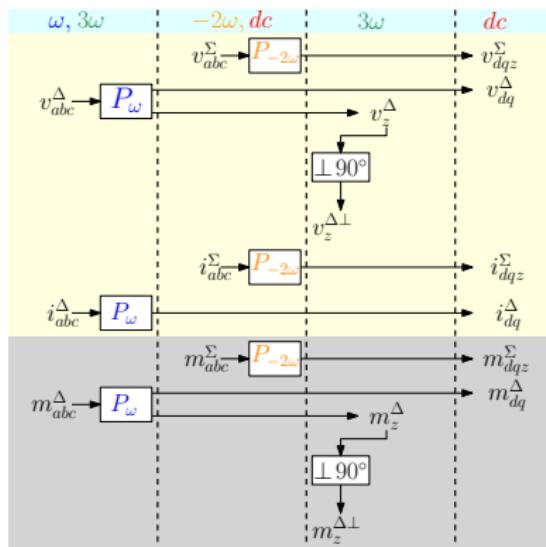
$$C_\sigma \frac{d}{dt} v_z^\Delta = \hat{\mathcal{X}}_{M z D}^\Delta \cos(3\omega) + \hat{\mathcal{X}}_{M z Q}^\Delta \sin(3\omega)$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta$$

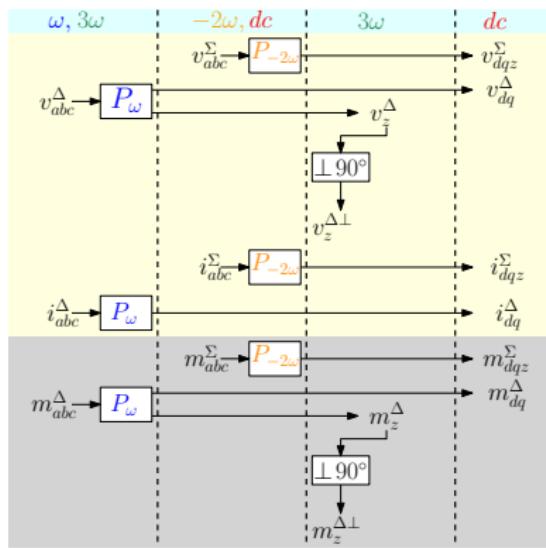
$$C_\sigma \frac{d}{dt} v_z^\Delta = \hat{\tau}_{M z D}^\Delta \cos(3\omega) + \hat{\tau}_{M z Q}^\Delta \sin(3\omega)$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables

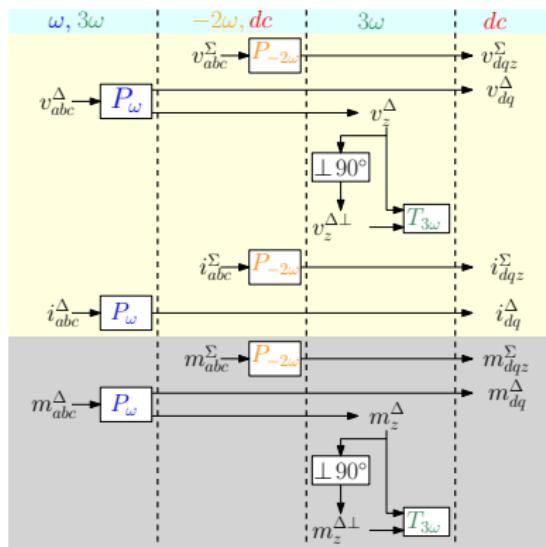


Control Variables

$$\begin{aligned}
 C_\sigma \frac{d}{dt} v_{dqz}^\Sigma &= \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{x}_{M dqz}^\Sigma \\
 C_\sigma \frac{d}{dt} v_{dq}^\Delta &= \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{x}_{M dq}^\Delta \\
 C_\sigma \frac{d}{dt} v_{z \alpha}^\Delta &= \hat{x}_{M z D}^\Delta \cos(3\omega) + \hat{x}_{M z Q}^\Delta \sin(3\omega) \\
 C_\sigma \frac{d}{dt} v_{z \beta}^\Delta &= \hat{x}_{M z D}^\Delta \sin(3\omega) - \hat{x}_{M z Q}^\Delta \cos(3\omega) \\
 L_\sigma \frac{d}{dt} i_{dqz}^\Sigma &= (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{v}_{M dqz}^\Sigma \\
 L_\delta \frac{d}{dt} i_{dq}^\Delta &= (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{v}_{M dq}^\Delta - v_{G dq}^\Delta
 \end{aligned}$$

Multi-frequency Park transforms + virtual system

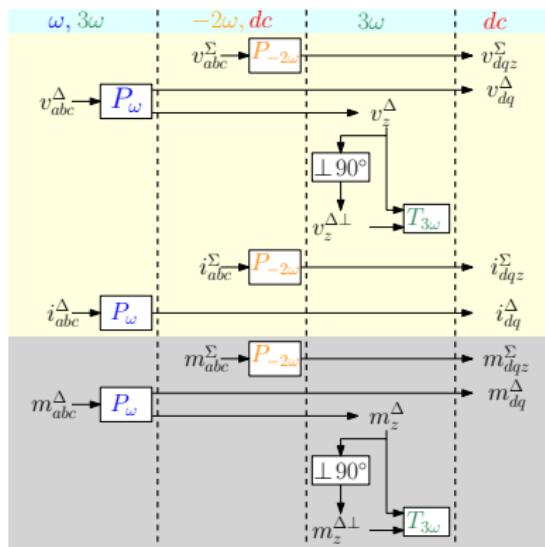
MMC Internal State Variables



$$\begin{aligned}
 C_\sigma \frac{d}{dt} v_{dqz}^\Sigma &= \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma \\
 C_\sigma \frac{d}{dt} v_{dq}^\Delta &= \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta \\
 C_\sigma \frac{d}{dt} v_{z\alpha}^\Delta &= \hat{\tau}_{M z D}^\Delta \cos(3\omega) + \hat{\tau}_{M z Q}^\Delta \sin(3\omega) \\
 C_\sigma \frac{d}{dt} v_{z\beta}^\Delta &= \hat{\tau}_{M z D}^\Delta \sin(3\omega) - \hat{\tau}_{M z Q}^\Delta \cos(3\omega) \\
 L_\sigma \frac{d}{dt} i_{dqz}^\Sigma &= (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{v}_{M dqz}^\Sigma \\
 L_\delta \frac{d}{dt} i_{dq}^\Delta &= (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{v}_{M dq}^\Delta - v_{G dq}^\Delta
 \end{aligned}$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\mathcal{T}}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dqz}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dqz}^\Delta + \hat{\mathcal{T}}_{M dqz}^\Delta$$

$$C_\sigma \frac{d}{dt} v_{z \alpha \beta}^\Delta = \mathcal{T}_{3\omega}^{-1} \hat{\mathcal{T}}_{M z DQ}^\Delta$$

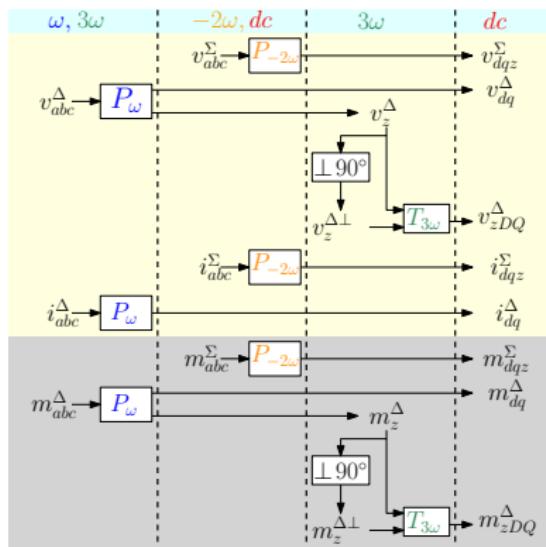
$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dqz}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dqz}^\Delta + \hat{\mathbf{v}}_{M dqz}^\Delta - v_{G dqz}^\Delta$$

G. Bergna-Diaz, J. Freytes, X. Guillaud, S. D'Arco, J.A. Suul, "Generalized Voltage-based State-Space Modelling of MMCs with Constant Equilibrium in Steady-State," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. 99, pp. 1-1

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\mathcal{T}}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\mathcal{T}}_{M dq}^\Delta$$

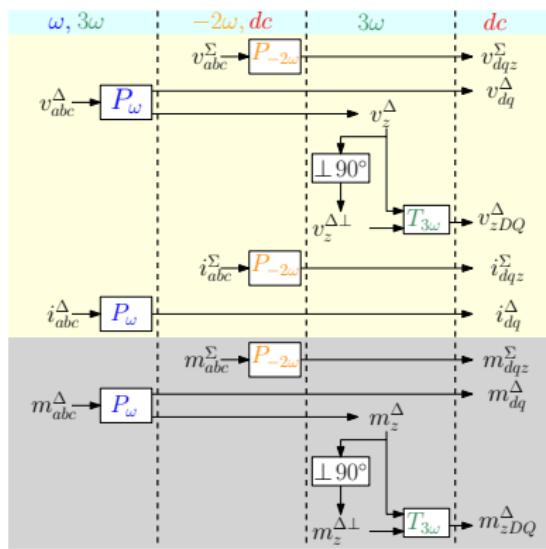
$$C_\sigma \frac{d}{dt} v_{z \alpha \beta}^\Delta = \mathcal{T}_{3\omega}^{-1} \hat{\mathcal{T}}_{M z DQ}^\Delta$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta$$

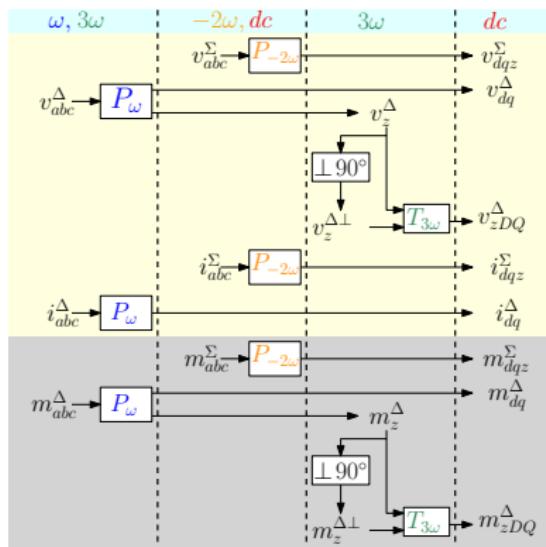
$$C_\sigma \frac{d}{dt} [T_{3\omega}^{-1} v_{zDQ}^\Delta] = T_{3\omega}^{-1} \hat{\tau}_{M zDQ}^\Delta$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta$$

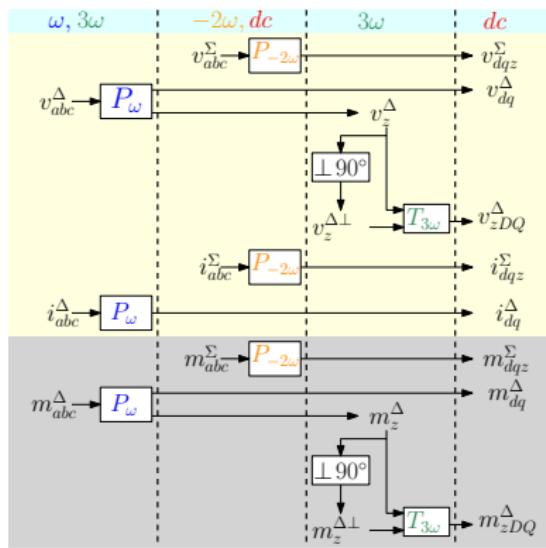
$$C_\sigma \frac{d}{dt} v_{zDQ}^\Delta = \mathbb{J}_2 C_\sigma 3\omega v_{zDQ}^\Delta + \hat{\tau}_{M zDQ}^\Delta$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta$$

$$C_\sigma \frac{d}{dt} v_{zDQ}^\Delta = \mathbb{J}_2 C_\sigma 3\omega v_{zDQ}^\Delta + \hat{\tau}_{M zDQ}^\Delta$$

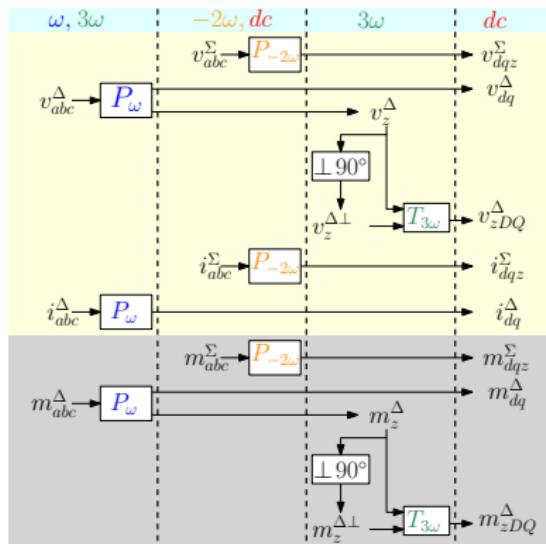
$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

— Generalized Nonlinear Time-Invariant Model

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



$$C_\sigma \frac{d}{dt} v_{dqz}^\Sigma = \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma$$

$$C_\sigma \frac{d}{dt} v_{dq}^\Delta = \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta$$

$$C_\sigma \frac{d}{dt} v_{zDQ}^\Delta = \mathbb{J}_2 C_\sigma 3\omega v_{zDQ}^\Delta + \hat{\tau}_{M zDQ}^\Delta$$

$$L_\sigma \frac{d}{dt} i_{dqz}^\Sigma = (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma$$

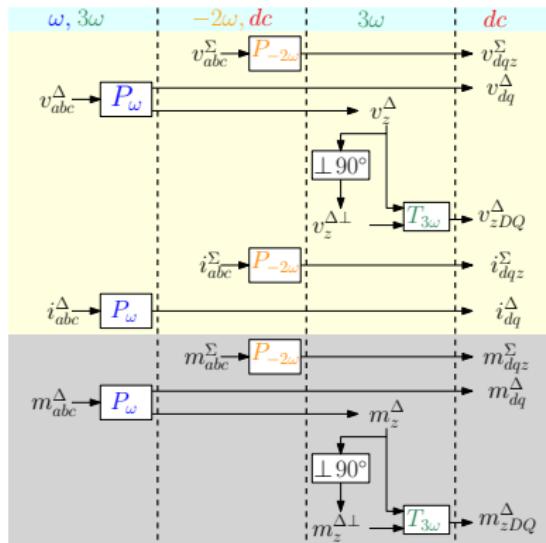
$$L_\delta \frac{d}{dt} i_{dq}^\Delta = (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta$$

— Generalized Nonlinear Time-Invariant Model

- Independent of the control signal & modulation

Multi-frequency Park transforms + virtual system

MMC Internal State Variables



Control Variables

$$\begin{aligned}
 C_\sigma \frac{d}{dt} v_{dqz}^\Sigma &= \mathbb{J}_3 C_\sigma 2\omega v_{dqz}^\Sigma + \hat{\tau}_{M dqz}^\Sigma \\
 C_\sigma \frac{d}{dt} v_{dq}^\Delta &= \mathbb{J}_2 C_\sigma \omega v_{dq}^\Delta + \hat{\tau}_{M dq}^\Delta \\
 C_\sigma \frac{d}{dt} v_{zDQ}^\Delta &= \mathbb{J}_2 C_\sigma 3\omega v_{zDQ}^\Delta + \hat{\tau}_{M zDQ}^\Delta \\
 L_\sigma \frac{d}{dt} i_{dqz}^\Sigma &= (\mathbb{J}_3 L_\sigma 2\omega - R_\sigma) i_{dqz}^\Sigma + \frac{1}{2} e_3 v_{dc} - \hat{\mathbf{v}}_{M dqz}^\Sigma \\
 L_\delta \frac{d}{dt} i_{dq}^\Delta &= (\mathbb{J}_2 L_\delta \omega - R_\delta) i_{dq}^\Delta + \hat{\mathbf{v}}_{M dq}^\Delta - v_{G dq}^\Delta
 \end{aligned}$$

— Generalized Nonlinear Time-Invariant Model

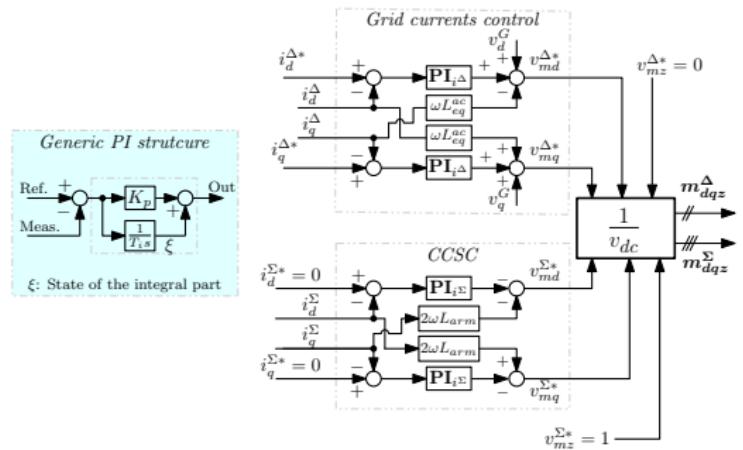
- **Independent** of the control signal & modulation
- Captures all* the nonlinear dynamics

G. Bergna-Diaz, J. Freytes, X. Guillaud, S. D'Arco, J.A. Suul, "Generalized Voltage-based State-Space Modelling of MMCs with Constant Equilibrium in Steady-State," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. 99, pp. 1-1

Model validation under CCSC - (1/3)

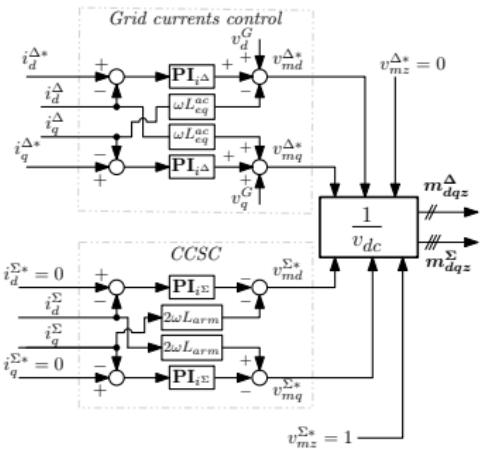
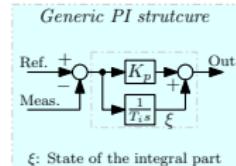
G. Bergna-Diaz, J. Freytes, X. Guillaud, S. D'Arco, J.A. Suul, "Generalized Voltage-based State-Space Modelling of MMCs with Constant Equilibrium in Steady-State," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. 99, pp. 1-1

Model validation under CCSC - (1/3)



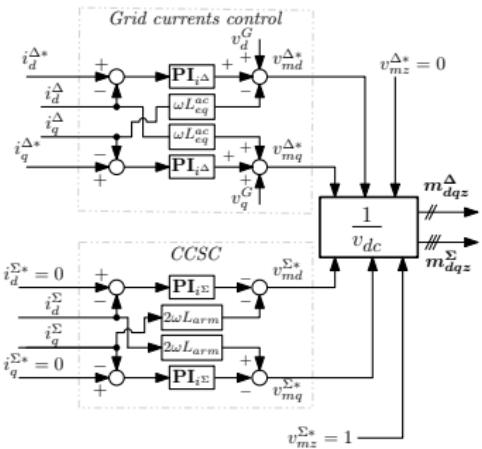
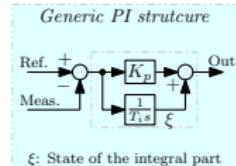
G. Bergna-Diaz, J. Freytes, X. Guillaud, S. D'Arco, J.A. Suul, "Generalized Voltage-based State-Space Modelling of MMCs with Constant Equilibrium in Steady-State," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. 99, pp. 1-1

Model validation under CCSC - (1/3)



On the models used for validation

Model validation under CCSC - (1/3)

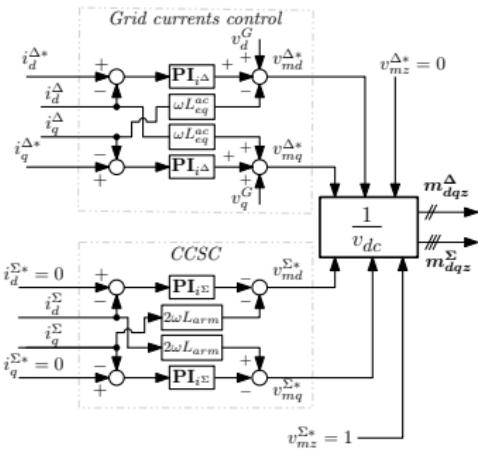
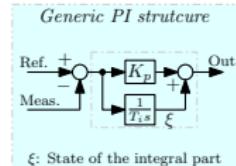


On the models used for validation

— Time-Invariant Model

- Multi-Frequency Park Trans.

Model validation under CCSC - (1/3)



On the models used for validation

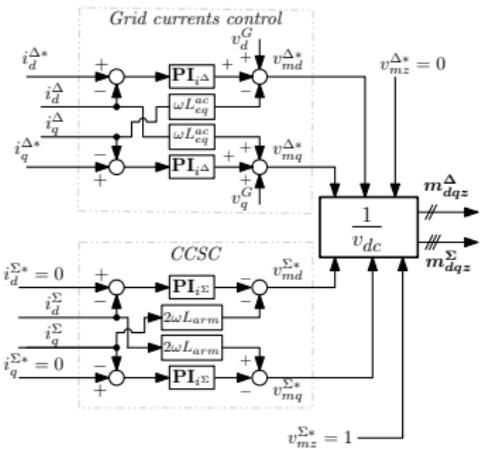
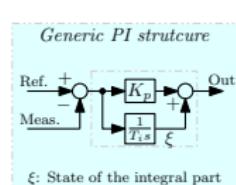
— Time-Invariant Model

- Multi-Frequency Park Trans.

— Average Arm Model

- Parent model - well established

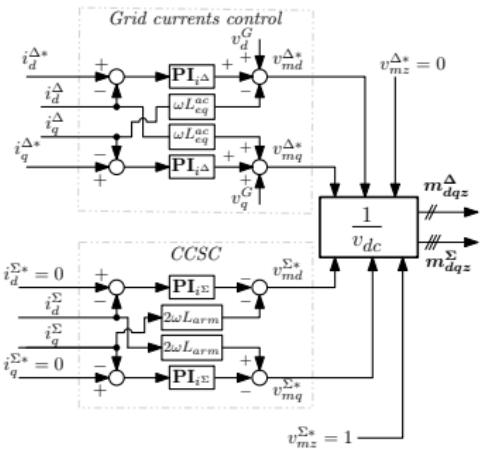
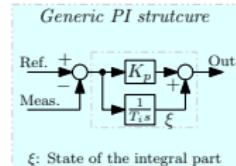
Model validation under CCSC - (1/3)



On the models used for validation

- Time-Invariant Model
 - Multi-Frequency Park Trans.
 - Average Arm Model
 - Parent model - well established
 - 400-level EMT Model
 - Includes switching.

Model validation under CCSC - (1/3)



On the models used for validation

— Time-Invariant Model

- Multi-Frequency Park Trans.

— Average Arm Model

- Parent model - well established

— 400-level EMT Model

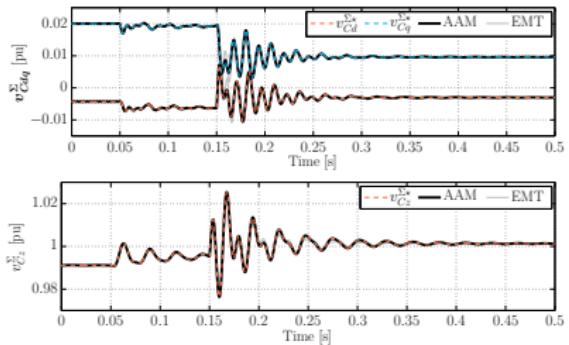
- Includes switching.

| | | | | | |
|--------------|-----------|--------------|----------|---|--------|
| U_{1n} | 320[kV] | R_f | 0.512[Ω] | Resp. time $i^{\Delta} \cdot \tau_i^{\Delta}$ | 10[ms] |
| f_n | 50[Hz] | L_f | 58.7[mH] | Damping $i^{\Delta} \cdot \zeta_i^{\Delta}$ | 0.7[-] |
| N | 400[-] | R_{σ} | 1.024[Ω] | Resp. time $i^{\Sigma} \cdot \tau_i^{\Sigma}$ | 5[ms] |
| C_{σ} | 32.55[μF] | L_{σ} | 48.9[mH] | Damping $i^{\Sigma} \cdot \zeta_i^{\Sigma}$ | 0.7[-] |

G. Bergna-Diaz, J. Freytes, X. Guillaud, S. D'Arco, J.A. Suul, "Generalized Voltage-based State-Space Modelling of MMCs with Constant Equilibrium in Steady-State," in *IEEE Journal of Emerging and Selected Topics in Power Electronics*, vol. PP, no. 99, pp. 1-1

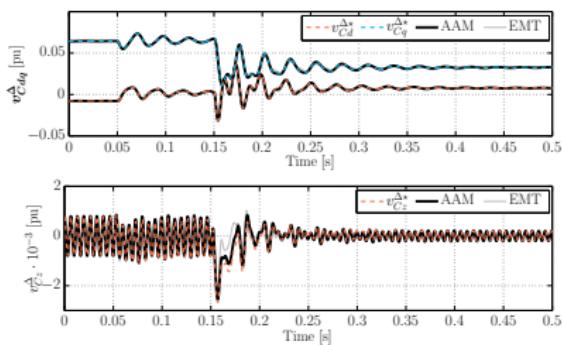
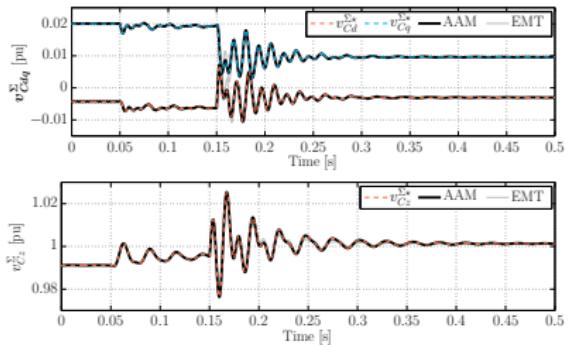
Model validation under CCSC - (2/3)

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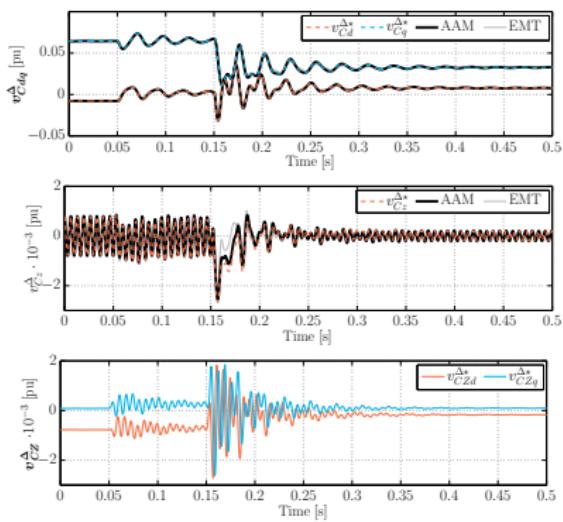
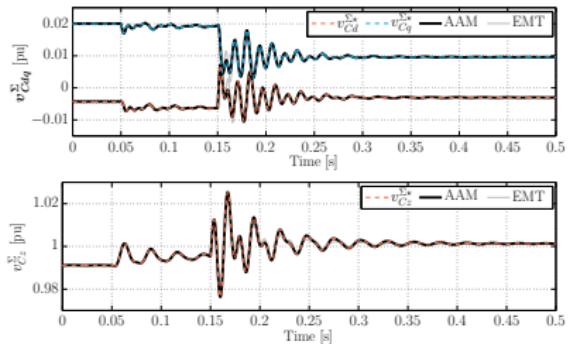


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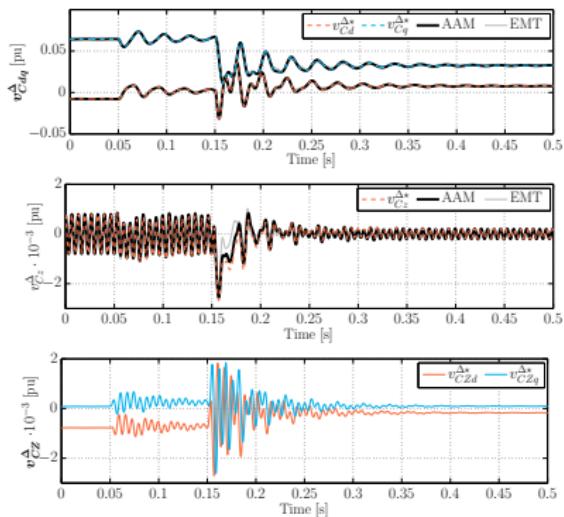
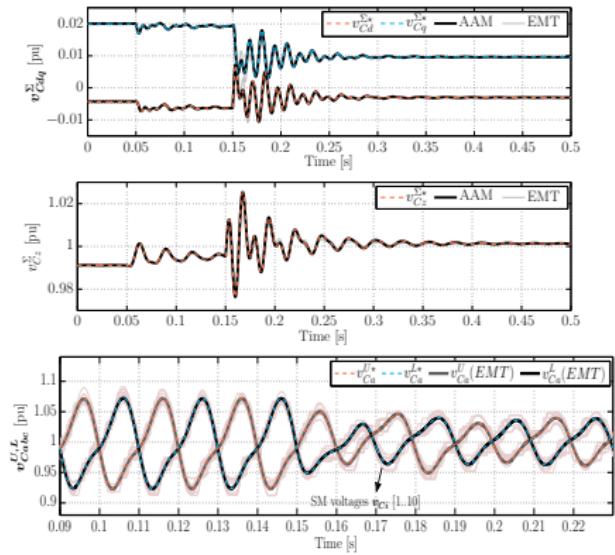
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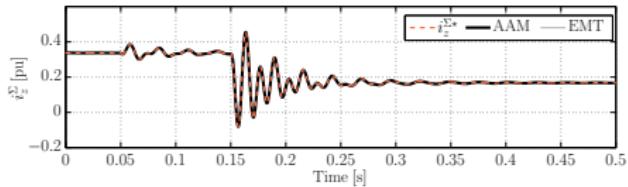
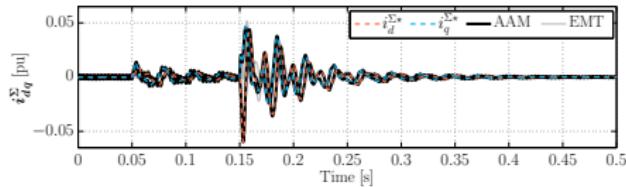
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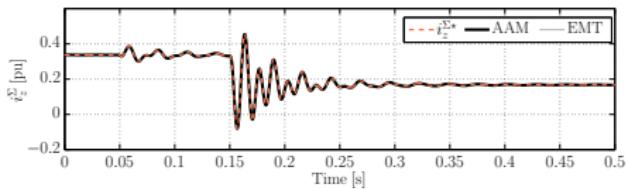
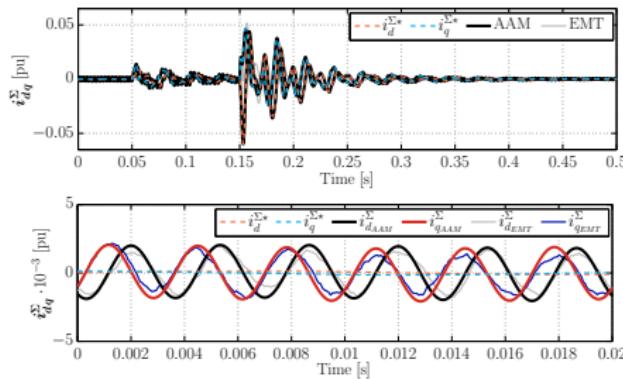
Model validation under CCSC - (3/3)

Model validation under CCSC - (3/3)



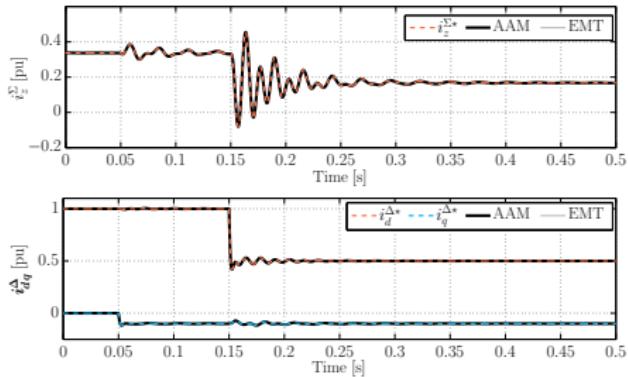
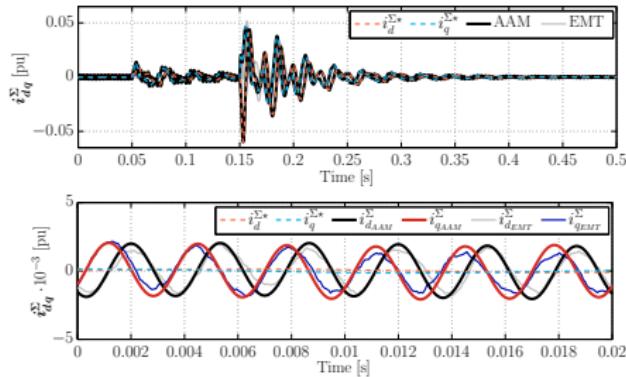
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Table of Contents



Introduction

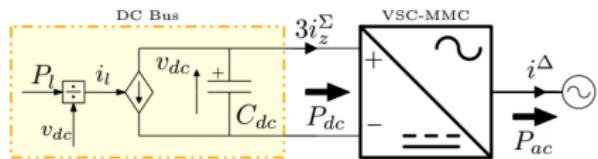
MMC Modelling for Time-Invariance

Energy Control for Stability Improvements

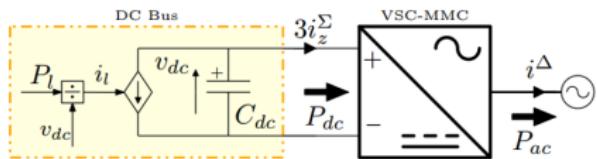
Conclusions

MMC Control for MTDC integration

MMC Control for MTDC integration

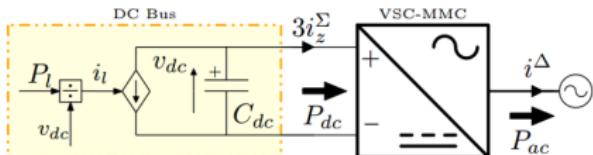


MMC Control for MTDC integration



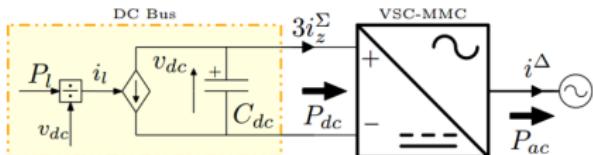
- v_{dc} is now a state-variable
- Constant Power Source/Load

MMC Control for MTDC integration



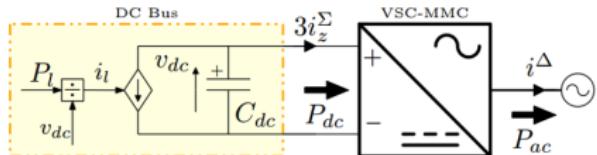
- v_{dc} is now a state-variable
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- Two control strategies are investigated:
 - Circulating Current Suppression Control
 - CCSC + Energy Control

MMC Control for MTDC integration



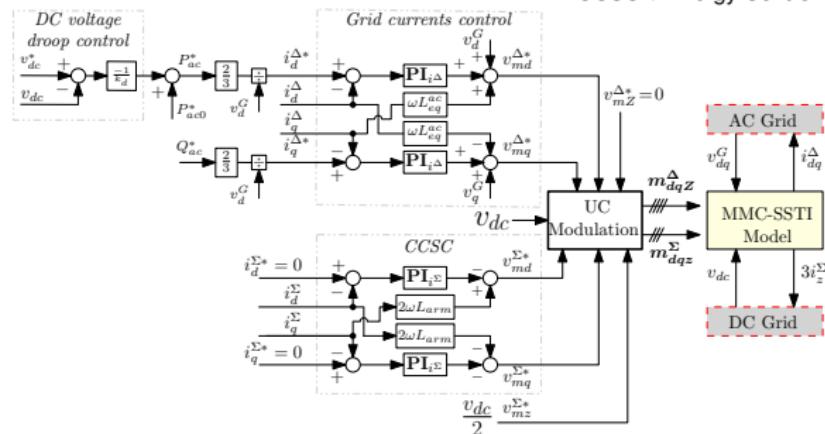
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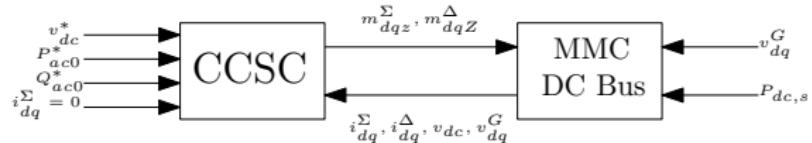
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CCSC for MTDC integration

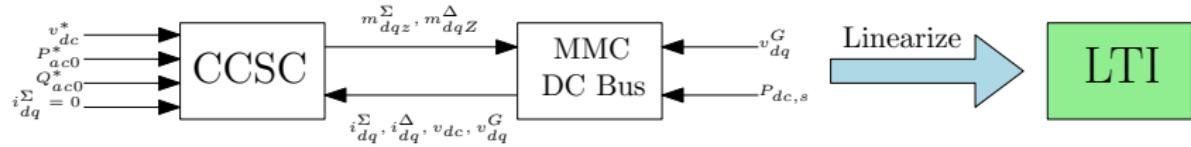
J. Freytes, G. Bergna-Diaz, J. A. Suul, S. D'Arco, F. Gruson, F. Colas, H. Saad, X. Guillaud, "Improving Small-Signal Stability of an MMC With CCSC by Control of the Internally Stored Energy," in *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 429-439, Feb. 2018.

CCSC for MTDC integration



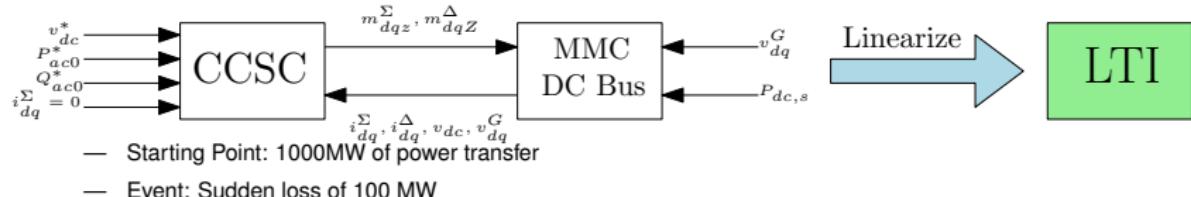
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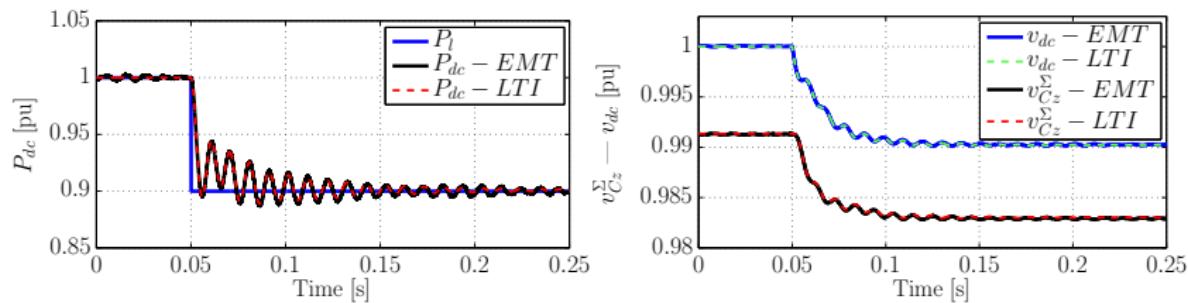
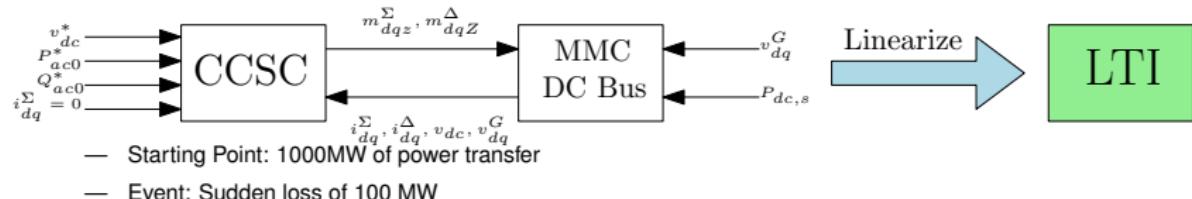
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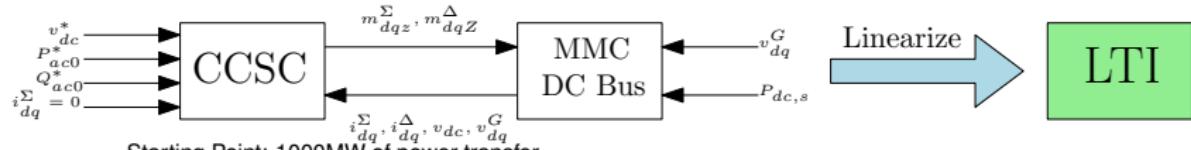
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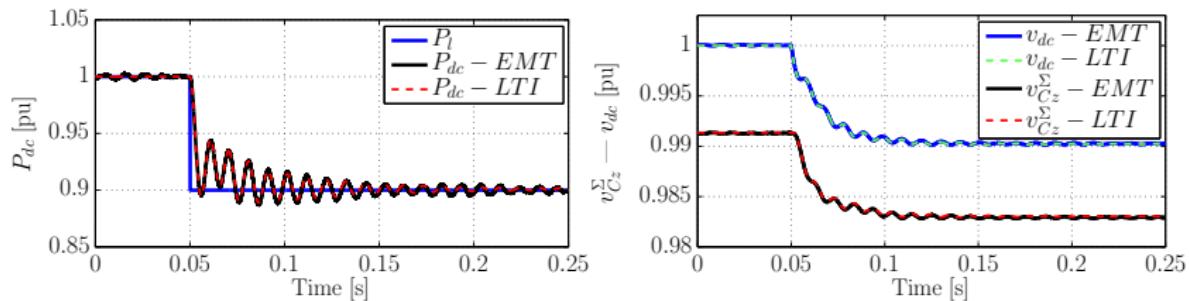


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CCSC for MTDC integration



- Starting Point: 1000MW of power transfer
- Event: Sudden loss of 100 MW



- Oscillations on the DC power and DC voltage
- Reflected on the arm capacitor voltages

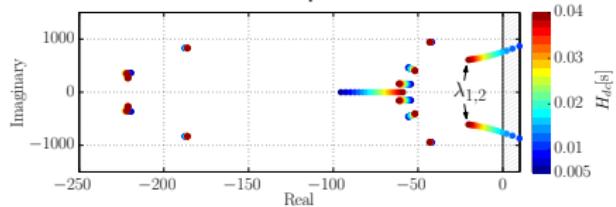
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CCSC for MTDC integration - Small-Signal Analysis

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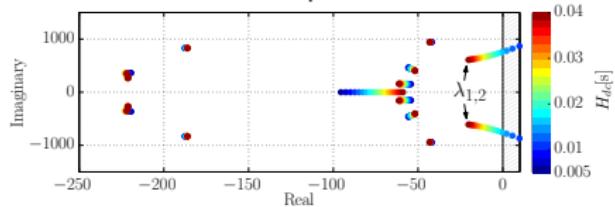
Variation of DC bus capacitance:



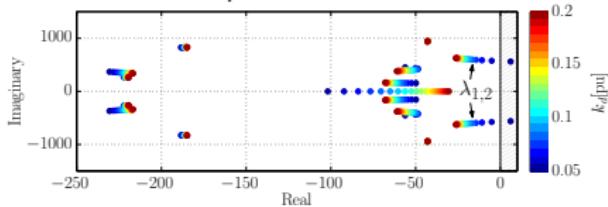
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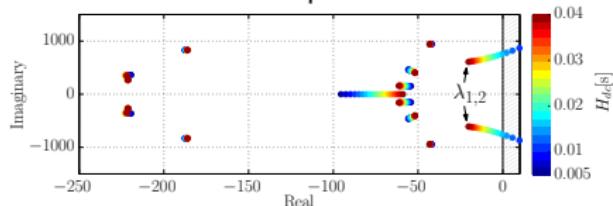
Variation of droop constant:



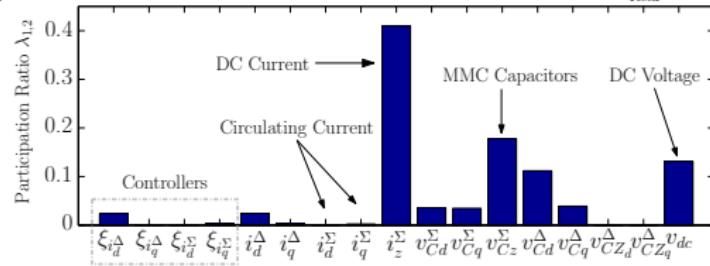
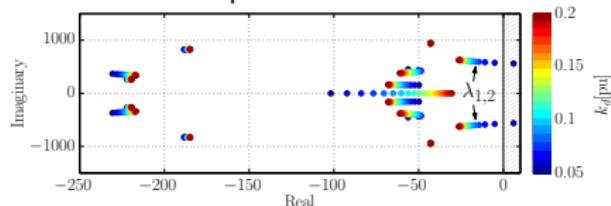
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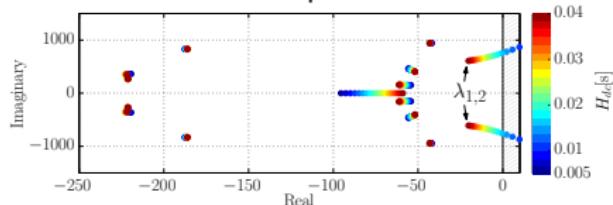
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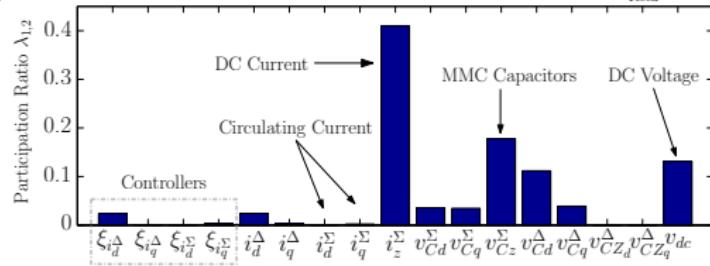
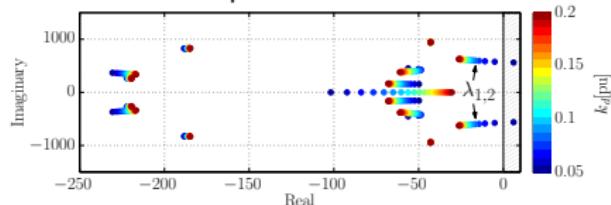
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CCSC for MTDC integration - Small-Signal Analysis

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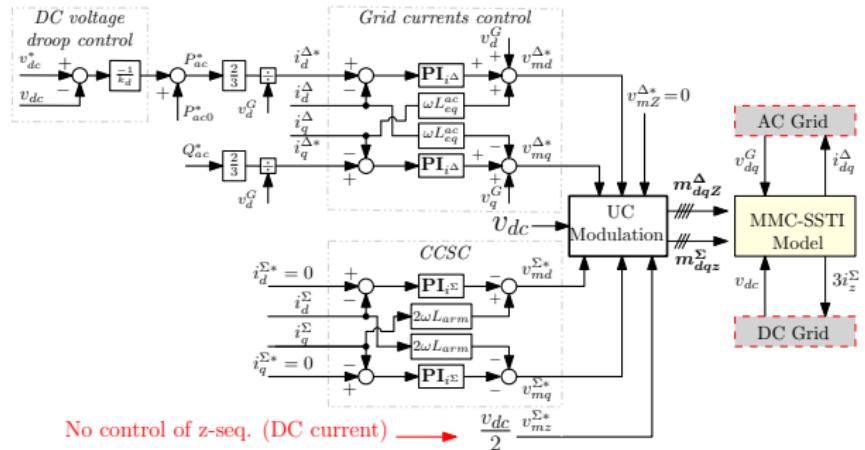
Instabilities are caused by uncontrolled DC current (i_z^Σ)
→ Let's control i_z^Σ !

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Improving the Dynamics with Energy Control

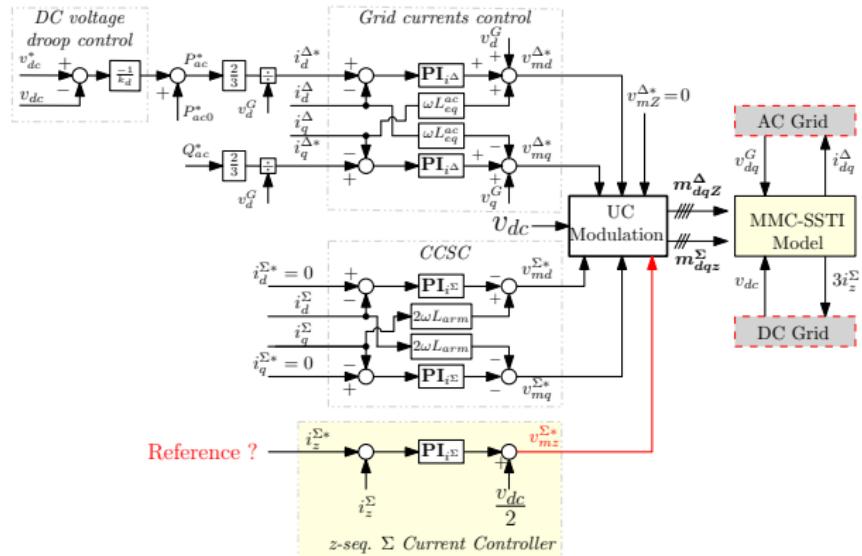
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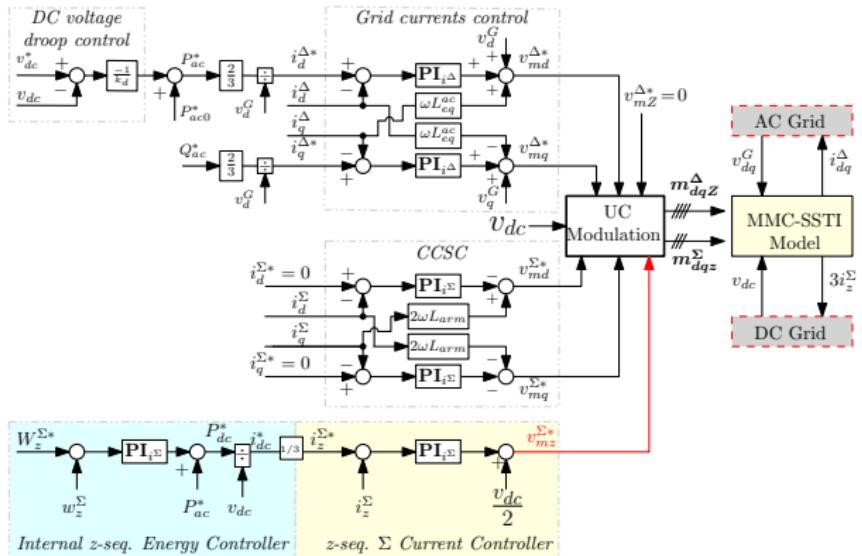
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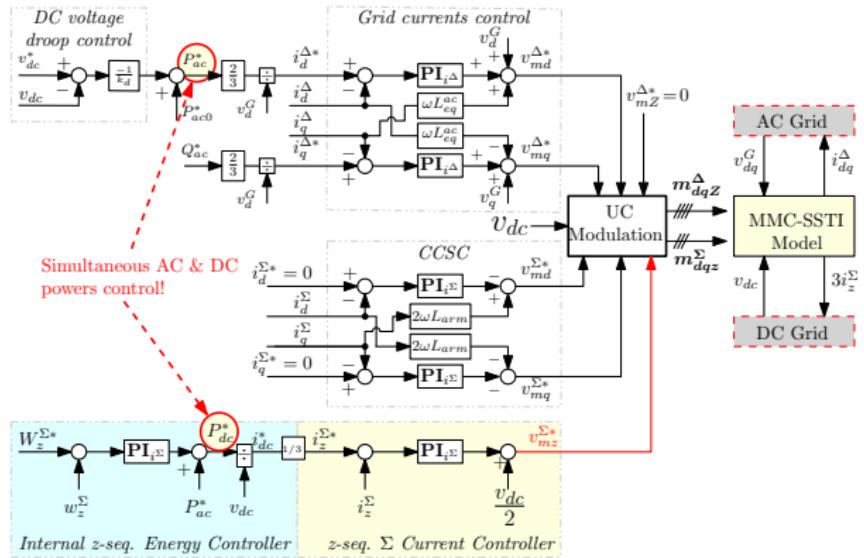
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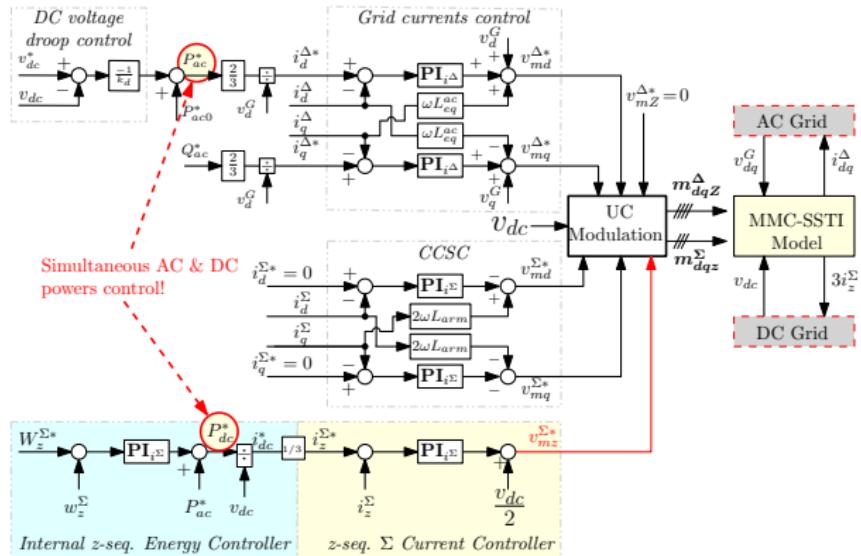
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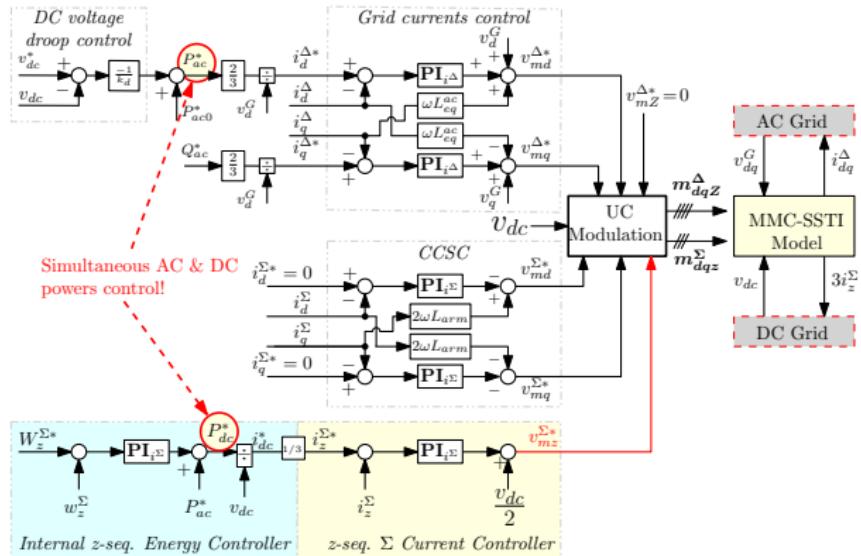
Improving the Dynamics with Energy Control



— All currents are now controlled,

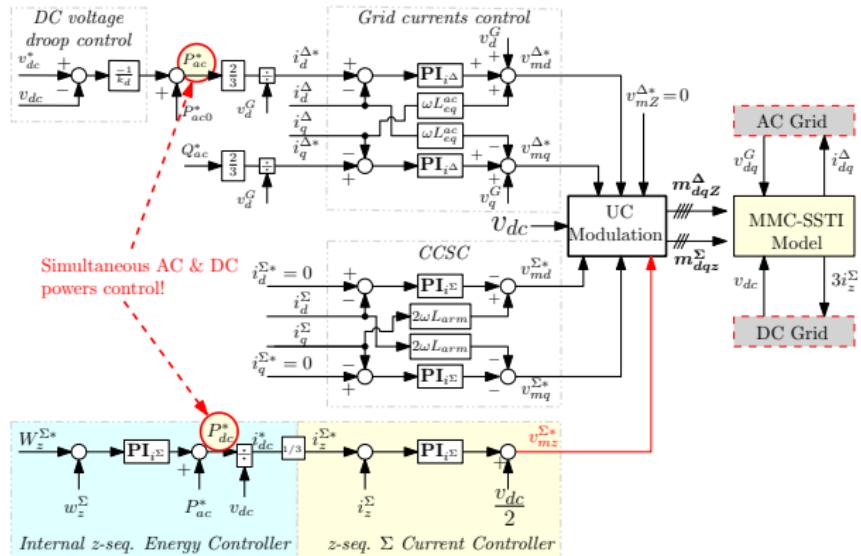
Simultaneous AC & DC powers control!

Improving the Dynamics with Energy Control



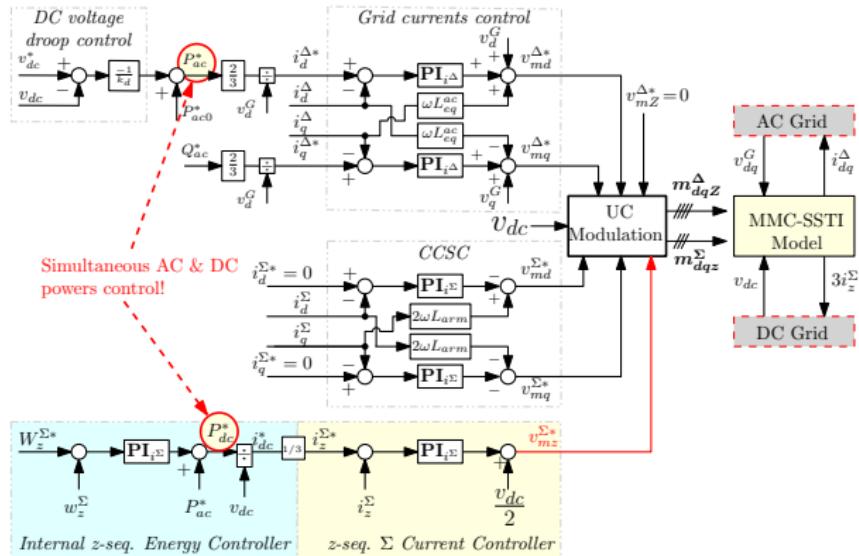
- All currents are now controlled,
- ...stability improvements are expected,

Improving the Dynamics with Energy Control



- All currents are now controlled,
- ...stability improvements are expected,
- Energy control allows this to be possible,

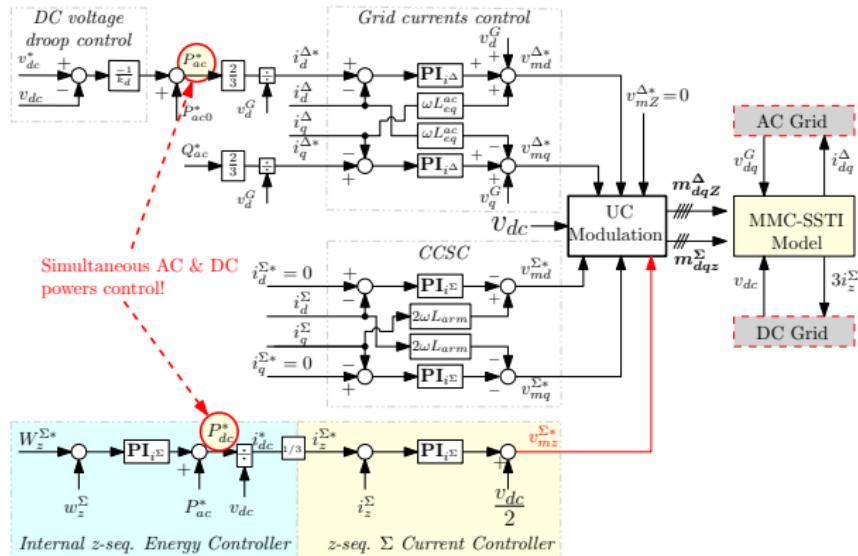
Improving the Dynamics with Energy Control



- All currents are now controlled,
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- Energy control allows this to be possible,
- Since otherwise, P_{ac}^* & P_{dc}^* would "fight" one another.

J. Freytes, G. Bergna-Diaz, J. A. Suul, S. D'Arco, F. Gruson, F. Colas, H. Saad, X. Guillaud, "Improving Small-Signal Stability of an MMC With CCSC by Control of the Internally Stored Energy," in *IEEE Transactions on Power Delivery*, vol. 33, no. 1, pp. 429-439, Feb. 2018.

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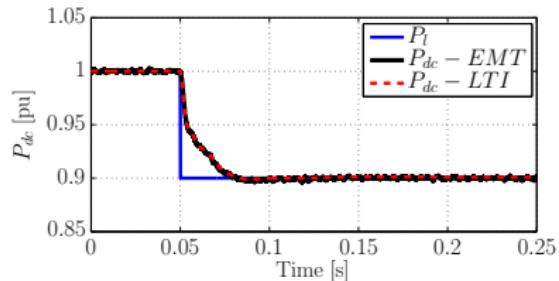


- All currents are now controlled,
- ...stability improvements are expected,
- Energy control allows this to be possible,
- Since otherwise, P_{ac}^* & P_{dc}^* would "fight" one another.
- (Notice that P_{ac}^* & P_{dc}^* roles can be inverted.)

Small-Signal Analysis of CCSC + Energy Control

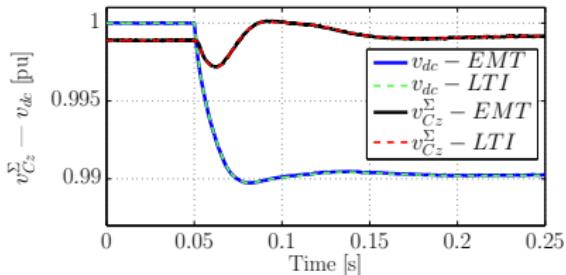
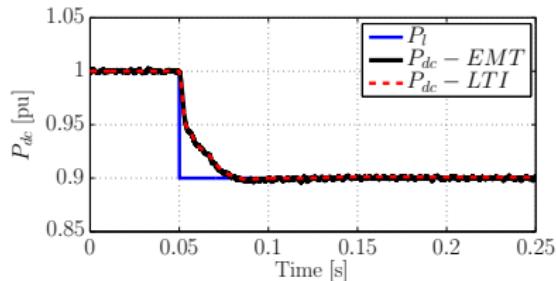
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Small-Signal Analysis of CCSC + Energy Control

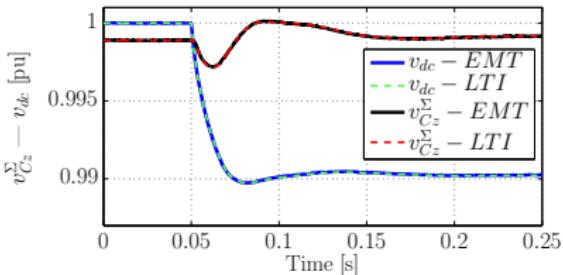
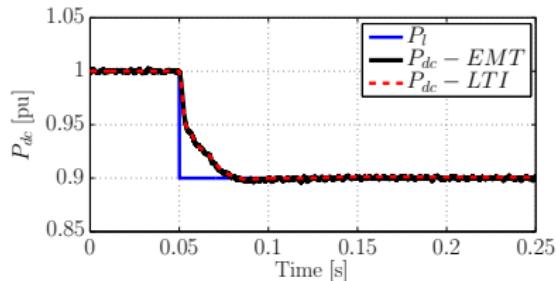


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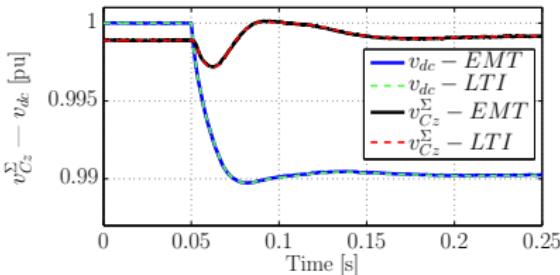
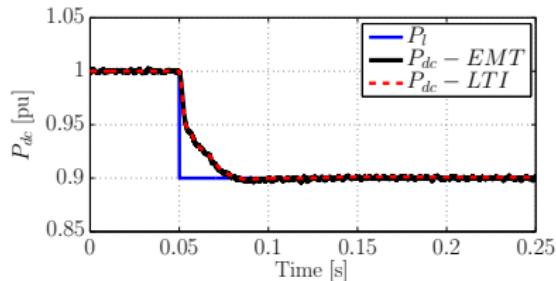


Small-Signal Analysis of CCSC + Energy Control



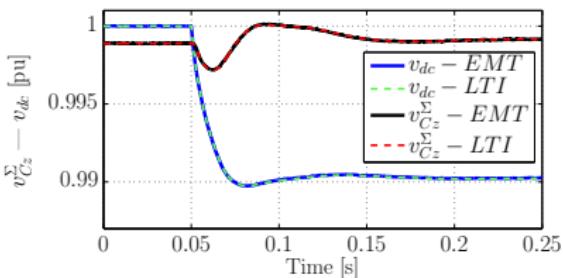
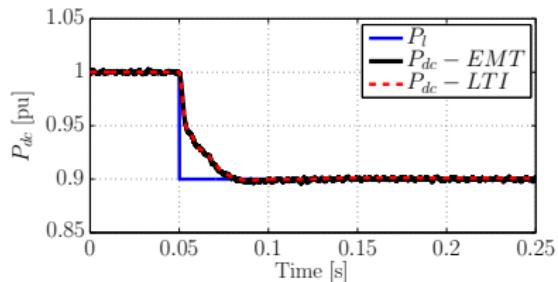
- No oscillations on the DC power nor DC voltage.

Small-Signal Analysis of CCSC + Energy Control



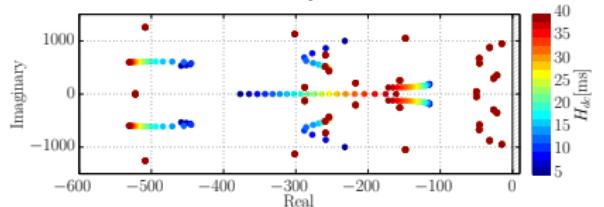
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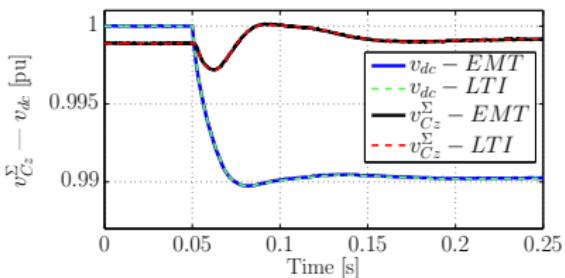
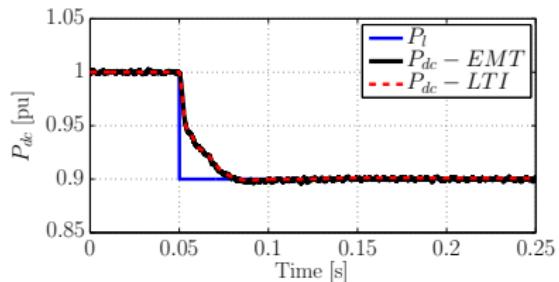
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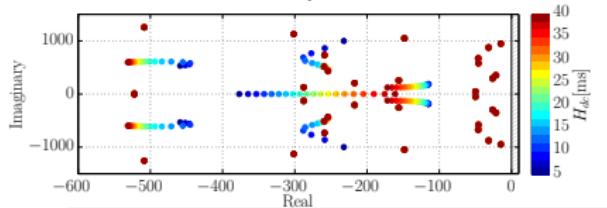
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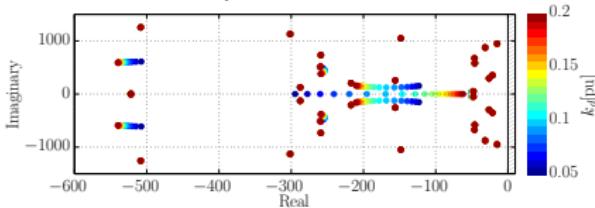


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Table of Contents



Introduction

MMC Modelling for Time-Invariance

Energy Control for Stability Improvements

Conclusions

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 - Controlling the dc current implies **energy control**,... to avoid conflict with the ac active current.



Thank you!

The Particular Case of *Compensated Modulation*



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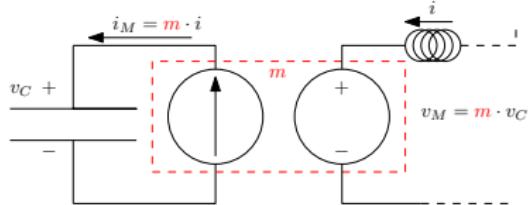
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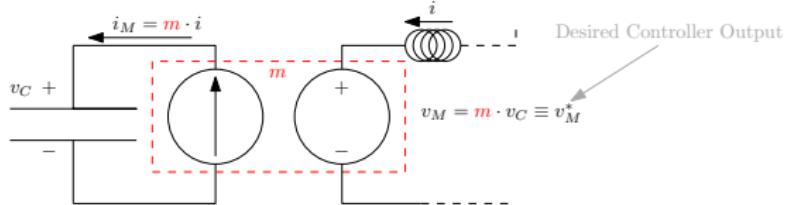
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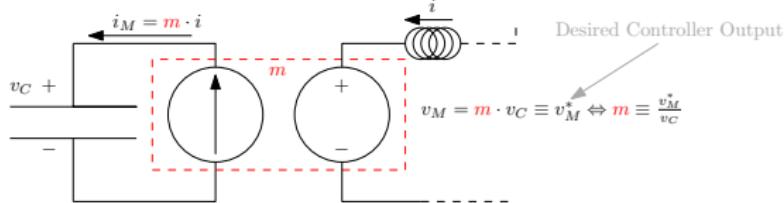
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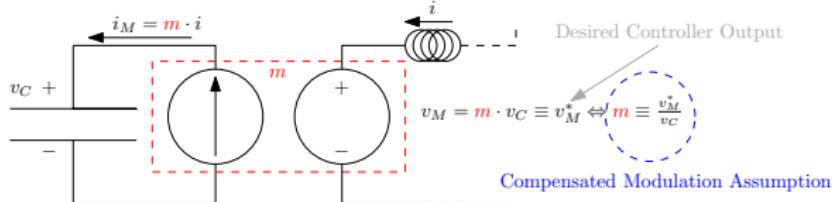
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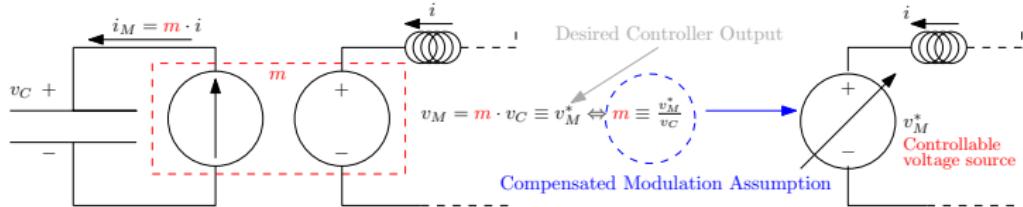
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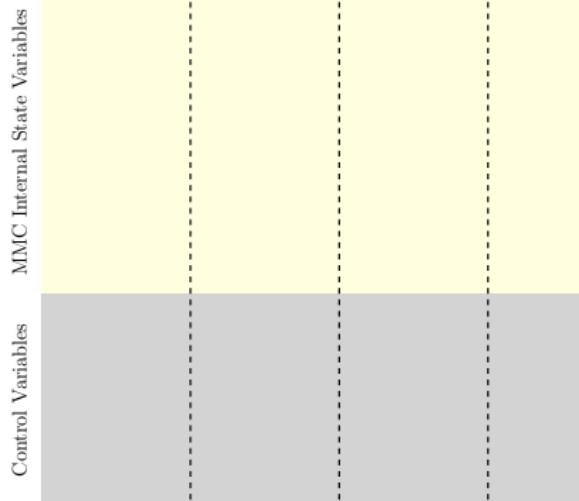
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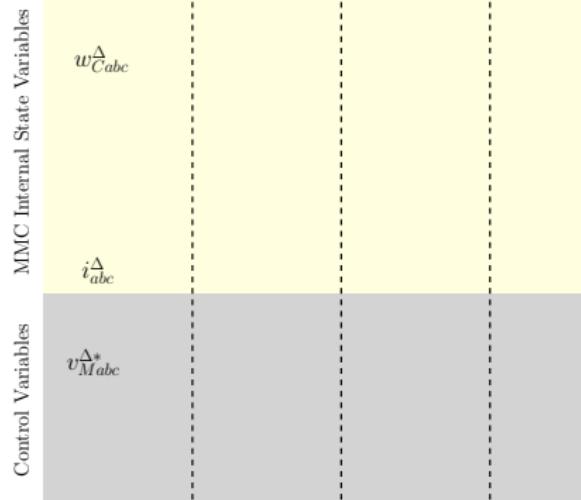
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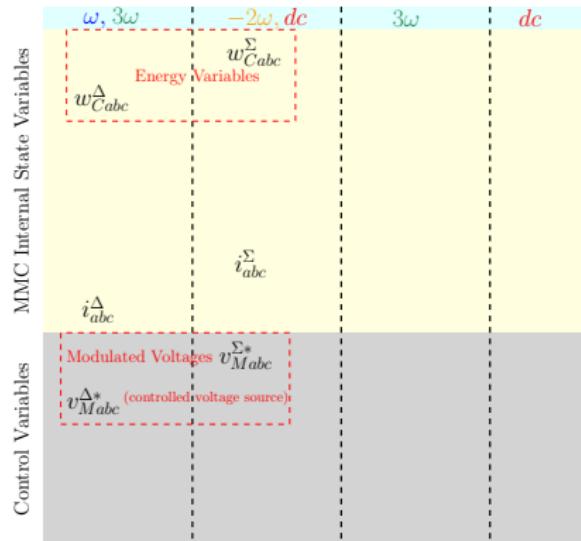
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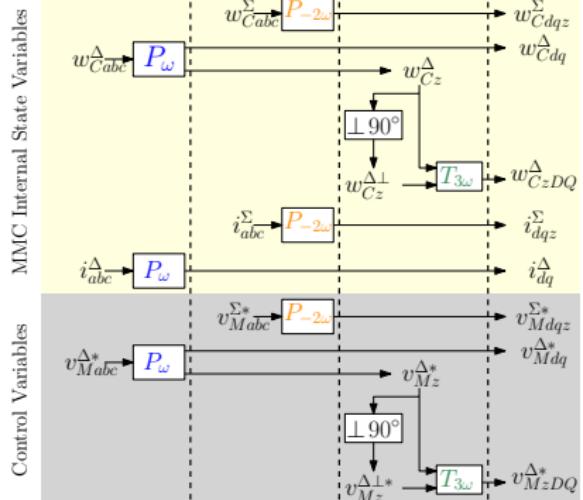
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| MMC Internal State Variables | $\omega, 3\omega$ | $-2\omega, dc$ | 3ω | dc |
|------------------------------|-------------------|----------------------|------------------|---------------------|
| w_{Cabc}^Δ | | w_{Cabc}^Σ | | |
| i_{abc}^Δ | | | i_{abc}^Σ | |
| Control Variables | | $v_{Mabc}^{\Sigma*}$ | | v_{Mabc}^{Σ} |

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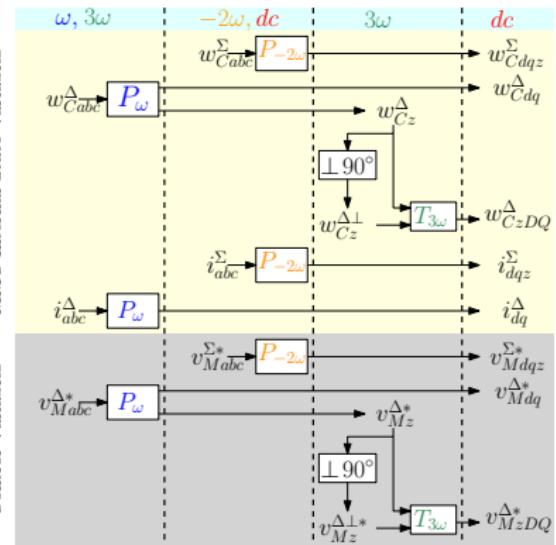


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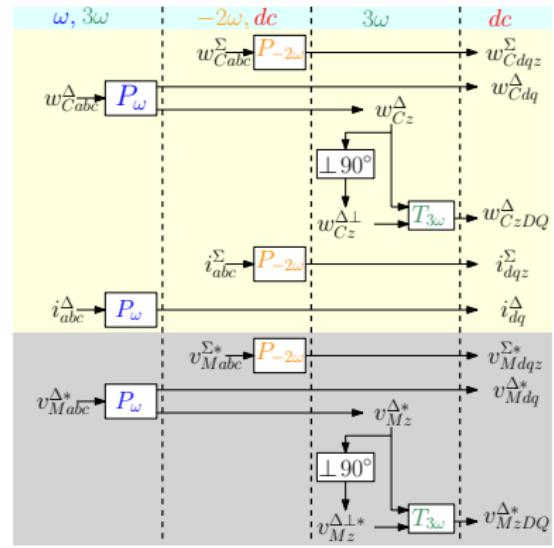
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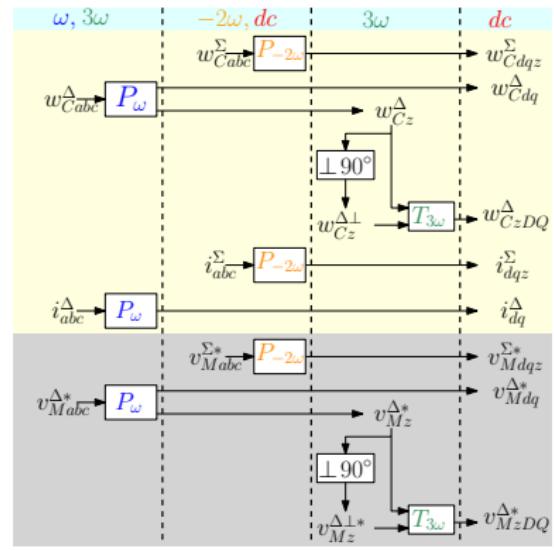
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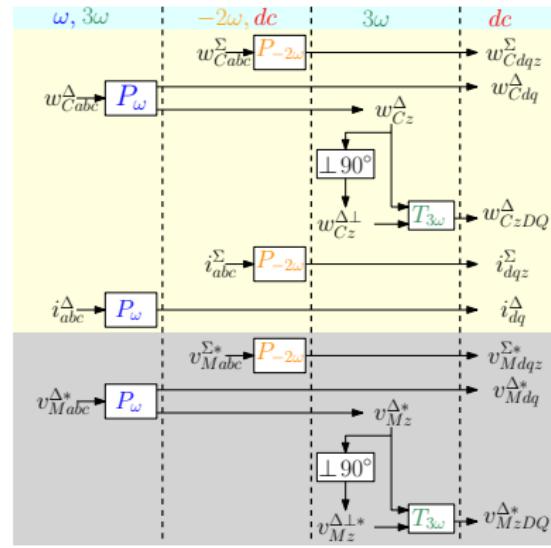
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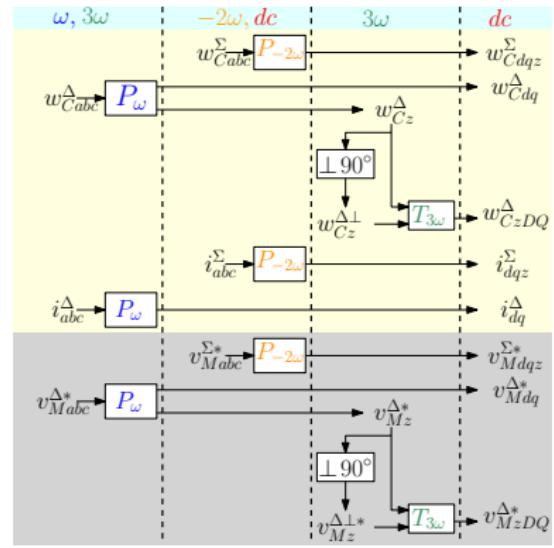
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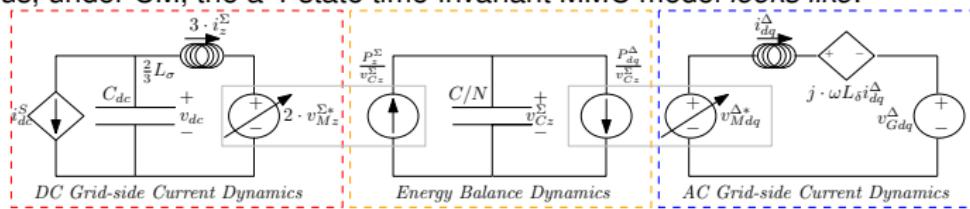
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Simplified 4-State (Terminal-Behaviour) MMC Model

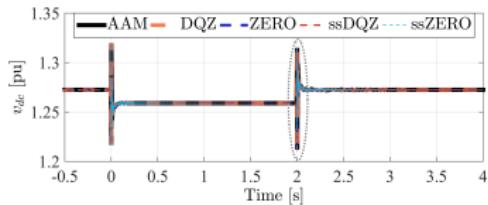
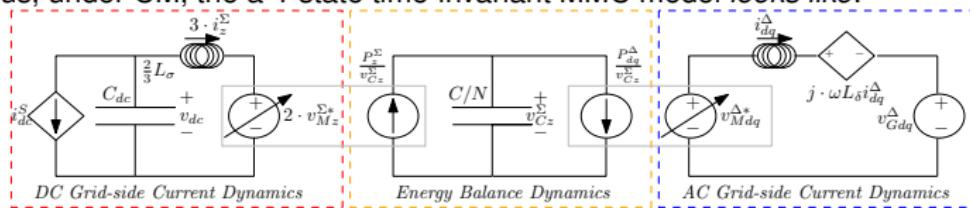
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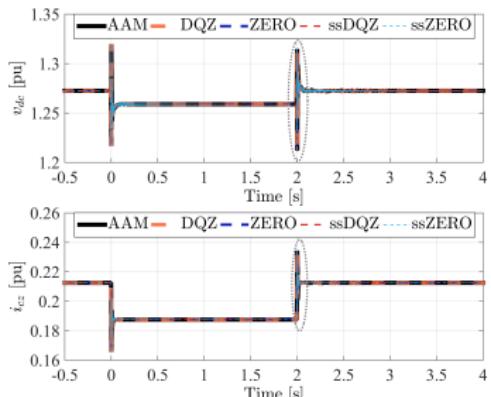
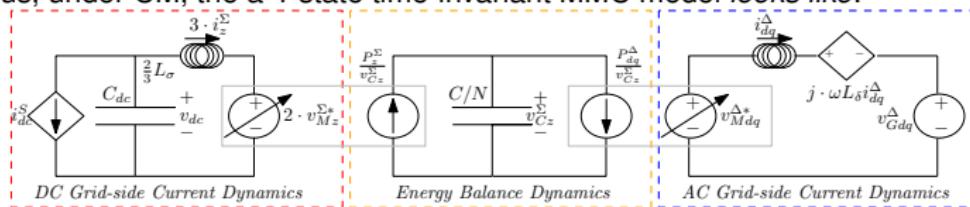
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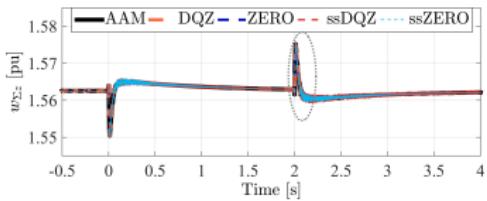
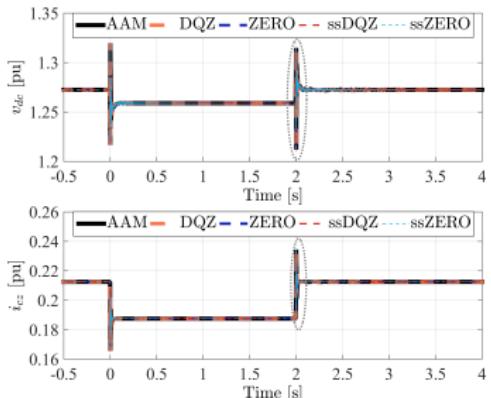
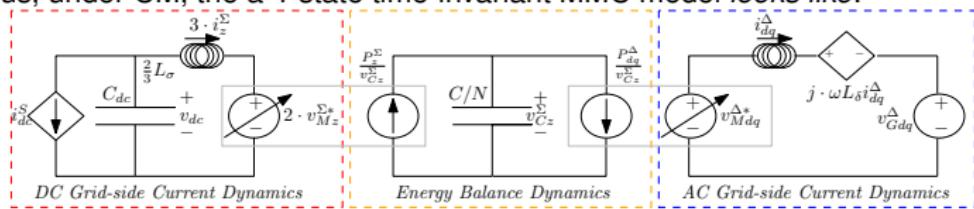
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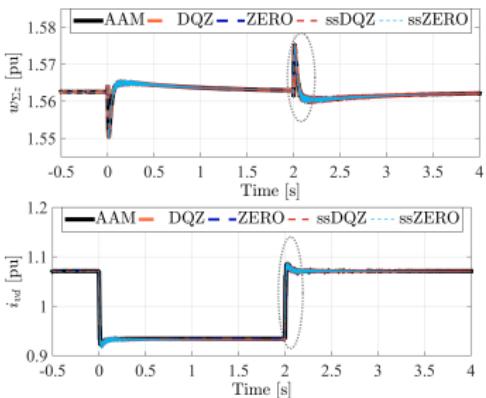
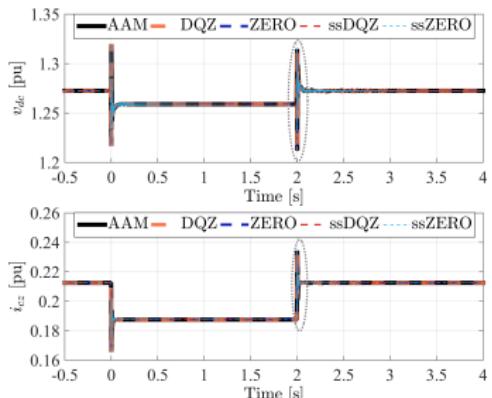
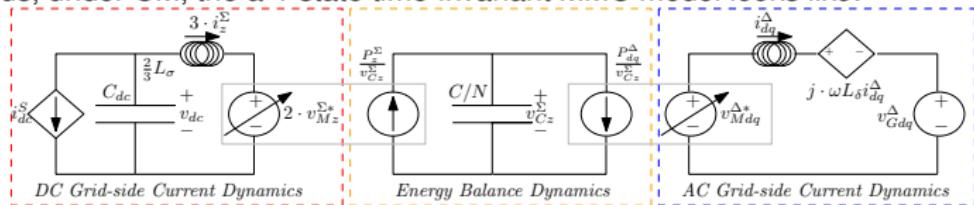
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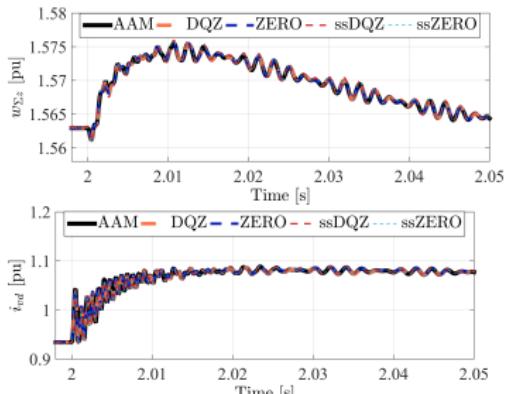
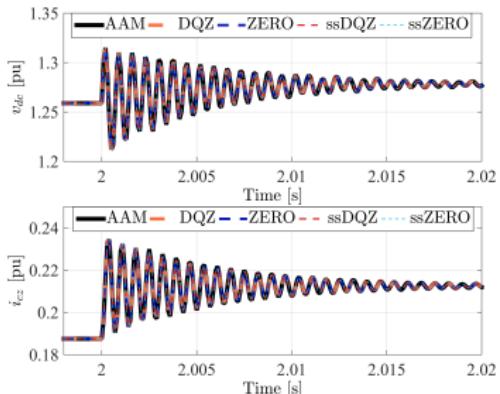
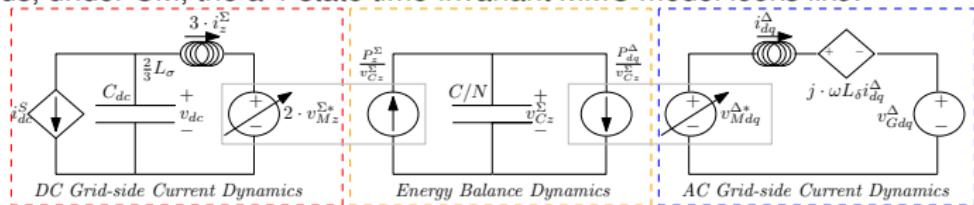
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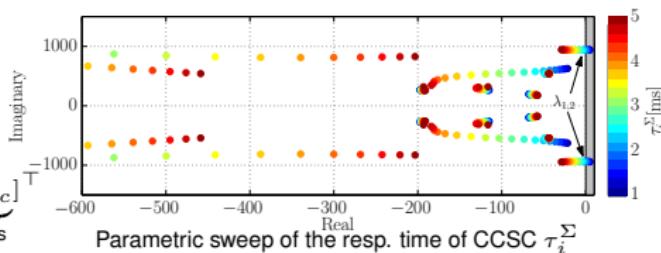
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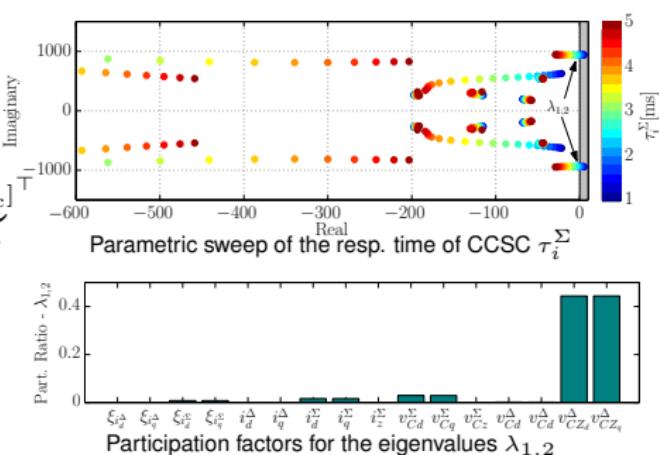
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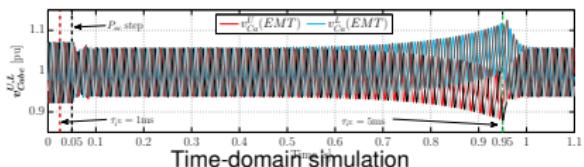
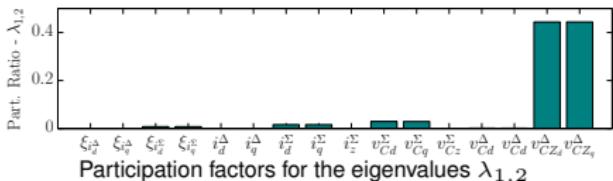
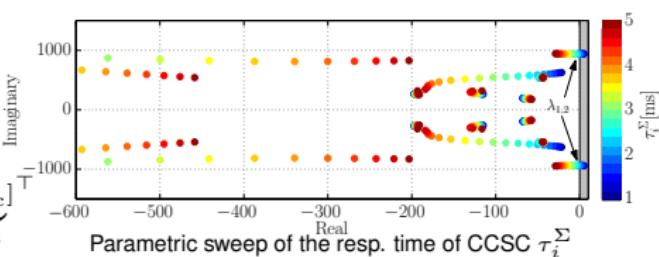
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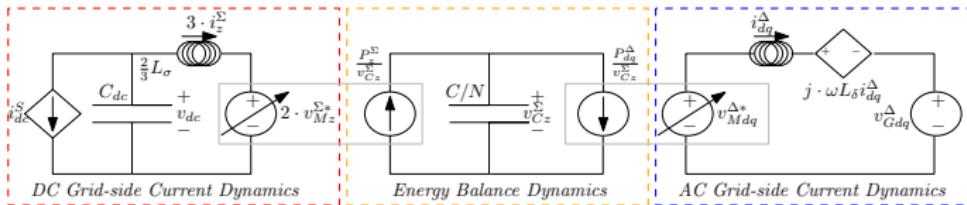
- and an equivalent Time-Invariant equivalent can be derived,
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DC and AC Current Roles: Extra Degree of Freedom

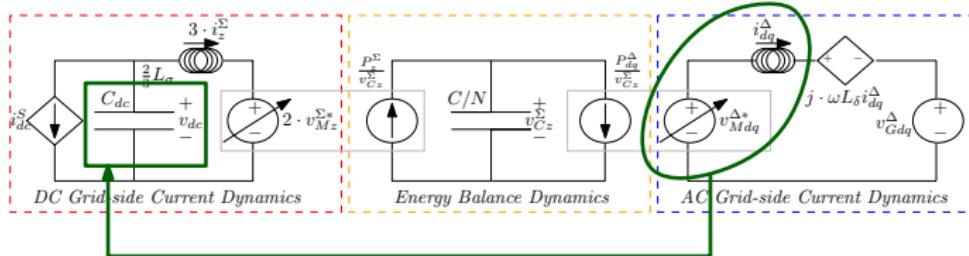
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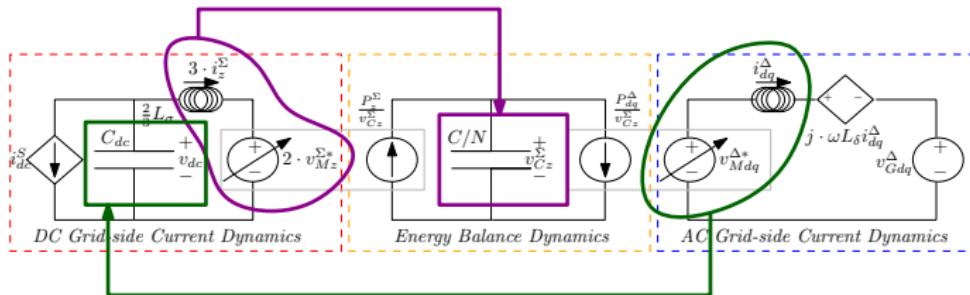
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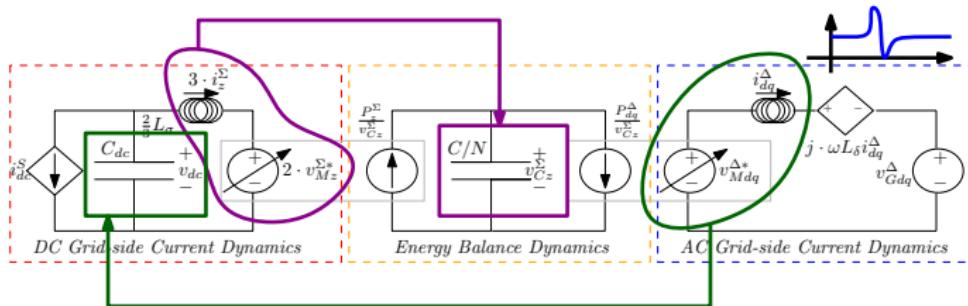
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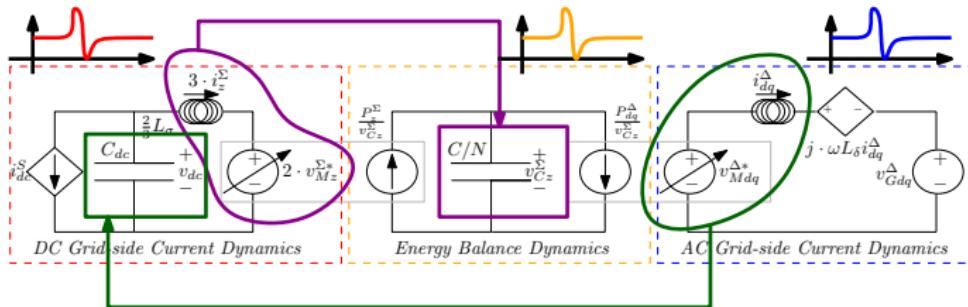
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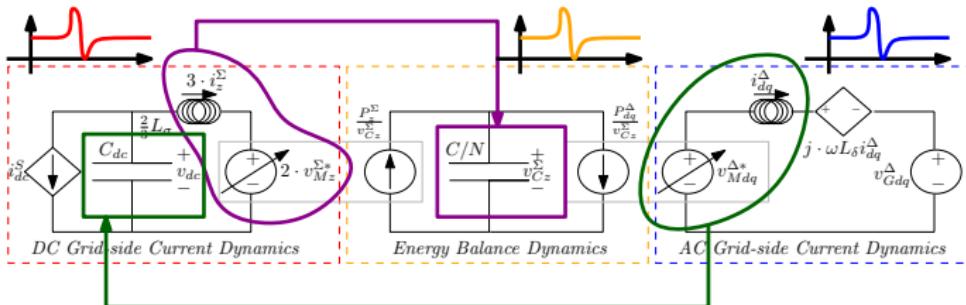
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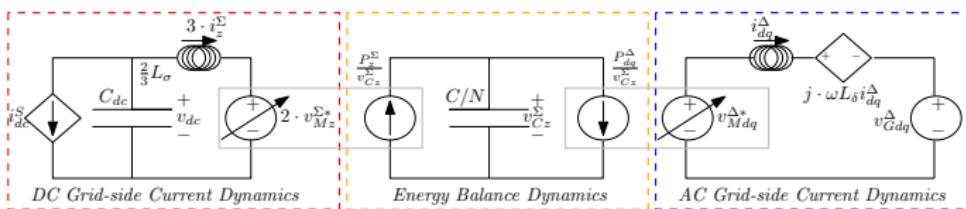


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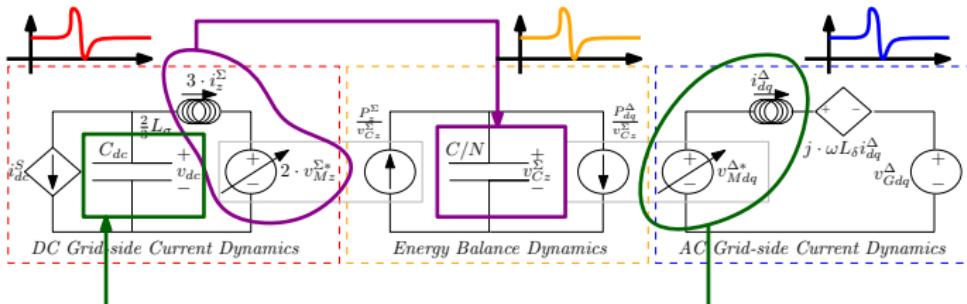


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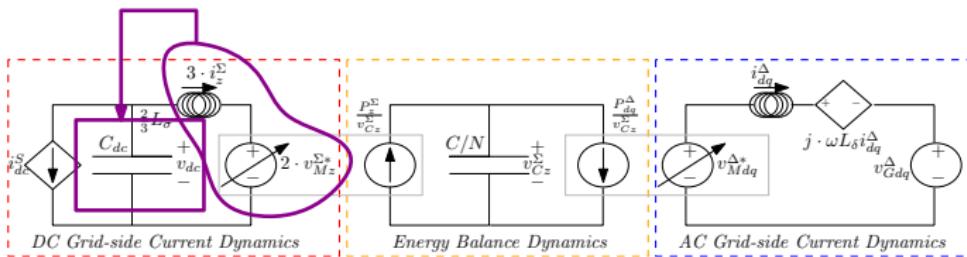


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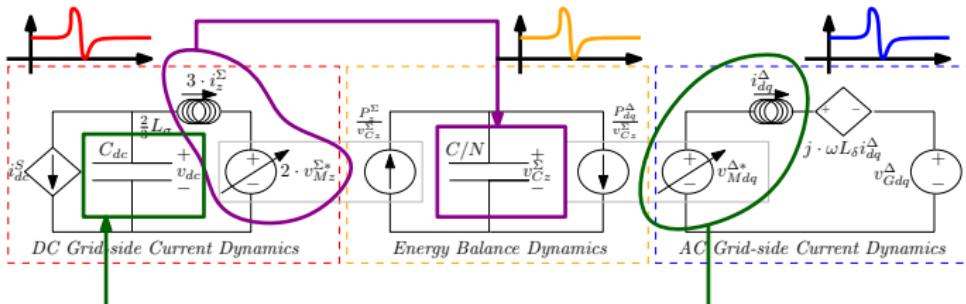


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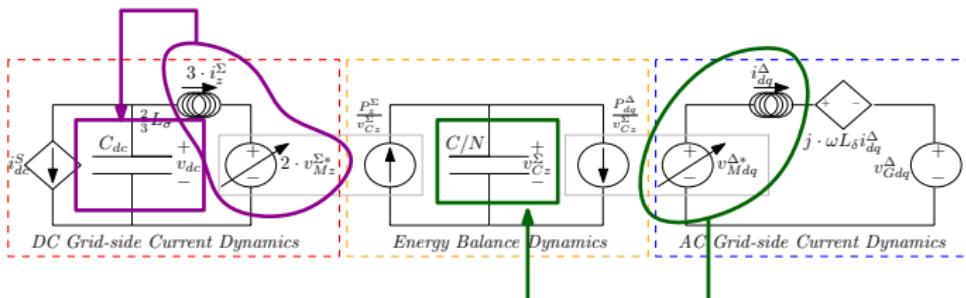


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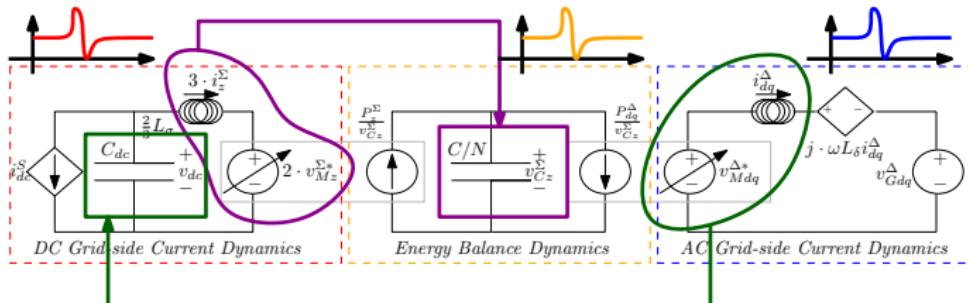


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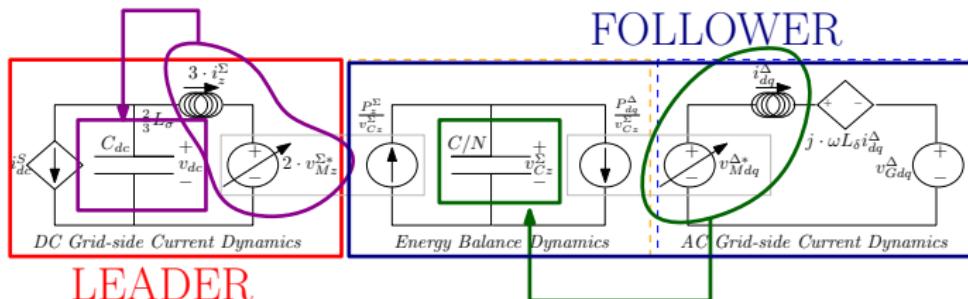


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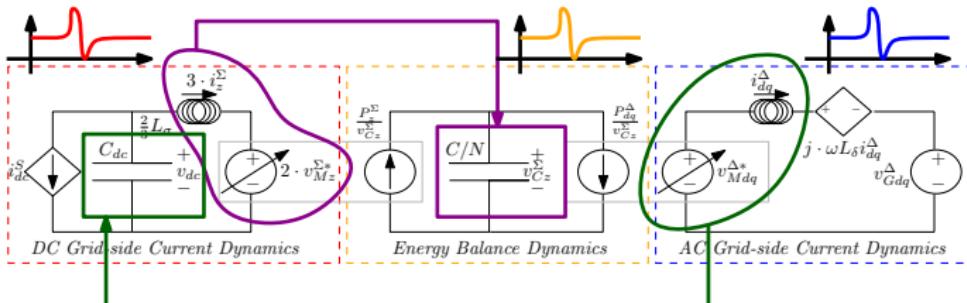


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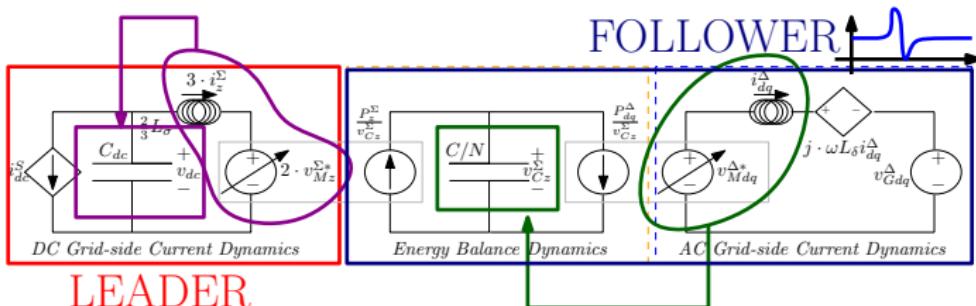


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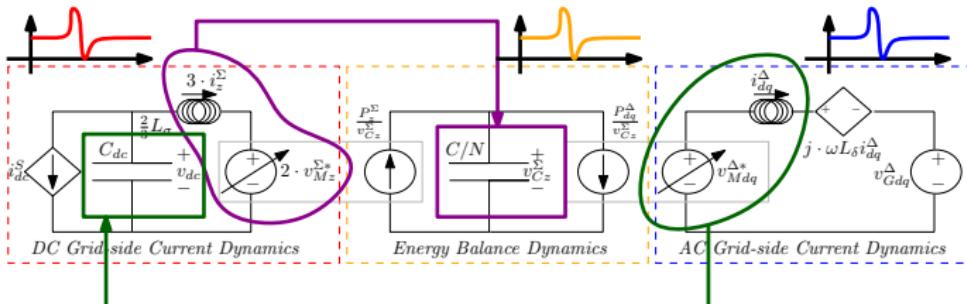
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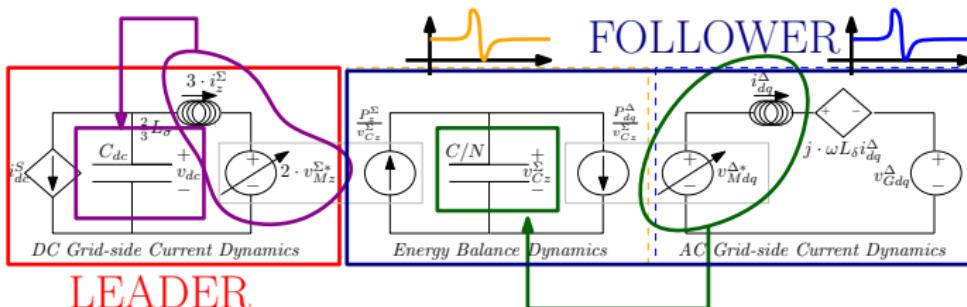
Conclusions

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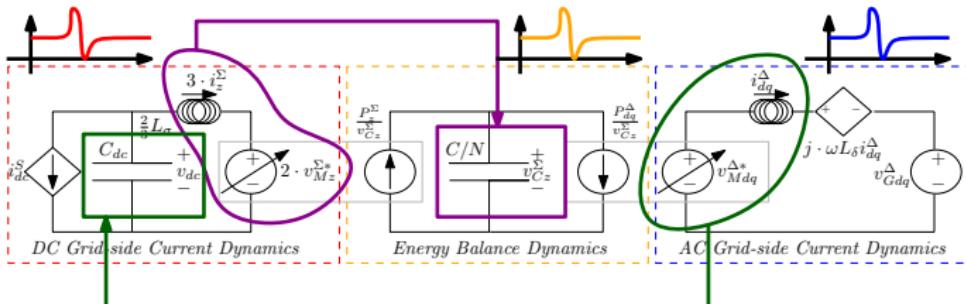


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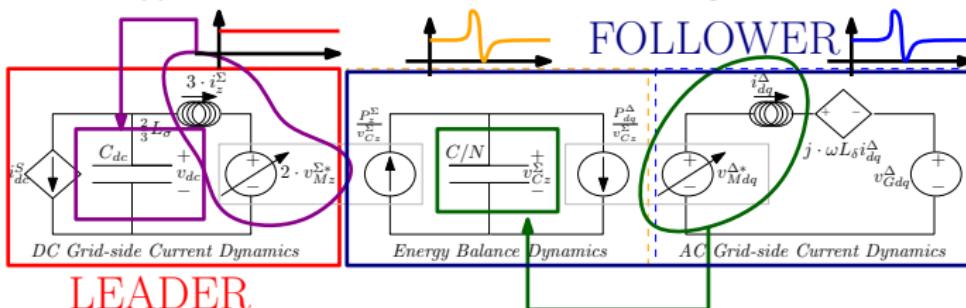


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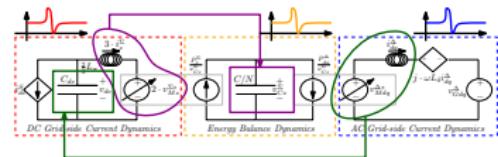


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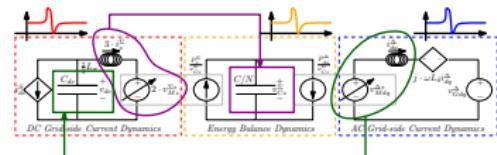
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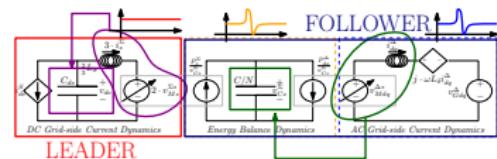
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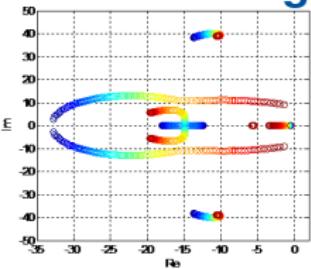
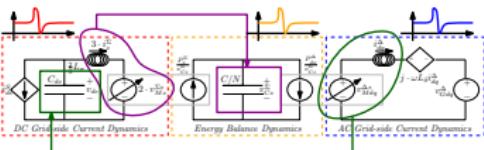


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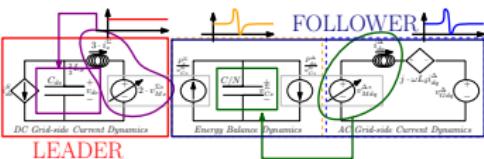
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DC and AC Current Roles: Small-Signal Analysis

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- DC Current $\rightarrow v_{dc}$



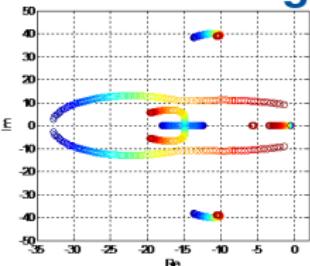
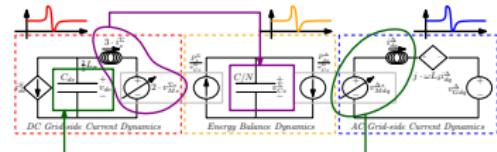
LEADER

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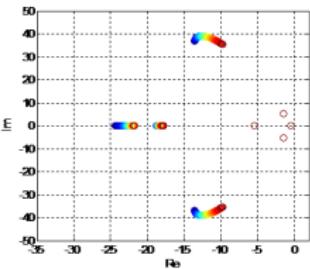
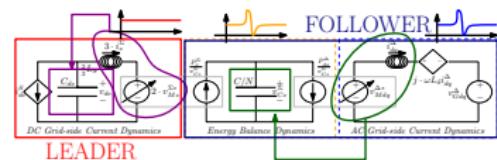
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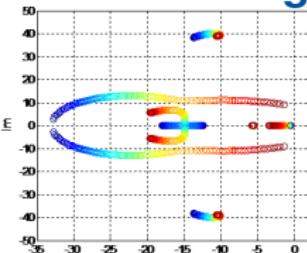
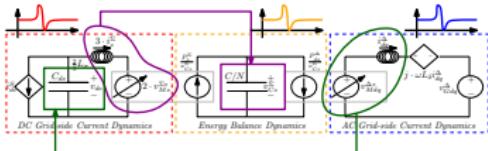


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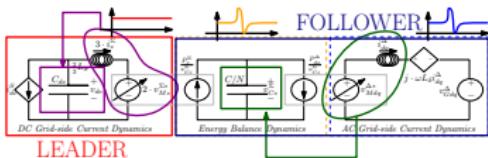
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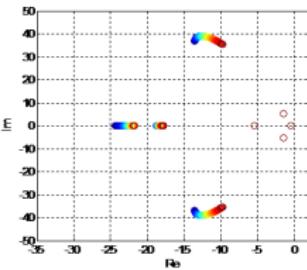


Very Nonlinear: Complicated Tuning.

- DC Current $\rightarrow v_{dc}$



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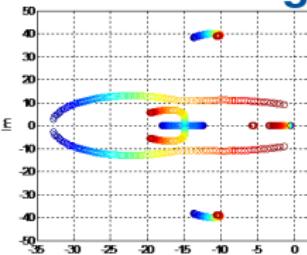
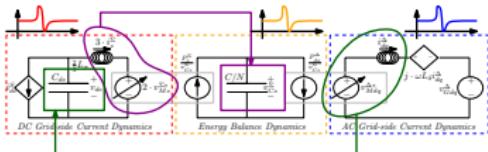


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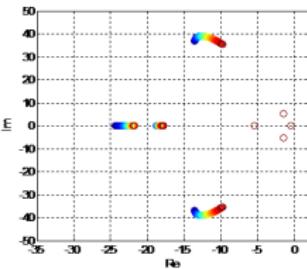
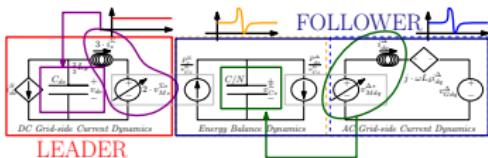
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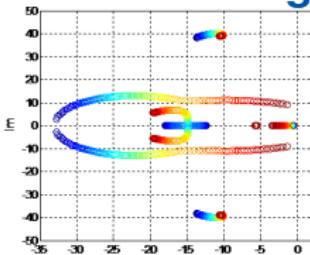
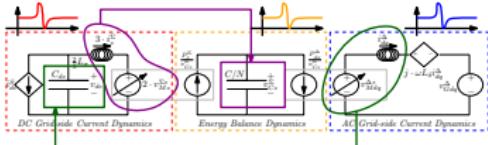
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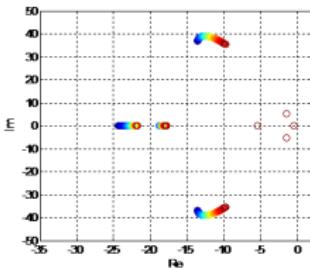
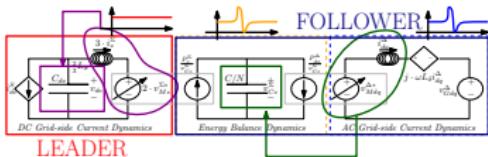


$$\Delta \dot{x} = A \cdot \Delta x + B \cdot \Delta u$$

| | |
|--------------------|----------|
| AC + Energy Buffer | COUPLING |
| COUPLING | DC |

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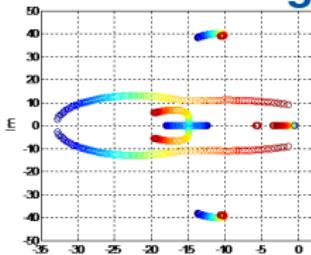
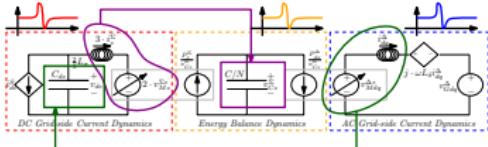


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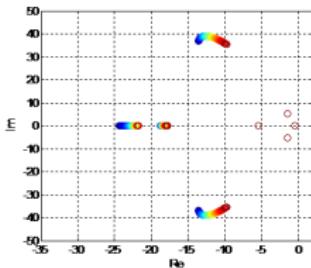
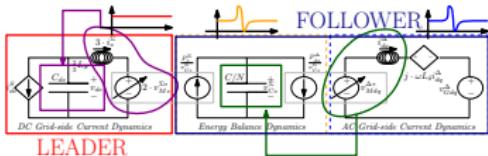
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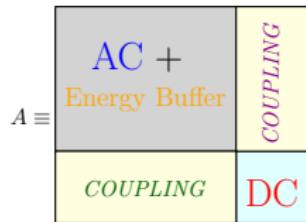
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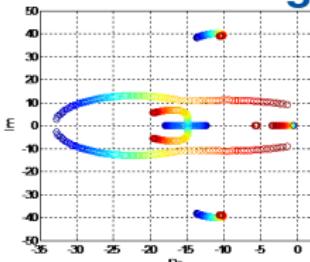
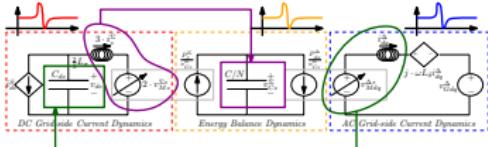
Coupled Matrix: Possible Interactions

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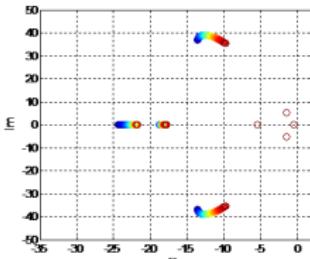
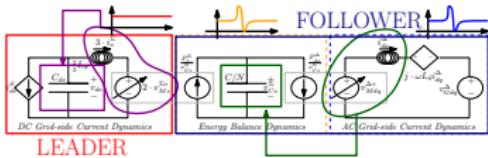
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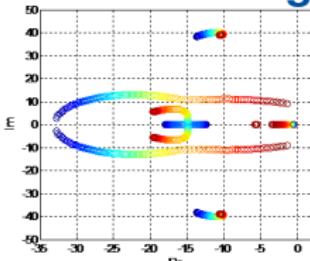
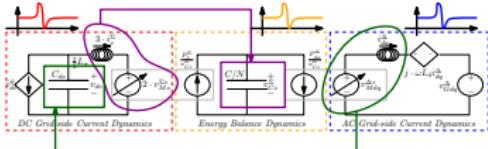
| | |
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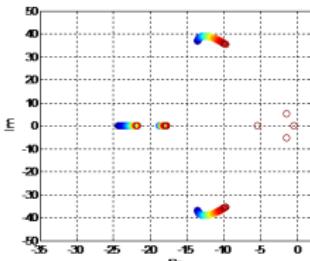
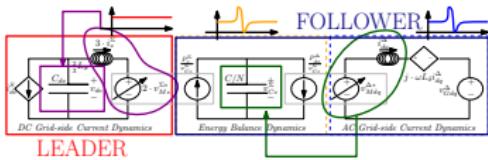
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Block Triangular Matrix: NO Interactions

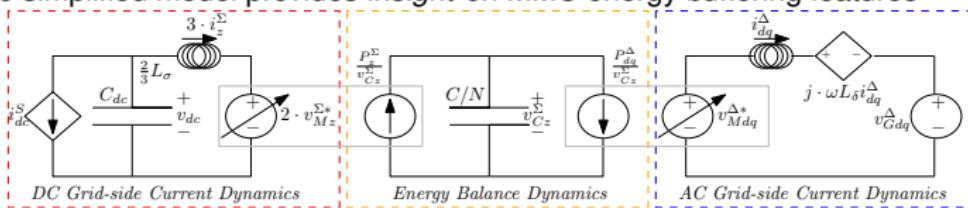
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MMC Energy Buffering Capabilities Revealed



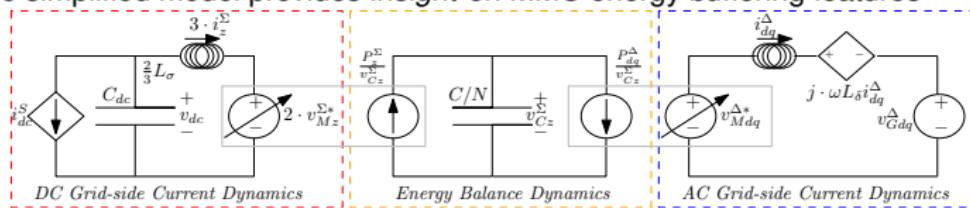
MMC Energy Buffering Capabilities Revealed

- The simplified model provides *insight* on MMC energy buffering features



MMC Energy Buffering Capabilities Revealed

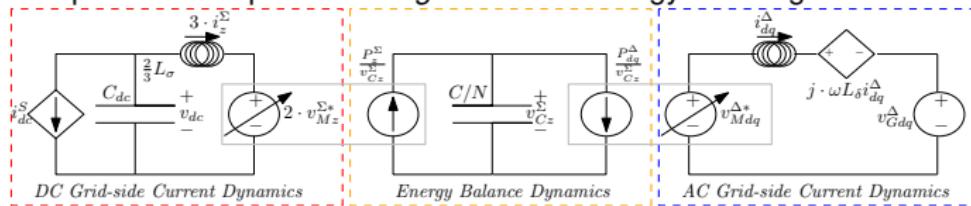
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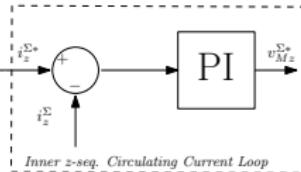
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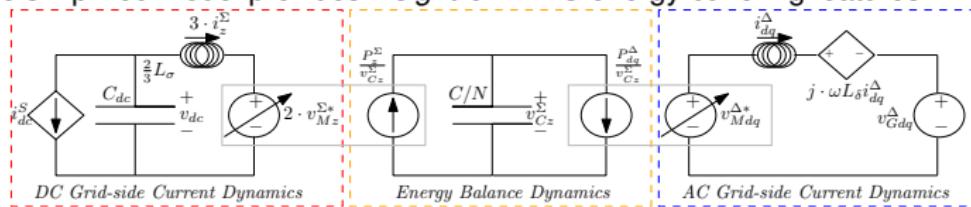


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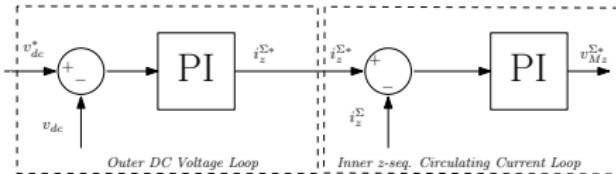


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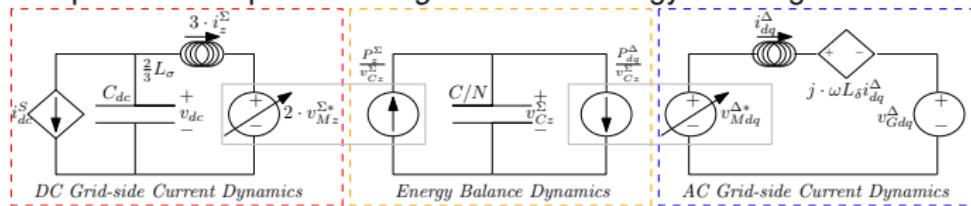


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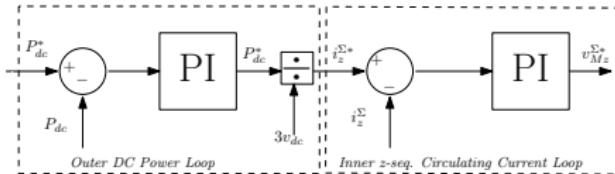


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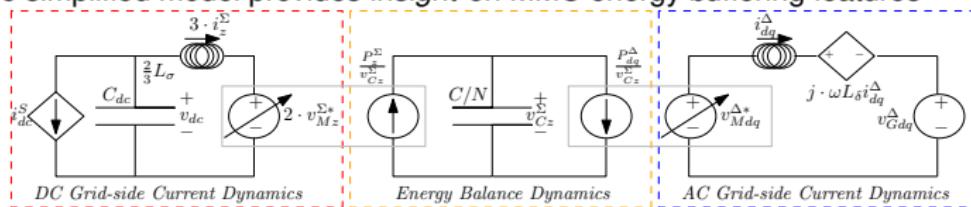


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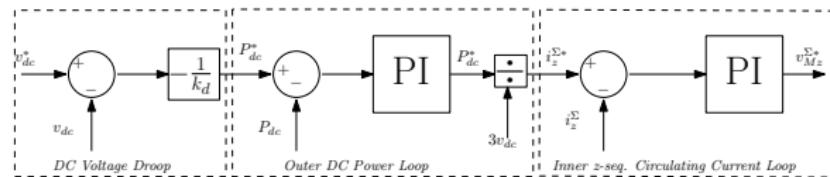


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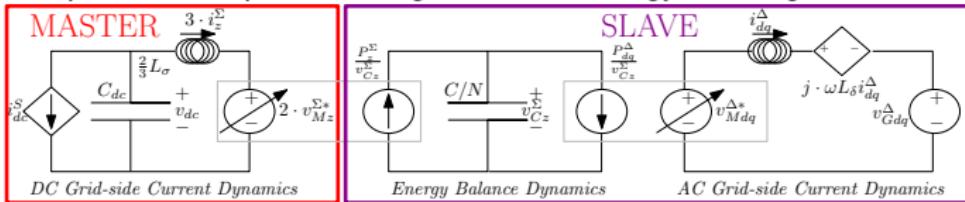


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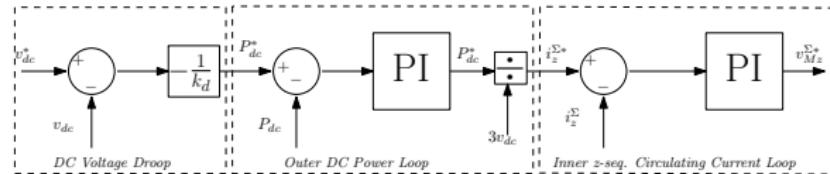


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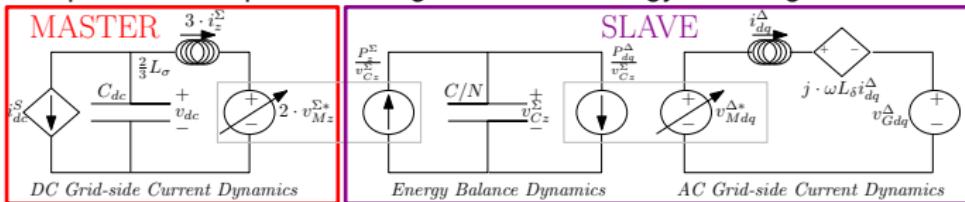


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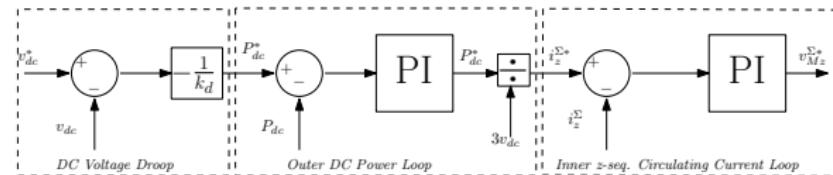


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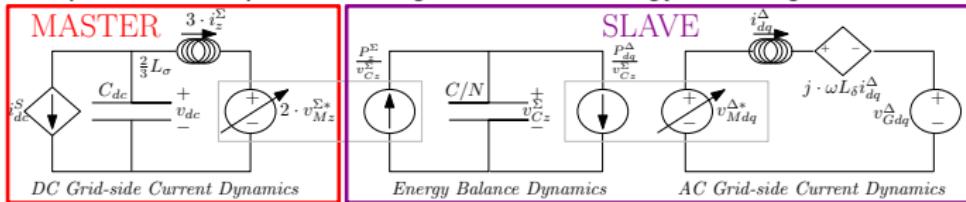
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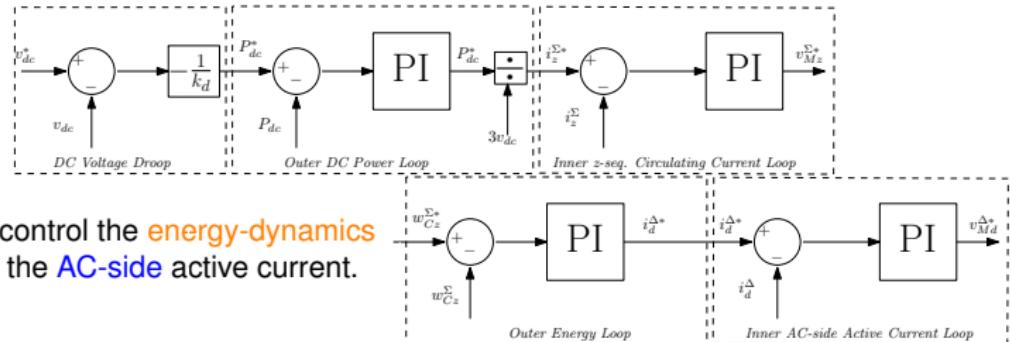
- $v_{Md}^{\Delta*}$ to control the **energy-dynamics** through the **AC-side** active current.

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