

Medium-Voltage Power Conversion Systems in the Next-Generation

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新幹線 (The Shinkansen)

Tokyo-Osaka : 515 km

2.5 hours at maximum speed : 270 km/h

The number of passengers : 1,323/16 cars

The fare for one way : 13,000 JPY (=110 USD)



Question

How much does one passenger pay for the
Charge of electricity from 13,000 JPY ?

Hint: 150, 750, or 1500 JPY (Gas: 130 JPY/liter)

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Answer

➤ **150 JPY**

✓ The maximum power of the 16 cars : 13.2 MW

✓ The total electric energy : 23 MWh

✓ The average power : $23 \text{ MWh} / 2.5 = 9.2 \text{ MW}$

✓ The number of passengers : 1,326

✓ The average power per passenger :

$$9.2 \text{ MW} / 1,326 = 7 \text{ kW}$$

✓ The total energy per passenger :

$$7 \text{ kW} \times 2.5 \text{ h} = 17.5 \text{ kWh}$$

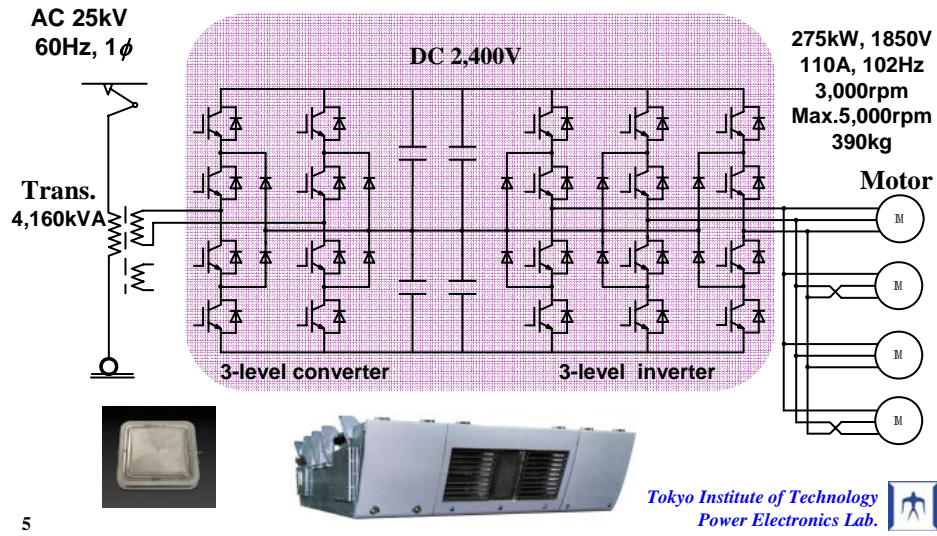
$17.5 \text{ kWh} \times 8 \sim 10 \text{ JPY/kWh} \doteq 150 \text{ JPY}$

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Main Power Circuit

Nozomi series 700



Applications of STATCOM and BTB in Japan

○ The 60-MW Electric Frequency Changer (Commissioned in 2004)

K. Kunomura, K. Yoshida, K. Ito, N. Nagayama, M. Otuki, T. Ishizaka, F. Aoyama, T. Yoshino, "Electric Frequency Converter," in *Proceedings of the 2005 International Power Electronics Conference (IPEC)*, Niigata, Japan, S71-4, 2005.

○ The 80-MVA STATCOM (Commissioned in 2004)

T. Fujii, S. Funahashi, N. Morishima, M. Azuma, H. Teramoto, N. Iio, H. Yonezawa, D. Takayama, and Y. Shinki, "A 80-MVA STATCOM for the Kanzaki Substation," in *Proceedings of the 2005 International Power Electronics Conference (IPEC)*, Niigata, Japan, S37-1, 2005.

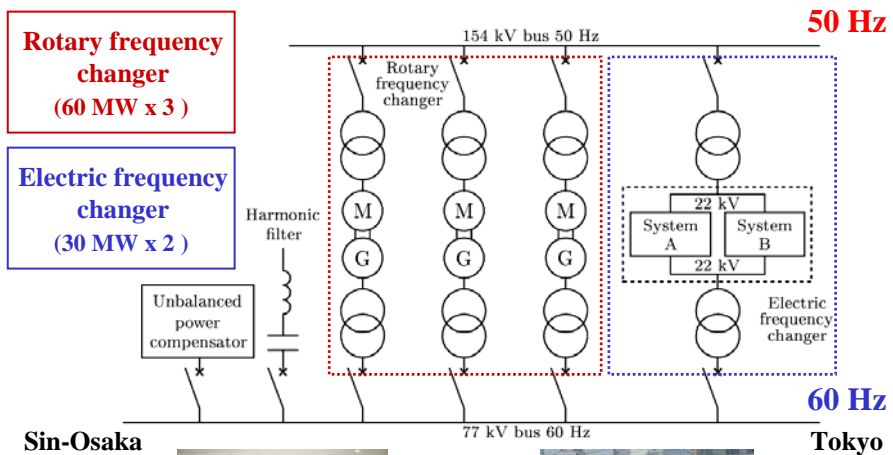
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The 60-MW Electric Frequency Changer



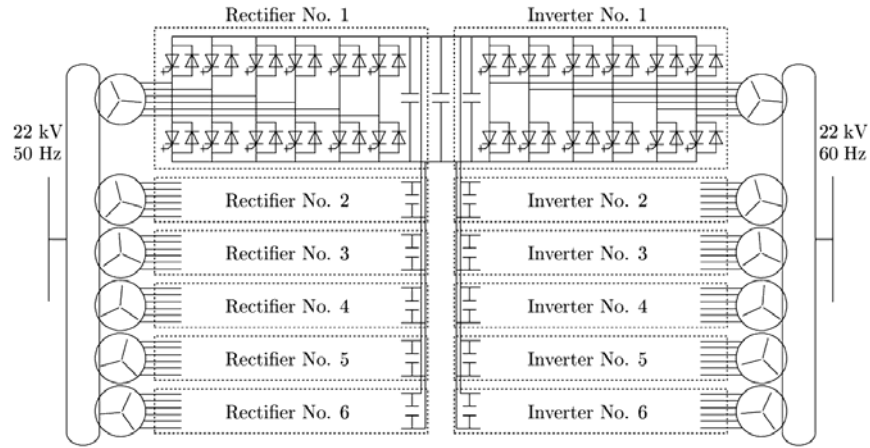
TOSHIBA



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Circuit Configuration of 30-MW Unit



6-kV 4-kA GTOs Efficiency : 96%

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Applications of STATCOM and BTB in Japan

○ The 60-MW Electric Frequency Changer (Commissioned in 2004)

K. Kunomura, K. Yoshida, K. Ito, N. Nagayama, M. Otuki, T. Ishizaka, F. Aoyama, T. Yoshino, "Electric Frequency Converter," in *Proceedings of the 2005 International Power Electronics Conference (IPEC)*, Niigata, Japan, S71-4, 2005.

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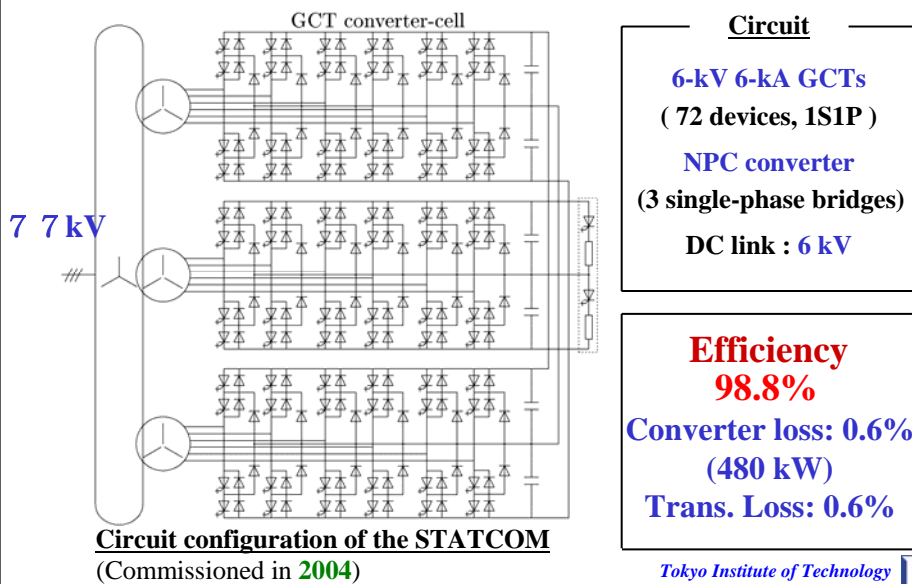
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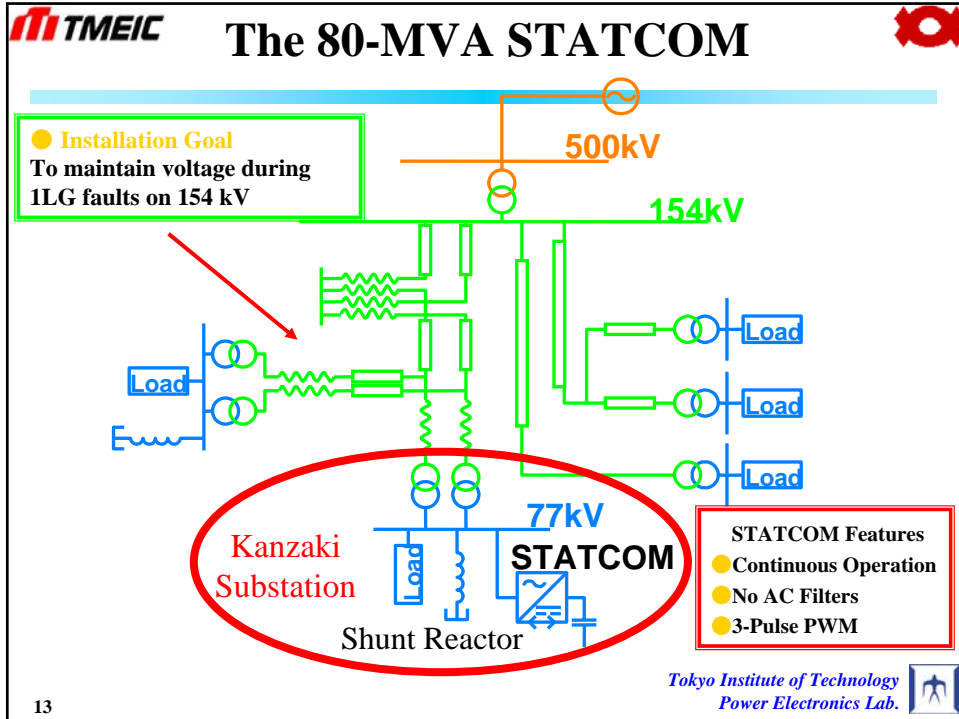
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The 80-MVA STATCOM



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The Medium-Power Conversion System based on Bi-directional Isolated DC/DC Converters

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DC Power Supply

1970's: Series Regulators

- Electric Isolation: **Line-Frequency Transformer**
↳ Heavy and Bulky
- Voltage Regulation: **Linear Operation**
↳ Low Efficiency

Today: Switching Regulators

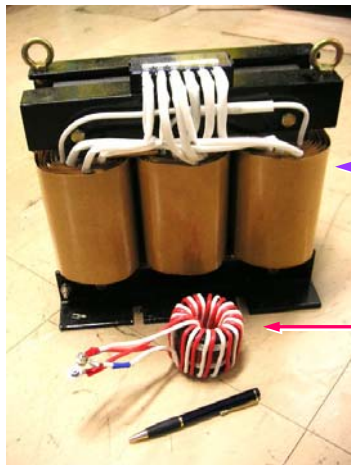
- Electric Isolation: **High-Frequency Transformer**
↳ Light and Compact
- Voltage Regulation: **Switching Operation**
↳ High Efficiency

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Why Are High-Frequency Transformers Useful?



Three-phase 200-V, 5-kVA,
50-Hz Transformer

Single-phase, 250-V, 5-kVA,
20-kHz Transformer

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Nominal System Voltages in Japan

Utility Distribution System : **6.6 kV**

Industrial Distribution System : **3.3/6.6 kV**

■ Functions of the 6.6-kV STATCOM

- Power factor correction
- Voltage regulation
- Load balancing

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Medium-Voltage Power Conversion Systems



- 6.6-kV Distribution Feeder
 - Ⓢ STATCOM
 - Ⓢ BTB (Back-to-Back) system



© TOSHIBA TOSVERT-MV
(3.3 kV, 1,800 kW)

- Industry
 - Ⓢ 3.3-kV/6.6-kV motor drive

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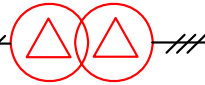


6.6-kV STATCOM for Utility and Industry

Today

1 MVA

6.6 kV



Transformer Weight : **4,000 kg**
Size : **1m × 2m × 2.5m**

Converter Weight : **1,000~2,000 kg**

Requirements : **Low Cost, Small Size, Light Weight**

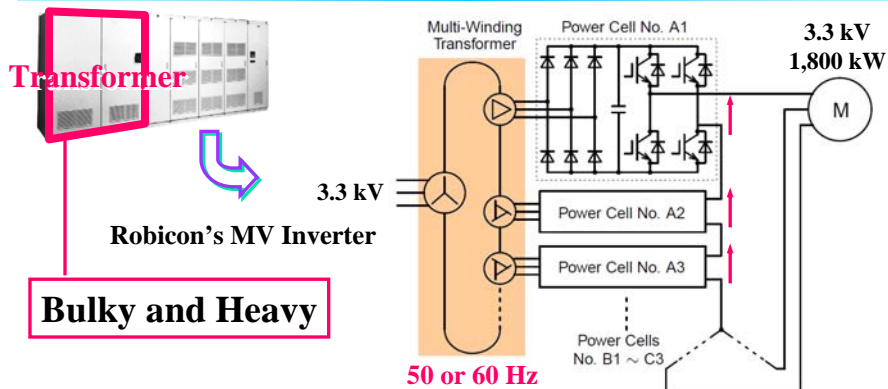
**The 6.6-kV Transformerless
STATCOM**

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Today's Medium-Voltage Motor Drives



Bulky and Heavy

© P. W. Hammond, *IEEE Trans. Ind. Applicat.*, vol. 33, no. 1, pp. 202-208, 1997

■ Roles of the multi-winding transformer (50/60 Hz) :

- ☉ To supply isolated voltages to each power cell
- ☉ To reduce harmonic currents

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Future Medium-Voltage Power Conversion

Today: Line-Frequency Transformer

Used for Voltage Matching and/or Electrical Isolation

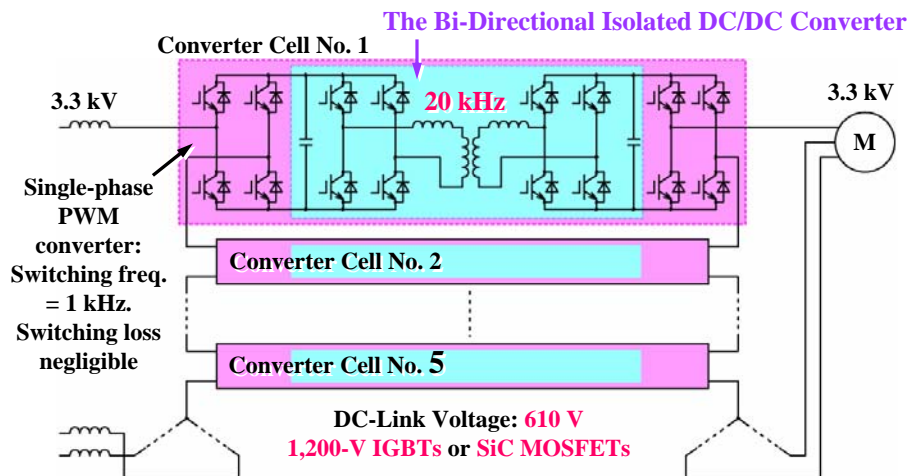
Future: Transformerless or High-Freq. Transformer

- Transformerless: Multi-level PWM Converters
 - Diode-Clamped, Flying Capacitor, and Cascaded
- High-Freq. Trans.: Bi-Directional Isolated DC/DC Converters

Power-Electronic DC Transformers

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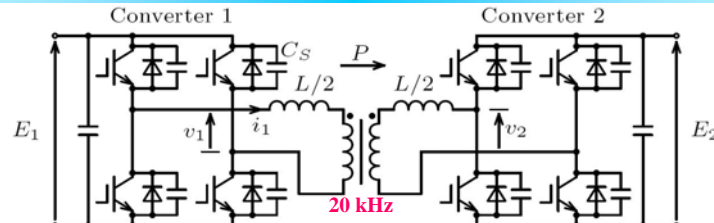
The Next-Generation Motor Drive



- The DC/DC converter dominates system efficiency

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The Bi-Directional Isolated DC/DC Converter



© R. W. De Doncker, et al., *IEEE Trans. Ind. Applicat.*, vol. 28, no. 6, pp. 1294-1301, 1991

	1991	2004 Winter	2010
Switching Devices	First-Generation IGBTs	Trench-Gate IGBTs	SiC MOSFETs
Core Material in Transformer	Ferrite	Finemet™* (Hitachi Metals)	New Material?
Efficiency (DC to DC)	90 ~ 92%	97%	Over 99%

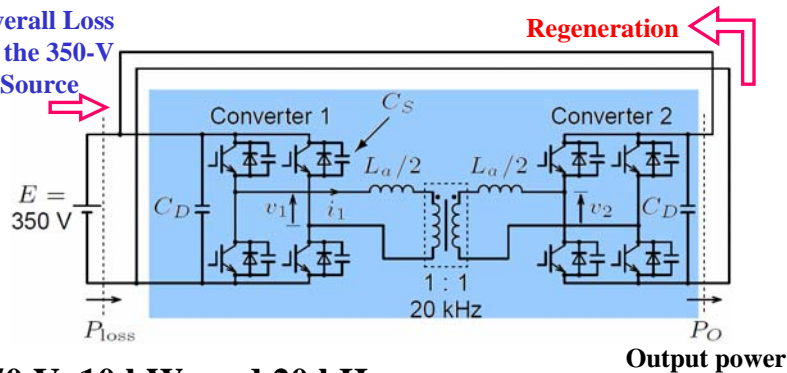
* Nano-crystalline soft-magnetic material
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The Experimental Circuit for Loss Analysis

The Overall Loss Fed by the 350-V DC Source



- 350 V, 10 kW, and 20 kHz
- Output DC power P_O is regenerated to Input DC terminals.
- Loss analysis estimates the possibility of SiC devices.

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Experimental Setup

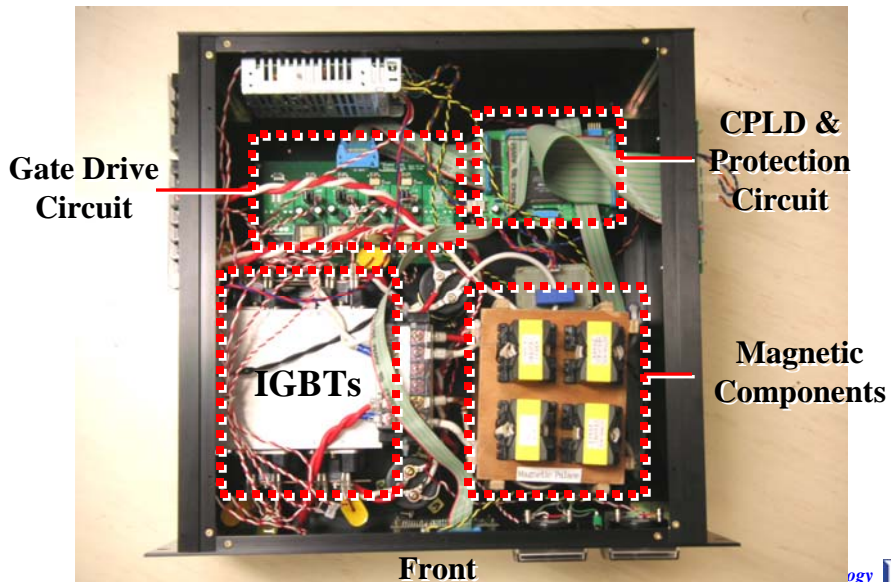


Controllable
via a personal
computer

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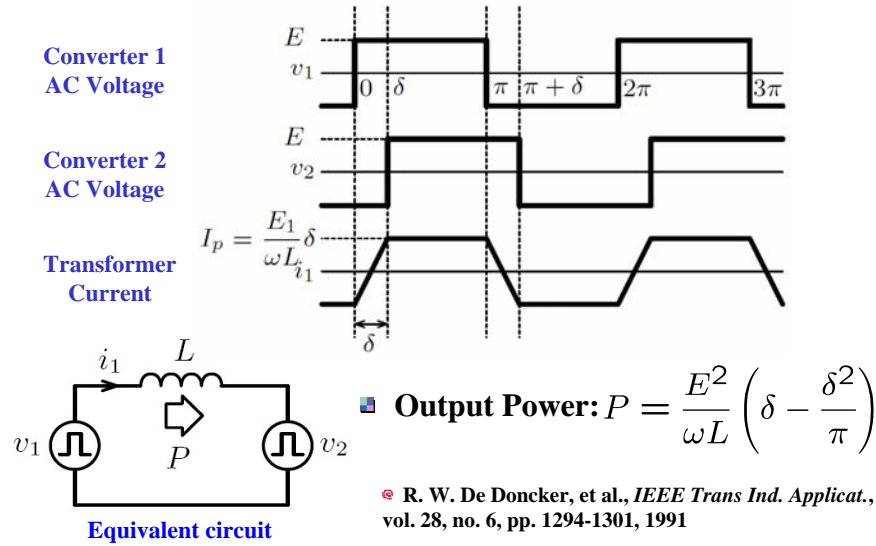
Experimental Setup



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Operation Principle

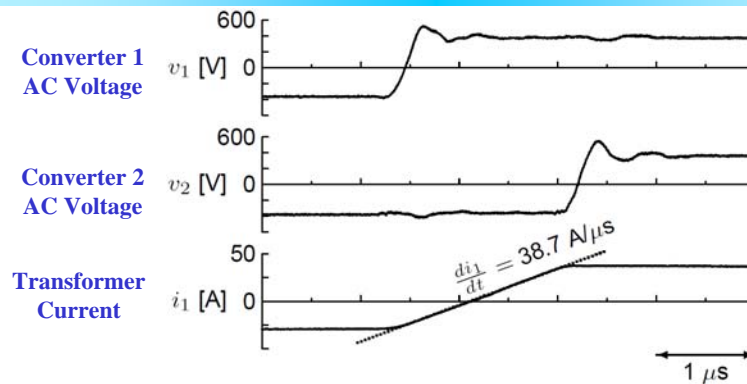


(L = transformer leakage and external inductors)

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Experimental Waveforms at 10 kW

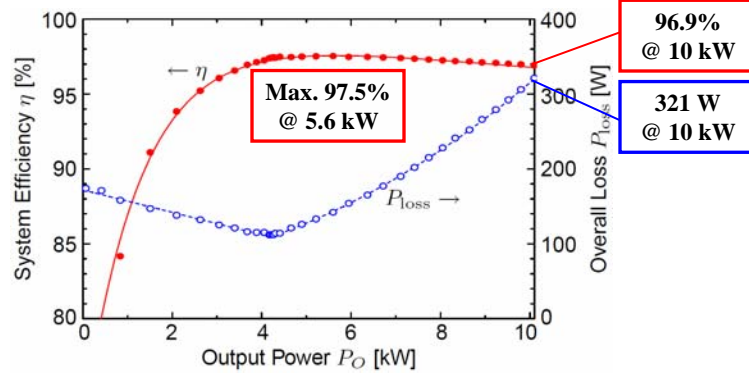


- $L = 18.6 \mu\text{H}$ and the phase shift: $\delta = 13 \text{ deg}$.
- Switching frequency: $f = 20 \text{ kHz}$
- di_1/dt values can be used in loss analysis.

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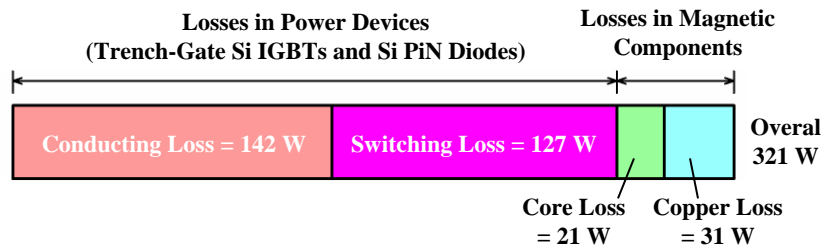
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Power P_O , Efficiency η , and Loss P_{loss}



- Overall Efficiency (DC to DC): Max. **97.5%**
- $P_{\text{loss}} = 321 \text{ W}$ @ $P_O = 10 \text{ kW}$
- What causes the 321-W loss?**

Loss Analysis Result at 10 kW



- Power-device loss (=269 W) is dominant in 321 W**
- When SiC-MOSFETs are used:**
Overall Loss $P_{\text{loss}} = 28 \text{ W} + 13 \text{ W} + 21 \text{ W} + 31 \text{ W}$
 $= 93 \text{ W}$ ($\eta = 99.1\%$)
- Assuming that the conducting loss is reduced to 20% and the switching loss is reduced to 10%, compared to Si IGBTs.

Source: Arai and Yoshida: "Fundamentals and Applications of SiC devices," Ohmsha, 2003 (in Japanese)

Applications and Markets

6.6-kV Distribution Line
STATCOM
BTB System

Traction
Commuter Train (1.5 kV)
Shinkansen (25 kV)

Industry
3.3-kV/6.6-kV
Motor Drive

UPS

**Distribution
Generation**

- Various application fields
- Energy conservation and distributed power generation: The market will continue to grow.

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A Medium-Voltage Transformerless Cascade PWM STATCOM with Star-Configuration

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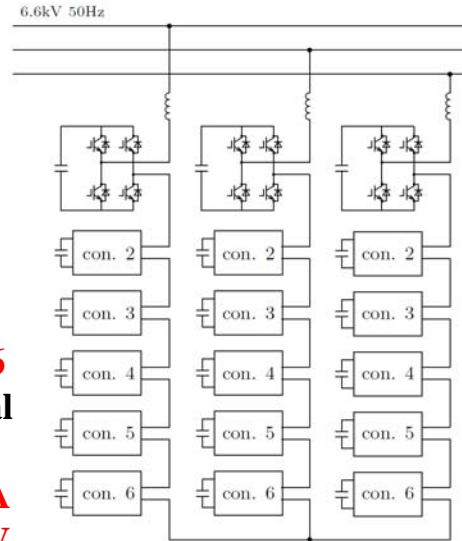
6.6-kV 1-MVA Cascade PWM STATCOM

General Features

- No Transformer
- Higher Voltage Levels
- Split DC Capacitors
- Voltage Imbalance

Design Example

- Cascade Number : $N = 6$
- 13 level in line-to-neutral
- 25 level in line-to-line
- 72 IGBTs: 1.7-kV, 200-A
- DC Voltage : 900-1,000V



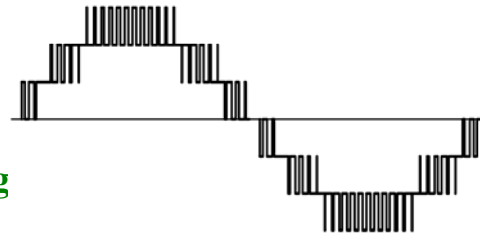
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Control of Cascade STATCOM

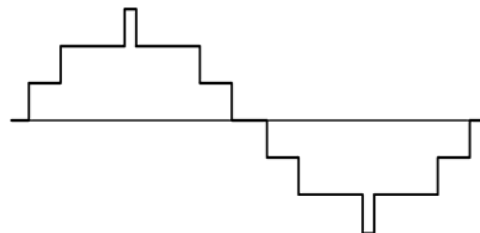
Pulse-Width Modulation

- @ Quick Response
- @ 6.6-kV in Japan
- @ Difficult Voltage Balancing
- No Practical Method



Staircase Modulation

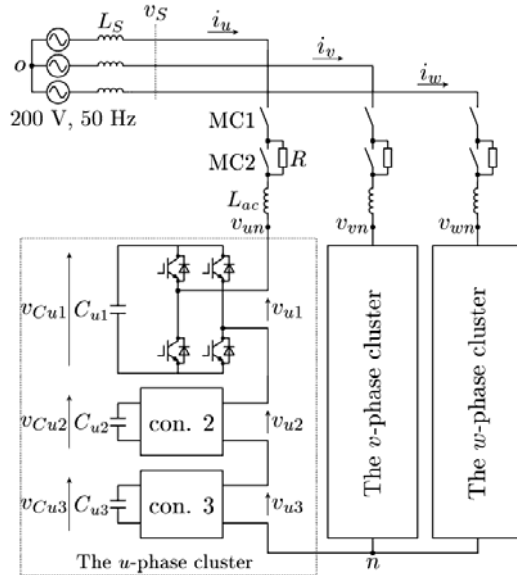
- @ Slow Response
- @ 13.8-kV in USA
- @ Easy Voltage Balancing
- Lai and Peng, IEEE Trans. on IA, 1996



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200-V 30-A 10-kVA Down-Scaled Model



Cascade Number $N = 3$

7-level in line-to-neutral

13-level in line-to-line

Phase-Shifted 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)

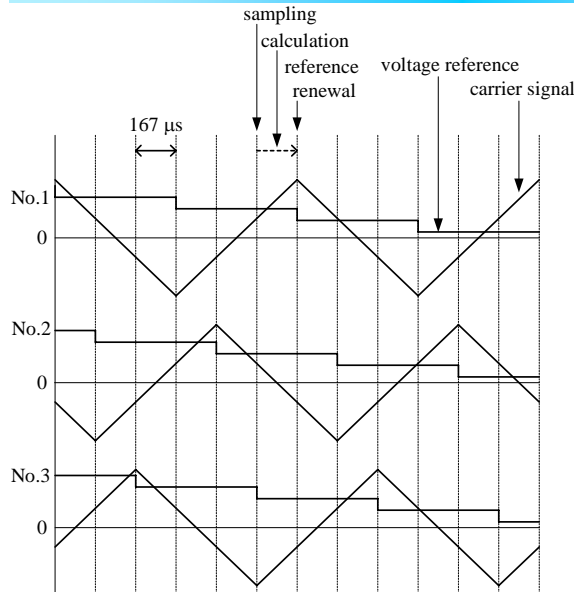
$C = 16.4$ mF

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Three Phase-Shifted Carrier Signals



Synchronous Sampling

Sampling frequency :

6 kHz (= 1 kHz x 2 x 3)

Sampling point:

every top and bottom

period : $500/3 = 0.167$ ms

Reference Renewal

at every top and bottom

of each carrier signal

renewal period: 0.5 ms

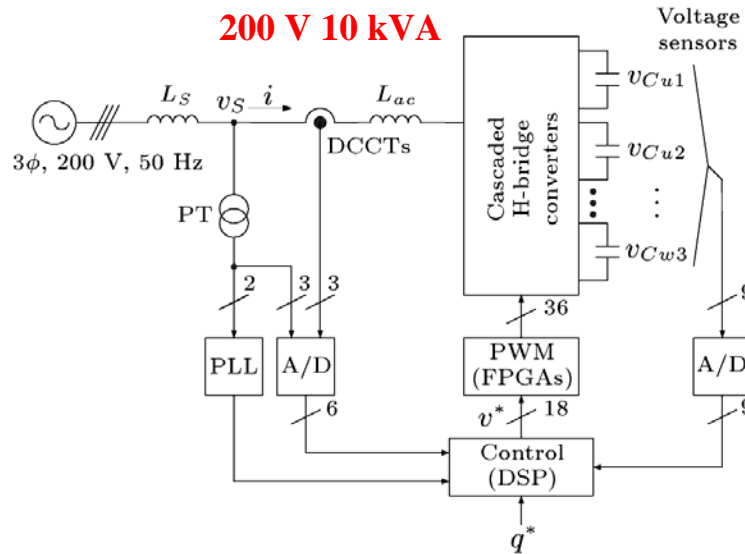
calculation time: 0.167 ms

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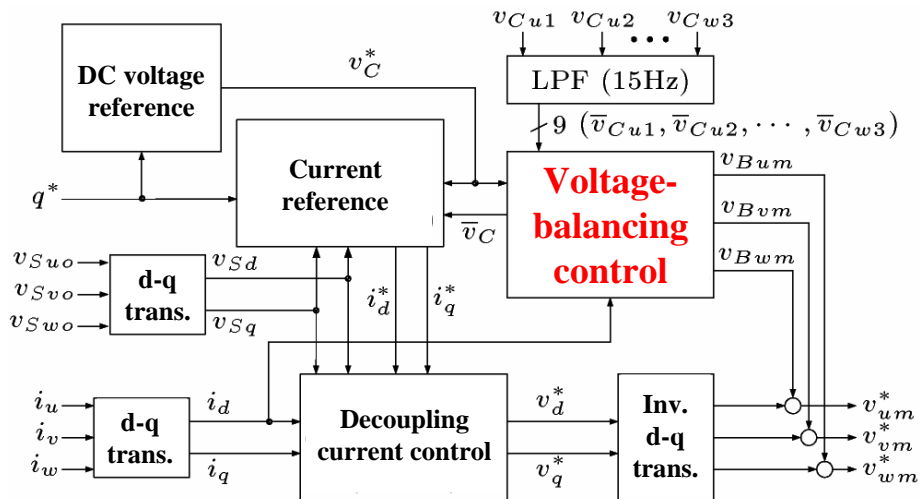
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Control of 200-V Down-Scaled Model



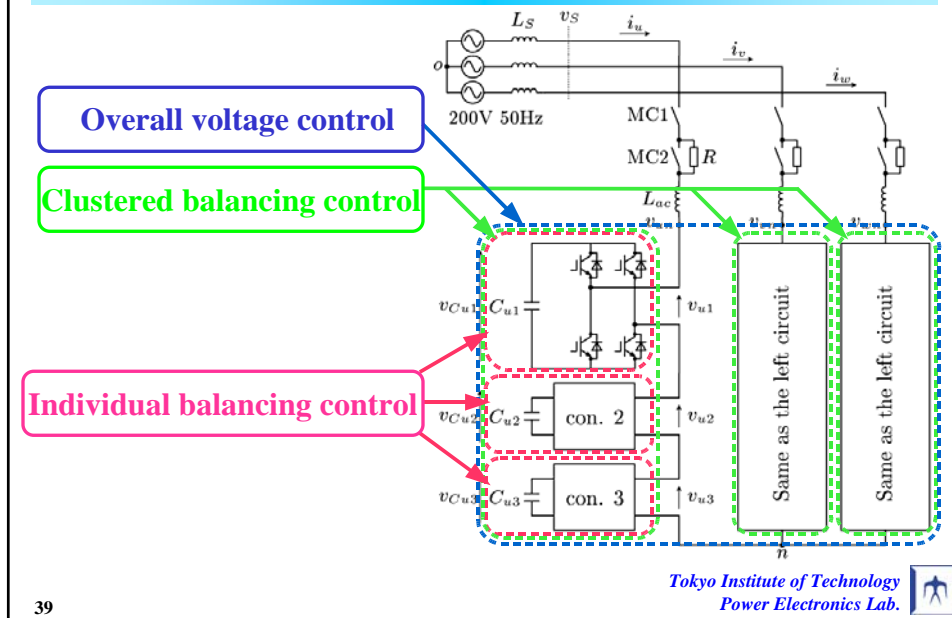
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Control Block Diagram



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DC-Capacitor Voltage Control



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Overall Voltage Control

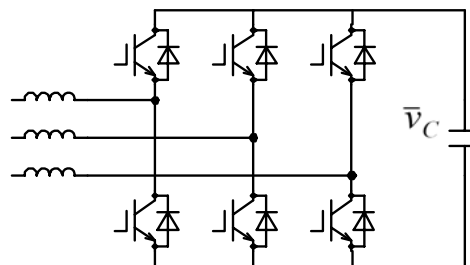
- **Control of the dc mean voltage of the nine capacitors**
- **Like a three-phase PWM converter**
- **d-q axis current control**

u-phase dc mean voltage

$$\bar{v}_{Cu} = \frac{1}{3} (\bar{v}_{Cu1} + \bar{v}_{Cu2} + \bar{v}_{Cu3})$$

Overall dc mean voltage

$$\bar{v}_C = \frac{1}{3} (\bar{v}_{Cu} + \bar{v}_{Cv} + \bar{v}_{Cw})$$

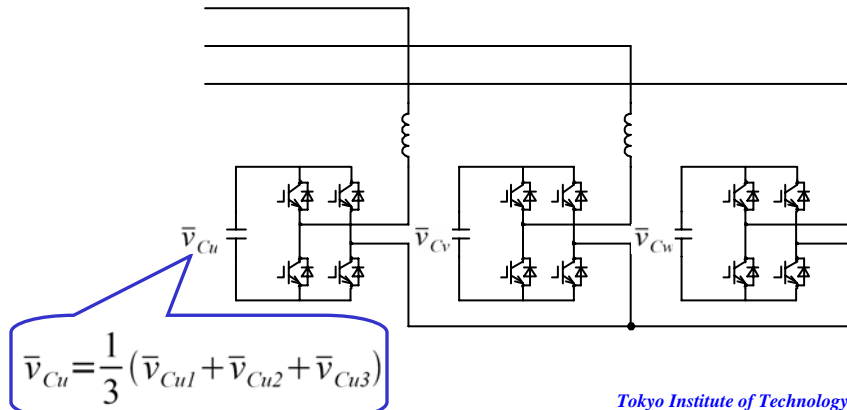


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Clustered Balancing Control

- Balancing of dc mean voltages between three clusters
- Like three single-phase converters
- d-axis voltage control, independent of three clusters



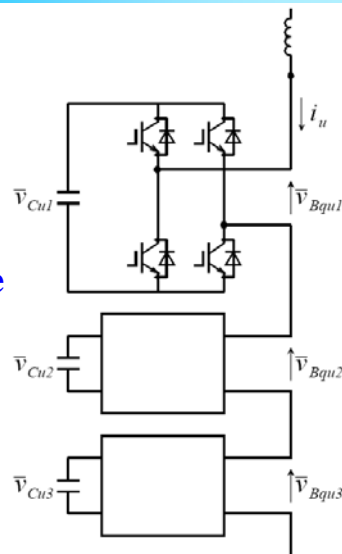
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Individual Balancing Control

- Balancing of three dc mean voltages in each cluster
- Like a single-phase cascaded PWM converter
- q-axis voltage control, independent of three clusters

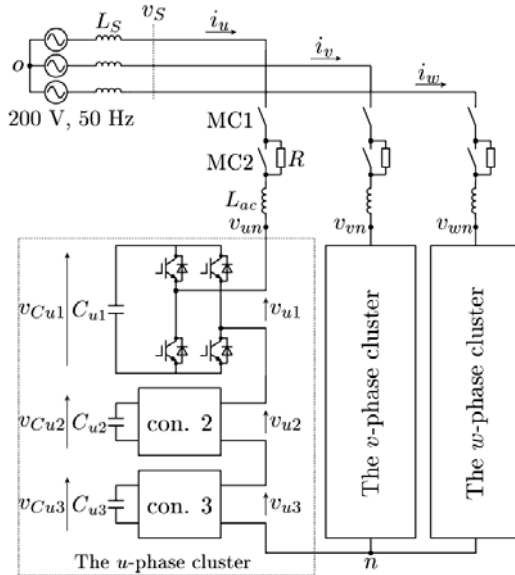
**No Interference with
Clustered Balancing Control**



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200-V 30-A 10-kVA Down-Scaled Model



Cascade Number $N = 3$

7-level in line-to-neutral

13-level in line-to-line

Phase-Shifted Sine 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)

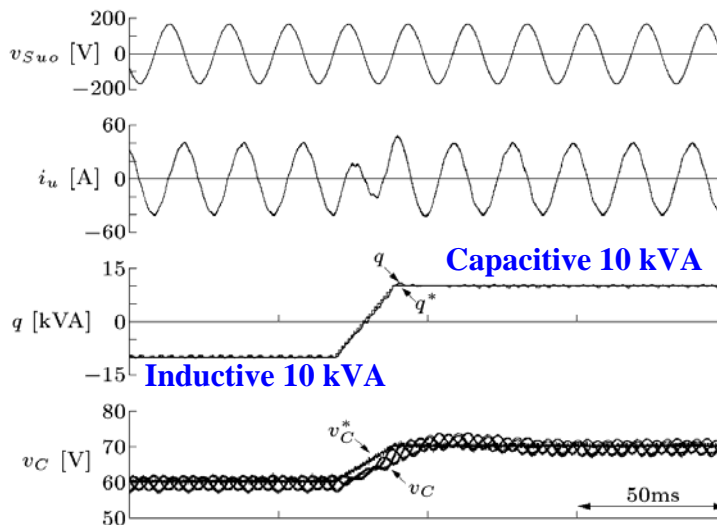
$C = 16.4$ mF

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From Inductive To Capacitive Operation



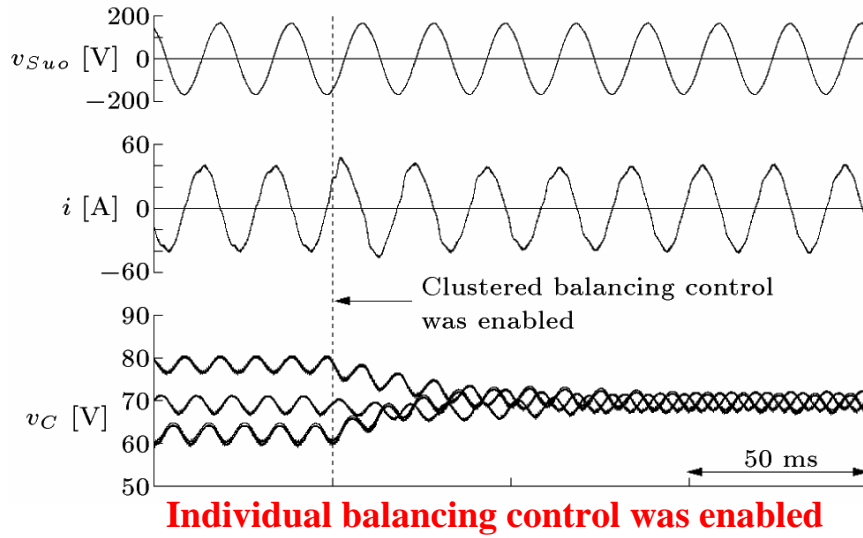
DC Voltage Control between 60 and 70 V

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Effect of Clustered Balancing Control



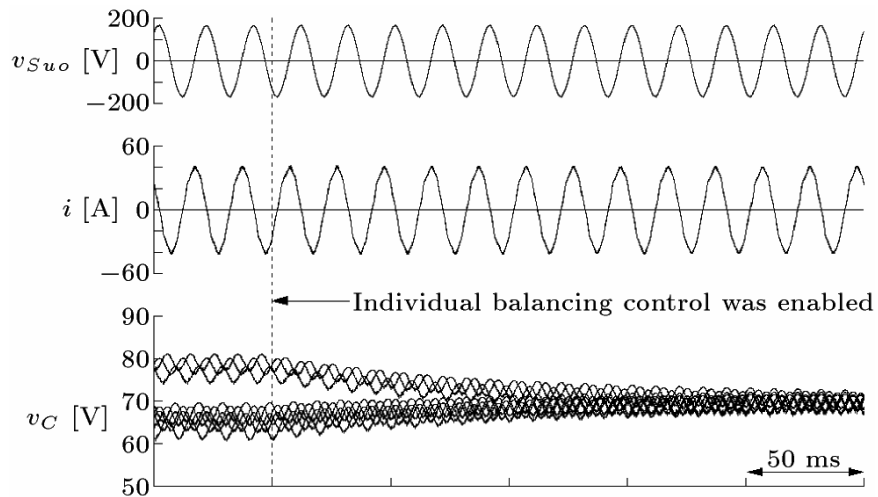
Individual balancing control was enabled

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Effect of Individual Balancing Control



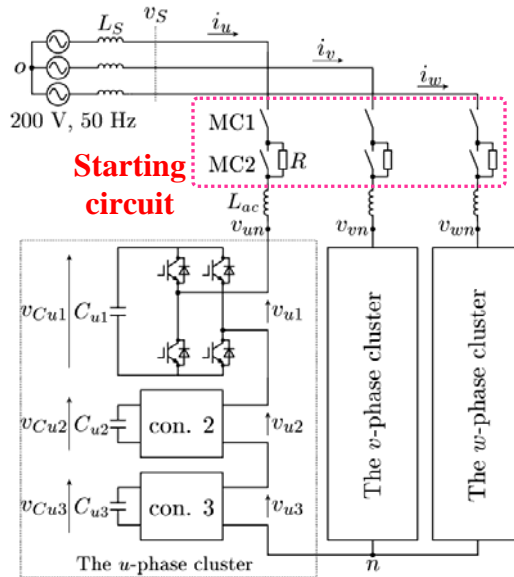
Clustered balancing control was enabled

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Start-up Procedure

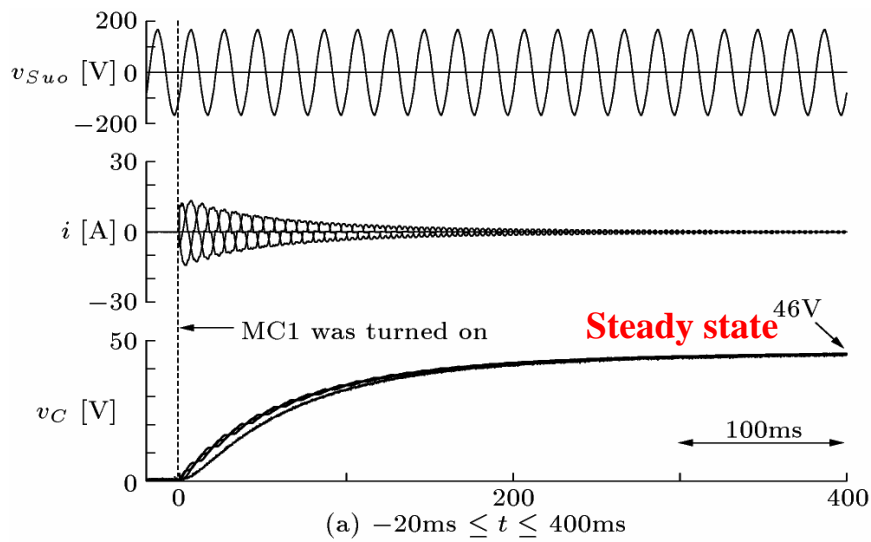


Starting circuit

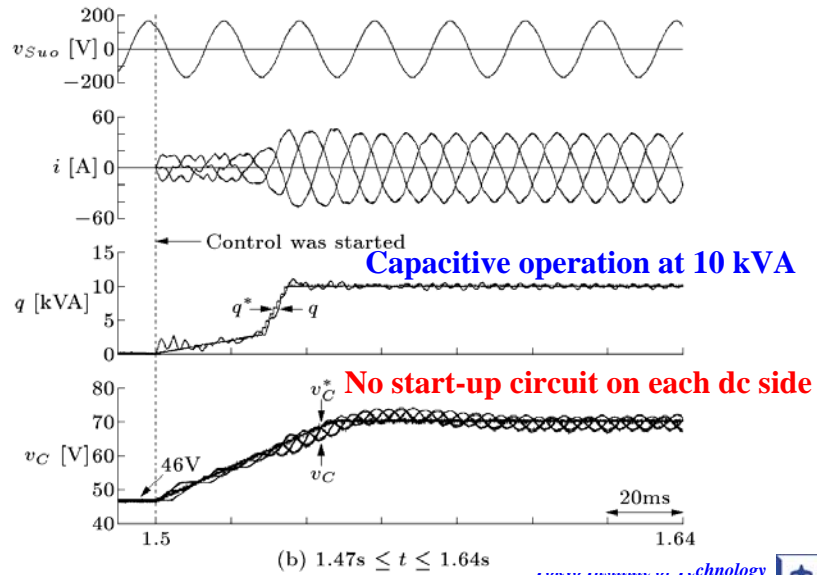
1. MC1 was turned on
2. Charged up via resistor
3. MC2 was turned on
4. Switching was started

No start-up circuit on each dc side

Experimental Waveforms During Starting



Experimental Waveforms During Starting

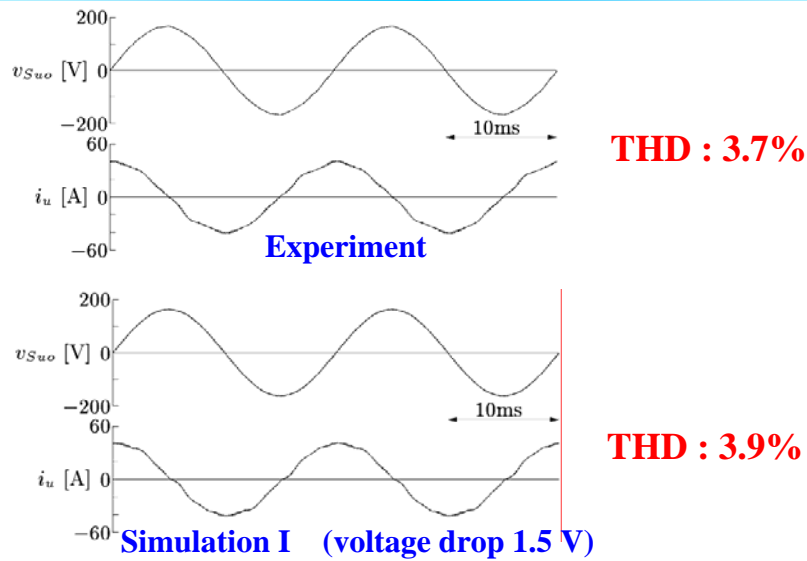


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Capacitive Operation at 10 kVA



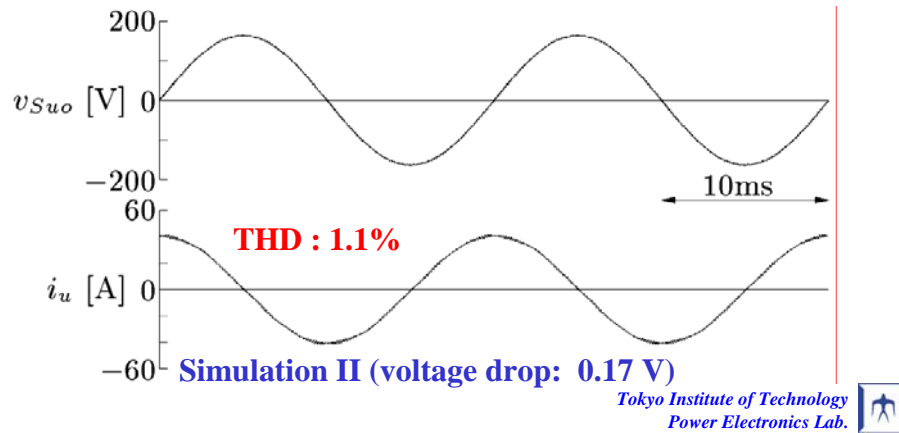
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Capacitive Operation at 10 kVA

- Ⓢ DC Voltage of the 6.6-kV System : 1 kV
- Ⓢ Voltage Drop in 1.7-kV IGBT/Diode : 2.5 V (0.25%)
- Ⓢ Equivalent to 0.17 V in a DC Voltage of 70 V



Conclusions

- 6.6-kV Transformerless Cascade STATCOM based on Phase-Shifted Sinusoidal PWM
- 200-V 10-kVA Down-Scaled Laboratory Model with Star-Configuration
- Experimental Verification of Voltage Balancing
Combination of Clustered Balancing Control with Individual Balancing Control

Easy Expansion into Higher Voltage Levels

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