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A Simplified-ISOP-CLLLC Converter with Wide Voltage Gain for Auxiliary Power Supply Systems of Urban Rail Vehicles

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Current Status of Subway Auxiliary Power Supply System

Shenzhen Metro Line 1

Beijing Metro Line 11

- ✓ More environmentally friendly
- ✓ More energy-saving
- ✓ More safer
- ✓ More smarter

- ✓ Light weight
- ✓ Efficient
- ✓ emergency travel
- ✓ intelligent

- Main AC loads: air conditioner (inverter), fan (inverter), air compressor, socket
- Main DC loads: control power supply, lighting, battery

The current auxiliary power supply system of domestic subways is mainly based on three-phase AC 380V and DC 110V busbars.

Traditional auxiliary power supply system architecture

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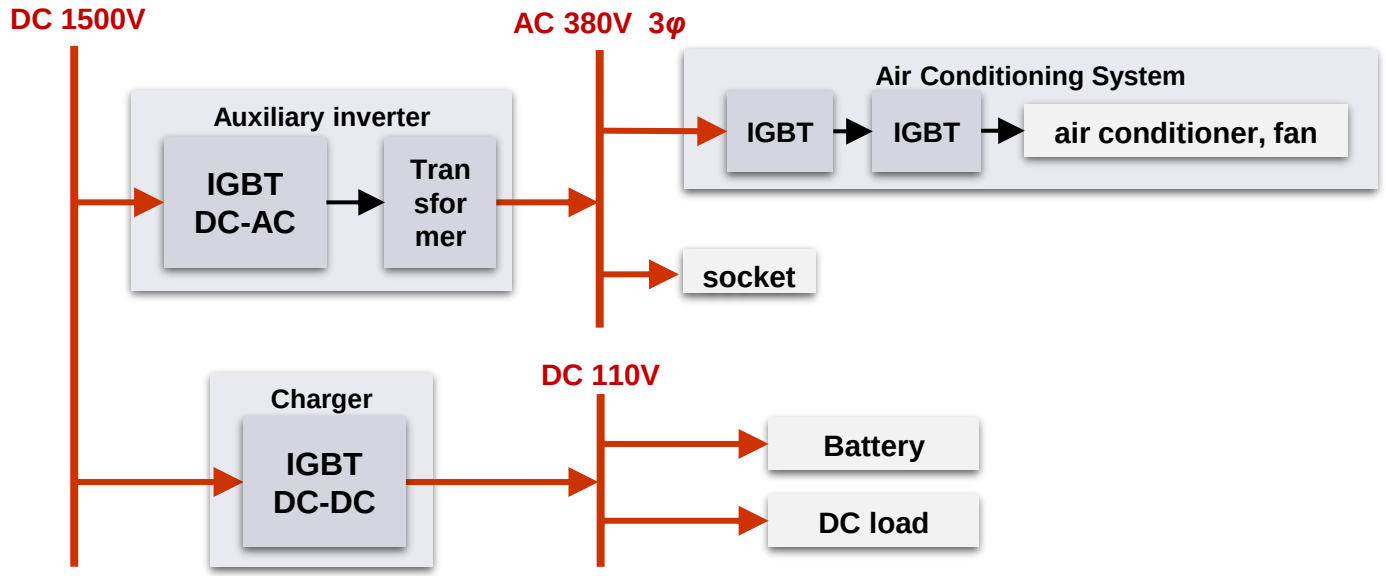
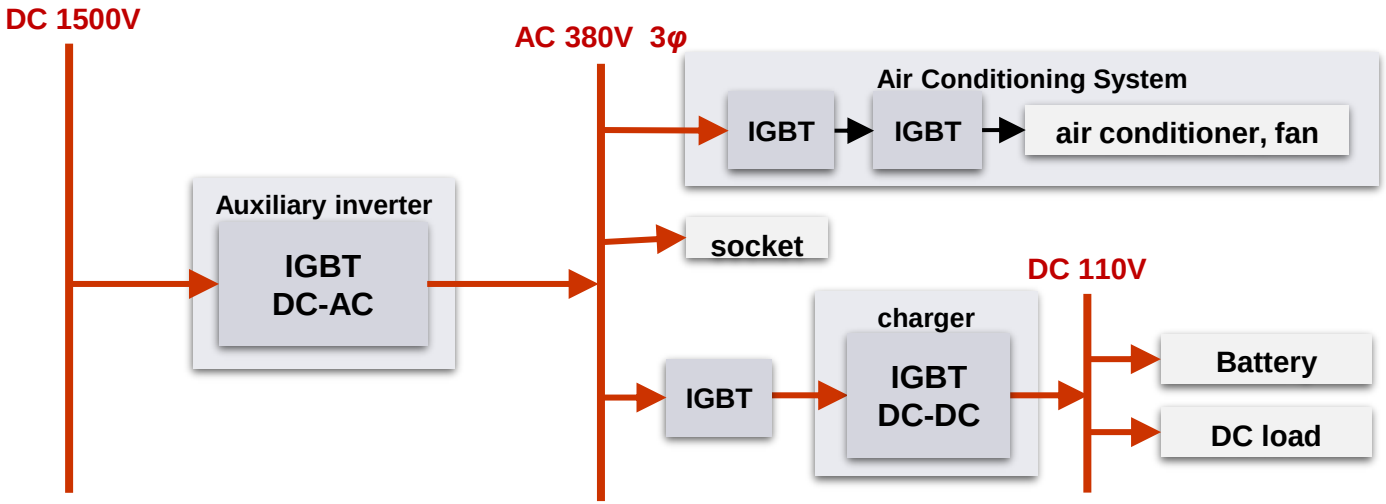
■ Auxiliary power supply system architecture based on power frequency transformer



- ➢ The busbar adopts a DC-AC-DC architecture:
- There are a large number of AC-DC and DC-AC conversion links.
- There is an industrial frequency transformer.
- The low-voltage battery does not have emergency traction capabilities.

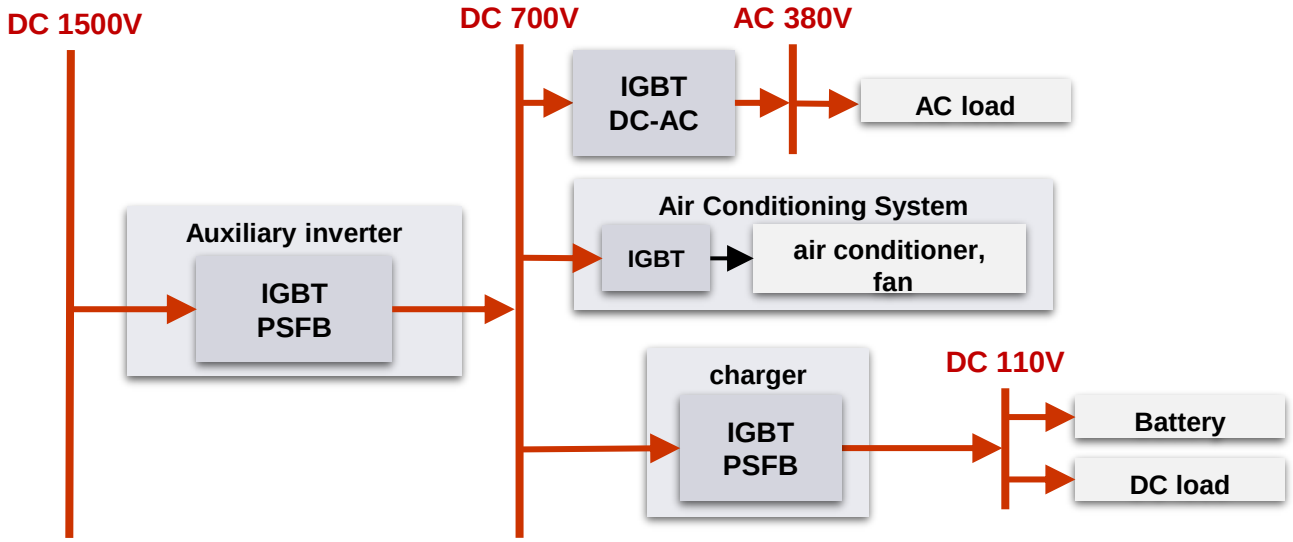
■ IGBT-based auxiliary power supply system architecture



- ➢ The busbar adopts a DC-AC-DC architecture:
- There are a large number of AC-DC and DC-AC conversion links.
- Low-voltage batteries do not have emergency traction capabilities.

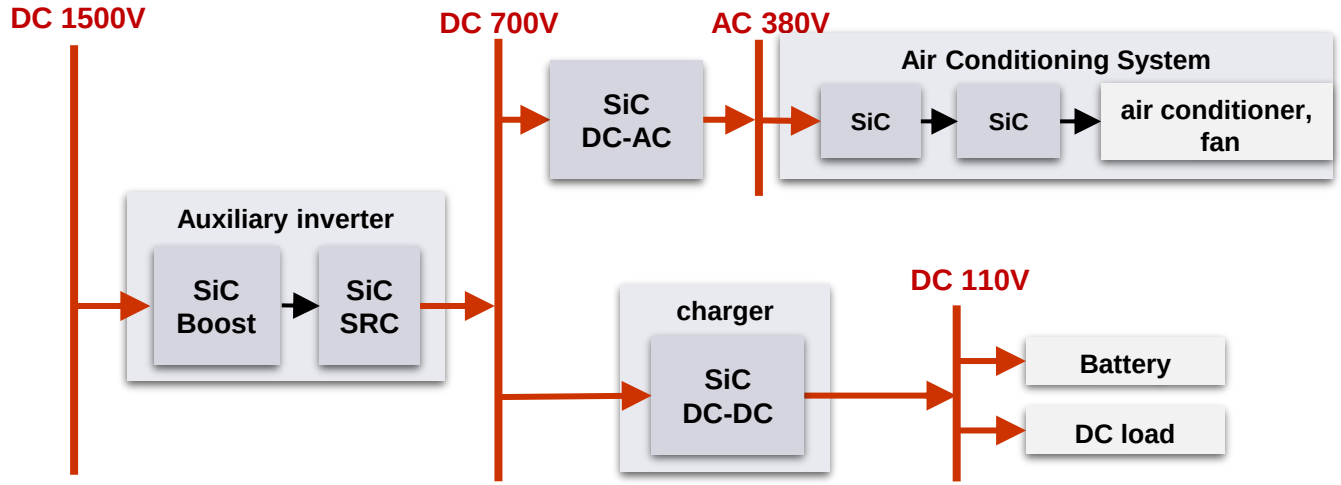
Traditional auxiliary power supply system architecture

IGBT-based auxiliary power supply system architecture



- The busbar adopts a DC-DC-AC architecture:
  - Reduced AC and DC links Use IGBT, high frequency and lightweight space
  - Low-voltage batteries do not have emergency traction capabilities

SiC-based auxiliary power supply system architecture



- The busbar adopts a DC-DC-AC architecture:
  - Use SiC to achieve high frequency and light weight
  - Low-voltage batteries do not have emergency traction capabilities

DC through SiC auxiliary converter architecture

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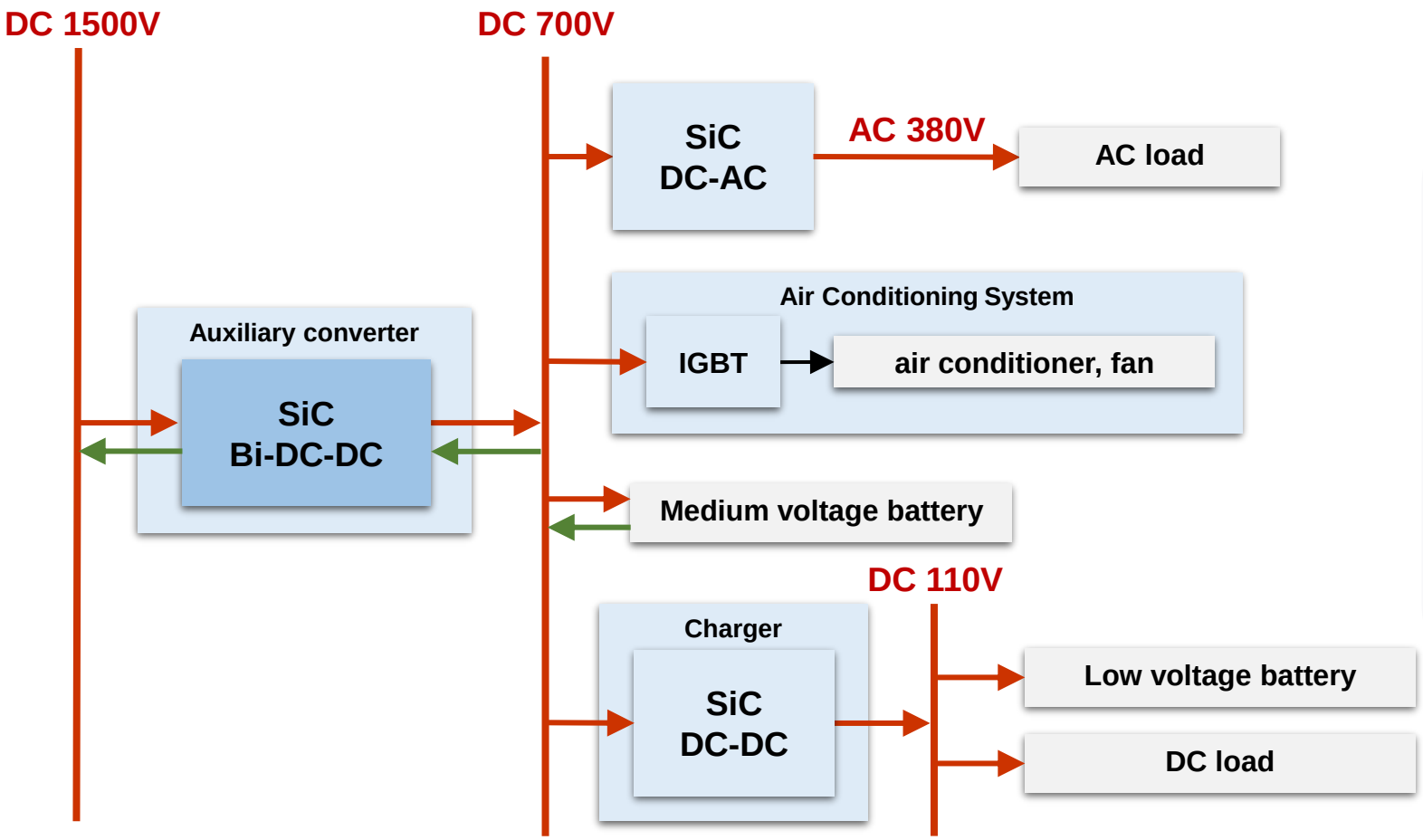
- The new auxiliary power supply system architecture proposed in this paper



- The busbar adopts a DC-DC-DC architecture:
  - Reduced AC and DC links
  - Used SiC to achieve high frequency and light weight
  - Added medium voltage battery to achieve emergency traction

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Bidirectional isolated DC-DC converter

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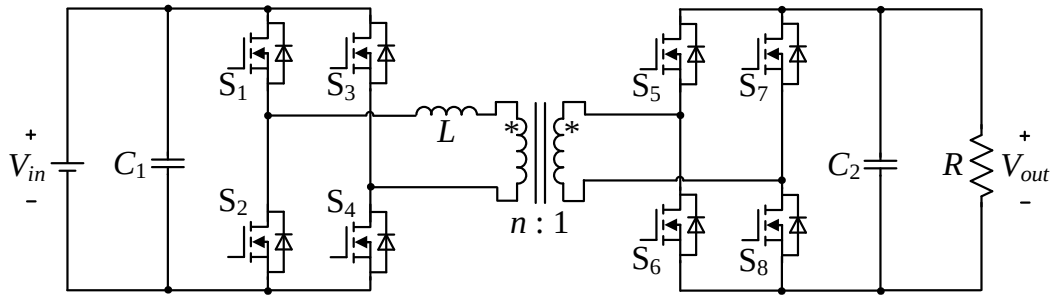
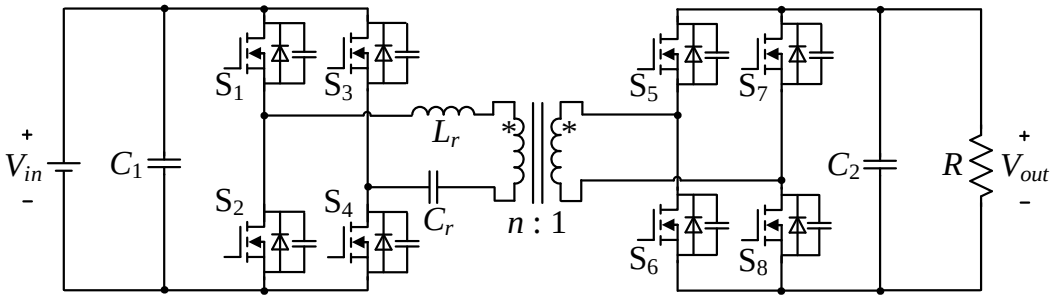


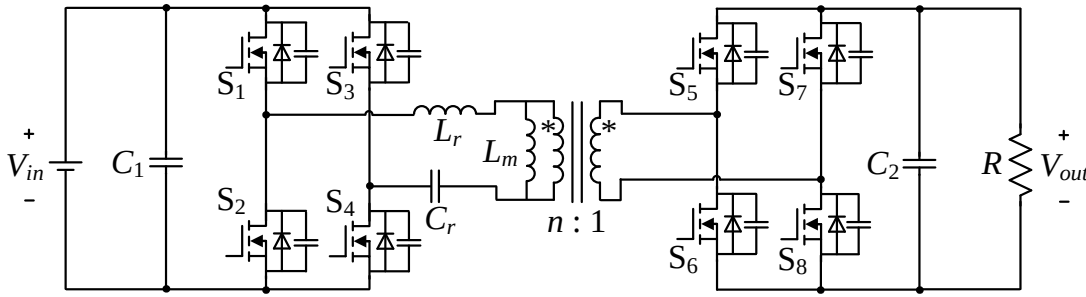
DAB



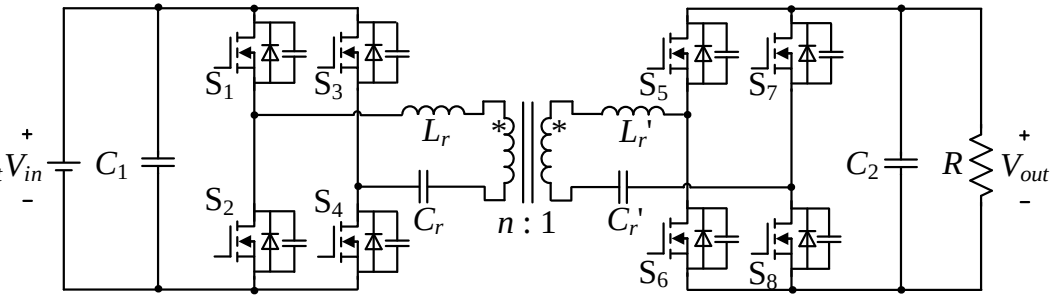
SRC

✓ Suitable for bi-directional power flow

Very small gain range



LLC

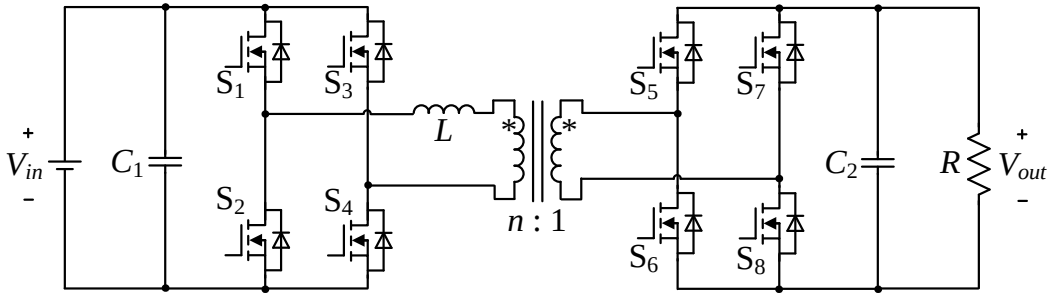


CLLLC

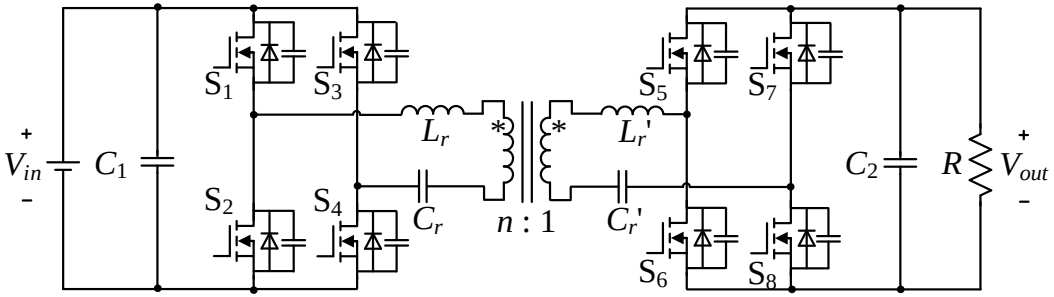
Reverse gain <1

✓ Suitable for bi-directional power flow

Bidirectional isolated DC-DC converter



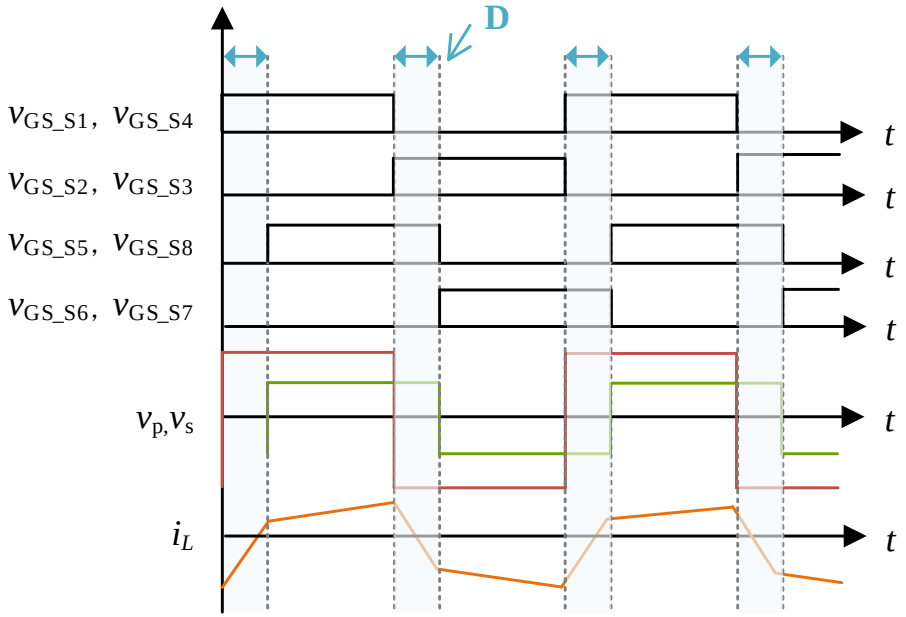
DAB



CLLLC

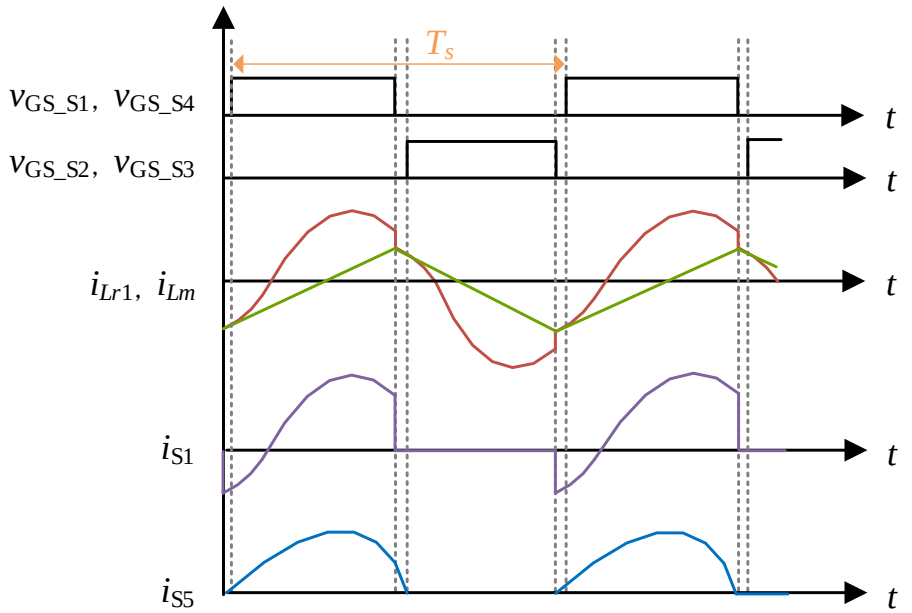
➢ Features of DAB (SPS) :

1. Fixed frequency operation, gain is determined by the phase shift ratio ;

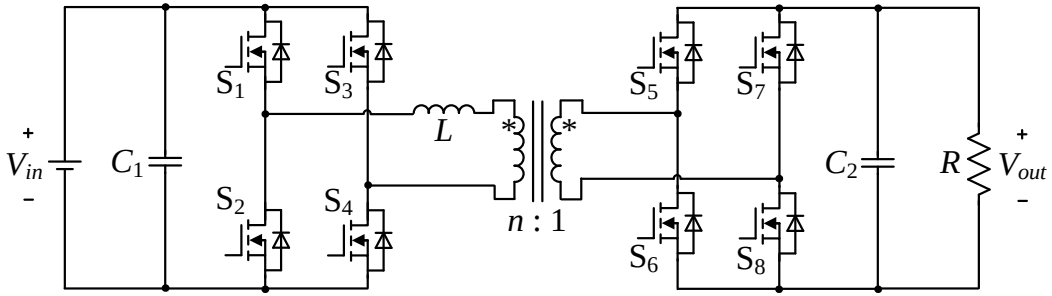


➢ Features of CLLLC :

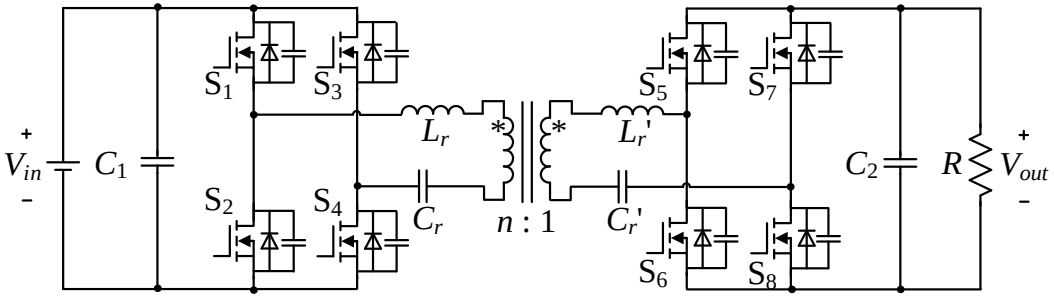
1. Variable frequency operation, gain is determined by frequency ;



Bidirectional isolated DC-DC converter



DAB

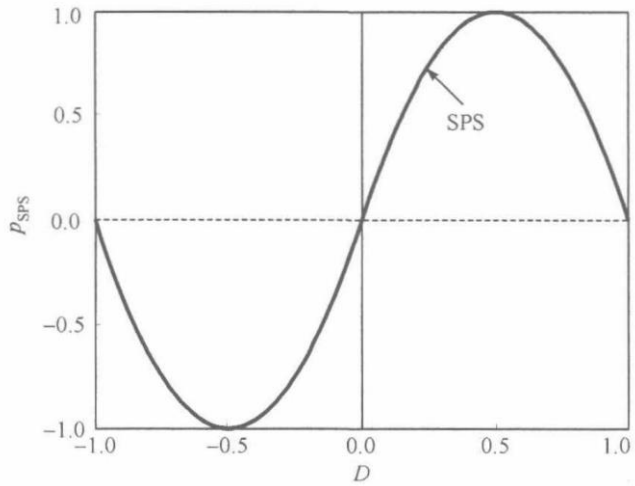


CLLLC

➢ Features of DAB (SPS) :

2. Wide achievable gain range;

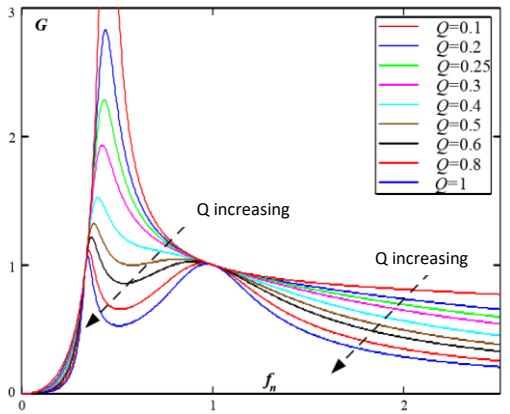
$$P = \frac{nV_{in}V_{out}D(1-D)}{2f_sL}$$

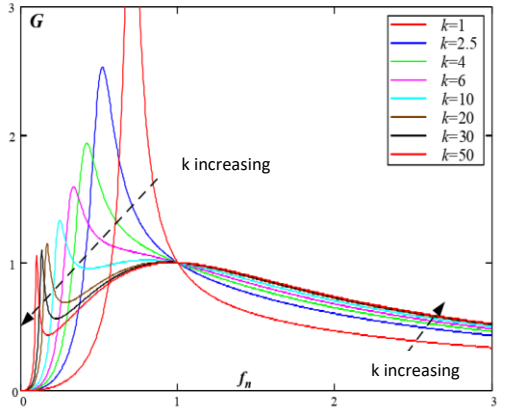


➢ Features of CLLLC :

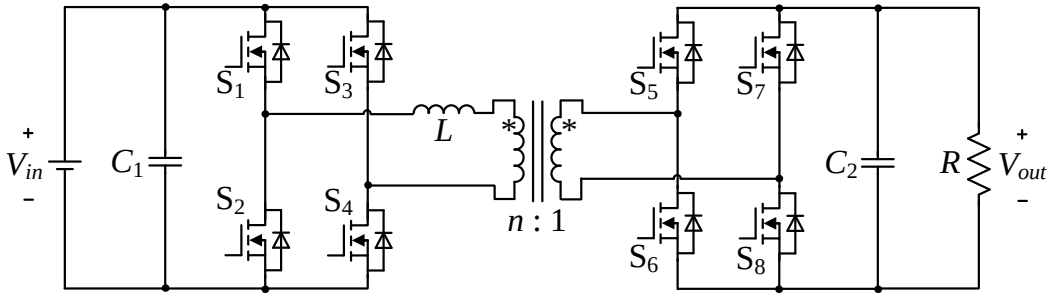
2. The achievable gain range is narrow (resonant cavity gain < 1.2 is optimal);

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{\left(1+\frac{1}{k}-\frac{1}{kf_n^{\,2}}\right)^2+\left(\frac{Q}{k}\right)^2\left[f_n(2k+1)-\frac{1}{f_n}(2k+2)+\frac{1}{f_n^{\,3}}\right]^2}}$$

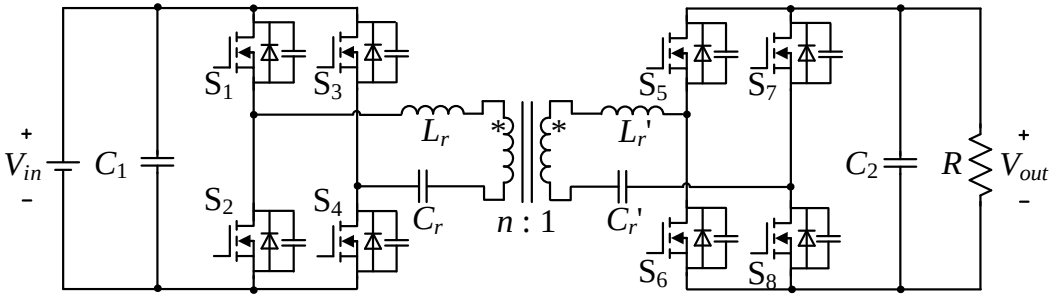




Bidirectional isolated DC-DC converter



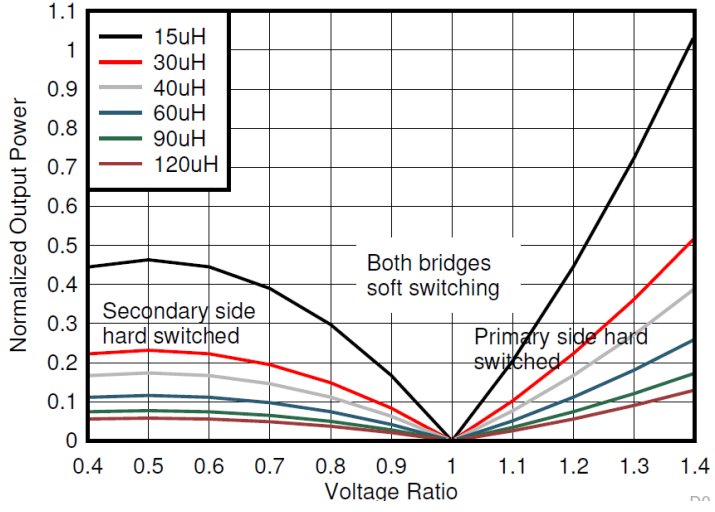
DAB



CLLLC

➢ Features of DAB (SPS) :

3. Under light load (<30%), the ZVS-on range becomes smaller, and ZVS-on can only be achieved on one side, the primary side or the secondary side.



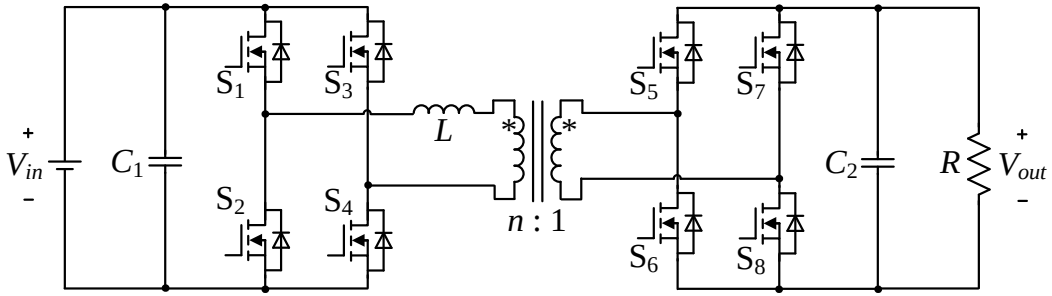
➢ Features of CLLLC :

3. The primary side switch tube can achieve ZVS-on in the full range, and the secondary side switch tube can also achieve ZVS-on in the full range by controlling t_{dead};

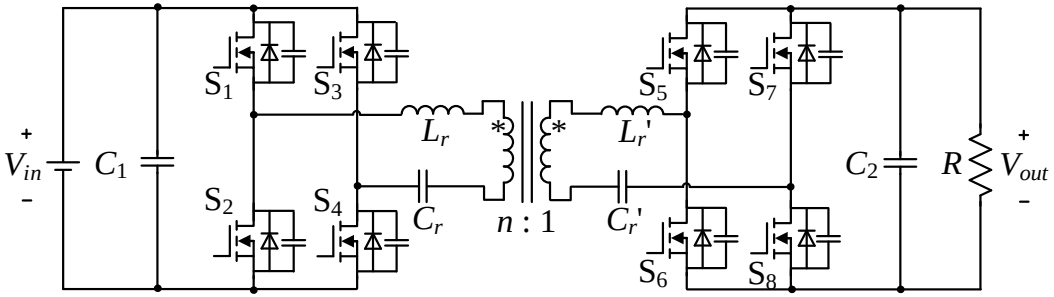
$$L_m \le \frac{V_{out}/V_{in}\, t_{dead}}{8 C_{oss} f_s}$$

$$\frac{[(K+1) f_n^{\,3} - f_n]\left\{Q^2\left[(2K+1) f_n^{\,2} - 1\right](f_n^{\,2} - 1) + f_n^{\,2}\right\}}{f_n^{\,4} + Q^2 (f_n - (K+1) f_n^{\,3})^2} \ge 0$$

Bidirectional isolated DC-DC converter



DAB



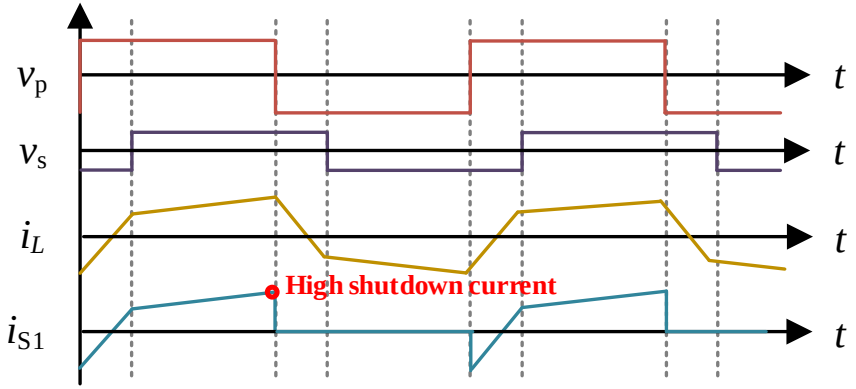
CLLLC

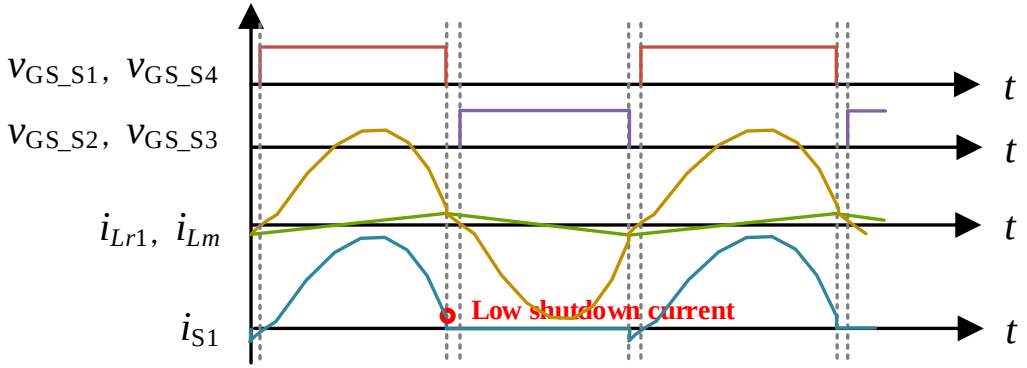
➢ **Features of DAB (SPS) :**

4. The primary side switch tube has a large turn-off current, large turn-off loss, and low efficiency; the same is true for the secondary side switch tube; EMI is not easy to solve.

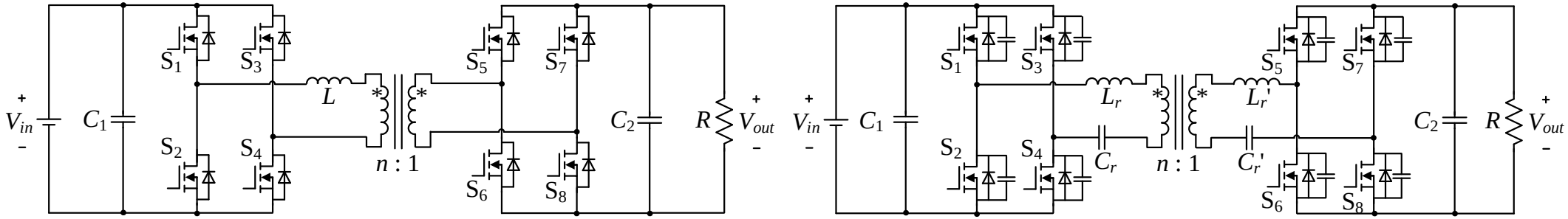
➢ **Features of CLLLC :**

4. The primary side switch tube has a small turn-off current and small turn-off loss; the secondary side switch tube achieves ZCS-off; and is EMI friendly.



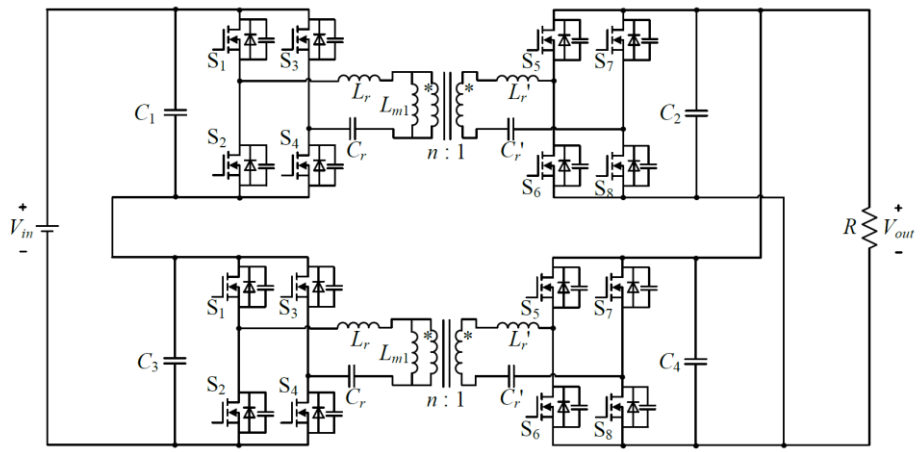


Comparison between DAB and CLLLC

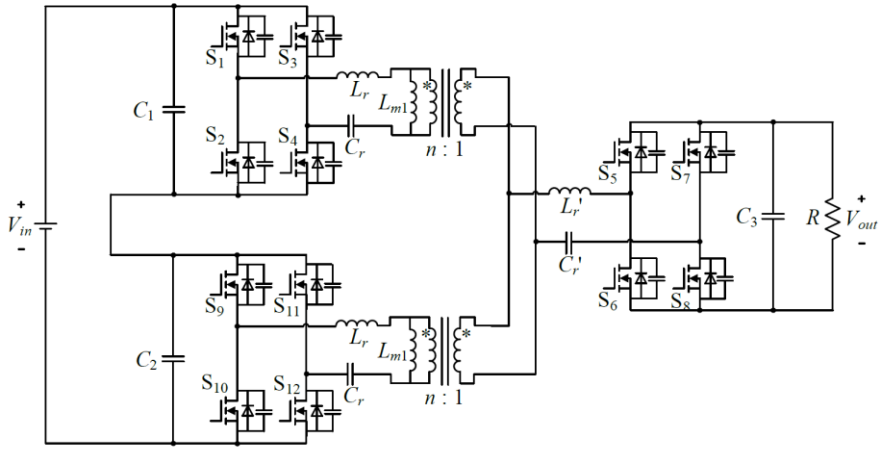


Topology selection	DAB（SPS）	CLLLC
Voltage Gain	Wide adjustable gain range	The gain adjustable range is narrow (the forward and reverse voltage gain is symmetrical)
Primary switch voltage stress	V_{in}	V_{in}
Primary switch current stress	AC inductor current peak	Resonance current peak
Primary switch tube opening status	Light load partial range ZVS-on	Full range ZVS-on
Primary switch off status	Hard turn-off (turn off at the peak point of AC inductor current)	Hard shutdown (shutdown at the excitation current peak point)
Secondary switch tube opening status	Light load partial range ZVS-on	Full range ZVS-on
Secondary switch off	Hard turn-off (turn off at the peak point of AC inductor current)	Full range ZCS-off

CLLLC Converter Based on Output Series and Output Parallel



Conventional ISOP-CLLLC Converter



The proposed ISOP-CLLLC converter proposed in this paper

- **Outputs are connected in series to reduce the voltage stress of the primary switch tube; Outputs are connected in parallel to reduce the number of components.**
- **Under the premise that the current capacity allows, *the secondary rectifier bridge and secondary resonant cavity are shared;***

- Input voltage fluctuates between 1000 and 1900 V, and output voltage fluctuates between 550 and 750 V.
- To reduce size and cost, discrete SiC devices are used.
- To reduce cost, the secondary rectifier bridge uses a control strategy without adding additional synchronous rectifier chips and current detection devices.

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Proposed ISOP-CLLLC converter topology and working principle

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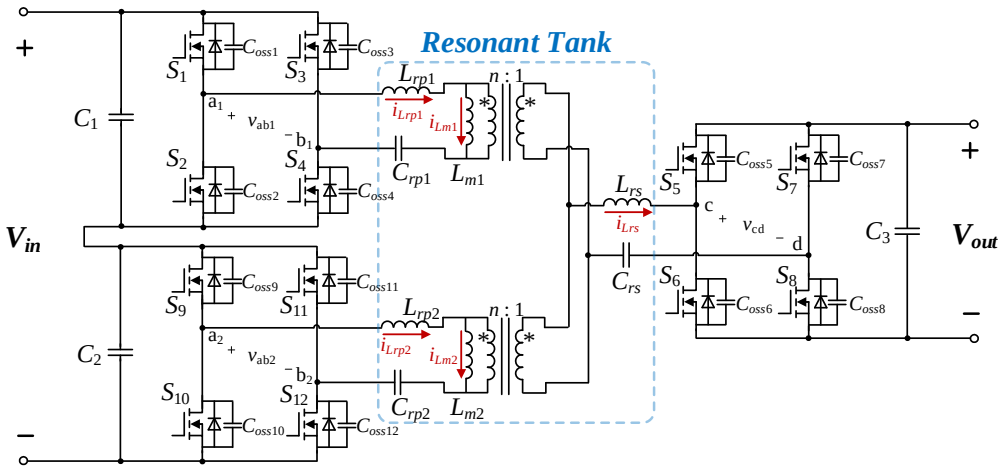
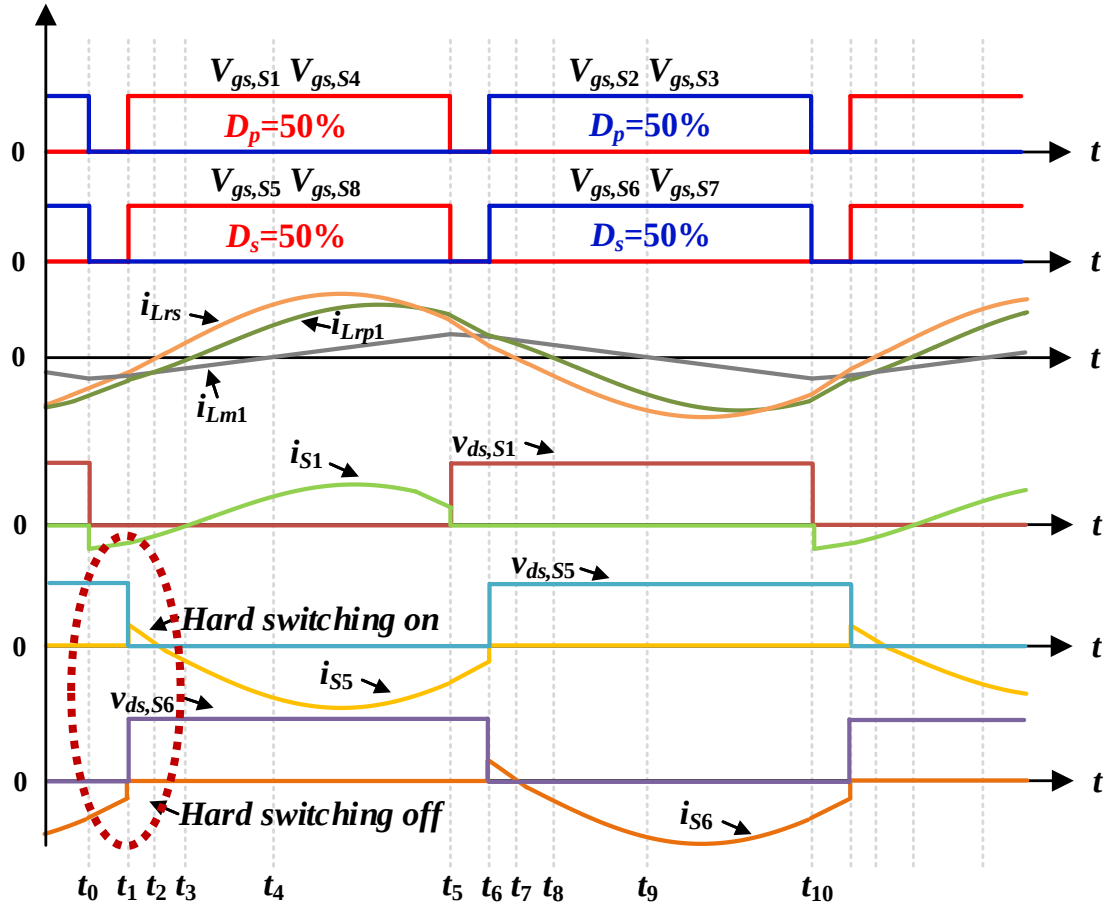


Proposed ISOP-CLLLC Converter

- The secondary side switch tube opens and closes at the same time as the primary side switch tube;
- The secondary side switch tube is hard-on and hard-off.



Conventional Control Method of Proposed ISOP-CLLLC Converter

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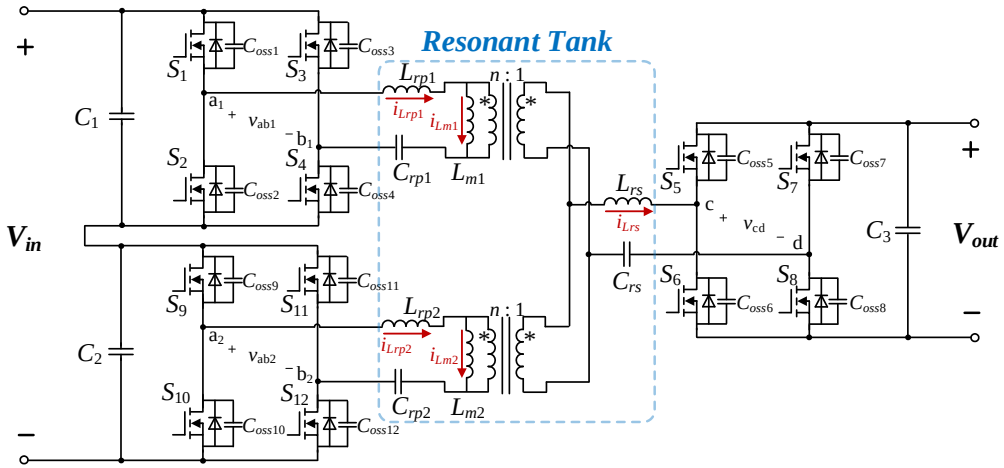
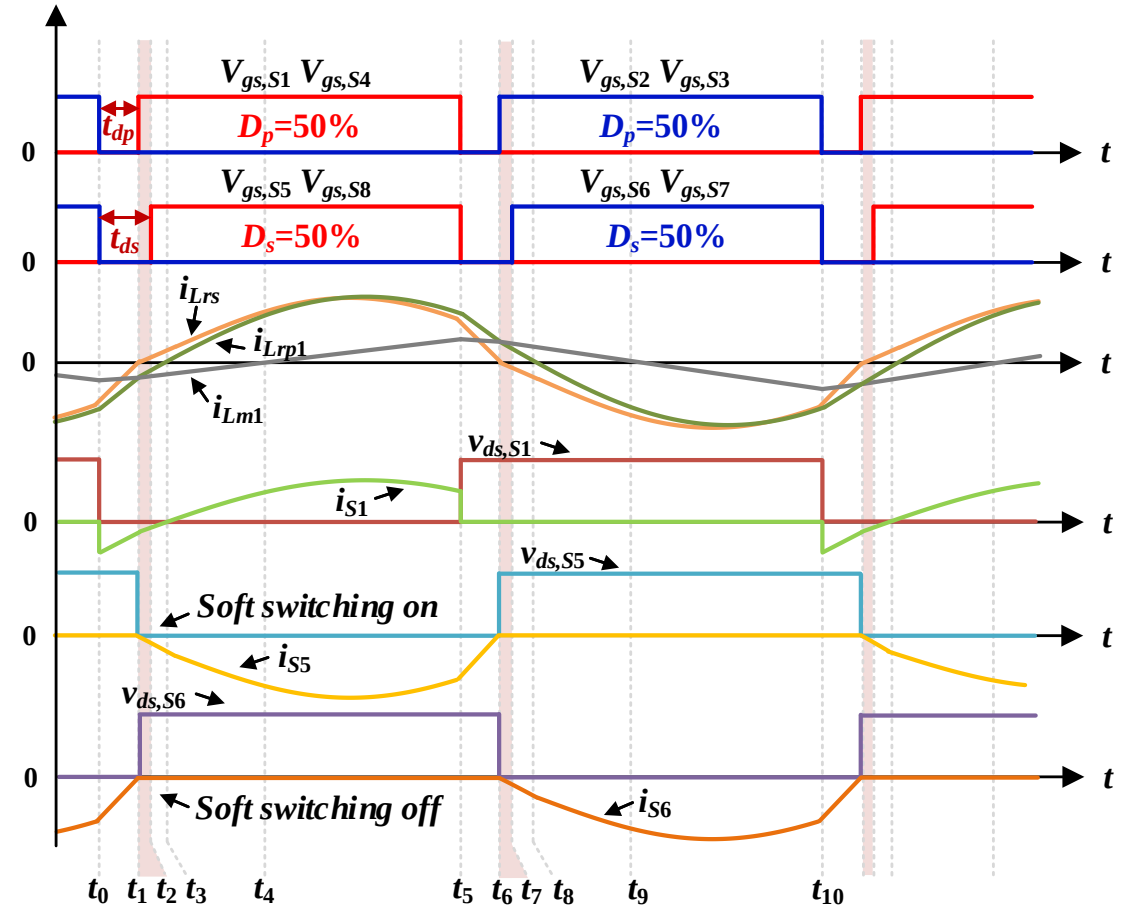
Improved strategy for achieving secondary side ZVS-on with proposed ISOP-CLLLC converter



Proposed ISOP-CLLLC Converter

- The secondary switch tube is turned on and off at the same time;
- The secondary switch tube is turned on with zero voltage and turned off with zero current.



Novel Control Method of Proposed ISOP-CLLLC Converter

Verification of Improvement Strategy

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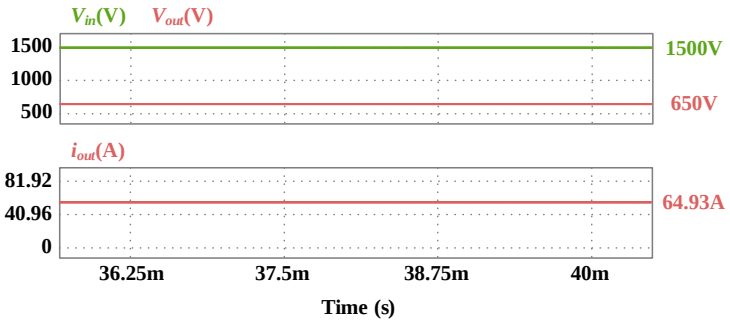
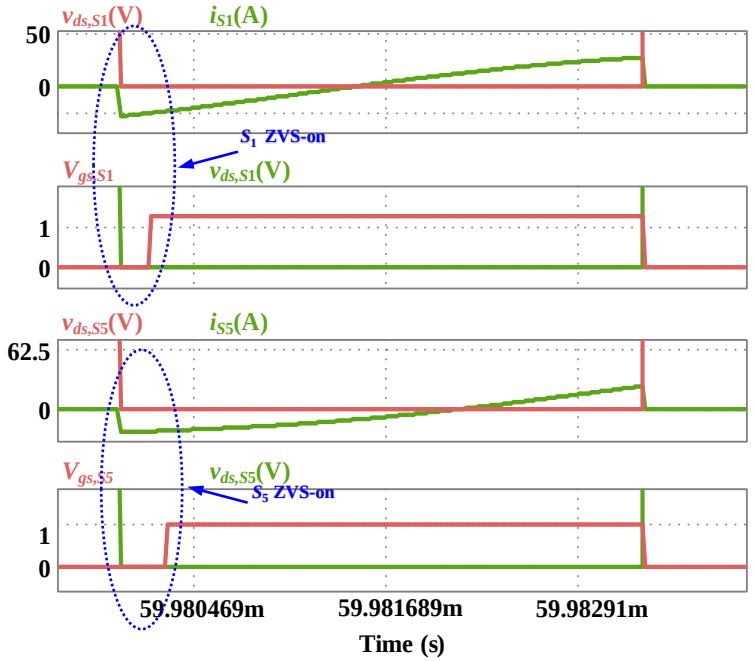
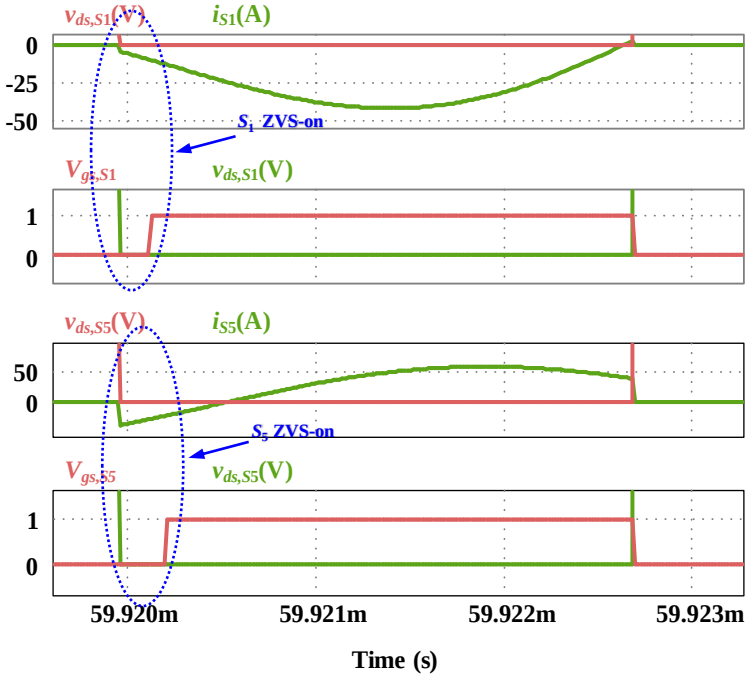
Input voltage 1500V, output voltage 650V, rated power 40kW



Full load 40kW forward waveform



Full load 40kW forward primary and secondary side switch soft switching waveform



Full load 40kW reverse primary and secondary side switch soft switching waveform

Verification of Improvement Strategy

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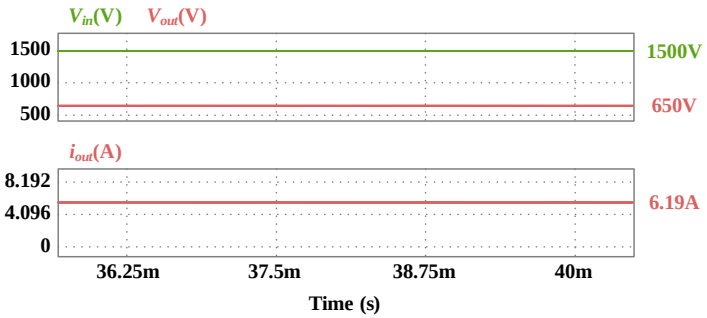
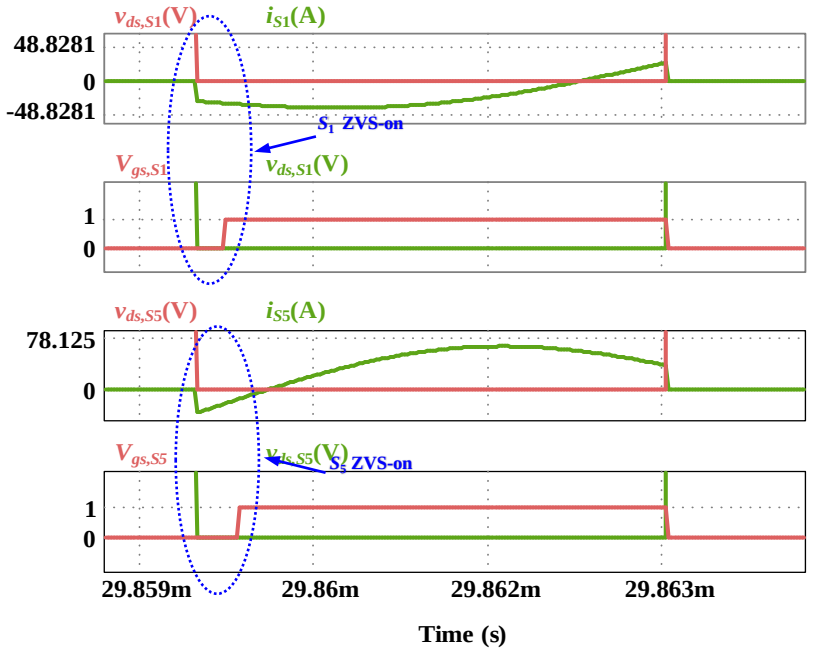
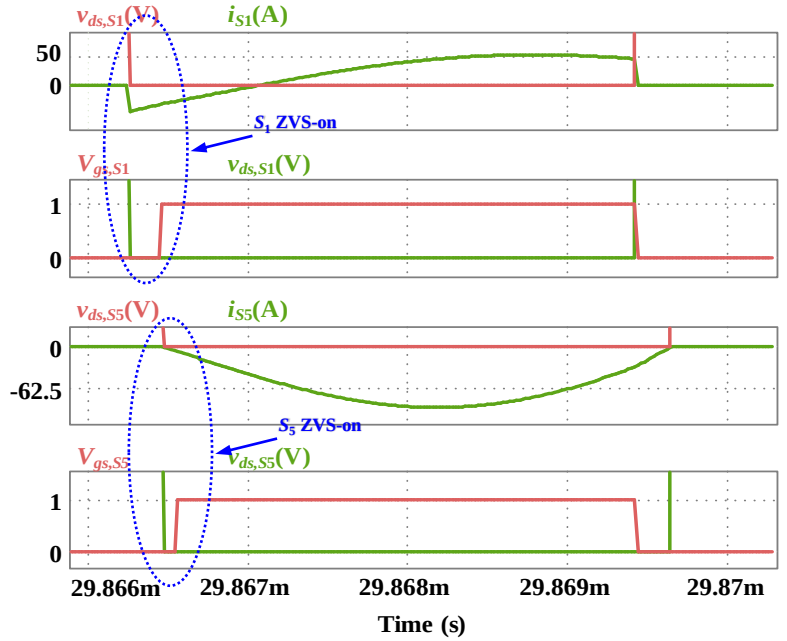
Input voltage 1500V, output voltage 650V, rated power 4kW



Light load 4kW forward input and output waveform



Light load 4kW forward primary and secondary side switch soft switching waveform



Light load 4kW reverse primary and secondary side switch soft switching waveform

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Conclusions

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- A DC-DC-DC architecture is proposed for a lighter and more efficient auxiliary power supply system for urban rail transit;
- A selection comparison and analysis of bidirectional DC-DC converters between the primary DC bus and the secondary DC bus are carried out, and a new ISOP-CLLLC converter is proposed;
- A new synchronous rectification control strategy is proposed for the new ISOP-CLLLC converter, which can achieve zero voltage turn-on and zero current turn-off of the primary and secondary side switches in a wide load range.

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Thank You!