Research Trends in Modular Multilevel Cascade Converters

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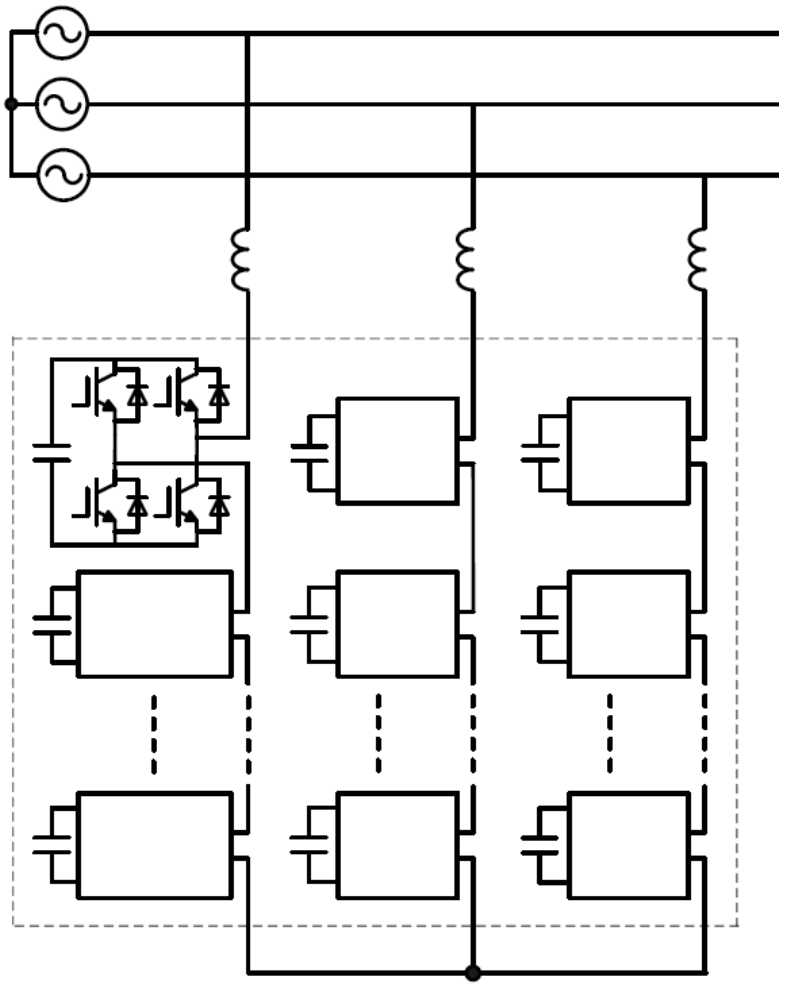
13th July 2021

Terminology Issue of Cascade Multilevel Converters and Modular Multilevel Converters

H. Akagi, "Multilevel Converters: Fundamental Circuits and Systems," *The Proceedings of the IEEE,* vol. 105, no. 11, pp. 2048-2065, Nov. 2017. (invited paper)

Terminology Issue of Cascade Multilevel Converters



Single-Star Bridge Cells (SSBC)

Three Different Technical Terms

"Cascade Multilevel Converter"

F. Z. Peng and J. S. Lai,
IEEE Trans. Ind. Appli.,1997

"Cascaded H-Bridge Converter"

Y. Fukuta and G. Venkataramanan,
IEEE IAS Annual Meeting, 2002

"Chain-Link Converter"

C. Oates, *EPE,* 2009

"Modular" structure and
"Multilevel" voltage waveforms

One of Modular Multilevel Converters

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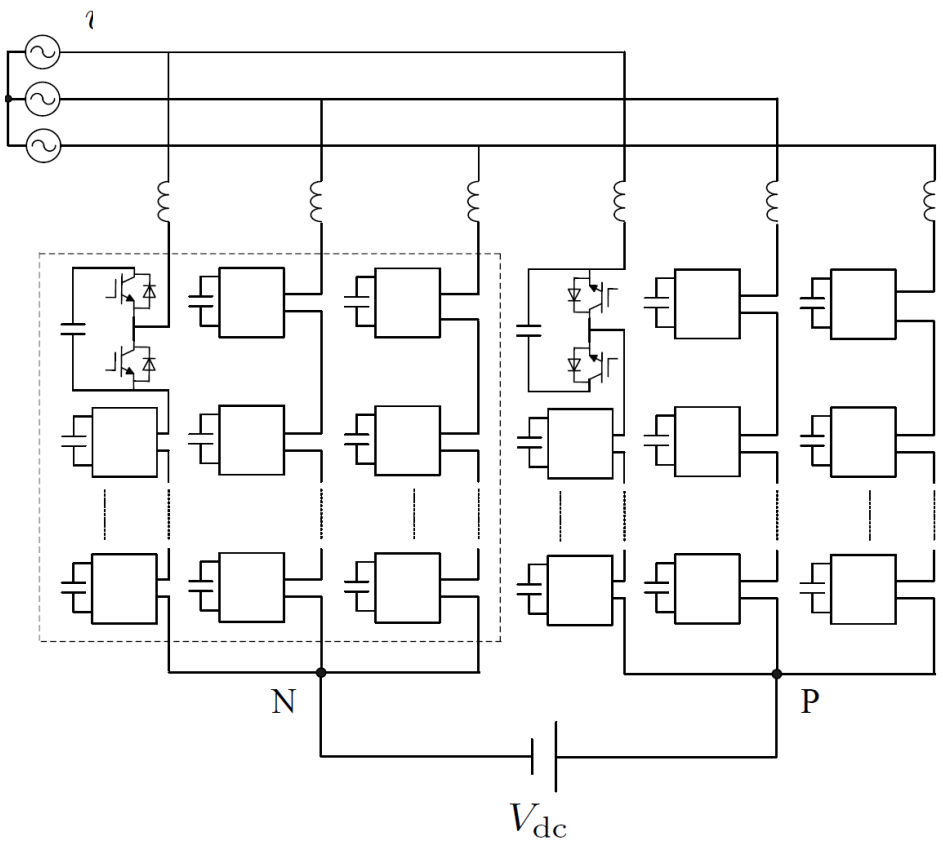
Terminology Issue of Modular Multilevel Converters



Double-Star Chopper Cells (DSCC)

Technical Term

"Modular Multilevel Converter"

R. Marquardt and A. Lesnicar,
EPE 2003

"Cascade" structure and
"Multilevel" voltage waveforms

One of Cascade Multilevel Converters

The two original names may cause confusion or misunderstanding.

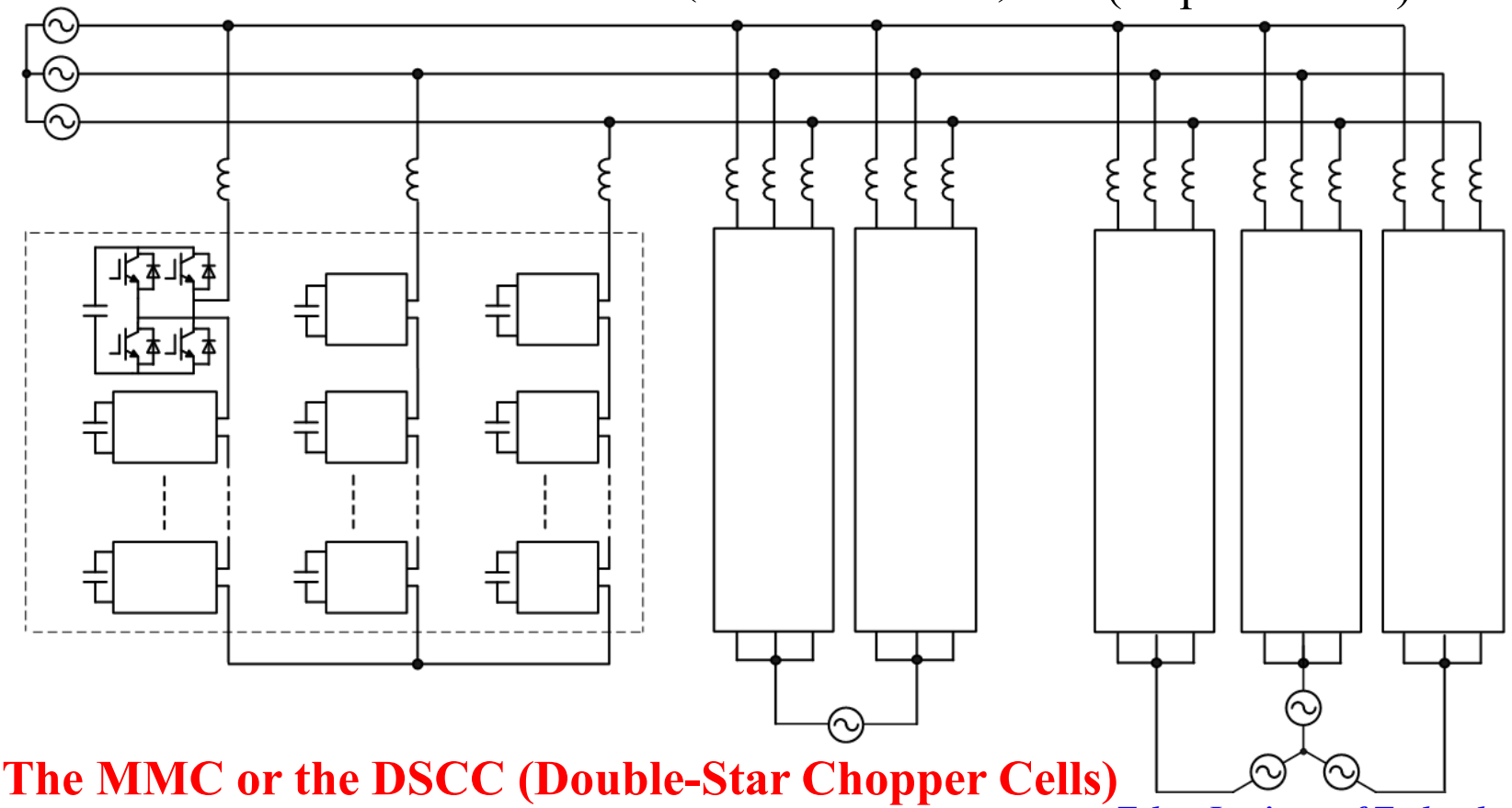
Classification and Terminology of the MMCC Family

Family name: MMCC (Modular Multilevel Cascade Converter)

SSBC
(Single-Star Bridge Cells)

DSBC
(Double-Star…)

TSBC
(Triple-Star…)



The MMC or the DSCC (Double-Star Chopper Cells) is a special case of the DSBC converter

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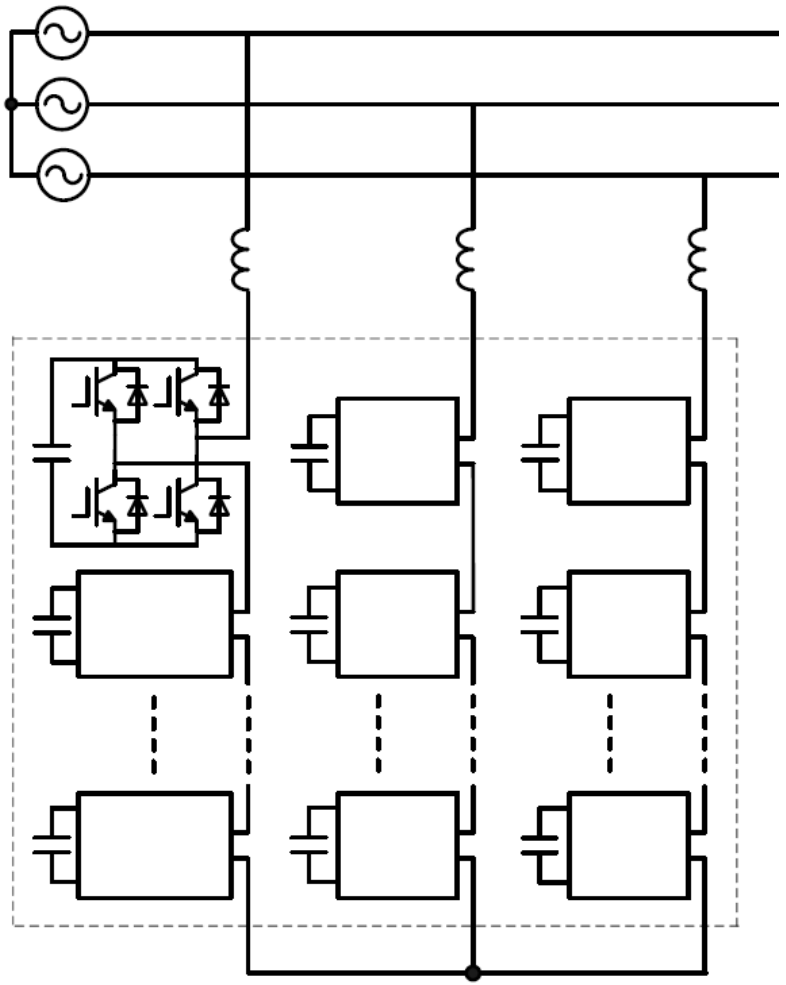
Medium-Voltage SSBC-Based SATCOM with Phase-Shifted-Carrier PWM

SSBC: Single-Star Bridge Cells

H. Akagi, S. Inoue, and T. Yoshii, "Control and performance of a transformerless cascade PWM STATCOM with star configuration," *IEEE Trans. Ind. Appli.,* vol. 43, no. 4, pp. 1041-1049, Jul./Aug., 2007.

Staircase Modulation and Phase-Shifted-Carrier PWM



Single-Star Bridge Cells (SSBC)

F. Z. Peng and J. S. Lai,
IEEE Trans. Ind. Appli., 1997

The use of GTO thyristors:
Staircase modulation (SCM)

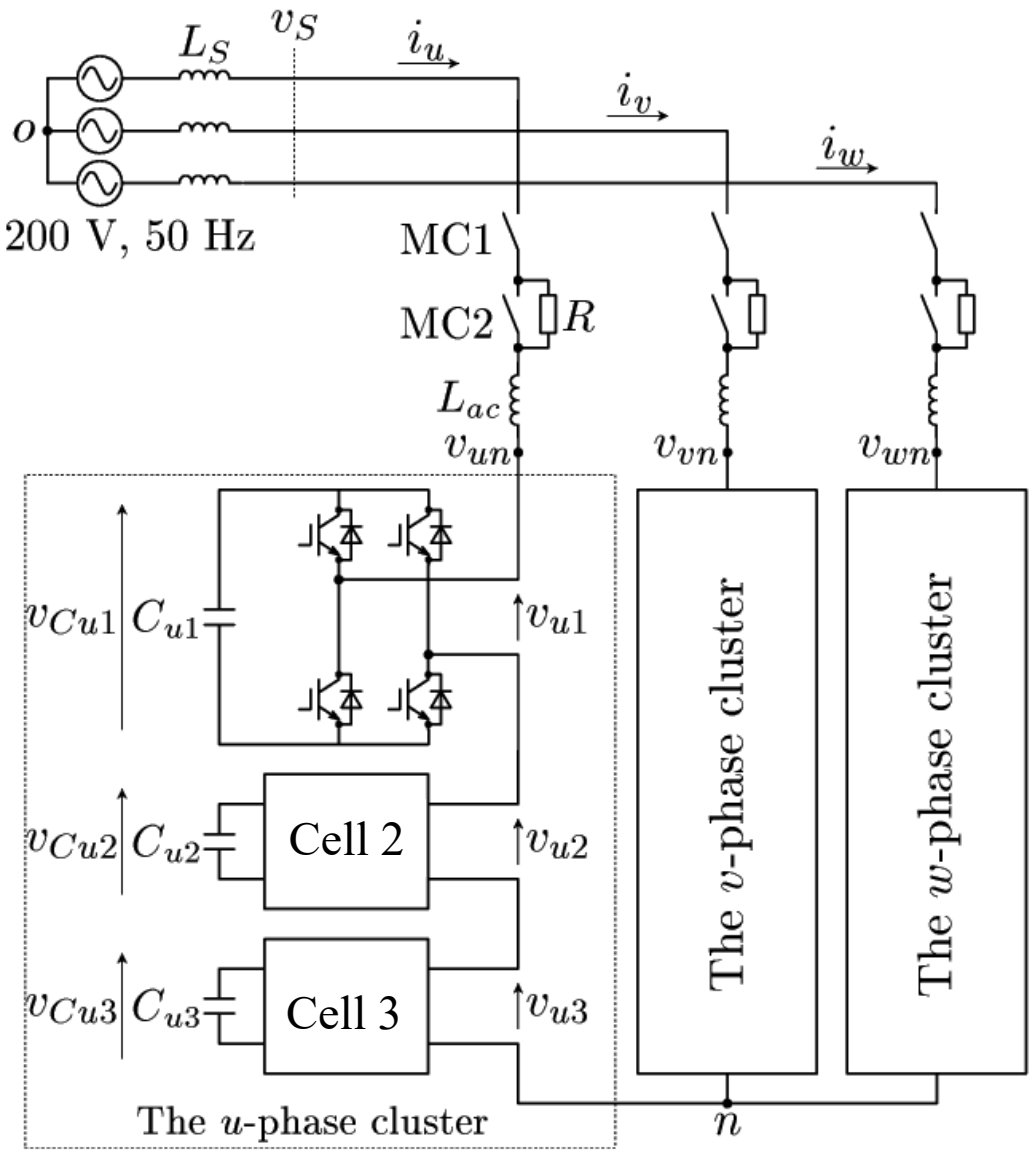
Capacitor-voltage balancing:
Swapping control

H. Akagi, S. Inoue, and T. Yoshii,
IEEE Trans. Ind. Appli., 2007

The use of IGBTs:
Phase-shifted-carrier PWM

Capacitor-voltage balancing:
Hierarchy control

200-V 10-kVA 50-Hz STATCOM for Experiment



Cell count per cluster: 3

7-level in line-to-neutral

13-level in line-to-line

Phase-Shifted-Carrier PWM

Carrier frequency: 1 kHz

Equiv. frequency: 6 kHz

L_S = 0.4% (40 mH)
L_{ac} = 10% (1.2 mH)
H = 36 ms (v_C = 70 V)
C = 16.4 mF

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What Brought both Phase-Shifted-Carrier PWM and Hierarchy Control to the STATCOM?

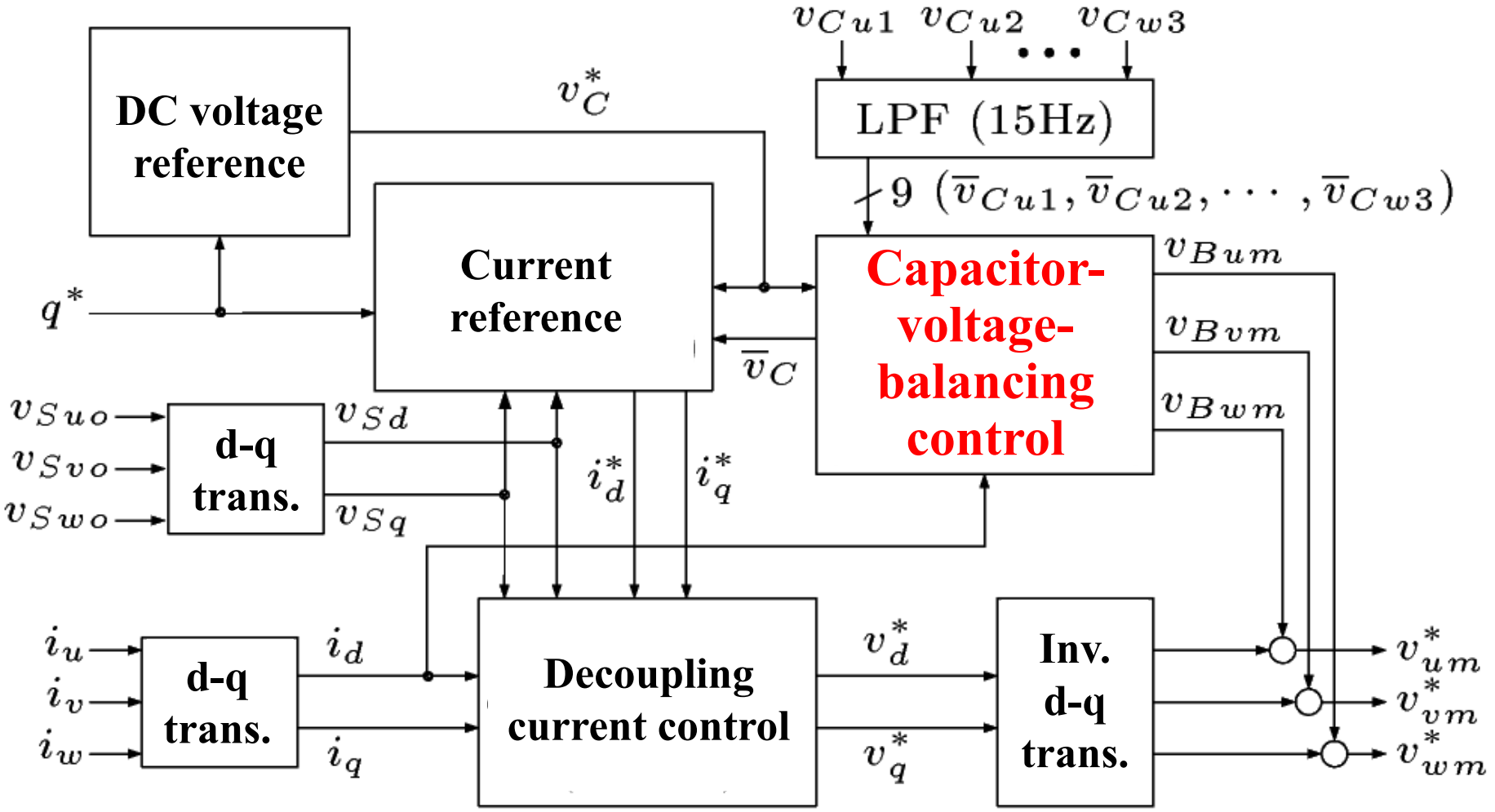
SSBC: Single-Star Bridge Cells

Easy expansion to any bridge-cell count per cluster for any SSBC-based STATCOM.

H. Akagi, "What led to success in academic research on the family of modular multilevel cascade converters," ECCE-Asia/IPEC-Niigata, pp. 2353-2359, 2018.

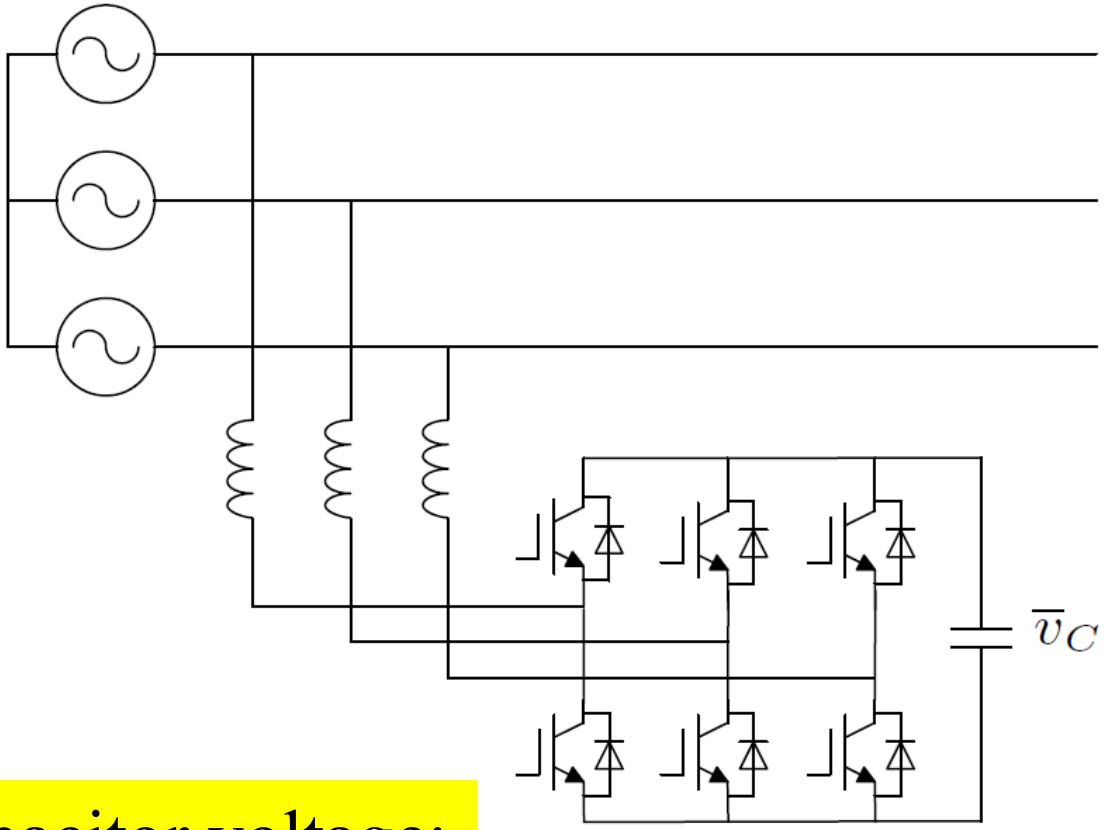
H. Akagi, "A review of developments in the family of modular multilevel cascade converters," IEEJ (IEE of Japan) Transactions, vol. 13, pp. 1222-1235, 2018. (invited paper)

Control Block Diagram for the STATCOM



Top Layer in Hierarchy Control

Overall Voltage Control and Reactive-Power control

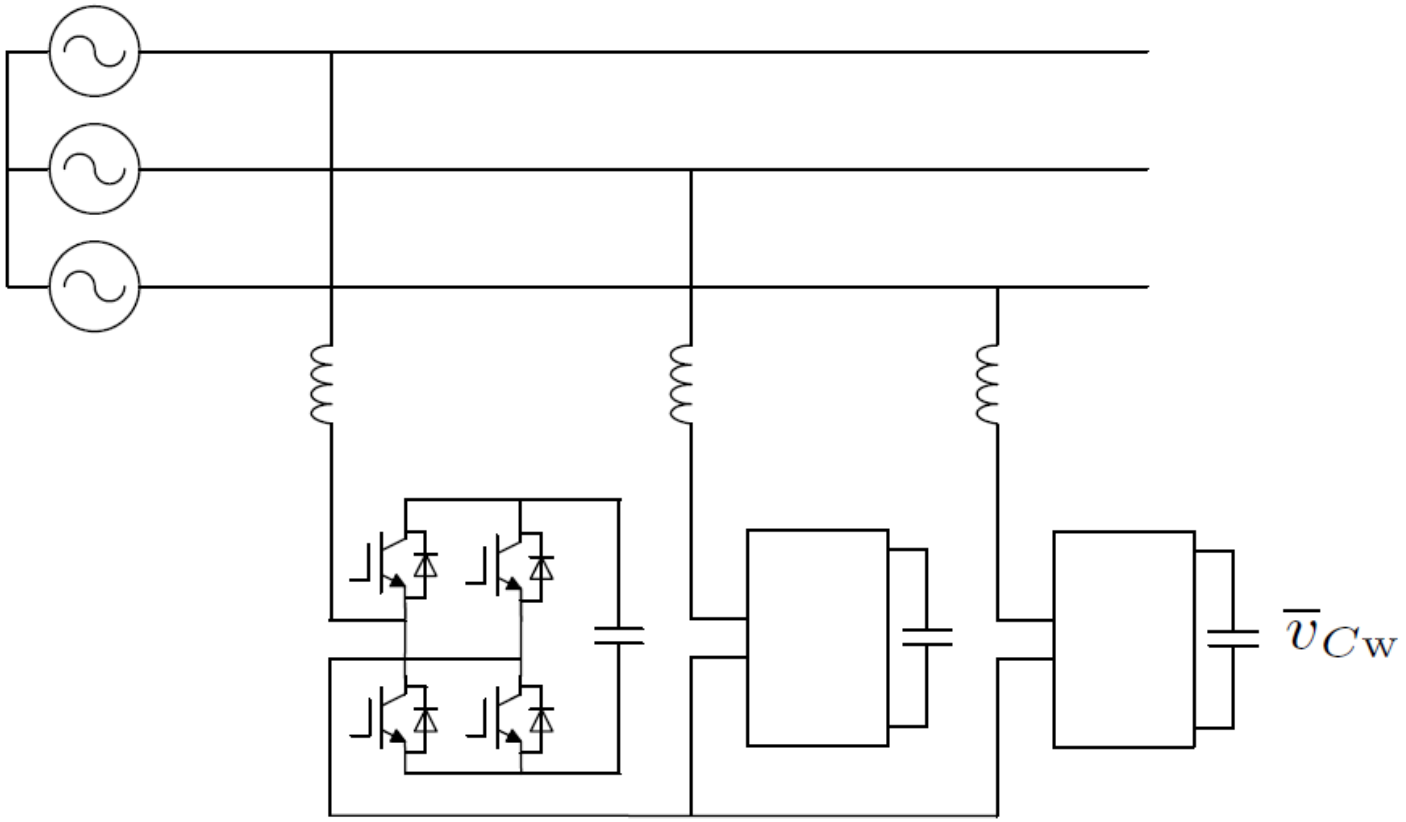


The single dc capacitor voltage:

Arithmetic average of all the dc capacitor voltages.

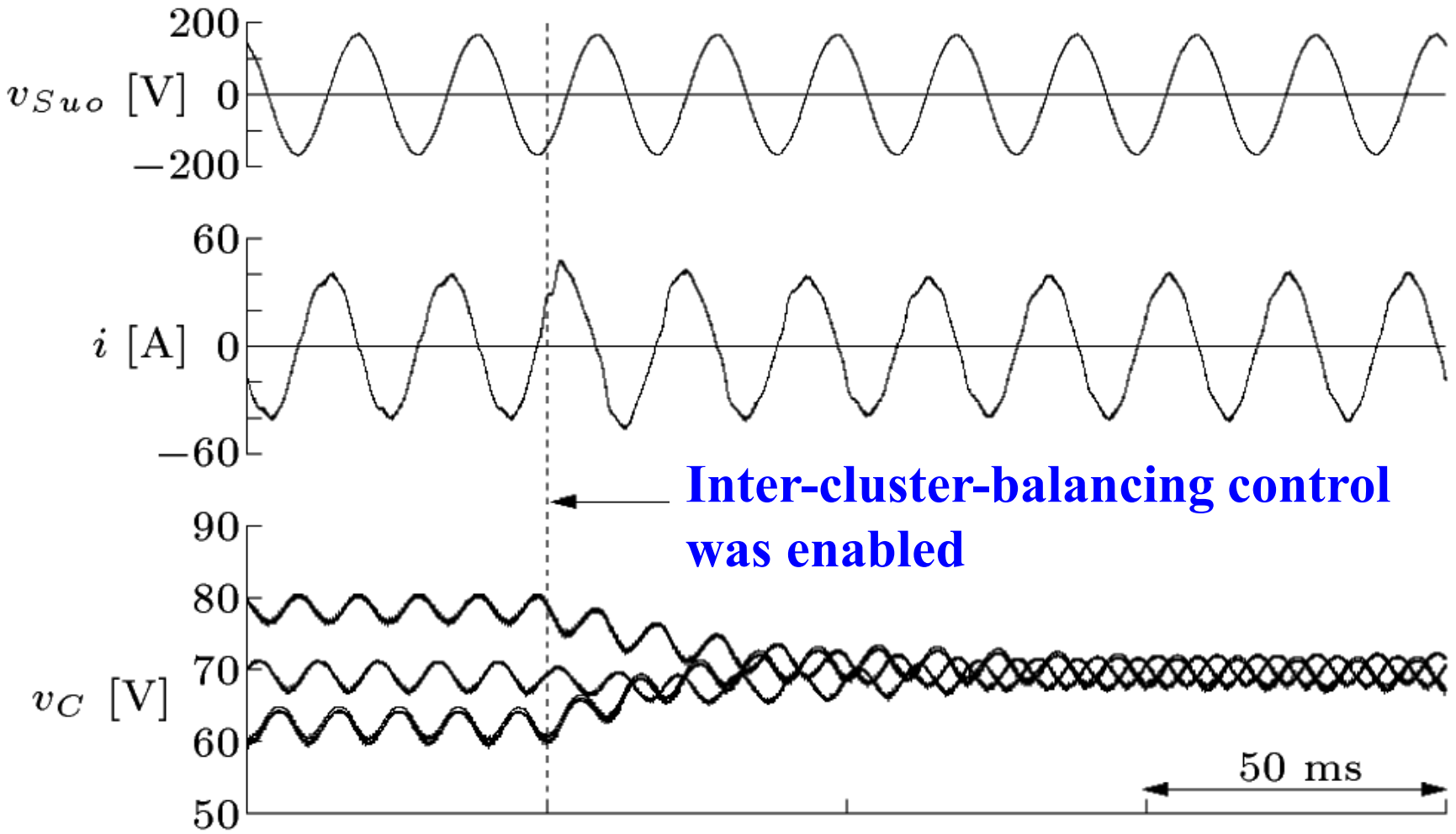
Middle Layer in Hierarchy Control

Inter-Cluster-Balancing Control



The single capacitor voltage in each bridge cell:
Arithmetic average of all the capacitor voltages in each cluster

Effect of Inter-Cluster-Balancing Control



Intra-cluster-balancing control remained enabled

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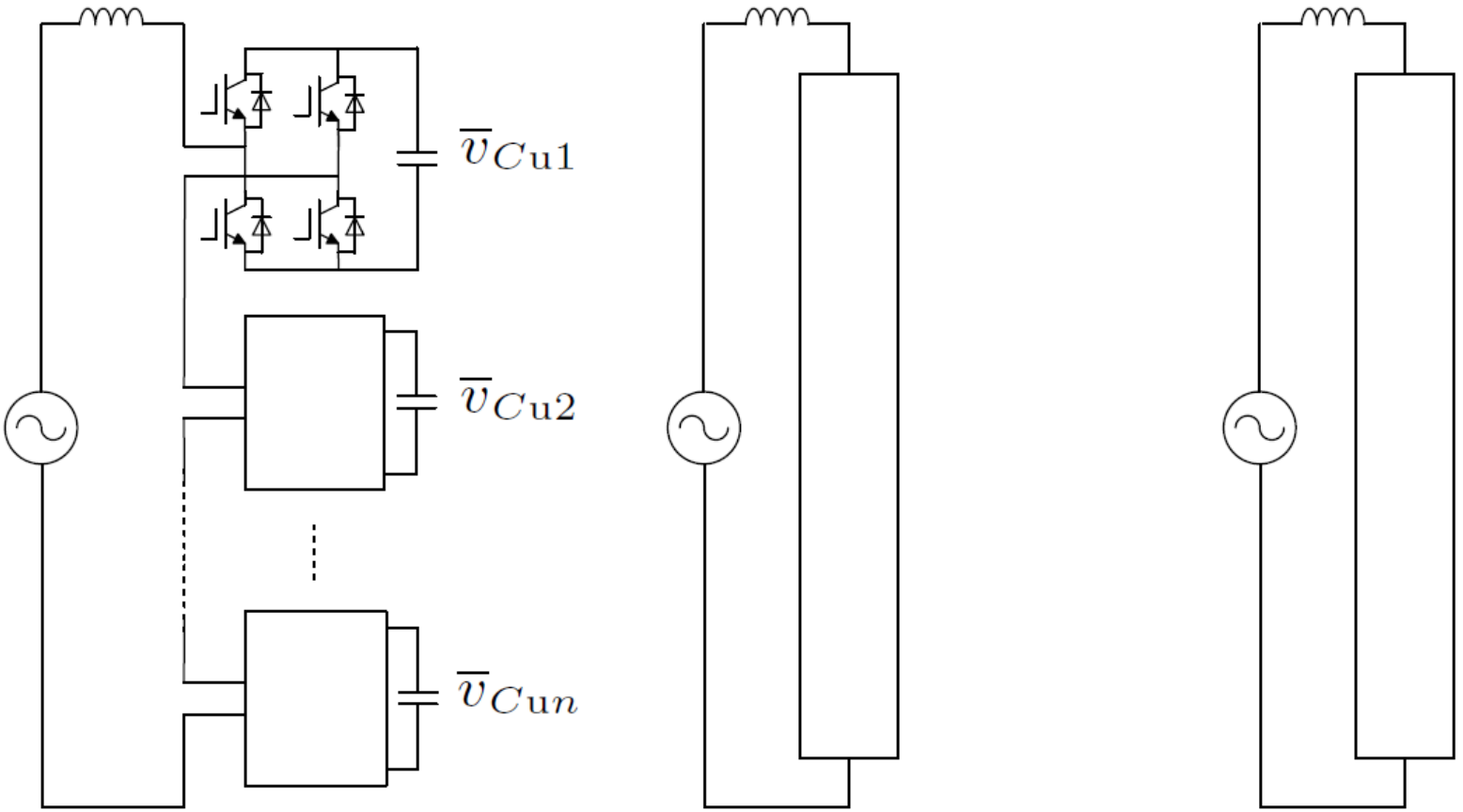
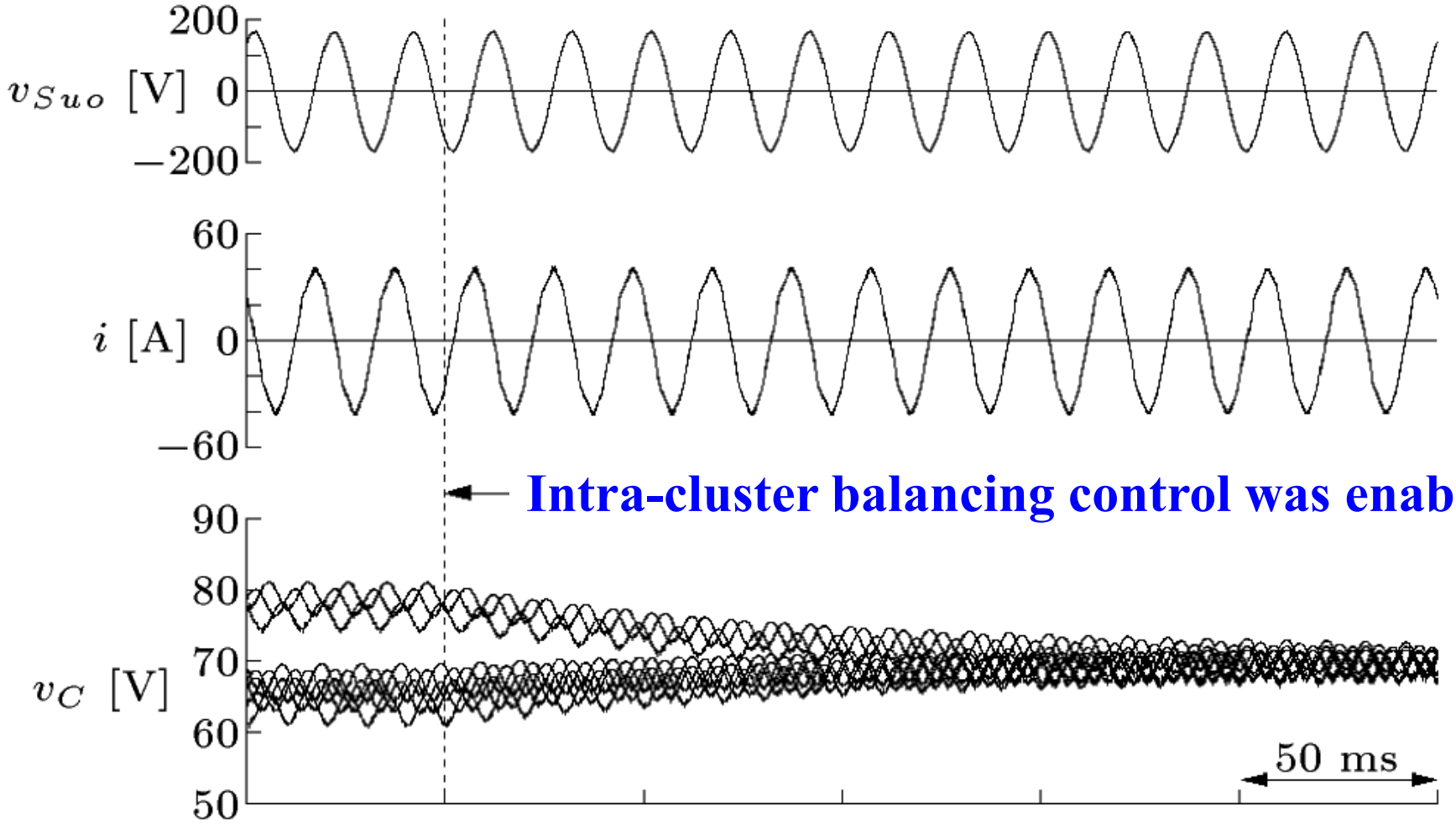
Bottom Layer in Hierarchy Control

Intra-Cluster-Balancing Control



Voltage balancing inside each cluster, independent of the three clusters

Effect of Intra-Cluster-Balancing Control



Inter-clustered balancing control remained enabled

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DSCC-Based BTB(Back-To-Back) System with Phase-Shifted-Carrier PWM

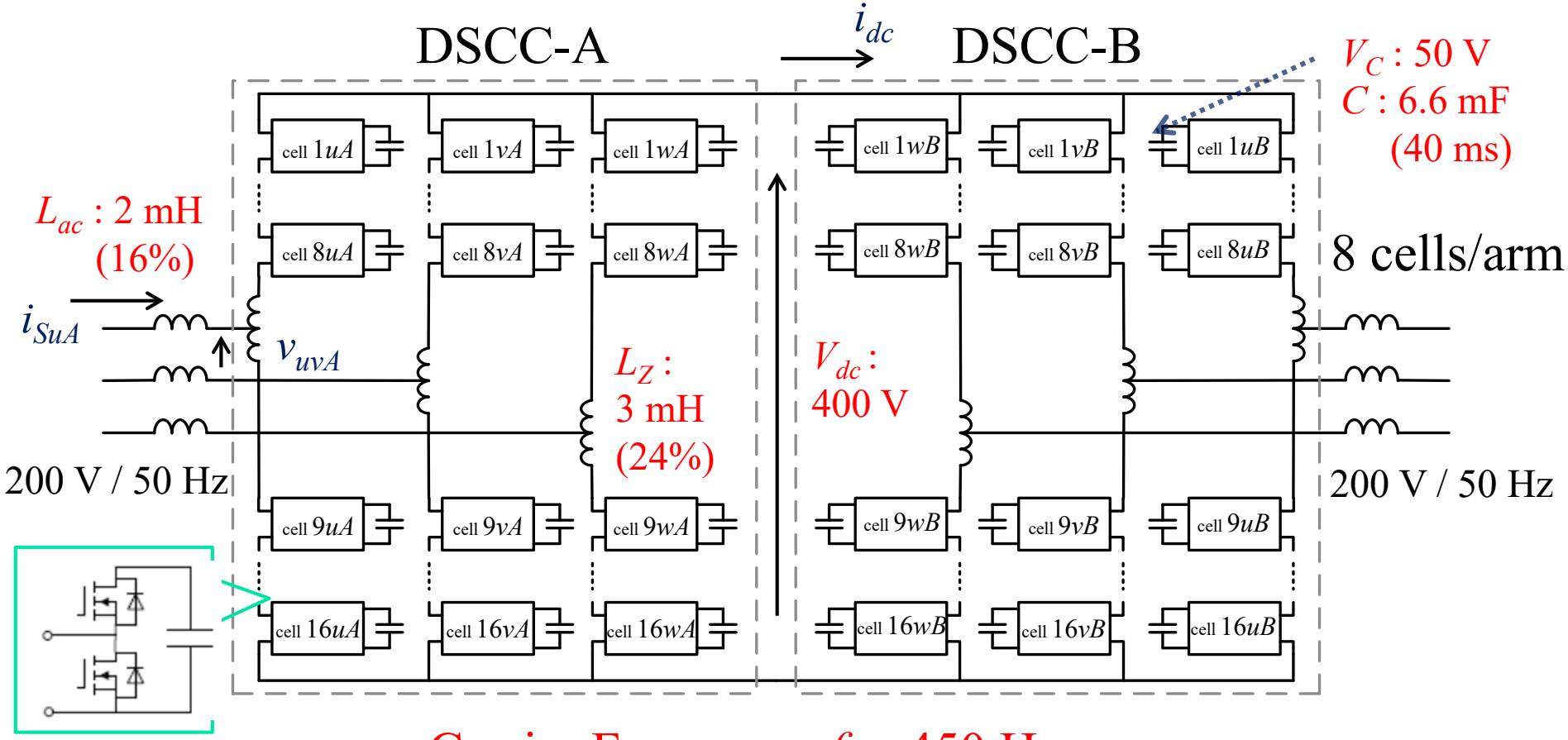
DSCC: Double-Star Chopper Cells

Key Concept: “Circulating Current”

K. Sekiguchi, P. Khamphkdi, M. Hagiwara, and H. Akagi, “A grid-level high-power BTB (back-to-back) system using modular multilevel cascade converters without dc-link capacitor,” *IEEE Trans. Ind. Appli.,vol. 50, no. 4, pp. 2648-2659,* Jul./Aug. 2014

Downscaled Model Rated at 400 Vdc and 10 kW

Neither DC-Link Capacitor nor DC Voltage Sensor



Carrier Frequency f_C : 450 Hz

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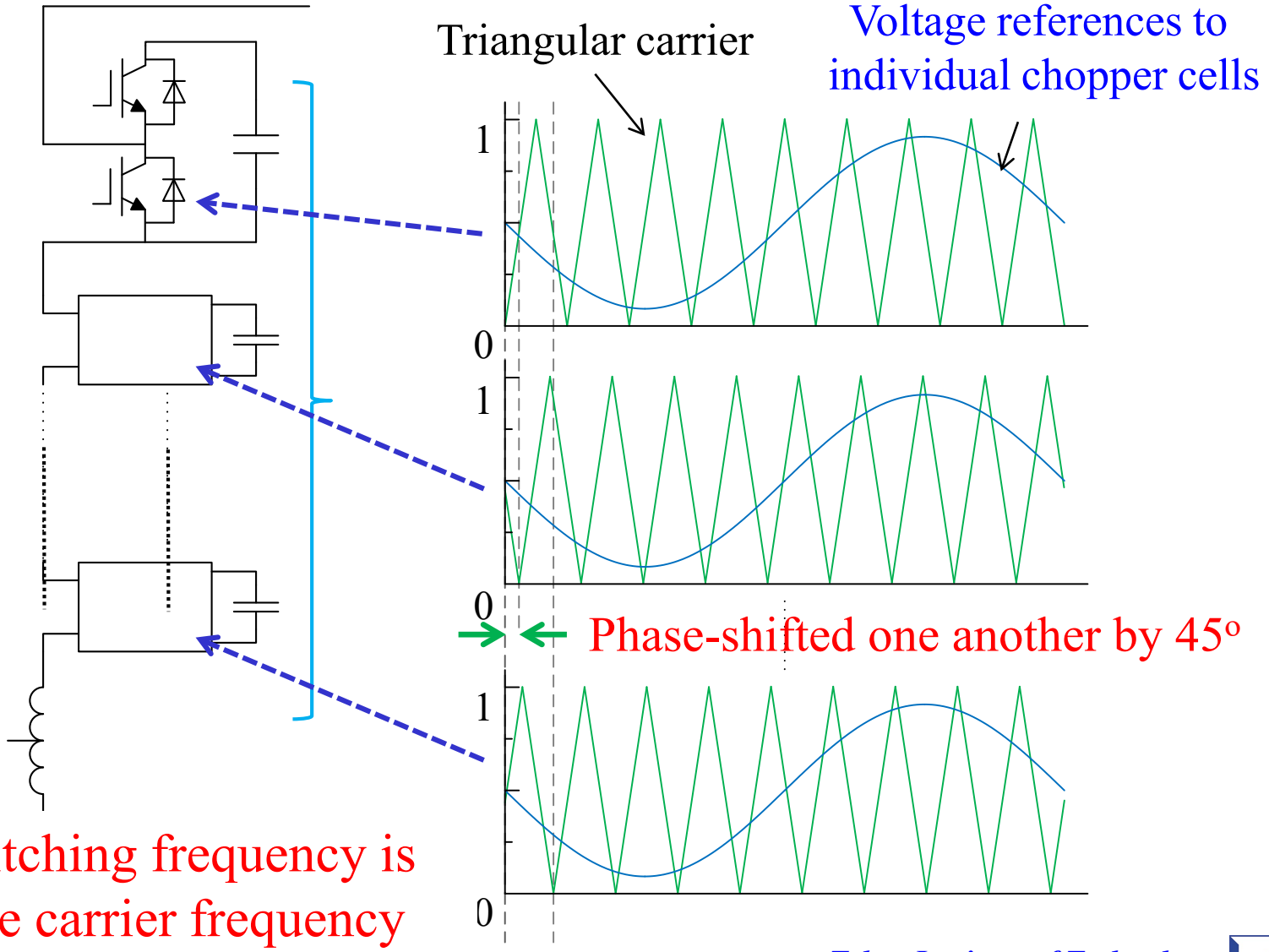
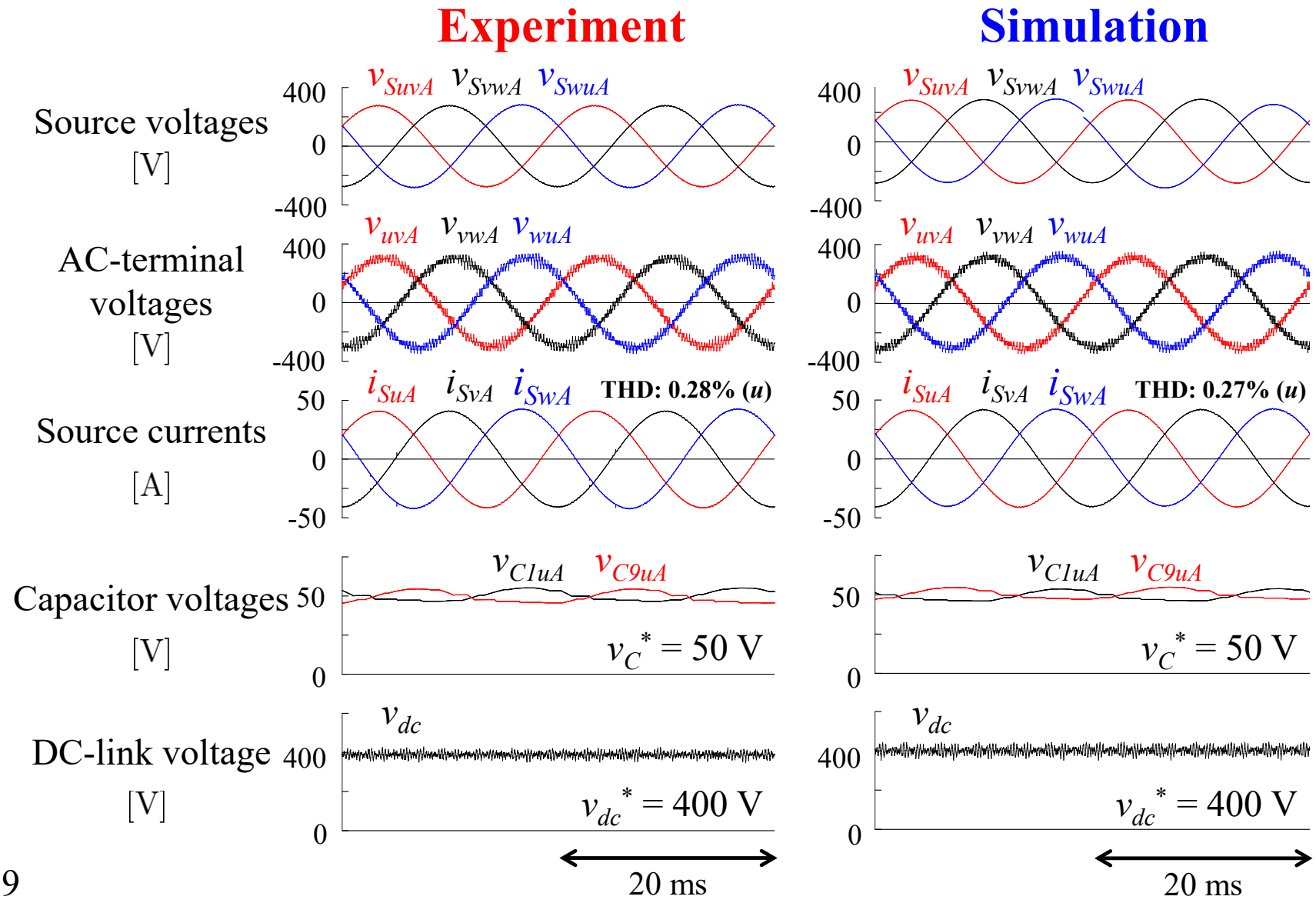
Phase-Shifted-Carrier PWM in Eight Chopper Cells per Arm

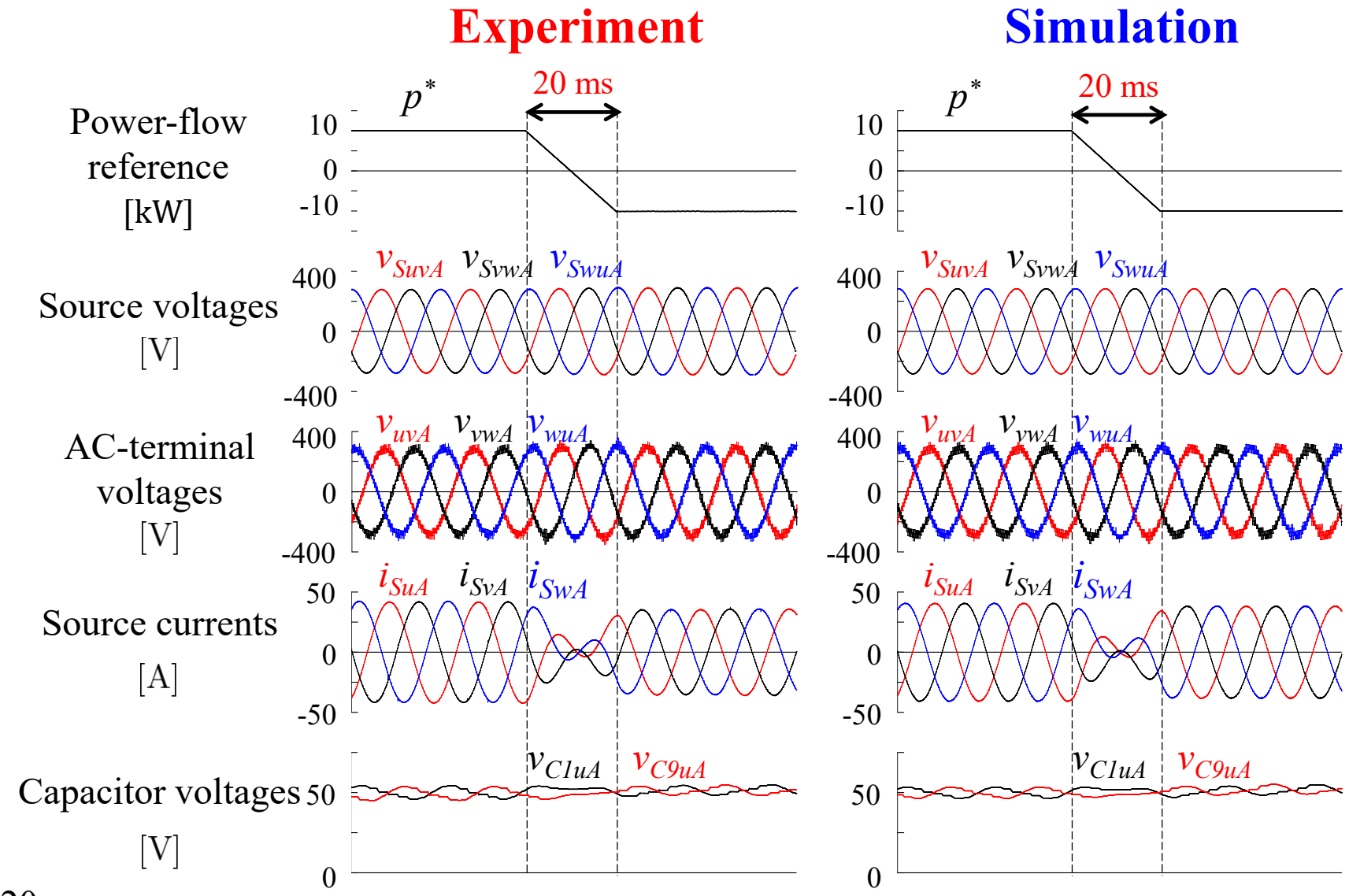


Actual switching frequency is equal to the carrier frequency

Steady State at 8.7 kW and 5.0 kvar (Capacitive)



Transition State: $p^* = \pm 10$ kW and $q^* = 0$



What Brought the Concept of Circulating Currents to the DSCC Converters with Phase-Shifted-Carrier PWM?

DSBC: Double-Star Chopper Cells

Similarity and Analogy between a Line-Commutated Cycloconverter with Circulating-Current Mode and a DSCC Converter

H. Akagi, "What led to success in academic research on the family of modular multilevel cascade converters," ECCE-Asia/IPEC-Niigata, pp. 2353-2359, 2018.

H. Akagi, "A review of developments in the family of modular multilevel cascade converters," IEEJ (IEE of Japan) Transactions, vol. 13, pp. 12222-1235, 2018. (invited review paper)

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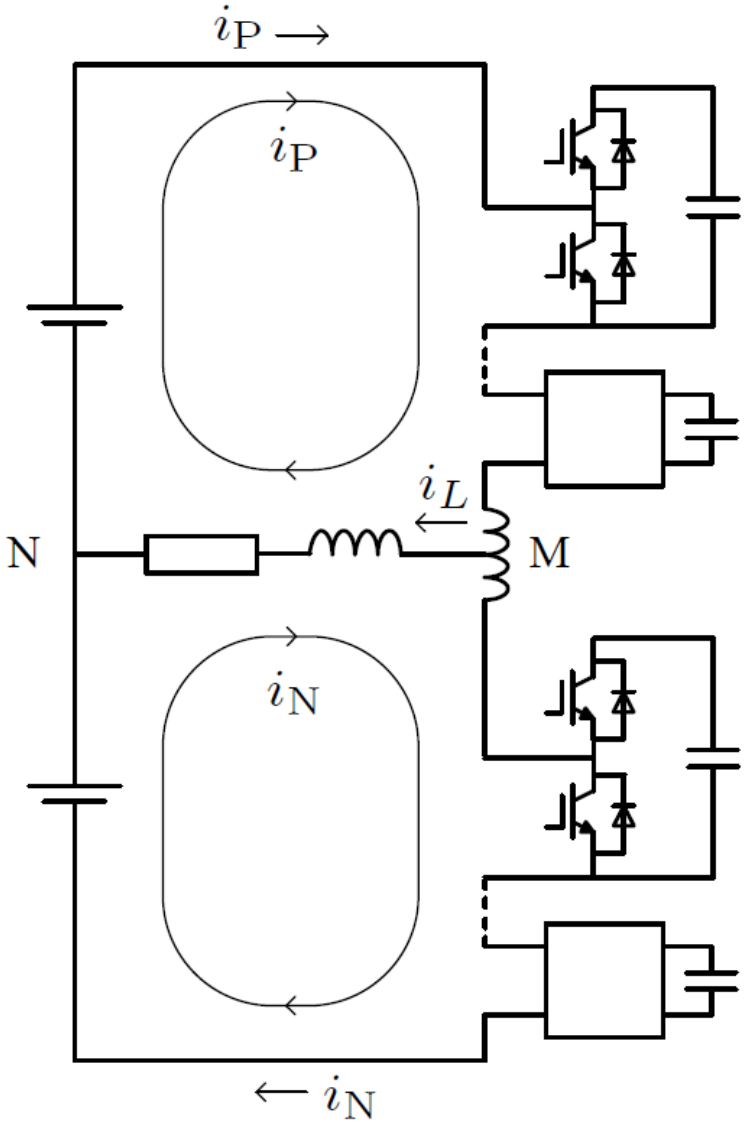
Two Independent Loop Currents i_P and i_N



DSCC inverter per leg

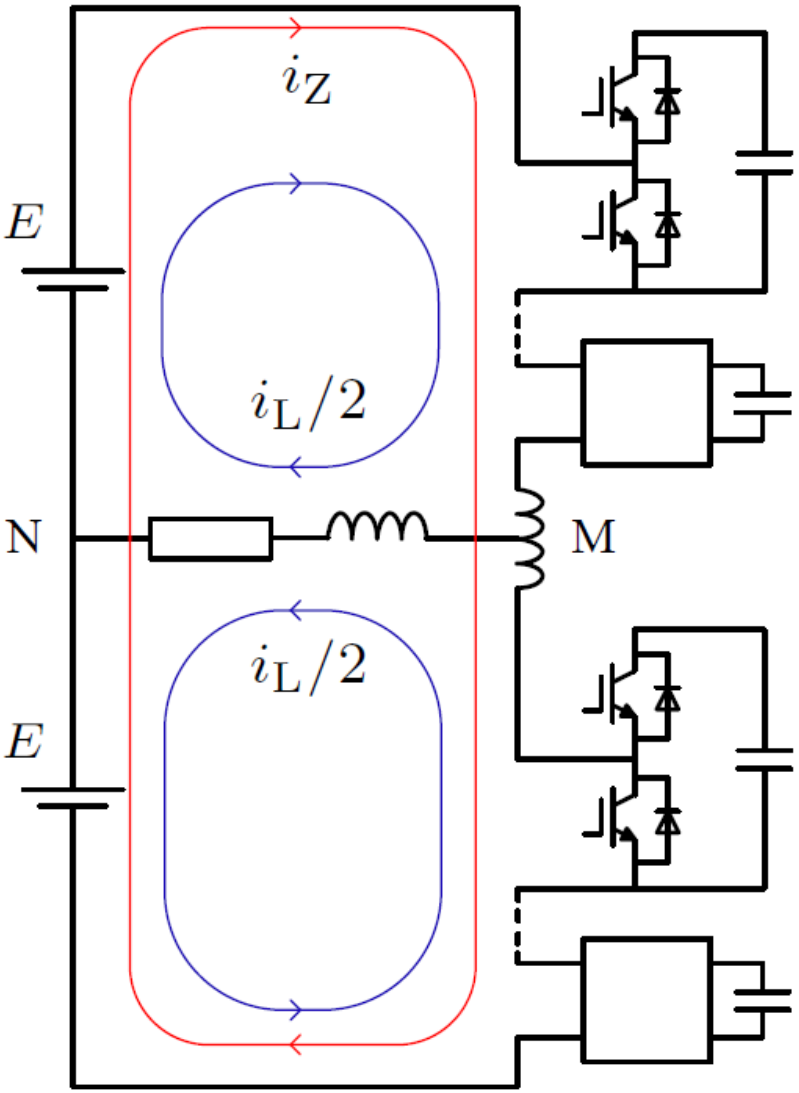
Applying KCL at point M

$$i_L = i_P - i_N$$

Two independent currents among i_L, i_P, and i_N

Selecting a pair of i_P and i_N failed in capacitor-voltage balancing.

Two Independent Loop Currents, i_Z and i_L



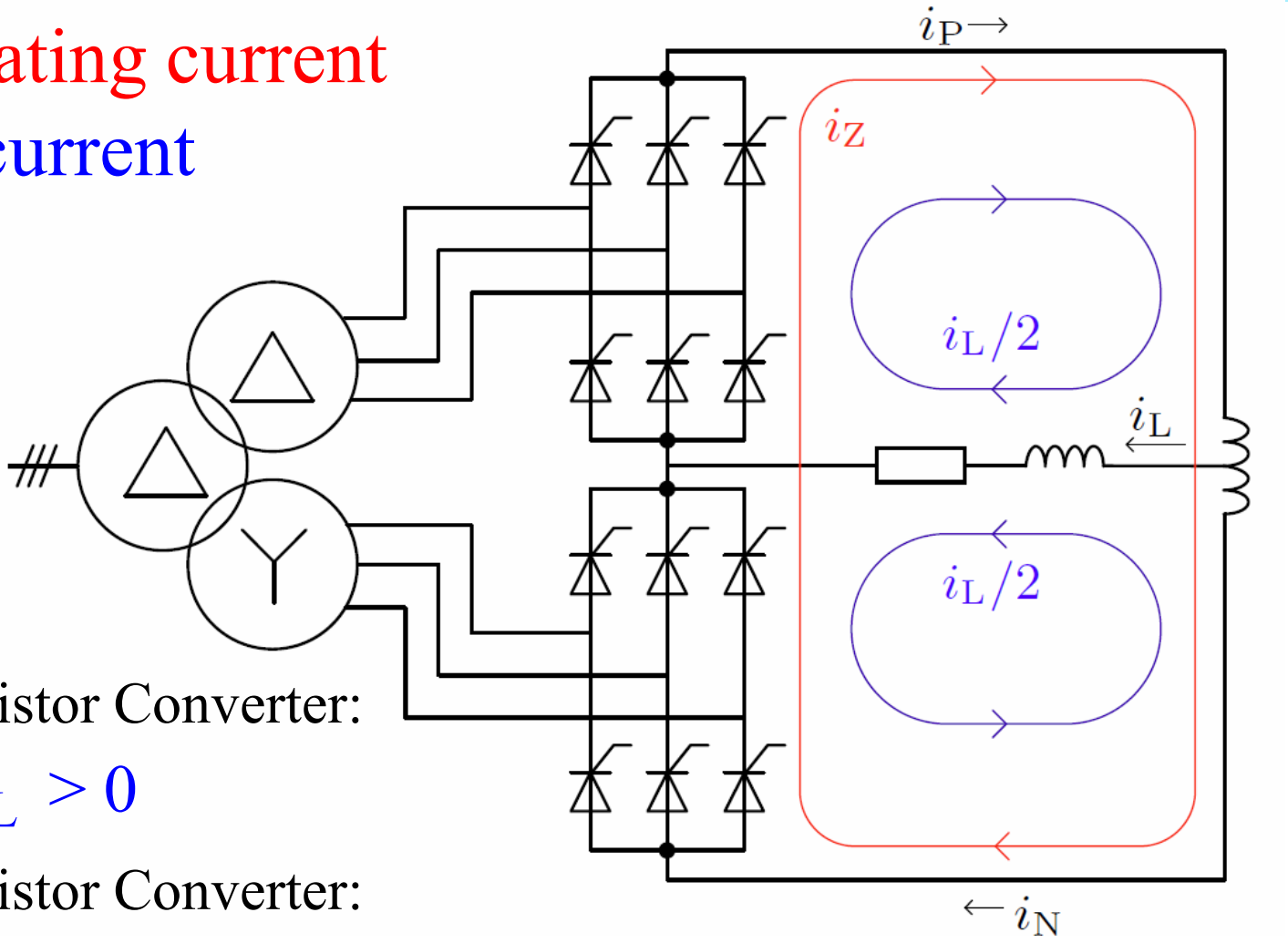
Selecting a pair of i_Z and i_L succeeded in capacitor-voltage balancing.

What triggered off this selection?

A Cycloconverter with Circulating-Current Mode

i_Z : Circulating current

i_L : Load current



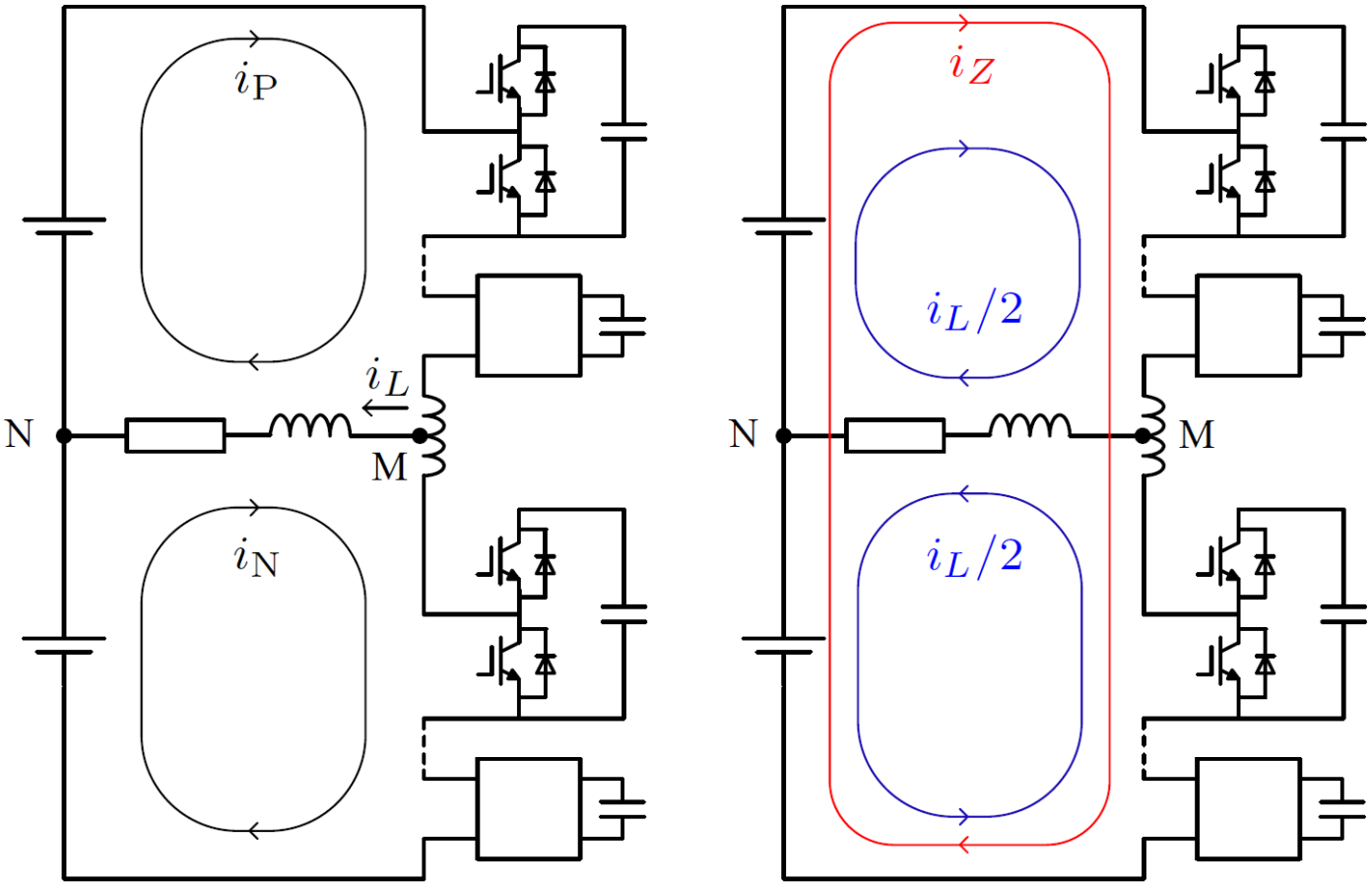
Positive Thyristor Converter:

$$i_P = i_Z + i_L > 0$$

Positive Thyristor Converter:

$$i_N = i_Z - i_L > 0$$

One pair of i_P and i_N, and the other of i_Z and i_L



i_P and i_N i_Z and i_L

Reversible Linear Transformation

The relation between a pair of i_P and i_N and that of i_Z and i_L

$$\begin{bmatrix} i_L \\ i_Z \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0.5 & 0.5 \end{bmatrix} \begin{bmatrix} i_P \\ i_N \end{bmatrix}$$

The determinant of the two-dimensional matrix is unity.

$$\begin{bmatrix} i_P \\ i_N \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 0.5 & 0.5 \end{bmatrix}^{-1} \begin{bmatrix} i_L \\ i_Z \end{bmatrix}$$

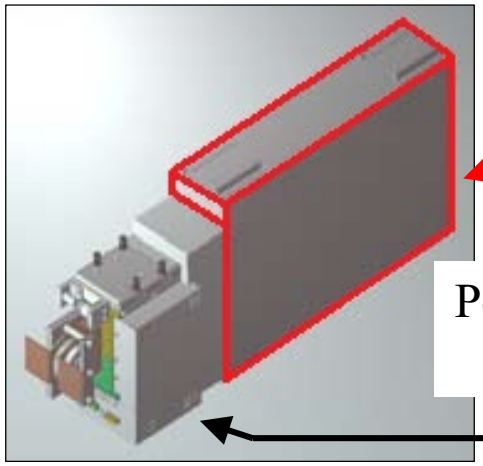
$$= \begin{bmatrix} 0.5 & 1 \\ -0.5 & 1 \end{bmatrix} \begin{bmatrix} i_L \\ i_Z \end{bmatrix}$$

Tomorrow's AC-Link Multi-Drive System

Y. Okazaki and H. Akagi,
"Feasibility Study of a Modular Multilevel DSBC Conversion System Equipped With Medium-Frequency Isolation Transformers for Driving Multiple Medium-Voltage Motors,"
IEEJ Transactions on Industry Applications, vol. 136, no. 12, pp. 1005-1014, Dec. 2016. (in Japanese)

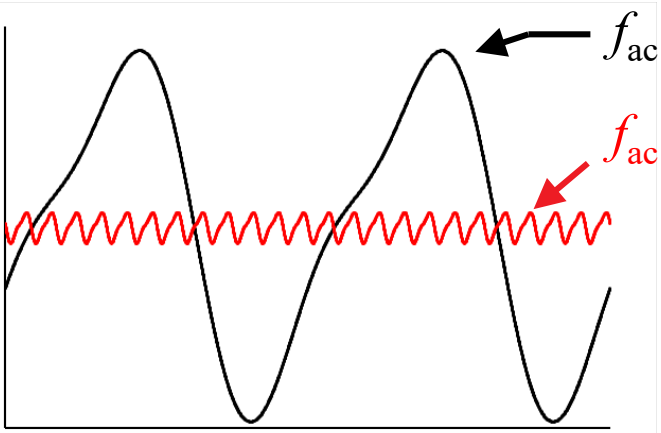
How to Reduce the Capacitor Size in MMC or DSCC

Chopper cell
at f_{ac} = 50 Hz



www.energy.siemens.com
Siemens HVDC Plus

Capacitor voltage waveforms



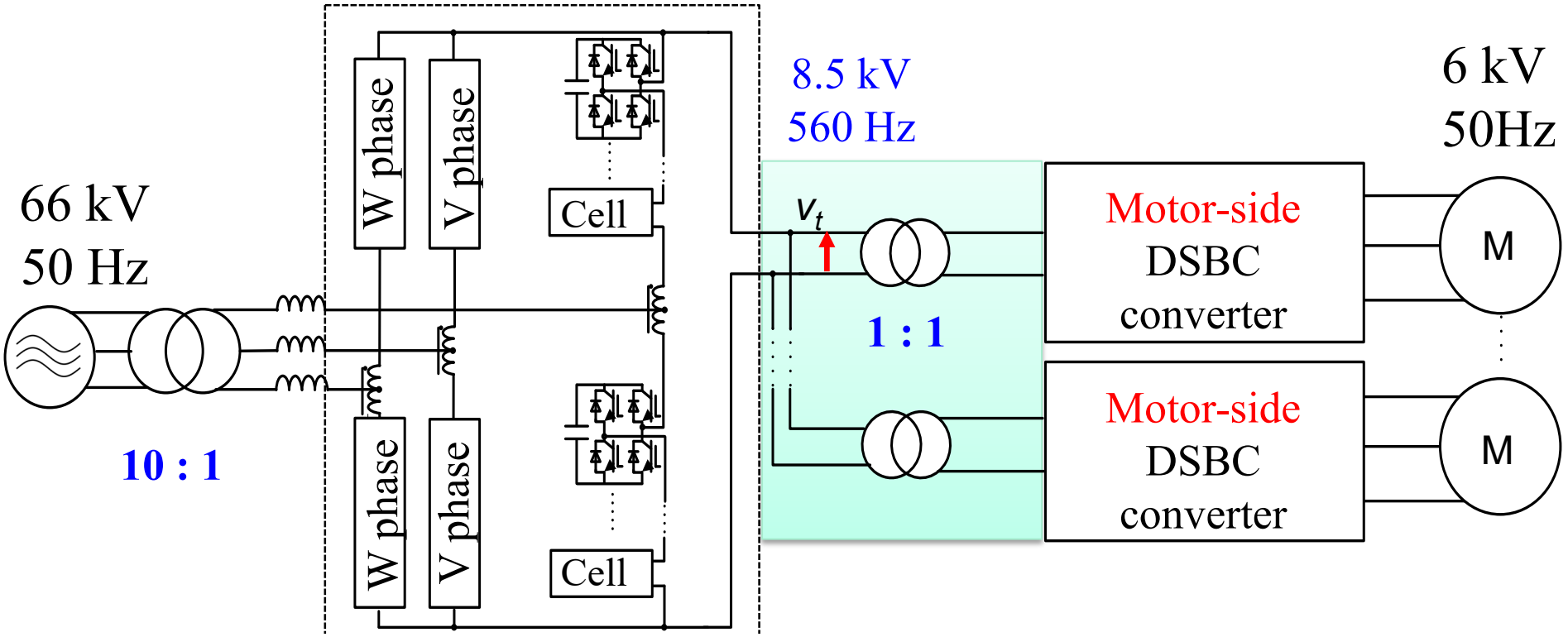
Voltage fluctuations $\propto 1/(C f_{ac})$

f_{ac} : Inverter ac frequency

C : Capacitance value

Making the ac frequency f_{ac} higher is accompanied by reducing the capacitor size.

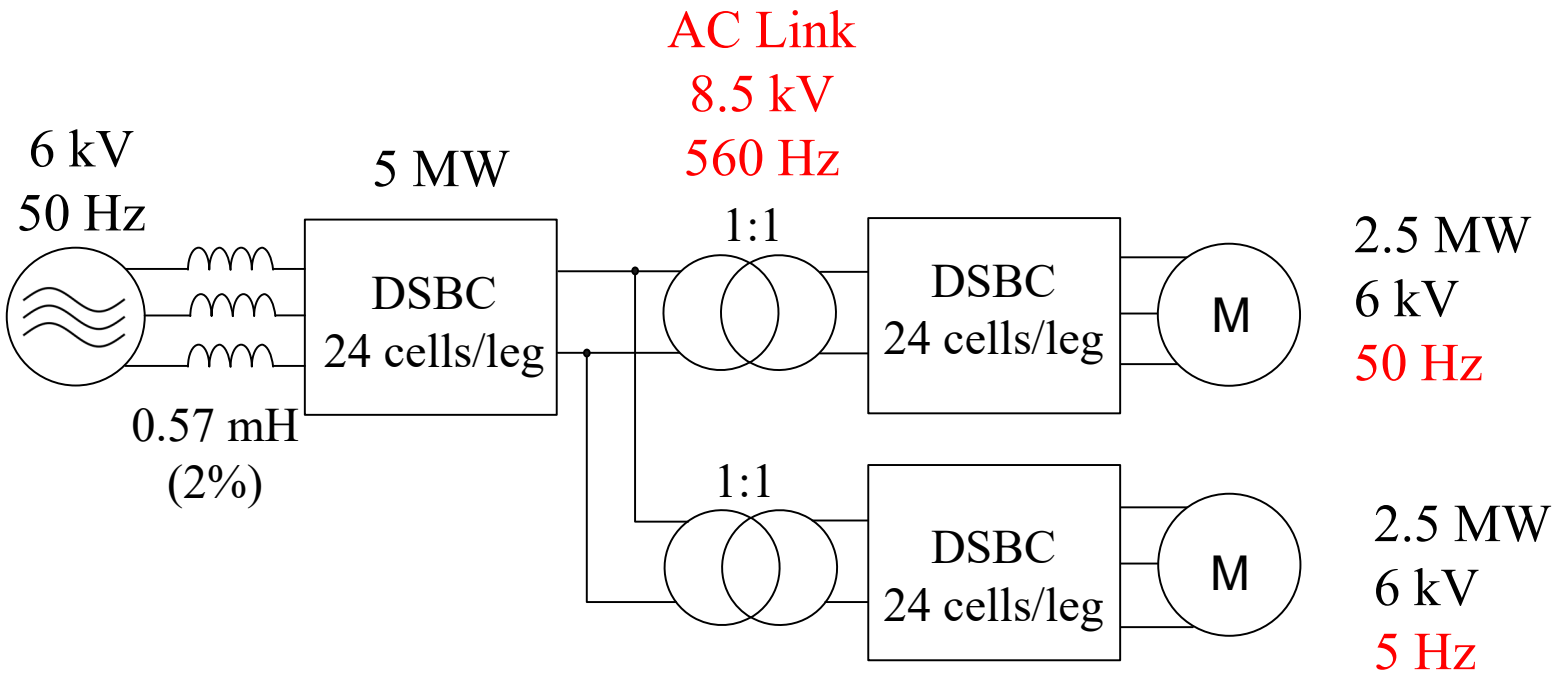
Tomorrow's AC-Link Multi-Drive System



Line-side DSBC converter

Each motor is galvanically isolated from the others as well as the ac mains.

A Basic System Configuration for Simulation



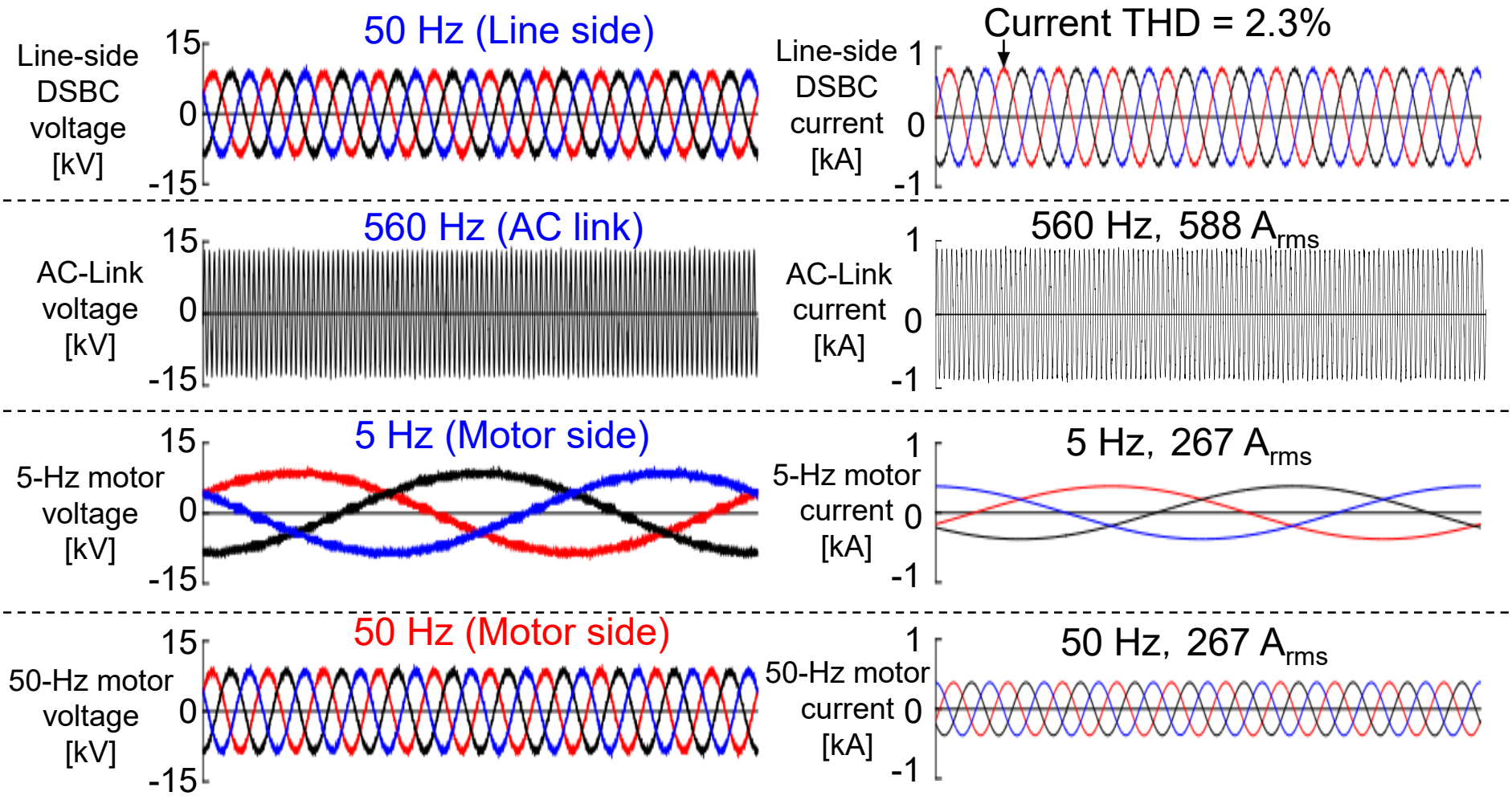
Simulation Conditions

Switching devices: 1.7-kV IGBTs

Each triangular carrier frequency: 1 kHz

Equivalent carrier frequency: 48 kHz

Simulated Waveforms of the three DSBC Converters



"Decoupled control" was confirmed among the three DSBC converters.

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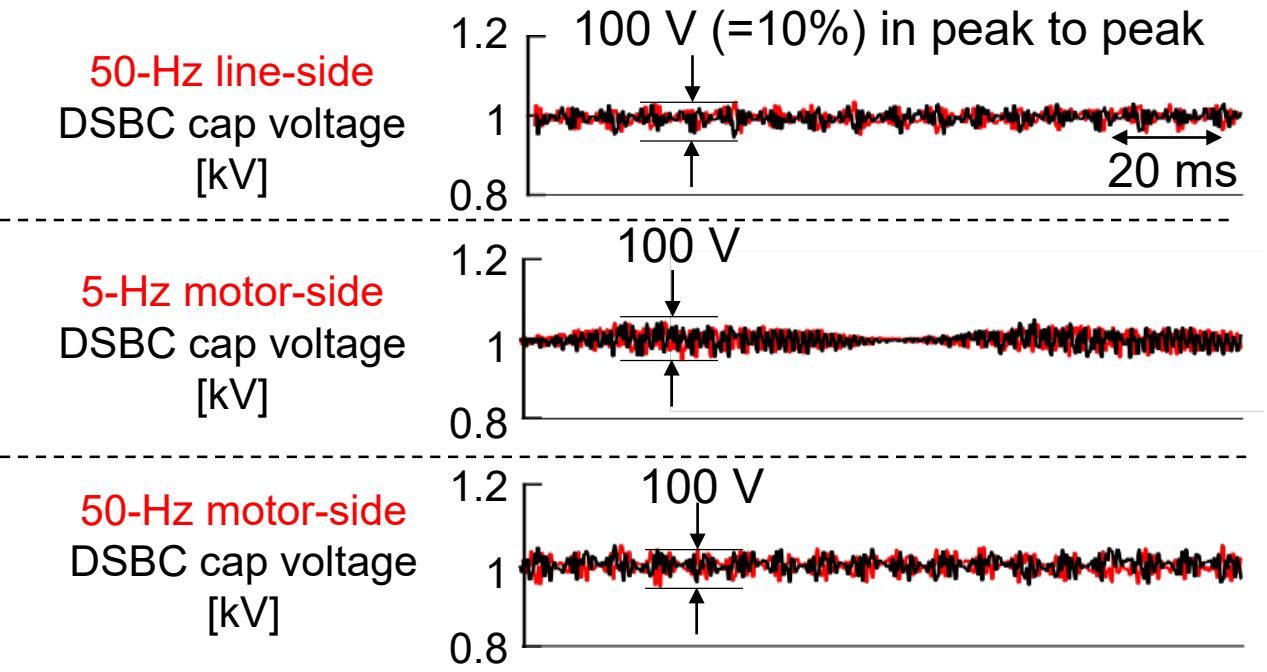
Simulated Waveforms of DC Capacitor Voltages



Unit capacitance constant: 20 ms

The capacitor size can be reduce practically to 1/10 or more, compared to that of an ac-link frequency of 50 Hz.

Conclusion

What has led to success in research on the modular multilevel cascade converters?

1. Phase-Shifted-Carrier PWM:

   Actual switching frequency equal to carrier frequency.

2. Hierarchy Control:

   Easy expansion to any bridge-cell or chopper-cell count.

Tomorrow's AC-Link Multi-Drive System:

Capable of galvanic isolation and voltage matching