The Cutting Edge of Power Electronics for High-Power Applications

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July 28, 2015

Tokyo Institute of Technology

Established in 1881

Environmental Energy Innovation (EEI) Building with 650-kW Photovoltaic, 100-kW Fuel-Cell, and 100-kWh Lithium -Ion Battery Energy Storage Systems

Energy Efficiency of Passenger Aircrafts

Airbus A340-300

Number of seats: 261

Max. take-off weight: 250,000 kg

Range: 12,800 km

Cruising speed: 875 km/h

Fuel Consumption (Energy Efficiency):

0.039 liters per seat/km

A340-300

Airbus A330-300

Number of seats: 261

Max. take-off weight: 233,000 kg

Range: 9,700 km

Cruising speed: 875 km/h

Fuel Consumption (Energy Efficiency):

0.035 liters per seat/km

A330-300

source: SCANORANAM, FEB 2007

What is Power Electronics? (1/2)

- **The IEEE Power Electronics Society** with a membership of 8,000 is one of some 40 IEEE Societies.
- **Power Electronics** is based on **switching operation** of power semiconductor devices such as **MOSFETs** and **IGBTs** for achieveing efficient power conversion.
- **Power Electronics Technology** encompasses

1. the effective use of electronic components,
2. the application of circuit and **control theory**,
3. the development of analytical tools toward conversion, **control**, and conditioning of electric power.

What is Power Electronics? (2/2)

- Power range： from **several watts** to **6.3 GW**
- Frequency range： from **0 Hz（dc）** to **13.56 MHz**
- Devices： semiconductors, magnetics, and capacitors
- **Controls**: DSPs, PLDs, FPGAs, A/D converters, and sensors of voltage, current, magnetic flux, position, speed, acceleration, temperature, etc.

Power Electronics is on the basis of

Devices, Circuits, Controls, and Systems

Practical Applications of Power Electronics

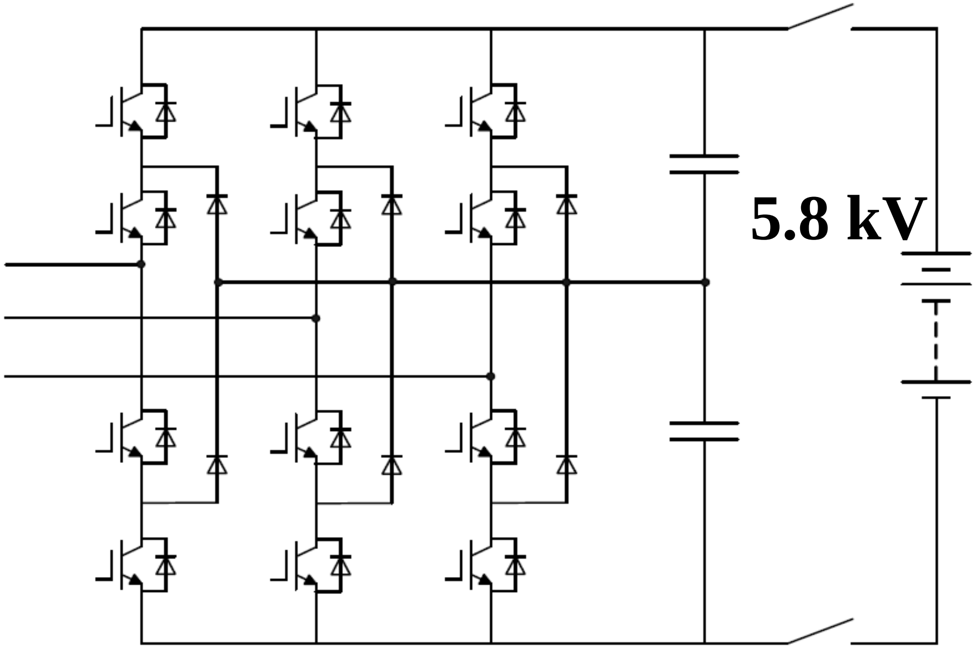
- Switching power supplies for computers and servers
- Home appliances：air conditioners, refrigerators, induction-heating cookers, microwaves, vacuum cleaners, laundry machines, electric fans, LED lamps, and so on.
- UPS (uninterruptable power supply)：from 1 kW to 1 MW
- Industrial induction heating：200 kHz 200 kW for surface quenching
- Industrial ac motor drives： fans/blowers, pumps, compressors, steel mils, and so on
- Transportation: high-speed and commuter trains, trams/street cars, electric vehicles, fuel-cell vehicles, ships/boats, and aircrafts
- Electric power utilities： photovoltaic inverters, battery energy storage systems, adjustable-speed pumped hydro storage, reactive-power controllers, high-voltage dc transmission systems

A Flexible, Effective, and Fault-Tolerant Battery Energy Storage System (BESS)

To be published in the IEEE Transactions on Power Electronics, or Early access

An Existing Battery Energy Storage System (BESS)

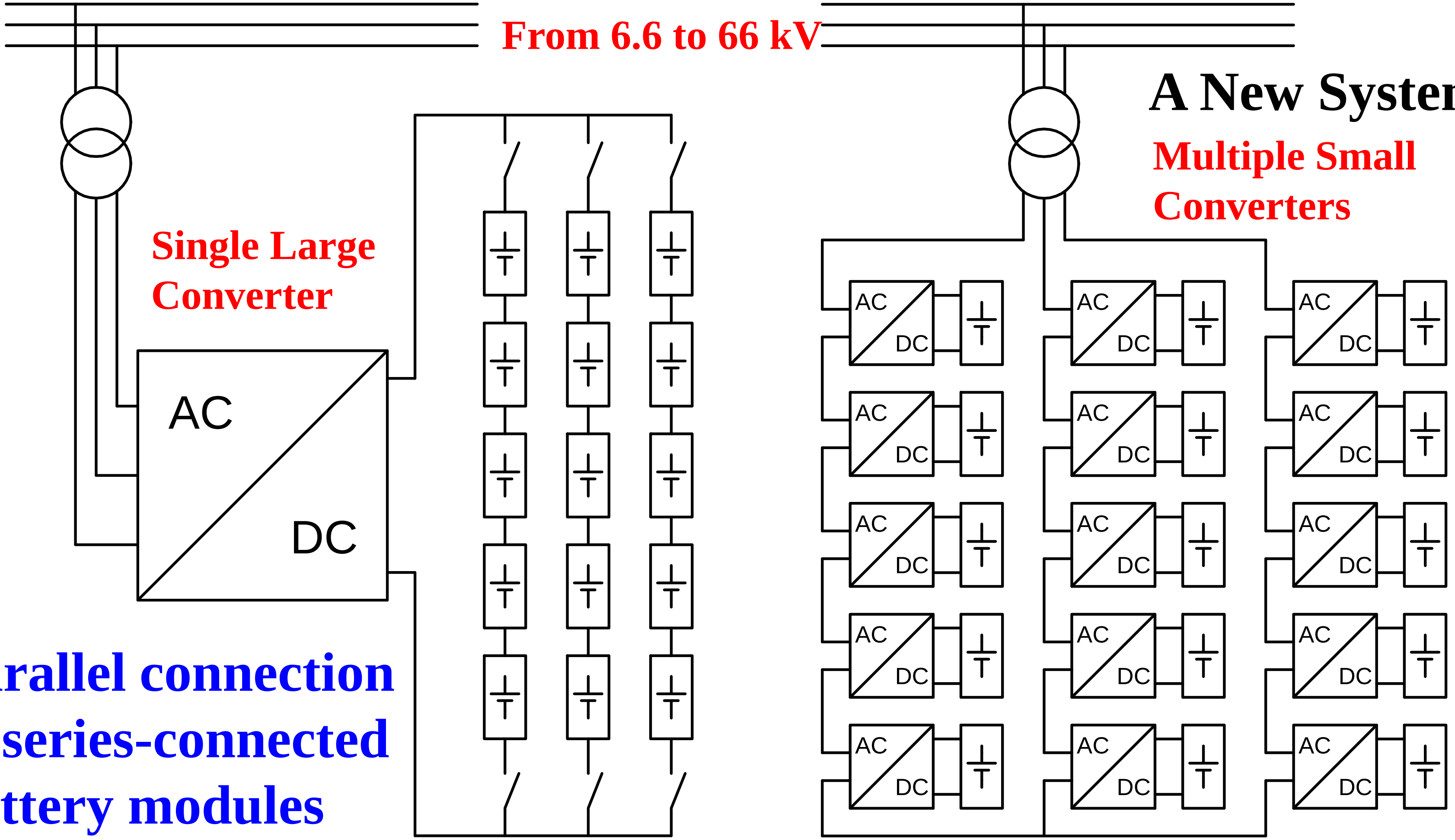
N. Wade, P. Taylor, P. Lang, and **J. Svensson**, **"Energy storage for power flow management and voltage control on an 11kV UK distribution network,"** in *Proc. CIRED'09,* Jun. 2009.



- EDF Energy Networks, UK
- **600-kW 200-kWh BESS for peak shaving**
- **Neutral-Point Clamped (NPC) Converter[1]**
- **Li-ion battery system**

[1] A. Nabae, I. Takahashi, and H. Akagi, "A New Neutral-Point-Clamped PWM Inverter," *IEEE Trans. Industry Applications*, vol. 17, no. 5, pp. 518-523, Sep./Oct. 1981. **Cited by 3214**

Comparisons between Existing and New BESSs



From 6.6 to 66 kV

A New System

Multiple Small Converters

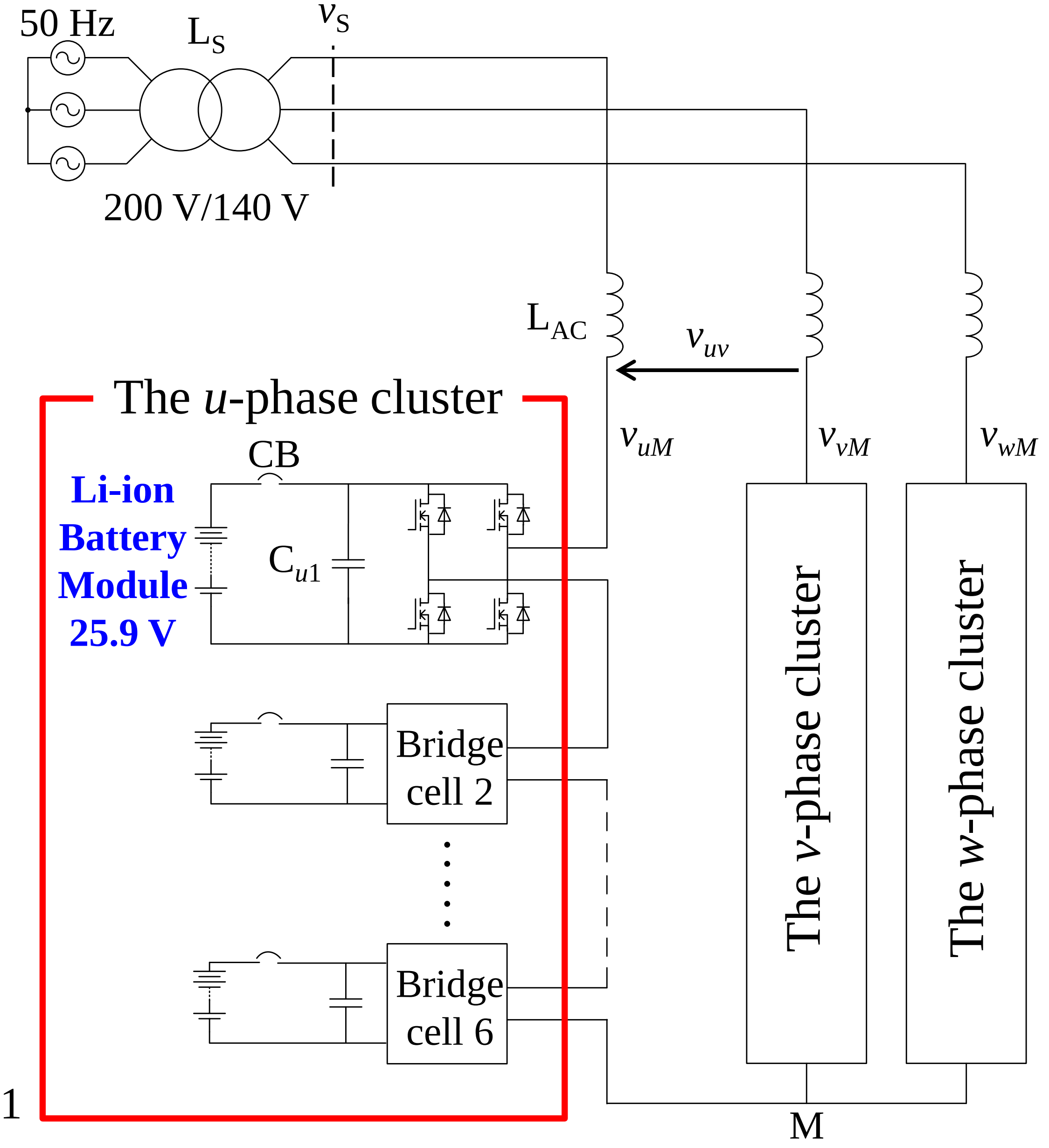
Single Large Converter

Parallel connection of series-connected battery modules

Existing System

One converter-to-one battery module

Three-phase 10-kW, 22-kWh Downscaled System



Circuit parameters

Nominal line-to-line rms voltage V_S	140 V
Rated power	10 kW
Cascade number	6
Background system Inductance L_S	0.10 mH (1.6%)
AC link Inductance L_{ac}	0.33 mH (5.3%)
DC capacitor capacitance	47 mF
Nominal battery voltage	**25.9 V**
Each battery capacity	1.2 kWh
PWM carrier frequency f_C	**1.75kHz**
Equivalent PWM carrier frequency	**21 kHz**

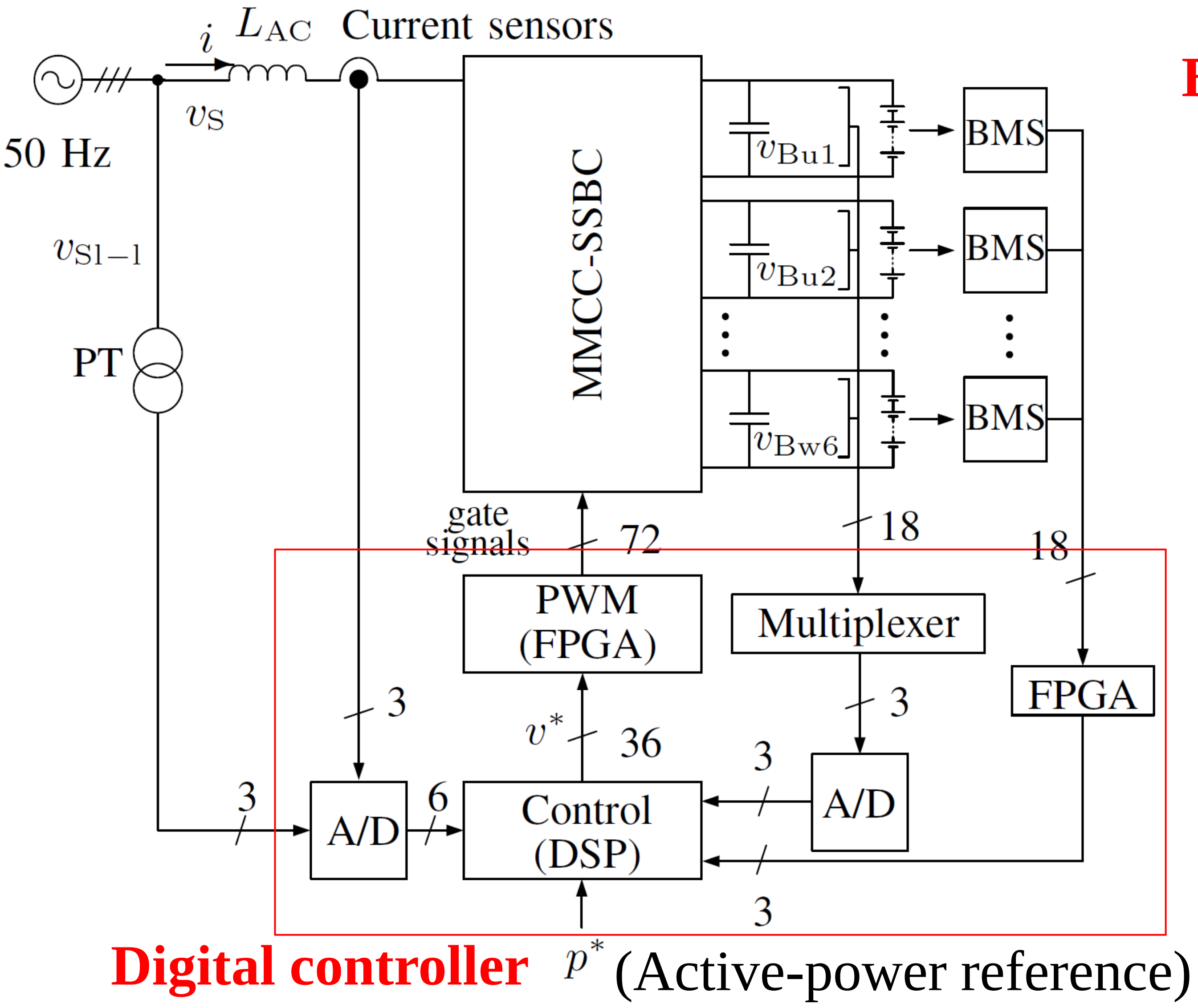
Tokyo Institute of Technology
Power Electronics Lab.

18 Li-Ion Battery Modules (25.9 V, 47.5 Ah)

Nominal voltage: 25.9 V (=3.7 V/cell times 7 cells)

Weight: 15 kg/module, Total capacity: **22 kWh**

Control System



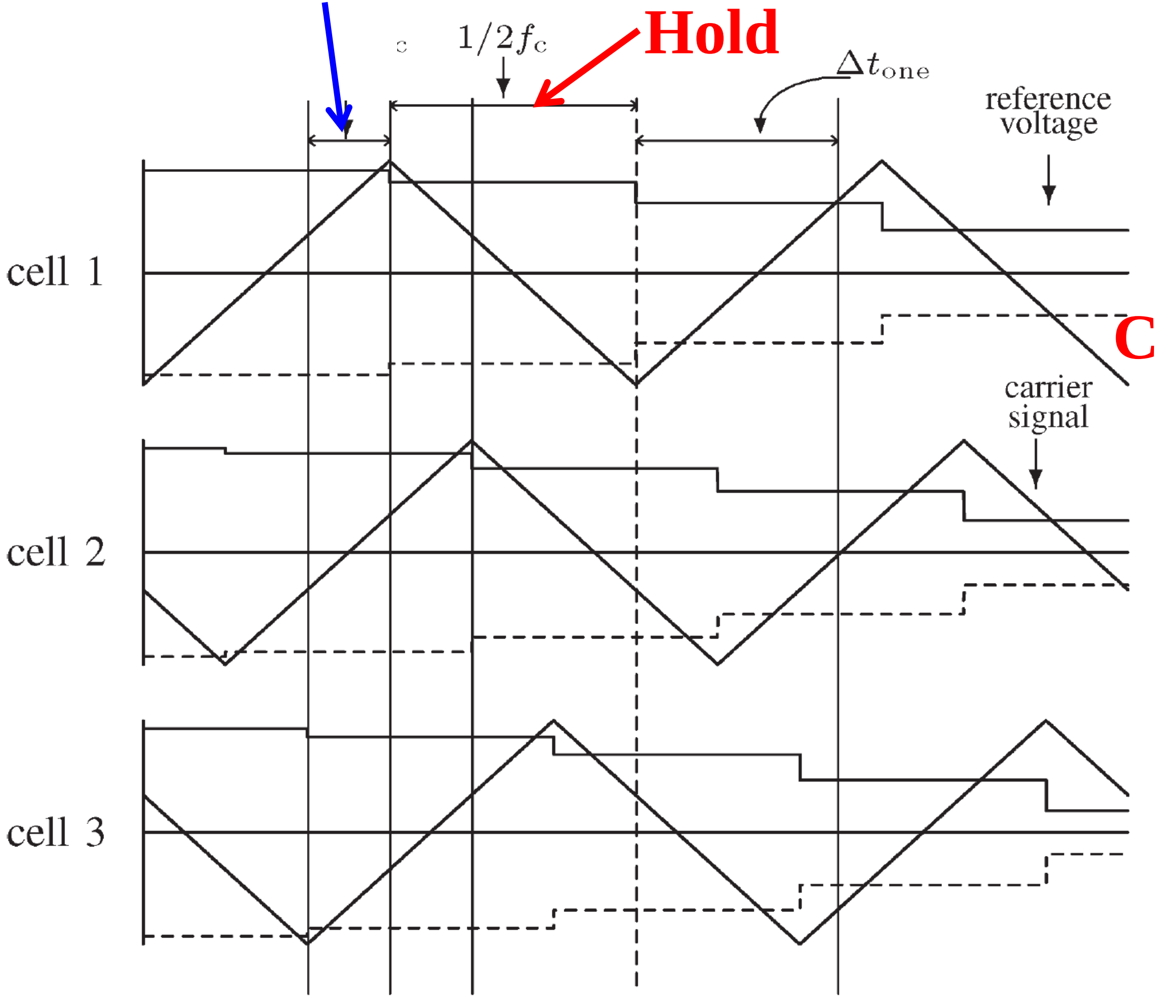
BMS:

Battery
Management
System

Signals

Input: 43
Output: 72

Phase-Shifted-Carrier PWM (One-Cell Update)



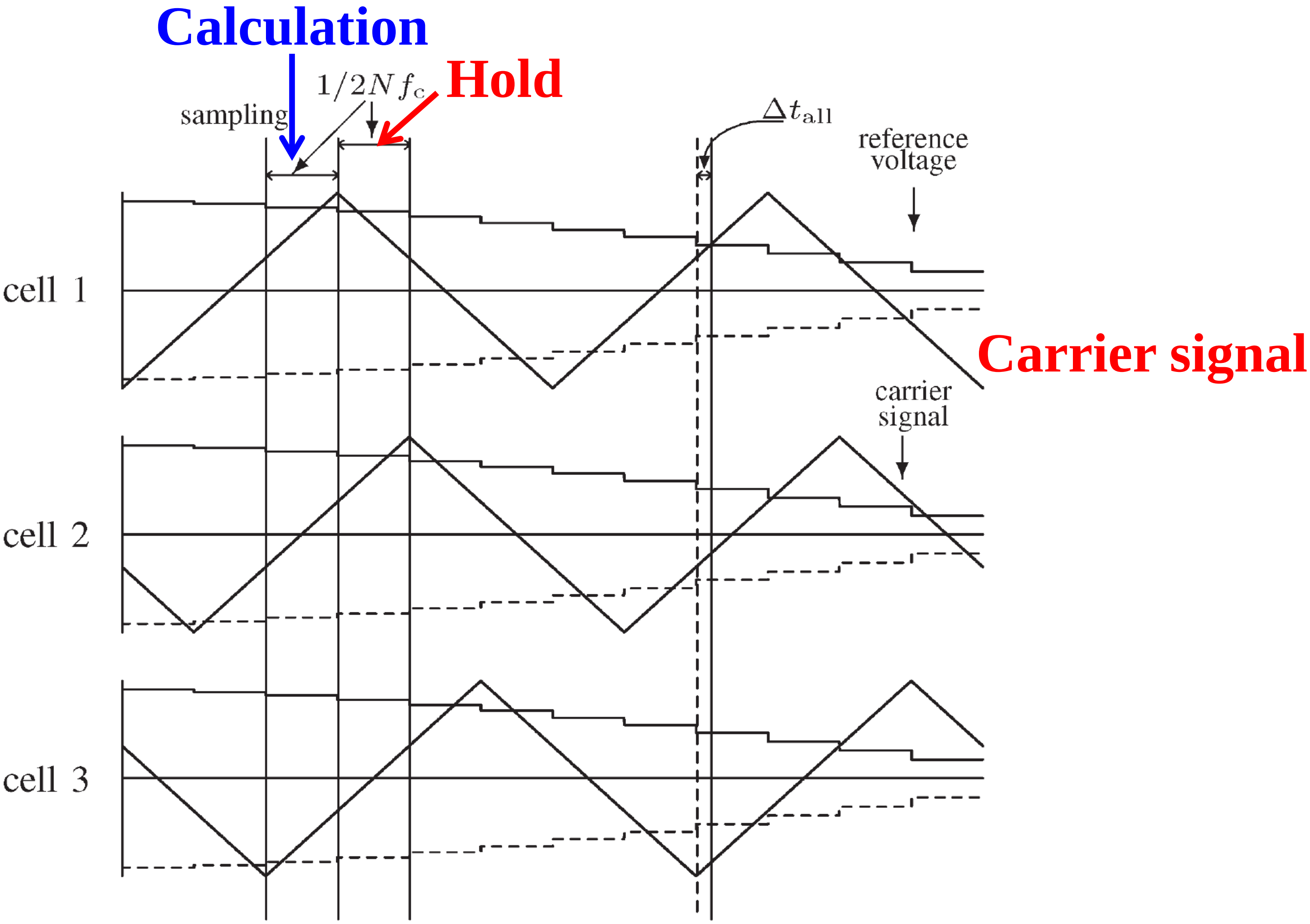
Calculation (within 40 µs)

Hold

Carrier signal

Hold time = *N* × Calculation time

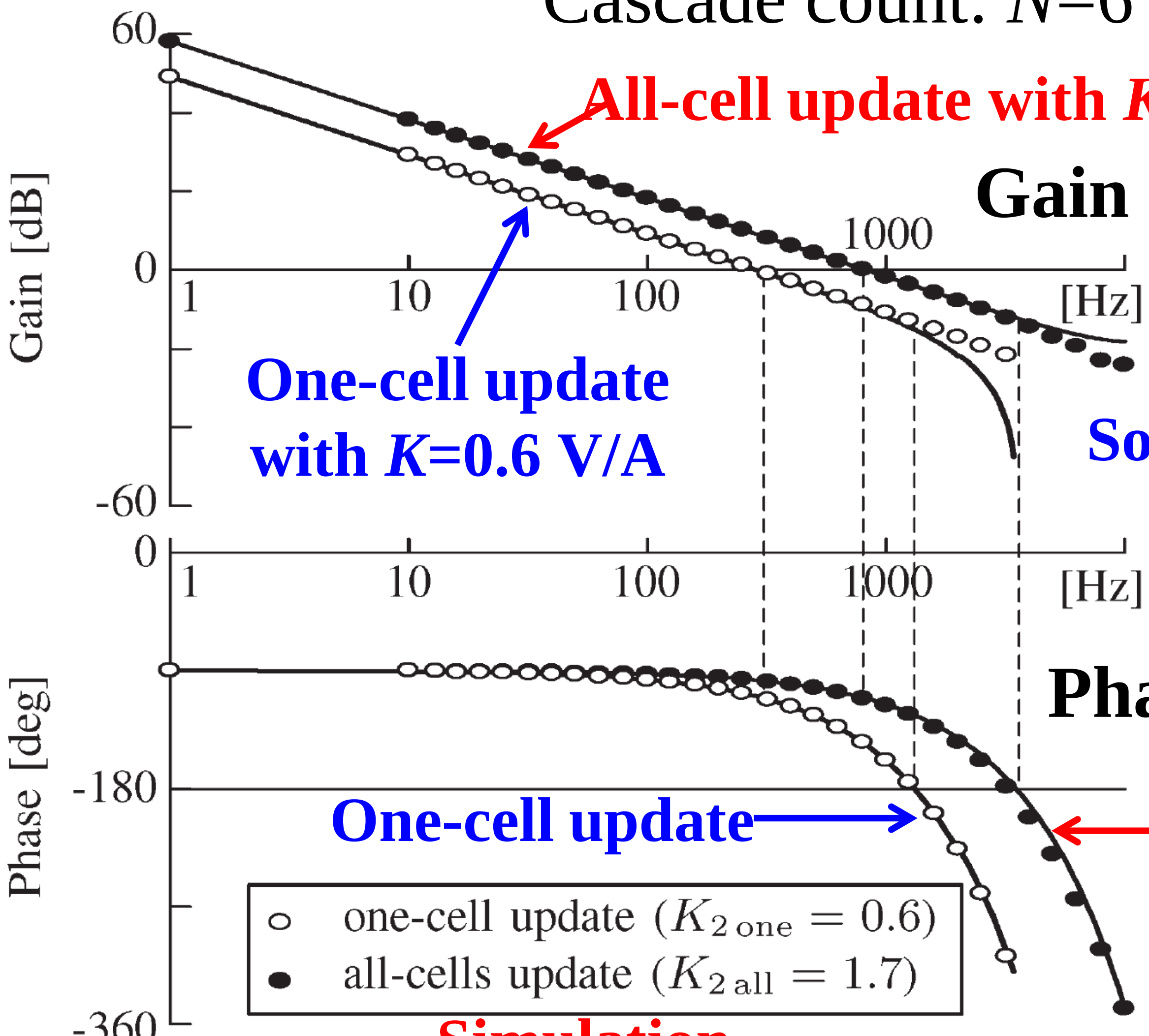
Phase-Shifted-Carrier PWM (All-Cell Update)



Hold time = Calculation time

Comparisons between Theory and Simulation in Open-Loop Transfer Function of Current Control

Cascade count: N=6



All-cell update with K=1.7 V/A

Gain margin: 12 dB

One-cell update with K=0.6 V/A

Solid lines: Theory

Phase margin: 70°

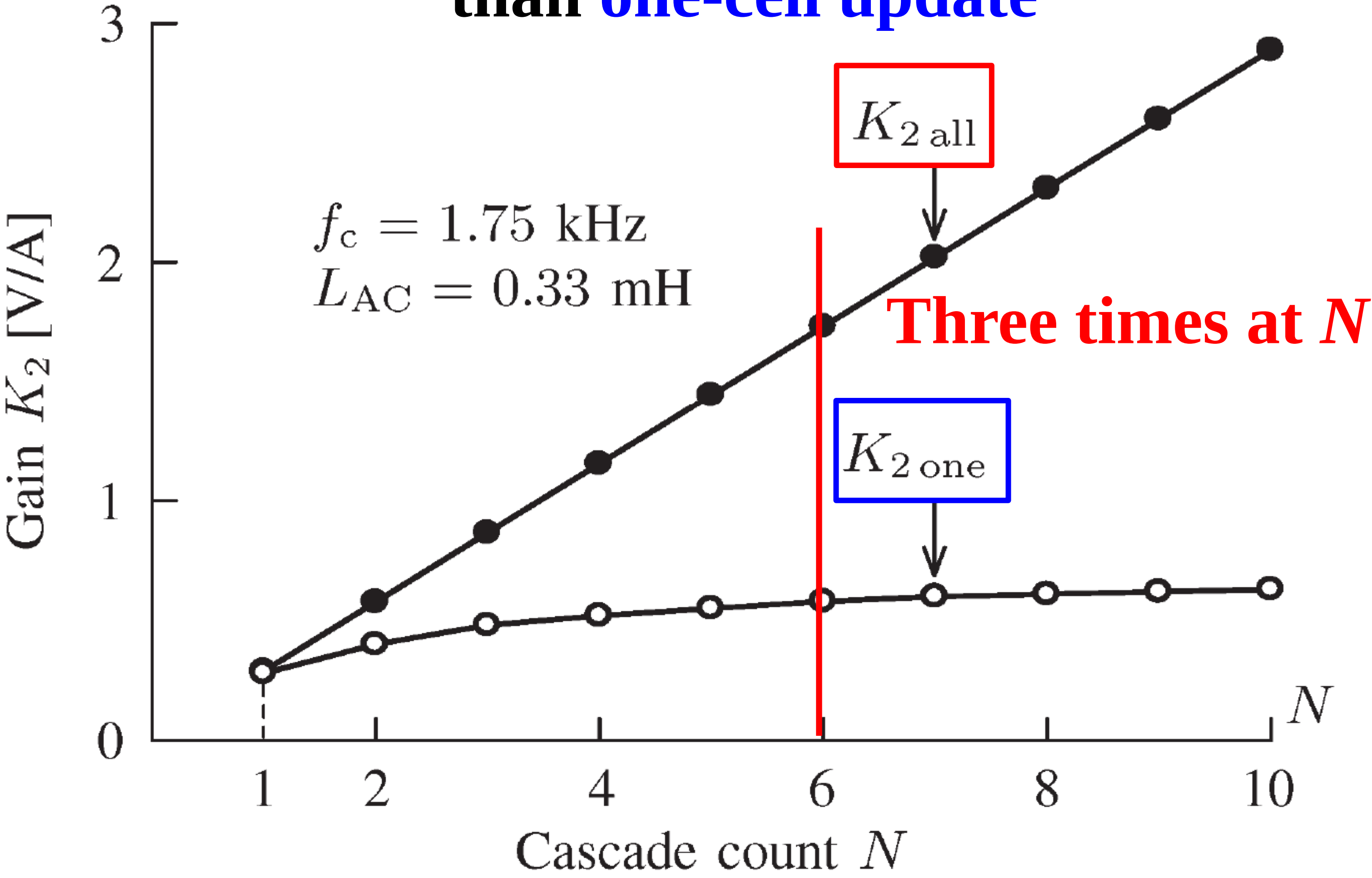
One-cell update

All-cell update

Simulation

Critical Damping Gain vs Cascade Count *N*

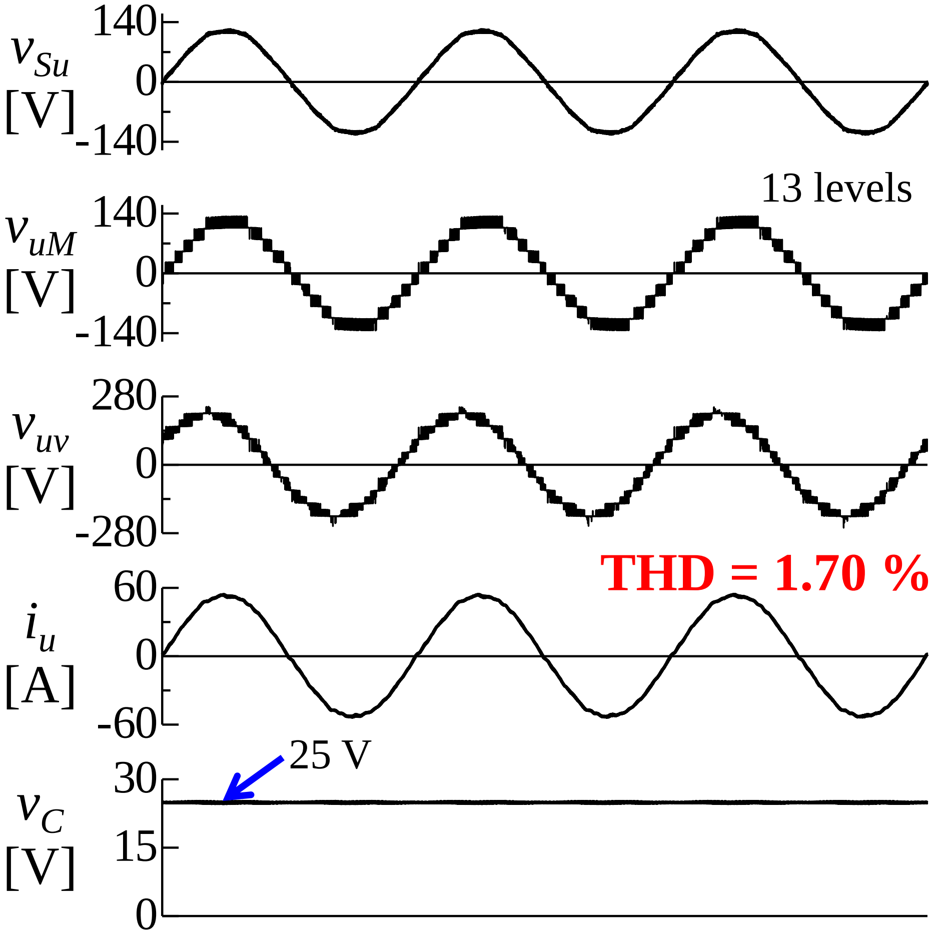
All-cell update is better in current controllability than one-cell update



Three times at *N*=6

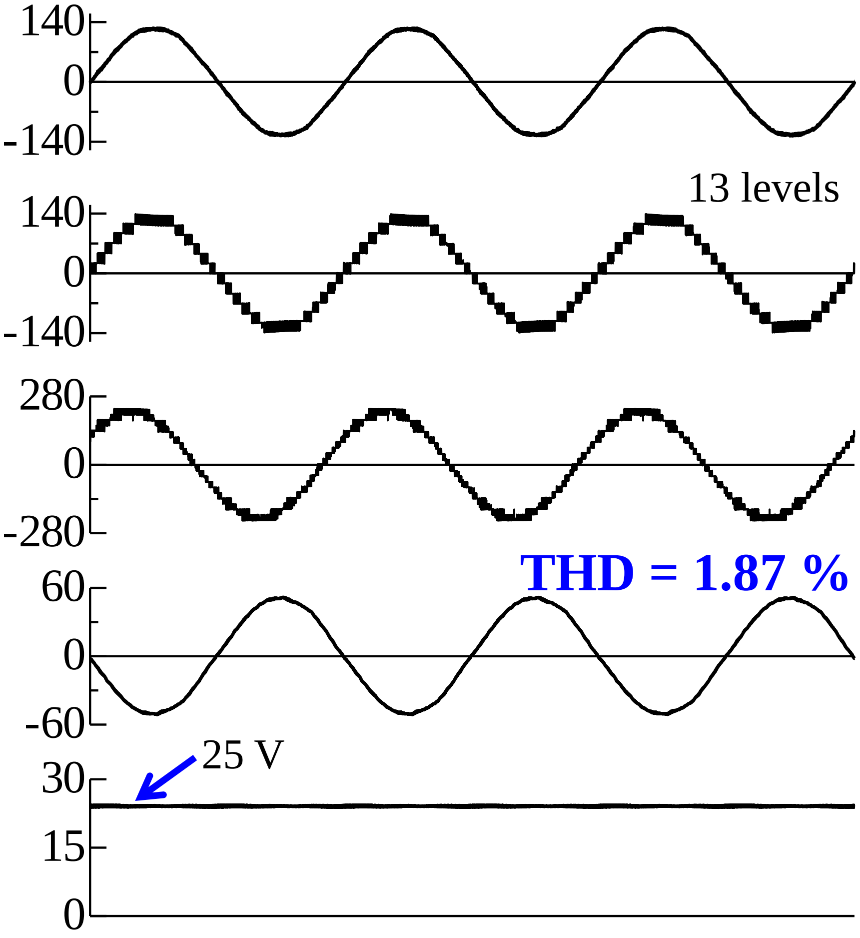
Experimental Waveforms (All-cell update)

Charge mode



THD = 1.70 %

Discharge mode

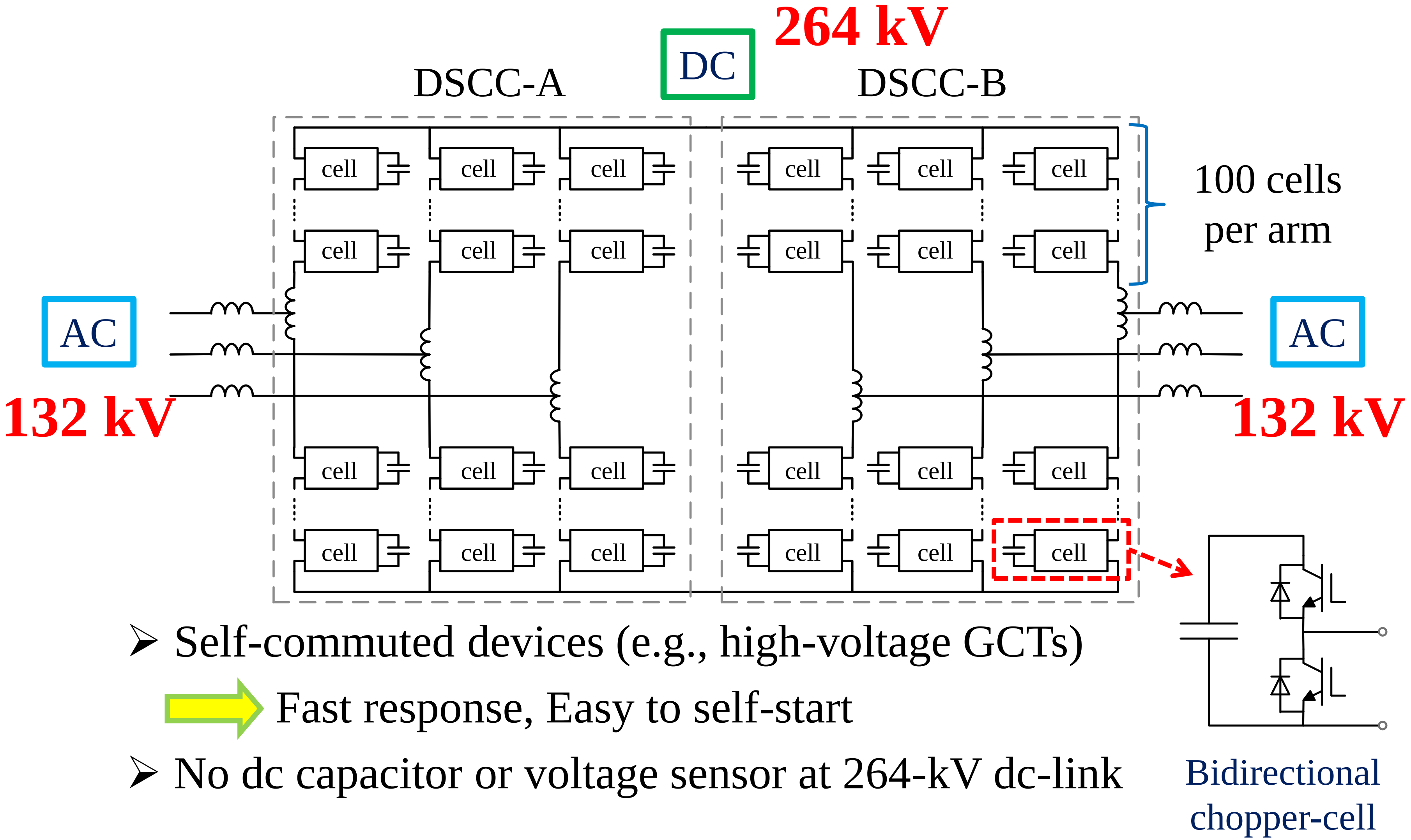


THD = 1.87 %

A Grid-Level High-Power DSCC-Based BTB (Back-To-Back) System Without Common DC-Link Capacitor

Published in the IEEE Transactions on Industry Applications,
vol. 50, no. 4, pp. 2648-2659, July/Aug. 2014

A Grid-Level DSCC-Based BTB System



- ➢ Self-commuted devices (e.g., high-voltage GCTs)

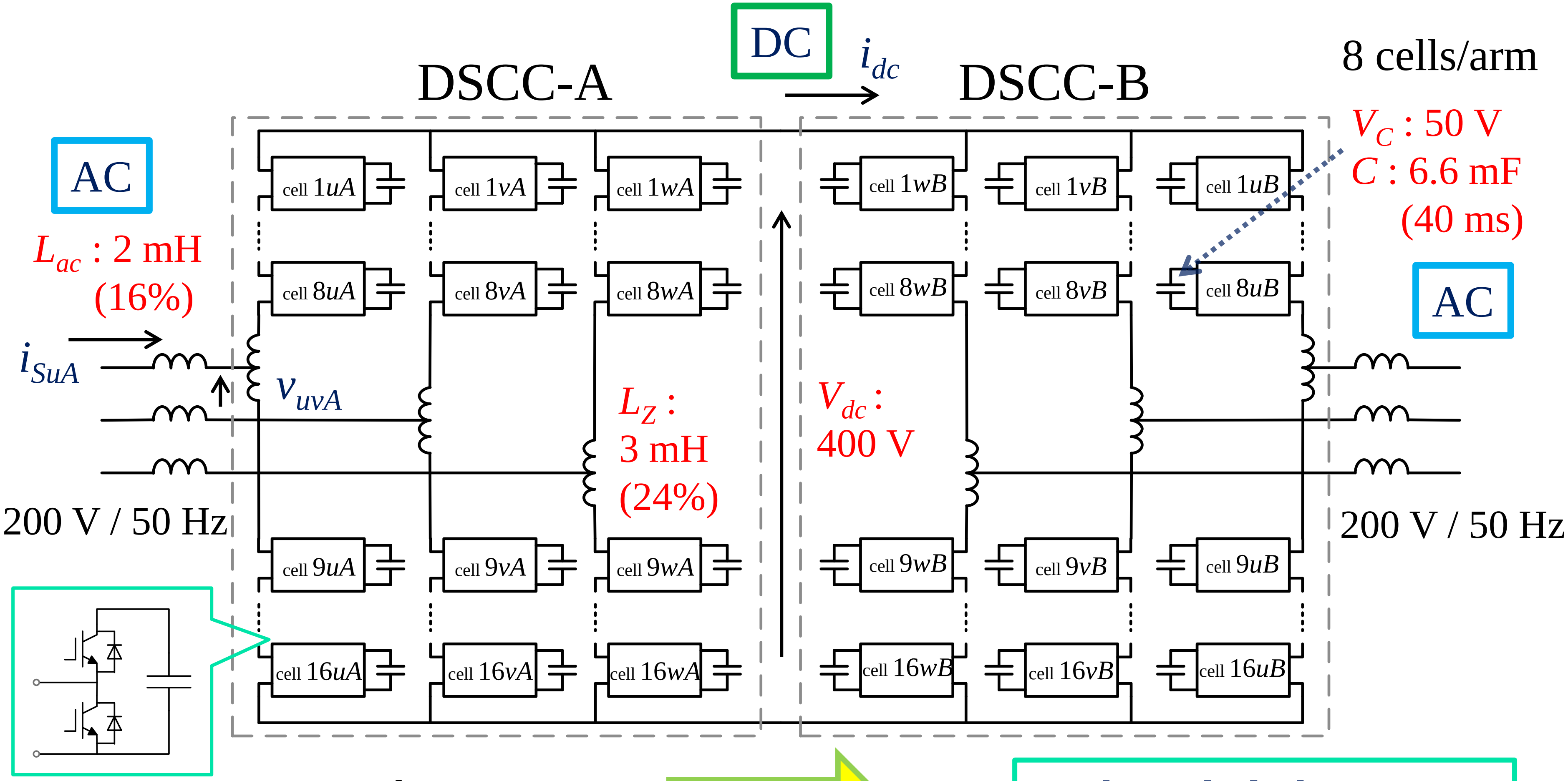
  ⇨ Fast response, Easy to self-start

- ➢ No dc capacitor or voltage sensor at 264-kV dc-link

Bidirectional
chopper-cell

Downscaled BTB Unit for Experiment

Three-phase 200-V, 10-kW BTB system



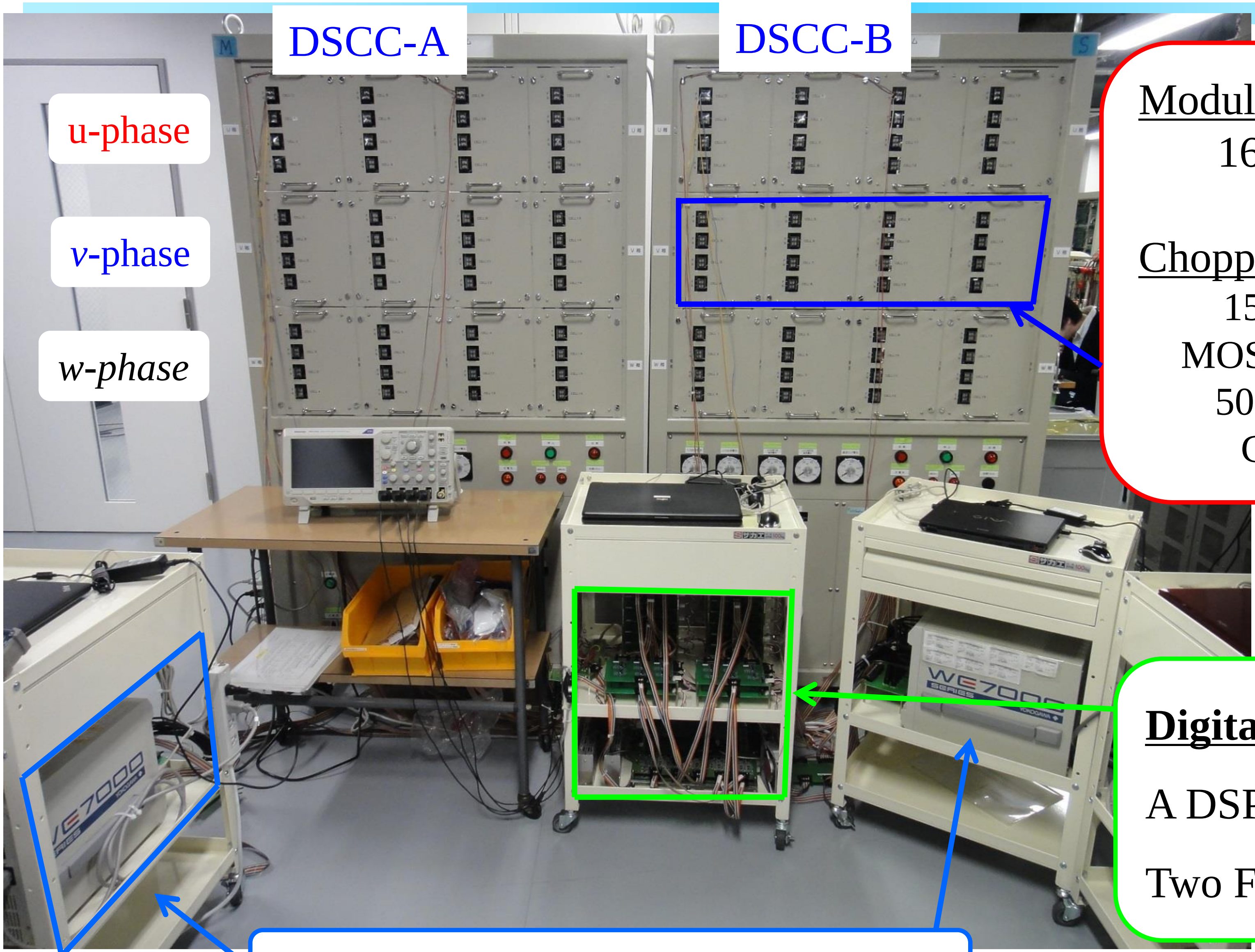
Carrier frequency
f_C : 450 Hz

Power

p

Without dc-link capacitor

Photo of three-phase 200-V 10-kW 50-Hz BTB System



<u>Module Structure</u>:
16 cells/leg

<u>Chopper Cell</u>:
150-V 70-A
MOSFET × 4 × 2
50-V 6.6-mF
Capacitor

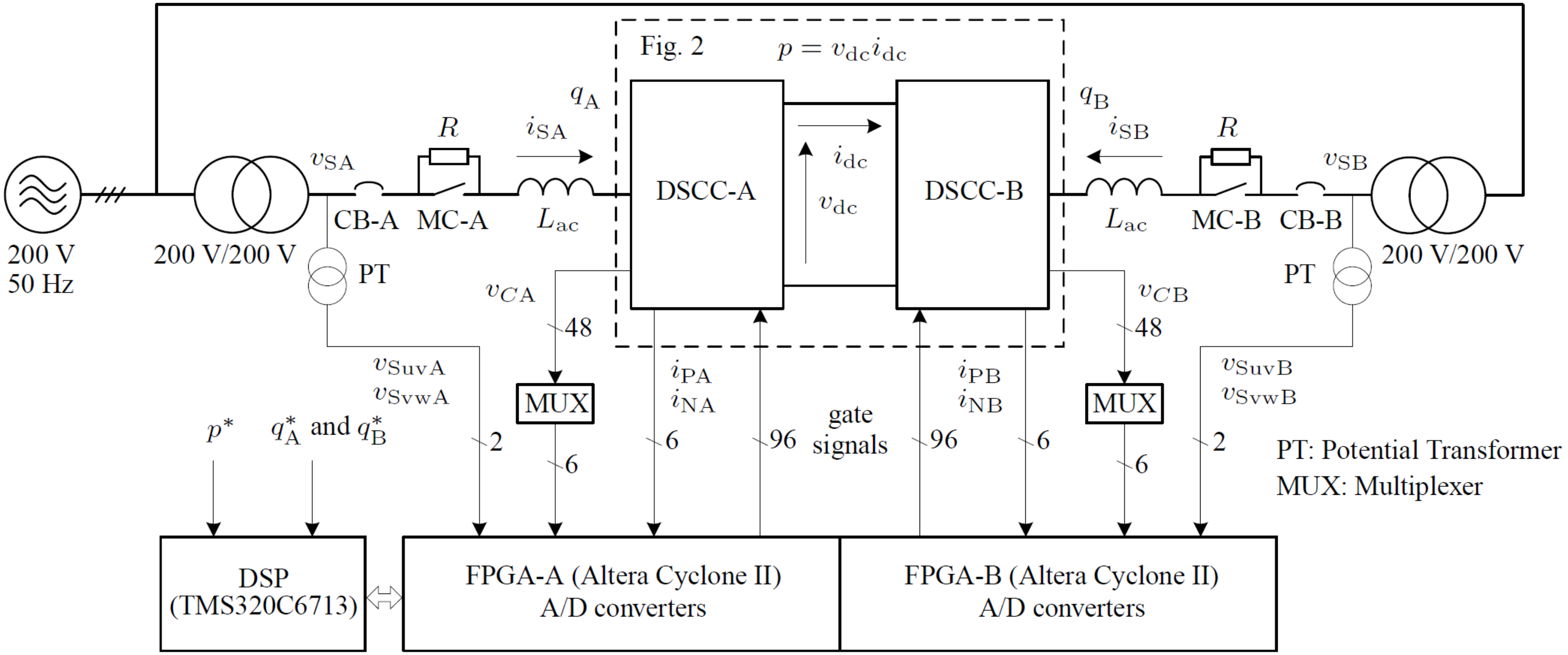
<u>Digital Controller</u>:

A DSP board and

Two FPGA boards

PC based data acquisition systems

Digital Control System



Detected signals

Line-to-line voltages	2 × 2
Arm currents	6 × 2
Capacitor voltages	48 × 2

Output: 192 (= 96 × 2) gate signals

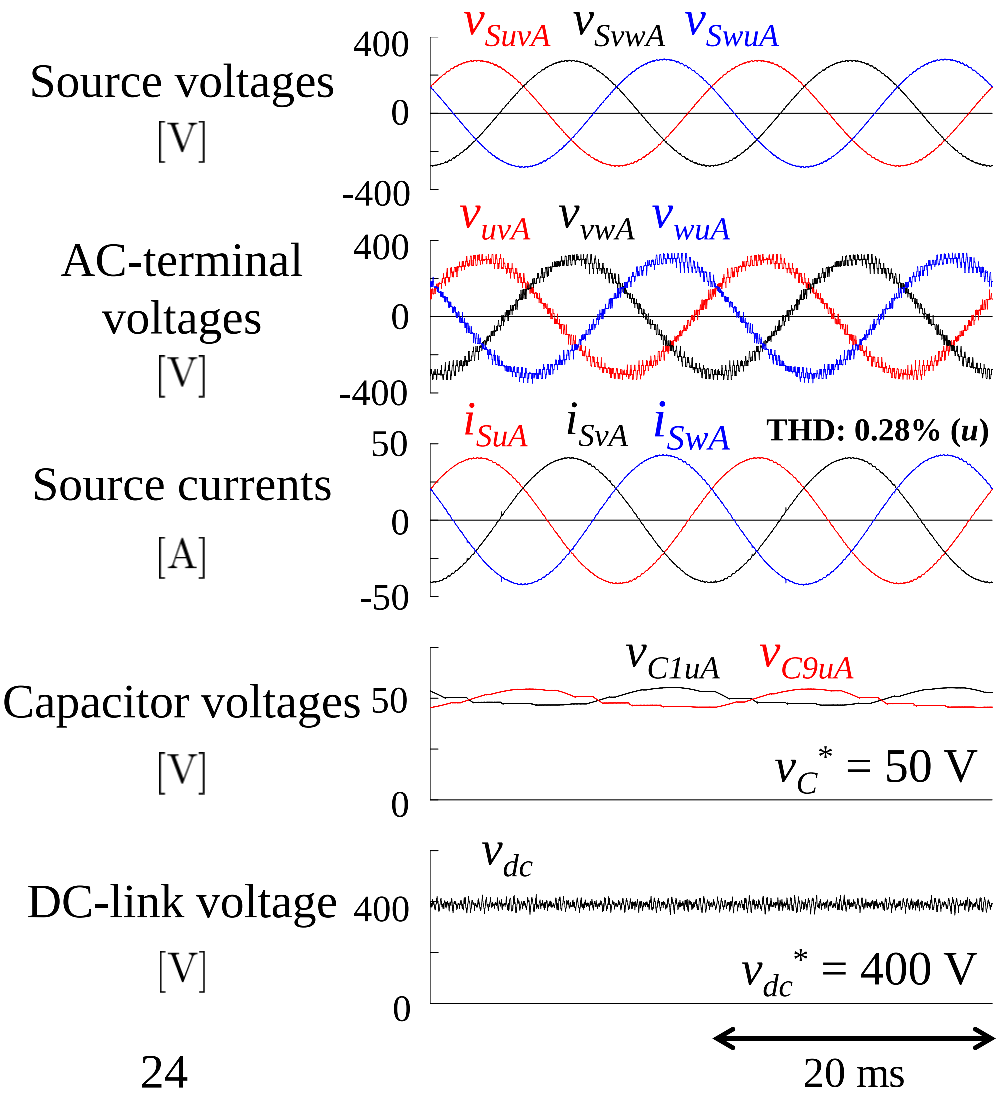
Sampling frequencies in digital control

arm currents: 7.2 kHz (= 450Hz × 16)

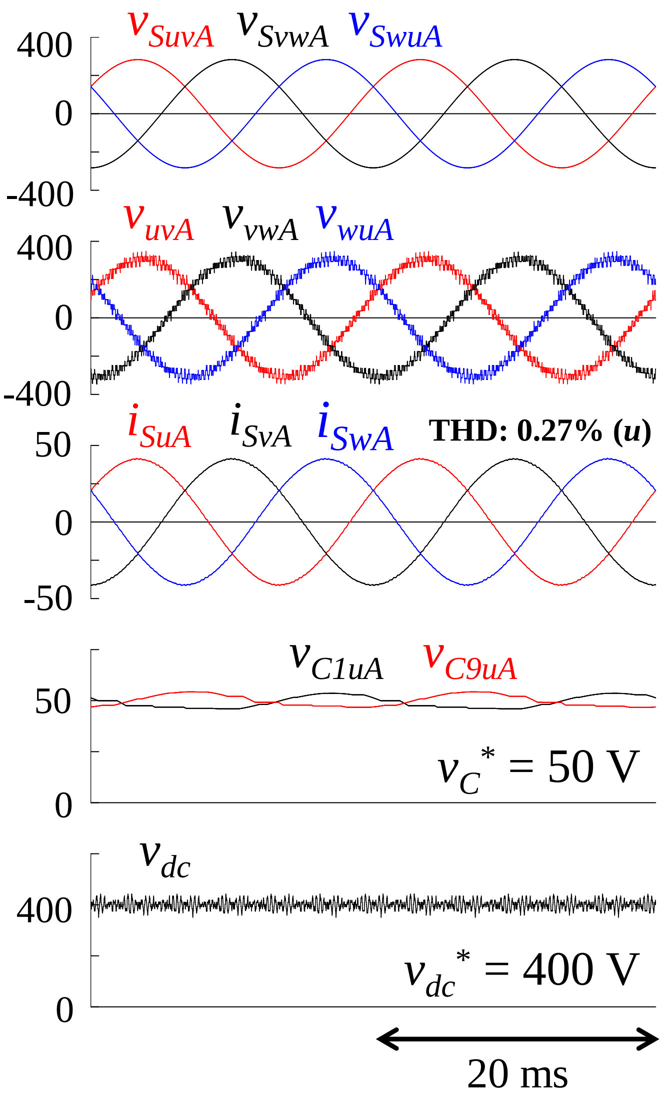
capacitor voltages: 450 Hz

Rectification (DSCC-A) at $p^* = +8.7$ kW, $q_A^* = -5.0$ kVA

Experiment



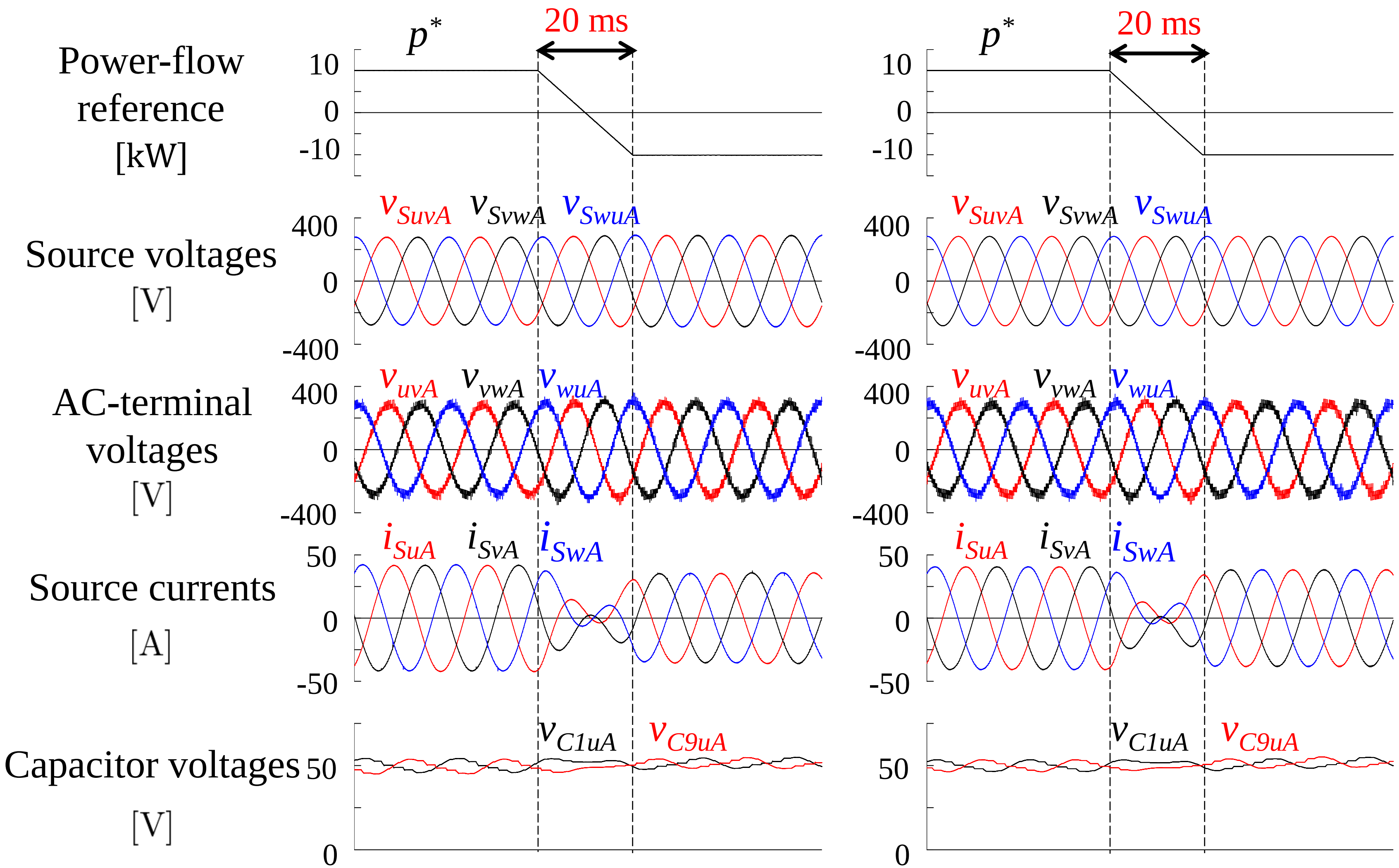
Simulation



Transition (DSCC-A) at p^* = +10 kW → -10 kW

$q_A^* = q_B^* = 0$

Experiment **Simulation**



A Low-Speed, High-Torque Motor Drive Using the Modular Multilevel Cascade Converter Based on Triple-Star Bridge Cells (MMCC-TSBC)

To be Published in the 2015 Sep./Oct. Issue of
the IEEE Transactions on Industry Applications, or Early access

Medium-Voltage High-Power Motor Drives

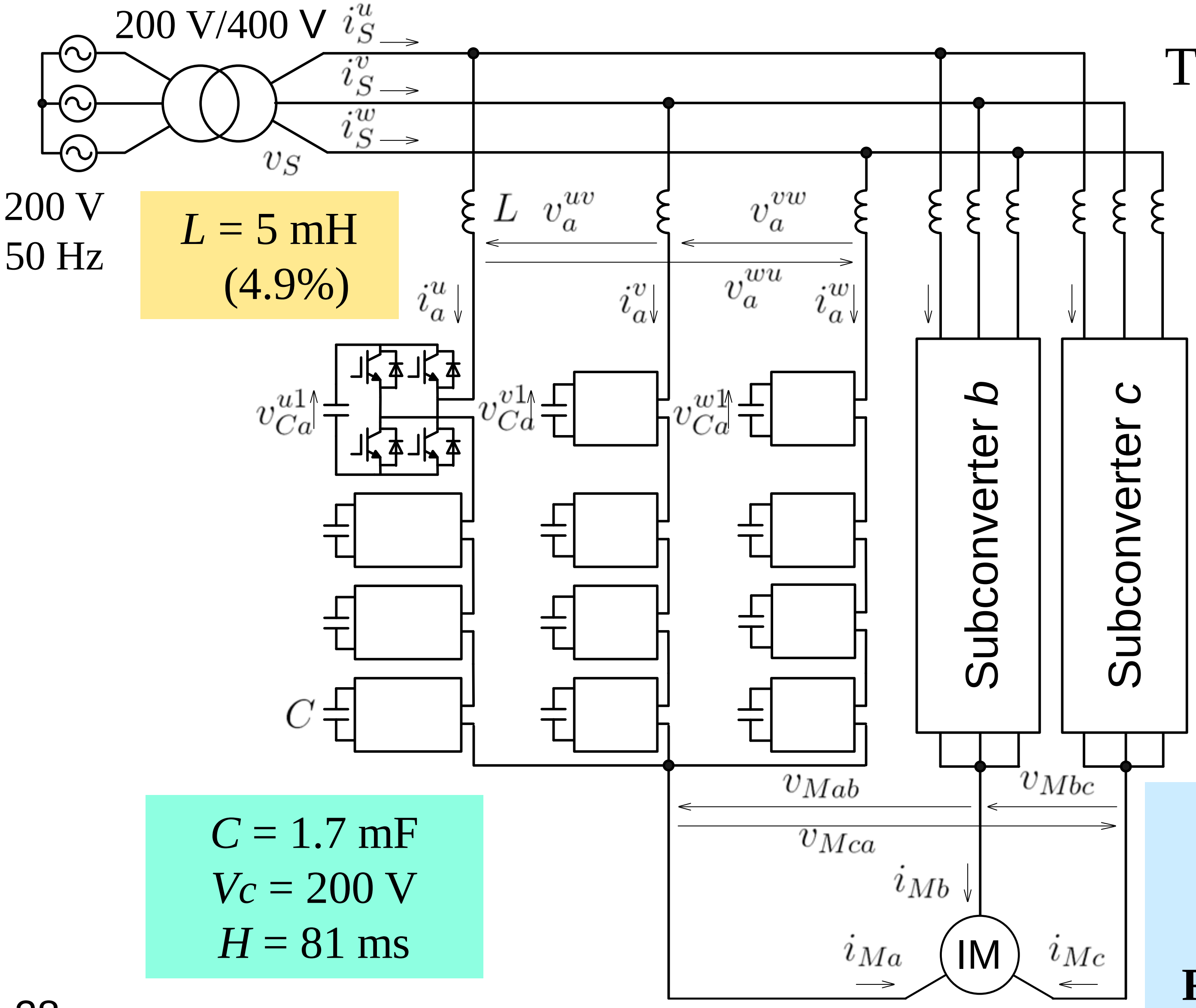
Blower fan from
Mitsubishi Heavy Industry

Cement mill drive
from ABB

Line-commutated cycloconverters using thyristors

Problems: Low lagging power factor
Complicated line harmonic currents

Three-phase 400-V 15-kW TSBC Converter



L = 5 mH (4.9%)

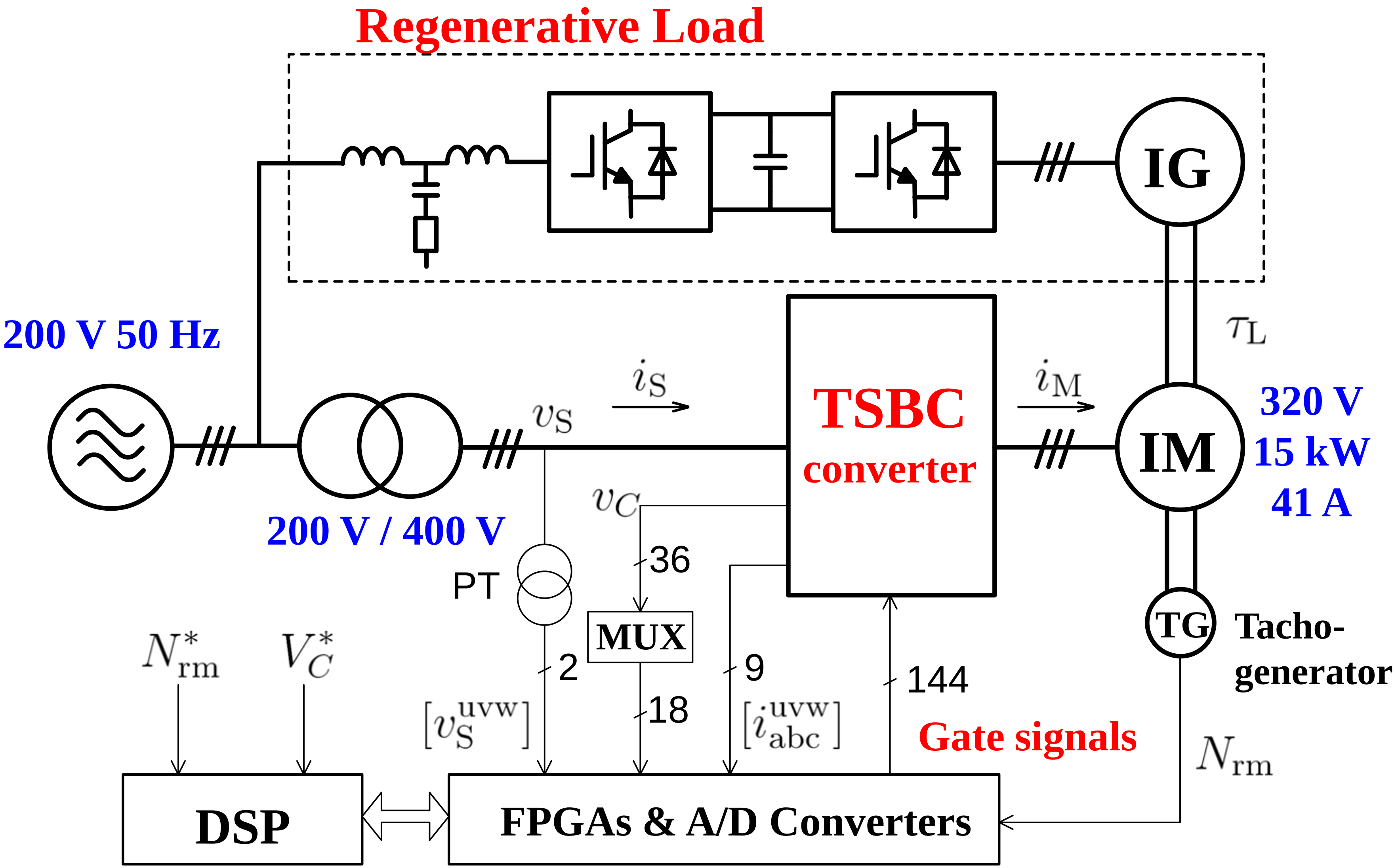
Three three-legged three-winding ac inductors

- Carrier freq.: **1 kHz**
- Equiv. carrier freq.: **8 kHz**
- Dead time: 4 ms

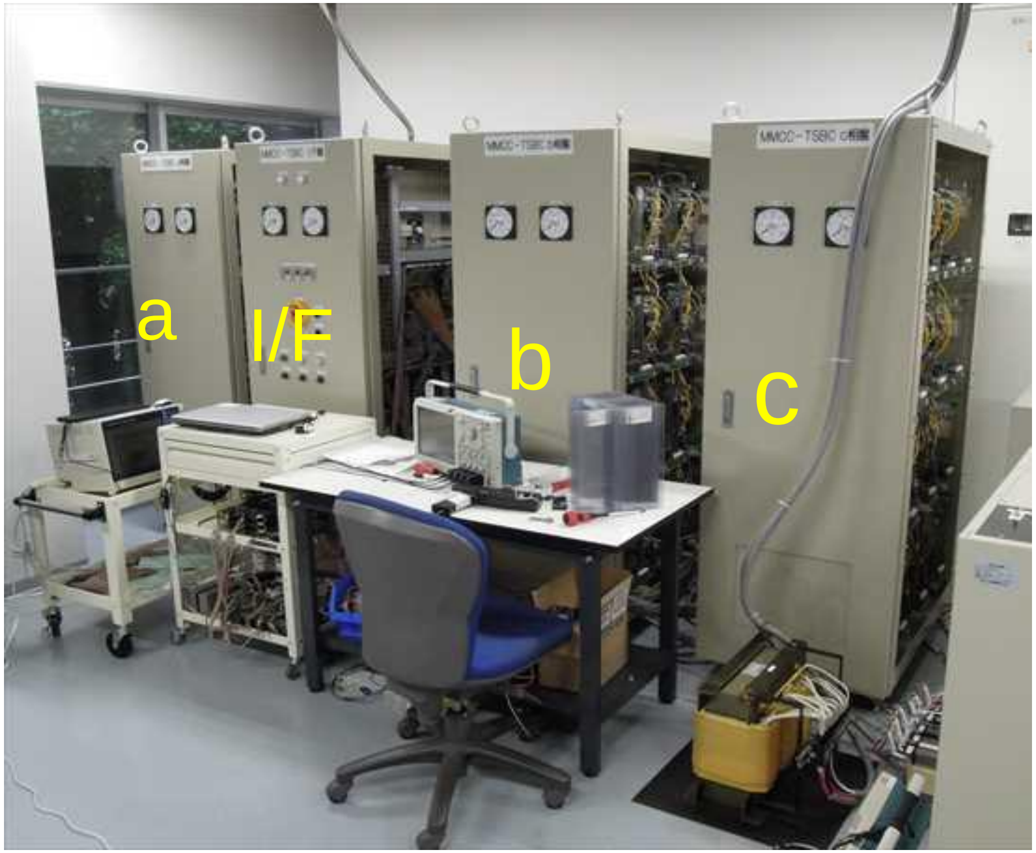
C = 1.7 mF
Vc = 200 V
H = 81 ms

320 V, 15 kW
38 Hz, 41 A
6 poles, 750 min^{-1}
Rated Torque Load

Overview of the Experimental System



Three-phase 400-V 15-kW Experimental System



4 Bridge Cells per Cluster

- 36 Bridge Cells
- 144 IGBTs

L = 5.0 mH (5%)

Three three-legged three-winding ac inductors

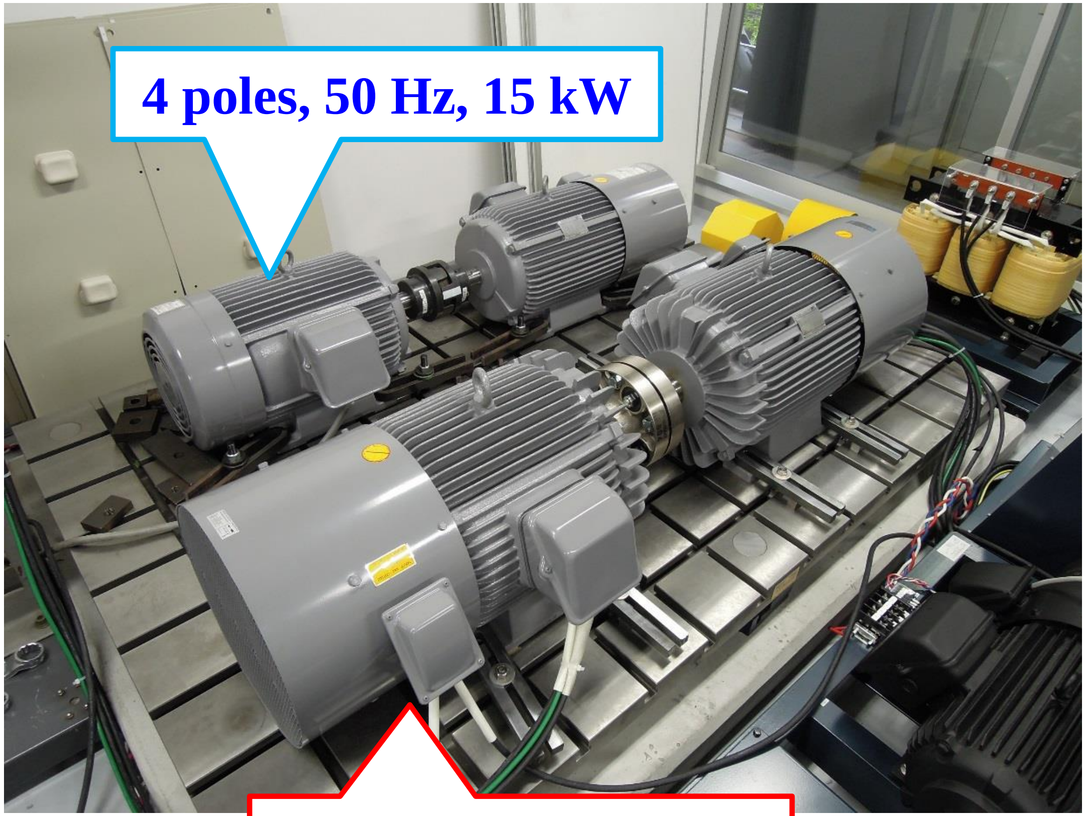
C = 1.7 mF

V_C = 210 V (rated)

H = 89 ms

Carrier frequency: 1 kHz

Three-phase 320-V 15-kW Induction Motor

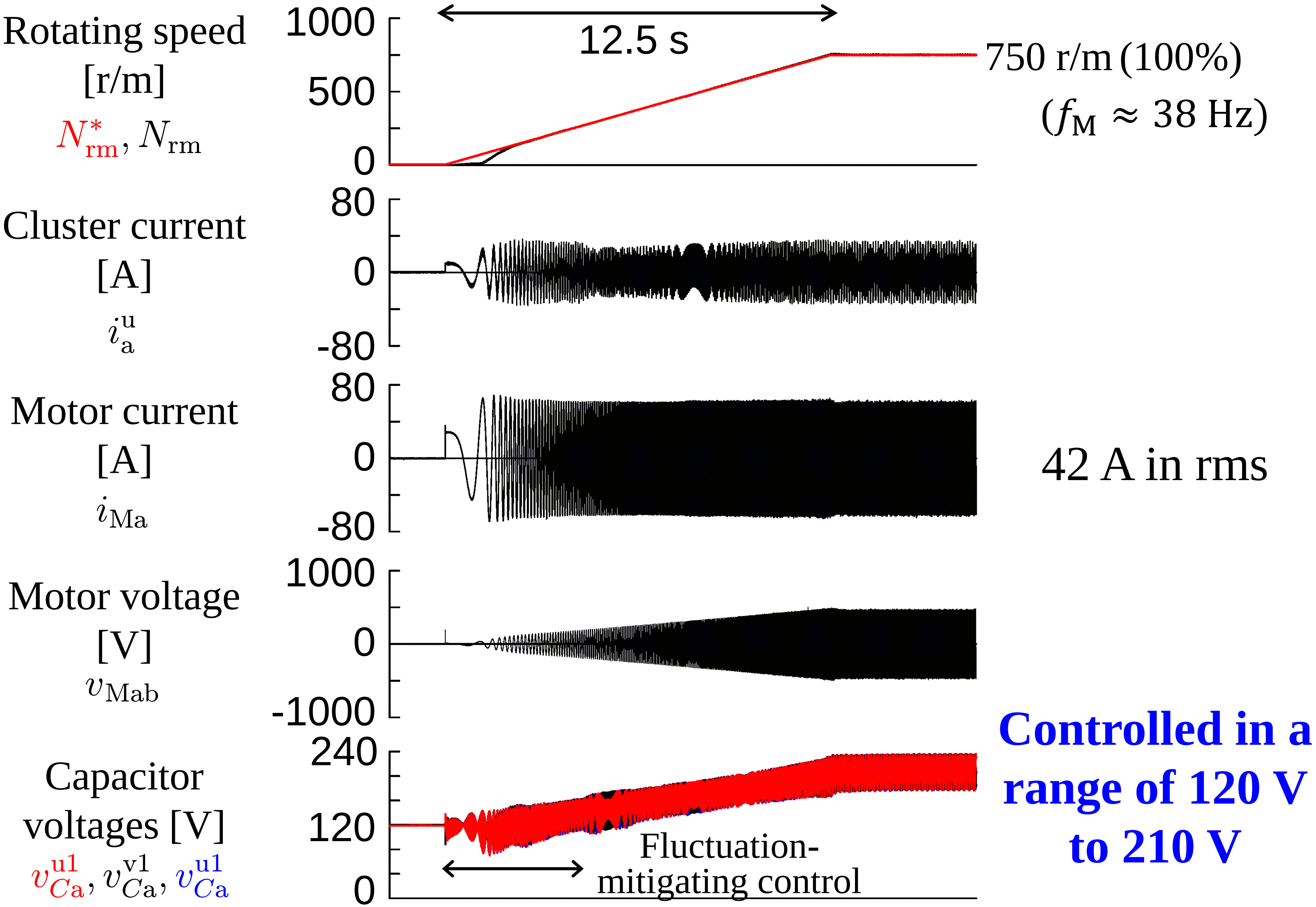


4 poles, 50 Hz, 15 kW

6 poles, 38 Hz, 15 kW

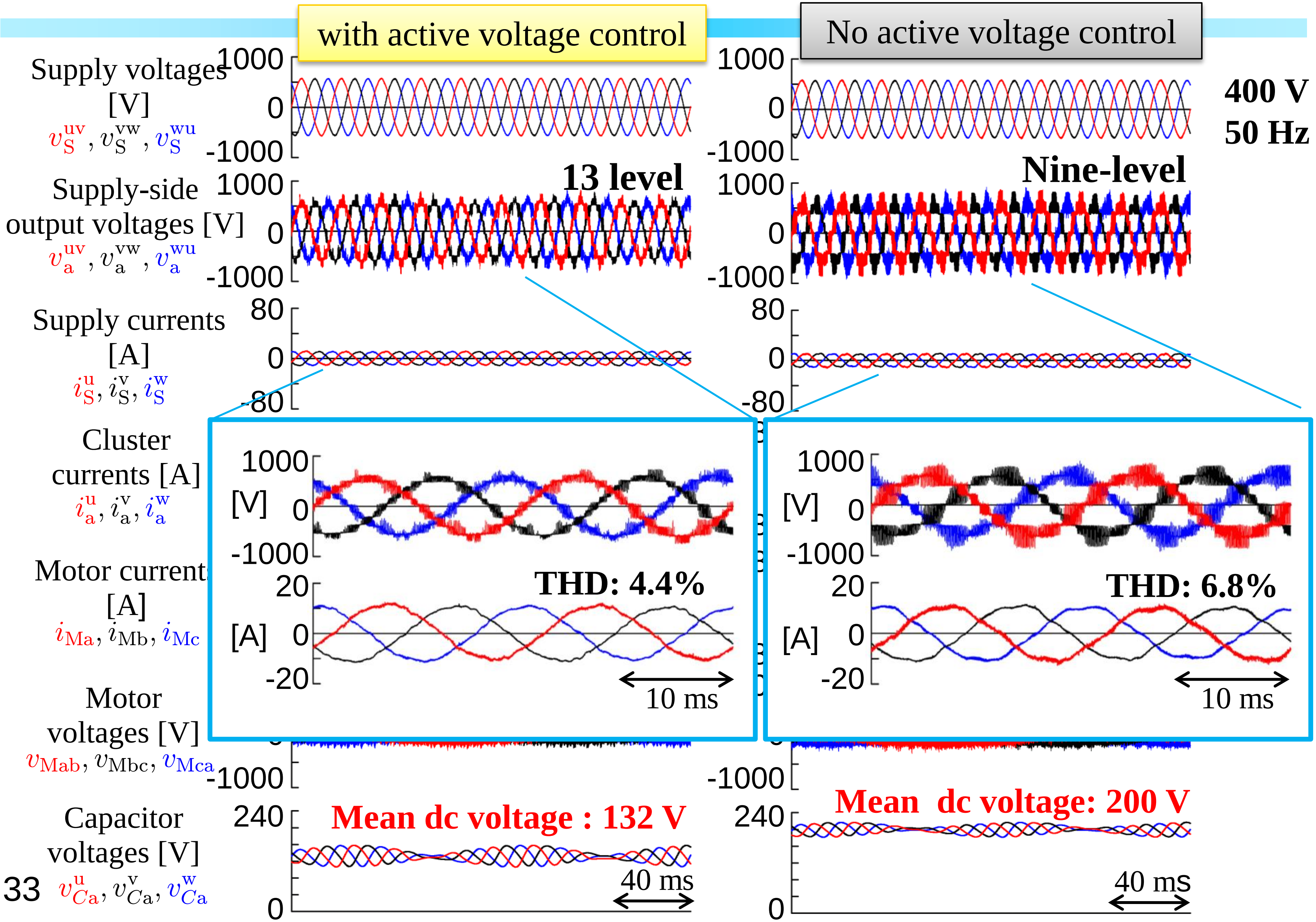
	Rated Values
Power	15 kW
Voltage	320 V
Current	41 A
Frequency	**38 Hz**
Rotating speed	750 r/m
Poles	**6**
Torque	191 N･m

Start-up Performance Loaded at 100% Torque



Controlled in a range of 120 V to 210 V

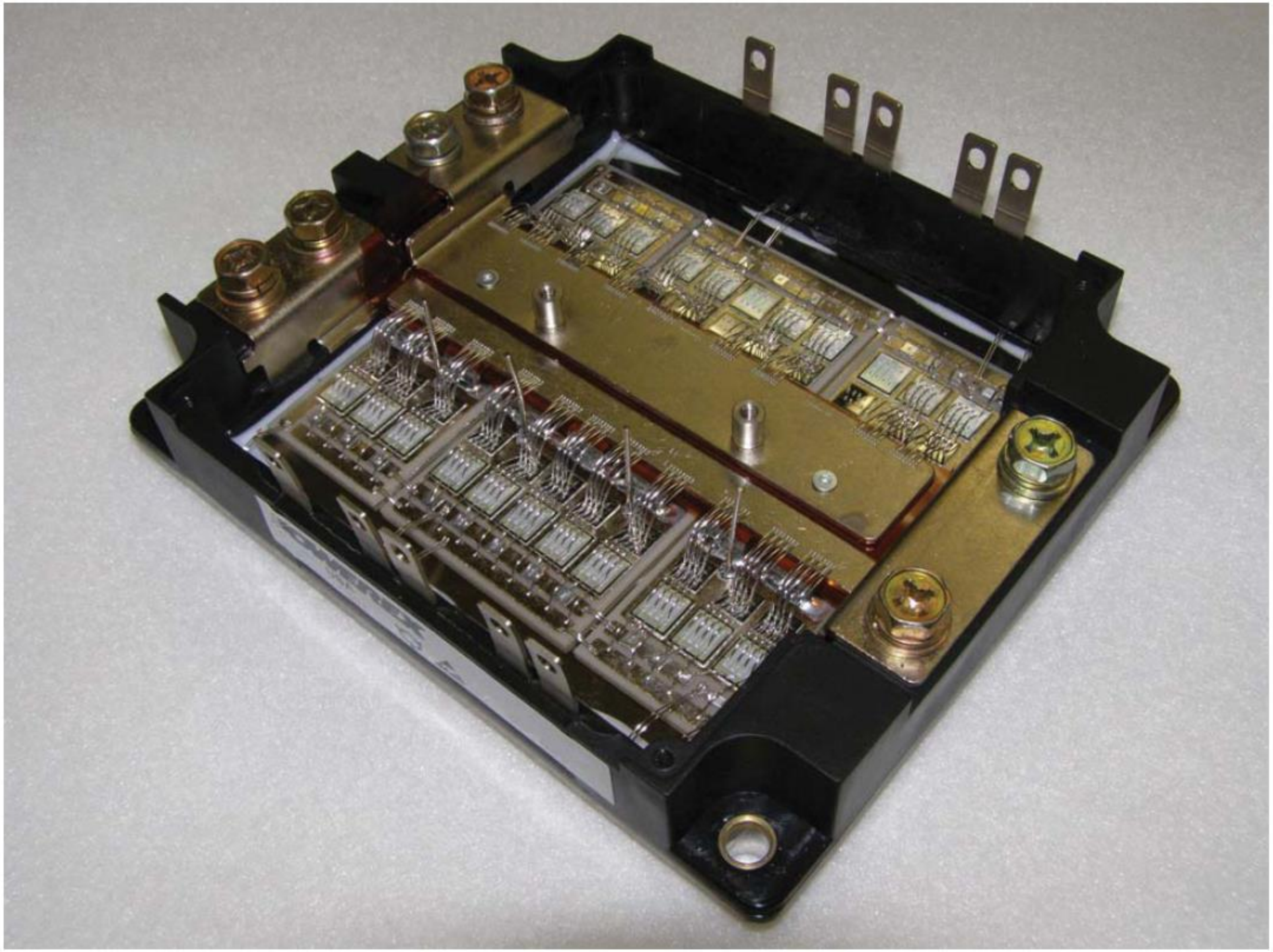
N_{rm} = 100 r/m (13%) Loaded at 100% Torque



Power-Loss Breakdown of a 750-Vdc, 100-kW, 20-kHz Bidirectional Isolated DC-DC Converter Using SiC-MOSFET/SBD Dual Modules

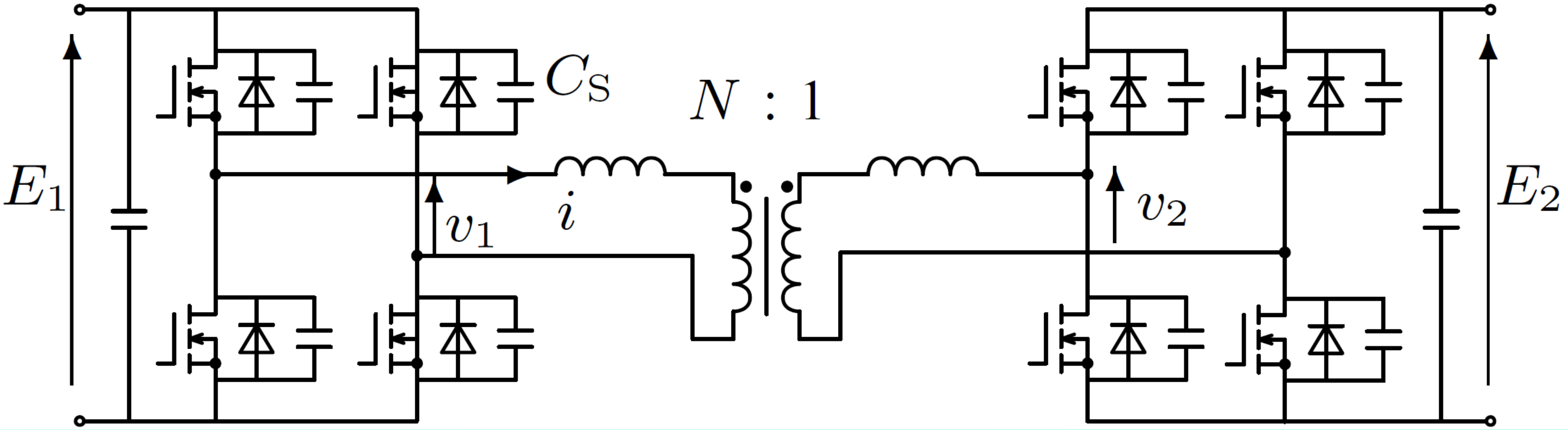
Published in the IEEE Transactions on Industry Applications,
vol. 51, pp. 420-428, Jan./Feb. 2015

1.2-kV, 800-A SiC-MOSFET/SBD Dual Module



R. Wood and T. Saken, “Evaluation of a 1200-V, 800-A All-SiC Dual Module,” IEEE Trans. on Power Electronics, vol. 26, no. 9, 2011

Bidirectional Isolated DC-DC Converter



Two Technical Terms

Functionality: Bidirectional Isolated DC-DC Converter

Circuit Topology: Dual-Active-Bridge Converter

Function/Operation

Both buck and boost function: $E_1 > E_2$ **and** $E_1 < E_2$ **When** N**=1**

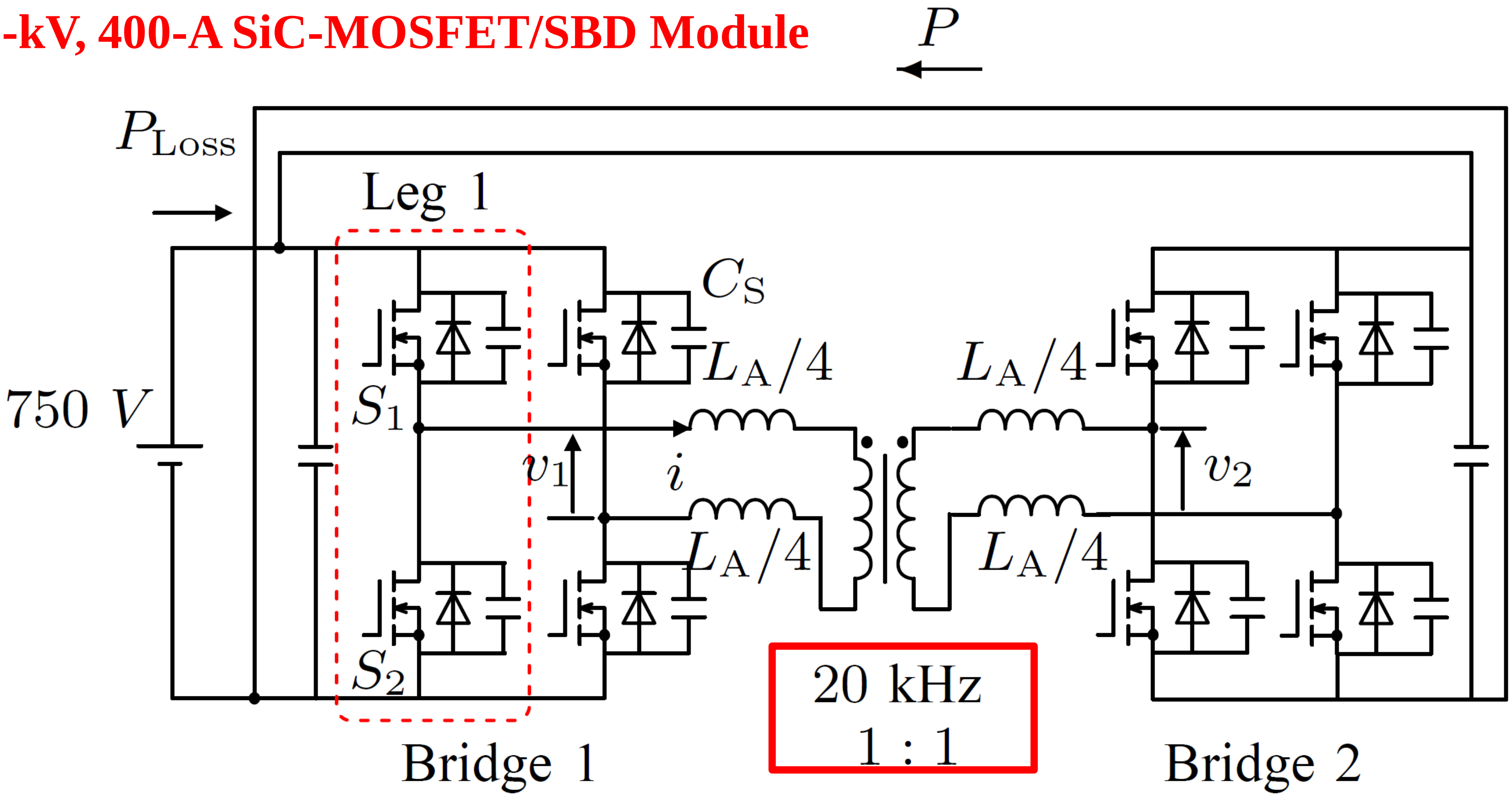
Zero-voltage-switching (ZVS) operation

Synchronous Rectification (limited to Si and SiC MOSFETs)

R. W. De Doncker, D. M. Divan, and M. H. Khealuwala, *IEEE Trans. IA*, 1991.

Experimental System at 750 V, 100 kW, and 20 kHz

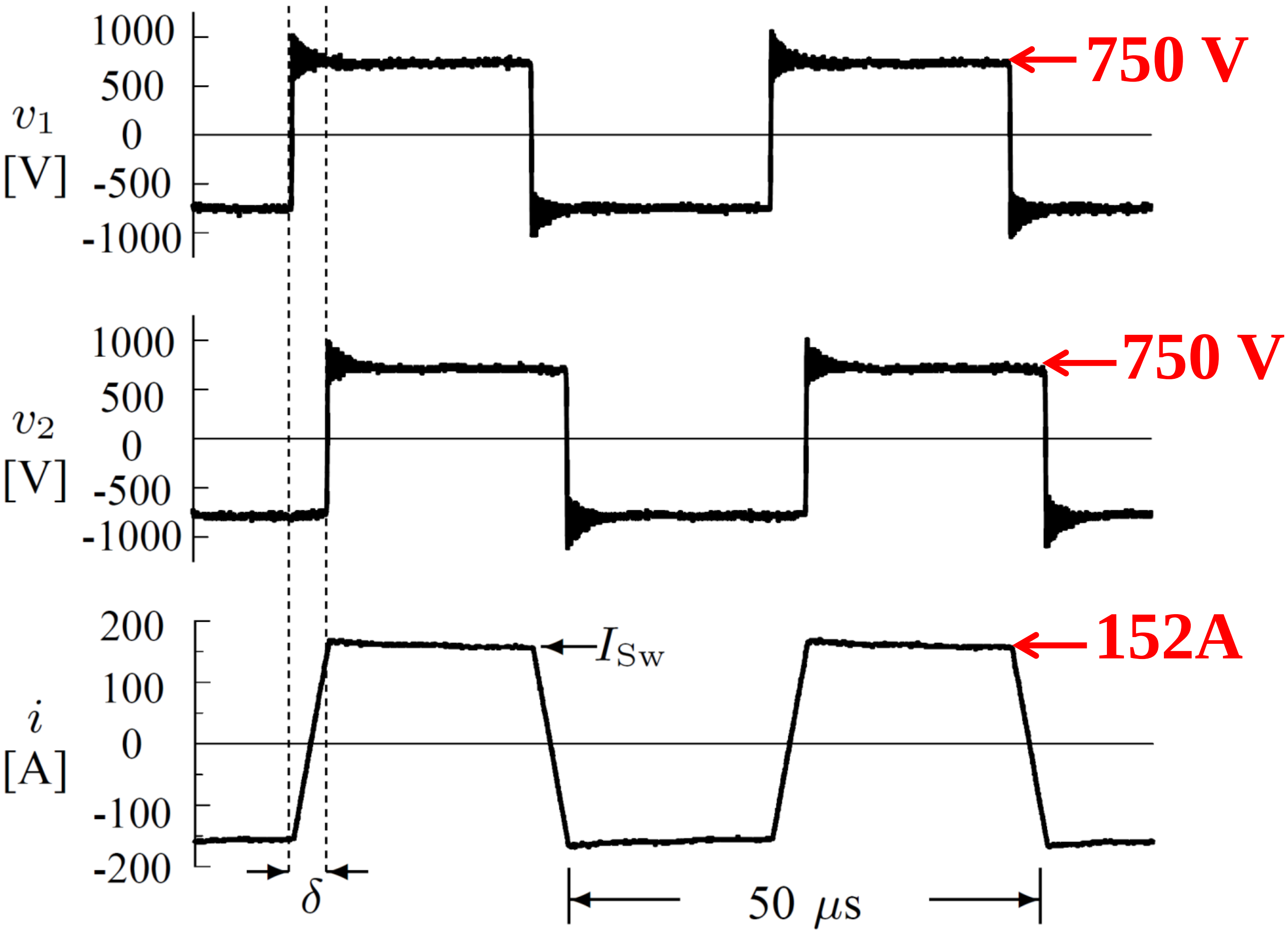
1.2-kV, 400-A SiC-MOSFET/SBD Module



Converter (dc-to-dc) efficiency with a tolerance of 0.03%

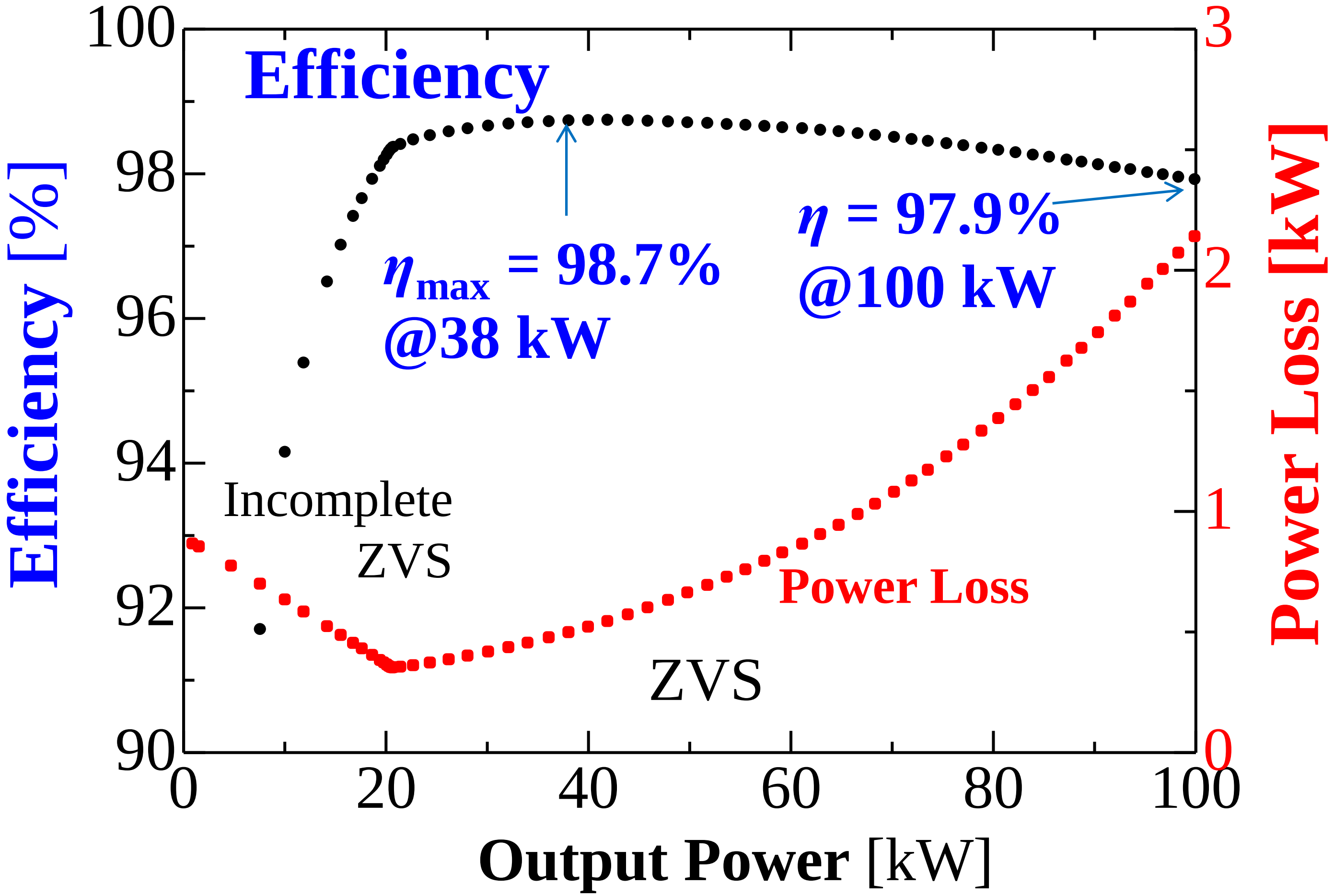
$$\eta = \frac{P}{P + P_{\mathrm{Loss}}}$$

Experimental Waveforms at 750 Vdc and 100 kW



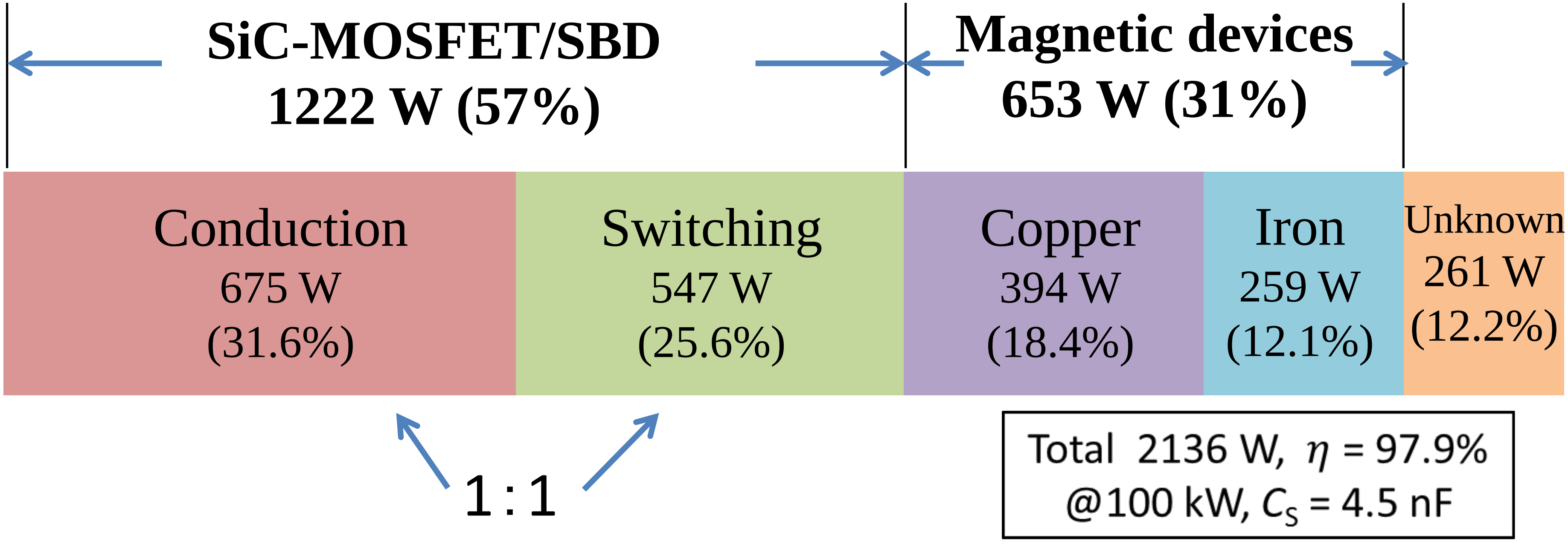
$T_{\mathrm{D}} = 0.6\ \mu\mathrm{s} \quad \delta = 26.6^\circ$

Power Loss and Efficiency



- Maximum Efficiency: **98.7 %**
- Rated-Power Efficiency: **97.9%**

Power-Loss Breakdown at 100-kW Operation



SiC-MOSFET/SBD
1222 W (57%)

Magnetic devices
653 W (31%)

Conduction	Switching	Copper	Iron	Unknown
675 W	547 W	394 W	259 W	261 W
(31.6%)	(25.6%)	(18.4%)	(12.1%)	(12.2%)

1 : 1

Total 2136 W, $\eta = 97.9\%$
@100 kW, $C_S = 4.5$ nF

- Power Loss in SiC-MOSFET/SBD: 60%
- Power Loss in Magnetic Devices: 30%
- Conducting and Switching Losses are Nearly Equal.

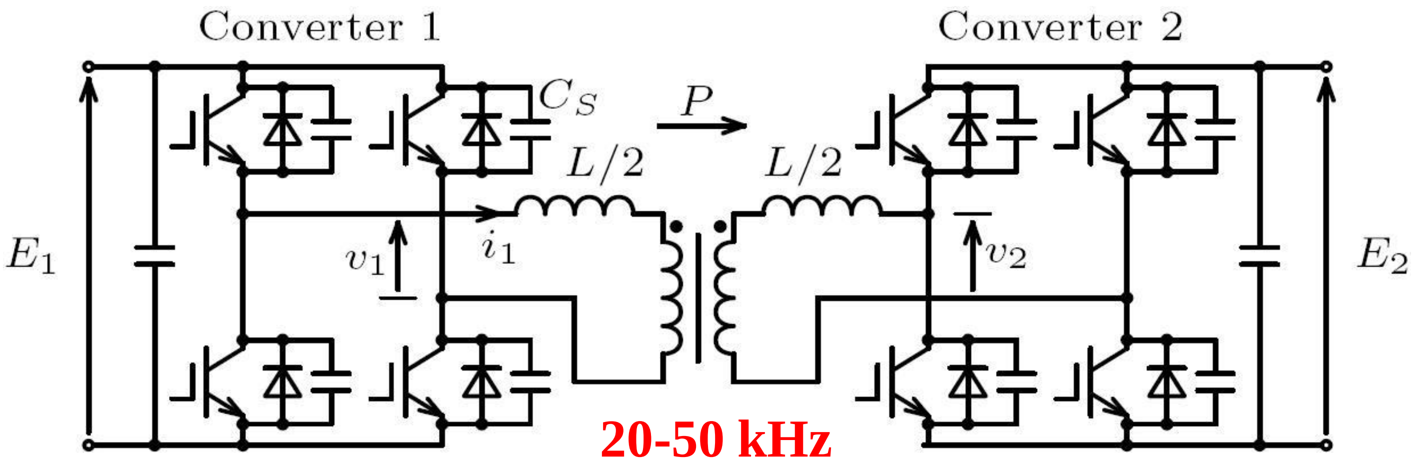
SiC-MOSFET/SBD and Si-IGBT/PND Modules

	SiC- MOSFET/SBD Dual Modules	Si-IGBT/PND Dual Modules(1)
Power rating	**100 kW**	**60 kW**
Reference voltage	**750 Vdc**	**750 Vdc**
Frequency	**20 kHz**	**4 kHz**
Power device	**1.2 kV and 400 A**	**1.2 kV and 300 A**
Maximum efficiency	**98.7%**	**97.8%**
Rated-Power Efficiency	**97.9%**	**96.9%**

(1) T. Chocktaweechock, K. Hasegawa, and H. Akagi, *IEEJ IAS Annual Meeting*, 1-94, Aug. 2012

Both dual modules have the same packaging in size, shape and pin/terminal arrangement.

Past, Present, and Future of the DC-DC Converters



20-50 kHz

(1) M. H. Kheraluwala, et al., *IEEE Trans. Ind. Applicat.*, vol. 28, no. 6, pp. 1295-1301, 1992

	1990(1)	2014 (Tokyo Tech)	2020?
Switching Devices	**Planar-Gate IGBTs**	**Planar-Gate SiC-MOSFETs**	**Trench-Gate SiC-MOSFETs**
Core Material in Transformer	**Ferrite**	**FINEMET™***	**New Magnetic Materials**
Efficiency (DC to DC)	**Below 90% @50 kW, 50 kHz**	**98% @100 kW, 20 kHz**	**Over 99% @100 kW, 20 kHz**

* Nano-crystalline soft-magnetic material from Hitachi Metals

What I want to emphasize

Power electronics people have been making a long voyage

from a **Silicon planet** to a **Silicon-Carbide planet**.

It will take five years from now to complete the wonderful voyage. This completion, as well as

the continuous development of "Control"

by leaps and bounds,

will bring a new world to power electronics.