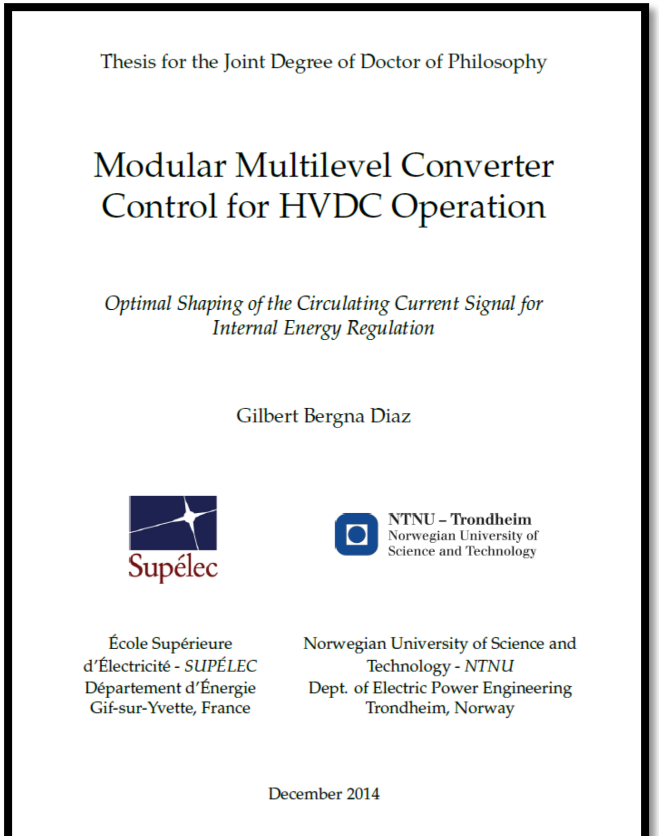
Modular Multilevel Converter Control for HVDC Operation

Optimal Shaping of the Circulating Current Signal for Internal Energy Regulation

My PhD Thesis in 30 seconds



Thesis for the Joint Degree of Doctor of Philosophy

Modular Multilevel Converter Control for HVDC Operation

Optimal Shaping of the Circulating Current Signal for Internal Energy Regulation

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December 2014

Sponsored by EDF R&D

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Thesis Outcomes:

- ***Two*** MMC control strategies:
  - Linear (Resonant controllers)
  - Non-linear (Passivity Theory)
- ***One*** lab-scale MMC

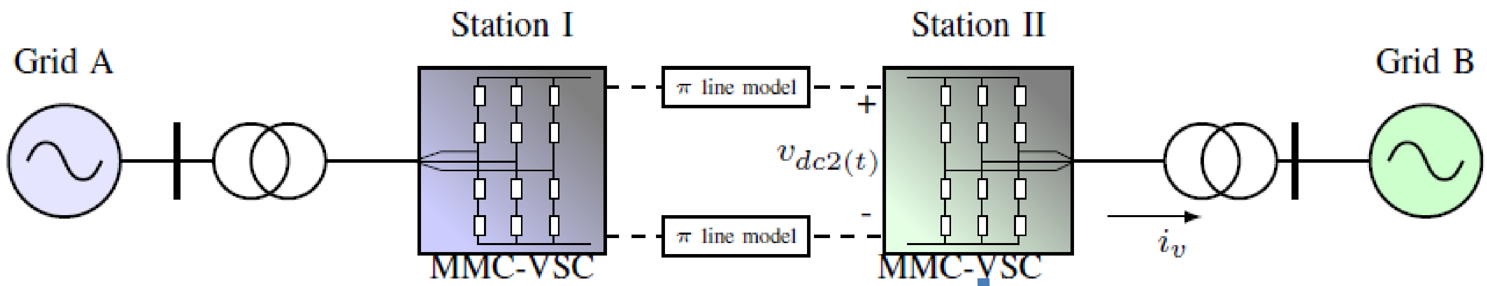
Overview

- Introduction
- Optimization of the circulating current.
- Circulating current signal for constant power under unbalanced grid conditions.
- Conclusions

Part I

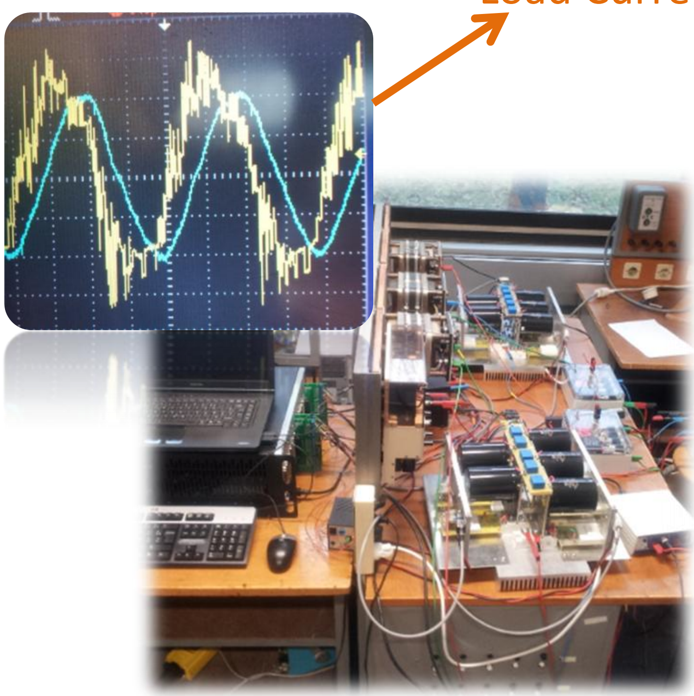
INTRODUCTION

The Modular Multilevel Converter

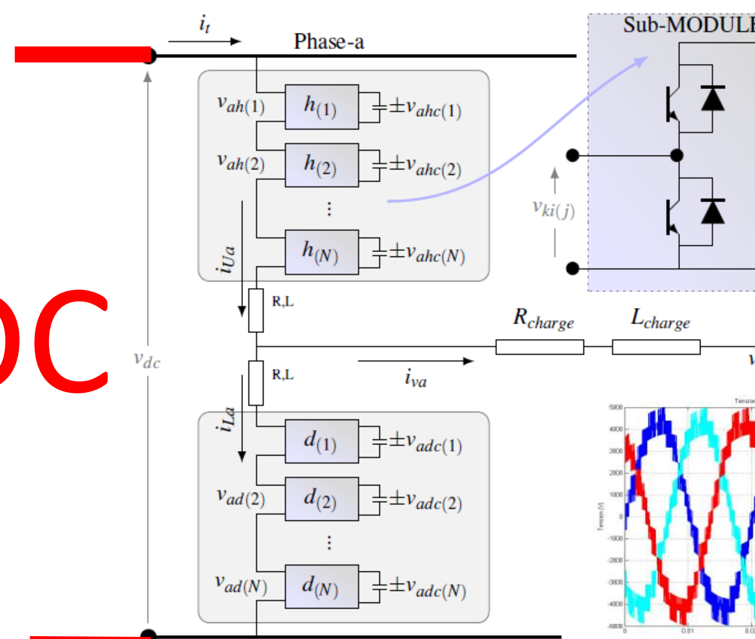


Lab Prototype:

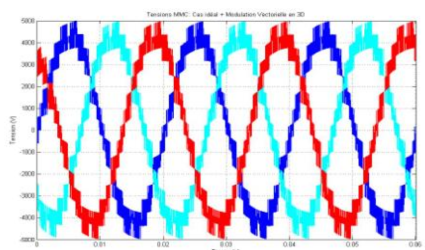
MMC Voltage and Load Currents



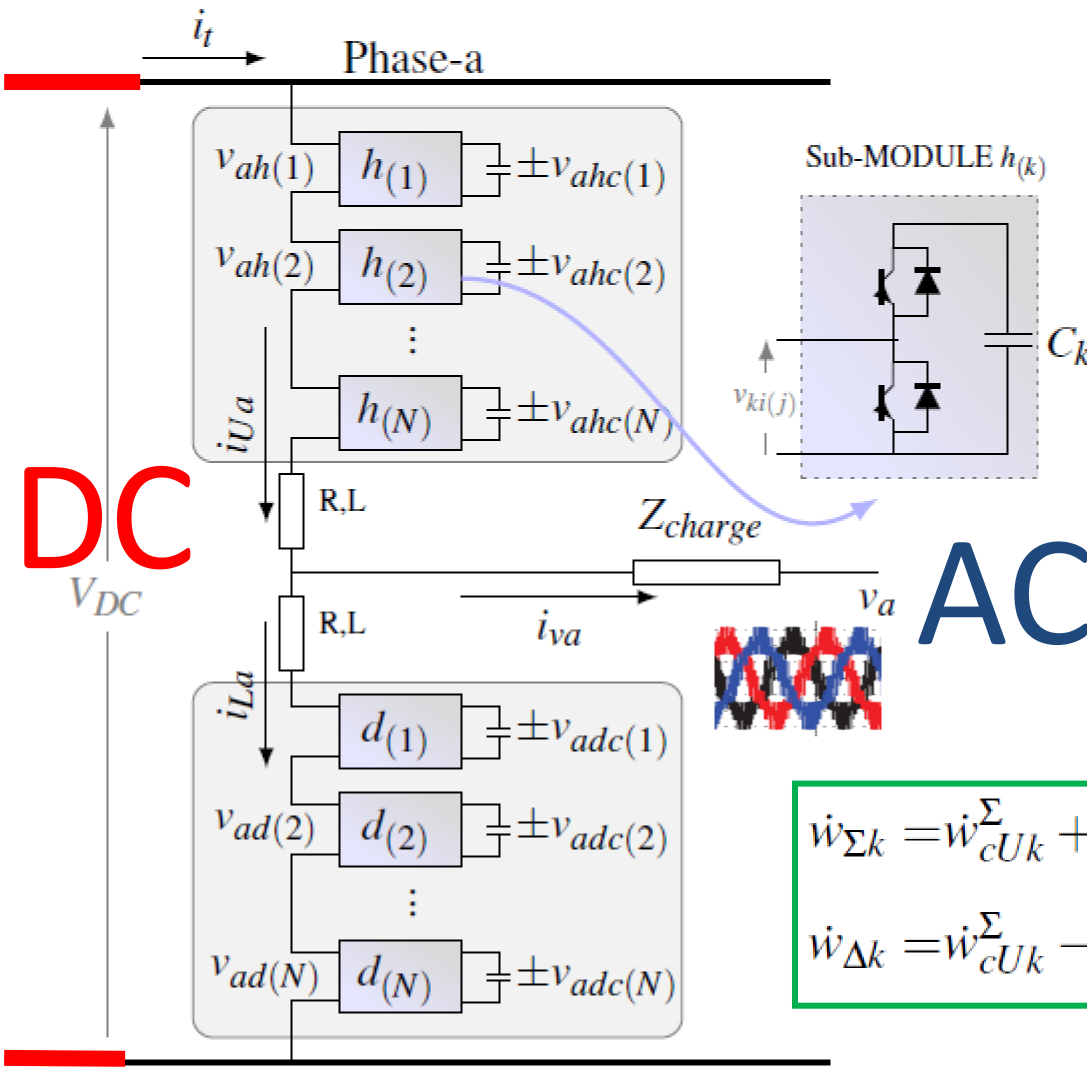
DC



AC



MMC Basics



Two Current variables:

1) Circulating current (i_{circ})
2) Grid current (i_v)

$$i_{ck} = \frac{i_{Uk} + i_{Lk}}{2}$$
$$i_{vk} = i_{Uk} - i_{Lk}$$

Two Energy variables:

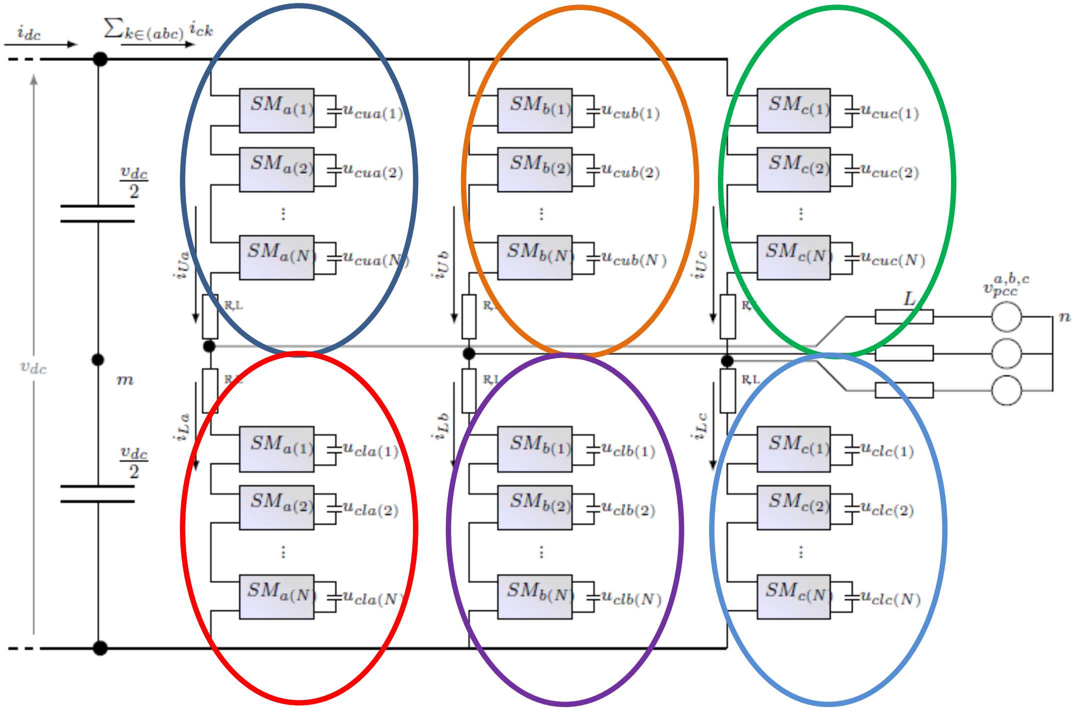
1) Energy Sum ($w_{\Sigma k}$)
2) Energy Difference ($w_{\Delta k}$)

$$\dot{w}_{\Sigma k} = \dot{w}^{\Sigma}_{cUk} + \dot{w}^{\Sigma}_{cLk} = -e_{vk} i_{vk} + (v_{dc} - 2u_{ck})\, i_{ck}$$
$$\dot{w}_{\Delta k} = \dot{w}^{\Sigma}_{cUk} - \dot{w}^{\Sigma}_{cLk} = \frac{i_{vk}}{2}(v_{dc} - 2u_{ck}) - 2e_{vk} i_{ck}$$

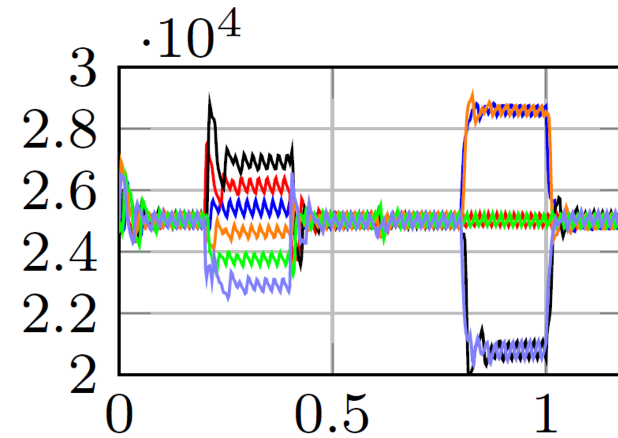
Motivation for a new "high-level" control strategy

	Good Dynamic Performance	Robust / Parameter independent	Circulating Current Control	Capacitive Energy Control	SM Voltage Measurement Independence	**Phase Independent Control**
OLC	X	X	√	√	√	√
CLC	X	√	X	√	X	√
CCSC	√	√	√	X	√	X
DDSRF	√	√	√	√	X	X
"My PhD Controller	**√**	**√**	**√**	**√**	**-**	**√**

Motivation: Need for a Robust and dynamically performant control scheme for phase / arm independent circulating current control and energy regulation.



Something like this...



Akagi's instantaneous p-q theory

- In αβo coordinates: $p(t) = (v_\alpha + jv_\beta)\cdot(i_\alpha + ji_\beta) = \overbrace{(v_\alpha i_\alpha + v_\beta i_\beta)}^{\text{p: Instantaneous Active Power}} + j\overbrace{(v_\alpha i_\beta - v_\beta i_\alpha)}^{\text{q: Instantaneous Imaginary Power or reactive power}}$

- In dqo coordinates: $p(t) = (v_d + jv_q)\cdot(i_d + ji_q) = (v_d i_d + v_q i_q) + j(v_d i_q - v_q i_d)$

Implementation of circulating current control strategies in <u>dqo</u> or <u>αβo</u> can be challenging.

- Does not allow direct and explicit control of individual variables of each phase/arm.
- High number of reference frame transformations, filters and decoupling loops for detecting the various frequency components of circulating currents, sum arm energy and arm energy difference variables.

MMC: Several frequency components in steady state.

- Circulating current: DC , +ω ,-2ω,.
- Grid current: +ω.
- Capacitive Energy Sum: DC ,-2ω.
- Capacitive Energy Difference: DC ,+ω.

Conventional Synchronous Reference Frame Control (SRFC)

-> Requires advanced decoupling techniques.

Clarke's Transform (applied to three DC variables)

abc

Identical and constant circulating currents

$$\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

αβo

Only zero seq.

abc

Different constant circulating currents (Unbalanced grid)

$$\frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

αβo

?

Park's Transform (applied to three DC variables)

abc

Identical and constant circulating currents

$$\frac{2}{3}\begin{bmatrix} cos(\theta) & cos\left(\theta-\frac{2\pi}{3}\right) & cos\left(\theta+\frac{2\pi}{3}\right) \\ -sin(\theta) & -sin\left(\theta-\frac{2\pi}{3}\right) & -sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

dqo

Only zero seq.

abc

Different constant circulating currents (Unbalanced grid)

$$\frac{2}{3}\begin{bmatrix} cos(\theta) & cos\left(\theta-\frac{2\pi}{3}\right) & cos\left(\theta+\frac{2\pi}{3}\right) \\ -sin(\theta) & -sin\left(\theta-\frac{2\pi}{3}\right) & -sin\left(\theta+\frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix}$$

dqo

?

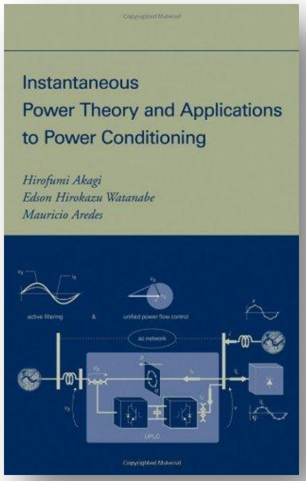
-> Controller will be designed in the MMC natural “abc” coordinates.

Part II: Arm-independent Energy Shaping and Regulation

OPTIMIZATION OF THE CIRCULATING CURRENT SIGNAL

Introduction to the instantaneous "abc" power theory

- Using the nomenclature proposed by H. Akagi, the instantaneous power theories can be classified into **two groups**:
  - The ***p-q theory***: defined using the αβ coordinates.
  - The ***abc theory*** *(or vectorial theory):* defined directly using the natural *abc* coordinates from the start.
- His book was devoted to the *p-q* theory…
- …however, there is a small section were he used the *abc theory* in combination with an optimization method to determined the active currents in phase coordinates.



Active current calculation by means of a minimization method (1/2)

Calculate the minimum currents of a three phase system:

$$min \to f\left(i_k\right) = \left(i_k\right)^2, k \in (abc)$$

…subject to the constraint of transferring the desired instantaneous power:

$$p_{3\varphi} = \sum_{k \in (abc)} v_k i_k$$

The above is an optimization problem, that can be solved using the Lagrange methodology.

$$\mathcal{L}\left(i_k, \lambda\right) = \left(i_k\right)^2 + \lambda \left(\sum_{k \in (abc)} v_k i_k - p_{3\varphi} \right)$$

Active current calculation by means of a minimization method (2/2)

$$\nabla_{i_k,\lambda}\mathcal{L}(i_k,\lambda)=0 \quad \begin{cases} \dfrac{\partial\mathcal{L}(i_k,\lambda)}{\partial i_k}=2i_k+\lambda v_k=0 \\ \dfrac{\partial\mathcal{L}(i_k,\lambda)}{\partial\lambda}=\sum\limits_{k\in(abc)}(v_k i_k)-p_{3\varphi}=0 \end{cases}$$

$$\boxed{i_k=\frac{p_{3\varphi}}{\sum_{k\in(abc)}v_k^2}v_k}$$

- The resulting current can be referred to as the *instantaneous active current*.
- This is the minimum current required to transfer the desired active power.

Generalized compensation theory for active filters

In 2012, A. Garcés *et al* **extended the previous results** by taking advantage of the inherent versatility of the optimization technique, applied to the case of a two level VSC active filtering.

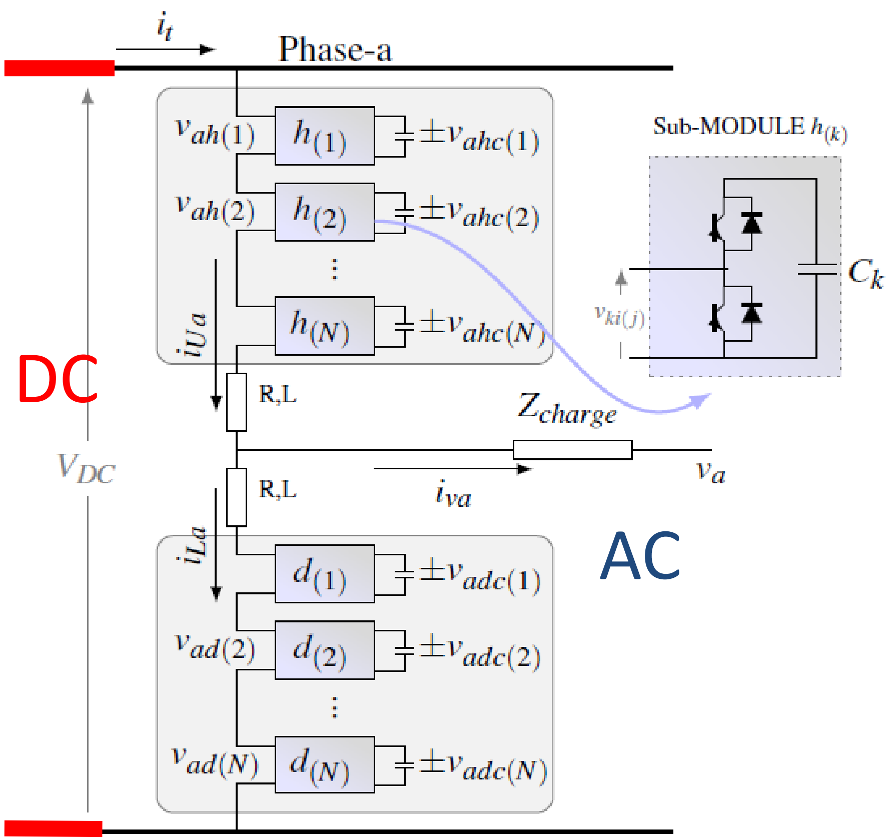
For instance, cancelation of the zero-sequence current in four wire –three phase systems:

$$\mathcal{L}\left(i_k, \lambda_P, \lambda_0\right) = \left(i_k\right)^2 + \underbrace{\lambda_P \left(\sum_{k\in(abc)} v_k i_k - p_{3\varphi}\right)}_{\text{Same formulation problem as before}} + \underbrace{\lambda_0 \left(\sum_{k\in(abc)} i_k\right)}_{\text{Additional Constraint}}$$

$$\boxed{i_k = \frac{p_{3\varphi}}{\sum_{k\in(abc)} v_k^2 - 3\left(v_o\right)^2} \cdot \left(v_k - v_o\right)}$$

A. Garces, M. Molinas, and P. Rodriguez, "A generalized compensation theory for active filters based on mathematical optimization in the *abc* frame," *Electric Power System Research*, vol. 90, no. 0, pp. 1-10, September 2012.

Applying the power theory to the MMC Circulating Current



Circulating current (i_{ck})

$$\boxed{i_{ck} = \frac{i_{Uk} + i_{Lk}}{2}}$$

IDEA:

- Apply the Lagrange methodology to the MMC ciruclating current.
- Minimize energy and current fluctuations.
- Use constraints to regulate the average energy.

MMC circulating current calculation for phase independent control

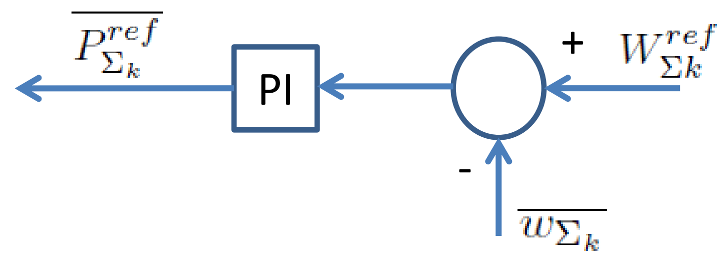
Objective function: Minimize the capacitive energy fluctuations & circulating current oscillations

$$min \rightarrow \frac{1}{T}\int_{to}^{to+T}\left[\alpha\left(\dot{w}_{\Sigma k}\right)^2+(1-\alpha)\left(v_{dc}i_{ck}\right)^2\right]dt$$

Constraints: The capacitive energy distribution (sum and difference) is being imposed.

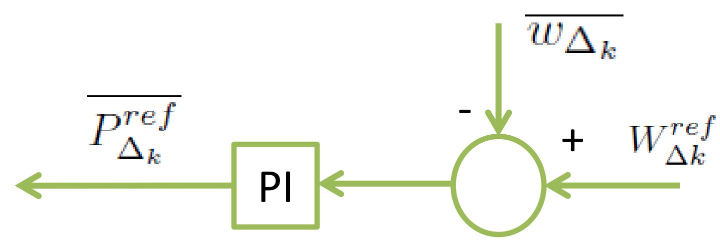
$$\frac{1}{T}\int_{to}^{to+T}\left(-e_{vk}i_{vk}+v_{dc}i_{ck}\right)dt=\overline{P_{\Sigma_k}^{ref}}$$

Average Dynamics of the Arm energy **Sum**



Average Dynamics of the Arm energy **Difference**

$$\frac{1}{T}\int_{to}^{to+T}\left(\frac{i_{vk}}{2}v_{dc}-2e_{vk}i_{ck}\right)dt=\overline{P_{\Delta_k}^{ref}}$$



MMC circulating current calculation for phase independent control (1/2)

Weighting factor

Objective function: Minimize the capacitive energy fluctuations & differential current oscillations

Lagrange Equation:

$$\mathcal{L}\left(i_{ck},\lambda_{\Sigma},\lambda_{\Delta}\right)=\frac{1}{T}\int_{to}^{to+T}\left[\alpha\left(\dot{w}_{\Sigma k}\right)^{2}+\left(1-\alpha\right)\left(v_{dc}i_{diffk}\right)^{2}\right]dt+\lambda_{\Sigma}\left(\overline{\dot{w}_{\Sigma k}}\left(t\right)-\overline{P^{ref}_{\Sigma_k}}\right)+\lambda_{\Delta}\left(\overline{\dot{w}_{\Delta k}}\left(t\right)-\overline{P^{ref}_{\Delta_k}}\right)$$

Lagrange's Multipliers

Constraints: The capacitive energy distribution (sum and difference) is being imposed.

By solving:

$$\nabla_{\left(i_{ck},\lambda_{\Sigma},\lambda_{\Delta}\right)}\mathcal{L}\left(i_{ck},\lambda_{\Sigma},\lambda_{\Delta}\right)=0$$

MMC circulating current calculation for phase independent control (2/2)

Energy Sum Controller

Weighting factor

Grid Instantaneaous Power

Energy Diff. Controller

MMC Load internal emf

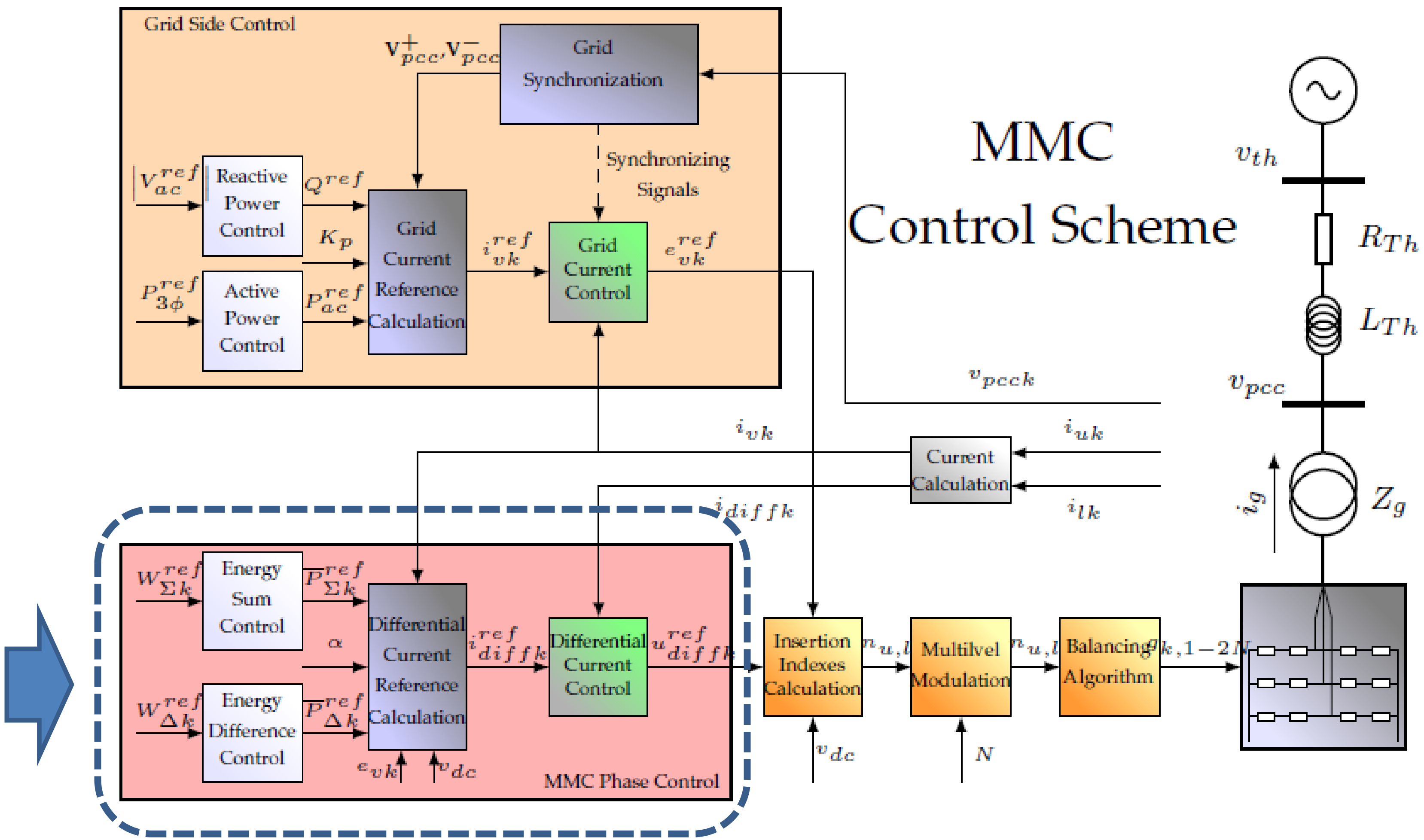
$$i_{ck} = \frac{\overline{P}^{ref}_{\Sigma k} + (1-\alpha)\overline{P}_{vk}}{v^2_{dc}} v_{dc} + \frac{\alpha P_{vk}}{v_{dc}} + \frac{-\overline{P}^{ref}_{\Delta k} e_{vk}}{2v^2_{dc}\left(e^{rms}_{vk,p.u.}\right)^2}$$

Voltage between MMC DC terminals

$$\overline{P}_{vk} = \frac{1}{T}\int_{to}^{to+T} e_{vk} i_{vk} dt$$

$$\left(e^{rms}_{vk,p.u.}\right)^2 = \frac{1}{T}\int_{to}^{to+T} \frac{e^2_{vk}}{v^2_{dc}} dt$$

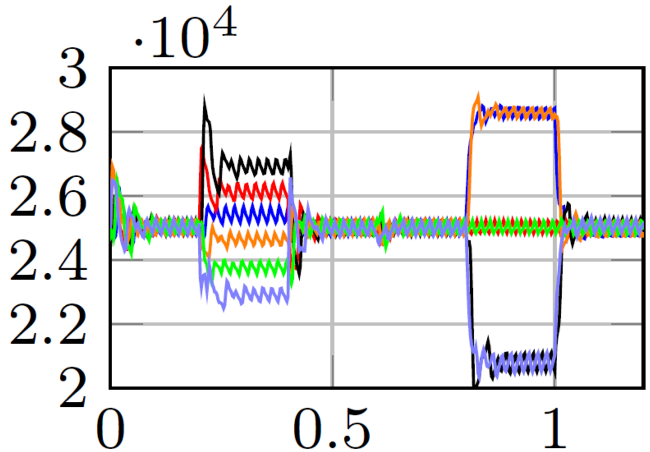
Control Scheme – Phase Independent Control of the MMC based on Mathematical Optimization

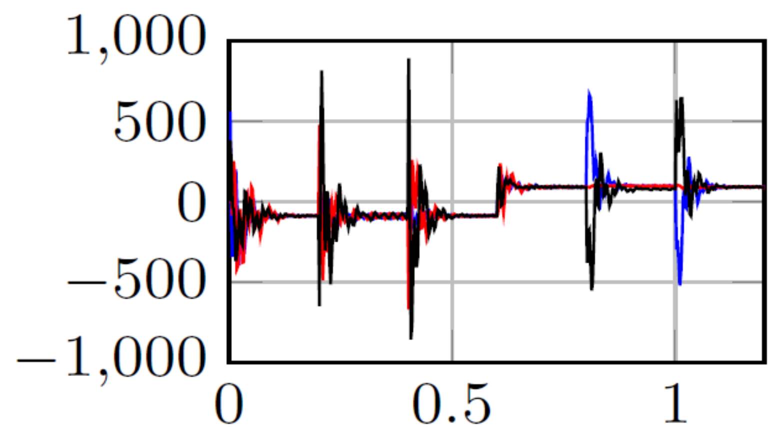


Some Simulation Results:

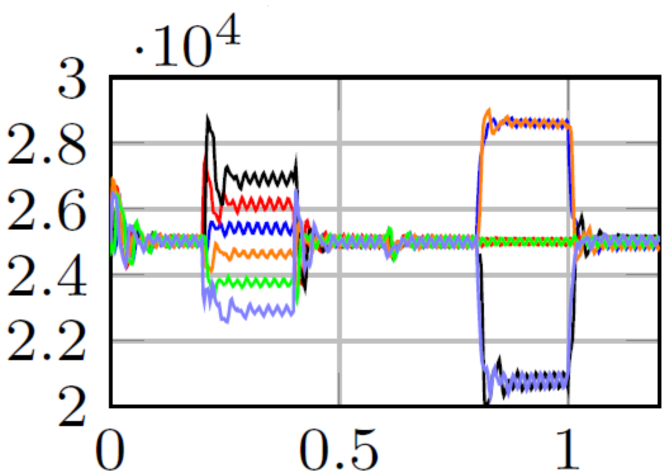
Capacitor Voltages (V) | Differential Currents (A)

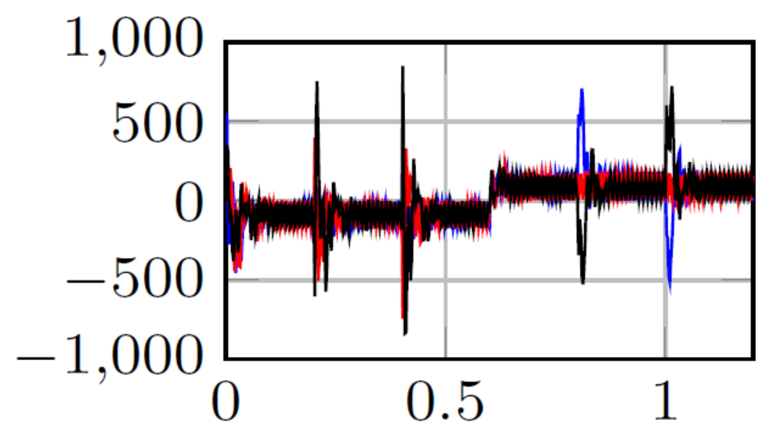
$\alpha=0$





$\alpha=1$



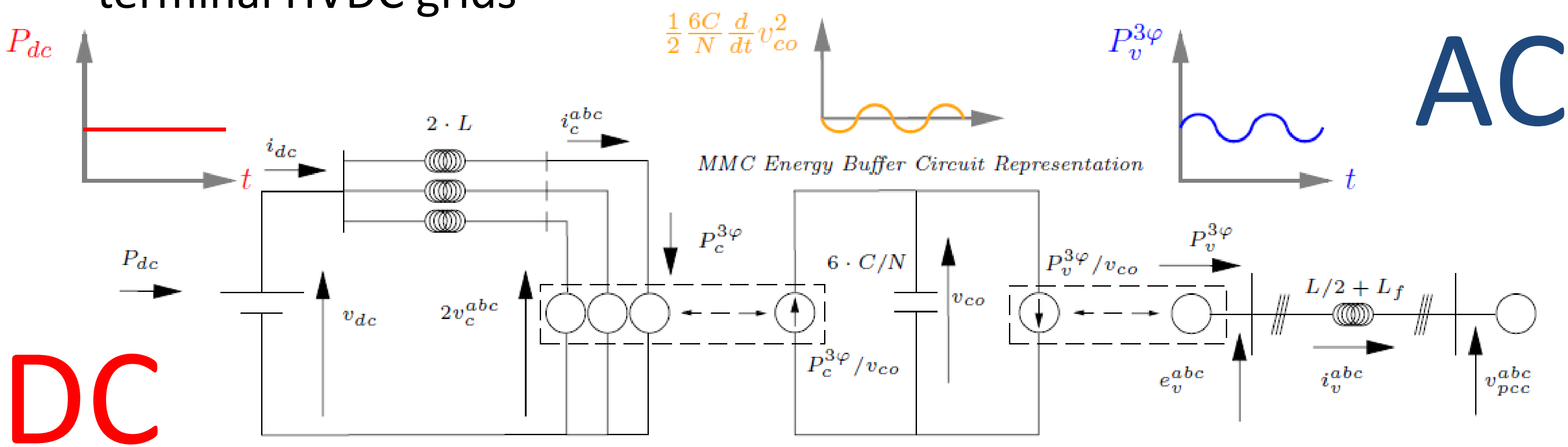


Part III: The MMC Energy Buffer

CIRCULATING CURRENT SIGNAL FOR CONSTANT POWER UNDER UNBALANCED GRID CONDITIONS

Conceptual possibilities of the MMC under unbalanced conditions

- The distributed sub-module capacitors of the MMC can be used to accumulate power oscillations and prevent them from propagating into the DC side, by properly controlling the circulating current.
- The grid current is left free for other purposes: constant grid active power, constant grid reactive power, balanced currents.
- MMC can be operated as a "Power Oscillation Firewall" for multi-terminal HVDC grids



Circulating current reference calculation suited for unbalances.

- Limitations of the circulating current reference equation:
  - The optimization procedure used considered each phase of the MMC completely independent!
  - This implies that it did not include the possibility for optimizing the operation of a 3-phase converter under an unbalanced condition in the AC grid.
- A new optimization is therefore required!
  - The goal is to always ensure constant power at the DC terminals of the converter.

New Optimization Problem, suitable for unbalanced grid conditions:

Reduce the difference between the NEW circulating current and the one previously calculated.

$$\mathcal{L}\left(i_{ck},\lambda\right) = \left(i_{ck} - \mathrm{I}_{ck}^{*Eq.}\right)^2 + \lambda\left(v_{dc}\sum_{k\in(abc)} i_{ck} - P_{dc}^{ref}\right)$$

Constant Power at the DC terminals of the MMC

Former circulating current equation

$$\frac{\overline{P}_{\Sigma k}^{ref} + (1-\alpha)\,\overline{P}_{vk}}{v_{dc}^2}v_{dc} + \frac{\alpha P_{vk}}{v_{dc}} + \frac{-\overline{P}_{\Delta k}^{ref}\,e_{vk}}{2v_{dc}^2\left(e_{vk,p.u.}^{rms}\right)^2}$$

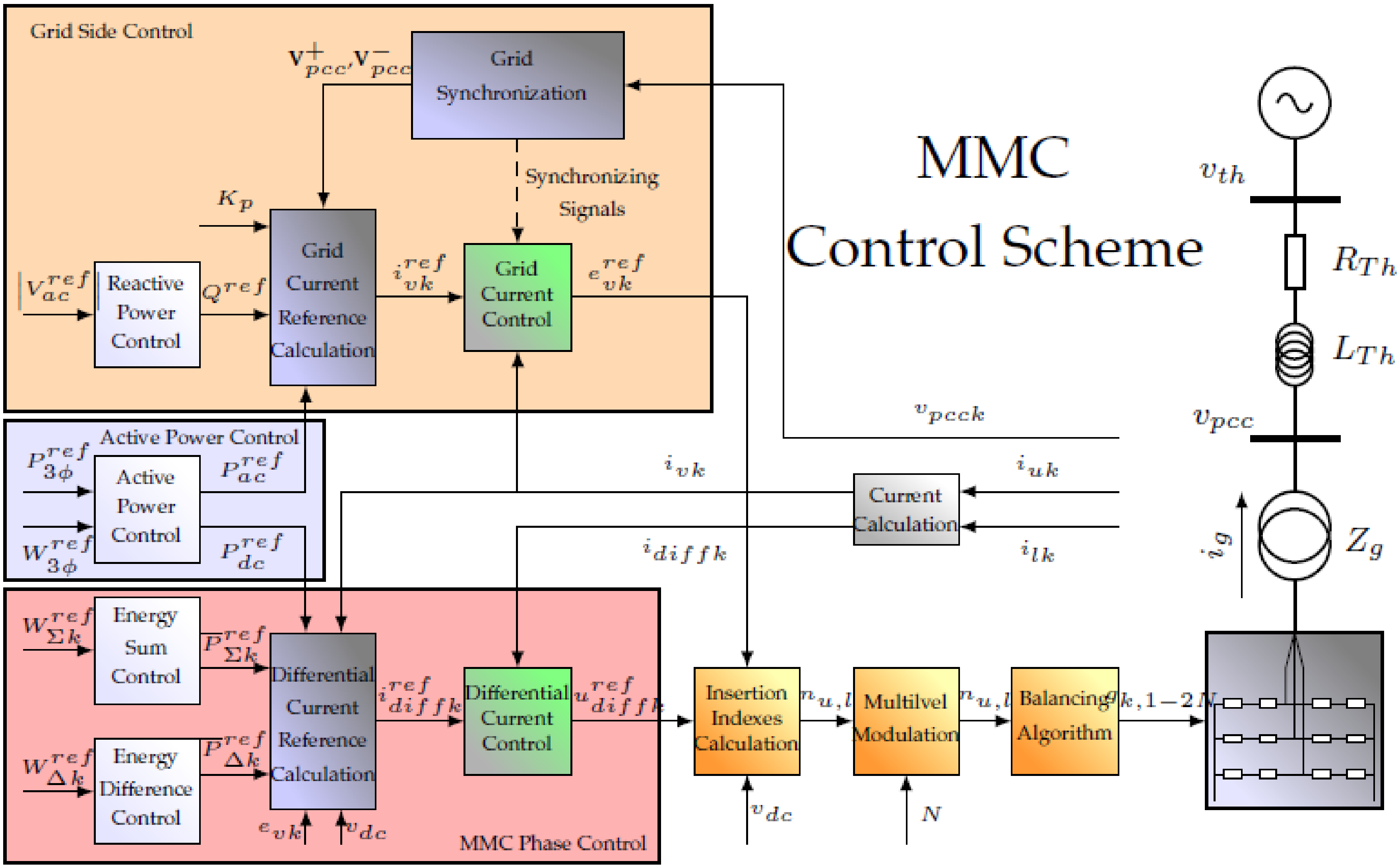
Solving: $\nabla_{(i_{diffk},\lambda)}\mathcal{L}(i_{diffk},\lambda)$, we obtain:

$$i_{ck} = \mathbf{I}^*_{ck} + \underbrace{\frac{1}{3}\frac{P^{ref}_{dc}}{v_{dc}}}_{\text{Possibility to control the DC power through the circulating current}} - \frac{1}{3}\sum_{k\in(abc)} \mathbf{I}^*_{ck}$$

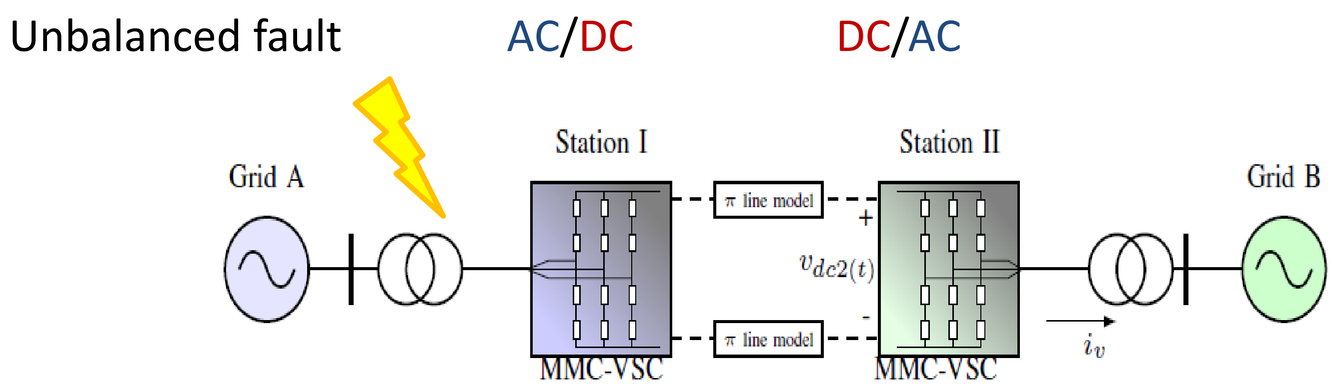
Or the more extended version:

$$i_{ck} = \frac{\overline{P}^{ref}_{\Sigma k} + (1-\alpha)\overline{P}_{vk}}{v_{dc}^2}v_{dc} + \frac{\alpha P_{vk}}{v_{dc}} + \frac{-\overline{P}^{ref}_{\Delta k} e_{vk}}{2v_{dc}^2\left(e^{rms}_{vk,p.u.}\right)^2}$$
$$- \sum_{k\in(abc)}\left(\frac{\overline{P}^{ref}_{\Sigma k} + (1-\alpha)\overline{P}_{vk}}{v_{dc}^2}v_{dc} + \frac{\alpha P_{vk}}{v_{dc}} + \frac{-\overline{P}^{ref}_{\Delta k} e_{vk}}{2v_{dc}^2\left(e^{rms}_{vk,p.u.}\right)^2}\right) + \frac{1}{3}\frac{P^{ref}_{dc}}{vdc}$$

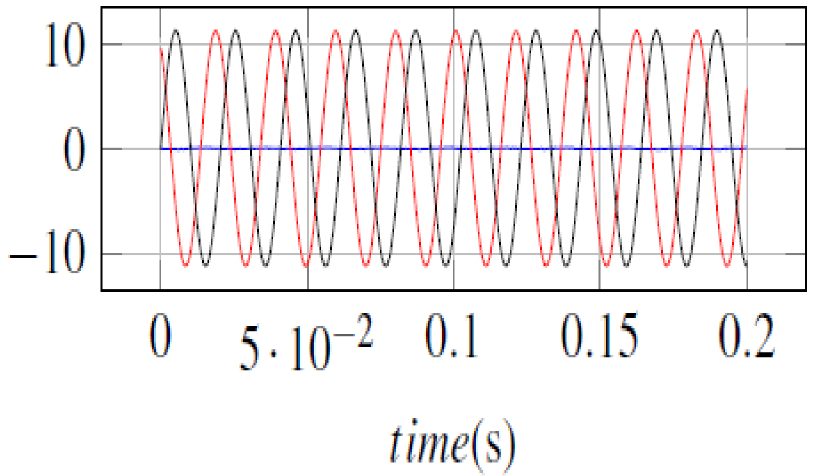
MMC Control Scheme suitable for balanced and unbalanced grid operation



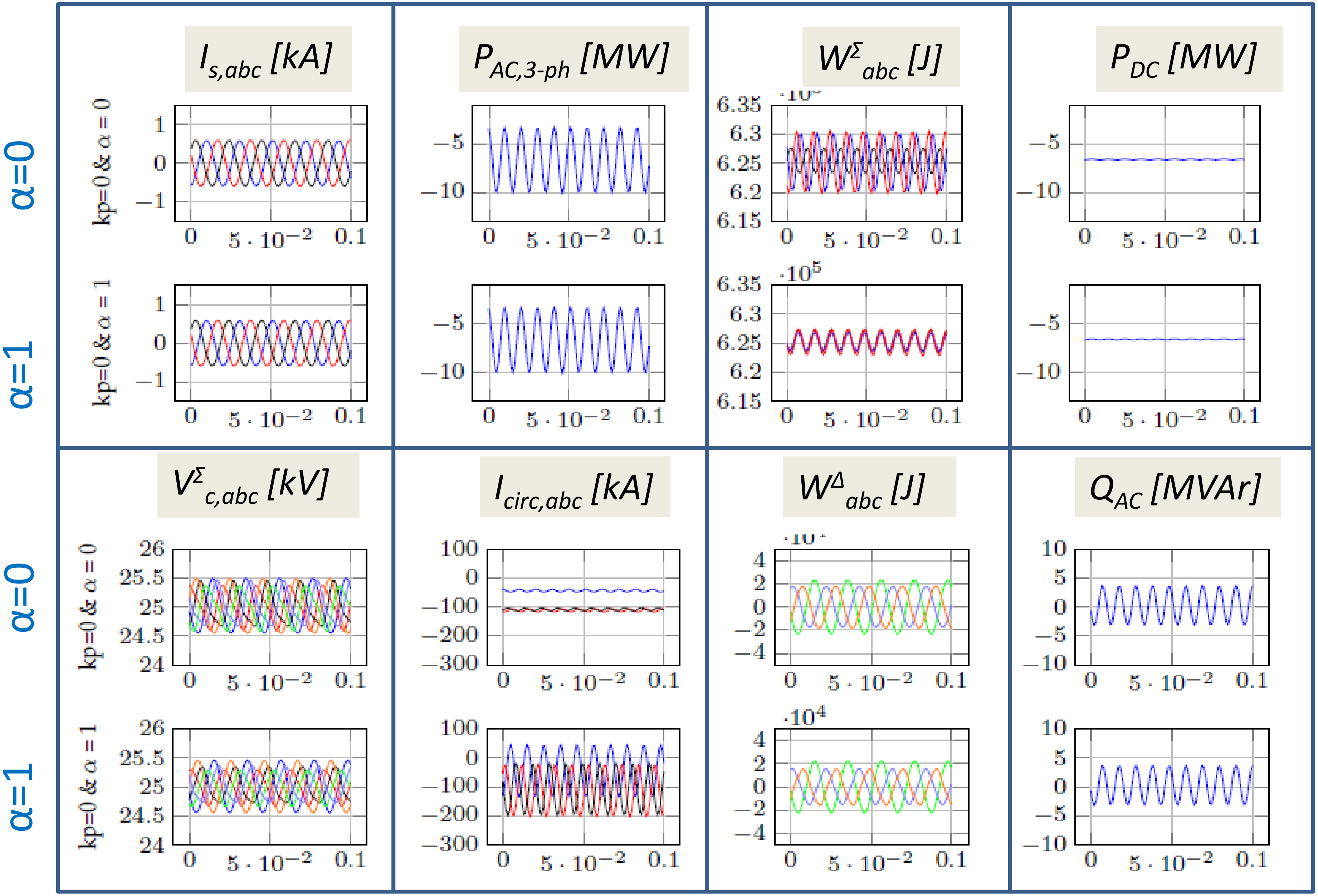
Simulation Results



Parameter	Value
Number of SM per arm	100
SM Nominal Voltage	5kV
SM Capacitance	5mF
Arm Inductance	3mH
Arm Resistance	0.1Ω



Proposed Control scheme suited for unbalances



Operation with α=0: Constant differential current

Operation with α=1: Minimized sum energy oscillations for all phases

Almost done!

CONCLUSIONS

- An control scheme in the "abc" frame, based on mathematical optimization is presented.
  - Using the Lagrange multipliers method, it is posible to calculate a minimized circulating current equation used as reference for the control action.
  - The control is able to ensure constant, non-oscillatory power flow at the DC side of the converter, even under unbalanced grid conditions.
- Such operation can be especially relevant for (multi-terminal) HVDC systems, where power fluctuations, and thus DC voltage fluctuations must be avoided because they negatively influence other converters connected to the same DC grid.

Merci!