茨城大学
Ibaraki University

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Three-Phase Interleaved LLC Converter with Capacitive Current Balancing and Reduced Switch Voltage Stress

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Highlights

- Automatic current balancing despite component tolerance
- Reduced RMS currents by asymmetric resonant operations
- 96.8% full-load efficiency at 1 kW

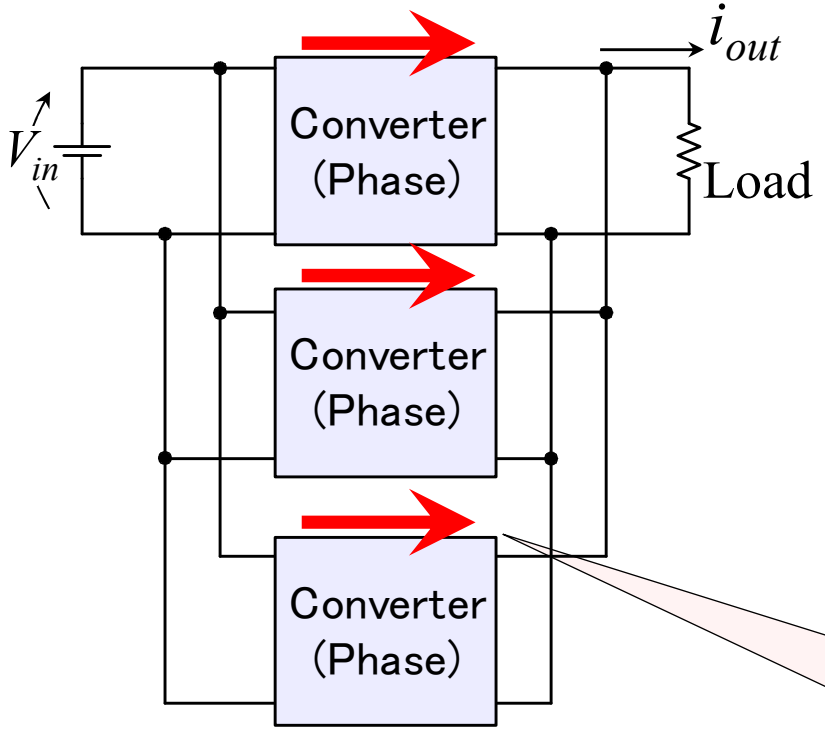
Outline

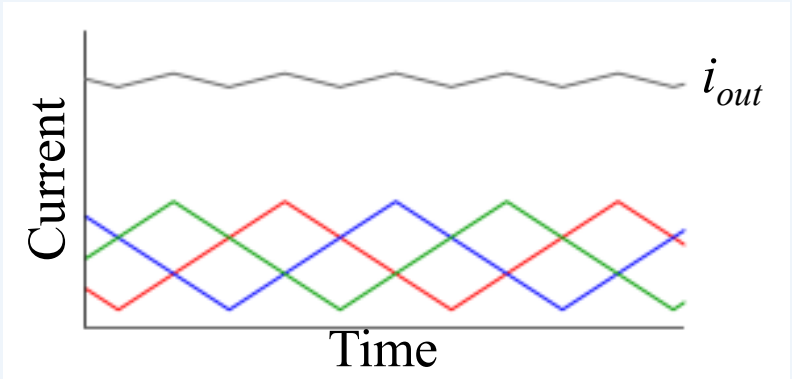
- **Background**
  - Interleaved PWM converter
  - Conventional interleaved LLC converter
- **Proposed three-phase interleaved LLC converter**
  - Asymmetric resonant operation
  - Automatic current balancing mechanism
  - Operation modes and reduced switch voltage stress
- **Experimental verification**
  - Current balancing
  - Switch voltage stress
  - Power conversion efficiency
- **Conclusions**

1-kW Prototype

Background

Interleaved Converter



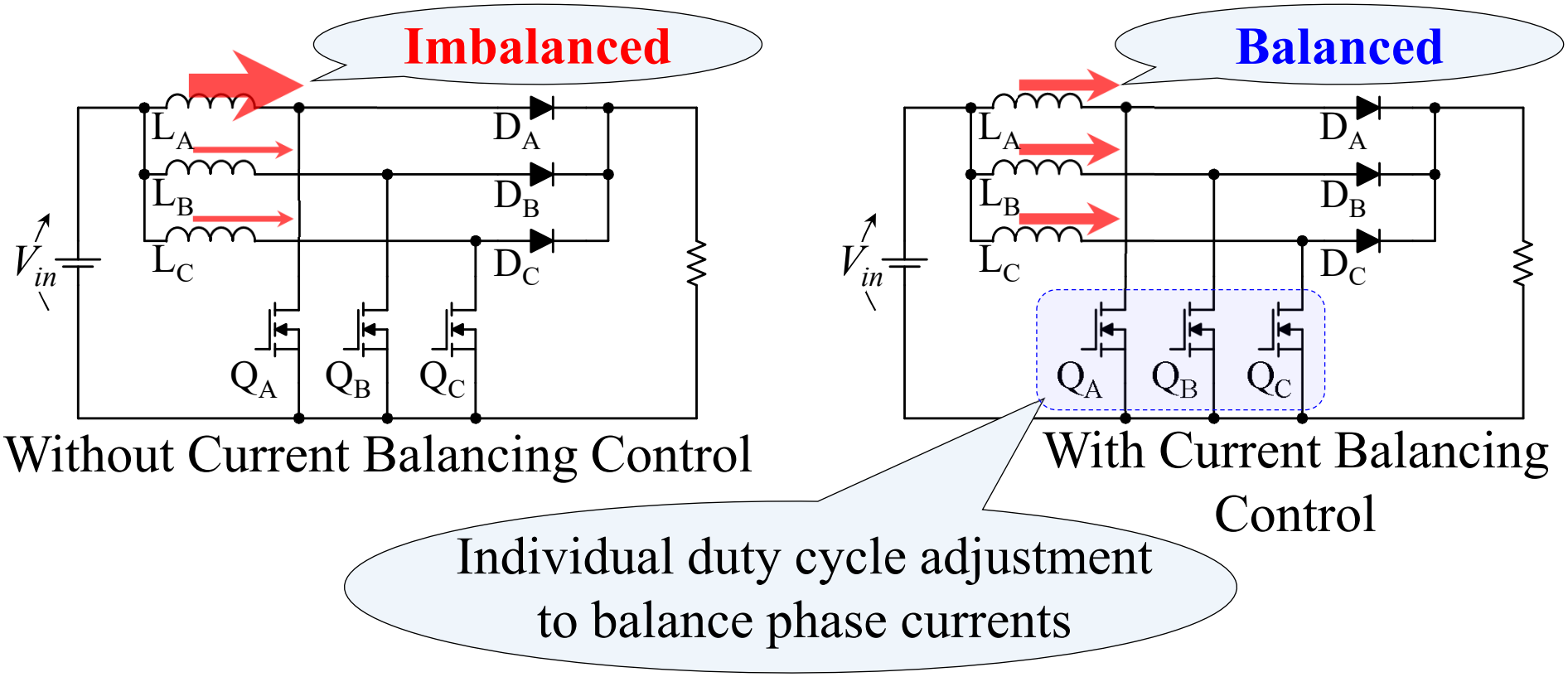


- Reduced current stress
- Reduced current ripple of input or output port

Current concentration
due to component tolerance

Required current balancing to avoid current concentration

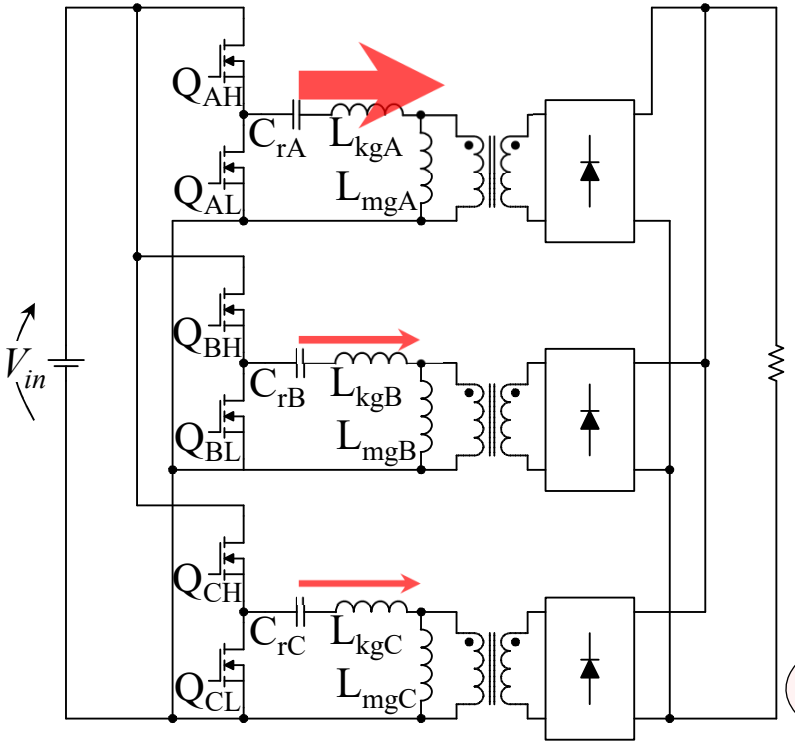
Interleaved PWM Converter



Additional feedback control loops and current sensors required

H.C. Chen, C.Y. Lu, and U.S. Rout, *IEEE Trans. Power Electron.*, vol. 33, no. 5, May 2018, pp. 3683–3687.

Interleaved LLC Converter



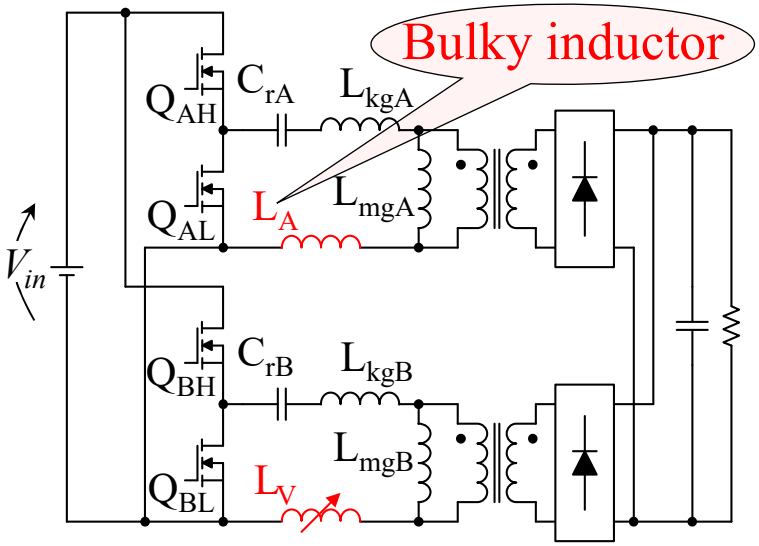
LLC converter

- Galvanic isolation
- Low EMI
- High efficiency
- Frequency-dependent gain characteristics

Individual switching frequency adjustment to balance phase current

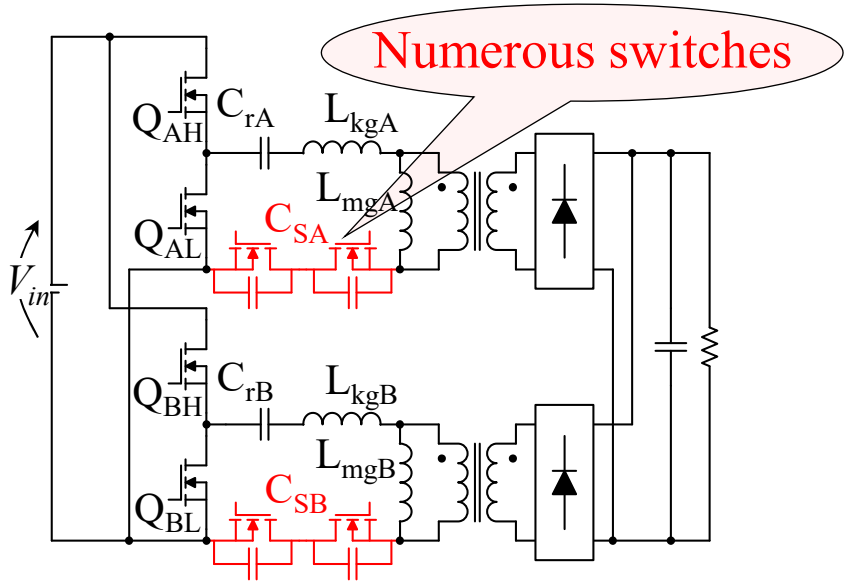
Cannot simply apply interleaving operation to LLC converter

With Current Balancing Control



With Variable Inductor†

Current imbalance under light load condition



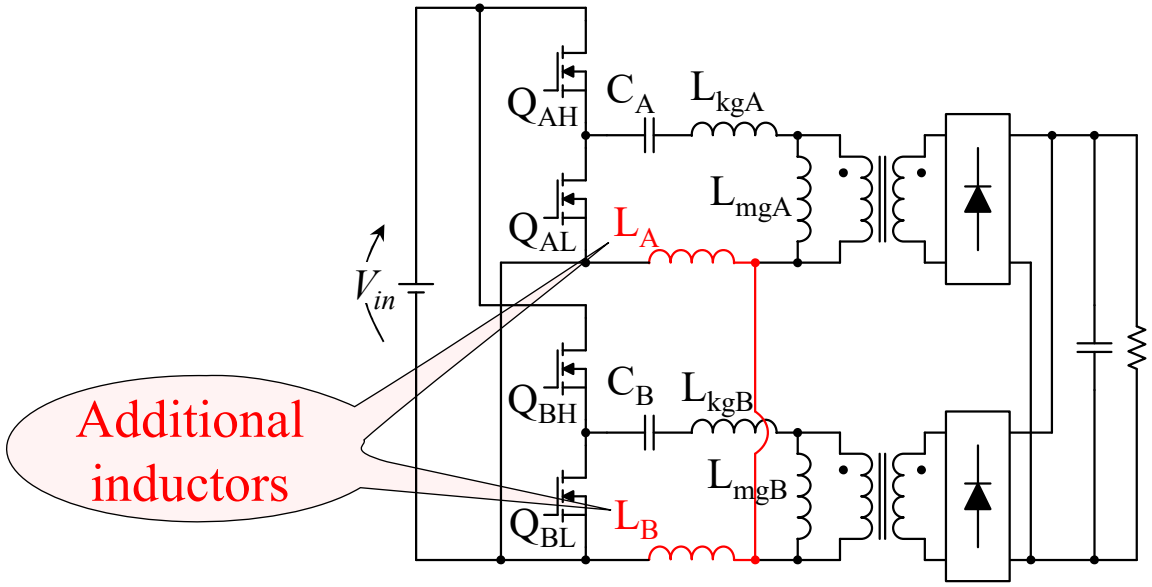
With Switch-Controlled Capacitor††

Current concentration caused by capacitance mismatch (e.g., 5%)

Current balancing control required

E. Orietti *et al*, in *Proc. Brazilian Power Electron. Conf.*, 2009, pp. 298–304, Oct. 2009. †
Z. Hu, *et al*., *IEEE Trans. Power Electron*., vol. 29, no. 6, pp. 2931–2943, Jun. 2014. ††

With Inductive Current Balancing

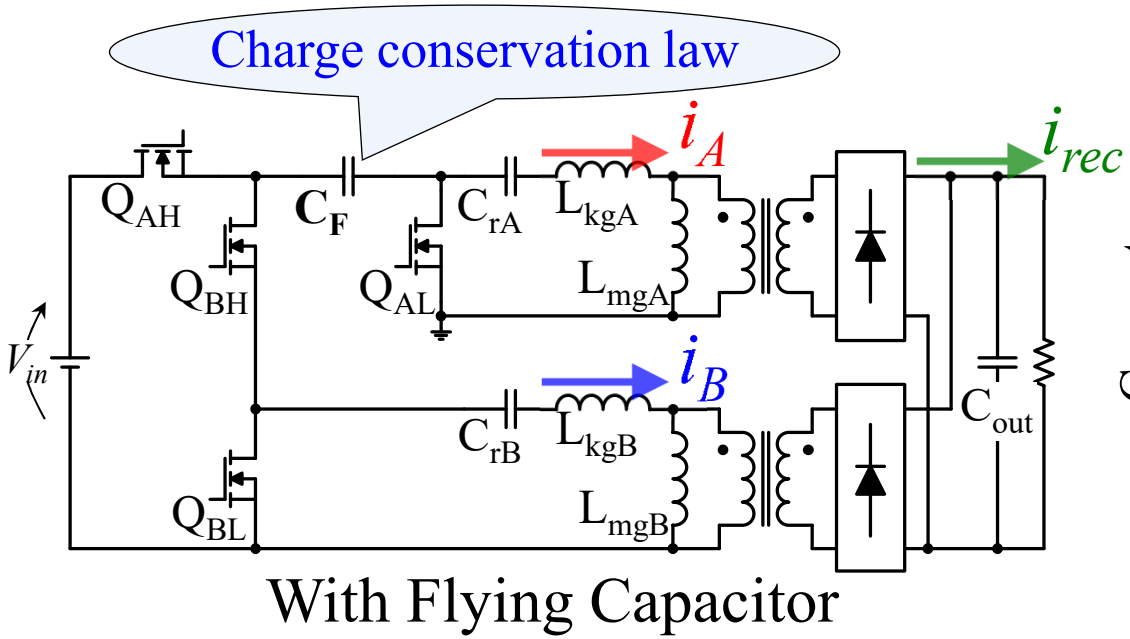


With Common Inductor

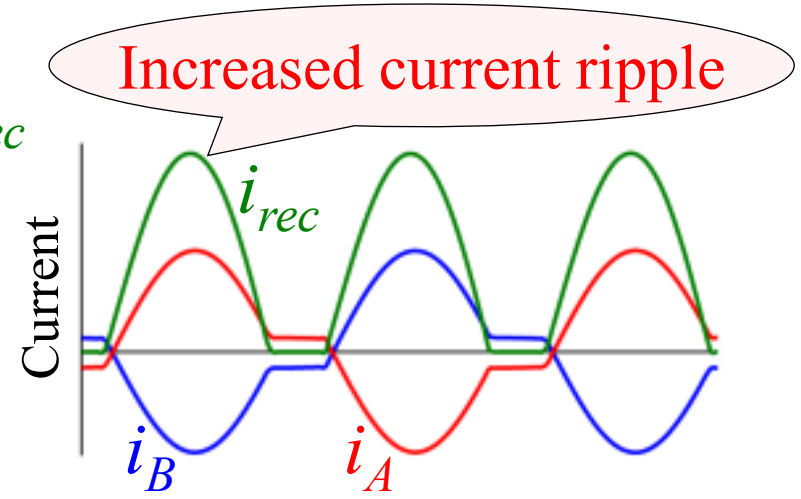
- Automatic current balancing
- Current imbalance under light load conditions

H. Wang *et al*., *IEEE Trans*. *Power Electron*., vol. 32, no. 9, pp. 6694–7009, Sep. 2017.

With Capacitive Current Balancing



With Flying Capacitor



Designed for only two phase topology

O. Kirshenboim and M.M. Peretz, *IEEE Trans. Power Electron.* vol. 33, no. 7, pp. 5613–5620, Jul. 2018.

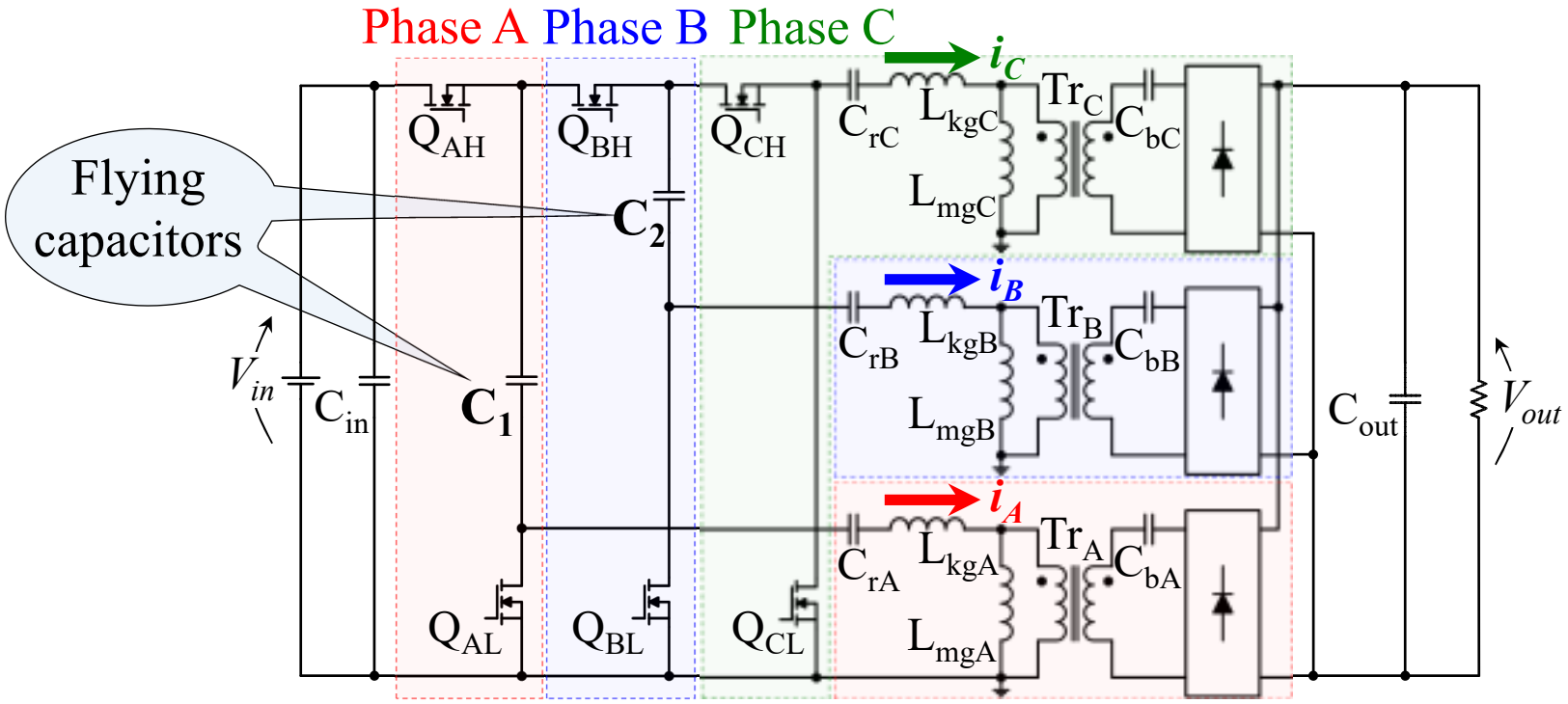
Research Objectives

Proposed interleaved LLC converter

- Automatic current balancing
- Reduced current ripple
- High extendibility
- Soft switching characteristics

Proposed 3-Phase Interleaved LLC Converter

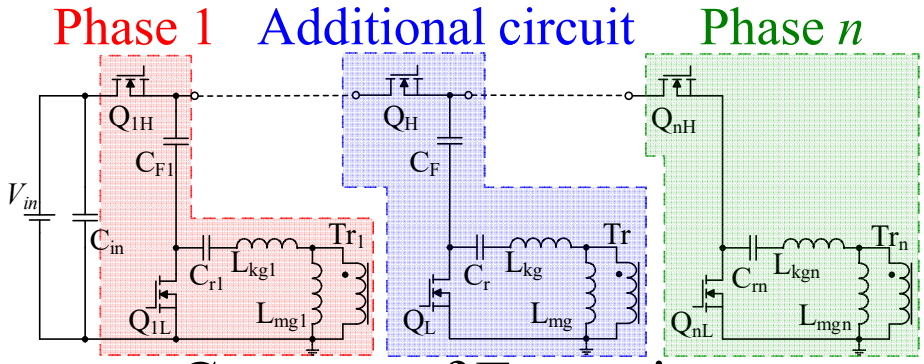
Proposed 3-Phase Interleaved LLC Converter



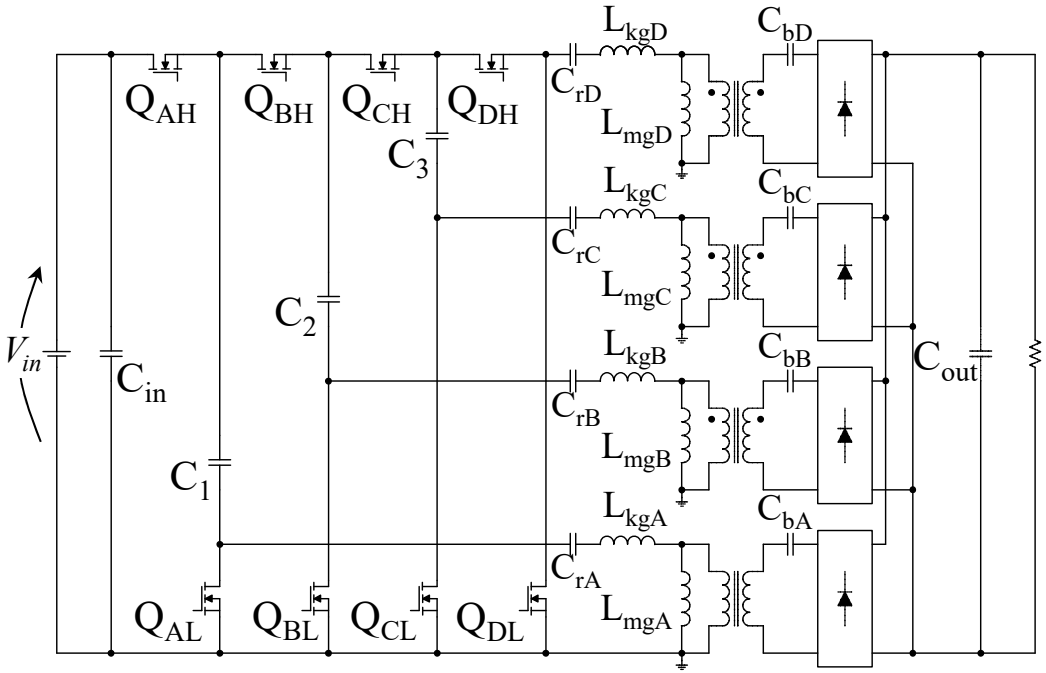
- $d = 0.33$ for high-side switches
- 120º out of phase
- PFM control

- Automatic current balancing
- Reduced switch voltage stress
- Asymmetric resonant operation
- High extendibility

Extension for Multiple Phases



Concept of Extension

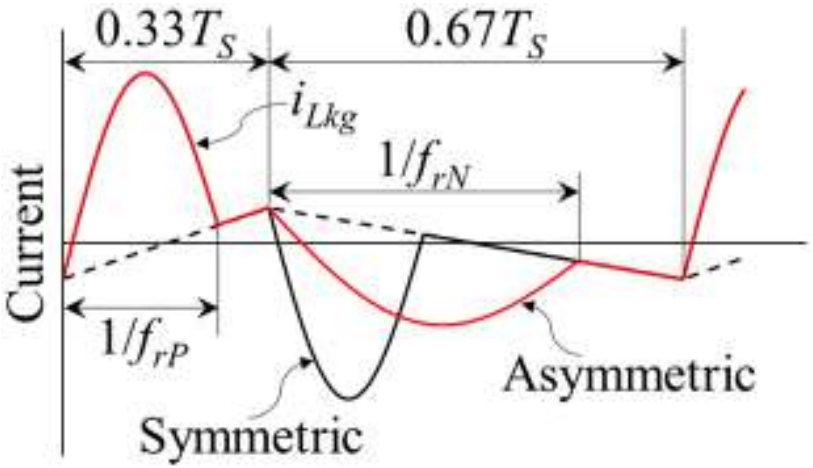


Four-phase interleaved LLC converter

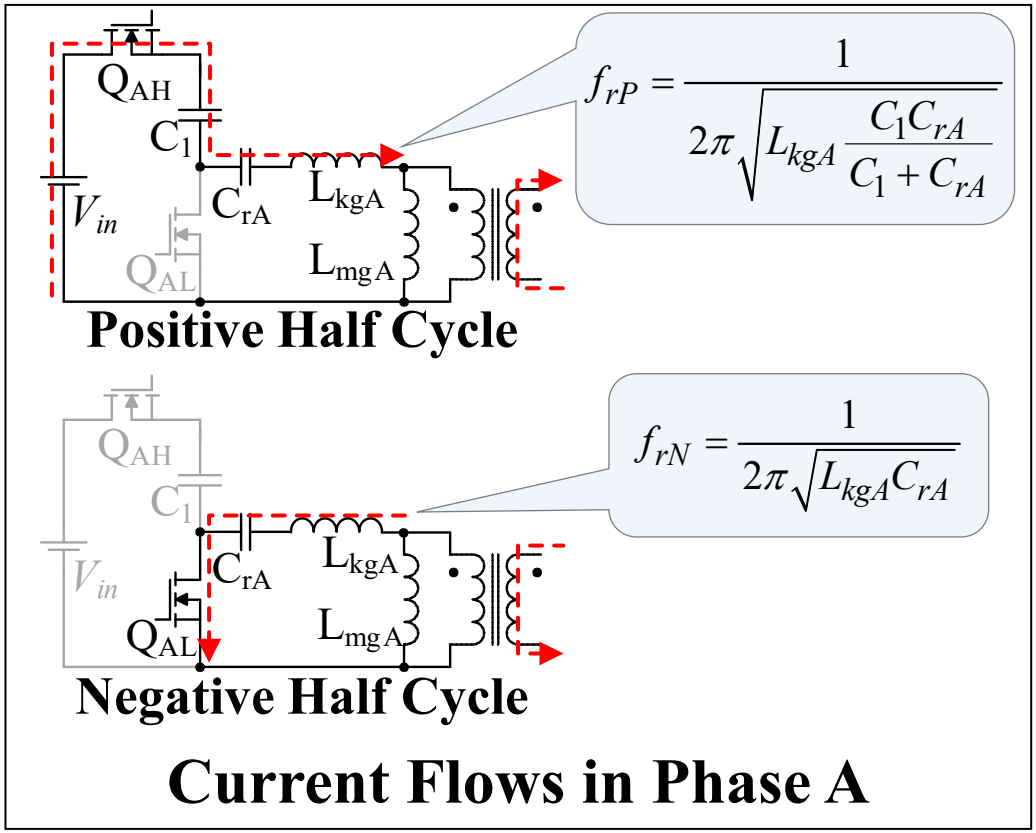
The number of phases can be arbitrarily changed

Operation Principle

Asymmetric Resonant Operation

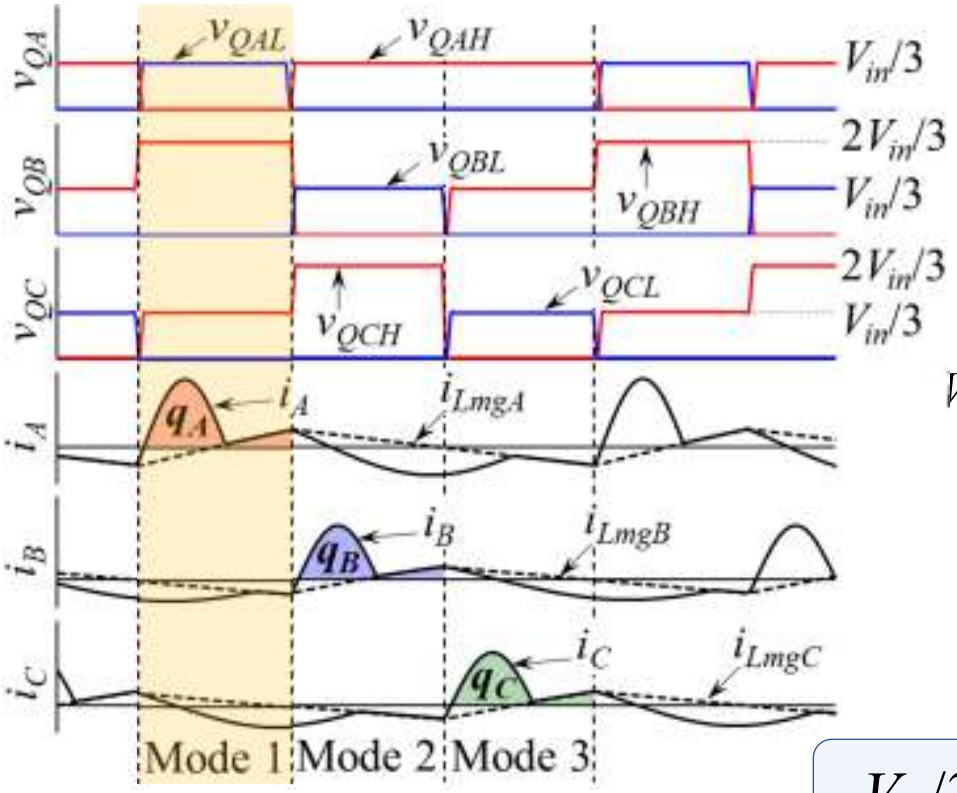


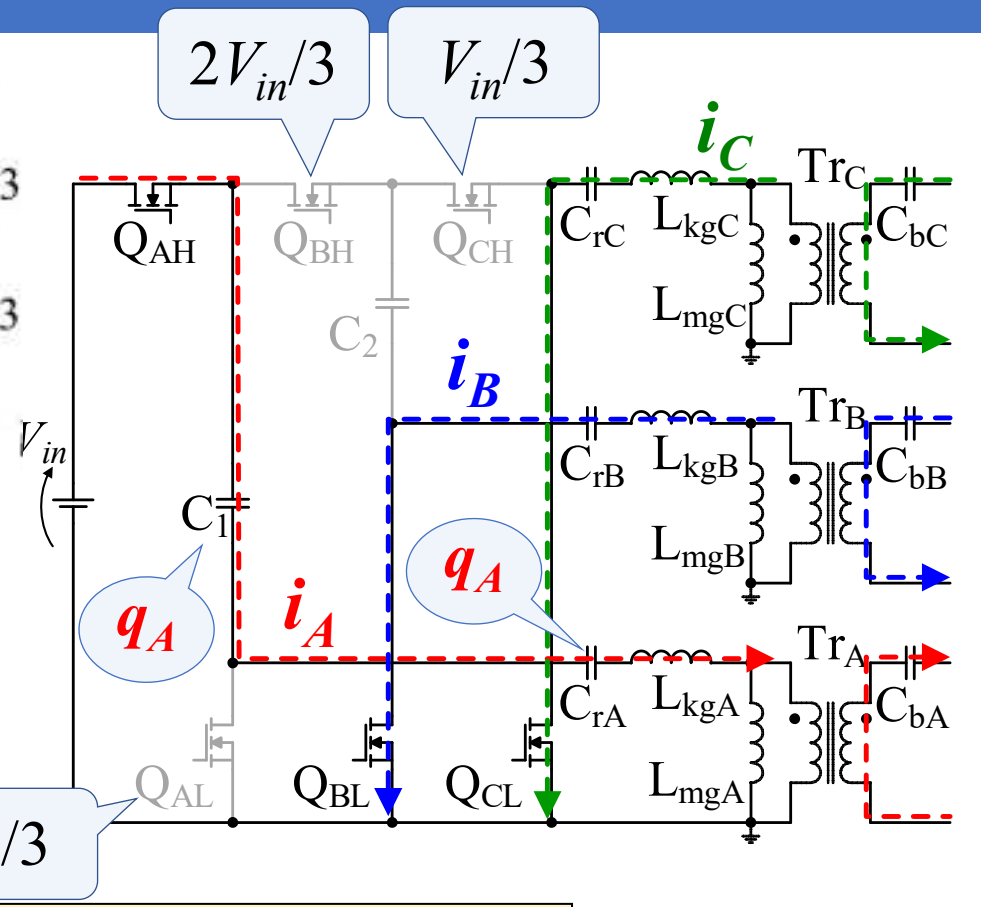
Current Waveforms



Reduced RMS currents thanks to asymmetric resonant operation

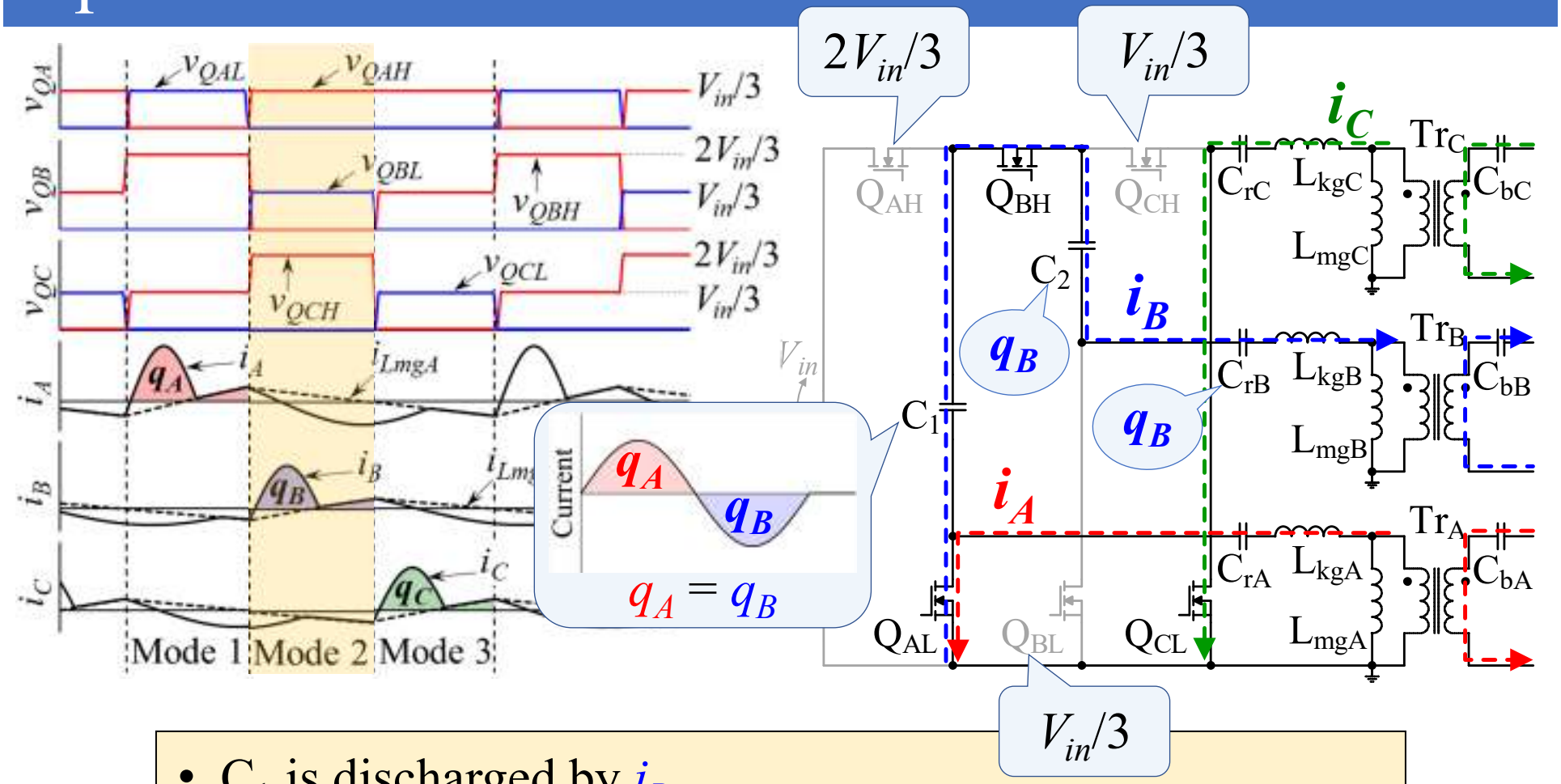
Operation: Mode 1





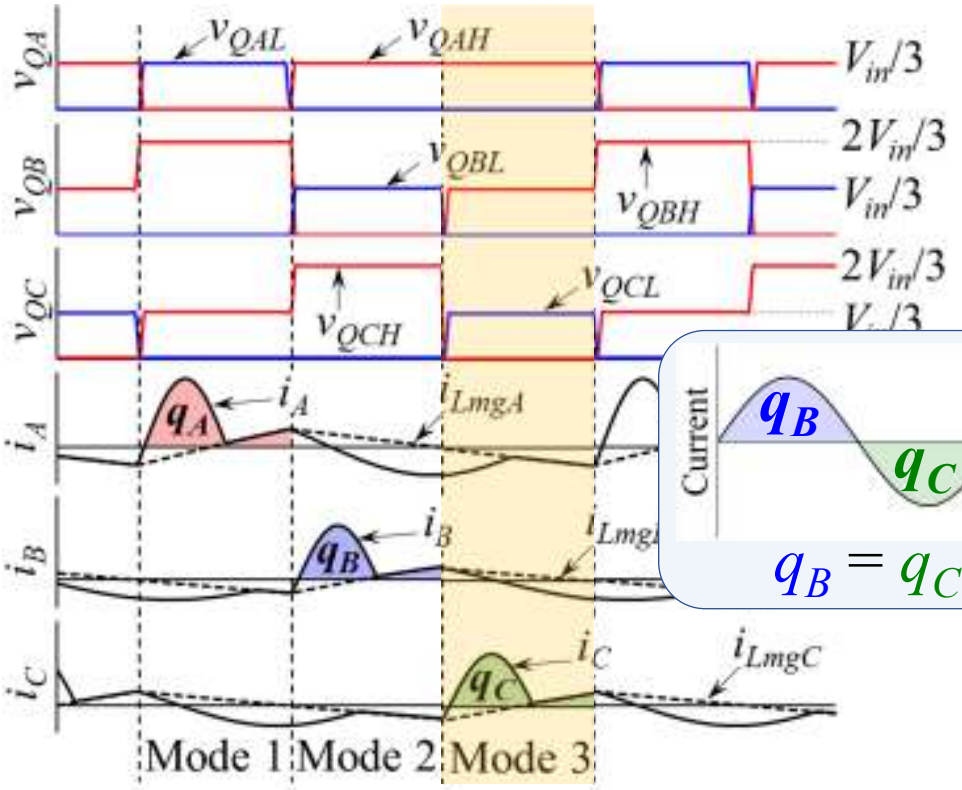
- C_1 takes part in resonance in Phase A
- i_A charges C_1

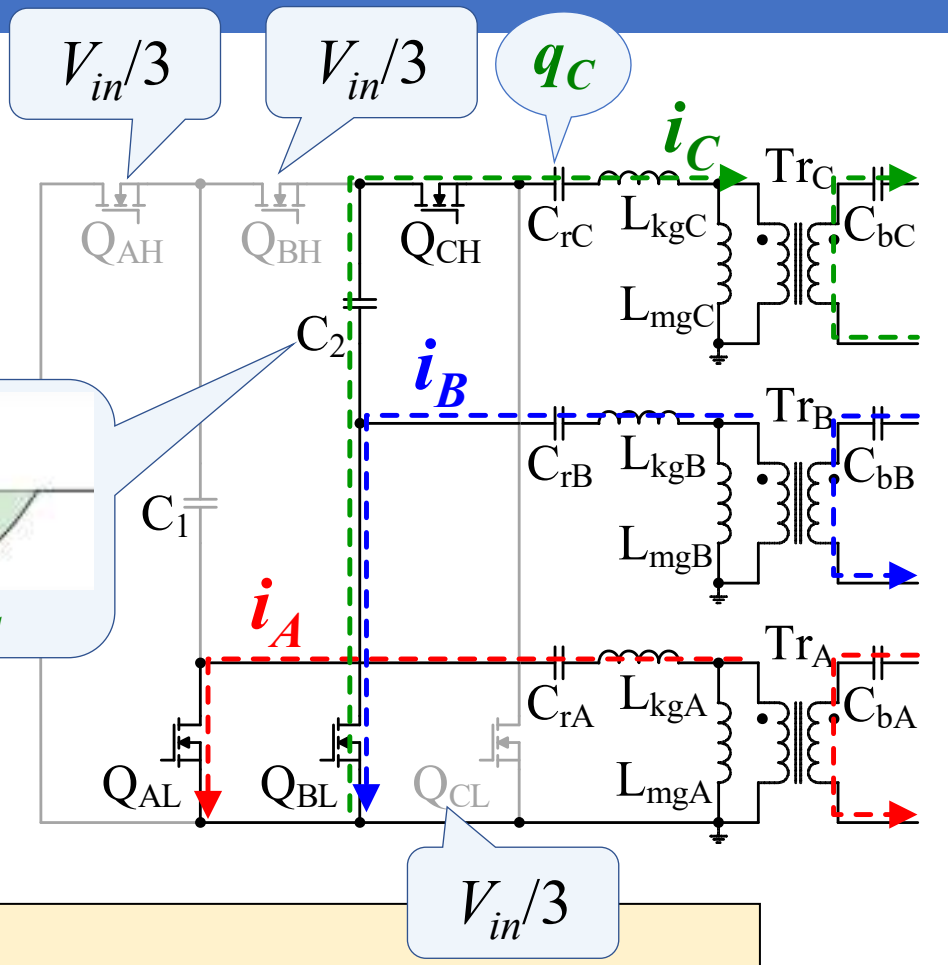
Operation: Mode 2



- C_1 is discharged by i_B
- Balanced i_A and i_B due to charge conservation of C_1
- C_1 and C_2 take part in resonance in Phase B

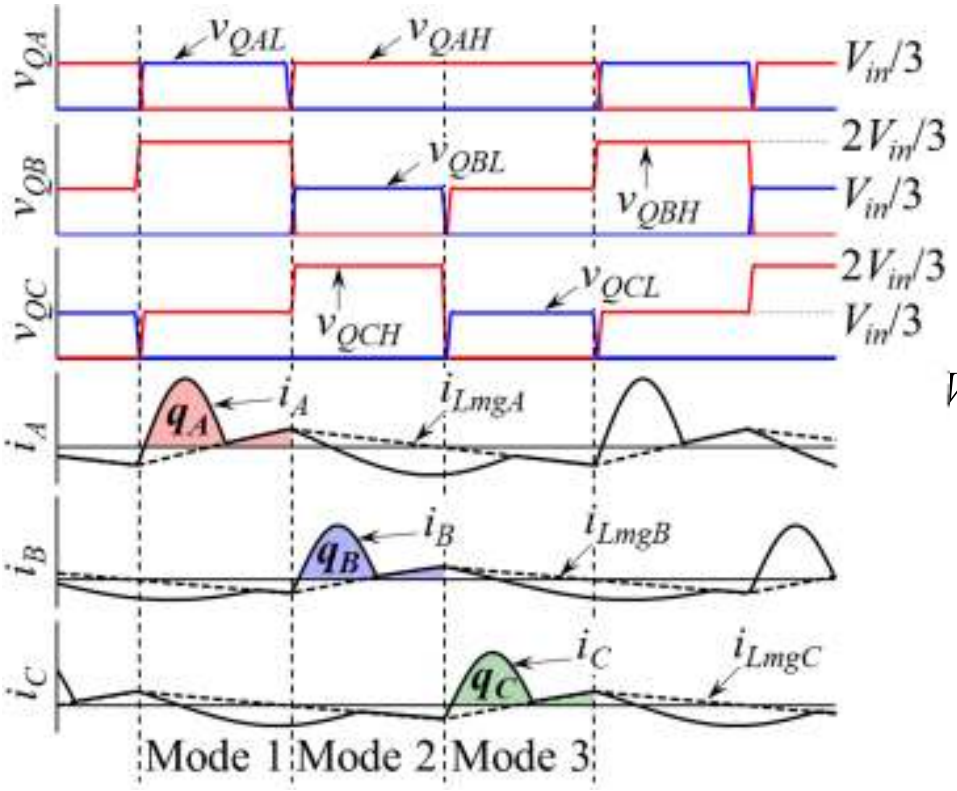
Operation: Mode 3

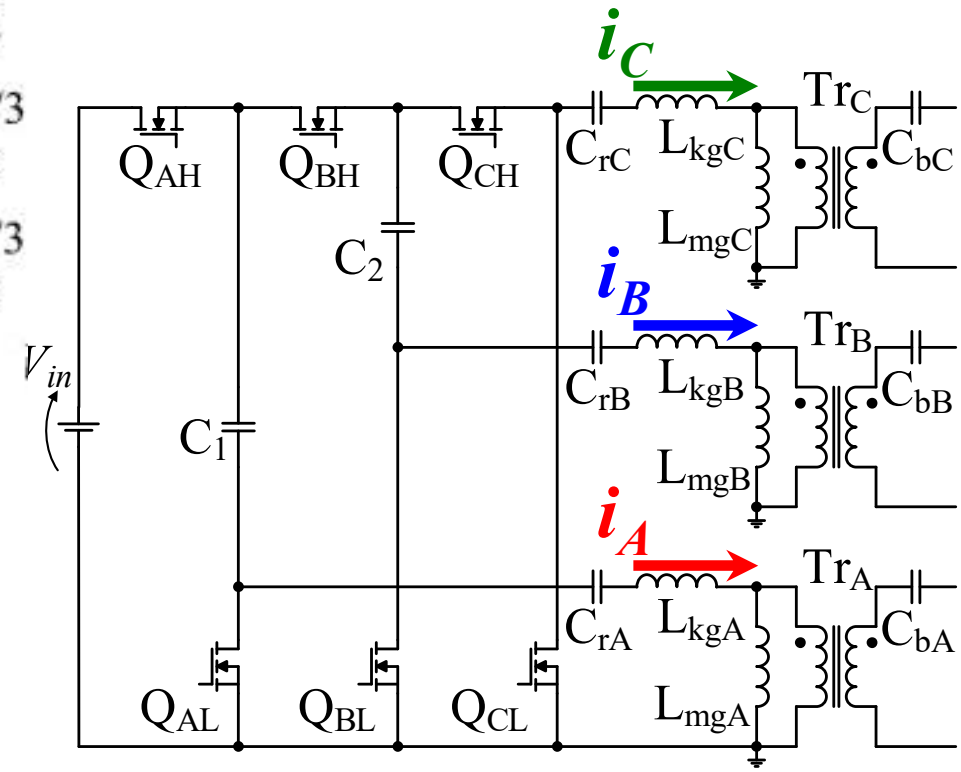




- C_2 is discharged by i_B
- Balanced i_B and i_C due to charge conservation of C_2
- C_2 takes part in resonance in Phase C

Operation: Summary

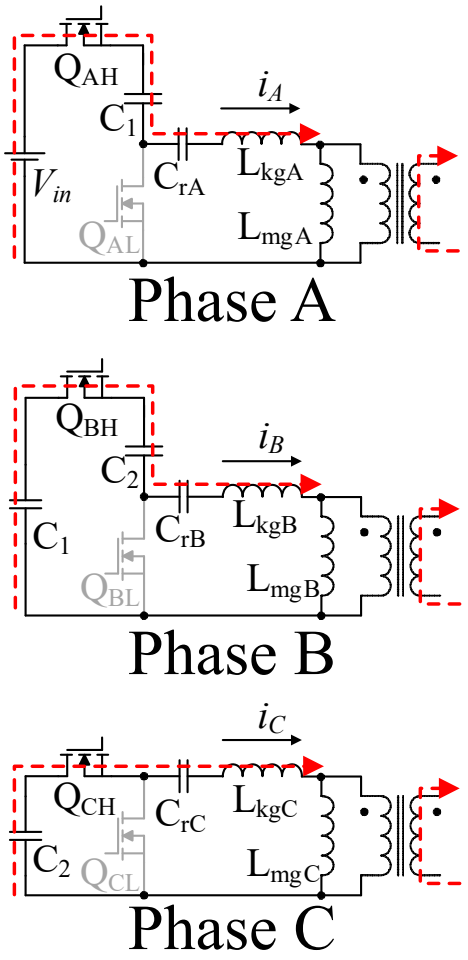




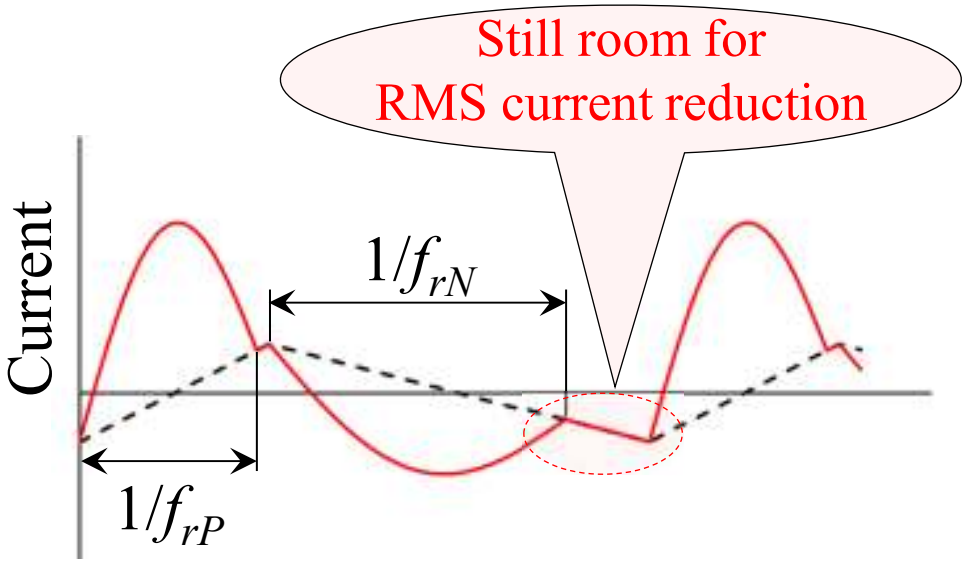
- Automatic current balancing: $i_A = i_B = i_C$
- C_1 and C_2 reduce switch voltage stress less than $2V_{in}/3$

Design Consideration

Designing Method of Flying Capacitors



Current Flows of Positive Half Resonance



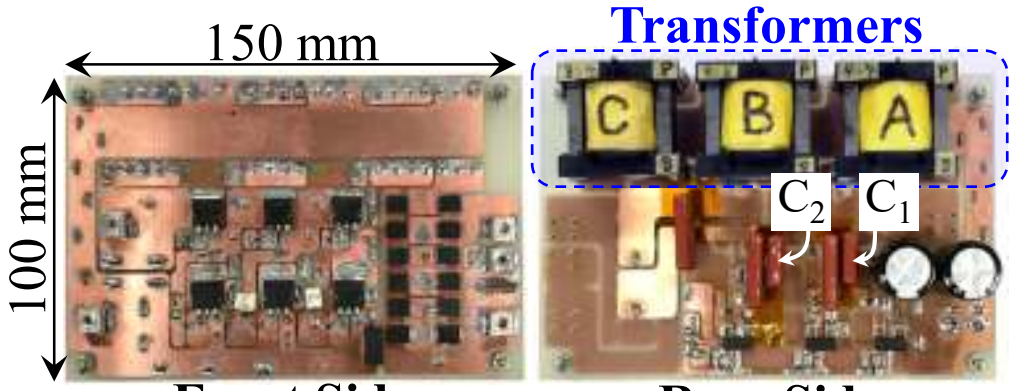
Current Waveforms

Optimum design of flying capacitor

$$f_{rP} : f_{rN} = 2 : 1$$

Experimental Verification

Prototype



1-kW Prototype

Parameters of transformers

	Value
Phase A	$N_1 : N_2 = 9 : 7$ $L_{kg} = 2.98$ μH, $L_{mg} = 60.7$ μH
Phase B	$N_1 : N_2 = 9 : 6$ $L_{kg} = 3.51$ μH $L_{mg} = 61.2$ μH
Phase C	$N_1 : N_2 = 8 : 7$ $L_{kg} = 3.49$ μH $L_{mg} = 49.3$ μH

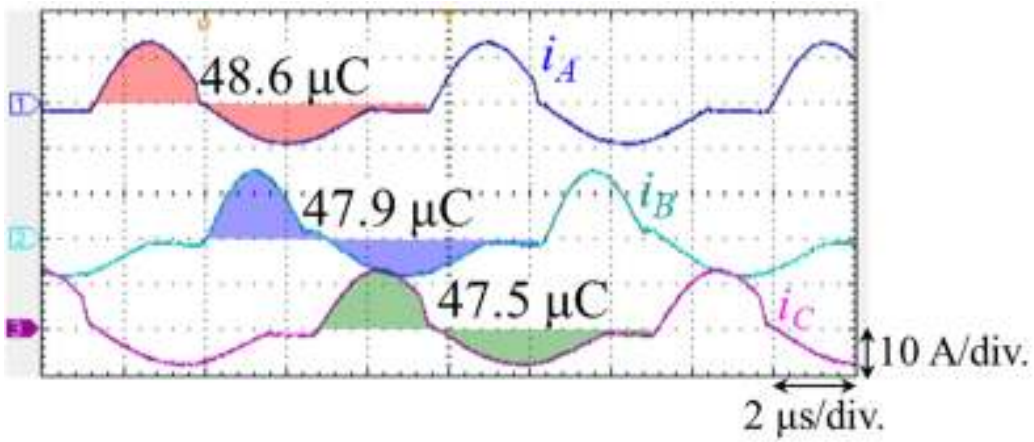
Experimental conditions

- Input voltage $V_{in} = 400$ V
- Output voltage $V_{out} = 48$ V

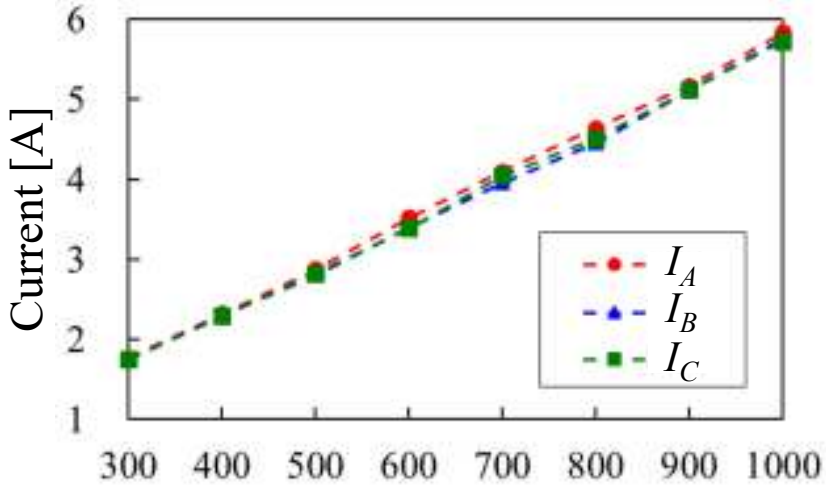
Experiments were performed with

- Asymmetric resonant operation
- Symmetric resonant operation

Automatic Current Balancing



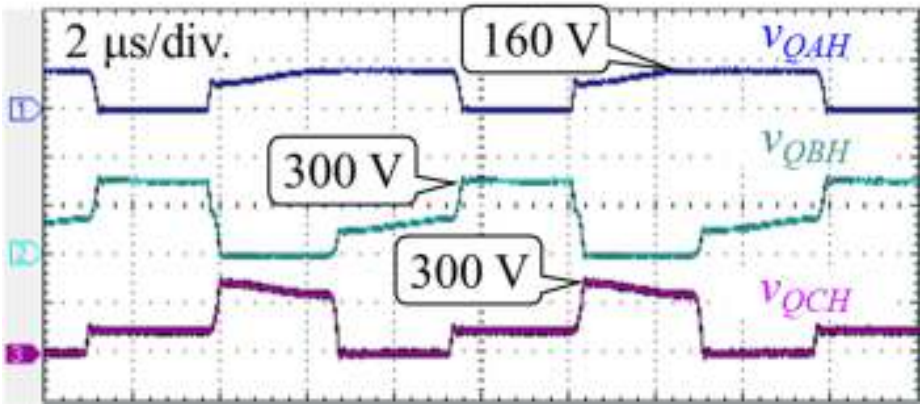
Current Waveforms of
Primary Phase Currents at 1 kW



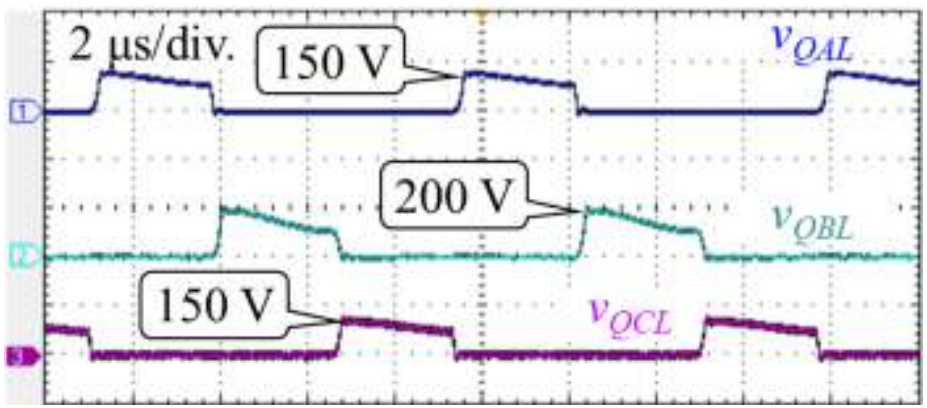
Average Absolute Value of
Primary Phase Currents

- Automatic current balancing despite severe mismatch in the transformers' parameter
- Reduced peak currents thanks to asymmetric resonance
- Current errors less than 2% over the entire power range

Switch Voltage Stress



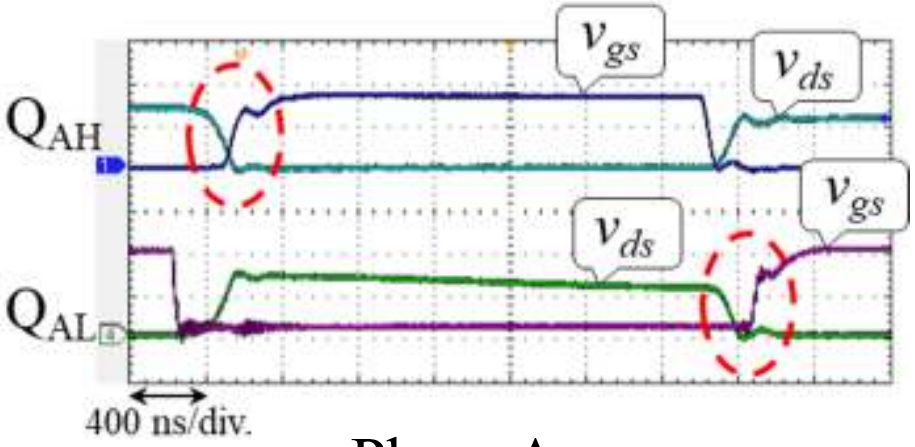
High-side Switch Voltage (200 V/div.)



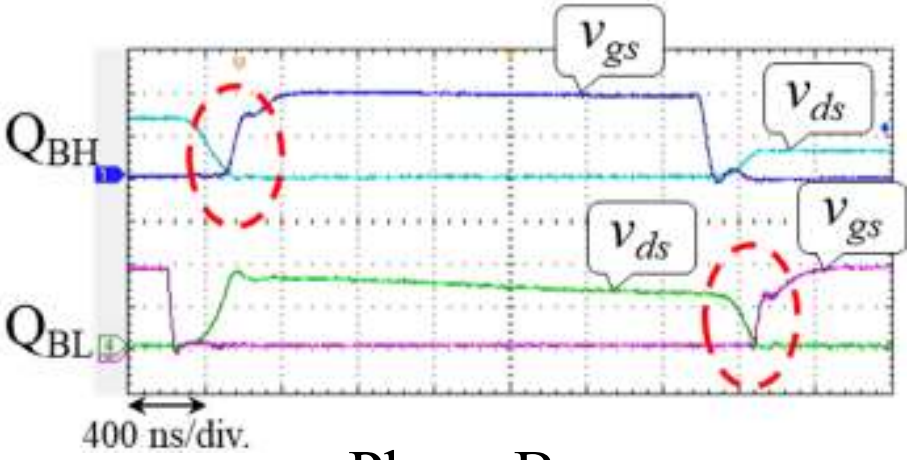
Low-side Switch Voltage (200 V/div.)

Suppressed to approximately less than $2V_{in}/3$

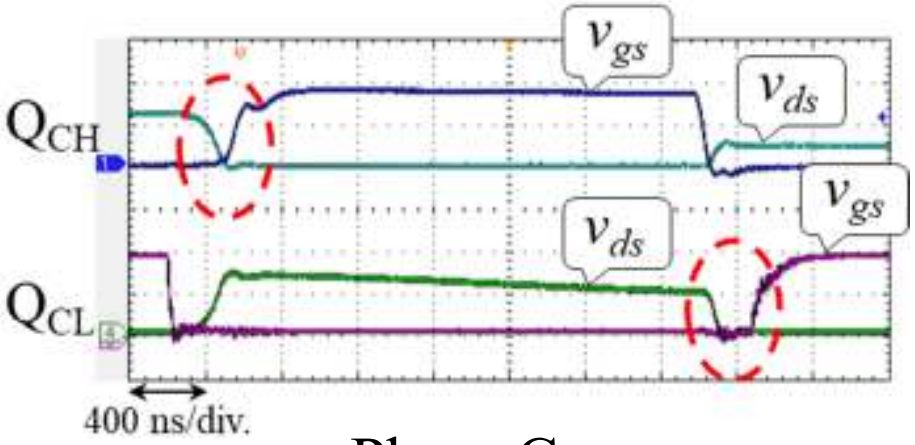
ZVS Waveforms



Phase A



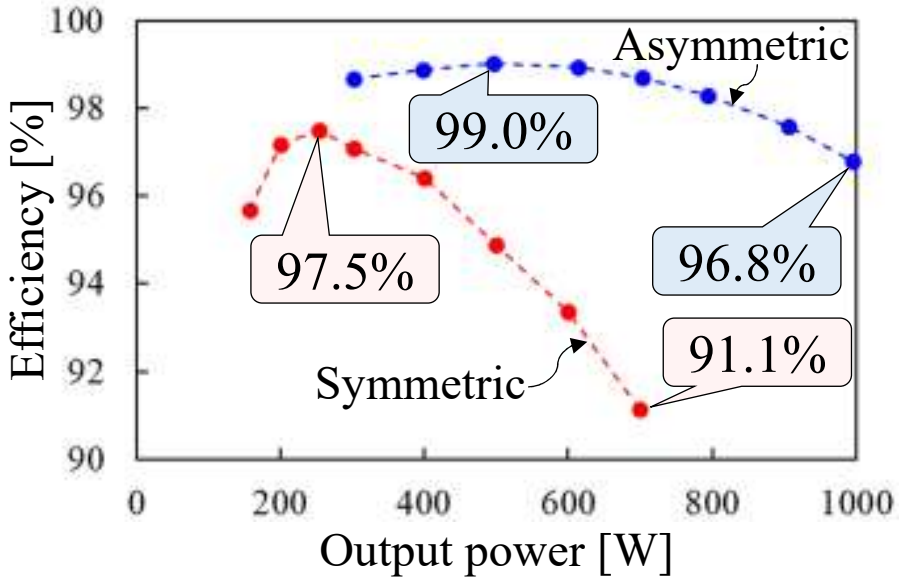
Phase B



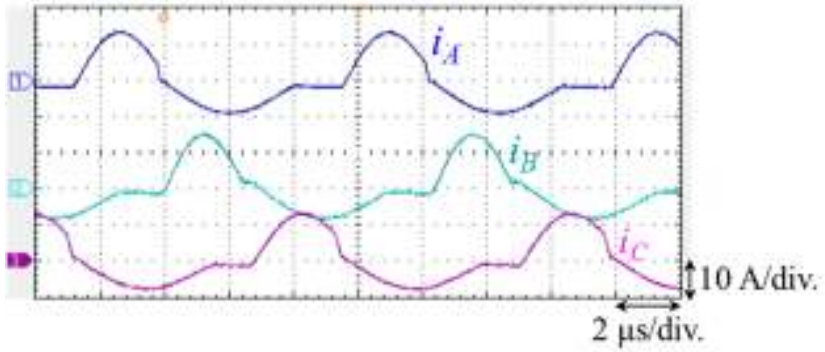
Phase C

Verified ZVS operation for all switches

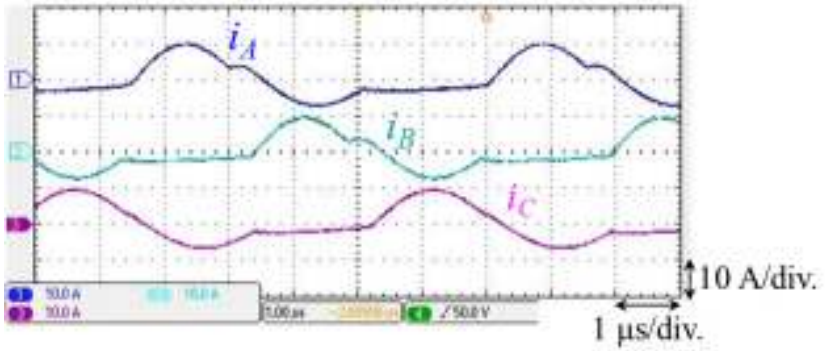
Power Conversion Efficiency



Power Conversion Efficiencies



Asymmetric Resonance (1 kW)



Symmetric Resonance (700 W)

Primary Phase Current Waveforms

Improved efficiency compared with those of symmetric

Conclusions

- 3-Phase interleaved LLC converter has been proposed
- The proposed converter adopts asymmetric resonant operation using flying capacitors to reduce RMS currents
- Experimental results demonstrated the automatic current balancing despite mismatched transformer parameters
- Switch voltage stresses were reduced to less than around $2V_{in}/3$
- Power conversion efficiency was improved thanks to asymmetric resonance