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A High-Power Step-Up DC Transformer for Renewable Energy Distribution Systems

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Research direction：

high-power isolated DC/DC converter & MVDC Grid

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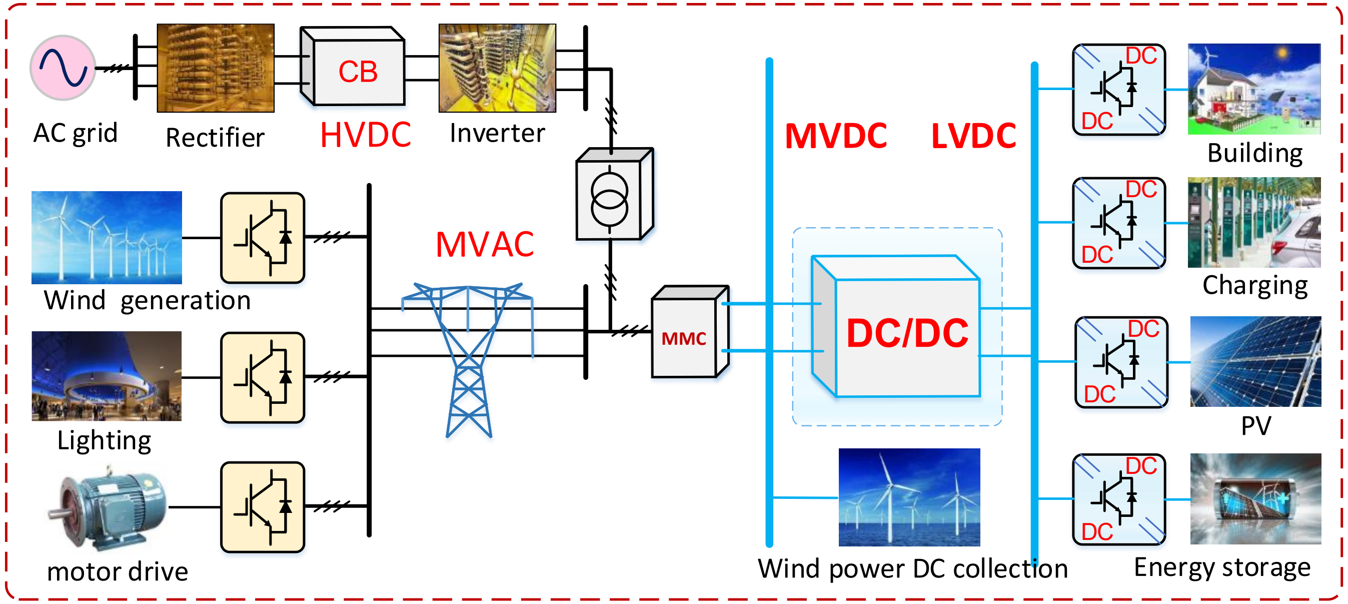
Background

- With the access of many types of DC electrical equipment, there is an urgent need to build a DC power distribution system !
- MVDC-LVDC DC/DC converter is the key technology of medium voltage and low voltage DC bus interconnection !



- high step-down ratio
- galvanic isolation
- wide input voltage range operation
- provide ports or interfaces to connect distributed power generators or energy storage device

Existing high power step-up DC-DC converter

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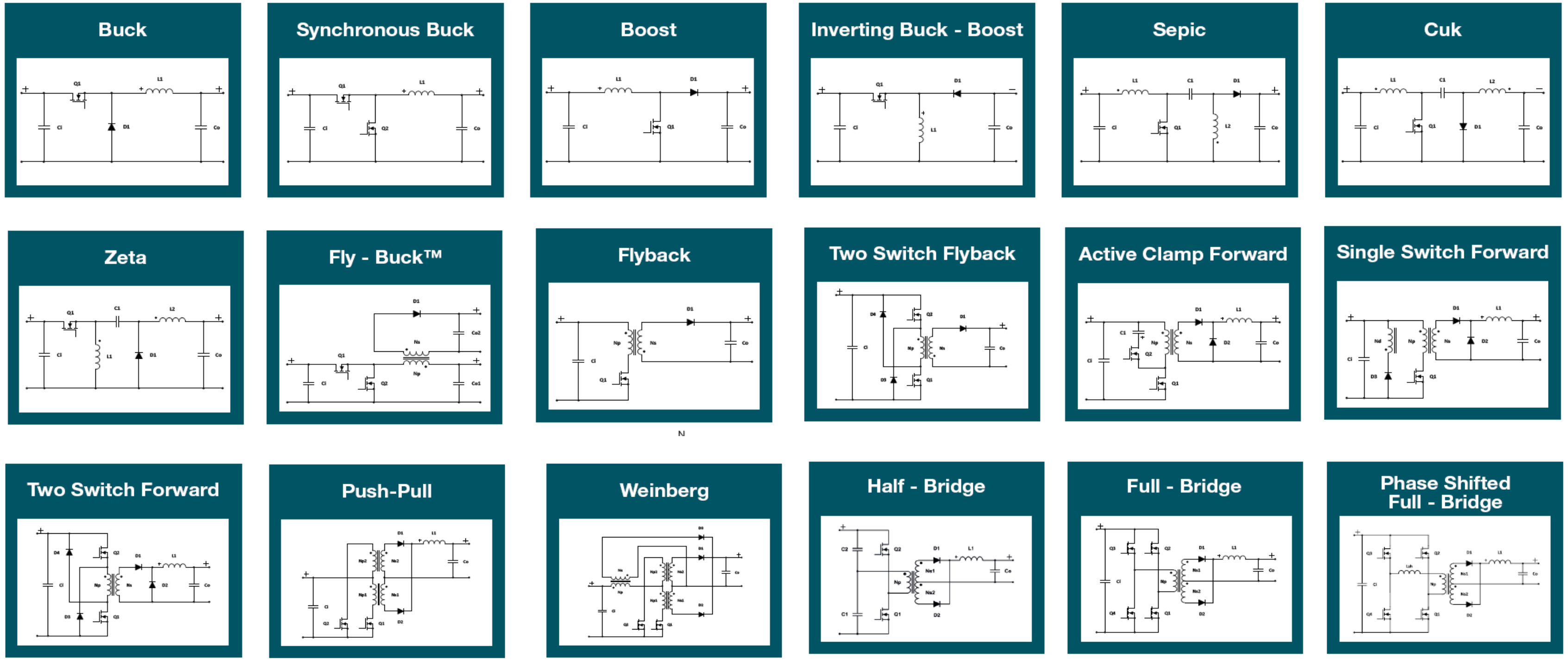
Voltage/Power: <3kV

■ Classical low voltage DC-DC converter

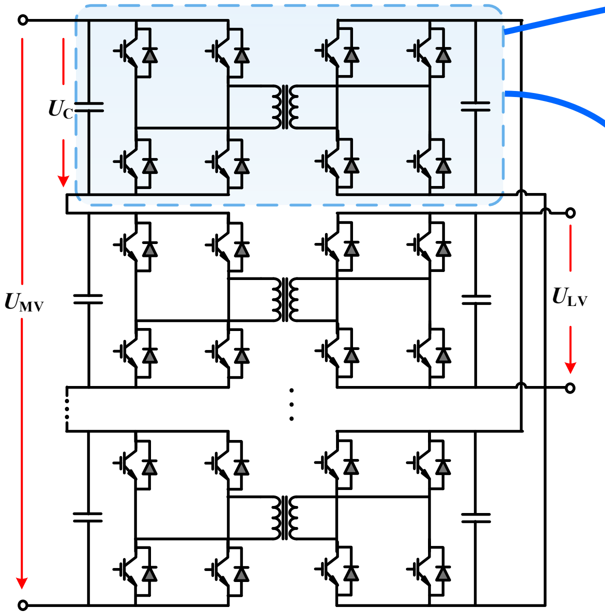
- Power supply applications under low voltage and low power
- Can’t readily be scaled up to hundreds of kilovolts and megawatt power ranges due to the limitations of losses, cost, dv/dt, filter and voltage ratings of the semiconductors



Existing high power step-up DC-DC converter

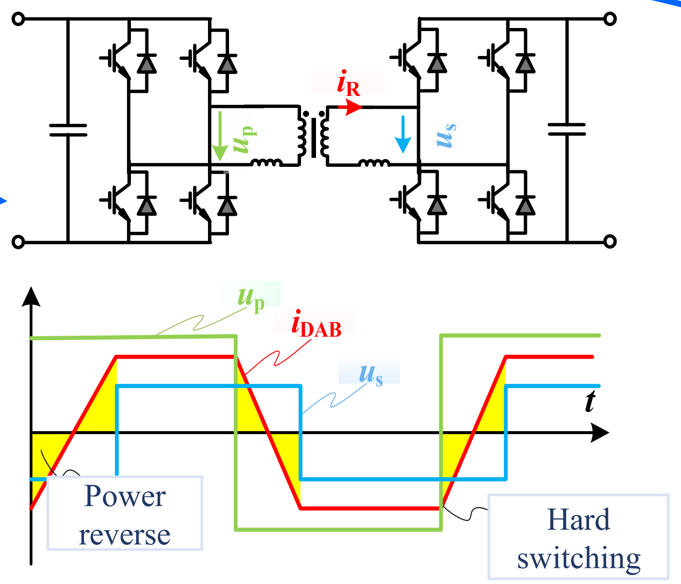
Voltage/Power: 3~50kV

■ Input-parallel output-series configuration



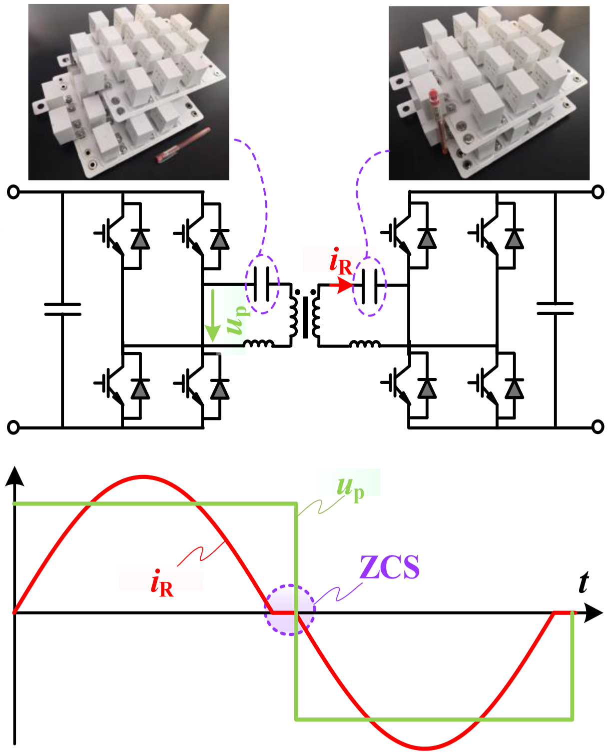
ISOP

- Two main power modules



①Dual active bridge (DAB)

- The circulating current
- Hard switching, high switching loss



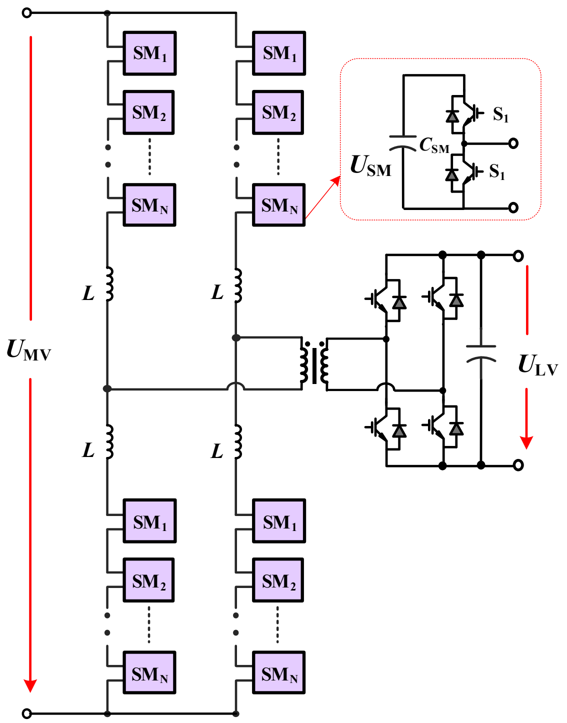
②Series resonant converter (SRC)

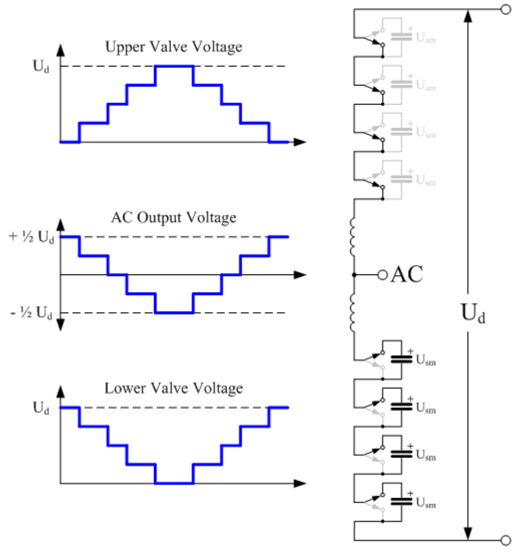
- Wide voltage regulation is not allowed
- Large number of high-voltage capacitors

➢ **A massive number of transformers with onerous requirement for high insulation** pcim ASIA SHANGHAI

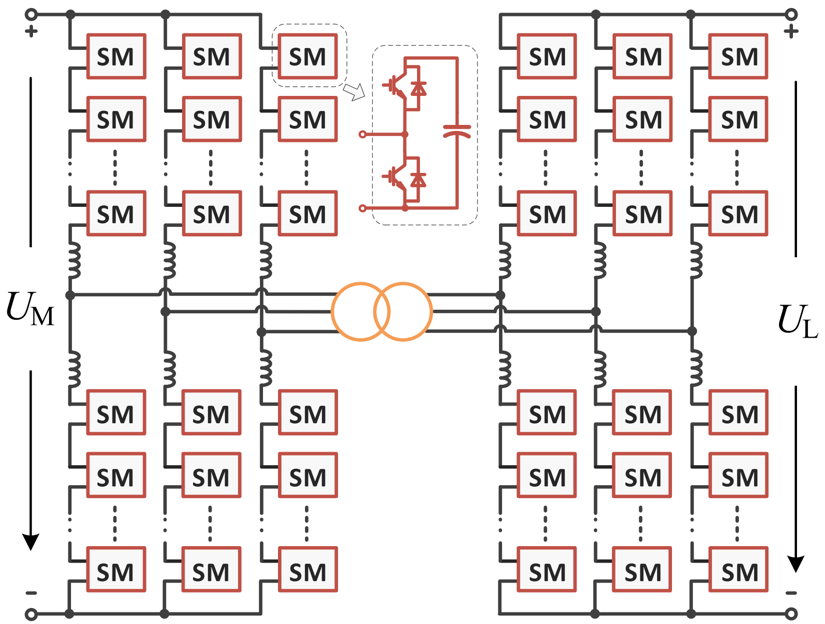
Voltage/Power: >50kV

■ DC-DC converter based on MMC





■ FTF-MMC



- **Many power devices and large losses**： half of the SMs are always bypassed at any time
- **A large capacitance and volume**： SM capacitors are charged or discharged by significant arm current for a long time
- **The step-down ratio is dependent on the transformer:** unsuited to wide voltage regulation

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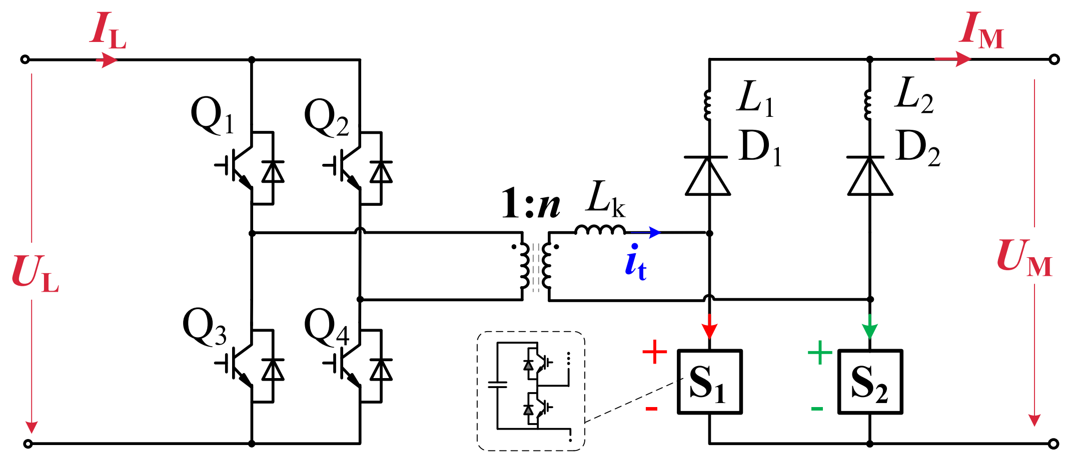
The proposed topology and operation principle

■ The proposed High-Power Step-Up DC Transformer topology



- **Diode**
  - ✓ low conduction loss
  - ✓ high-power density
  - ✓ high current rating
- **Arm:**
  - ✓ high controllability of the voltage and current waveforms
  - ✓ ZCS-enabled IGBT operation
- **IGBT rectifier:**
  - ✓ Eliminates tail current losses
  - ✓ Reduces switching stress

- ■ **LVDC side：IGBT rectifier**
- ■ **Transformer：around 500Hz**
- ■ **MVDC side：Diode valves + Arms (cascaded by half bridge SMs)**

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The proposed topology and operation principle

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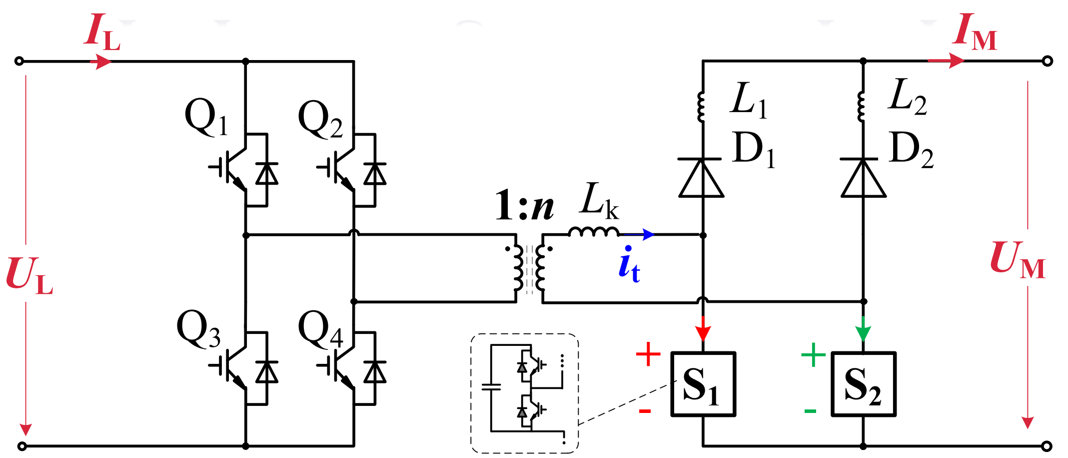
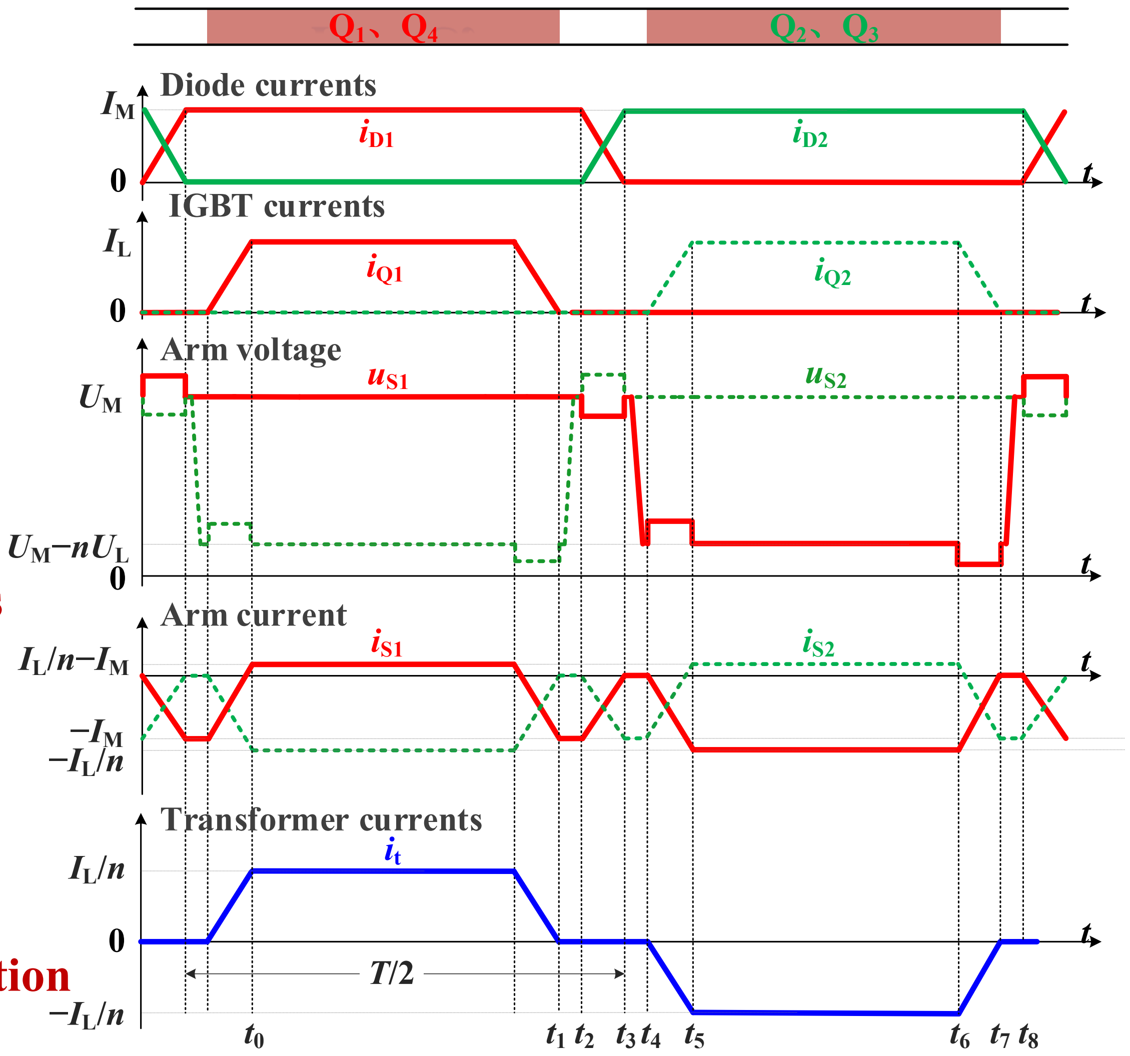
■ The proposed High-Power Step-Up DC Transformer topology





■ **Output Current waveforms design：**

Interleaved trapezoidal waveform → smooth DC currents

■ **Voltage modulation：**

Similar to two-level modulation → lower capacitance

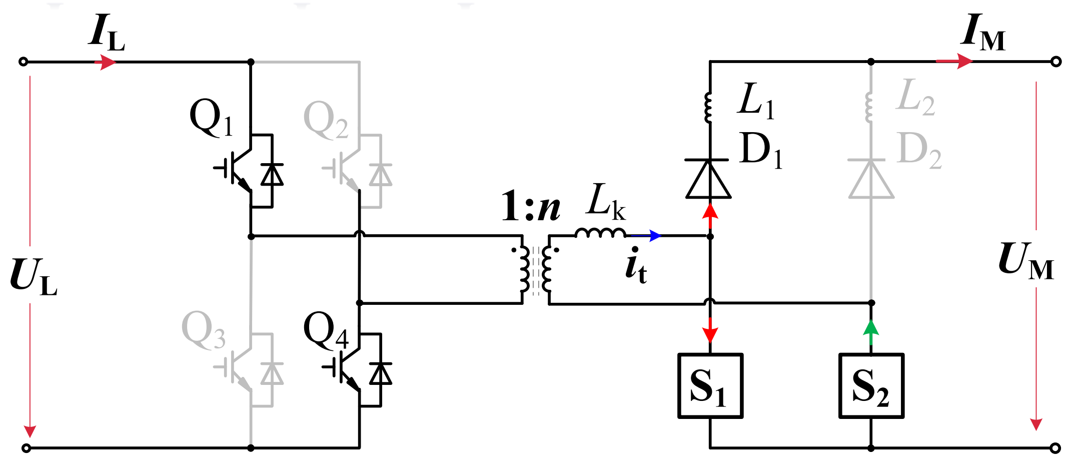
■ **High controllability of the arms**

Arm coordinated commutation → IGBTs ZCS

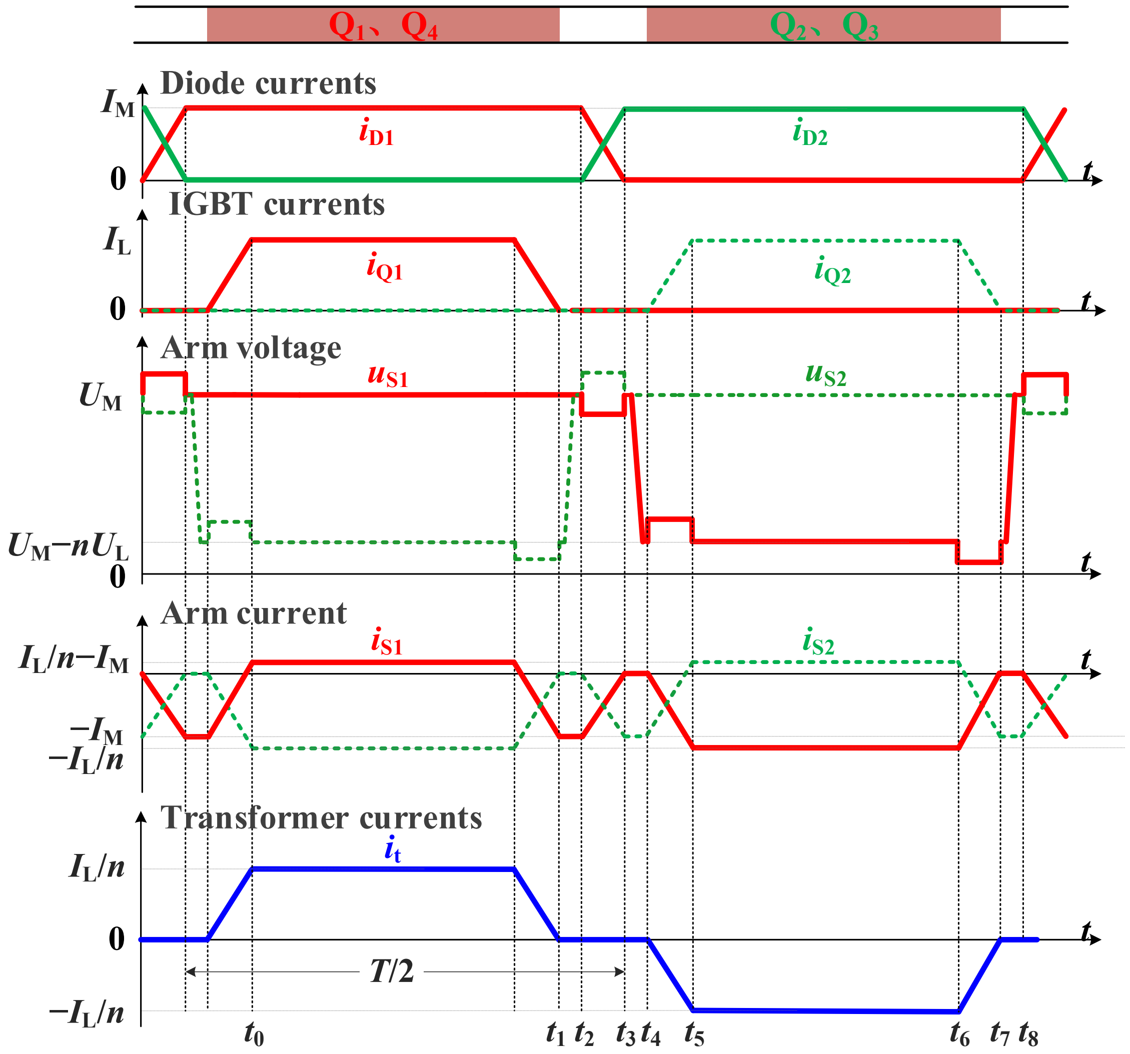
Adjust the duty cycle of SMs → wide voltage range regulation

The proposed topology and operation principle

■ Operation principle



(a) t_0~t_1

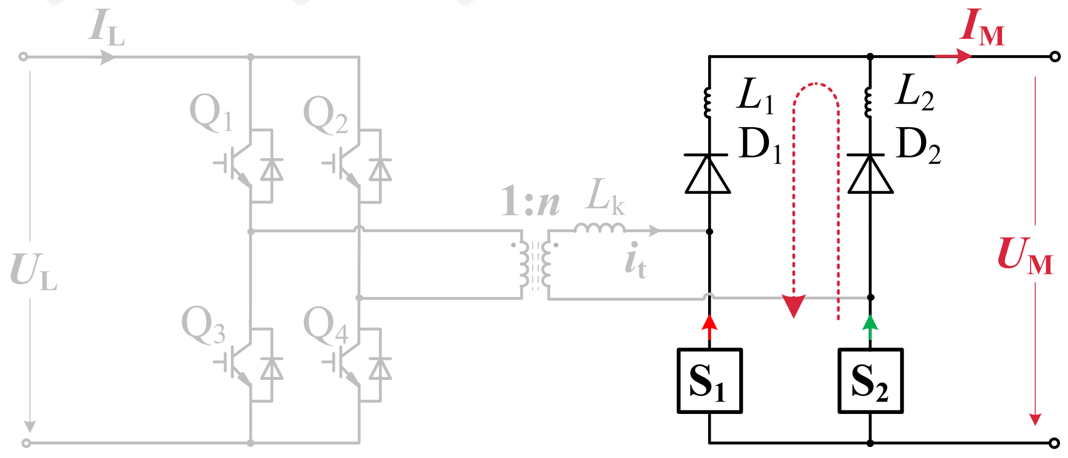


■ Constant current stage:

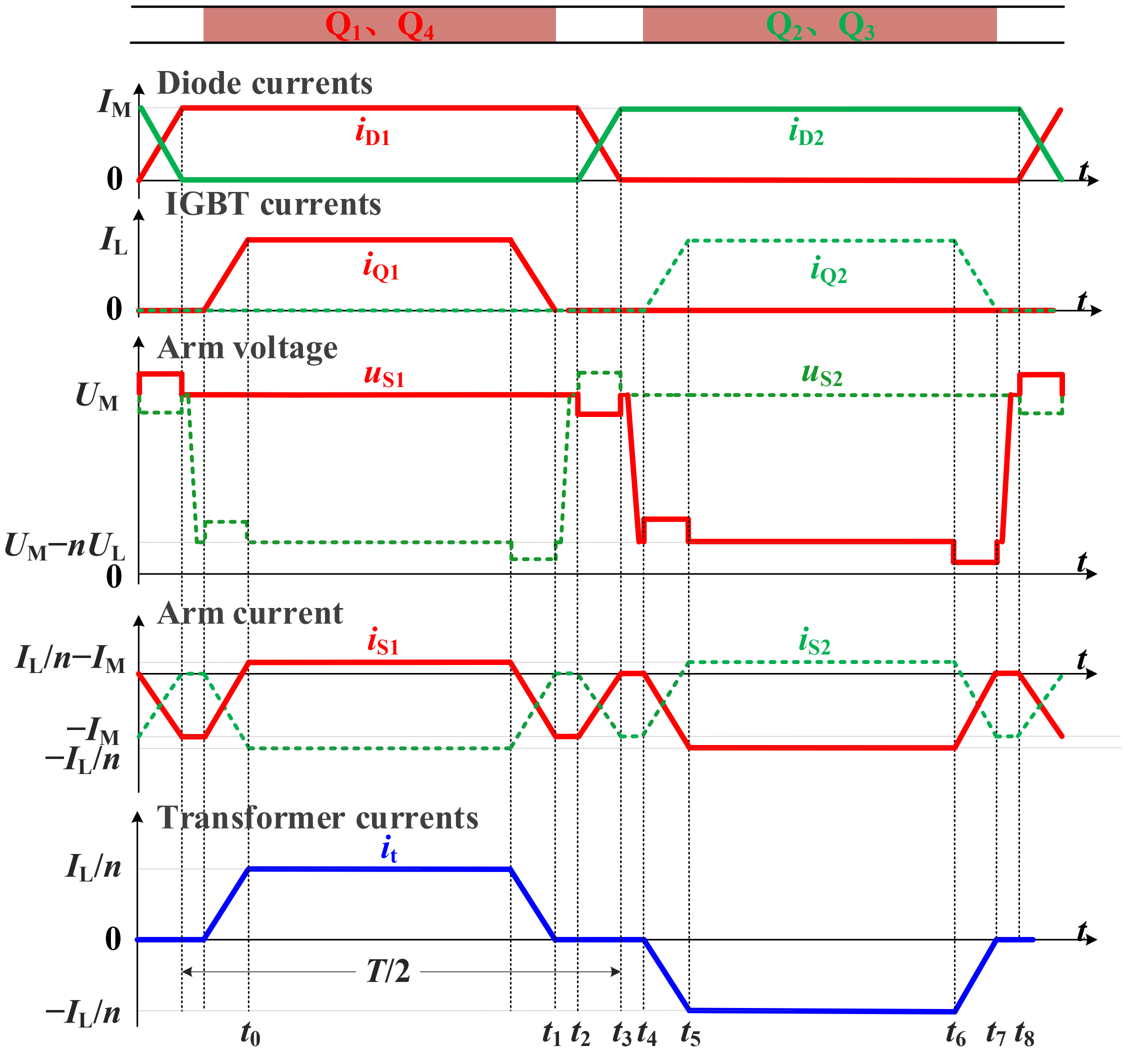
- Two IGBTs Q_1 & Q_4 ($i_{Q1}=I_L$) , and one diode D_1 are in on-state ($i_{D1}=I_M$)
- One arm S_1 needs to support the MV-side voltage ($u_{S1}=U_M$)
- Another arm S_2 needs to control transformer current, sustains the voltage difference ($u_{S2}= U_M-nU_L>0$)

The proposed topology and operation principle

Operation principle



(b) $t_1 \sim t_4$

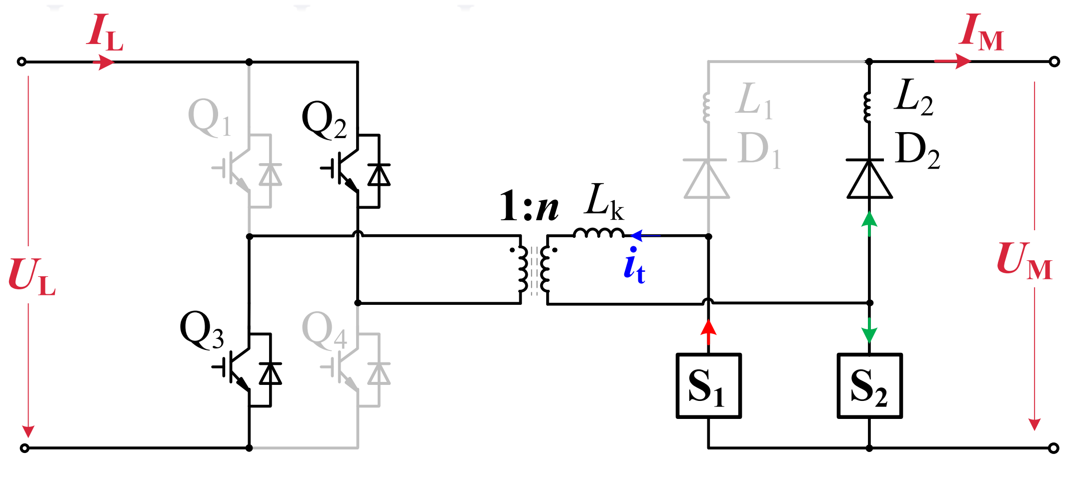


Diode Commutation Stage:

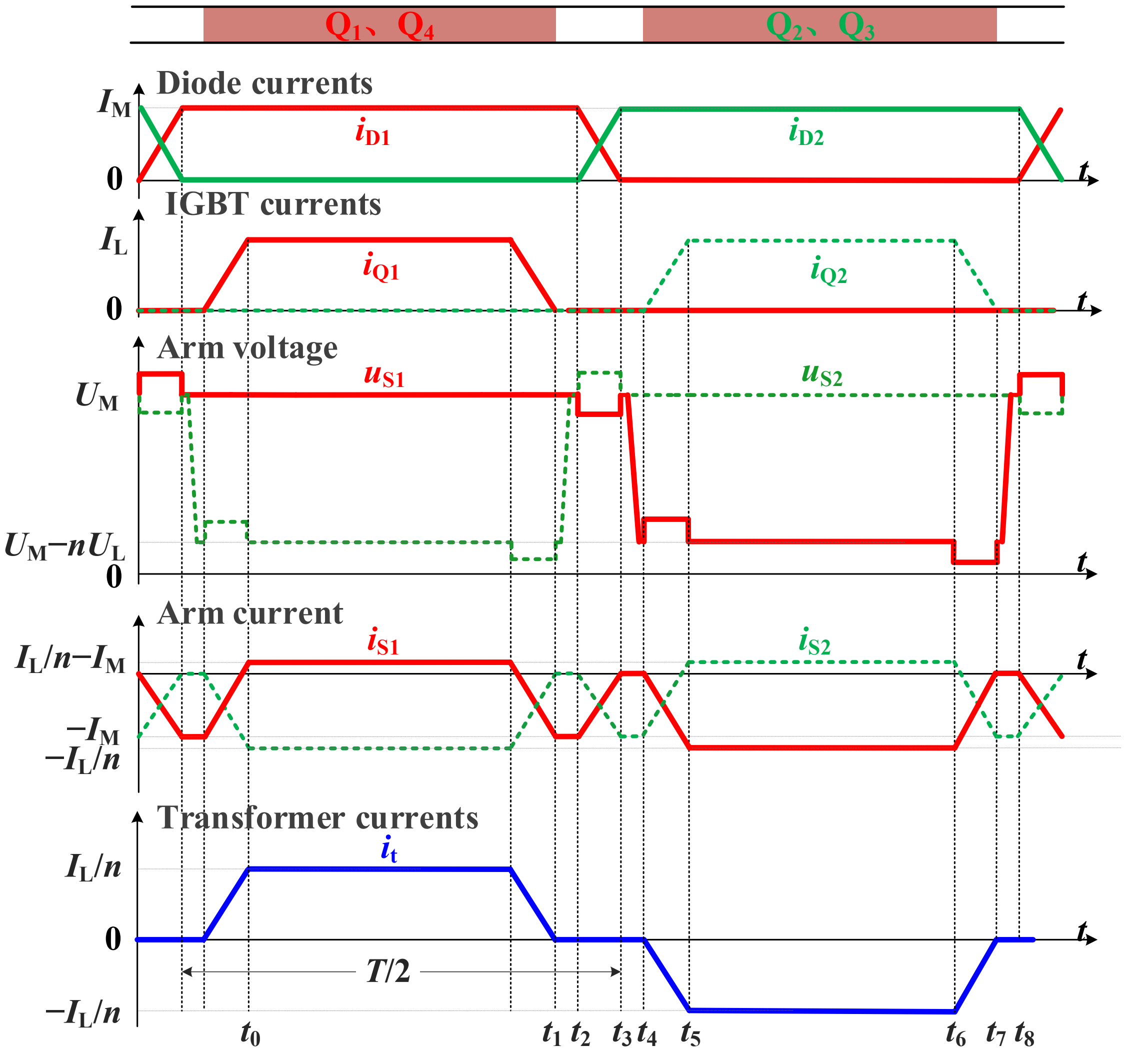
- Arms produce opposite voltage (U_D) across corresponding diode. Inductors L_j of the two phases → linear commutation
- One diode D_2 current rises from 0 to I_M, where the other diode D_1 falls from I_M to 0 with the same rate

The proposed topology and operation principle

Operation principle



(c) t_4~t_7



IGBT Commutation Stage:

- Arms produce opposite voltage (U_Q) across corresponding IGBT leakage inductors L_k
- IGBT Q_2&Q_4 current rises from 0 to I_M
- IGBT conduction duty cycle determines the operating frequency

$$D = \frac{T - 4(T_u + T_c)}{T}$$

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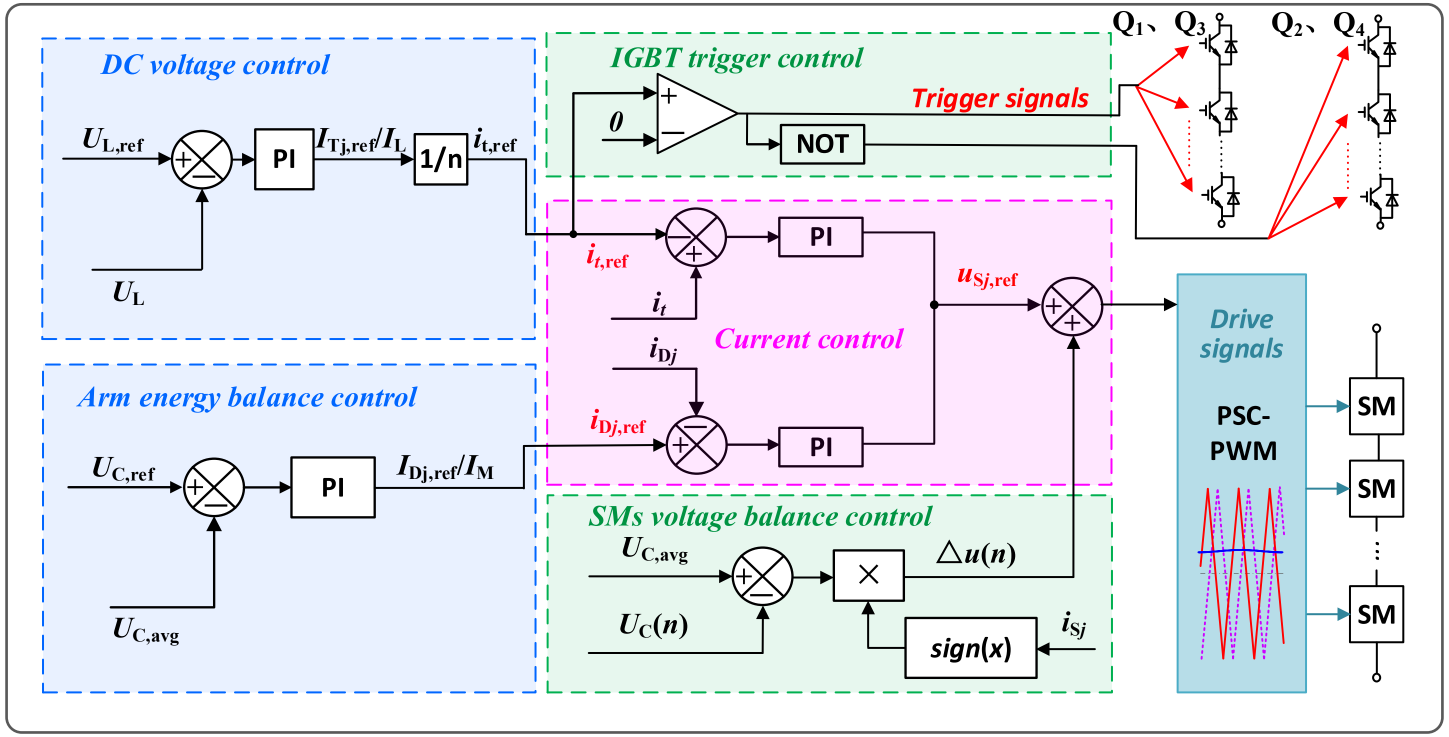
Control strategy



- **DC voltage control & the arm energy balance control**
  - Generate transformer current and diode current reference signals $i_{t,ref}$ & $i_{Dj,ref}$
- **Current control**
  - $i_{j,ref} - i_{Dj,ref} = i_{Sj,ref}$, perform closed-loop control on the bridge arm current and diode current. Then with the voltage feedforward control, the arm voltage modulation wave is obtained.
- **SMs and IGBT valves control**
  - PWM modulation & capacitor voltage balanced control → SMs driving signals & trigger signal of IGBT valves.

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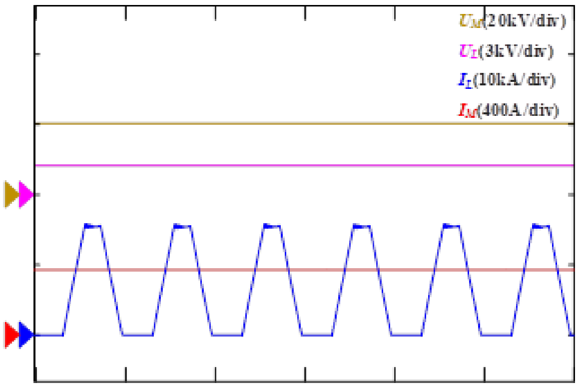
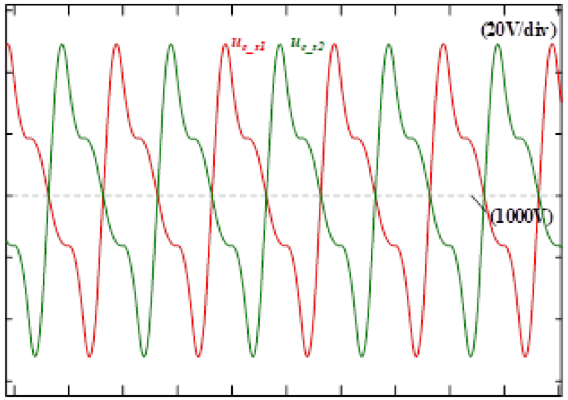
Simulation Verification

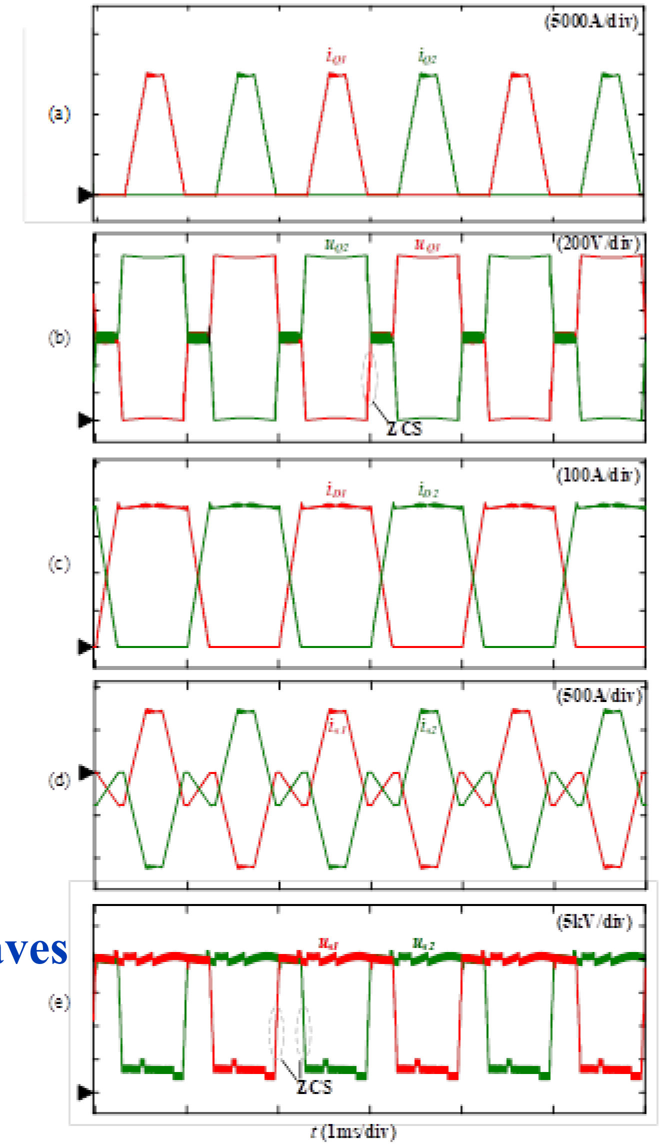
■ Steady state simulation results

Simulation parameters

Parameters	Simulation
Power rating P	7.8MW
LV-side voltage U_L	1.2kV
MV-side voltage U_M	20kV
Transformer frequency f	500Hz
Transformer turn ratio n	1:14
No. of SMs per arm N	25
Duty cycle of IGBT conduction α	0.42
SM capacitance C_{SM}	1.92mF
Average SM capacitance C voltage U_C	1kV
PWM carrier frequency f_{sw}	2500Hz
Inductance L_j	200uH
Leakage Inductance L_{kj}	100uH
Commutation time T_c	240us
Voltage changing time T_u	50us







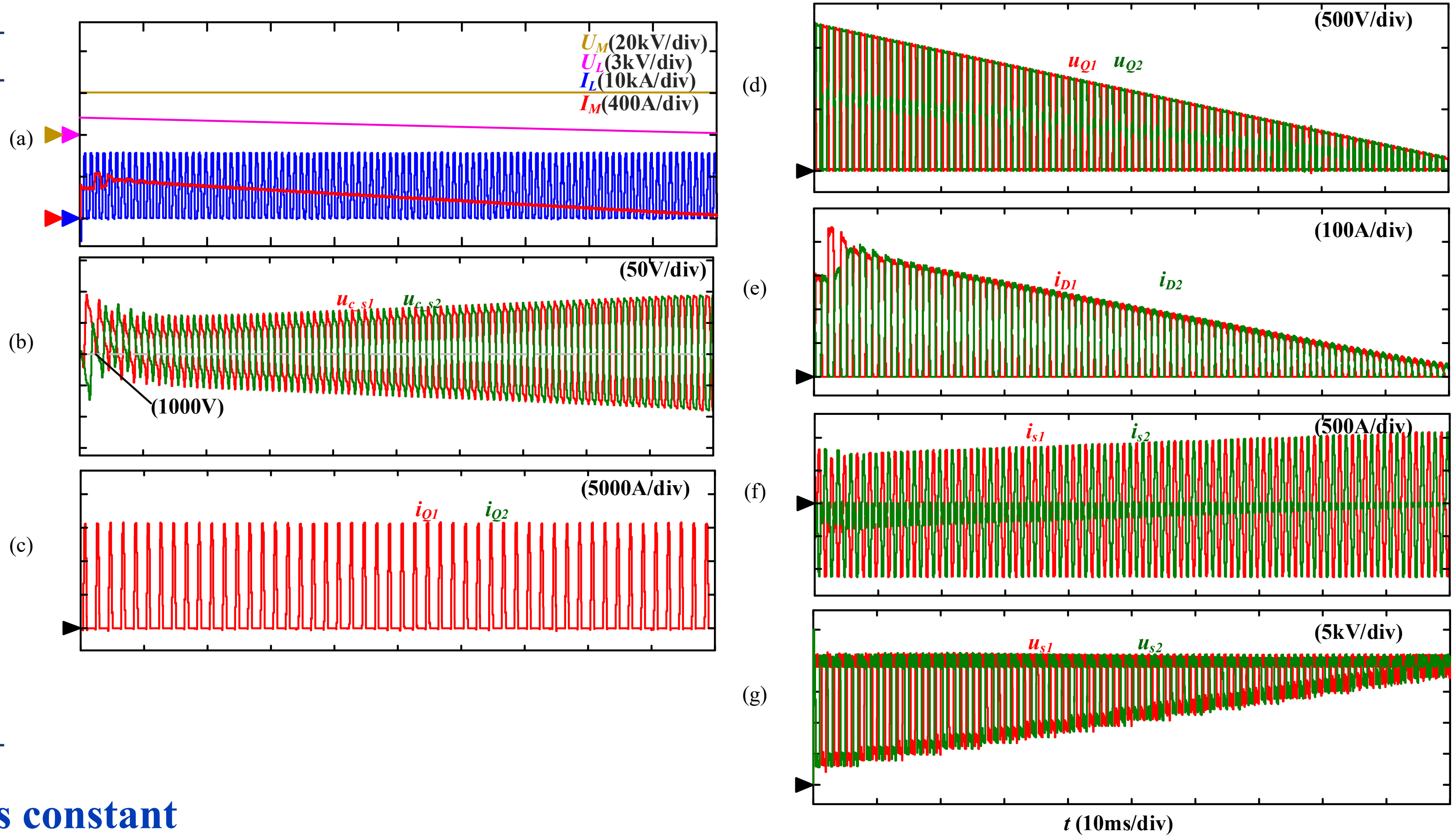
- The current of the transformer and the diode are interleaved trapezoidal waves
  →I_M is continuous and smooth
- The commutation process of IGBT and diode are linear.
- LV side IGBTs and SMs achieve ZCS

Simulation Verification

■ Dynamic simulation results

Simulation parameters

Parameters	Simulation
Power rating P	7.8MW
LV-side voltage U_L	1.2～0kV
MV-side voltage U_M	20kV
Transformer frequency f	500Hz
Transformer turn ratio n	1:14
No. of SMs per arm N	25
Duty cycle of IGBT conduction α	0.42
SM capacitance C_{SM}	1.92mF
Average SM capacitance C voltage U_C	1kV
PWM carrier frequency f_{sw}	2500Hz
Inductance L_j	200uH
Leakage Inductance L_{kj}	100uH
Commutation time T_c	240us
Voltage changing time T_u	50us



- U_L changes in a wide range, U_M is constant
- Linear commutation, ensuring the smooth transition
- As U_L decreases, the capacitance voltage fluctuation of the SM will increase.

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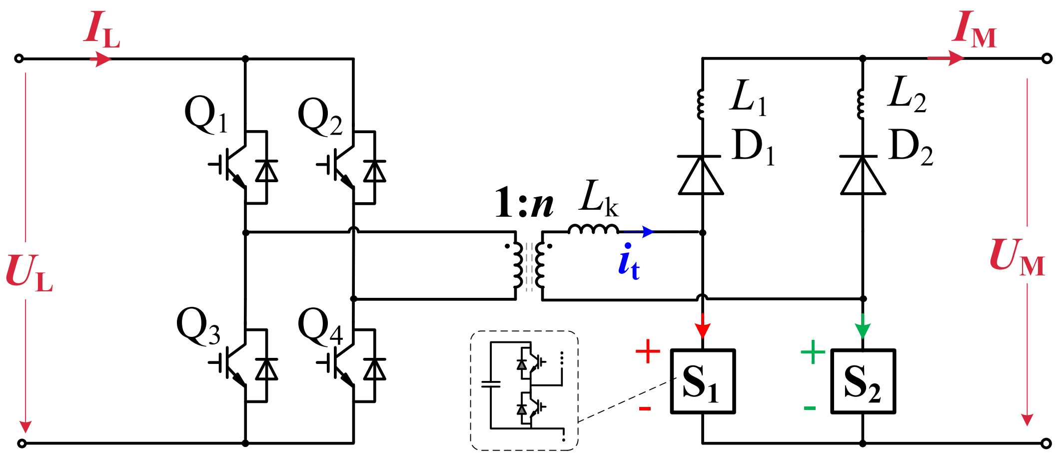
Conclusion



- **Topology combines the modular multilevel arm, IGBTs and diodes with low cost and high power density, which has the advantages of high efficiency, low cost and light weight.**
- **The IGBTs on the LVDC side achieve zero-current turn-off with a wide soft-switching range, eliminating the drawbacks of high turn-off losses and current stress caused by IGBT tail current, thereby enhancing the efficiency and reliability of the DC transformer.**
- **On the MVDC side, a combination of diodes and submodule arms is adopted, this configuration enables wide voltage range regulation and high-quality current control.**

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Thanks for your attention!

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24 September 2025

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