An Introduction to Modular Multilevel Converters

UNIVERSIDAD DE CHILE

Roberto Cárdenas Dobson
Full professor, PhD, Msc., Bsc.
Department of Electrical Engineering
University of Chile

UNIVERSIDAD DE CHILE

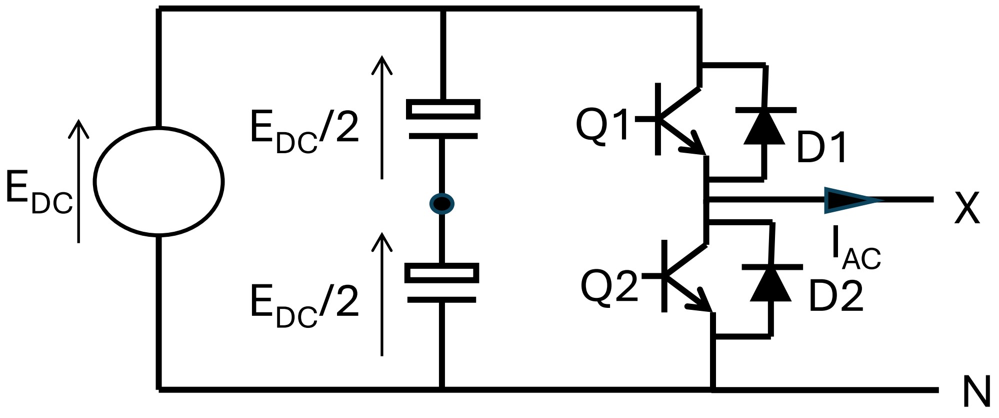
Modular Multilevel Converters

- There are three main topologies in the Modular Multilevel Chain Converter family.

- These are the M2C, (modular multilevel converter), the M3C or modular multilevel matrix converter and the H-MMC also known as Hexverter.

- The most important topology is the M2C, because of its applications in high-voltage dc transmission. It is also the topology with more real-life applications.

Half Bridge

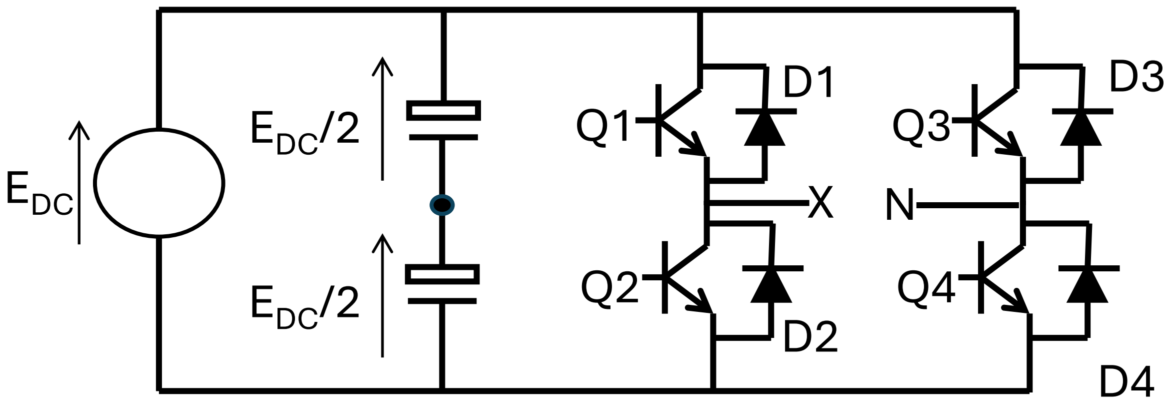


2-level Inverter leg

The basic building block of MMC and 2-level converters

Gated Device	Direction of I_{AC}	Conducting Device	V_{XN}
Q1	+	Q1	$+E_{DC}$
Q1	-	D1	$+E_{DC}$
Q2	+	D2	0
Q2	-	Q2	0

Full Bridge

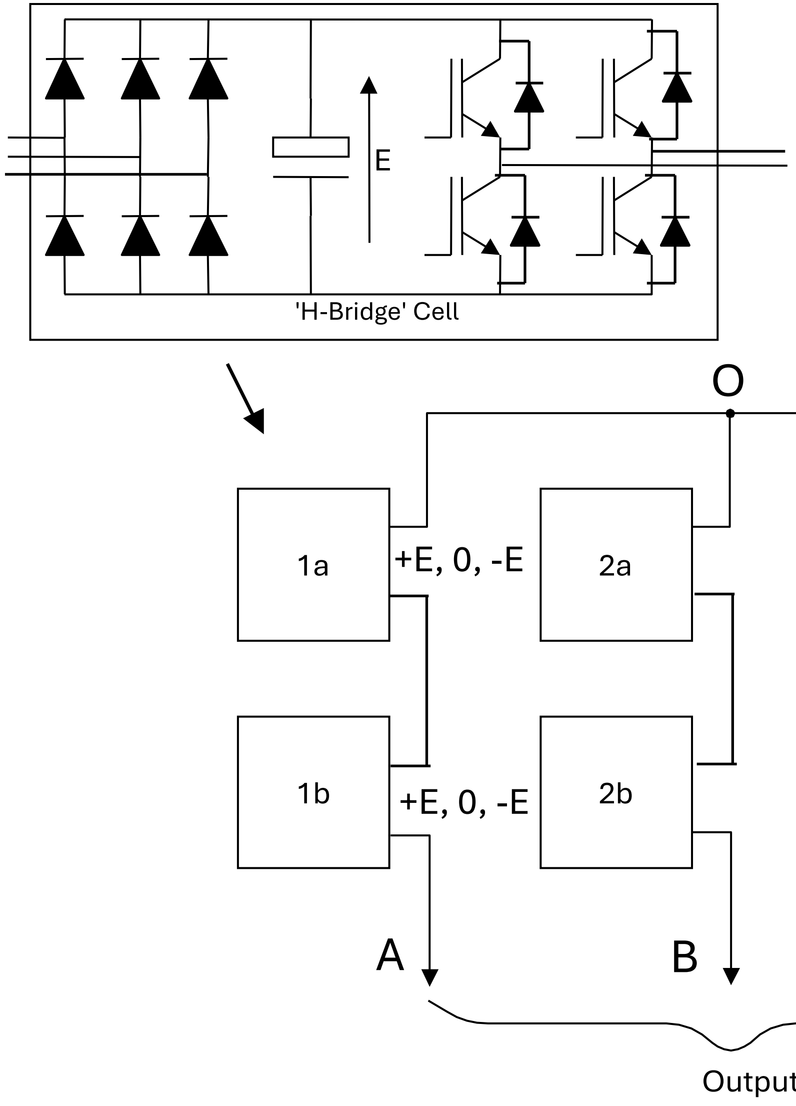


3-level topology and produce negative and positive voltage.

The basic building block of M3C and H-MMC Topologies

Gated Device L1	Gated Device L2	V_{XN}
Q1	Q3	0
Q1	Q4	$+E_{DC}$
Q2	Q3	$-E_{DC}$
Q2	Q4	0

The cascade H-bridge Converter

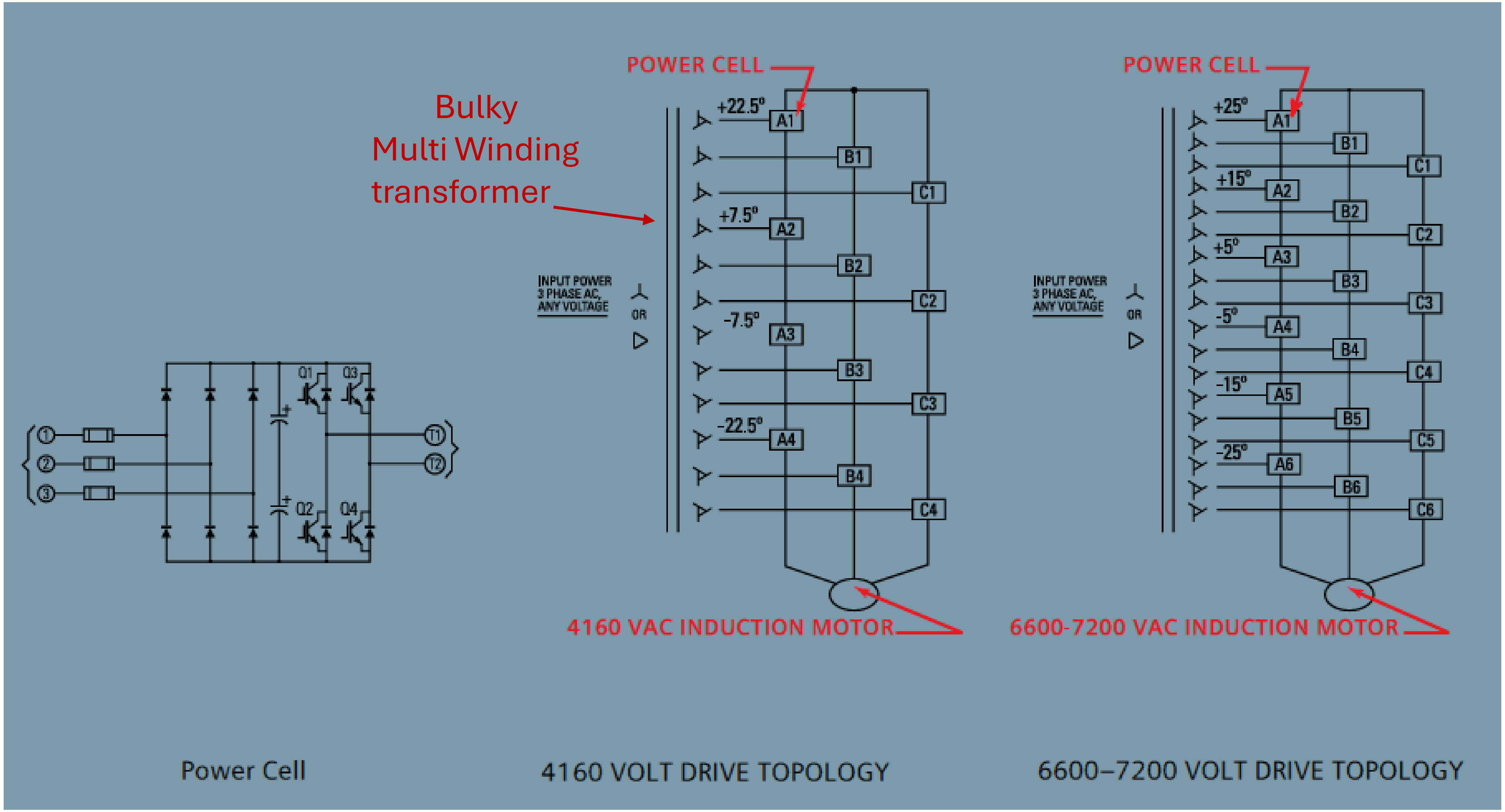


- Each H-bridge must have an isolated DC supply - usually derived from an isolated AC supply via a diode bridge
- Each bridge can produce +E, 0, -E independently

With K H-bridges per phase, V_{AO} etc has 2K+1 levels and V_{AB} has 4K+1 levels

Circuit shown has 5-levels in V_{AO} and 9-levels in V_{AB}

Perfect Harmony or Robicon Drive System



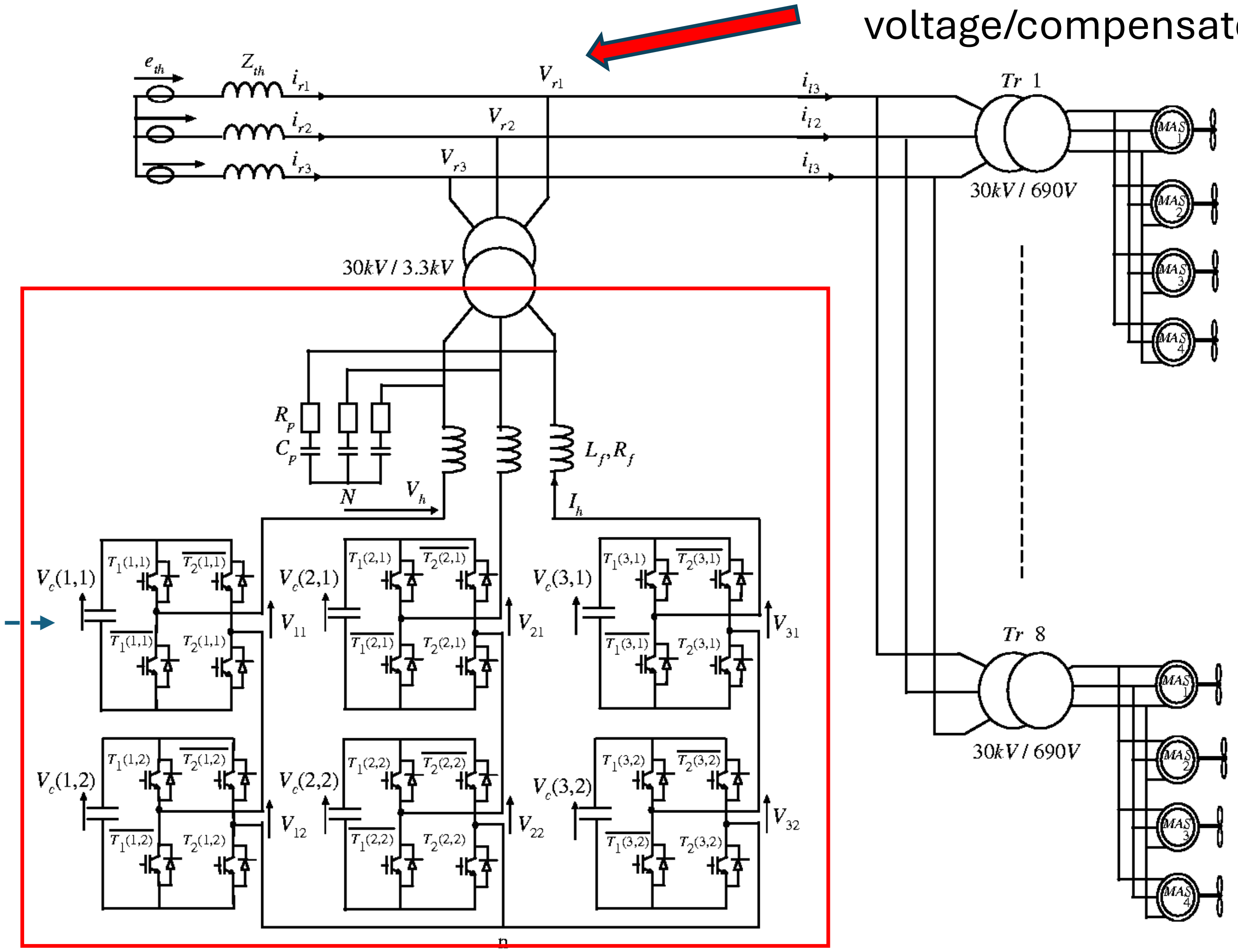
Phase shifting transformer gives cancellation of rectifier harmonics at the input side

Low Power Density Solution

Cascaded H-Bridge Converter

320 MVAR
30KV

Inject reactive power to stabilise grid voltage/compensate power factor



Floating dc-link Capacitor
Similar to the M2C topology

Static VAR compensator (STATCOM)
Reactive power only – no need for DC side power source

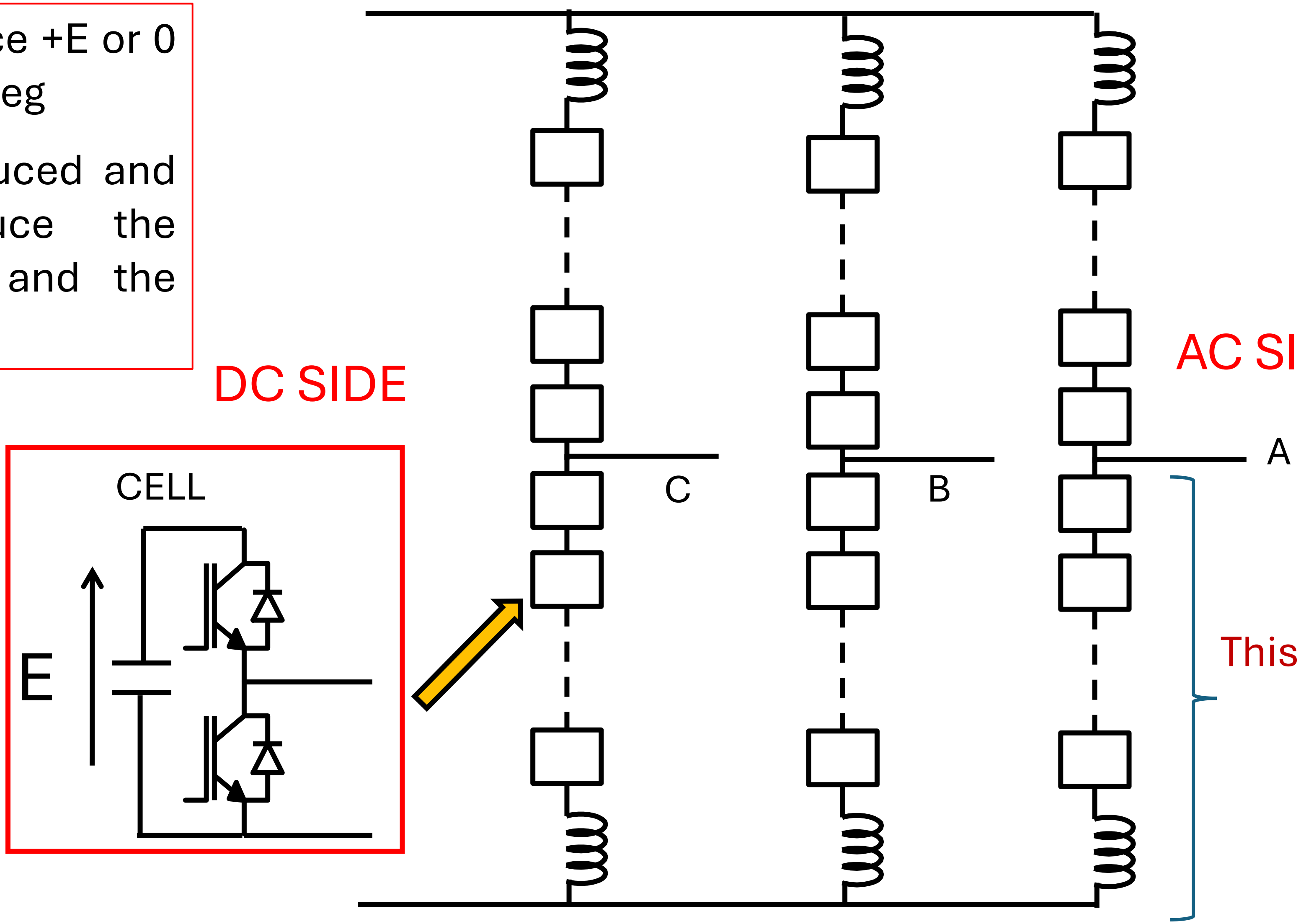
Marquardt Converter or Modular Multilevel Converter

Modular-Multilevel-Converter (M^2LC)

Each cell can introduce +E or 0 into the chain in each leg

Cells must be introduced and removed to produce the desired AC voltage and the correct DC voltage

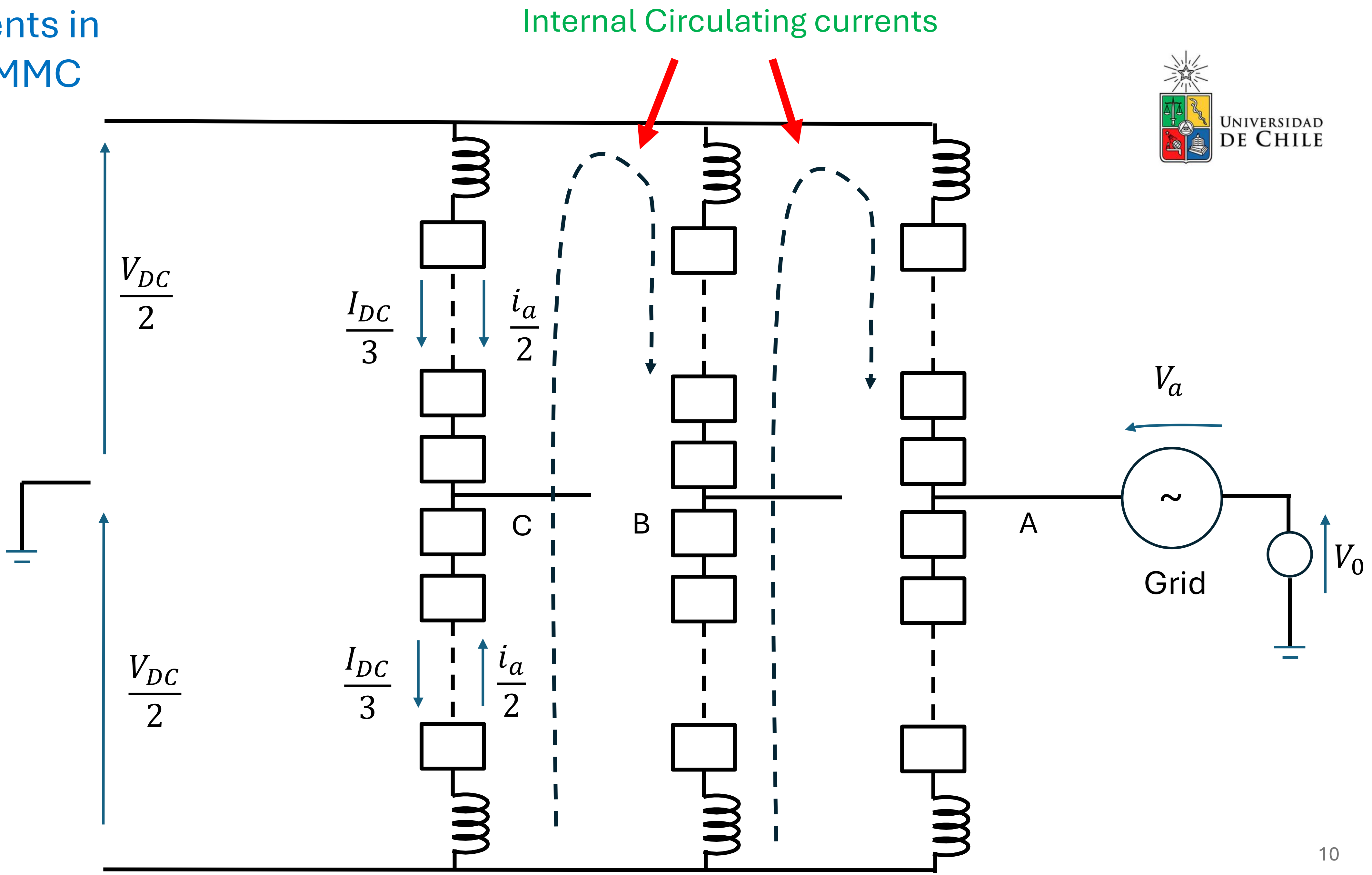
Floating Capacitors!!



AC SIDE

This is usually called "cluster"

Currents in the MMC

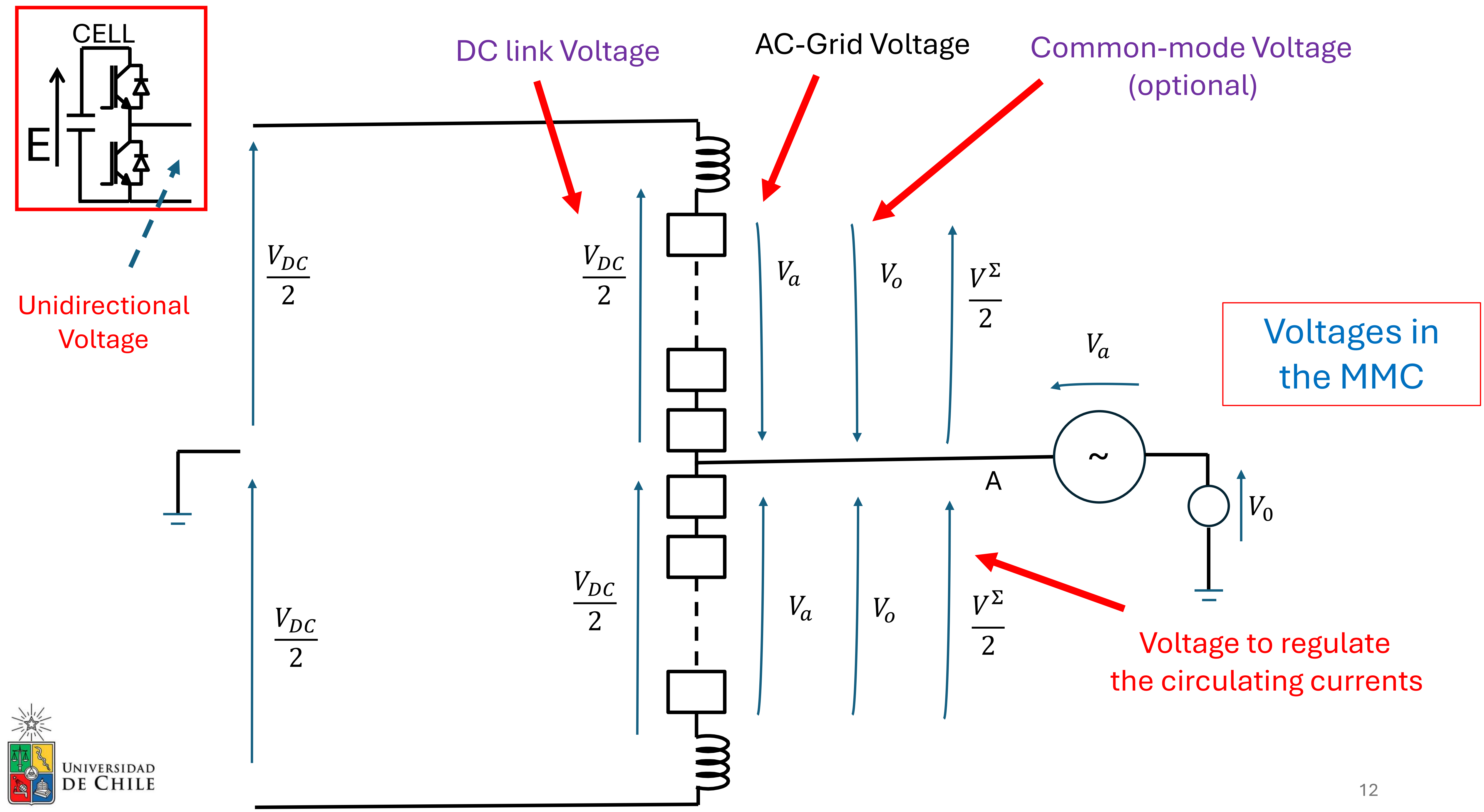


Currents in the MMC

- In steady-state operation, the current in each cluster is $I_{dc}/3 + i_{ac}/2$.

- To balance the energy in all the clusters two degrees of freedom are available. The circulating currents and the common mode voltage.

- The circulating currents are internals to the converter, they neither appear at the AC nor at the DC side. They are usually composed of different frequencies and different sequences.


CELL
E
Unidirectional Voltage
DC link Voltage
AC-Grid Voltage
Common-mode Voltage (optional)
Voltages in the MMC
$\frac{V_{DC}}{2}$
$\frac{V_{DC}}{2}$
V_a
V_o
$\frac{V^{\Sigma}}{2}$
V_a
A
V_0
$\frac{V_{DC}}{2}$
$\frac{V_{DC}}{2}$
V_a
V_o
$\frac{V^{\Sigma}}{2}$
Voltage to regulate the circulating currents
Universidad de Chile

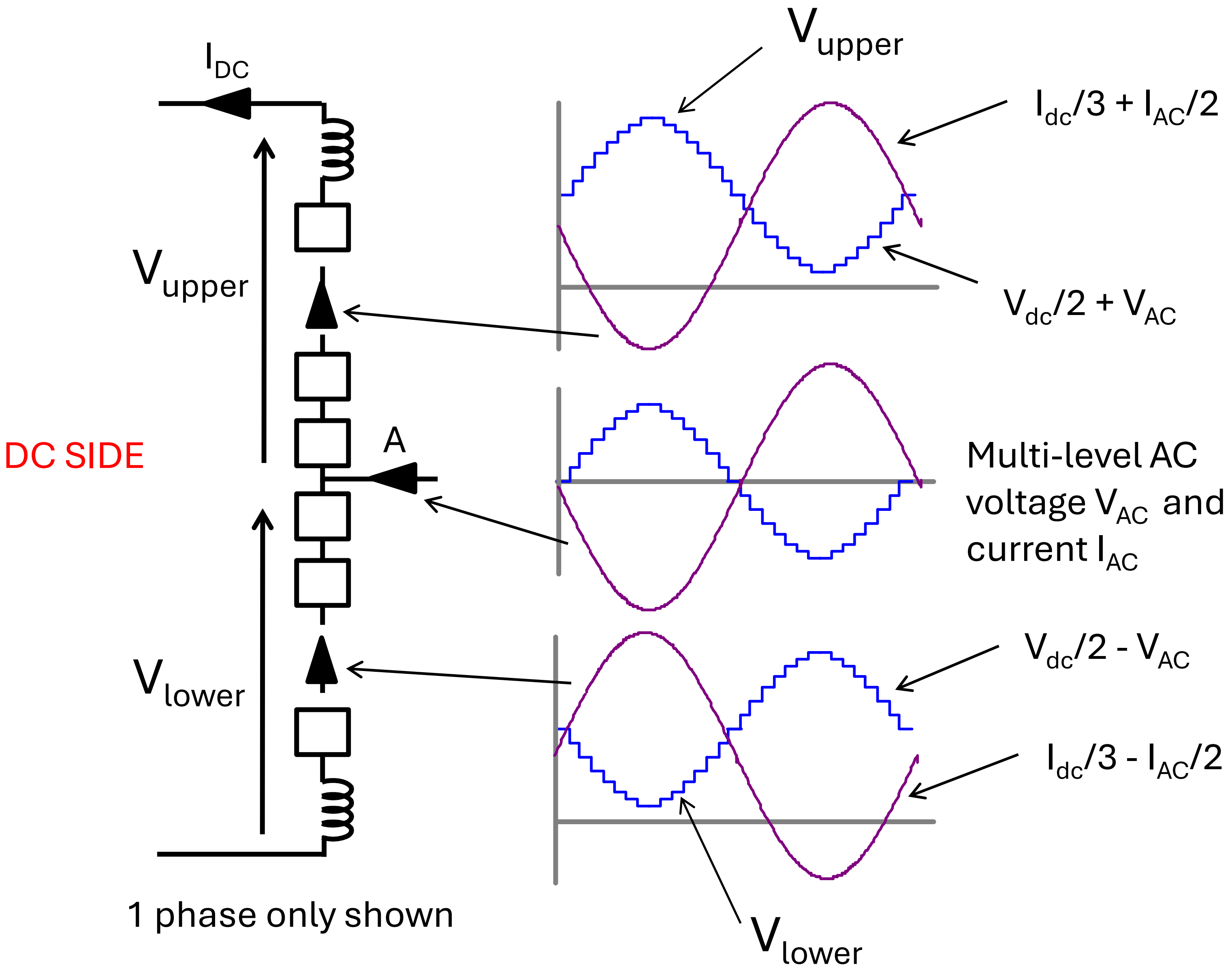
Voltages in the MMC

- Each cluster in an MMC, synthesises at least two voltage components, $\frac{V_{dc}}{2}$ and v_a.

- Common-mode voltage could be added if required.

- “Circulating voltages”, required to impose the circulating currents, are also required.

Modular-Multilevel-Converter (voltage and Currents)



1 phase only shown

Marquardt Converter

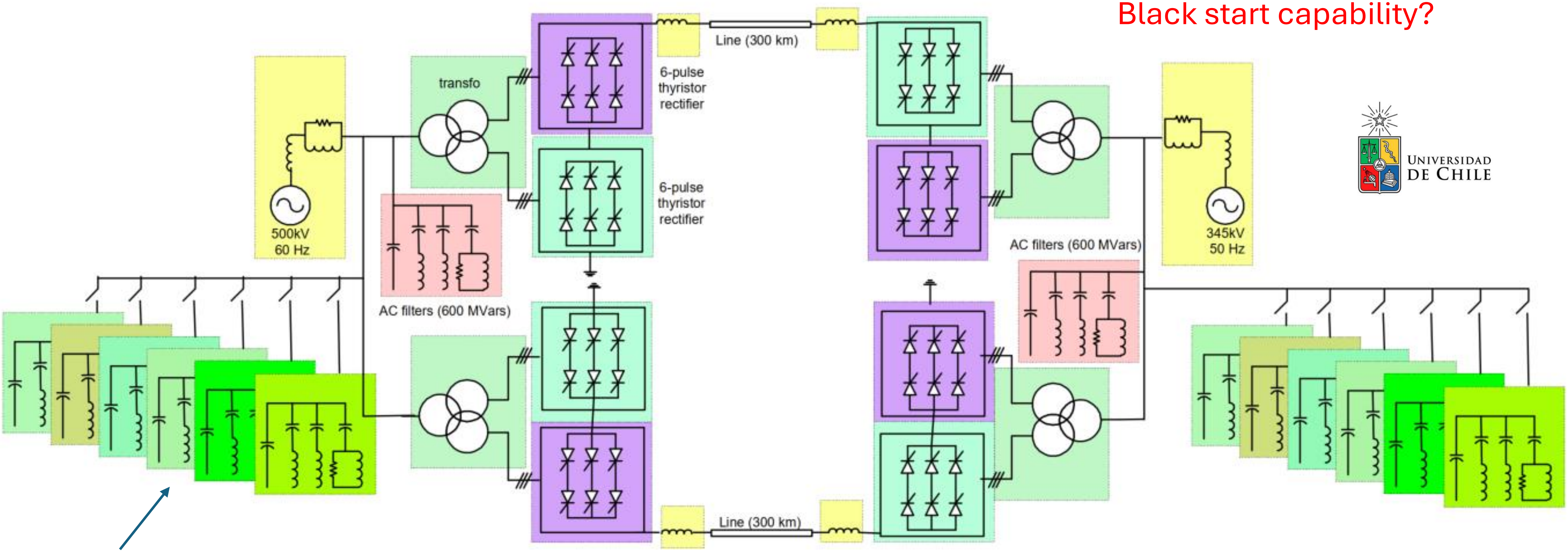
- The main application is HVDC transmission, replacing the previous topologies based on thyristors.

- Siemens has produced commercial solutions for drive applications. This is the “Perfect Harmony” series.

- A modified MMC, with a mix of half-bridges and full bridges in each cluster has also been proposed for HVDC transmission.

Previous Topologies for HVDC transmission

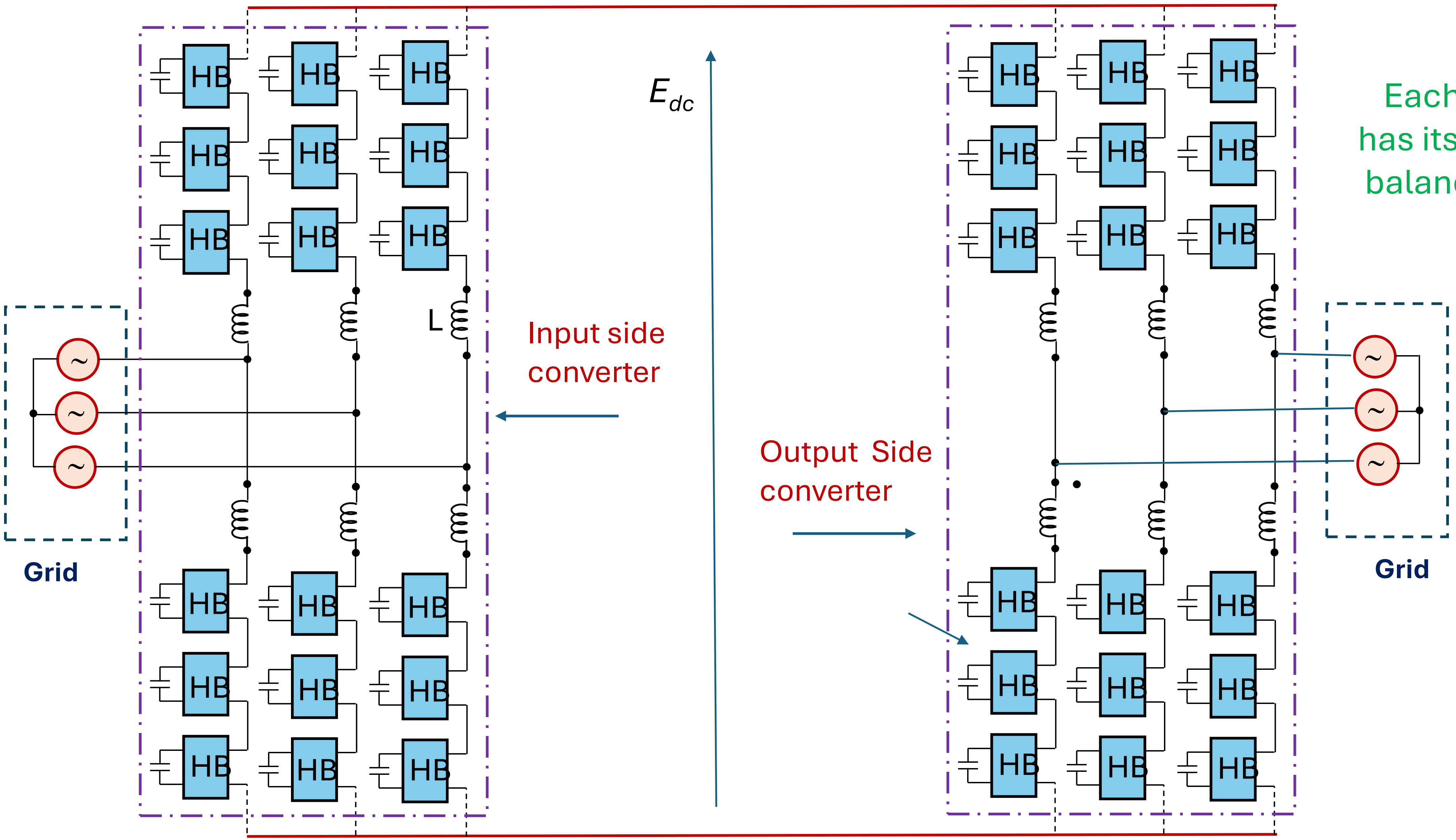
Black start capability?



A lot of filtering devices

Difficult to connect a distribution feeder in the middle of the line

HVDC Transmission using back-to-back MMCs



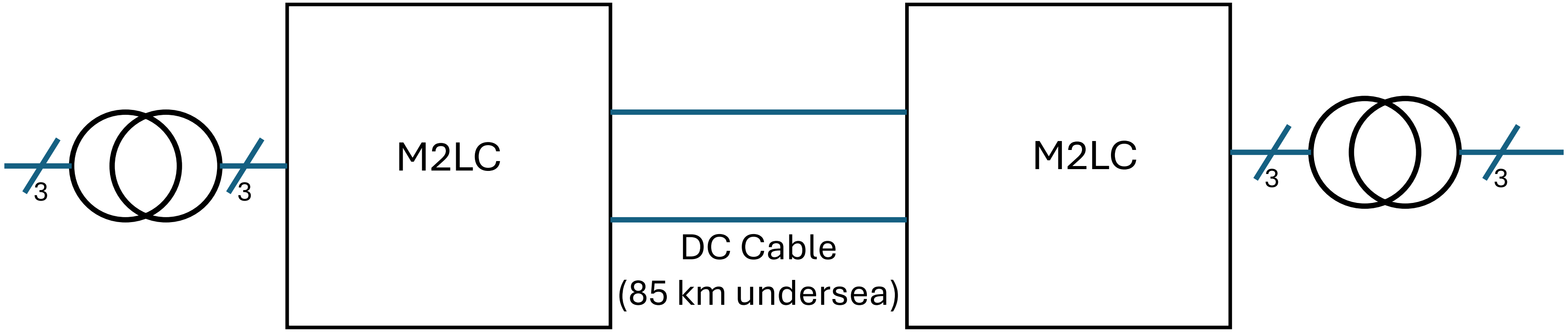
Each converter has its own energy balancing control

UNIVERSIDAD DE CHILE

Modular-Multilevel-Converter (M^2C)

(First commercial application of MMCs for HVDC)

The system was completed in November 2010. The Trans Bay Cable Project was the first commercially operated HVDC system to use the Siemens HVDC Plus Modular Multi-Level Converter (MMC) VSC system.



Switching device hall

Trans Bay Cable Project

Siemens HVDC Plus

400MW

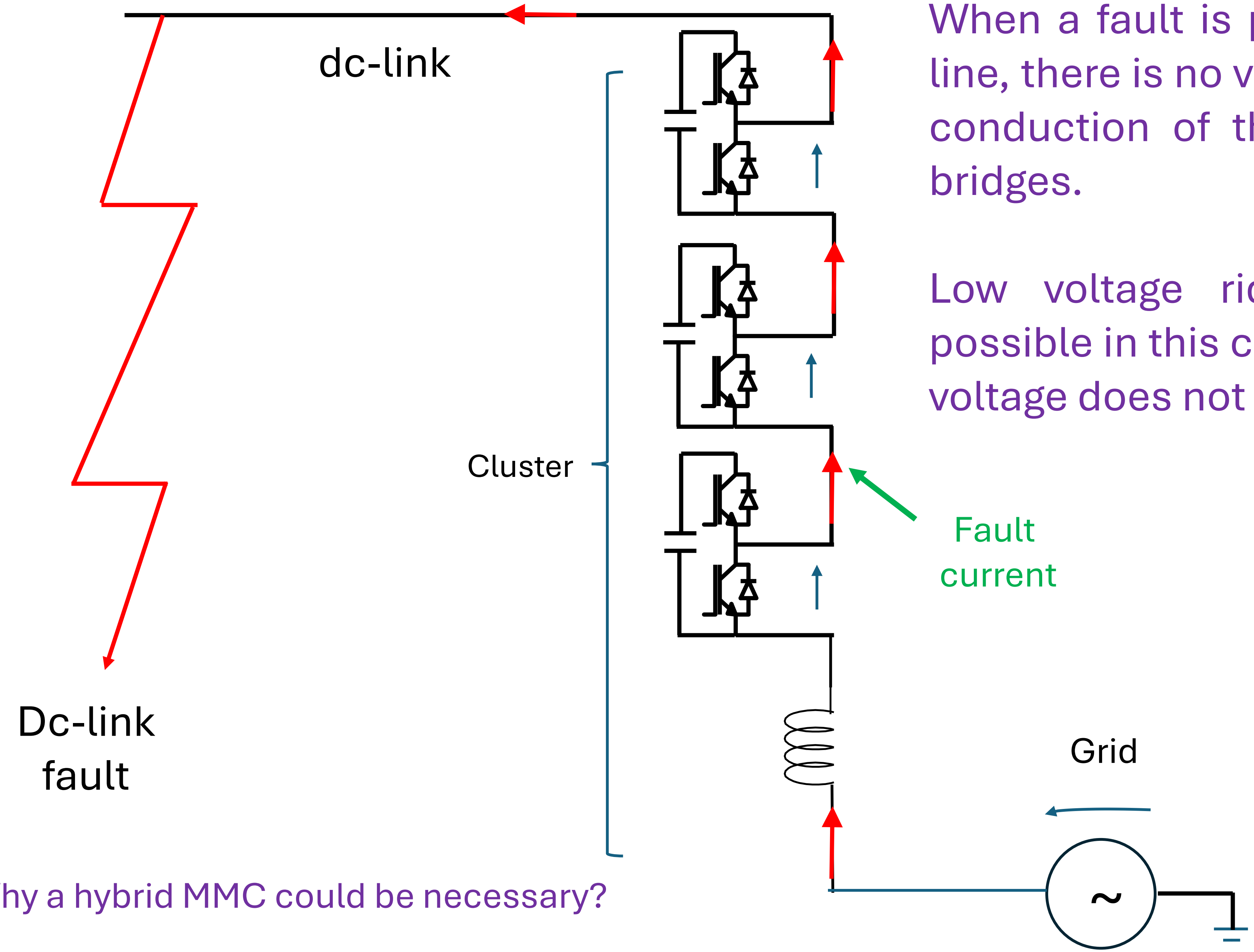
+-200kV DC

230kV/138kV AC

5184 IGBTs!

Hybrid MMC

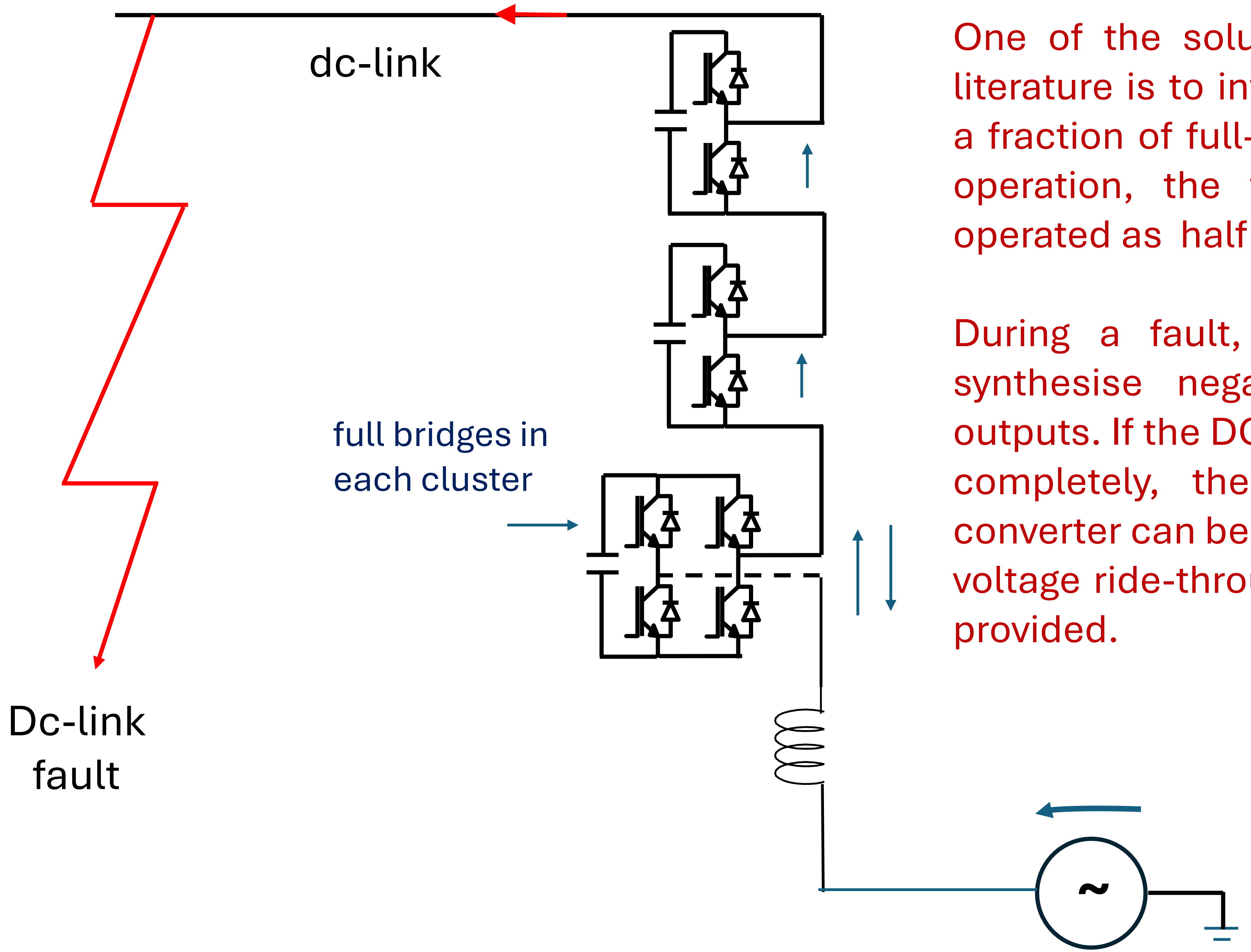
To the best of my knowledge, it is not commercially available.



When a fault is produced in an HVDC line, there is no voltage left to block the conduction of the diodes in the half bridges.

Low voltage ride-through is hardly possible in this case, even if the dc-link voltage does not collapse entirely.

Why a hybrid MMC could be necessary?



One of the solutions proposed in the literature is to introduce in each cluster a fraction of full-bridges. During normal operation, the full bridges could be operated as half bridges.

During a fault, the full bridges can synthesise negative voltage at their outputs. If the DC-link does not collapse completely, then the diodes of the converter can be blocked and some low-voltage ride-through capability could be provided.

Hybrid MMC

- Early work in the Hybrid-MMC was performed by Barry Williams (Glasgow). His group also discussed the application of the Hybrid-MMC in drives, because it reduces some problems of MMC, such as reducing the circulating current at the machine's starting-up.

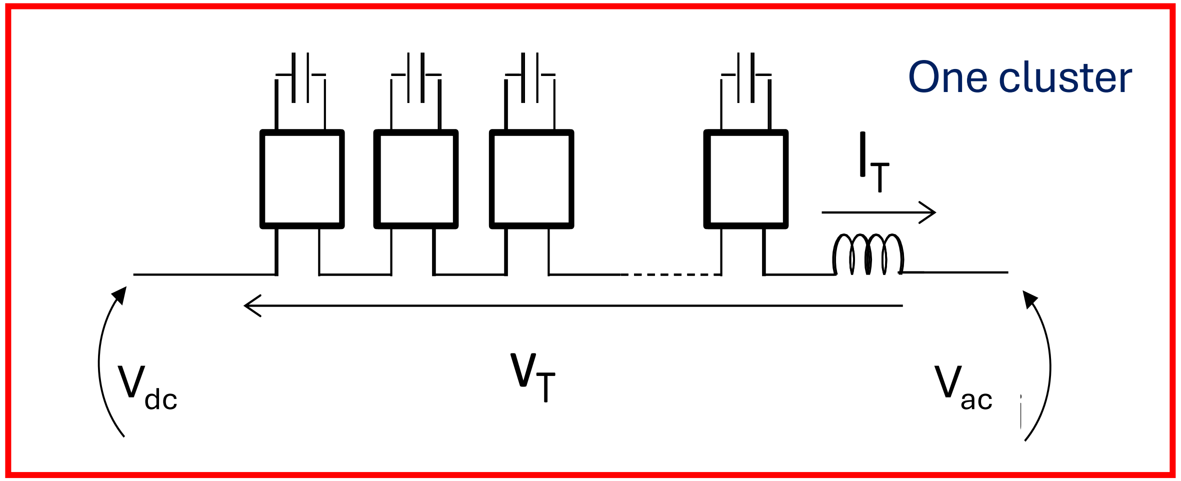
- Operating the MMC with reduced voltage during a dc-link fault, may produce problems for balancing the energy in the half-bridge cells. This has been studied by some people including one of our PhD students.

B. Li, S. Zhou, D. Xu, S. J. Finney, and B. W. Williams, "A hybrid modular multilevel converter for medium-voltage variable-speed motor drives,'' IEEE Trans. Power Electron., vol. 32, no. 6, pp. 4619–4630, Jun. 2017

F. Donoso, R. Cardenas, M. Espinoza, J. Clare, A. Mora and A. Watson, "Experimental Validation of a Nested Control System to Balance the Cell Capacitor Voltages in Hybrid MMCs," in IEEE Access, vol. 9, pp. 21965-21985, 2021, doi: 10.1109/ACCESS.2021.3054340

MMC for Drive Applications

Problems with the MMC for Drive applications during machine starting-up



$$i_T = i_{dc} + i_{ac}$$

$$i_{ac} = I_m sin(\omega_e t)$$

ω_e= very low

$$P_T = (V_{dc} - V_{ac})(i_{dc} + i_{ac})$$

$$P_T = V_{dc} i_{dc} - V_{dc} i_{ac} - V_{ac} i_{dc} - V_{ac} i_{ac}$$

During starting up the current i_{ac} could be large if high torque is required. Moreover, at that operating point, the ac-side frequency is low. Hence, large low-frequency oscillations are produced in the instantaneous power P_T which are reflected as large low-frequency oscillations in the cluster capacitor voltages.

Solution for low-frequency oscillations in P_T

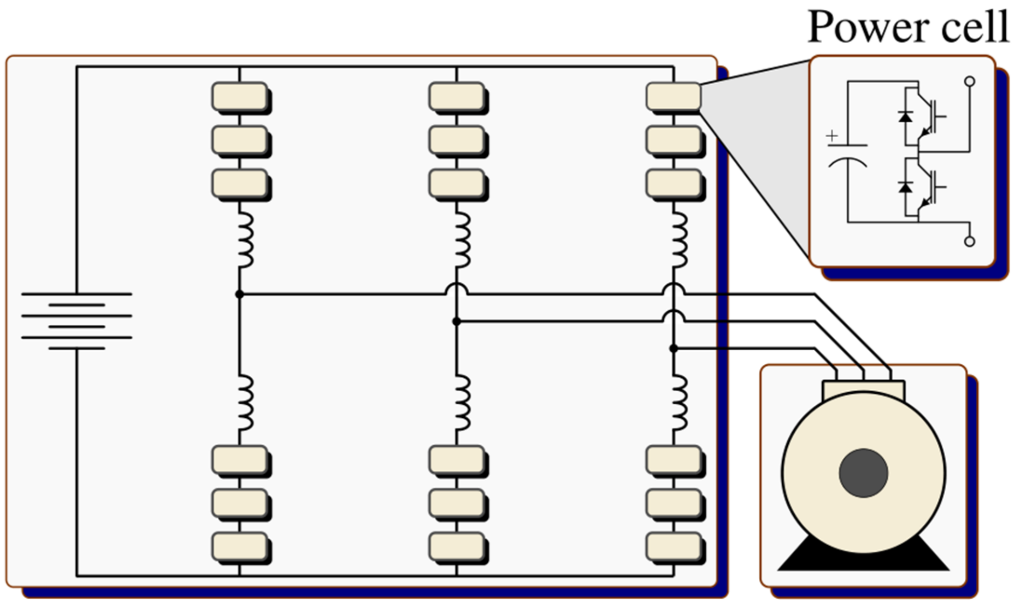
- The solution used to control the capacitor voltage oscillations during starting up is to use relatively large common-mode voltage and circulating currents to compensate for the capacitor voltage oscillations.

- However, according to the research group of Professor H. Akagi, the M2C is not a good solution for drives operating at low rotational speed with large torque current.

- According to them, the M2C is more suitable for applications where the electrical torque is proportional to ω_r^2. For instance, pumps and fans.

Y. Okazaki *et al*., "Experimental Comparisons Between Modular Multilevel DSCC Inverters and TSBC Converters for Medium-Voltage Motor Drives," in *IEEE Transactions on Power Electronics*, vol. 32, no. 3, pp. 1805-1817, March 2017, doi: 10.1109/TPEL.2016.2562103

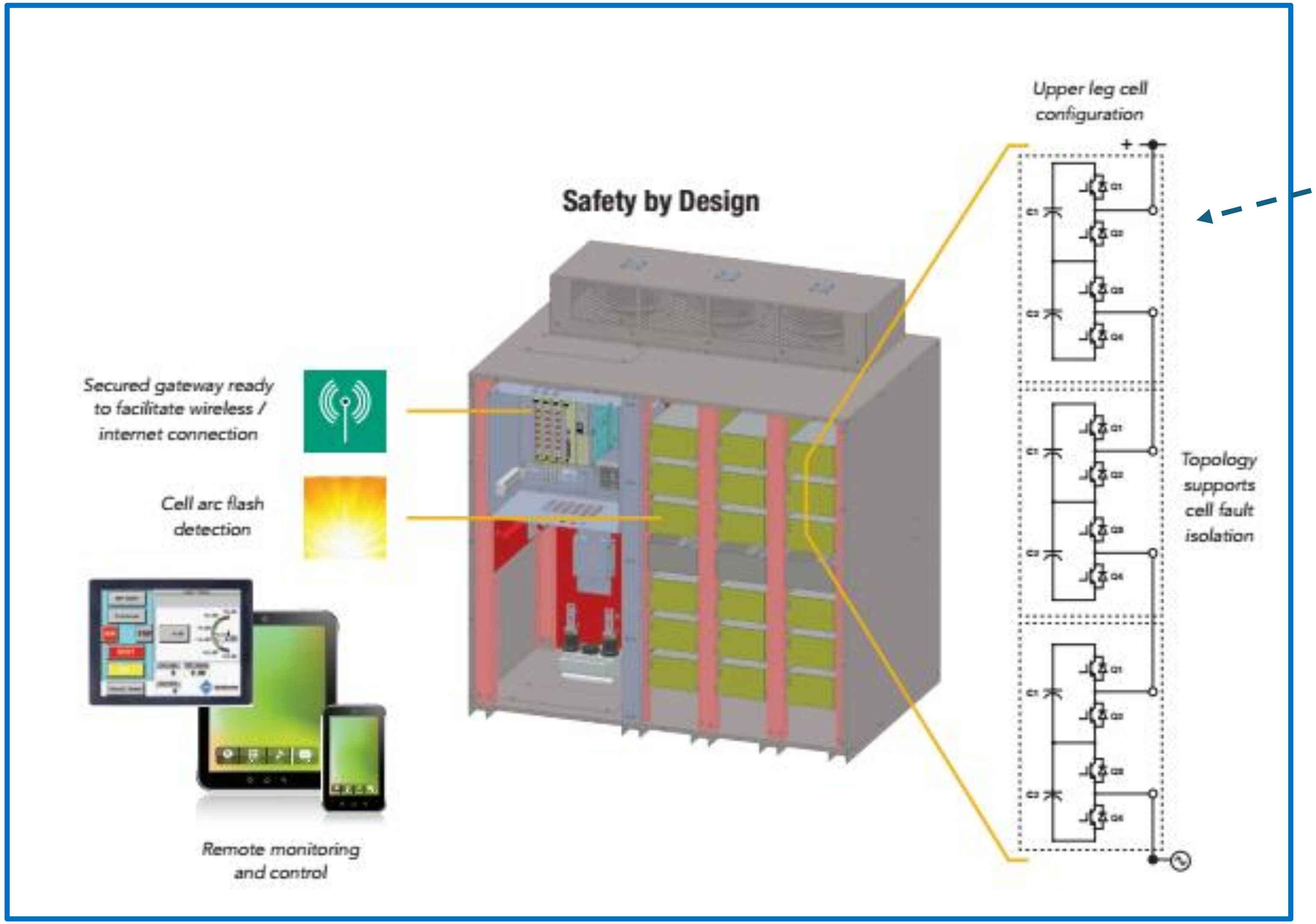
MMC for High Power Drive Applications



- Siemens and Benshaw (USA) have already produced commercial solutions for M2C based-drives in the MW range.

Commercial Solutions
Benshaw Drive

Benshaw Drive



Notice that they use a different type of cell.

2.3kV to 6.6KV
Nominal Power
up to $\approx 10MW$

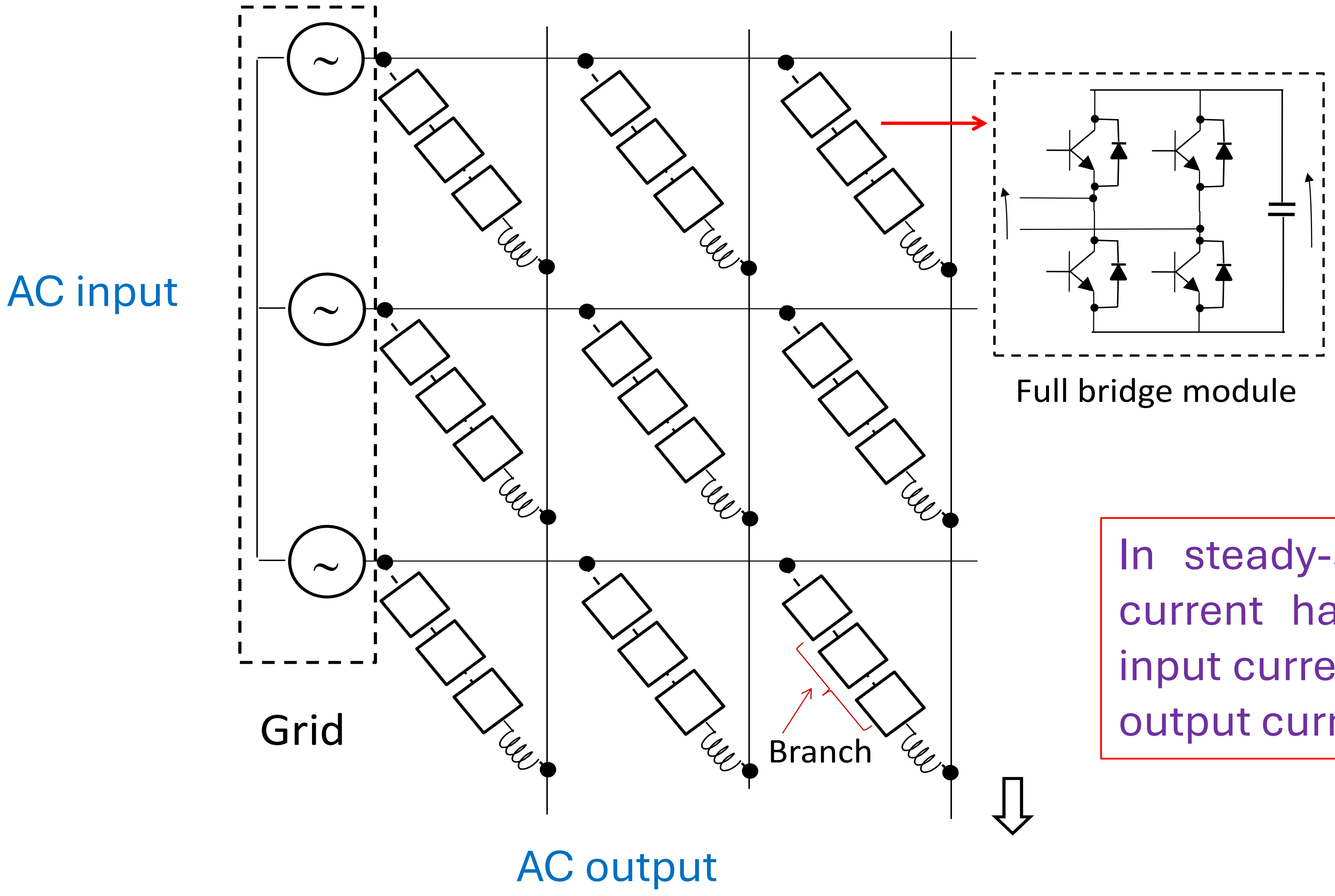
Siemens Drive (up to 13.3MW)

Drive Features	
Output power	4 – 13.3 MVA
Output voltage	ALM 3.3 – 6.6 kV MoM M2C 3.3 – 7.2 kV MoM NPC 3.3 – 4.4 kV BrM 4.16 – 6.6 kV
Cooling	Water-cooled
Topology	Line side: cell-based Multi-level Modular Converter (M2C), Diode Front End (DFE) or Basic Line Module Motor side: Multi-level Modular Converter or 3 Level Neutral Point Clamp (3L-NPC)
Drive quadrants	2 or 4 quadrant operation available
Rules and standards	IEC, EN, CE, EAC, CSA (on request)
Motor type	Induction motors (incl. high-speed motors) Synchronous motor for M2C (on request) Separately excited synchronous motors
Arc fault tested	Yes
Supply	Separate converter transformer (e.g. dry or oil-type) Transformerless configuration
Open/closed-loop control	Vector control with and without speed encoder
Efficiency of converter	98.5%

Universidad de Chile

Modular Multilevel Matrix Converter

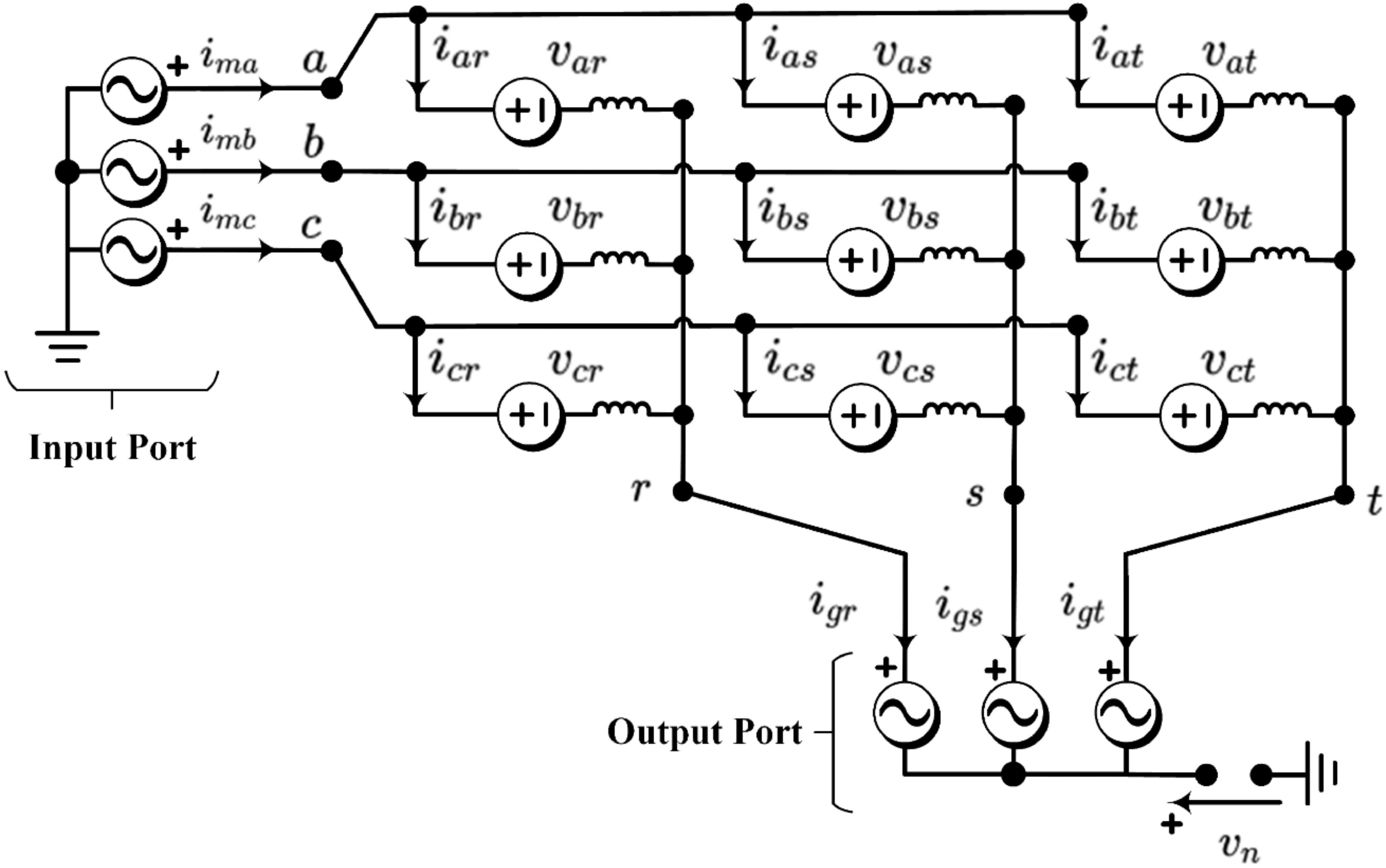
Modular Multilevel Matrix Converter



In steady-state, the cluster current has one-third of the input current + one-third of the output current.

This is an AC-to-AC topology. To achieve the same using M2C back-to-back operation is required

Voltages in the M3C



Modular Multilevel Matrix Converter

- The modular multilevel matrix converter, M3C, is an AC-to-AC topology. It is composed of nine clusters, each one with *n* full bridges.

- Instead of two circulating currents (M2C case), the M3C has four linearly independent currents. Therefore, for balancing purposes, four circulating currents and a common-mode voltage could be used.

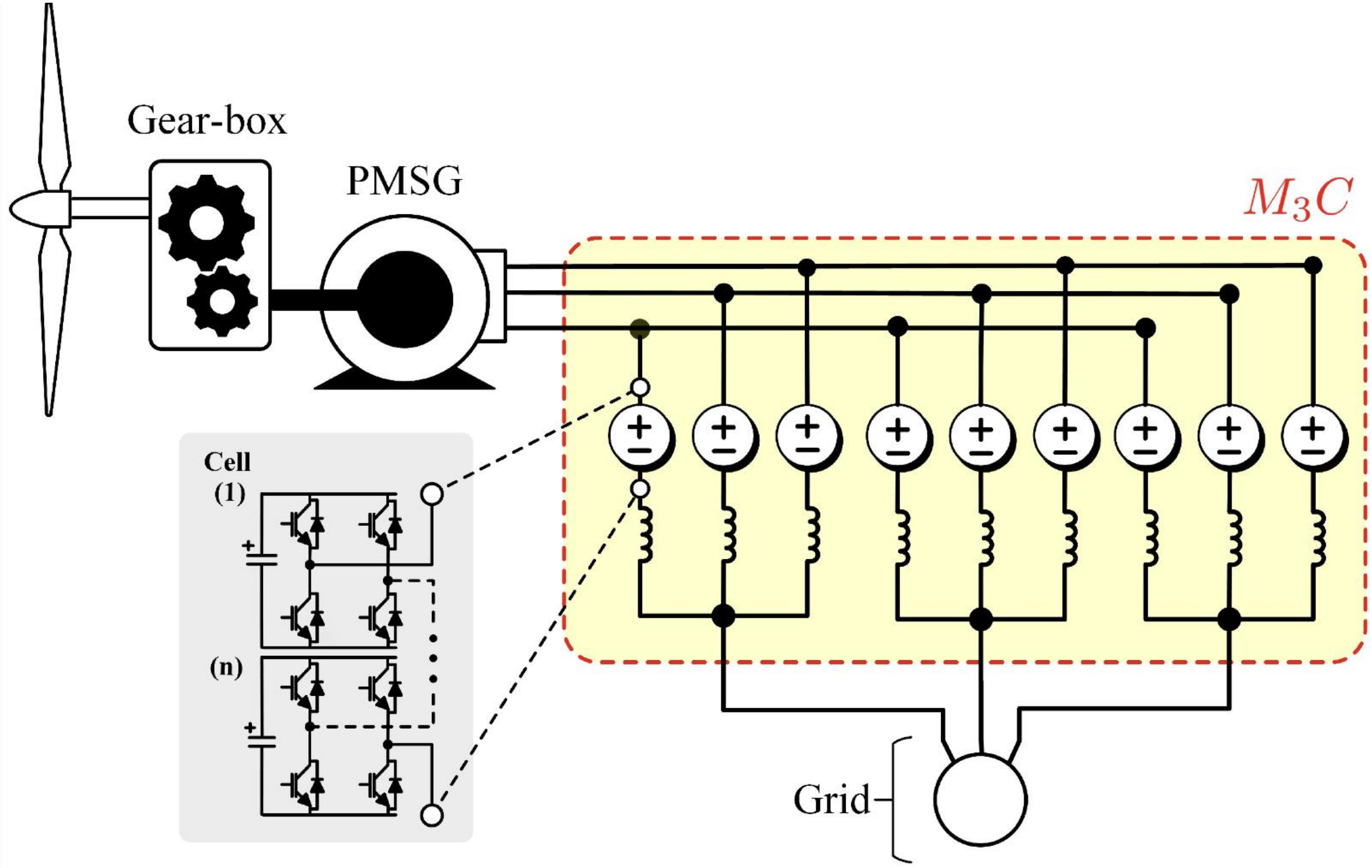
- To the best of my knowledge, there are no commercial applications of this topology yet. However, according to Professor H. Akagi, it is expected that the M3C will replace the cyclo-converter topologies used in mining and railway applications (e.g. 20-28 MW SAG Mills).

H. Akagi, "Multilevel Converters: Fundamental Circuits and Systems," in *Proceedings of the IEEE*, vol. 105, no. 11, pp. 2048-2065, Nov. 2017, doi: 10.1109/JPROC.2017.2682105.

Some of the Proposed Applications for the M3C

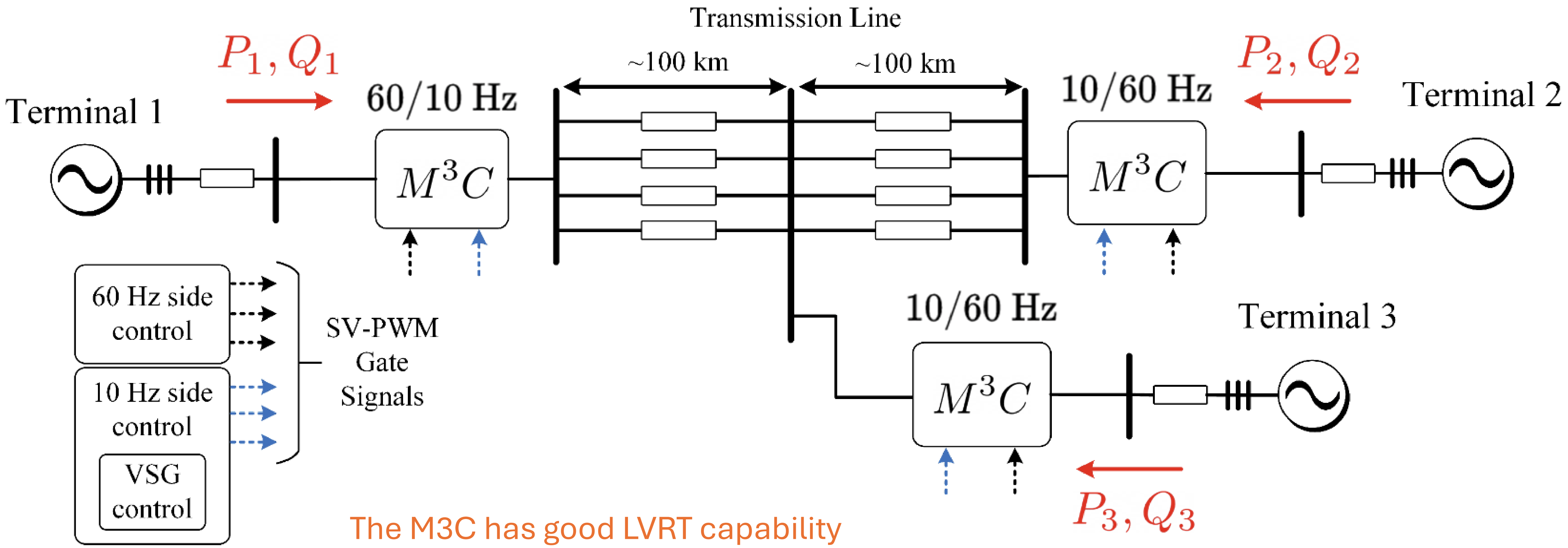
UNIVERSIDAD DE CHILE

High power Drive Applications Including Generation



Diaz, M.; Cardenas, R.; Espinoza, M.; Rojas, F.; Mora, A.; Clare, J.C.; Wheeler, P. Control of Wind Energy Conversion Systems Based on the Modular Multilevel Matrix Converter. *IEEE Trans. Ind. Electron.* **2017**, *64*, 8799–8810.

High Power Low-Frequency AC Transmission



The M3C has good LVRT capability

Al-Tameemi, M.; Miura, Y.; Liu, J.; Bevrani, H.; Ise, T. A novel control scheme for multi-terminal low-frequency AC electrical energy transmission systems using modular multilevel matrix converters and virtual synchronous generator concept. *Energies* **2020**, *13*, 747.

General Comments

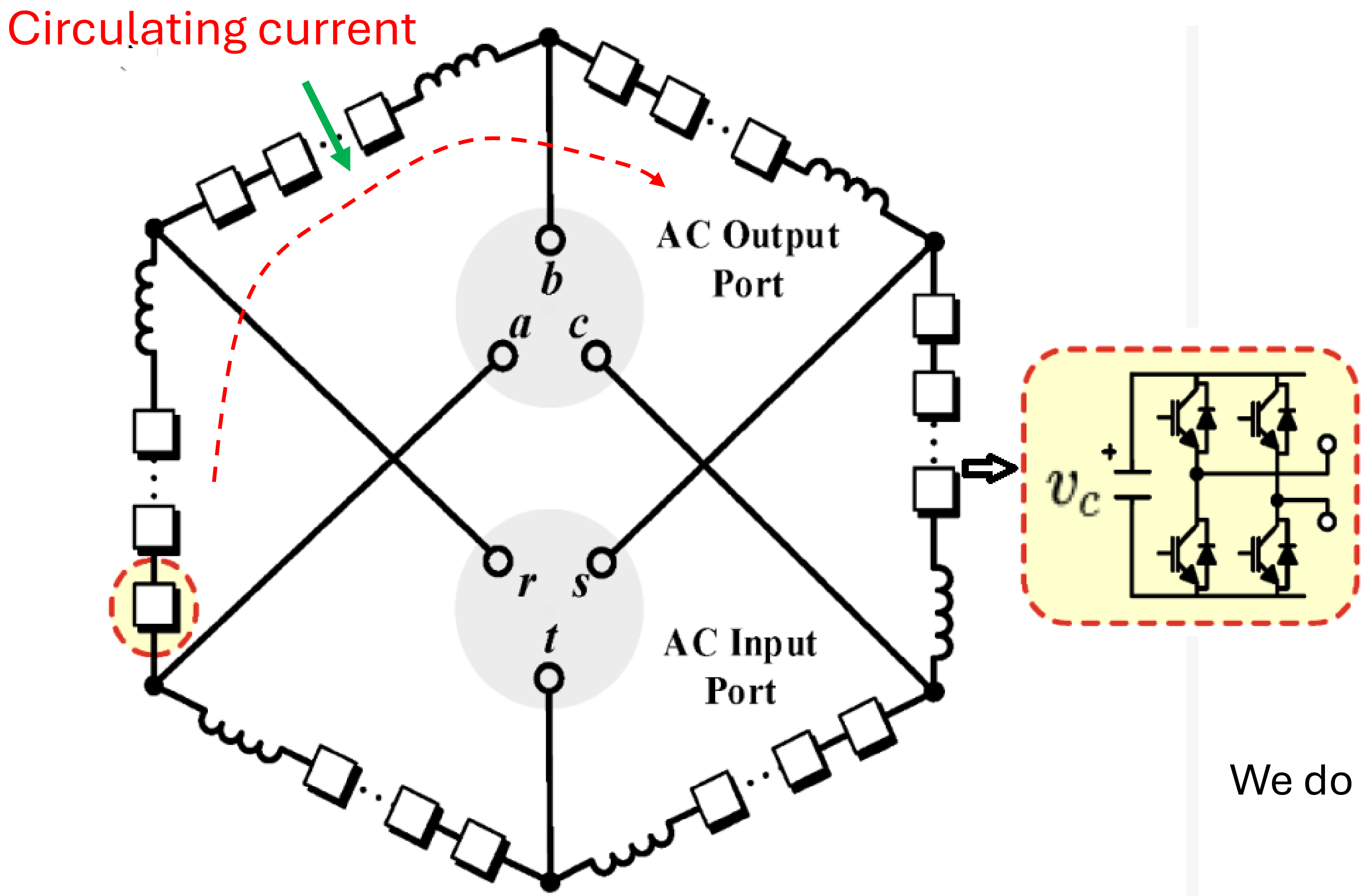
- For drive applications, the M3C can operate with high torque current during the starting up of the electrical motor.

- However, it could have problems with large capacitor voltage oscillations produced when the input and output AC frequencies are equal or have similar values.

- The M3C can be operated to obtain relatively high frequencies at the outputs. For instance, to feed a medium-frequency isolation transformer. It has also been proposed to interface high-velocity generators, for instance, generators driven by gas turbines.

Hexverter

- The Hexverter is the simplest of the AC to AC proposed topologies. It requires six clusters, each one composed of full bridges. It has room for only one circulating current and that current, as well as the common mode voltage, are the only degrees of freedom which can be used for balancing purposes.



We do not have (yet) an experimental rig with a Hexverter

Hexverter

- The Hexverter is considered a reduced M3C. In fact, the M3C can be operated as a Hexverter in case of a cluster fault.

- The Hexverter is considered a suitable option for a lower power range than the M3C. It has been proposed for medium voltage drives and medium voltage generators. For large powers, it is reported (by Mertens' group) as less competitive.

- It is not considered a suitable option for operation where large capacitor voltage oscillations are produced. For instance, operation with similar AC frequencies at the input and output ports.

D. Karwatzki, L. Baruschka and A. Mertens, "Survey on the Hexverter topology — A modular multilevel AC/AC converter," *2015 9th International Conference on Power Electronics and ECCE Asia (ICPE-ECCE Asia)*, Seoul, Korea (South), 2015, pp. 1075-1082, doi: 10.1109/ICPE.2015.7167914

An Introduction to the M2C Modelling

Universidad de Chile

Modelling of the M2C

- We used the model proposed by Felix Kammerer, Michael Braun et al from the Karlsruhe Institute of Technology, Germany.

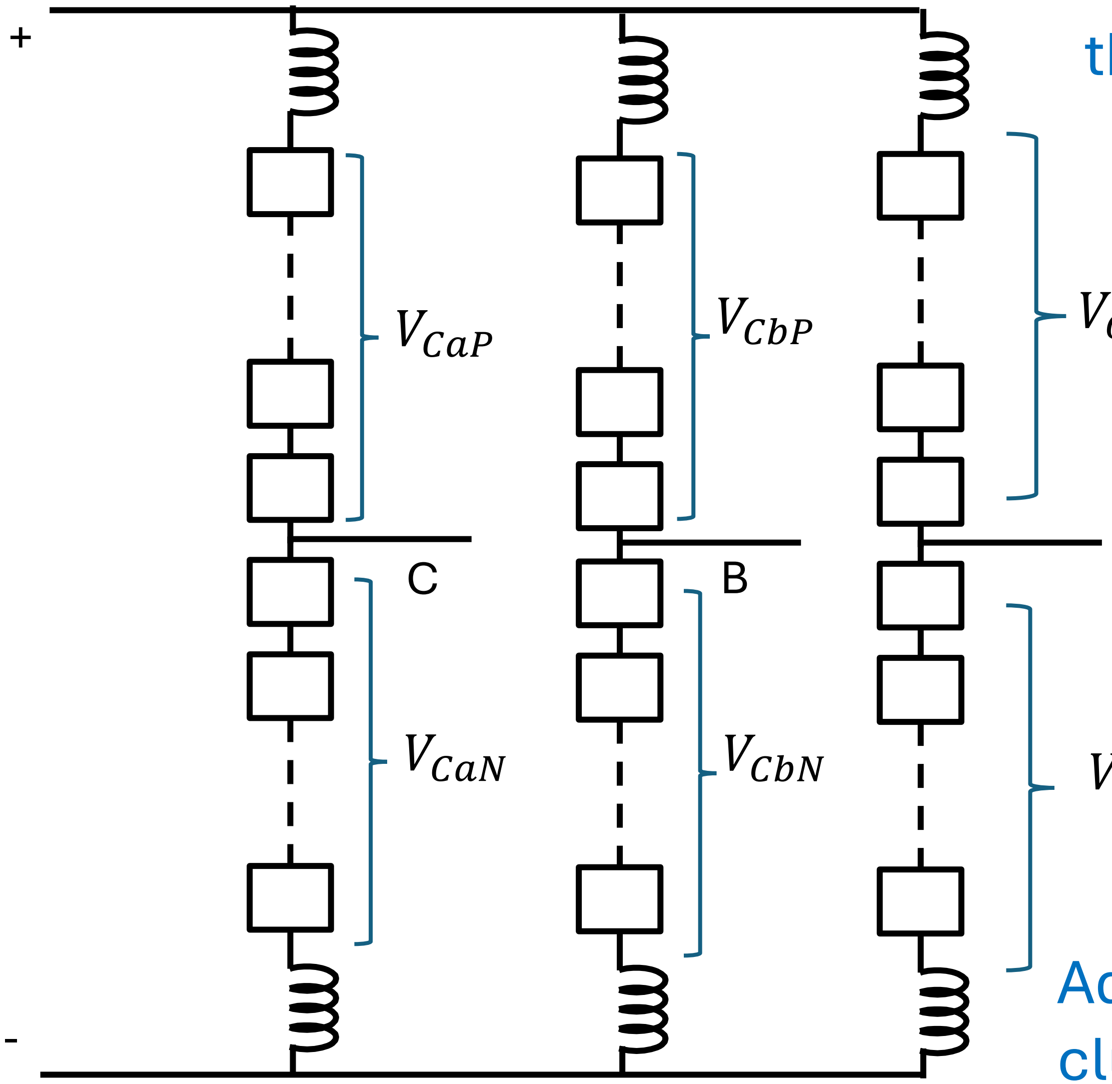
- The model uses $\alpha\beta0\Sigma\Delta$ coordinates, for a 5-dimensional space.

There are more models reported in the literature. None of them seem to be simple to understand

F. Kammerer, M. Gommeringer, J. Kolb and M. Braun, "Energy balancing of the Modular Multilevel Matrix Converter based on a new transformed arm power analysis," *2014 16th European Conference on Power Electronics and Applications*,, 2014, pp. 1-10, doi: 10.1109/EPE.2014.6910939.

Balancing the Energy in the Converter

Addition of all the capacitor voltages in the cluster of phase “c”, positive cluster.



$$V_{CcP} = \sum_{1}^{n} V_{Ccpi}$$

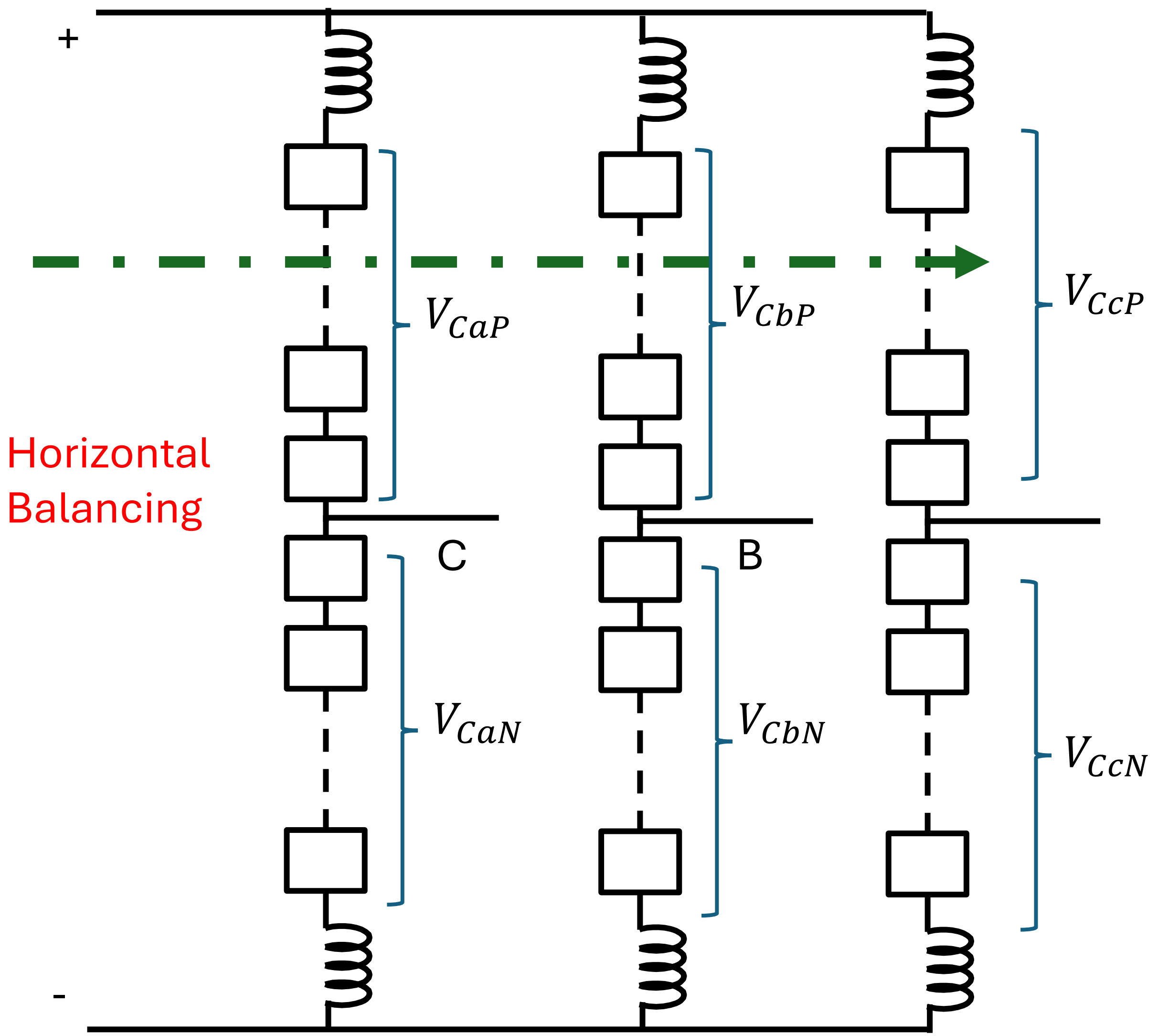
AC SIDE

$$V_{CcN} = \sum_{1}^{n} V_{Ccni}$$

The energy is “balanced”, when all the clusters have the same total capacitor voltages.

Addition of all the capacitor voltages in the cluster of phase “c”, negative cluster.

"Horizontal" pole-to-pole Balancing



$$V_{CaP} + V_{CaN} = V_{CbP} + V_{CbN} = V_{CcP} + V_{CcN}$$

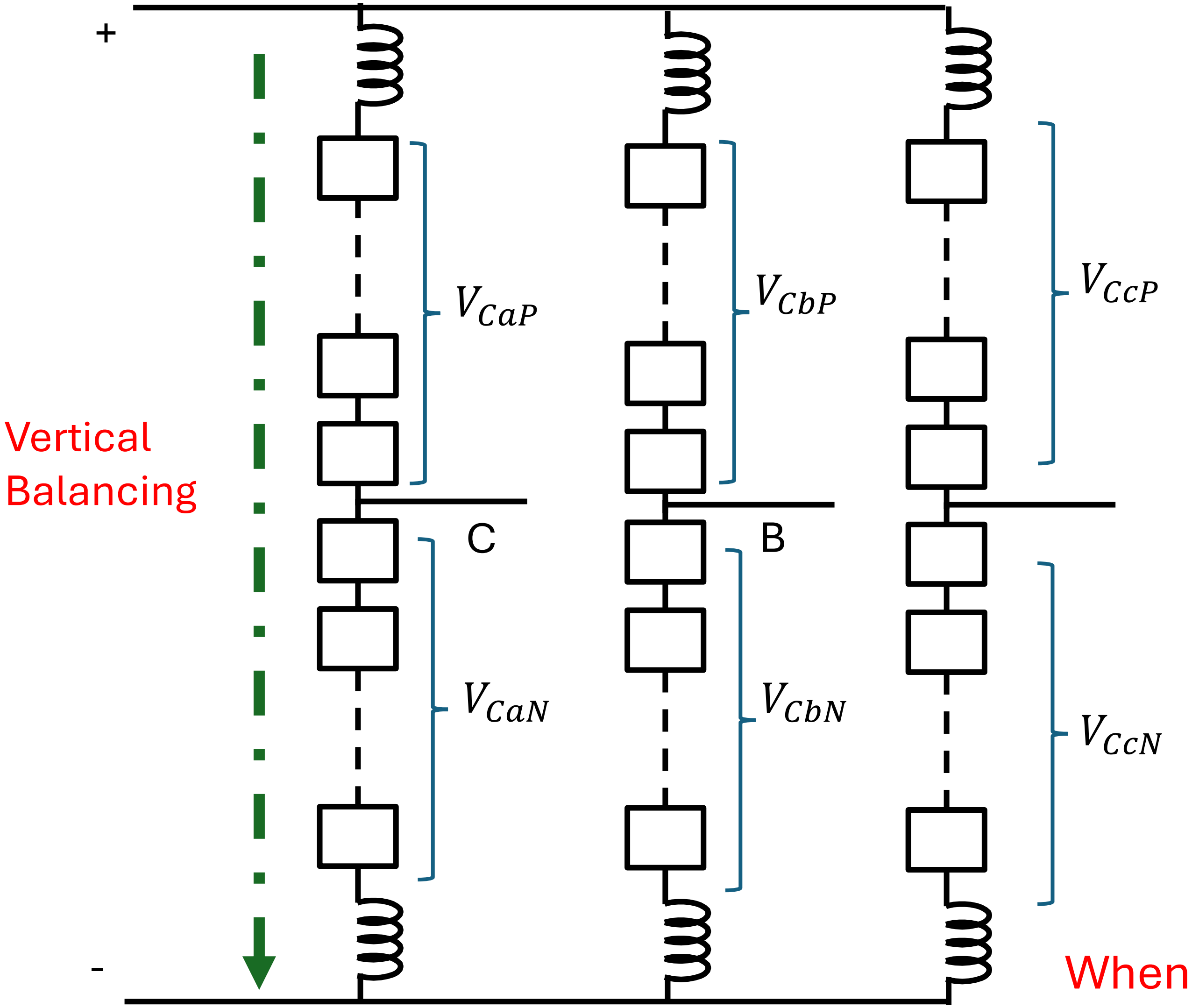
$$V_{Ca}^{\Sigma} = V_{Cb}^{\Sigma} = V_{Cc}^{\Sigma}$$

One way to ensure that $V_{Ca}^{\Sigma} = V_{Cb}^{\Sigma} = V_{Cc}^{\Sigma}$ is to apply the $\alpha - \beta - 0$ transform.

$$\begin{bmatrix} V_{C\alpha}^{\Sigma} \\ V_{\beta}^{\Sigma} \\ V_{Co}^{\Sigma} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{2} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} V_{Ca}^{\Sigma} \\ V_{Cb}^{\Sigma} \\ V_{Cc}^{\Sigma} \end{bmatrix}$$

When balanced $V_{C\alpha}^{\Sigma}$=0, $V_{C\beta}^{\Sigma} = 0$, $V_{C0}^{\Sigma} = 2V_{C_{cluster}}$

“Vertical” Pole-to-Pole Balancing



$$V_{CaP} - V_{CaN} = V_{CbP} - V_{CbN} = V_{CcP} - V_{CcN}$$

$$\downarrow$$

$$V_{Ca}^{\Delta} = V_{Cb}^{\Delta} = V_{Cc}^{\Delta}$$

$$\downarrow$$

One way to ensure that $V_{Ca}^{\Delta} = V_{Cb}^{\Delta} = V_{Cc}^{\Delta}$ is to apply the $\alpha - \beta - 0$ transform.

$$\begin{bmatrix} V_{C\alpha}^{\Delta} \\ V_{C\beta}^{\Delta} \\ V_{Co}^{\Delta} \end{bmatrix} = \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{2} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix} \begin{bmatrix} V_{Ca}^{\Delta} \\ V_{Cb}^{\Delta} \\ V_{Cc}^{\Delta} \end{bmatrix}$$

When the MMC is balanced then $V_{C\alpha}^{\Delta}$=0, $V_{C\beta}^{\Delta} = 0$, V_{Co}^{Δ} =0

UNIVERSIDAD DE CHILE

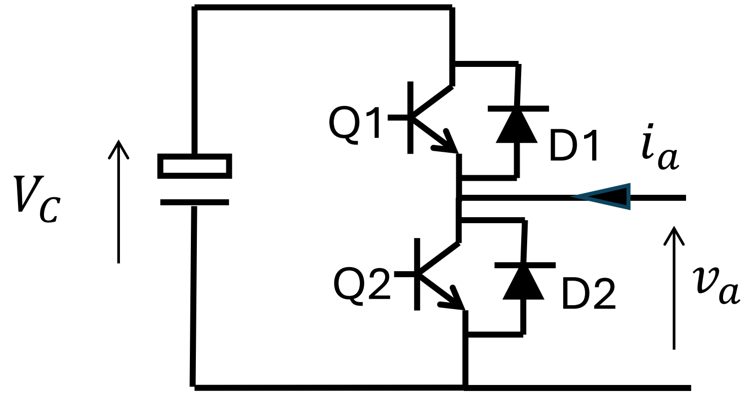
$\alpha\beta0\Sigma\Delta$ Transform

- Finally, the $\alpha\beta0\Sigma\Delta$ Transform, can be written as:

$$\begin{array}{c} \begin{array}{ccc} 0 & 0 & V_{C_{cluster}} = V_C^* \end{array} \\ \begin{bmatrix} V_{C\alpha}^{\Sigma} & V_{C\beta}^{\Sigma} & V_{Co}^{\Sigma} \\ V_{C\alpha}^{\Delta} & V_{C\beta}^{\Delta} & V_{Co}^{\Delta} \end{bmatrix} \\ \begin{array}{ccc} 0 & 0 & 0 \end{array} \end{array} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2} \\ 1 & -1 \end{bmatrix} \begin{bmatrix} V_{CaP} & V_{CbP} & V_{CcP} \\ V_{CaN} & V_{CbN} & V_{CcN} \end{bmatrix} \begin{bmatrix} \frac{2}{3} & -\frac{1}{3} & -\frac{1}{2} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \\ \frac{1}{3} & \frac{1}{3} & \frac{1}{3} \end{bmatrix}^{T}$$

Five of these voltages has to be driven to zero to balance the M2C

Capacitor Voltage and Power in a Half-bridge

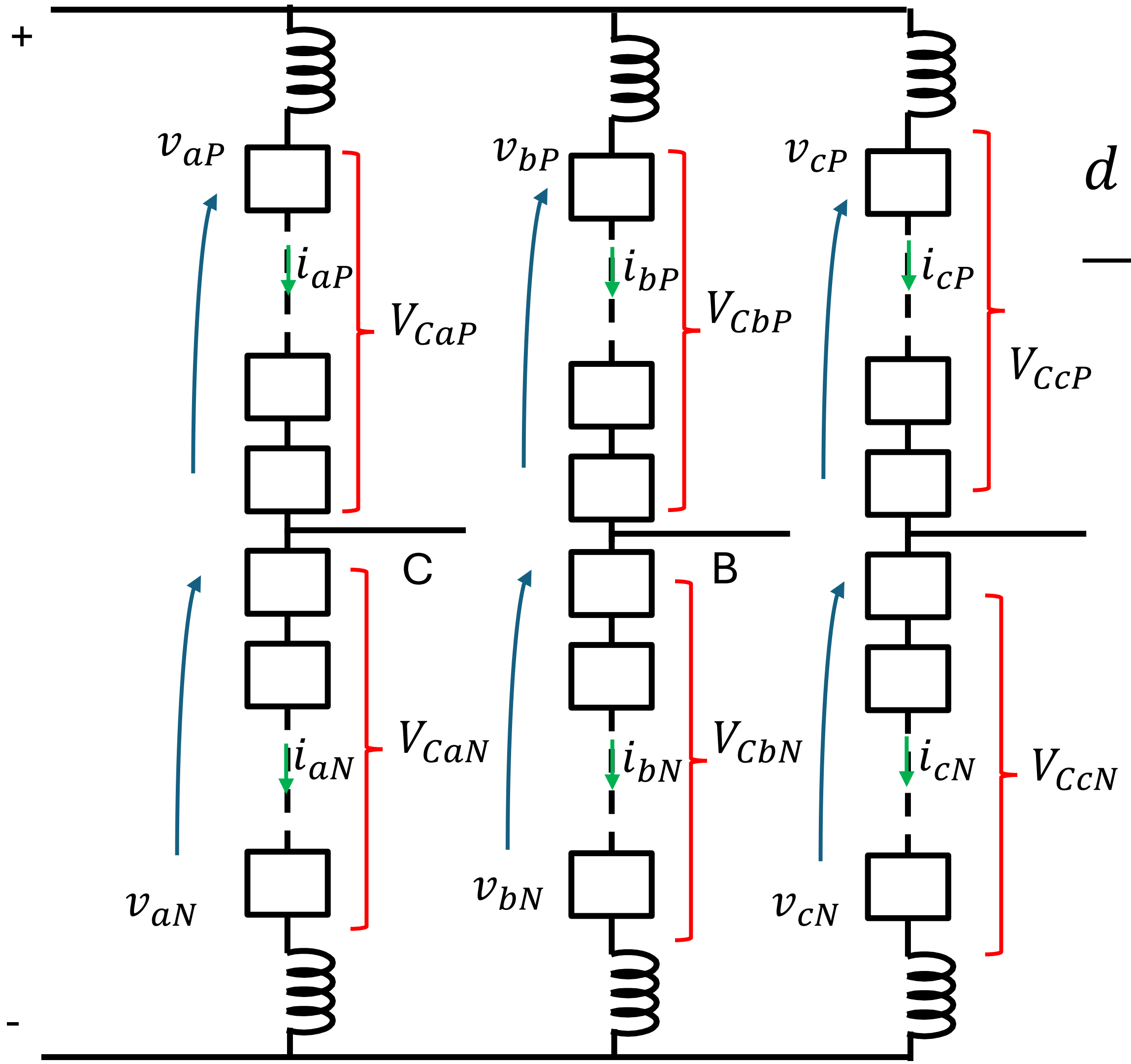


- As we know, the relationship between the power P and the energy W is:

$$\boxed{\frac{\partial W}{\partial t} = P \;\Rightarrow\; \frac{\partial\left[\frac{1}{2}C \cdot V_C^2\right]}{\partial t} = \mathrm{v_a} \cdot i_a}$$

- If it assumed that the capacitor voltages are well regulated with small oscillations around the average value, then:

$$\boxed{\frac{\partial V_C}{\partial t} \approx \frac{1}{C V_c^*} \mathrm{v_a} \cdot i_a}$$



Variation around V_C^*

Instantaneous power
In each cluster

$$\frac{d\begin{bmatrix} V_{CaP} & V_{CbP} & V_{Ccp} \\ V_{CaN} & V_{CbN} & V_{CcN} \end{bmatrix}}{dt} = \frac{\begin{bmatrix} v_{aP}i_{aP} & v_{bP}i_{bP} & v_{cP}i_{cP} \\ v_{aN}i_{aN} & v_{bN}i_{bN} & v_{cN}i_{cN} \end{bmatrix}}{nCV_C^*}$$

n=number of half-bridge cells in a cluster.

If the $\alpha\beta0\Sigma\Delta$ transform is applied to both sides of the power equation, then (after rather complex manipulations) the following equations can be obtained:

M. Espinoza, R. Cárdenas, M. Díaz and J. C. Clare, "An Enhanced dq-Based Vector Control System for Modular Multilevel Converters Feeding Variable-Speed Drives," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 4, pp. 2620-2630, April 2017, doi: 10.1109/TIE.2016.2637894

State equations of the MMC

$$\frac{dV^{\Sigma}_{c\alpha\beta}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{2}V_{\mathrm{dc}}\cdot \underline{i}^{\Sigma}_{\alpha\beta} - \frac{1}{4}\left(\underline{i}_{\alpha\beta}\underline{v}_{\alpha\beta}\right)^{c} - \frac{1}{2}v_0\underline{i}_{\alpha\beta}\right]$$

$$\frac{dV^{\Delta}_{c\alpha\beta}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{2}V_{\mathrm{dc}}\underline{i}_{\alpha\beta} - \frac{2}{3}i_{\mathrm{dc}}\underline{v}_{\alpha\beta} - \left(\underline{v}_{\alpha\beta}\underline{i}^{\Sigma}_{\alpha\beta}\right)^{c} - 2v_0\underline{i}^{\Sigma}_{\alpha\beta}\right]$$

$$\frac{dV^{\Delta}_{c0}}{dt} = \frac{1}{\mathrm{K}}\left[-\Re\left(\underline{v}_{\alpha\beta}\underline{i}^{\Sigma\,c}_{\alpha\beta}\right) - \frac{2}{3}i_{\mathrm{dc}}v_0\right]$$

$$\frac{dV^{\Sigma}_{c0}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{6}V_{\mathrm{dc}}i_{\mathrm{dc}} - \frac{1}{4}\Re\left(\underline{v}_{\alpha\beta}\underline{i}^{c}_{\alpha\beta}\right)\right]$$

When the M2C is balanced

$$V^{\Sigma}_{C\alpha\beta} \rightarrow 0 + j0$$

$$V^{\Delta}_{C\alpha\beta} \rightarrow 0 + j0$$

$$V^{\Delta}_{C0} \rightarrow 0$$

$$V^{\Sigma}_{C0} \rightarrow V_{C_{cluster}}$$

Symbol	Meaning		Symbol	Meaning
V_{dc}	dc-link voltage		v_0	common-mode voltage
i_{dc}	dc-link current		$\Re$	Real part of a product
K	$= nCV_C^*/T_s$		$\underline{i}_{\alpha\beta}$	Grid-side currents $i_\alpha + ji_\beta$
$\underline{v}_{\alpha\beta}$	Grid-side voltage $v_\alpha + jv_\beta$		$\underline{i}^{\Sigma}_{\alpha\beta}$	Circulating currents $i^{\Sigma}_{\alpha} + ji^{\Sigma}_{\beta}$
c	Complex conjugate operator		T_s	Sampling period.

UNIVERSIDAD DE CHILE

Research on CCS-MPC for M2C at the University of Chile

Power Electronic Lab

Modular Multilevel Topologies

- We have implemented an M3C of 27 full-bridge cells (54 switching signals) and a back-to-back Hybrid-M2C with 36 cells. in each cluster, there is a semiconductor module which can be operated as a full bridge or a half bridge if required.

- A Hexverter is being implemented. We expect to have one of them fully operational at the end of 2024.

- For the implementation of M2C control system, a good control platform is required. For instance, an M3C of 27 cells require 54 switching pulses, measuring 9 cluster currents, six input/output currents and 27 cells voltages.

- For modular multilevel control we are now using Dspace Microlab Box control platform with processing powers of 8000 MFLOPs.

Continuous Control Set Model Predictive Control (CCS-MPC)

- The M2C is a Multiple Input Multiple Output (MIMO) plant. However, most of the control systems proposed in the literature are based on SISO-designed control loops. The cross-couplings between variables and states are just neglected for controller design purposes.

- Therefore, MIMO model predictive controllers have been proposed to control the M2C. One of the main advantages of “conventional” MPC (the one used in chemical plants since 1995) is to handle linear constraints. In our case, an external modulator is used to synthesise the voltage.

S. Fuchs, M. Jeong, and J. Biela, “Long horizon, quadratic programming based model predictive control (MPC) for grid connected modular multilevel converters (MMC),” in *Proc. Ind. Electron. Conf.*, 2019, pp. 1805–1812

CCS-MPC for M2C

UNIVERSIDAD DE CHILE

State equations obtained from the modelling

$$\frac{dV^{\Sigma}_{c\alpha\beta}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{2}V_{\mathrm{dc}}\cdot \underline{i}^{\Sigma}_{\alpha\beta} - \frac{1}{4}\left(\underline{i}_{\alpha\beta}\underline{v}_{\alpha\beta}\right)^{c} - \frac{1}{2}v_0\underline{i}_{\alpha\beta}\right]$$

$$\frac{dV^{\Delta}_{c\alpha\beta}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{2}V_{\mathrm{dc}}\underline{i}_{\alpha\beta} - \frac{2}{3}i_{\mathrm{dc}}\underline{v}_{\alpha\beta} - \left(\underline{v}_{\alpha\beta}\underline{i}^{\Sigma}_{\alpha\beta}\right)^{c} - 2v_0\underline{i}^{\Sigma}_{\alpha\beta}\right]$$

$$\frac{dV^{\Delta}_{c0}}{dt} = \frac{1}{\mathrm{K}}\left[-\Re\left(\underline{v}_{\alpha\beta}\underline{i}^{\Sigma c}_{\alpha\beta}\right) - \frac{2}{3}i_{\mathrm{dc}}v_0\right]$$

$$\frac{dV^{\Sigma}_{c0}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{6}V_{\mathrm{dc}}i_{\mathrm{dc}} - \frac{1}{4}\Re\left(\underline{v}_{\alpha\beta}\underline{i}^{c}_{\alpha\beta}\right)\right]$$

The total converter energy is not related to the circulating currents. It is a slow variable and controlled using a PI.

$$\dot{x} = Ax + Bu + P$$

P=Perturbations $u = \left[i^{\Sigma}_{\alpha}\ i^{\Sigma}_{\beta}\right]^{T}$

Forward Euler

$$x_{k+1} = A_d x_k + B_d u_k + P_k$$

A_d, B_d, P_k=discretised version of the continuous matrices

Y. Arias-Esquivel, R. Cárdenas, M. Urrutia, M. Diaz, L. Tarisciotti and J. C. Clare, "Continuous Control Set Model Predictive Control of a Modular Multilevel Converter for Drive Applications," in IEEE Transactions on Industrial Electronics, vol. 70, no. 9, pp. 8723-8733, Sept. 2023

Cost Function

Weights to be selected by the designer

Optimal control actions To be obtained by the algorithm

$$\text{Maximise } J = \begin{bmatrix} V_{C\alpha}^{\Sigma}(k+1) \\ V_{C\beta}^{\Sigma}(k+1) \\ V_{C\alpha}^{\Delta}(k+1) \\ V_{C\beta}^{\Delta}(k+1) \\ V_{C0}^{\Delta}(k+1) \end{bmatrix}^T \overbrace{\begin{bmatrix} \lambda_1 & 0 & 0 & 0 & 0 \\ 0 & \lambda_2 & 0 & 0 & 0 \\ 0 & 0 & \lambda_3 & 0 & 0 \\ 0 & 0 & 0 & \lambda_4 & 0 \\ 0 & 0 & 0 & 0 & \lambda_5 \end{bmatrix}} \begin{bmatrix} V_{C\alpha}^{\Sigma}(k+1 \\ V_{C\beta}^{\Sigma}(k+1 \\ V_{C\alpha}^{\Delta}(k+1) \\ V_{C\beta}^{\Delta}(k+1) \\ V_{C0}^{\Delta}(k+1) \end{bmatrix} + \overbrace{\begin{bmatrix} i_{\alpha}^{\Sigma*}(k) \\ i_{\beta}^{\Sigma*}(k) \end{bmatrix}}^T \begin{bmatrix} \lambda_i & 0 \\ 0 & \lambda_i \end{bmatrix} \overbrace{\begin{bmatrix} i_{\alpha}^{\Sigma*}(k) \\ i_{\beta}^{\Sigma*}(k) \end{bmatrix}}$$

Subject to

Constraint 1.....
Constraint 2.....
Constraint 3.....
Constraint 4.....

The constraints are, for instance, to ensure that in each cluster, the peak current is below the maximum value.

- The optimal problem is then solved by the **Active-Set method**, which is an efficient constrained optimisation algorithm when the number of restrictions is low.
- For 12 restrictions the DSPACE control platform takes 14μS to implement the whole control system including the level-shifted PWM.

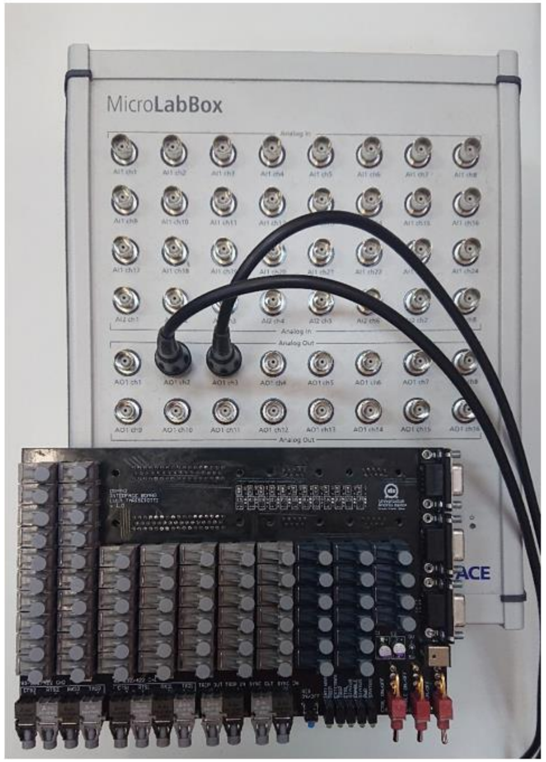
- We first test the control system performance using PLECS RT, a hardware in the loop platform. The control systems are implemented using the Dspace Microlab-Box systems.

2700 MFLOPs

Plecs-RT1

16 ADs 2 Msps
16 DAs 2 Msps
32 digital inputs
32 digital outputs

+



8000 MFLOPs

(Millions of Floating point instructions per second)

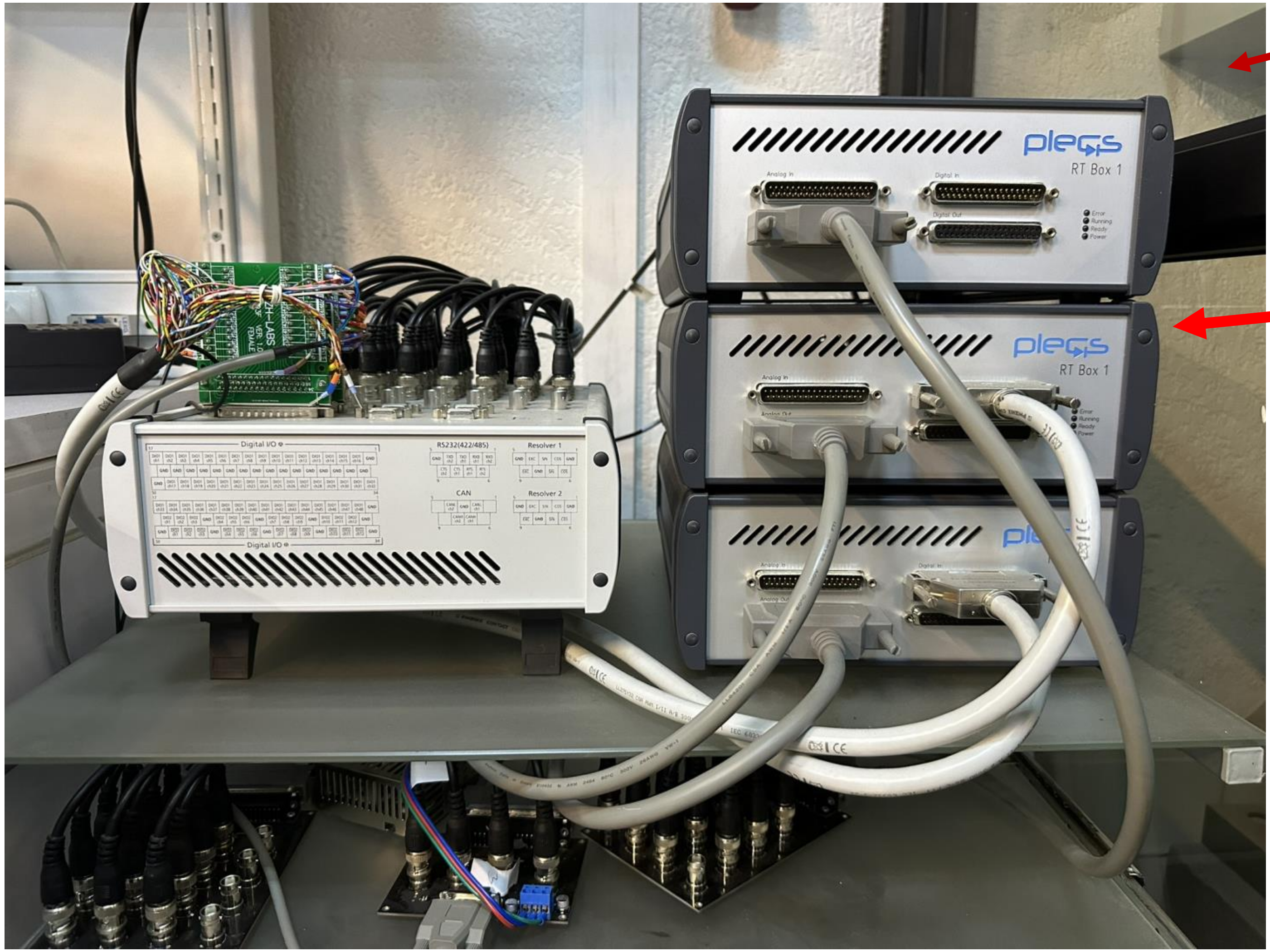
Dspace
8 14-bit ADs, 10Msps
24 16 bit-ADs, 1Msps
16 16 bit-DAs $1\mu S$.
40 PWM signals (For this optical board)

UNIVERSIDAD DE CHILE

Hardware in the Loop Systems

Dspace Microlab Box

The PWM signals are provided by the Dspace platform



≈5 μS.
Implementation step

PLECS-RT. It is used to implement the M3C and M2C topologies.

Programmed in PLECS

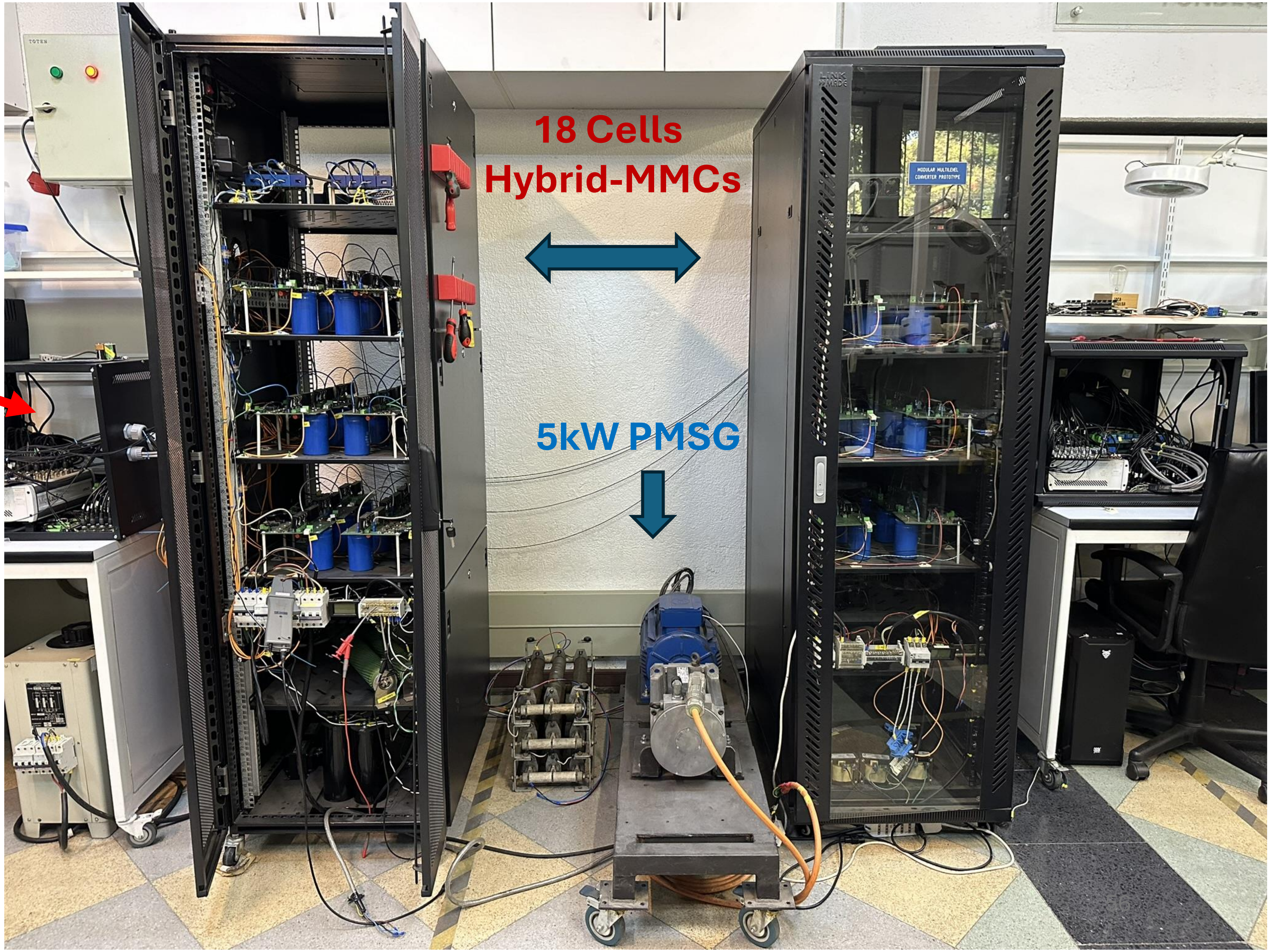
A good tool for debugging purposes and can be remotely accessed by students

Back to Back System

Universidad de Chile

Flag of
Costa Rica

Dspace controller, optical board
and 21 (LEM) voltage traducers



Experimental Results

f_s= 10 kHz
T_s=50 μS.

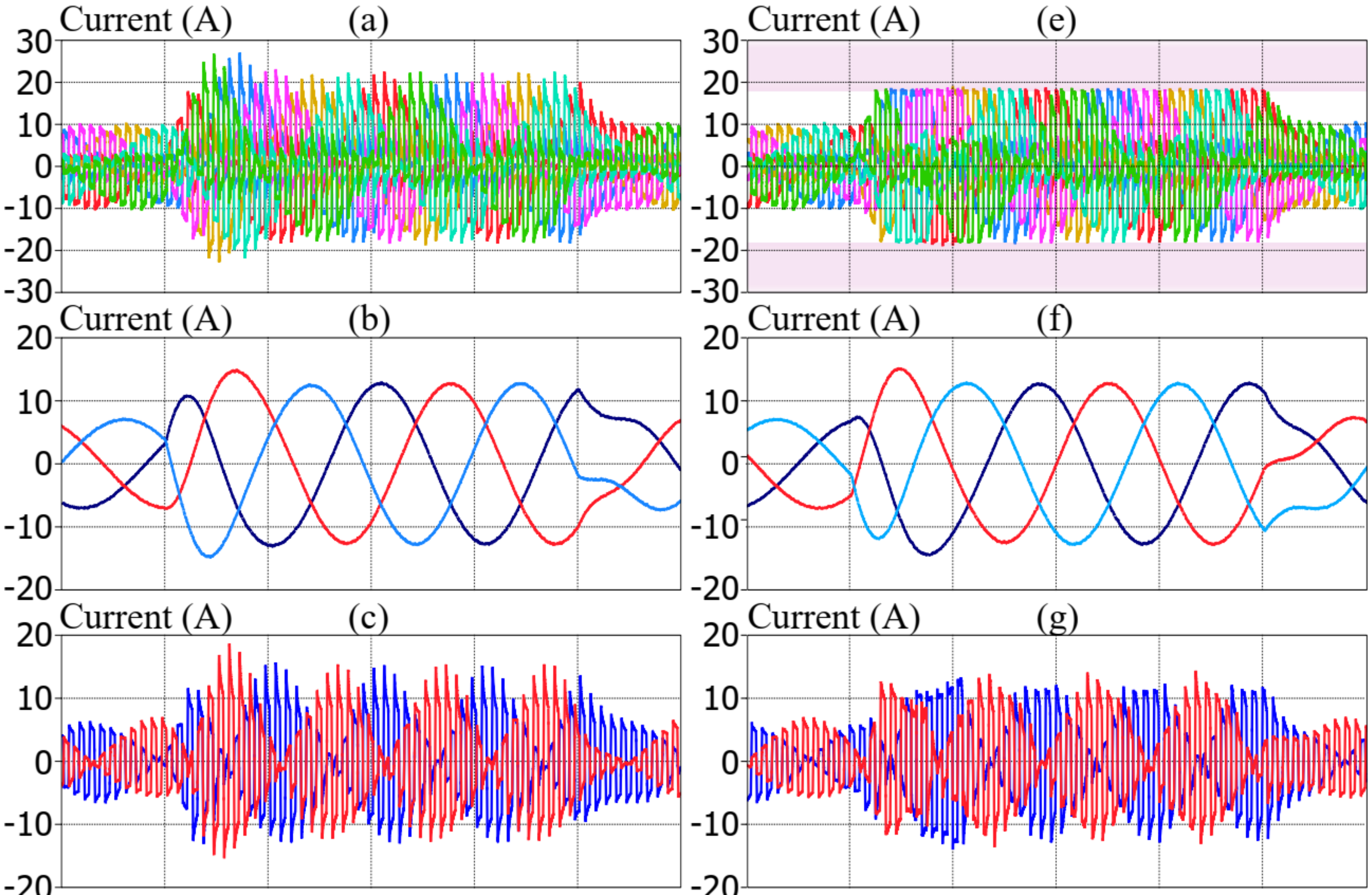
No constraints in
the Cluster Currents

With constraints in
the Cluster Currents I_{max}=18A

Cluster
Currents

AC output
Currents

Circulating
Currents



Experimental Results

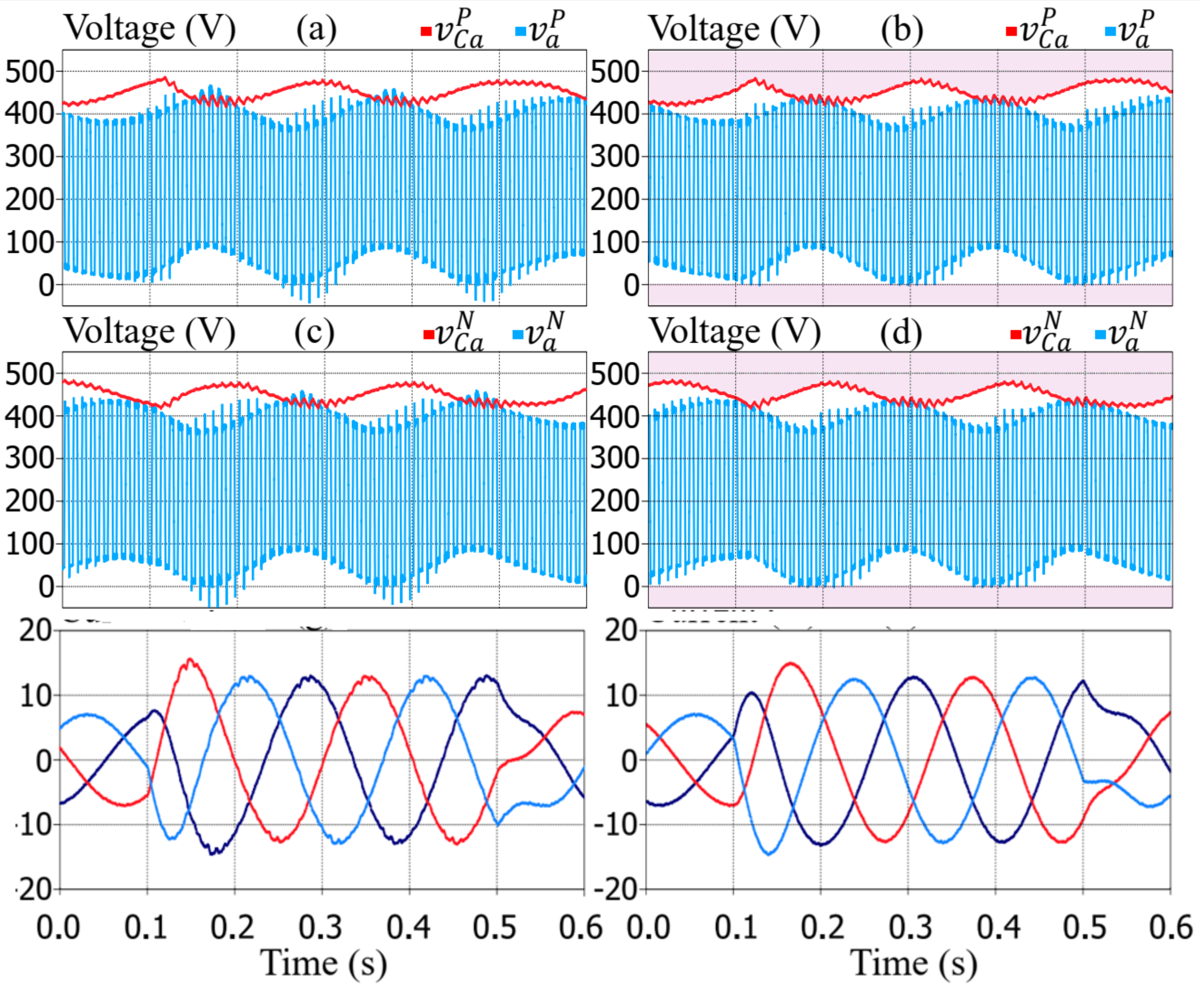
No constraints in the Cluster Voltages

With constraints in the Cluster Voltages

Red=peak capacitor voltage
Blue = Synthesised voltage
Positive cluster

Red=peak capacitor voltage
Blue = Synthesised voltage
Negative cluster

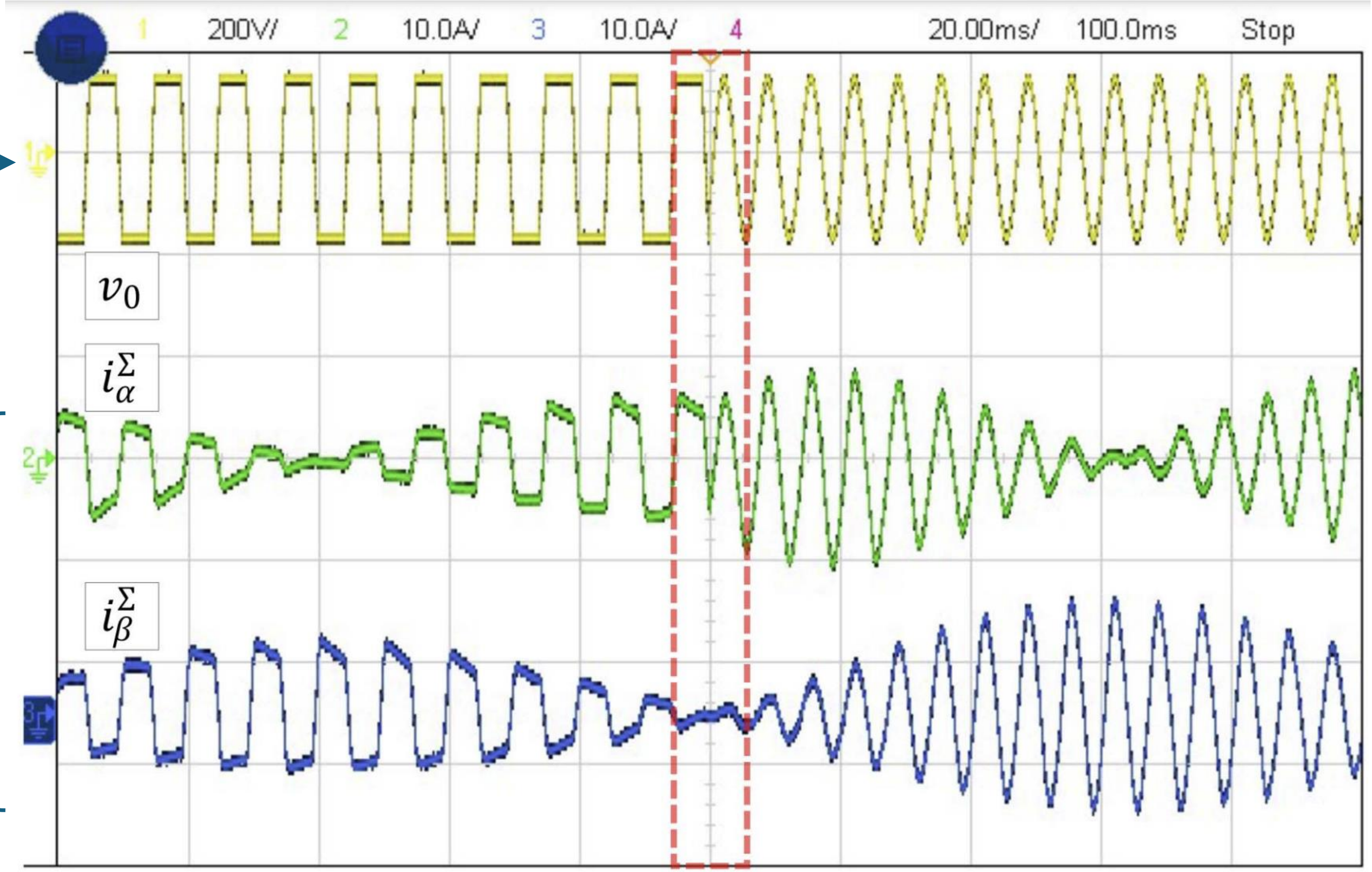
AC Output Currents



Optimising the Cost Function

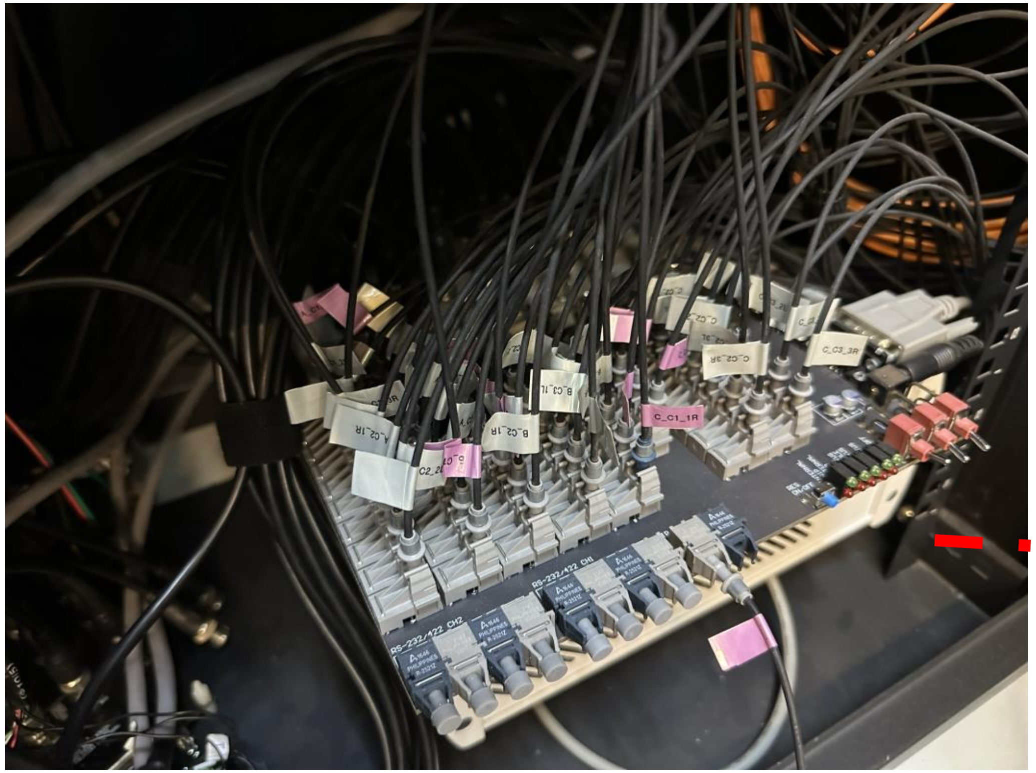
Common mode voltage

Circulating Currents

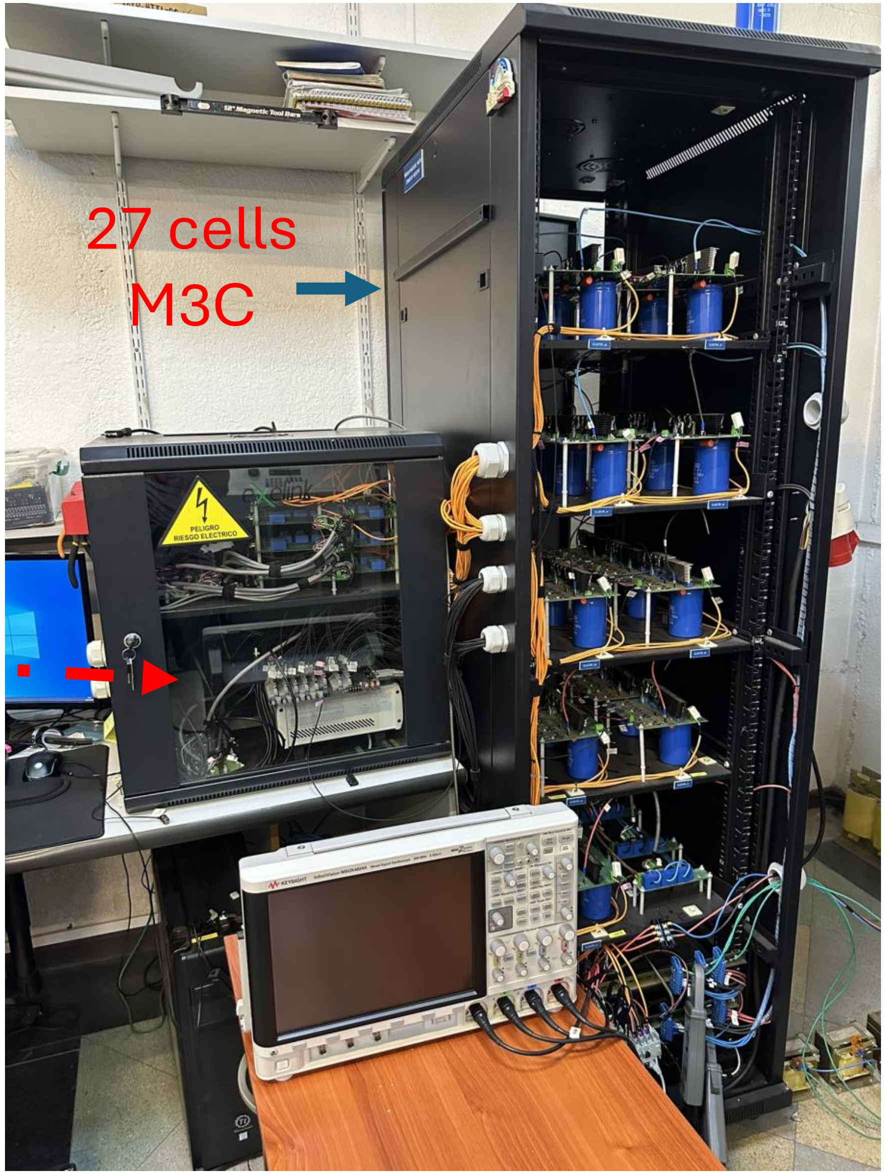


$$\frac{dV_{c\alpha\beta}^{\Delta}}{dt} = \frac{1}{\mathrm{K}}\left[\frac{1}{2}V_{\mathrm{dc}}\underline{i}_{\alpha\beta} - \frac{2}{3}i_{\mathrm{dc}}\underline{v}_{\alpha\beta} - \left(\underline{v}_{\alpha\beta}\underline{i}_{\alpha\beta}^{\Sigma}\right)^{c} - 2v_0\underline{i}_{\alpha\beta}^{\Sigma}\right]$$

Modular Multilevel Matrix Converter



Dspace Systems



Any Question?