Low Power Characteristics of Three-Phase Isolated Secondary-Resonant Single-Active-Bridge DC-DC Converter Using a Y-Δ Connected Transformer

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Workshop[1]

Research Background and Purpose

Background

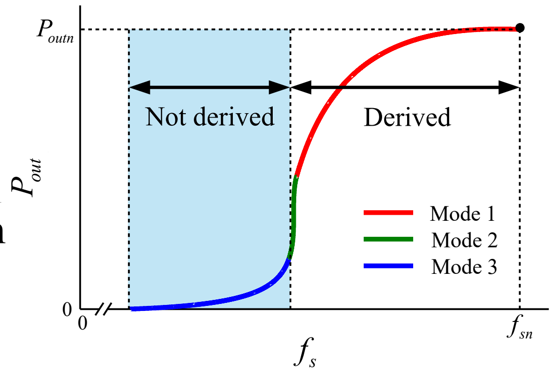
Environmental issues : Achieving carbon neutrality
→Quick chargers for EVs and DC power distribution system

Three-Phase Isolated Secondary-Resonant Single-Active-Bridge DC-DC Converter Using a Y-Δ Connected Transformer

・compact ・high-efficiency ・high-power

Derived { Mode 1 : representing the range around the rated power; Mode 2 : output power rapidly changes }

Not derived { Mode 3 : representing low power operation }



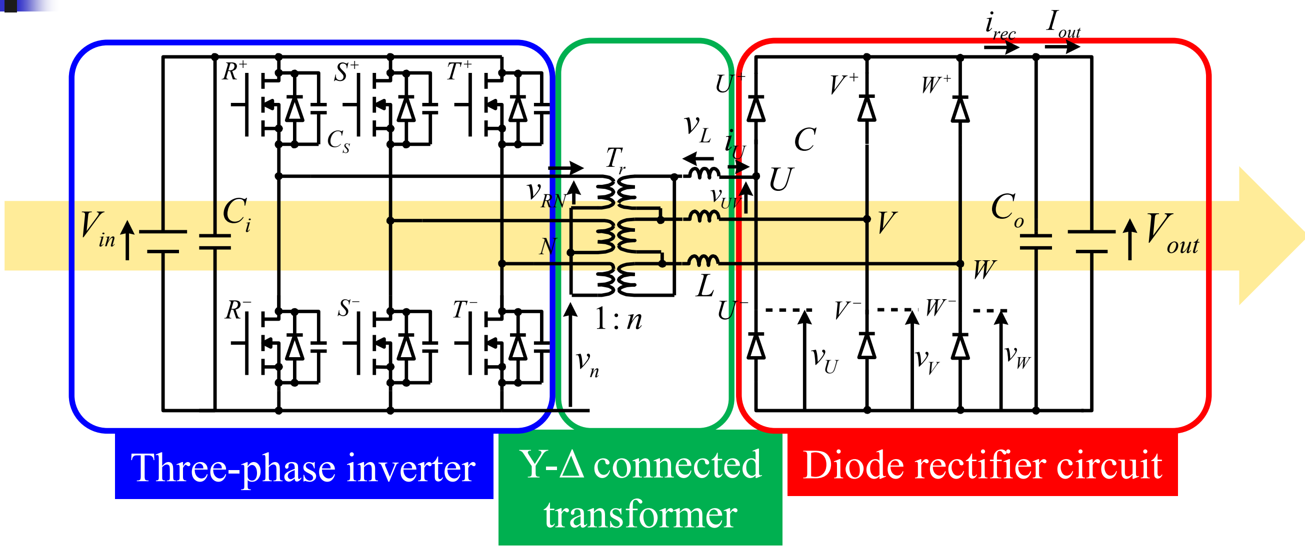
<u>Theory</u> is necessary for proper circuit design

➢ **Purpose**

Derivation of Low-Power Characteristics for Zero Output Power

Workshop[2]

Conventional circuit



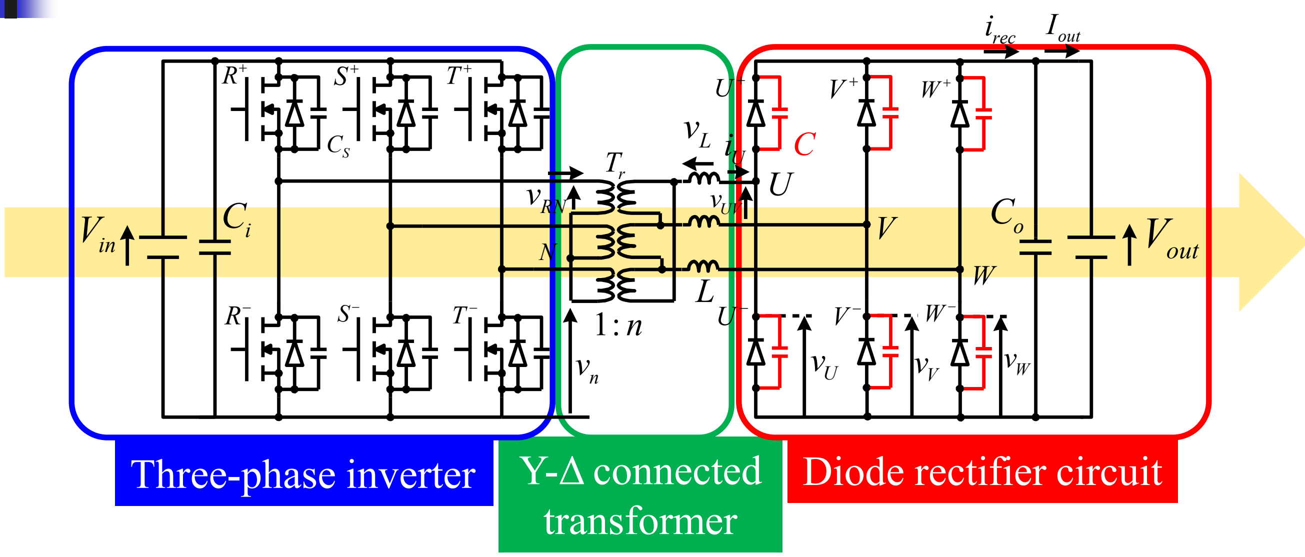
Single-Active-Bridge (SAB) DC-DC converter

◎
- The secondary side consists of passive components
  → Unidirectional power transmission・Simple circuit configuration
- Loss reduction by soft switching

△
- Increased transformer capacity → Larger circuit size
- Higher input voltage than load voltage required → High-voltage devices

Workshop[3]

Proposed Circuit



Secondary-Resonant Single-Active-Bridge (SR-SAB) DC-DC Converter

Resonant capacitor *C* is connected in parallel with the secondary-side diode
- LC resonance with leakage inductance *L* achieves high power factor
  → Transformer miniaturization
- Power transfer possible even when input voltage equals load voltage

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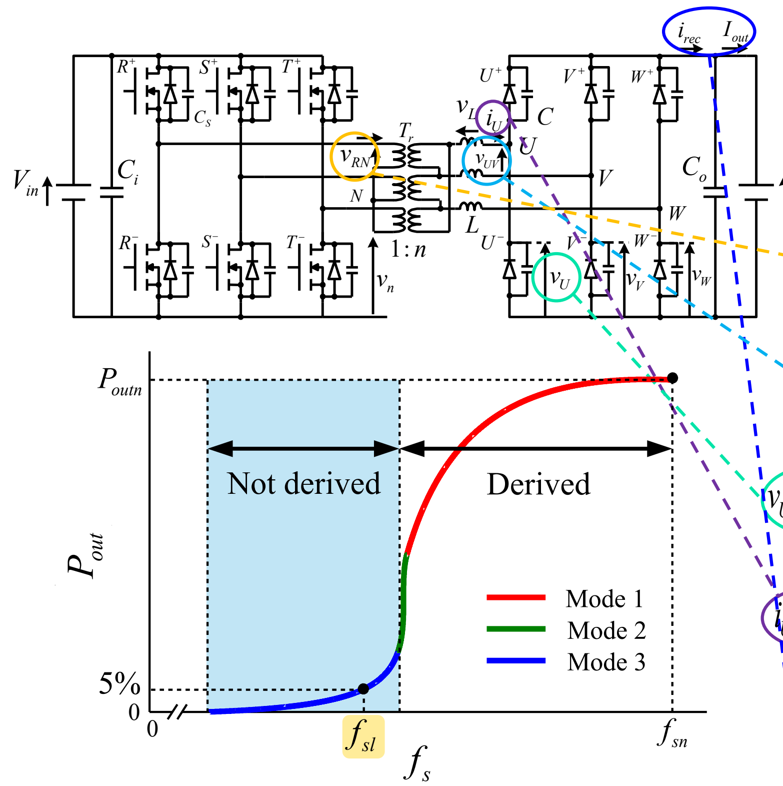
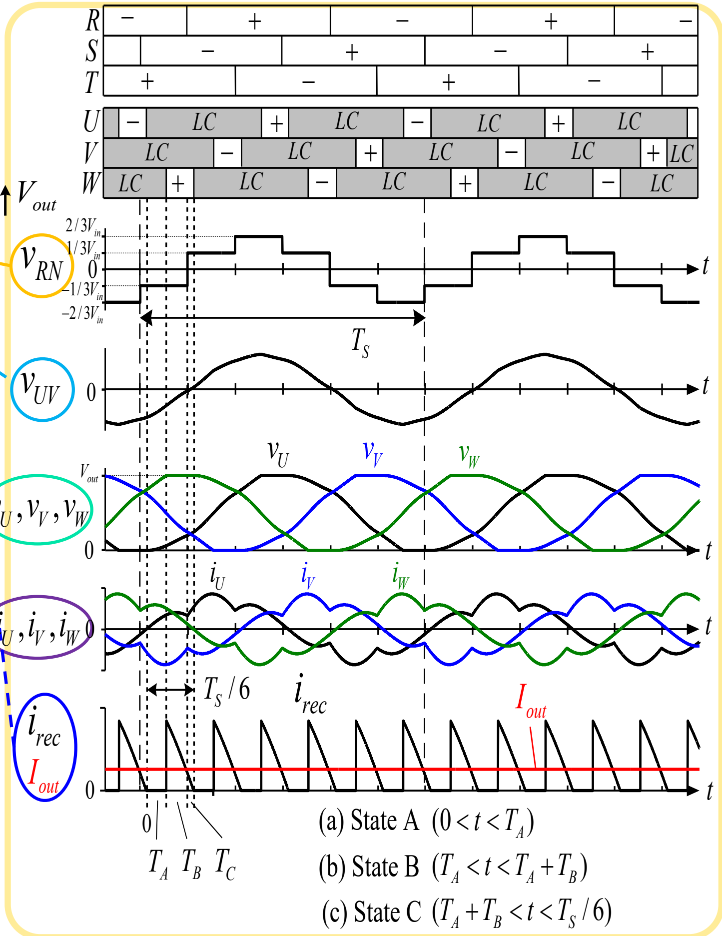
<u>Compact, high-efficiency, high-power circuit</u>

△→◎

Theoretical waveforms (Mode 3)





Derive the theory by dividing the operation into State A, B, and C

Operating theory

<Voltage equation of the transformer>

$$\begin{bmatrix} v'_{RN} \\ v'_{SN} \\ v'_{TN} \end{bmatrix} = L\frac{d}{dt}\begin{bmatrix} i_U - i_V \\ i_V - i_W \\ i_W - i_U \end{bmatrix} + \begin{bmatrix} v_{UV} \\ v_{VW} \\ v_{WU} \end{bmatrix} \Rightarrow \begin{bmatrix} v'_{RN} - v'_{TN} \\ v'_{SN} - v'_{RN} \\ v'_{TN} - v'_{SN} \end{bmatrix} = 3L\frac{d}{dt}\begin{bmatrix} i_U \\ i_V \\ i_W \end{bmatrix} + \begin{bmatrix} v_{UV} - v_{WU} \\ v_{VW} - v_{UV} \\ v_{WU} - v_{VW} \end{bmatrix}$$

v'_{RN}: secondary−referred value of primary voltage v_{RN}

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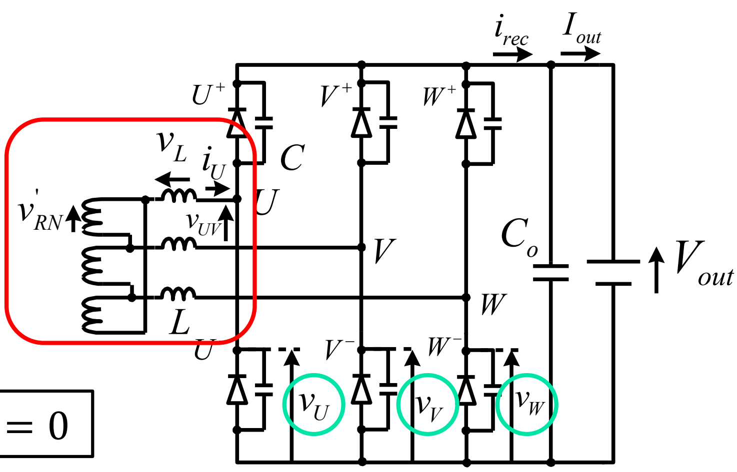
When the transformer turns ratio is n

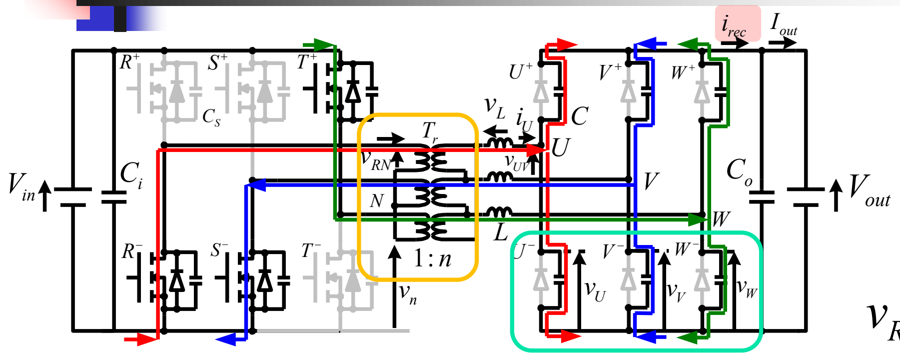
$v'_{RN} = n \times v_{RN}$

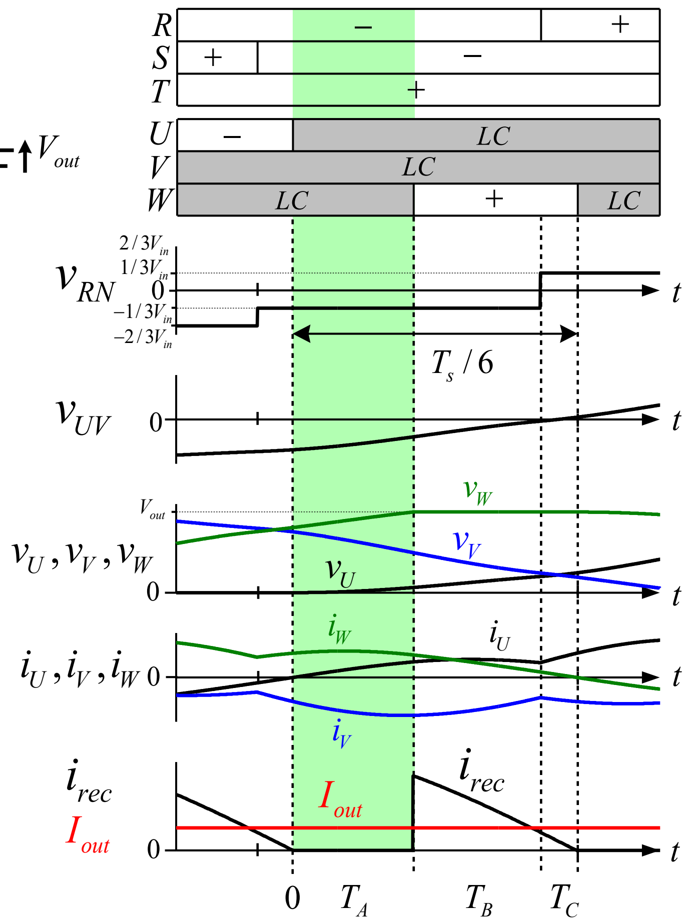


< Constraint condition > $i_U + i_V + i_W = 0$

Theory derivation based on diode voltages v_U, v_V, and v_W

State A $(0 < t < T_A)$





★ No output current flow

$t = 0$: Start of U phase resonance

$\rightarrow t = T_A$: End of W phase resonance

● $v'_{RN} - v'_{TN} = n(-V_{in}/3 - 2V_{in}/3) = -nV_{in}$

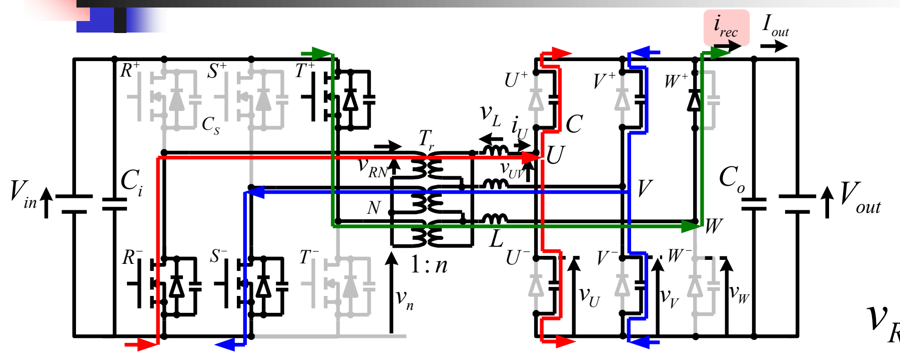
●
$$v_U(t) = \frac{1}{C}\int_0^{T_A}\frac{i_U(t)}{2}dt$$

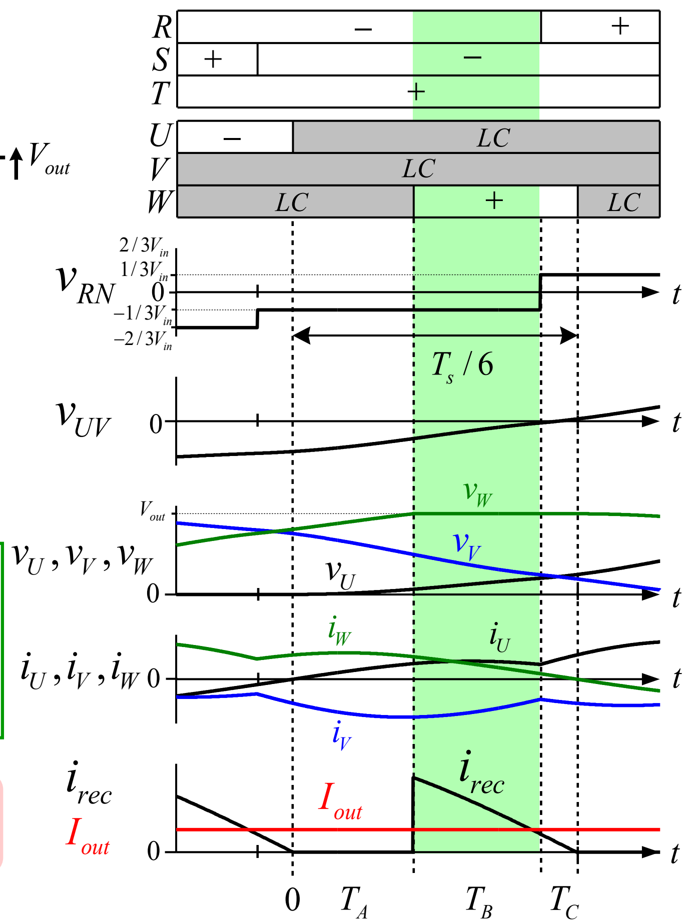
$$v_V(t) = \frac{1}{C}\int_0^{T_A}\frac{i_V(t)}{2}dt + \underline{v_V(0)}$$

Initial value

$$i_{rec}(t) = 0$$

State B $(T_A < t < T_A + T_B)$





★ LC Resonance occurs in phases U, V

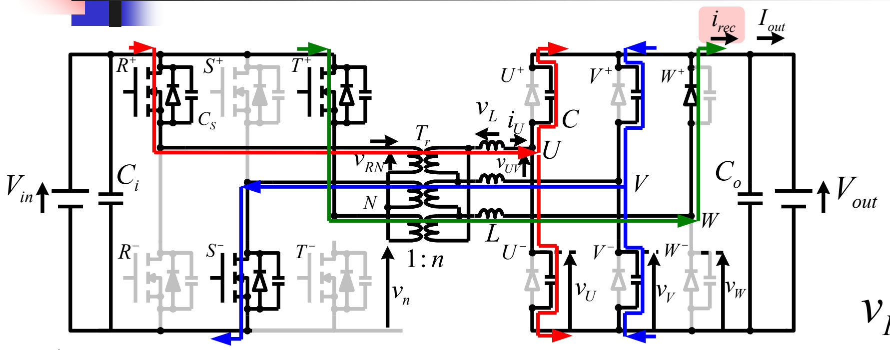
$t = T_A$: End of W phase resonance

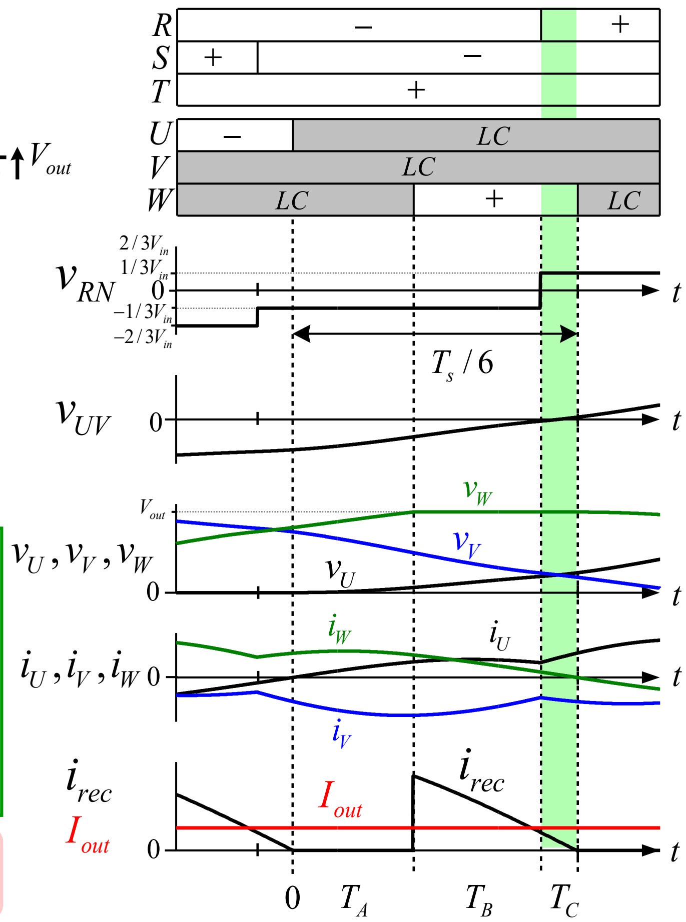
$\rightarrow t = T_A + T_B$: Switching of switch R

$$i_W(t) = \{3nV_{in} - 2V_{out} + v_U(T_A) + v_V(T_A)\}\sqrt{\frac{2C}{3L}}\sin\frac{t - T_A}{\sqrt{6LC}} + i_W(T_A)\cos\frac{t - T_A}{\sqrt{6LC}}$$

$$i_{rec}(t) = \frac{1}{2}i_U(t) + \frac{1}{2}i_V(t) + i_W(t) = \frac{1}{2}i_W(t)$$

State C ($T_A + T_B < t < T_s/6$)





★ <u>Different switching state from State B,</u>
<u>but same secondary-side resonance condition</u>

$t = T_A + T_B$: Switching of switch R

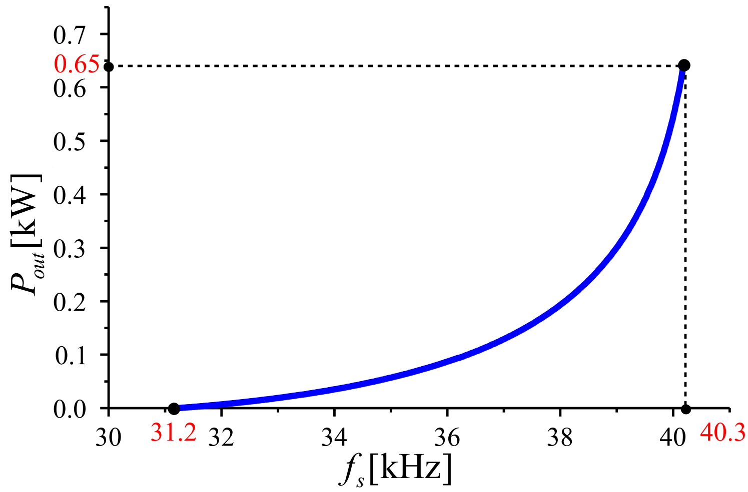
→ $t = T_s/6$: Start of phase-W resonance

$$i_W(t) = \{3nV_{in} - 2V_{out} + v_U(T_A + T_B) + v_V(T_A + T_B)\}\sqrt{\frac{2C}{3L}}\sin\frac{t - T_A - T_B}{\sqrt{6LC}} + i_W(T_A + T_B)\cos\frac{t - T_A - T_B}{\sqrt{6LC}}$$

$$i_{rec}(t) = \frac{1}{2} i_W(t)$$

Output power characteristics (Mode 3)

Parameters	Symbols	Values
Output Power	P_{out}	0 – 0.65 kW
Input voltage	V_{in}	250 V
Output voltage	V_{out}	250 V
Turn ratio of transformer	n	10/9
Leakage inductor	L	17 μH
Resonant capacitor	C	110 nF
DC capacitor	C_i, C_o	1500 μH



$$P_{out} = V_{out} \times I_{out} = V_{out} \times \frac{6}{T_s}\int_0^{T_s/6} i_{rec}(t)dt = 6V_{out} f_s \int_0^{T_s/6} i_{rec}(t)dt$$

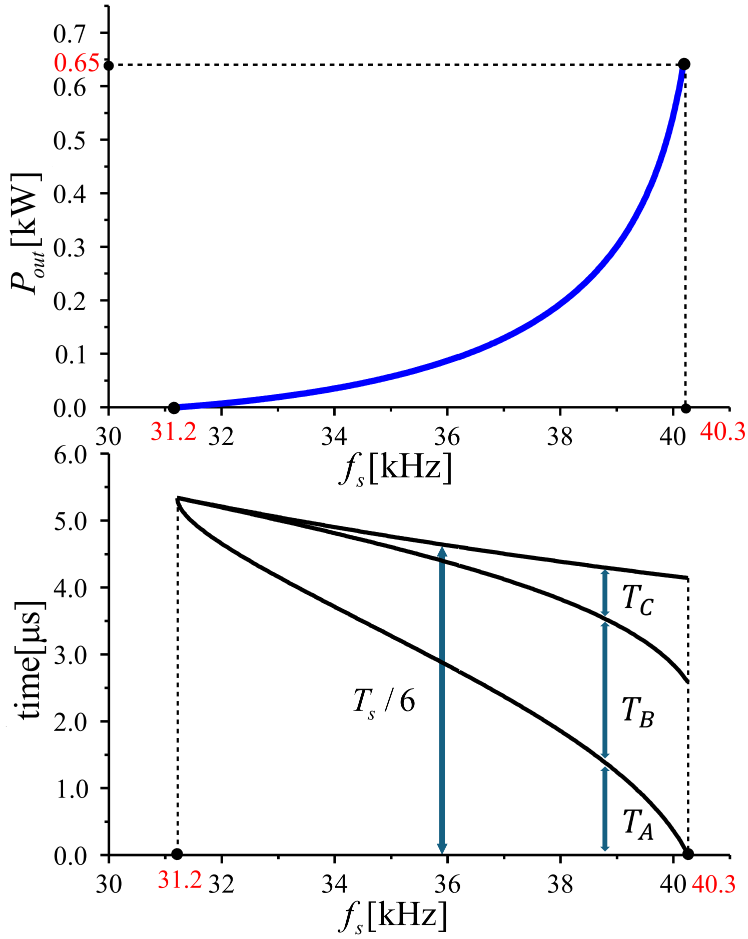
- Output power can be controlled by transformer frequency f_s

  ⬇

  Simple control using a single variable
- <u>Wide-range power control</u> through design of n, L, and C

Output power characteristics（Mode 3）

Parameters	Symbols	Values
Output Power	P_{out}	0 – 3.7 kW
Input voltage	V_{in}	250 V
Output voltage	V_{out}	250 V
Turn ratio of transformer	n	10/9
Leakage inductor	L	17 μH
Resonant capacitor	C	110 nF
DC capacitor	C_i, C_o	1500 μH



Lower frequency
→ Longer State A duration T_A relative to period T_s

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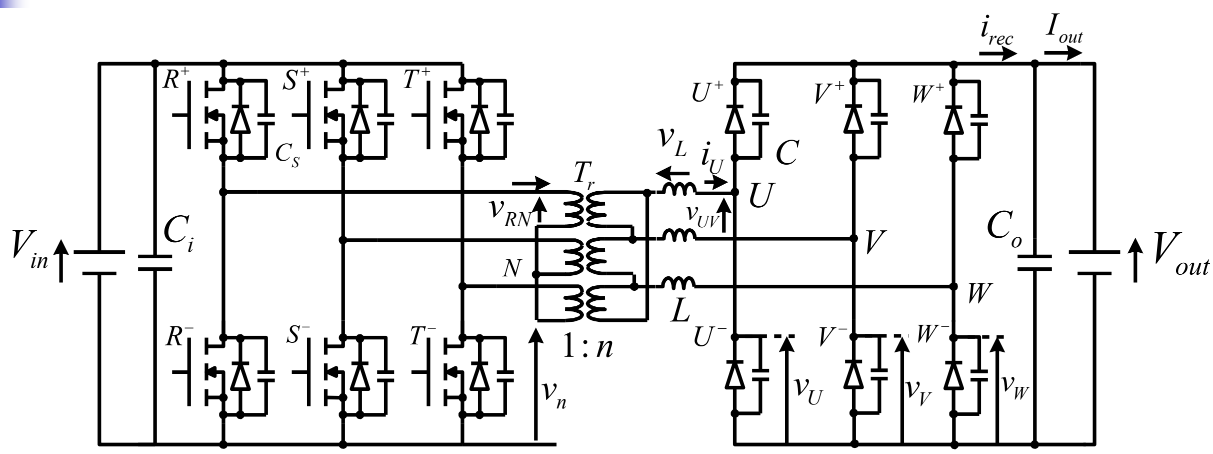
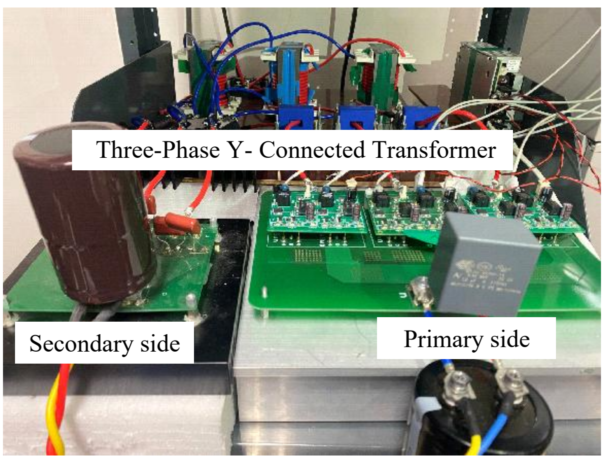
Reduced output-current conduction time
→ <u>Lower output power</u>

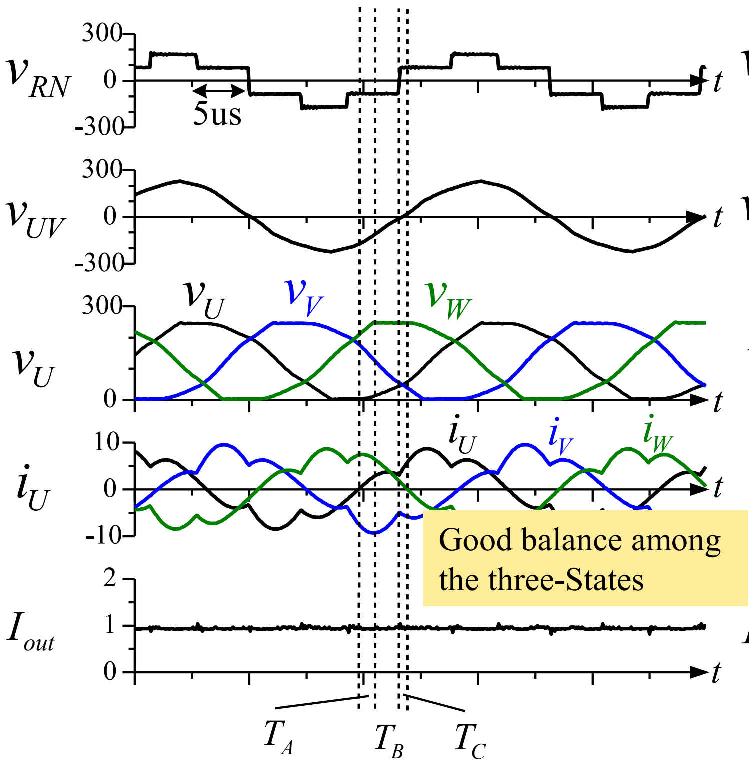
Experimental conditions



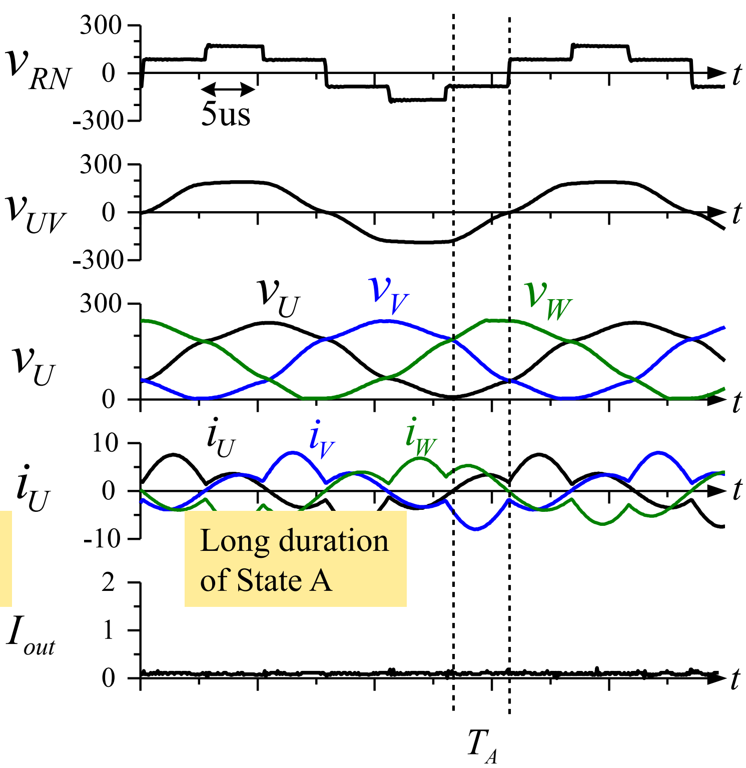


Parameters	Symbols	Values
Output Power	P_{out}	0 – 3.7 kW
Switching frequency	f_s	32 – 53 kHz
Input voltage	V_{in}	250 V
Output voltage	V_{out}	250 V
Turn ratio of transformer	n	10/9
Leakage inductor	L	17 μH
Resonant capacitor	C	110 nF
DC capacitor	C_i, C_o	1500 μH

Experimental waveforms

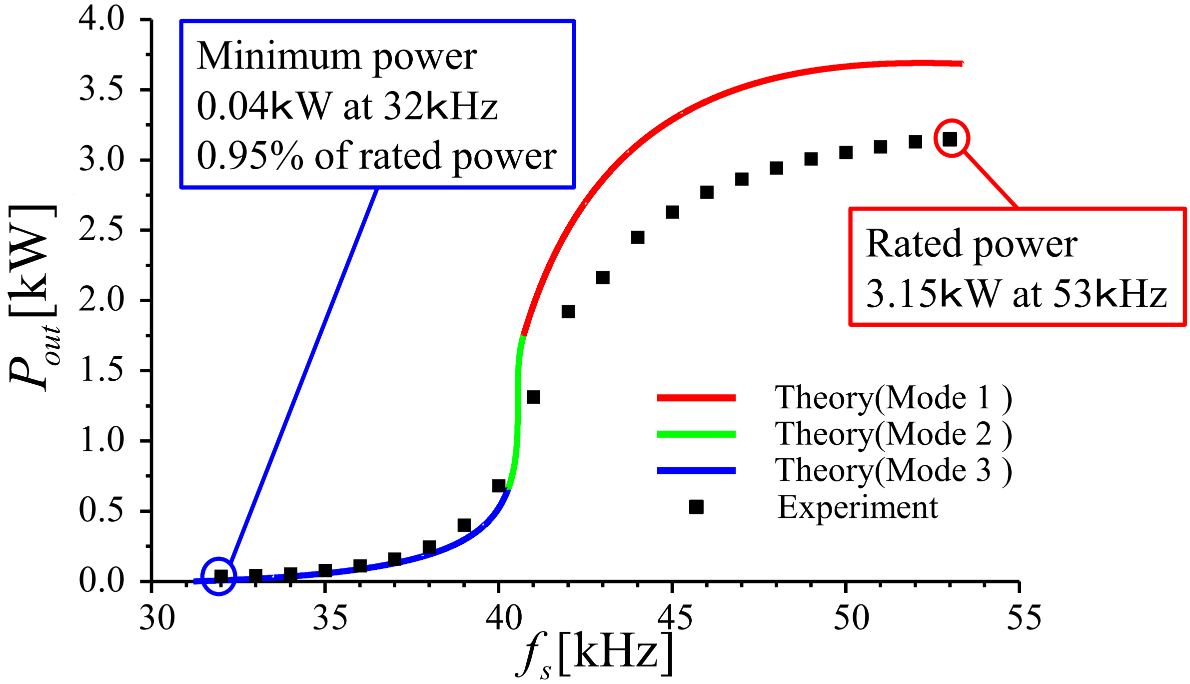


Fundamental waveform f_s =38 kHz
P_{out} = 0.247 kW, i_{out} = 0.99 A



Zero-power waveform f_s =32 kHz
P_{out} = 0.04 kW, i_{out} = 0.15 A

Experimental Results



- ● Theoretical and experimental results agree in Modes 2 and 3
- ▲ Large discrepancy in Mode 1

➡ Near rated power, large current causes voltage drops due to transformer winding resistance

Conclusions

Purpose

- Proposed SR-SAB converter achieves lower primary-side voltage rating, smaller transformer size, and higher efficiency than the conventional converter
- Theoretical derivation of low-power operation for circuit design enabling wide-range power control

Method

- Circuit operation analysis using transformer voltage equations

Result

- Low power characteristics of the proposed converter were theoretically derived
- Output power reduced to 0.95% of rated power in experiments