Evolution of Dual-Active-Bridge (DAB) Converters for High-Power Applications

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November 11, 2023

Application of 3.3-kV SiC-MOSFET Modules to the Bullet Train

Japanese high-speed trains: N700S

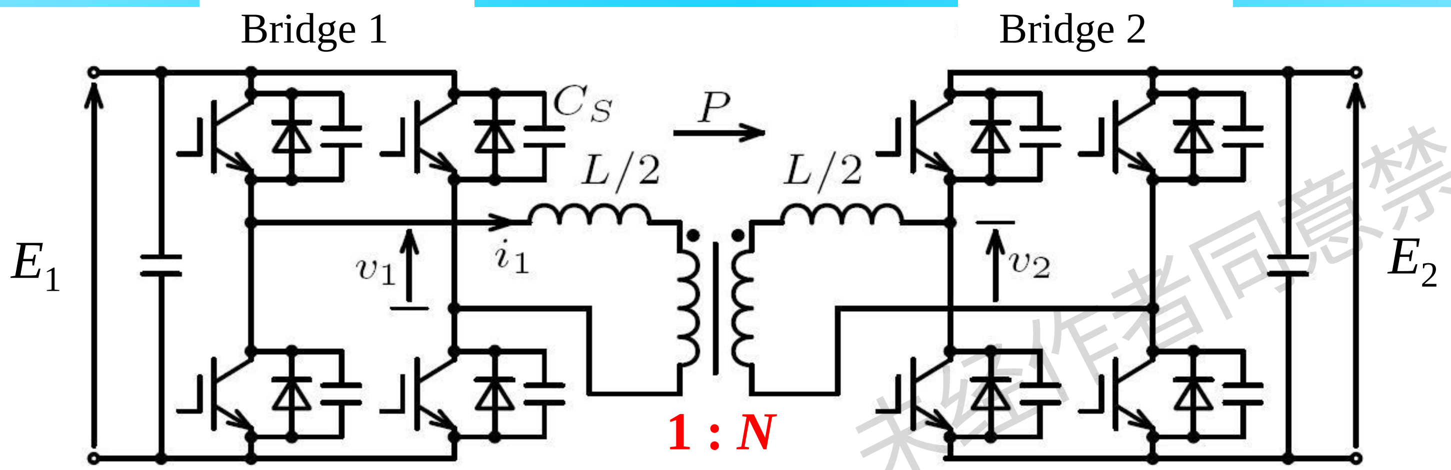
☆ Commercial operation:
Since July 2020

☆ Nominal catenary voltage:
25 kV and 50 Hz

☆ Traction:
Four induction motors per car

☆ Power conversion:
Three-level neutral-point-clamped PWM converters and inverters using 3.3-kV SiC-MOSFET modules

A Single-Phase Non-Resonant DAB Converter



R. W. DeDoncker, D. M. Divan, and M. H. Khealuwala, IEEE Trans. IA, Jan./Feb. 1991.
M. H. Khealuwala, R. Gascoigne, D. M. Divan, and E. Bauman, IEEE Trans. IA, Nov./Dec. 1992.

☆ Two Technical Terms

from Functionality: Bidirectional Isolated DC-DC Converters

from Circuit configuration: Dual-Active-Bridge (DAB) Converters

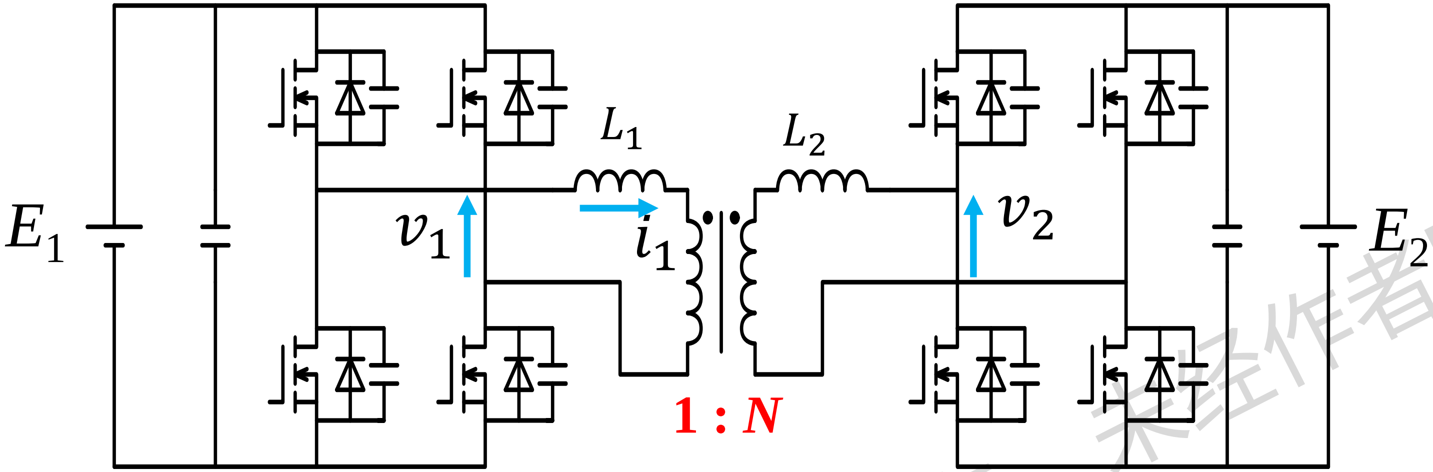
☆ Function/Operation

Both buck and boost functions: $NE_1 > E_2$ and $NE_1 < E_2$ (Max. efficiency at $NE_1 = E_2$)

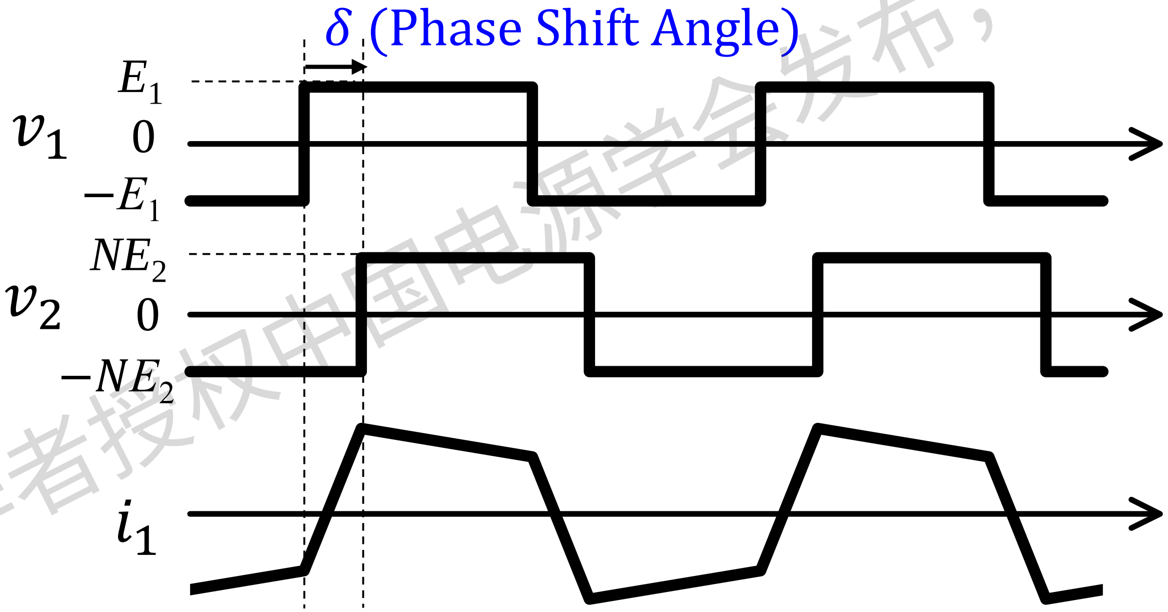
Zero-voltage-switching (ZVS) operation

☆ Synchronous Rectification, but limited to Si-MOSFETs and SiC-MOSFETs

Control and Operation of a DAB Converter with SPS



SPS: Single Phase Shift



Single-Phase-Shift (SPS) Control at $NE_1 > E_2$

Power Transfer

$$P = \frac{E_1 E_2}{2\pi f L N}\delta\left(1 - \frac{|\delta|}{\pi}\right)$$

f : Operating frequency

L : Primary-referred inductors ($= L_1 + L_2/N^2$) and leakage inductances

Recent Papers on High-Power DAB Converters

- The **100-kW**, 16-kHz DAB converter using two 1.2-kV 400-A SiC-MOSFET Quad (4-in-1) modules, presented by the Tokyo Institute of Technology (Tokyo Tech) in Japan

  99.2% at 100 kW and $E_1 = E_2 = 850$ V with Single Phase Shift (SPS) Control [1]

  99.0% at 100 kW and E_1 =750 V and $E_2 = 850$ V with Double Phase Shift (DPS) control [2]

  R. Haneda and H. Akagi [1] IEEE Trans. on Power Electronics, vol. 35, no. 10, Oct. 2020.
  [2] IEEE Trans. on Industry Applications, vol. 58. no. 1, Jan./Feb. 2022.

  Tokyo Tech gave priority to efficiency improvements.

- The **500-kW**, 20-kHz DAB converter using four 1.2-kV 1.2-kA SiC-MOSFET Dual (2-in-1) modules, presented by the Karlsruhe Institute of Technology (KIT) in Germany

  97.2% at 504 kW, and $E_1 = E_2 = 800$ V with SPS Control

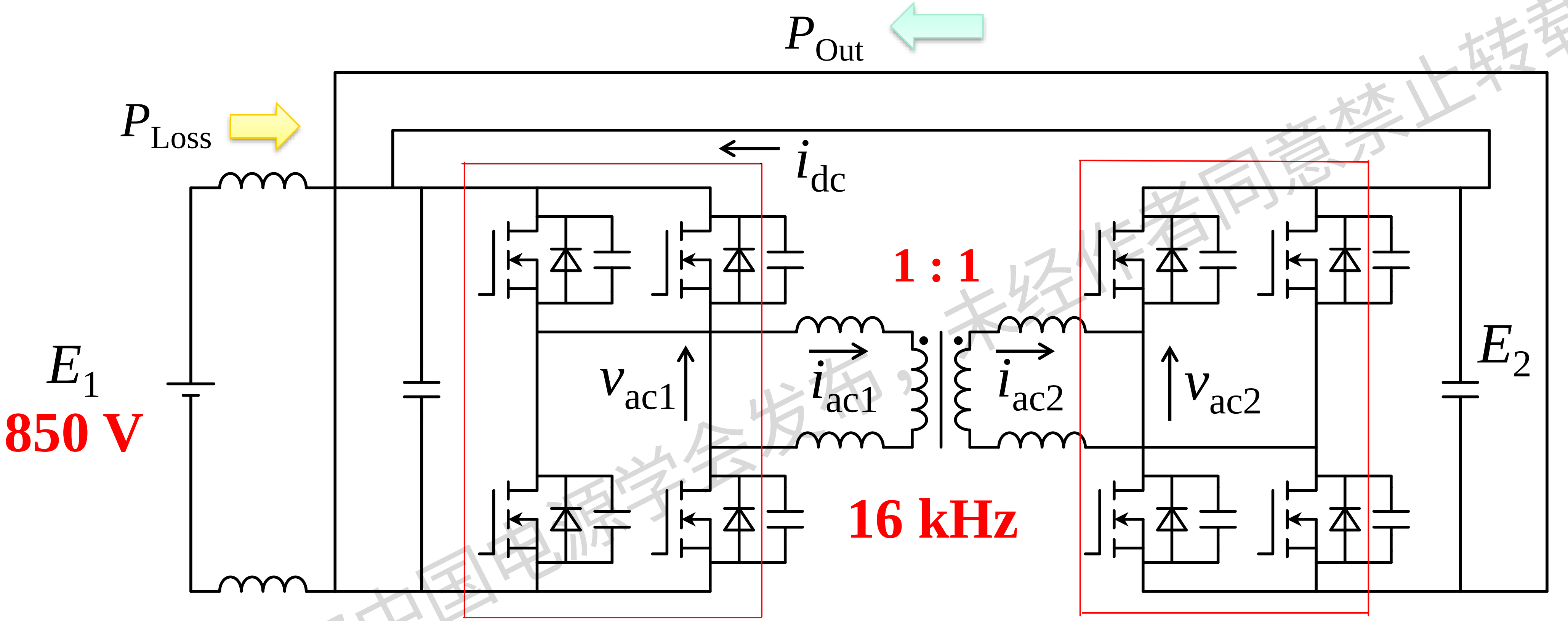
  F. Sommer, N. Menger, T. Merz, N. Soltau, S. Idaka, and M. Hiller, IPEC-Himeji / ECCE-Asia, May 2022.

  KIT may give priority to cost reductions.

850-V, 100-kW, 16-kHz DAB Converters using 1.2-kV 400-A SiC-MOSFET Quad (4-in-1) Modules at $\boldsymbol{E_1 = E_2}$

R. Haneda and H. Akagi, “Design and performance of the 850-V 100-kW 16-kHz bidirectional isolated DC-DC converter using SiC-MOSFET/SBD H-bridge modules,” IEEE Trans. on Power Electronics, vol. 35, no. 10, pp. 10013-10025, Oct. 2020.

850-V, 100-kW, 16-kHz DAB Converter at $E_1 = E_2$



$$\eta = \frac{P_{Out}}{P_{Loss} + P_{Out}}$$

Error < 0.01%

1.2-kV 400-A SiC-MOSFET Quad (4-in-1) Modules

Manufacturer: Mitsubishi Electric Corporation

Part Number: FMF400BX-24A (currently EOL)

The 2nd-Generation 1.2-kV 400-A SiC-MOSFET Quad (4-in-1) Module

MITSUBISHI
ELECTRIC

<Full SiC Power Modules>

FMF400BX-24B

HIGH POWER SWITCHING USE
INSULATED TYPE

The 2nd-generation version following FMF400BX-24A, currently available from the market.

fourpack

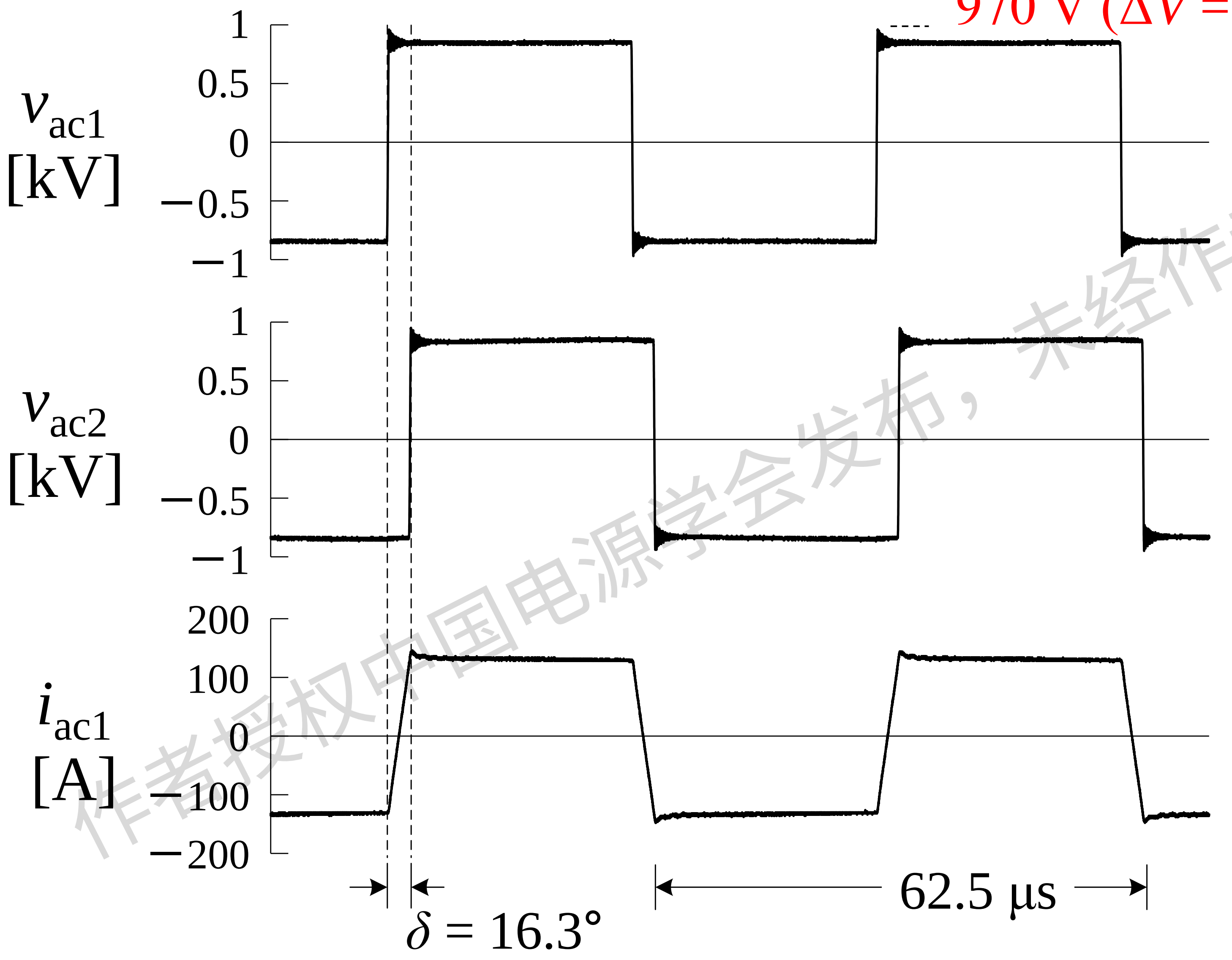
Drain current I_D .... 400 A

Drain-Source voltage V_{DSX} .... 1200 V

Maximum junction temperature T_{vjmax} .... 175 °C

- Silicon Carbide MOSFET + Silicon Carbide Schottky Barrier Diode
- Flat base Type
- Copper base plate
- RoHS Directive compliant
- Recognized under UL1557, File E323585

Experimental Waveforms ($E_1 = E_2$ = 850 Vdc, 100 kW, 16 kHz)



Efficiency (dc-to-dc)

99.2⁺% with FMF400BX-24A (measured)

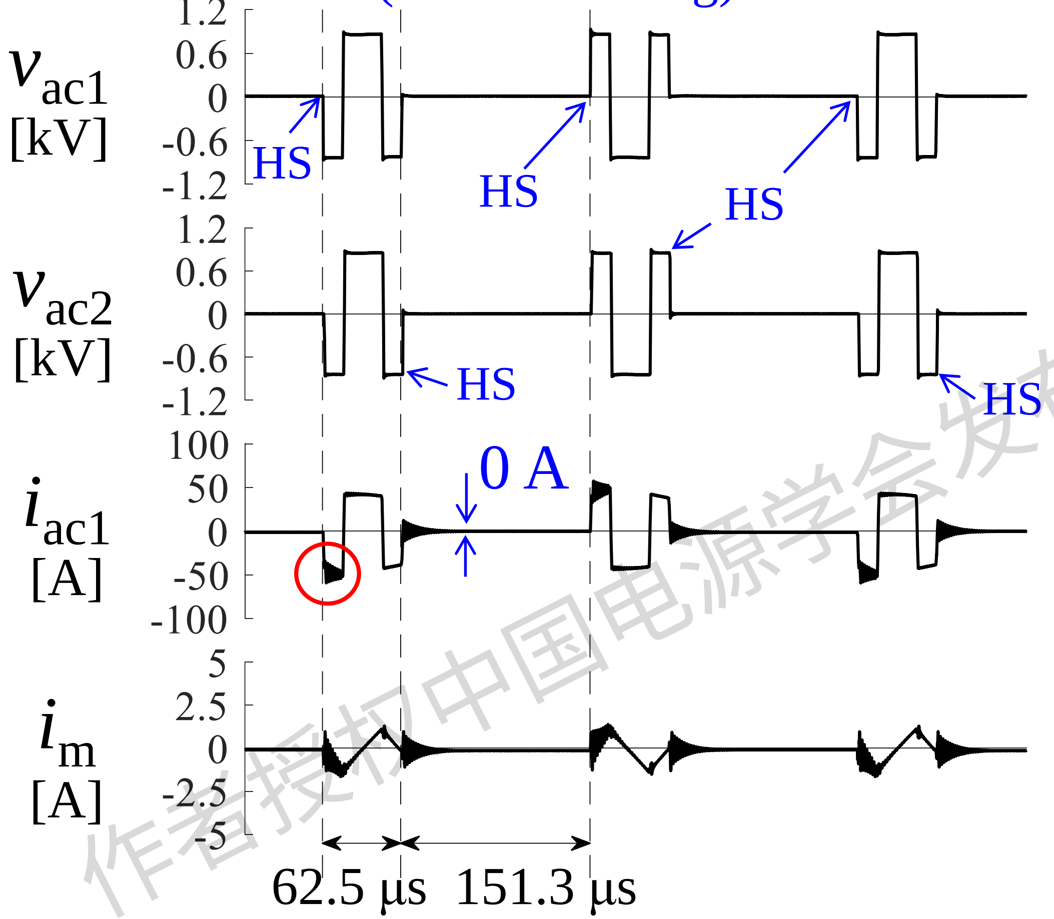
99.3⁺% with FMF400BX-24B (estimated)

I_{rms} = 128 A

Intermittent Operation at 850 V, 10 kW, and 16 kHz

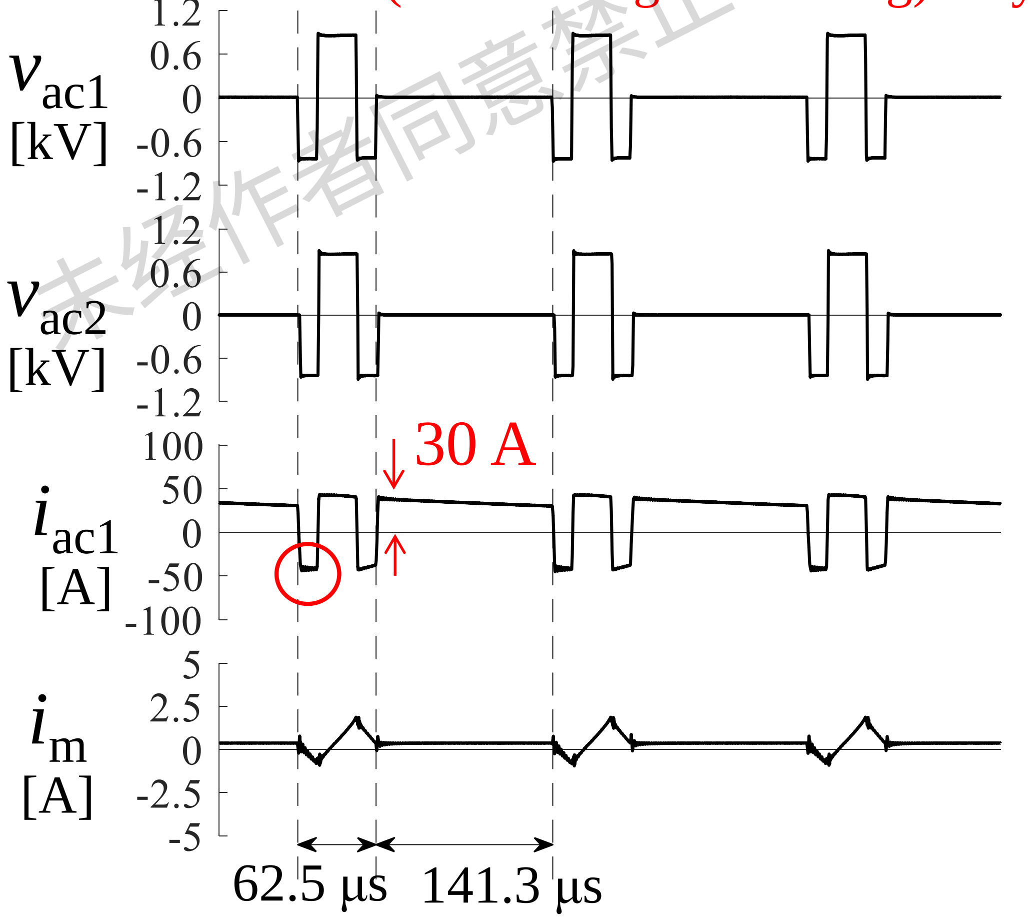
Discontinuous Current Mode

HS (hard Switching) and ZVS mixed



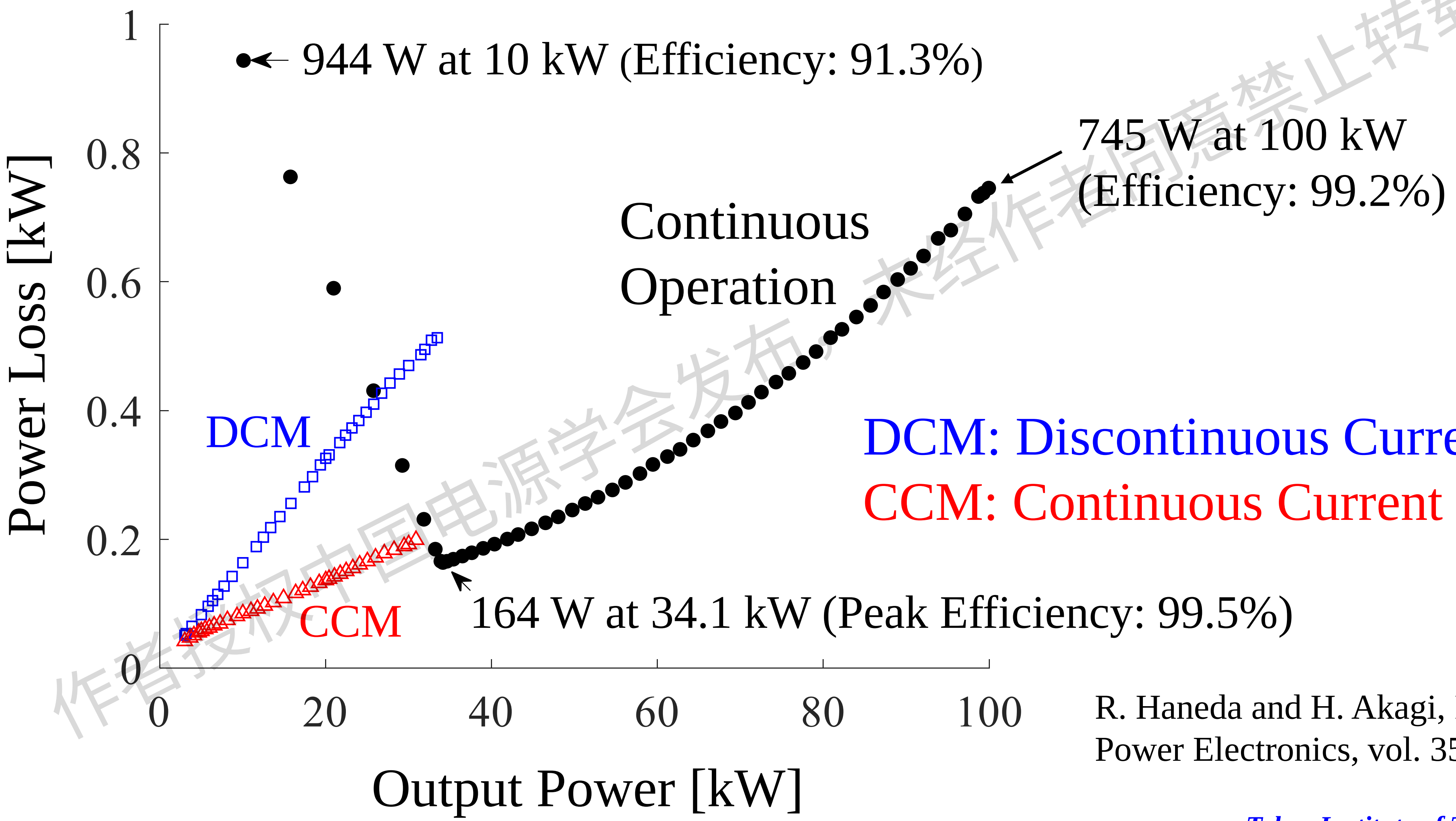
Continuous Current Mode

ZVS (Zero-Voltage Switching) only



Efficiency (dc-to-dc): 98.4% → 99.2% (+0.8%)

Measured Power Losses of the 850-V 16-kHz DAB Converter

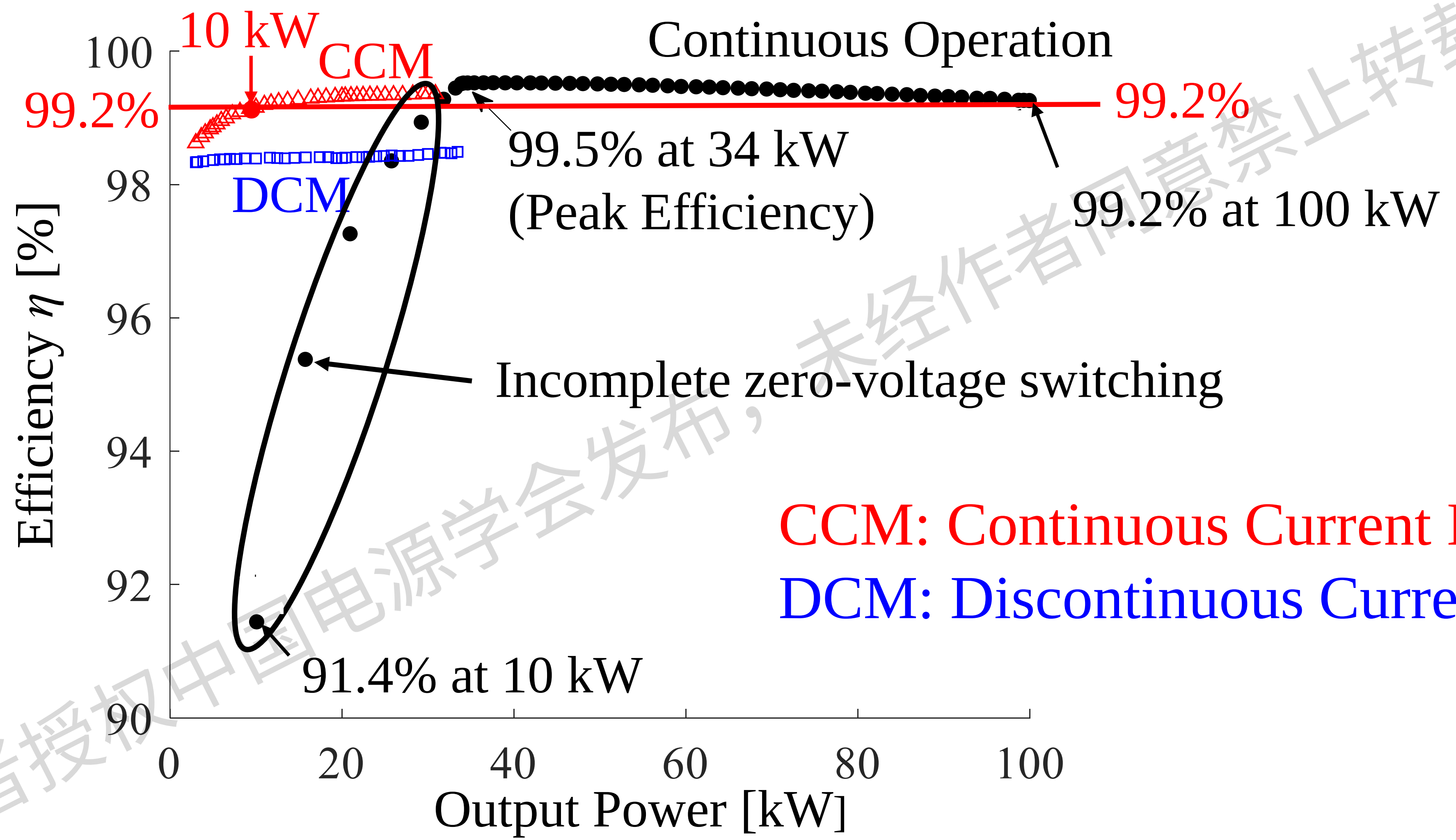


DCM: Discontinuous Current Mode

CCM: Continuous Current Mode

R. Haneda and H. Akagi, IEEE Trans. Power Electronics, vol. 35, Oct. 2020.

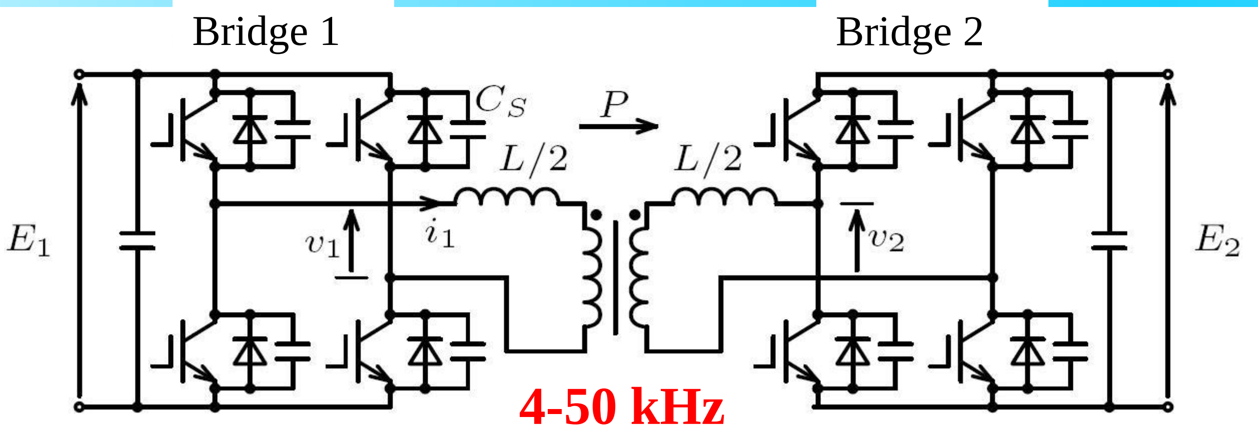
Efficiency (dc-to-dc) Comparison at 850 V and 16 kHz



CCM: Continuous Current Mode
DCM: Discontinuous Current Mode

Efficiency: 99.2% or higher in a broad range of 10 to 100 kW

Evolution of DAB Converters in Efficiency (1/2)



[1] M. Khealuwala, R. Gascoigne, D. Divan, and E. Bauman, IEEE Trans. IA, vol. 28, Nov./Dec. 1992.

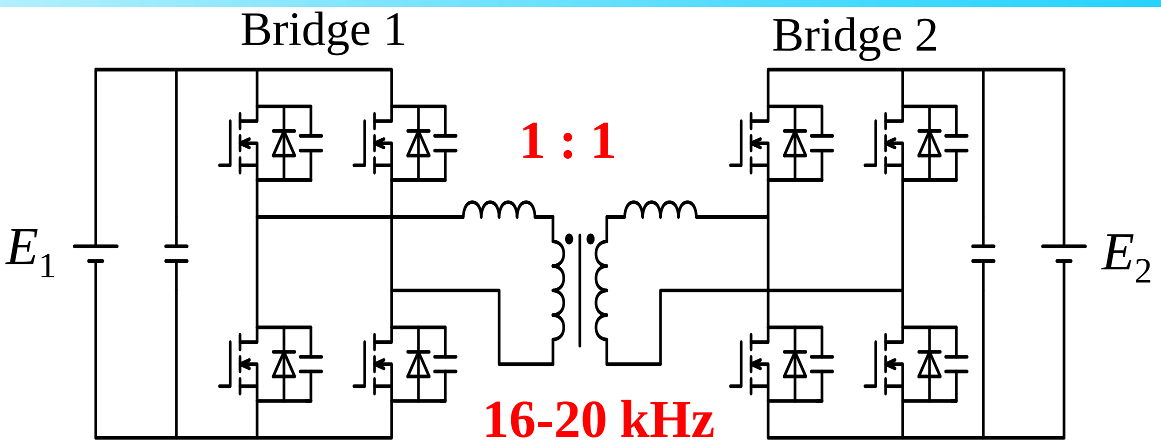
[2] S. Inoue and H. Akagi, IEEE Trans. PEL, vol. 22, March 2007.

[3] T. Chocktaweechock and H. Akagi, IEE of Japan IAS Annual Conference, Aug. 2012.

Year (Academia)	1992 (UW-Madison*) [1]	2007 (Tokyo Tech) [2]	2012 (Tokyo Tech) [3]
Switching Devices	Planer-Gate IGBT modules	Trench-Gate IGBT modules	Trench-Gate IGBT modules
Magnetic Material in Transformer	PC40 Ferrite	FINEMET™** (Thickness: 18 μm)	FINEMET™* (Thickness: 18 μm)
DC-to-DC Efficiency (Power Loss)	87.2% (12.8%) @ 170 V / 1288 V 48 kW and 50 kHz	96.9% (3.1%) @ 350 V / 350 V 10 kW and 20 kHz	96.9% (3.1%) @ 750 V / 750 V 60 kW and 4 kHz

* University of Wisconsin-Madison
** Nano-crystalline soft-magnetic material from Hitachi Metals

Evolution of DAB Converters in Efficiency (dc-to-dc) (2/2)



[4] H. Akagi, T. Yamagishi, N. M. L. Tan, S. Kinouchi, Y. Miyazaki, and M. Koyama, IEEE Trans. IA, vol. 51, Jan./Feb. 2015.

[5] R. Haneda and H. Akagi, IEEE Trans. PEL, vol. 35, Oct. 2020.

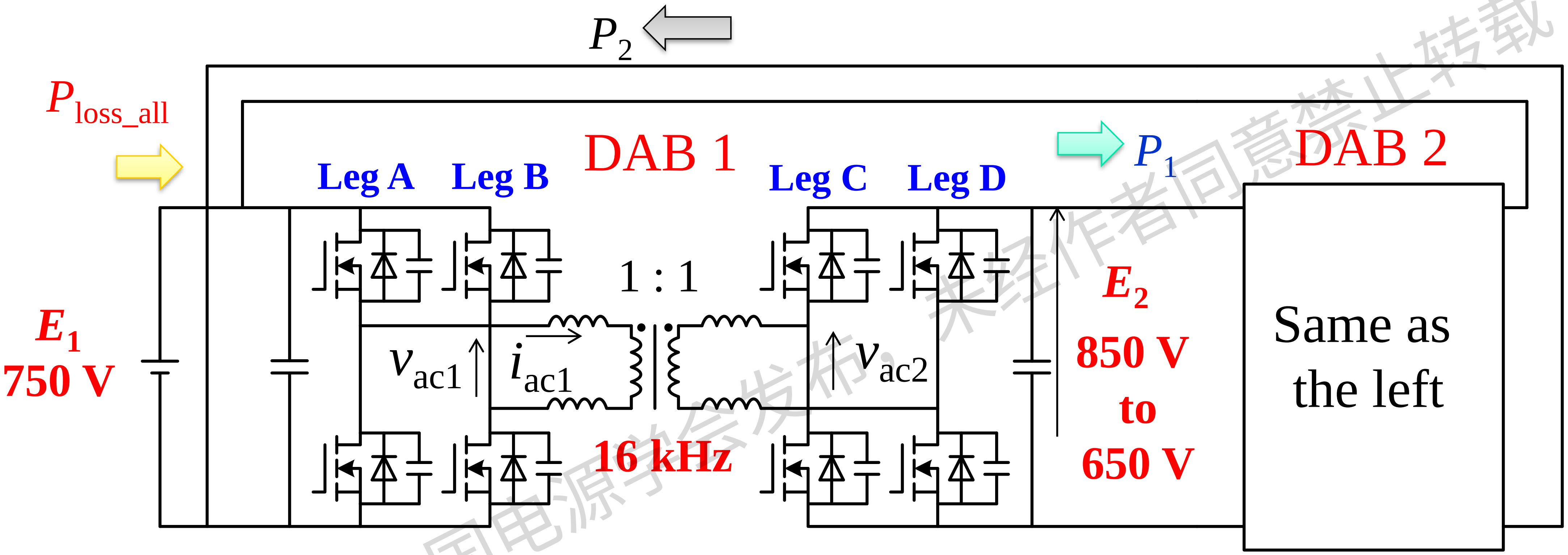
Year (Academia)	2015 (Tokyo Tech) [4]	2020 (Tokyo Tech) [5]	2030?
Switching Devices	Planer-Gate SiC-MOSFET dual modules	Planer-Gate SiC-MOSFET quad modules	Trench-Gate/SJ SiC-MOSFET quad modules
Magnetic Material in Transformer	FINEMET™* (Thickness: 18 μm)	FINEMET™* (Thickness: 14 μm)	New or improved magnetic materials
DC-to-DC Efficiency (Power Loss)	98.3% (1.7%) @ 750 V / 750 V 100 kW and 20 kHz	99.2% (0.8%) @ 850 V / 850 V 100 kW and 16 kHz	99.6% (0.4%) @ 850 V / 850 V 100 kW and 16 kHz

* Nano-crystalline soft-magnetic material from Hitachi Metals

750-V, 100-kW, 16-kHz DAB Converters using 1.2-kV 400-A SiC-MOSFET Quad (4-in-1) Modules at $\boldsymbol{E_1 \neq E_2}$

R. Haneda and H. Akagi, "Power-loss characterization and reduction of the 750-V 100-kW 16-kHz dual-active-bridge converter with buck and boost mode," IEEE Trans. on Industry Applications, vol. 58, no. 1, pp. 541-553, Jan./Feb. 2022.

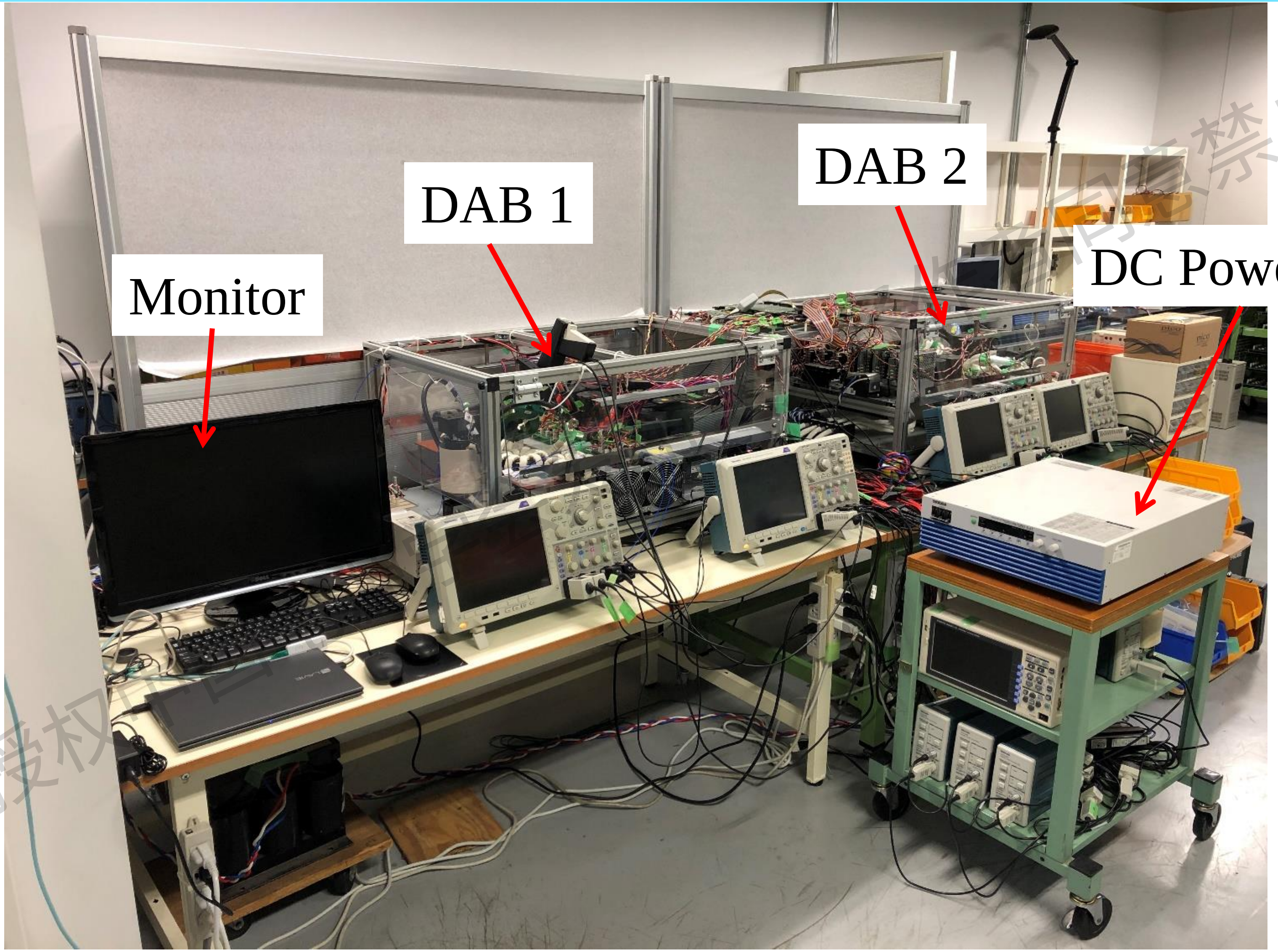
Experimental Circuit Capable of Operation at $E_1 \neq E_2$



$$P_{loss} \doteqdot P_{loss\_all} / 2$$

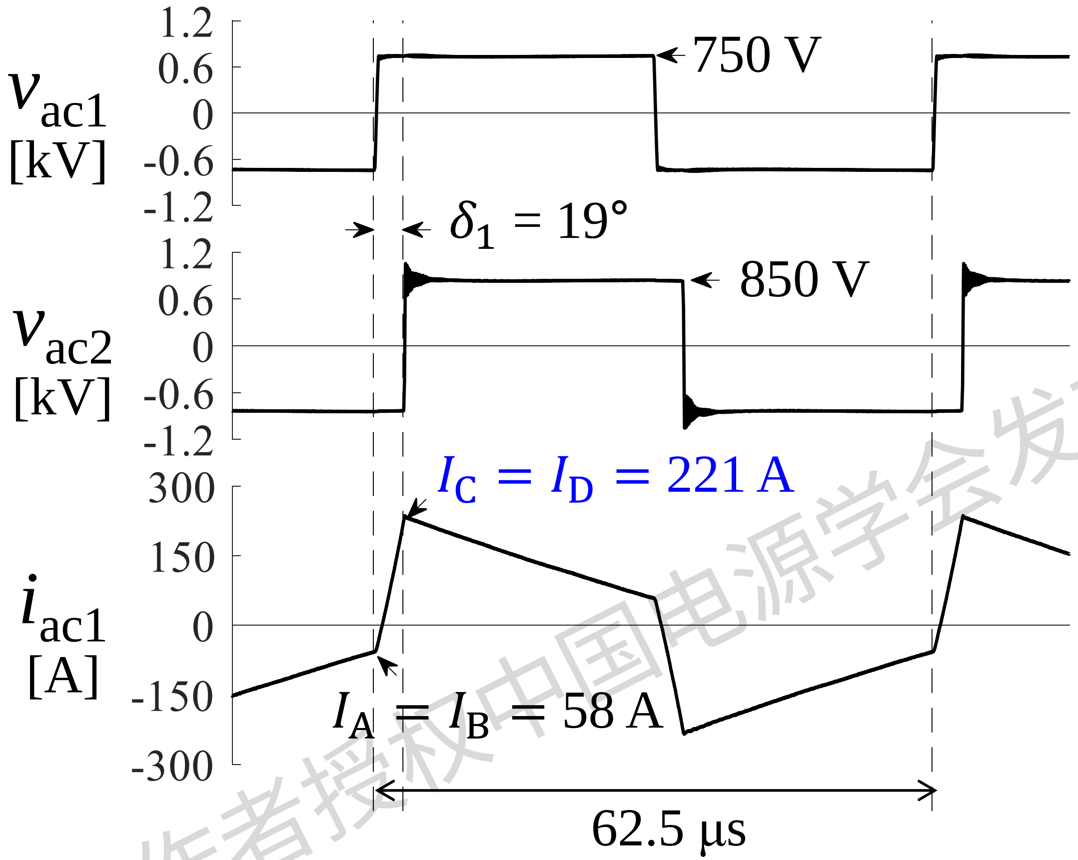
Efficiency of DAB 1: $\eta = \dfrac{P_1}{P_1 + P_{loss}} \doteqdot \dfrac{P_1}{P_1 + P_{loss\_all} / 2}$

The Photo of the System Capable of Operation at $\boldsymbol{E}_1 \neq \boldsymbol{E}_2$



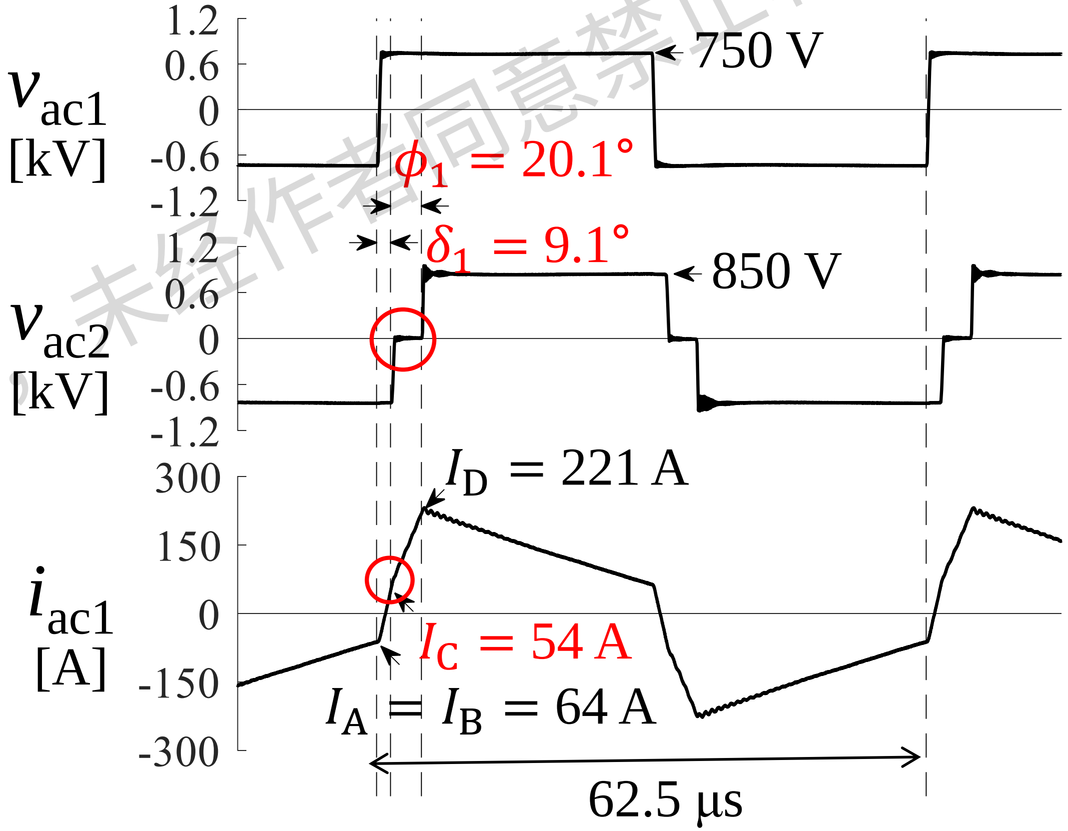
Comparisons in Waveform and Efficiency between SPS and DPS

Single Phase Shift (SPS)



Efficiency: 98.8%

Double Phase Shift (DPS)



Efficiency: 99.0% (+0.2%)

$E_1 = 750$ V, $E_2 = 850$ V, 100 kW, and 16 kHz

New Findings from the 100-kW DAB Converters

Continuous Ratings : 850 Vdc, 100 kW, and 16 kHz, with forced air cooling
Power Devices: the 1st-generation 1.2-kV, 400-A SiC-MOSFET quad modules

- Single-phase-shift (SPS) control at $\boldsymbol{E_1 = E_2 = 850}$ **V**

  Measured efficiencies (dc-to-dc)

  99.2% at the rated power of 100 kW

  99.5% (peak efficiency) at 34 kW

  99.2% at 10 kW

- Double-phase-shift (DPS) control at $\boldsymbol{E_1 = 750}$ **V** and $\boldsymbol{E_2 = 850}$ **V**

  Measured efficiency (dc-to-dc)

  99.0% at the rated power of 100 kW

Requests to Scientists and Engineers of Power Devices

- Performance improvements in SiC-MOSFET modules:
  - ☆ Specific on-state resistance: 1/2
  - ☆ Switching loss: 1/2
  - ☆ Parasitic inductance between the dc terminals: 1/2

- Cost reduction of SiC-MOSFET modules:
  - ☆ Purchase price at a user level: 1/2

Thanks for your Attention!

Tokyo Institute of Technology was inaugurated in 1881.