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Solid-State Power Filters: Reducing Passive Components by Power Electronic Devices

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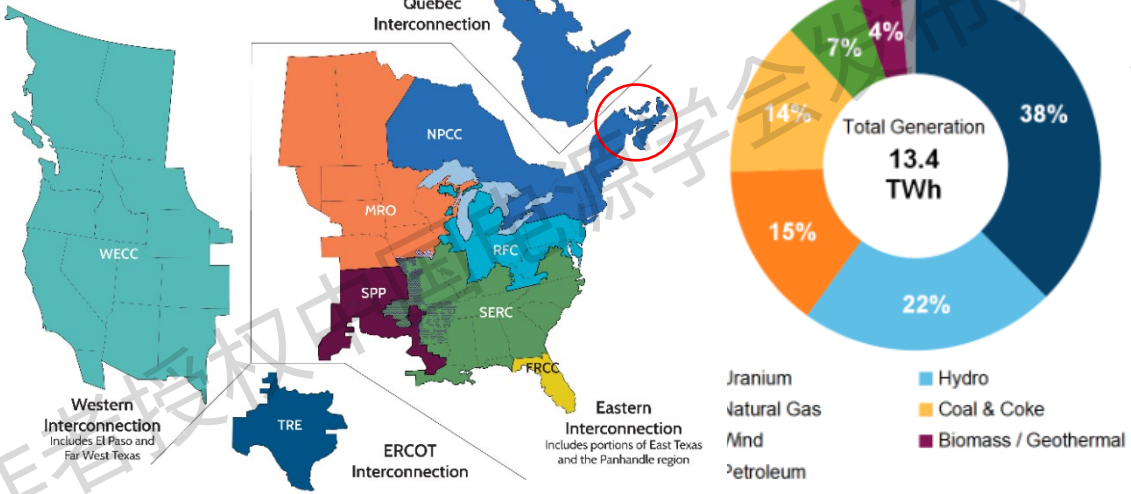
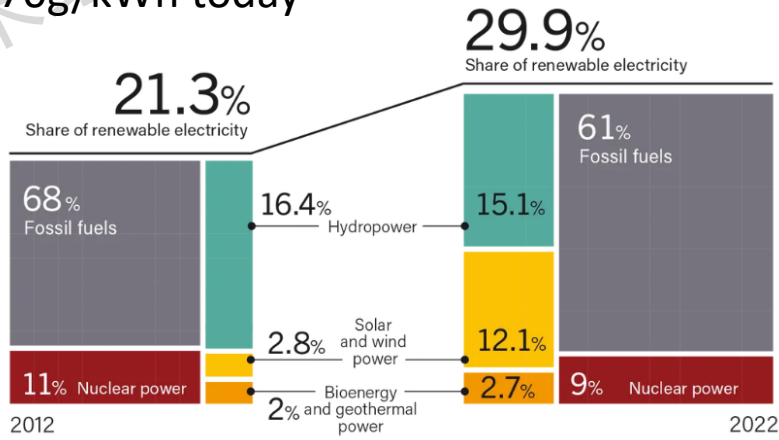
Contents

- **Distributed Energy Resources (DERs) – a bigger picture**
- **Highlights of Power Electronic Technologies for DERs - zoomed**
- **Solid-State Power Filters in DER Inverters - focused**

NB Power GHG emissions: 450g/kWh in early 2000's to 270g/kWh today





Courtesy of: *REN21, "RENEWABLES 2023 GLOBAL STATUS REPORT."*

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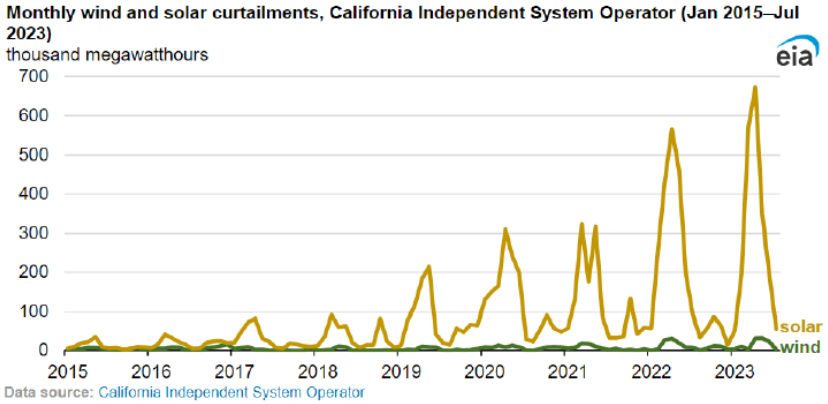
System Operation: Resources for Ancillary Services

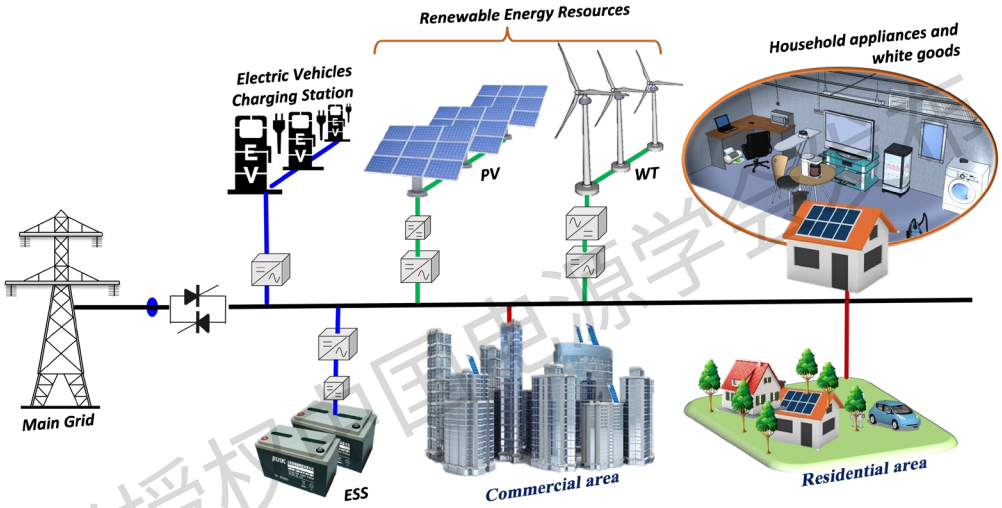


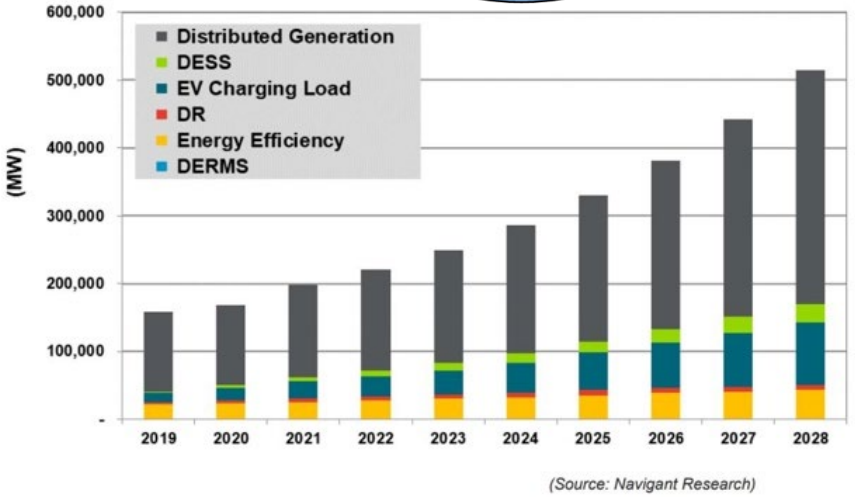
Capacity-Based Operational Resources

Need more flexible resources

Distributed Energy Resources (DERs)

- DER: distributed generation (DG) systems (the largest share now), electricity storage facilities (incl. EVs), managed loads (e.g. demand response, energy efficiency, indirectly & directly controlled loads)





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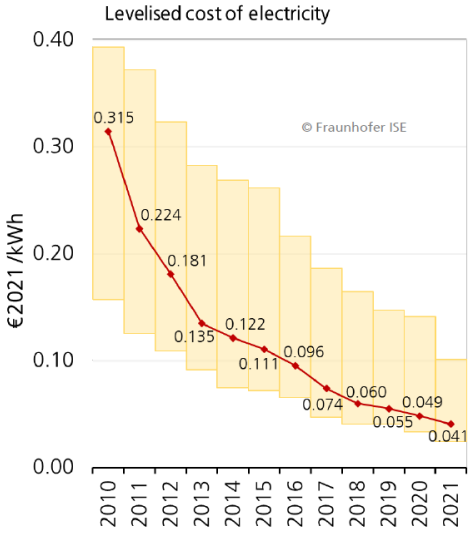
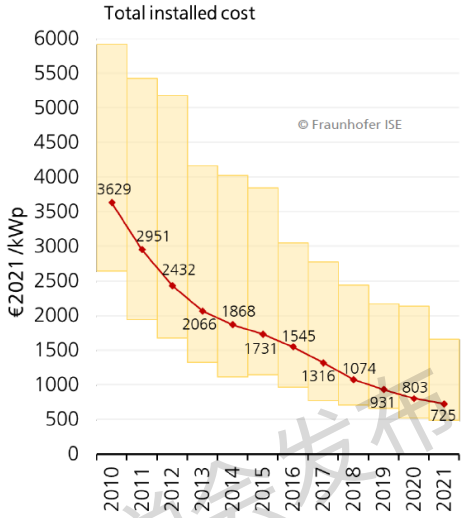
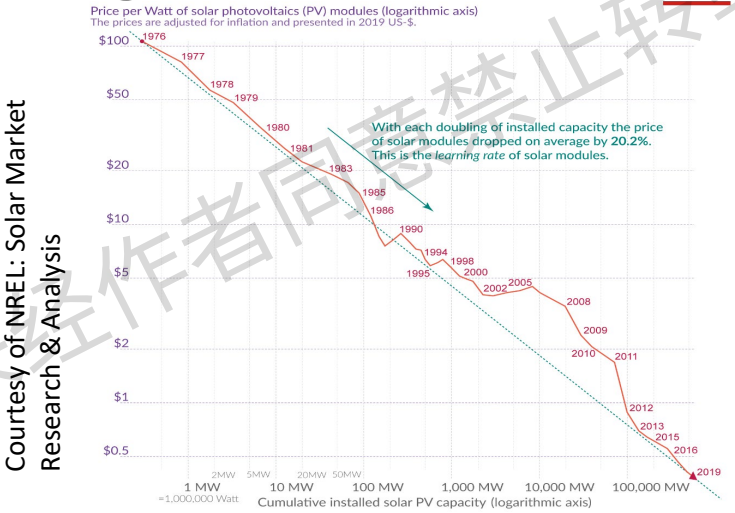
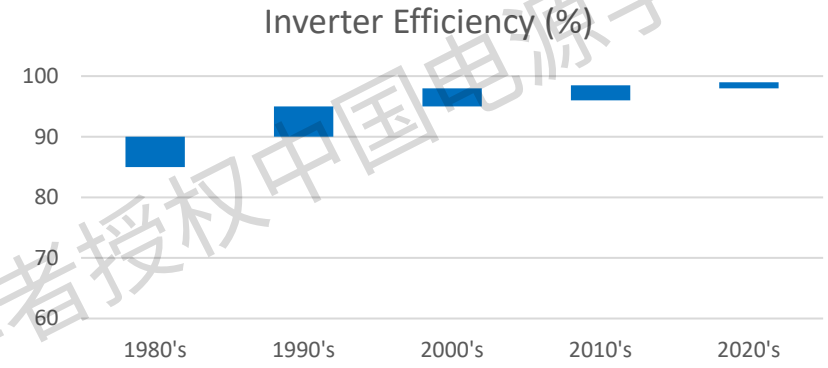
DER: Dropping Prices and Improving Performance



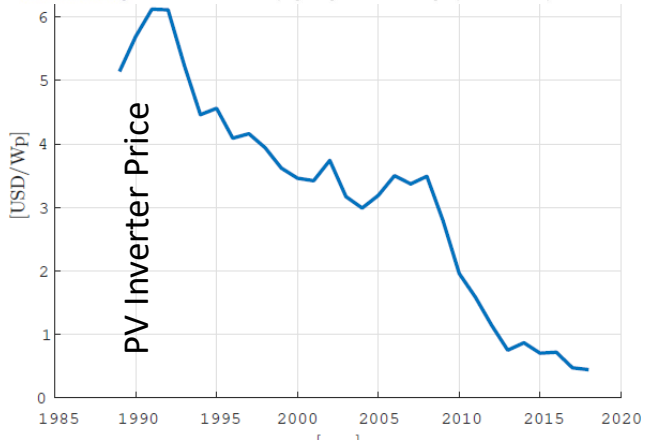




Courtesy of NREL: Solar Market Research & Analysis



Courtesy of "Real options valuation of photovoltaic power investments in existing buildings", Renewable and Sustainable Energy Reviews, October 2019

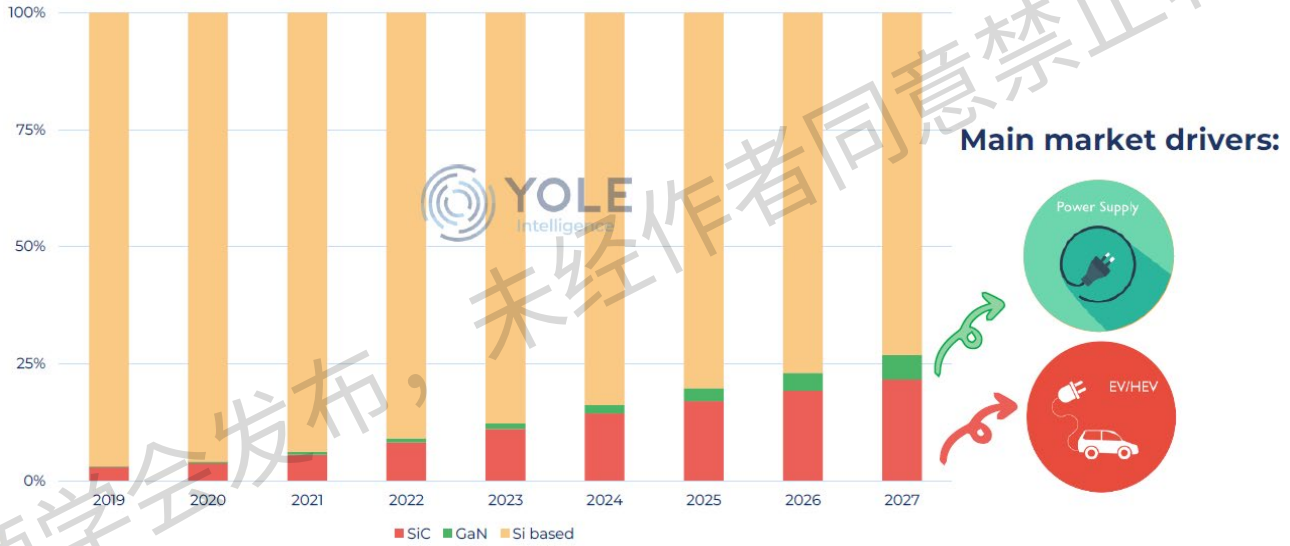


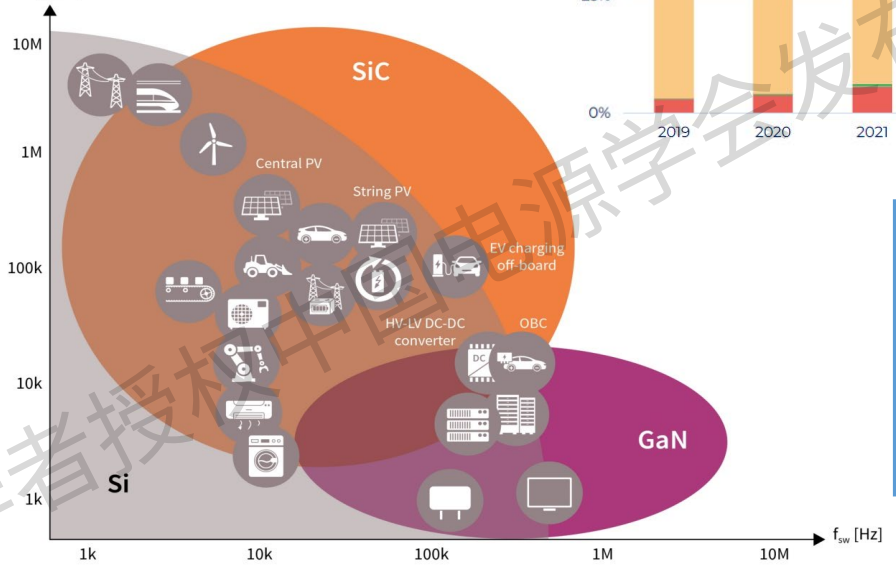
Wide Bandgap Power Semiconductors

25W, $100 1990's

55W, $50 2000's

65W, $16 2023





SiC/GaN devices enable **more efficient, lighter, smaller form factor** power converters operating at high frequencies, and at elevated temperatures with reduced cooling.

Evolution of Standards – Increasing Grid Support Functions of DERs

1990's

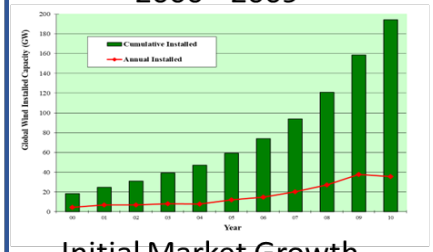
Electricity Market Deregulation
Very small DER market

IEEE 519-1992
ANSI C84.1-1995
UL 1741-1999

Compliance with power system specifications:

Voltage range
Frequency range
Synchronization
THD (harmonics)

2000 - 2009



Initial Market Growth
Lead: wind energy

IEEE 929-2000
IEEE 1547-2003
UL 1741-2010
CSA C22.2 No.107.1-01

+ Safety & protection:
Not to regulate voltage
Anti-islanding

+ Power quality:
THD&TDD (harmonics)
DC injection

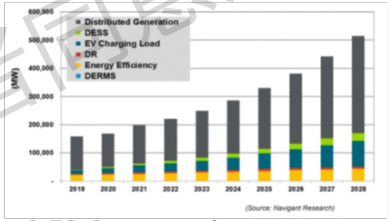
2010 - 2019

Accelerated DER Growth
Lead: solar (PV) energy

IEEE 1547a-2014 & 2018;
IEEE 2030.2
UL 1741 SA & CA Rule 21
CSA C22.3 No.9 (Canada)
EN 50438:'13, EN 50549:'19

+ System support functions:
V & f regulation
V & f ride-through
Power curtailment
Ramp rate
Wider power factor

2020 & Beyond

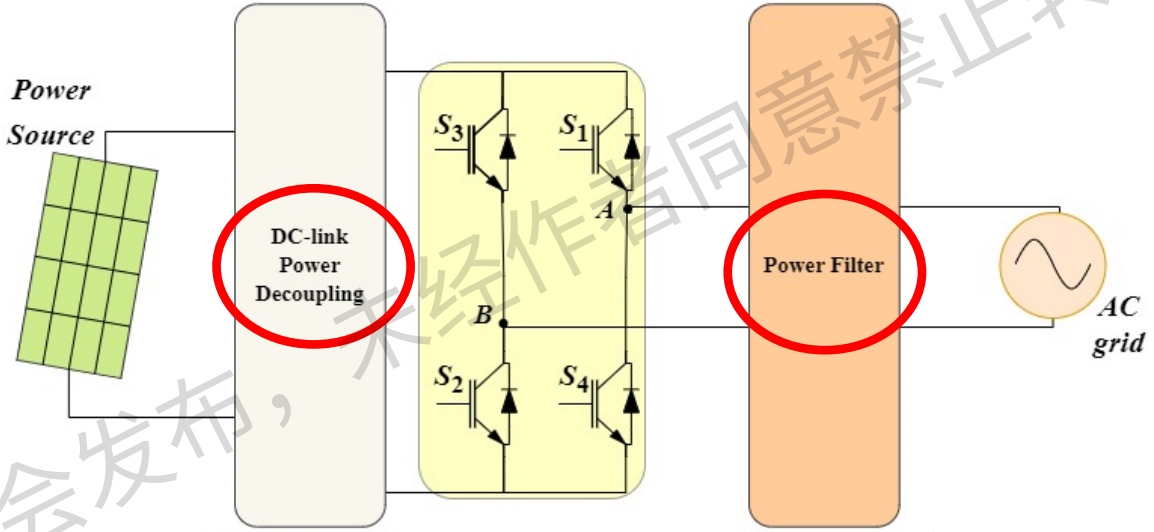


DER Penetration
Lead: energy storage/EVs

IEEE 1547a-2020
IEEE 2030.11-2021
IEEE P2800

+ More flexibility/functions:
Interoperability
Communication
Management

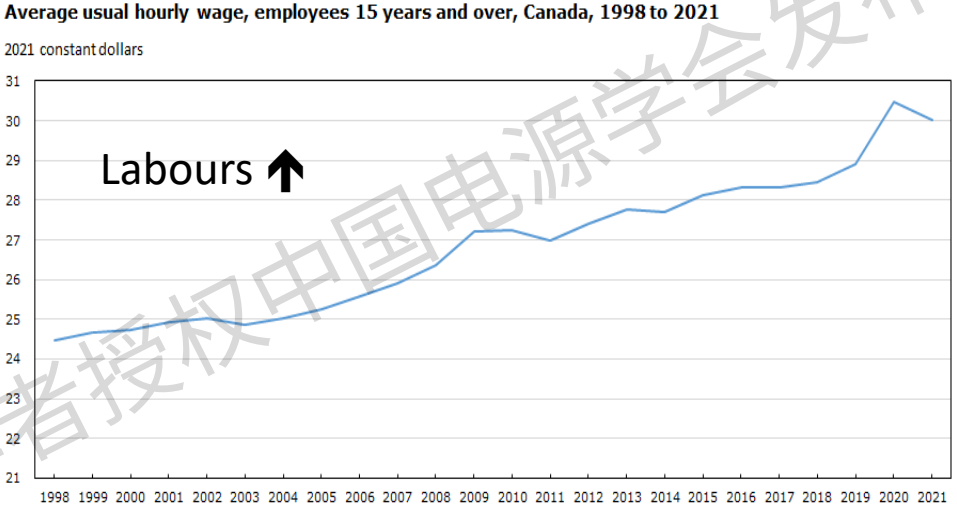
Traditional DER Inverters – to be improved



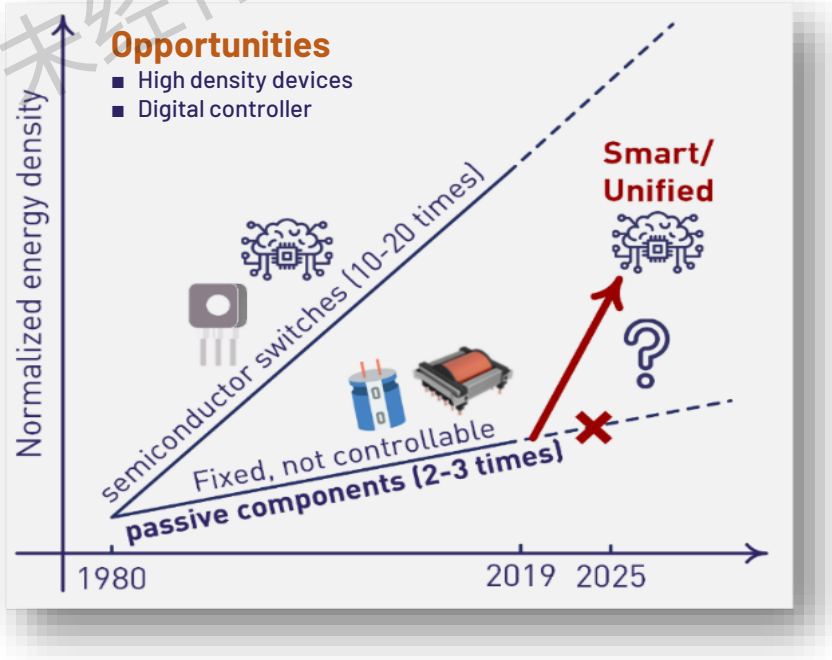
Passive Power Filters:
20% ~ 40% volume

Passive → Solid-State Power Filters?

Costs Are an Issue, but Opportunities Exist

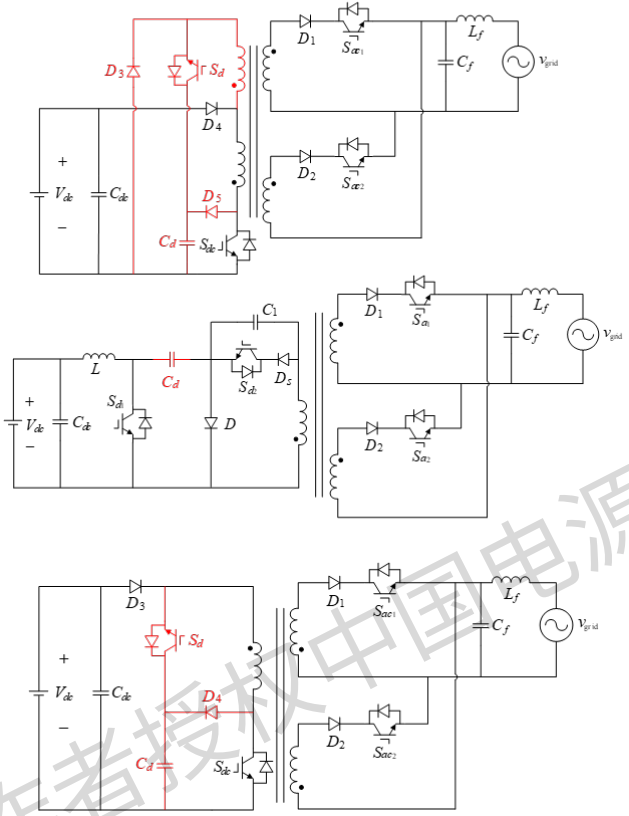


- Costs of active components are still high as compared to passive components at the DER converter level

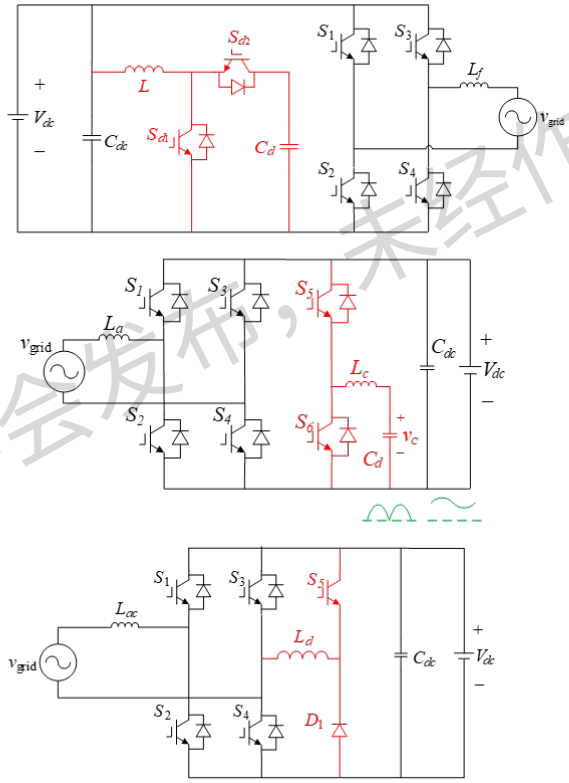


Active Power Decoupling: replacing large electrolytic capacitors

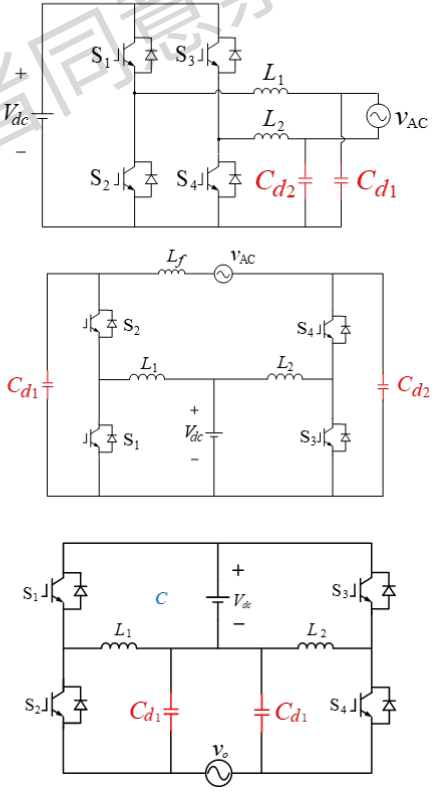
Flyback-type



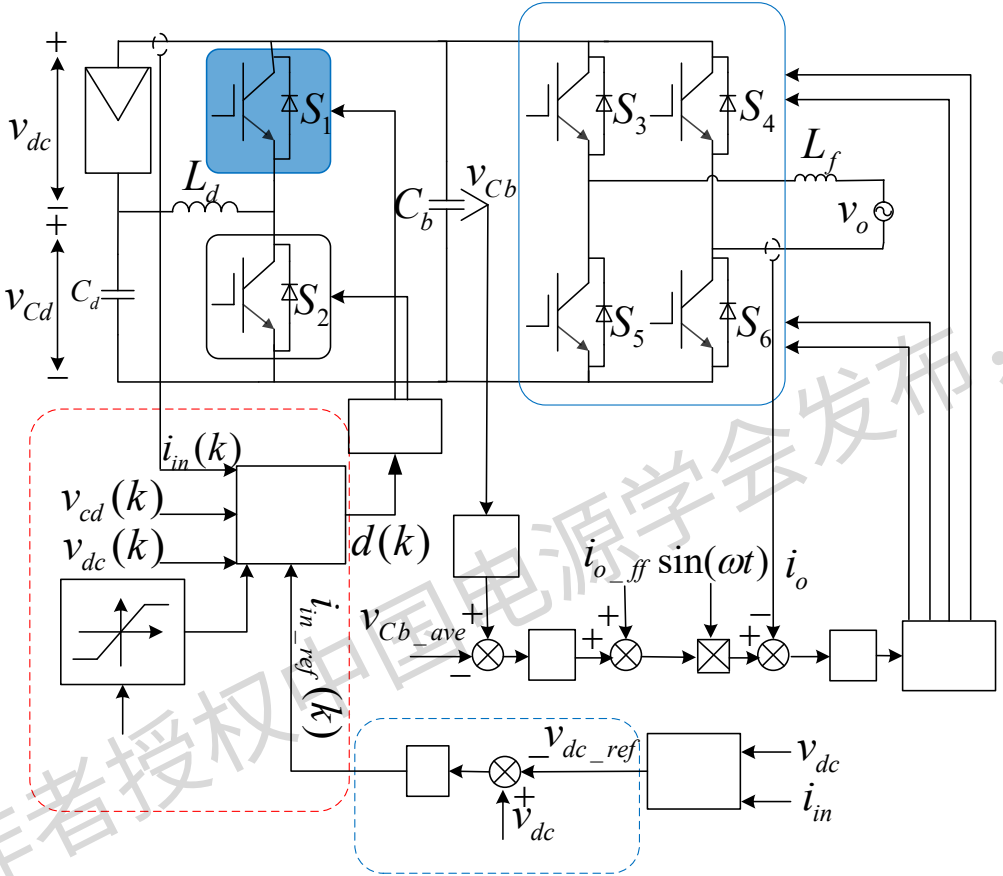
Bridge-type



Differential-type



Power Decoupling for PV Inverters



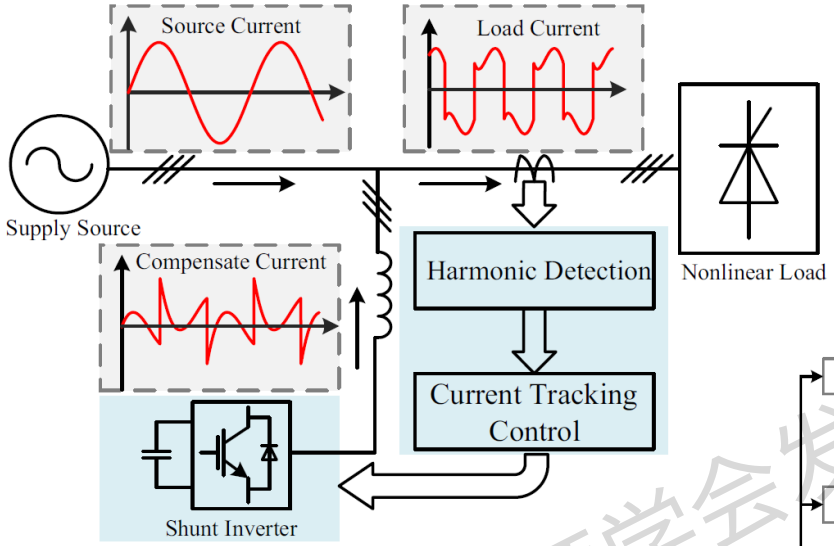
Opportunities to reduce dc link capacitance by 10 times

Electrolytic capacitors → Film capacitors

C_d	Decoupling capacitance	160 μF
C_b	DC-link capacitance	80 μF
f_{AC}	Output AC frequency	50 Hz
f_{sw}	Sw. freq. of bridge	20 kHz
f_s	Sw. freq. of front-end	40 kHz

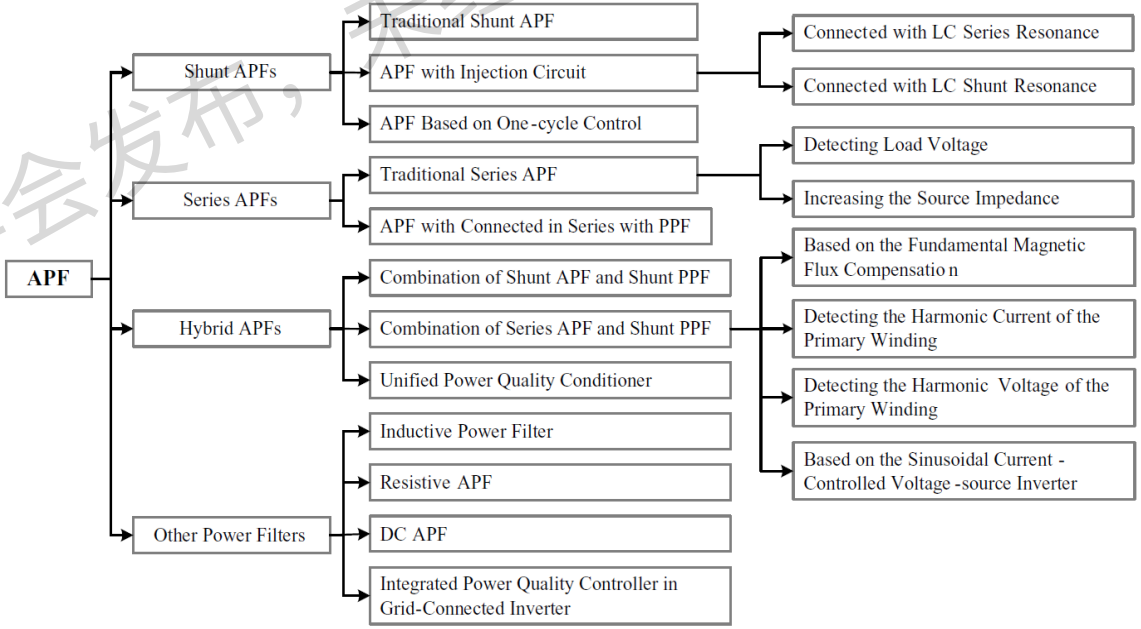
Output filters (grid-side) are still large and heavy → solid-state power filters

Active Power Filters – replacing passive PF

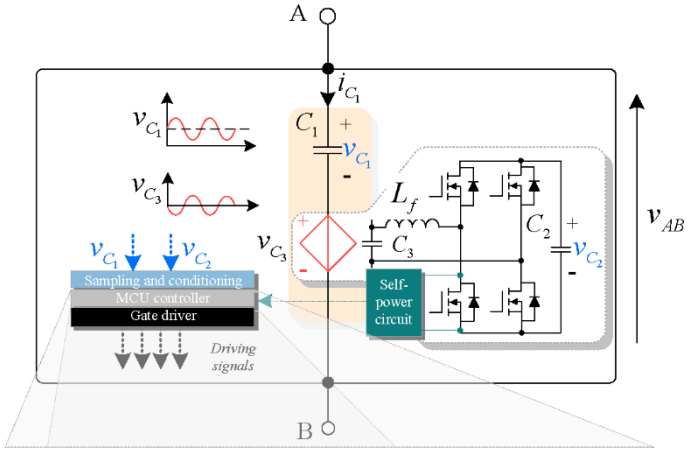


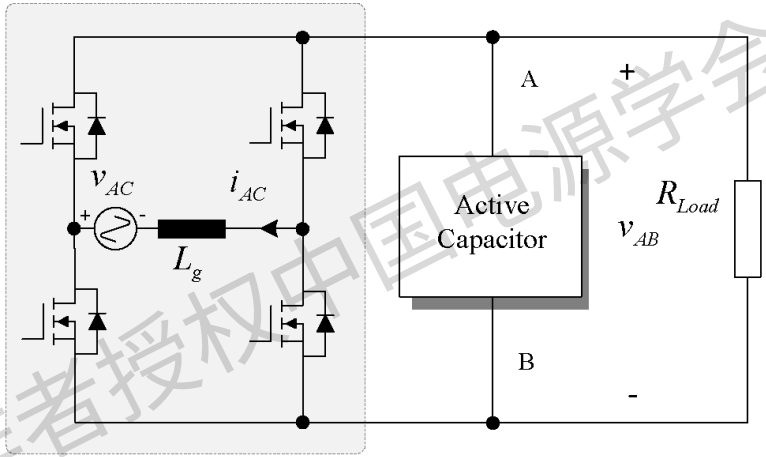
Mitigating power quality issues:

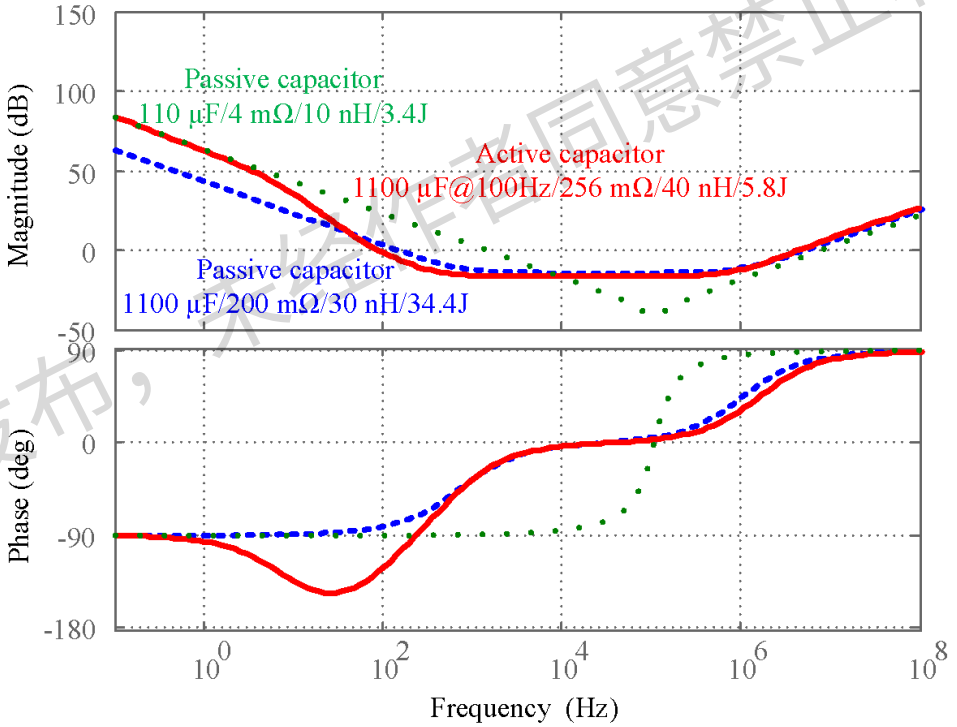
- Harmonics
- Reactive power
- Other power quality issues
- Generally used for power systems



Two-Terminal Active Capacitors

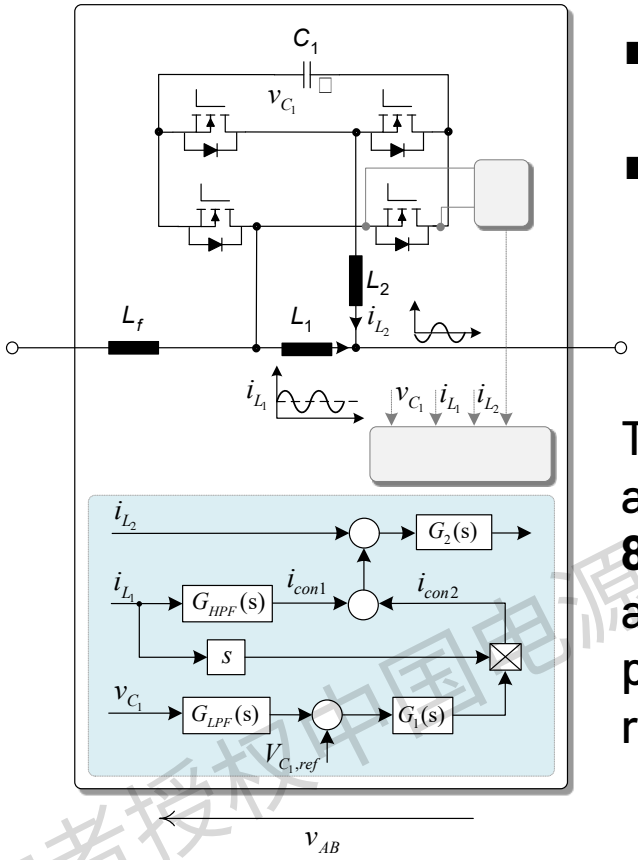






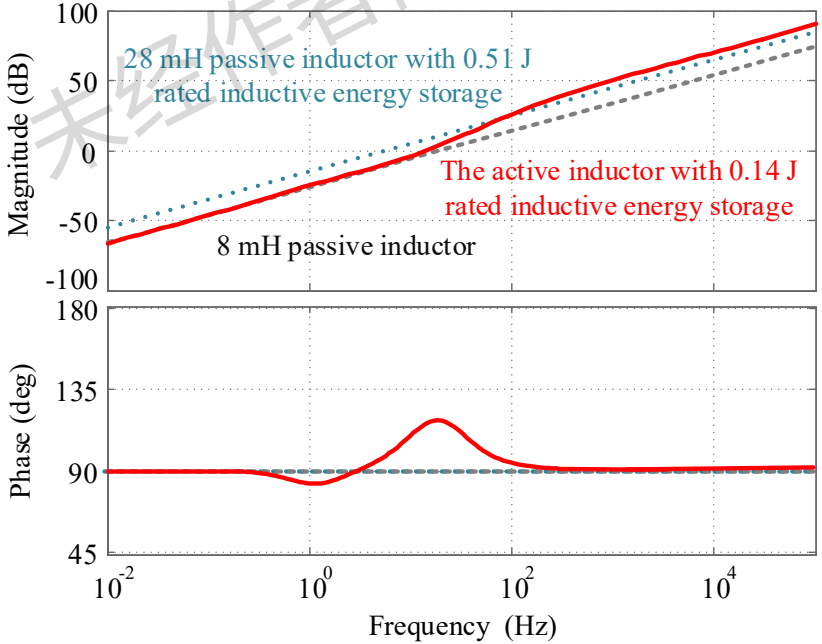
Source: Haoran Wang and Huai Wang, "A two-terminal active capacitor," IEEE Transactions on Power Electronics, vol. 32, no. 8, pp. 5893-5896, Aug. 2017.

Two-Terminal Active Inductor



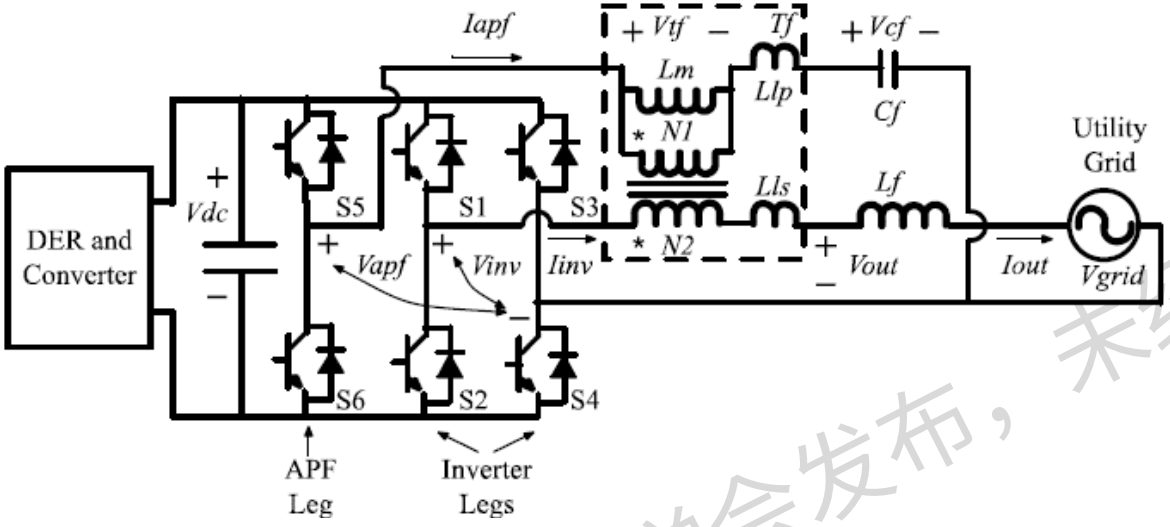
- Current control based on internal voltage and current information of the auxiliary circuit
- Similar impedance with passive inductor in frequency of interest

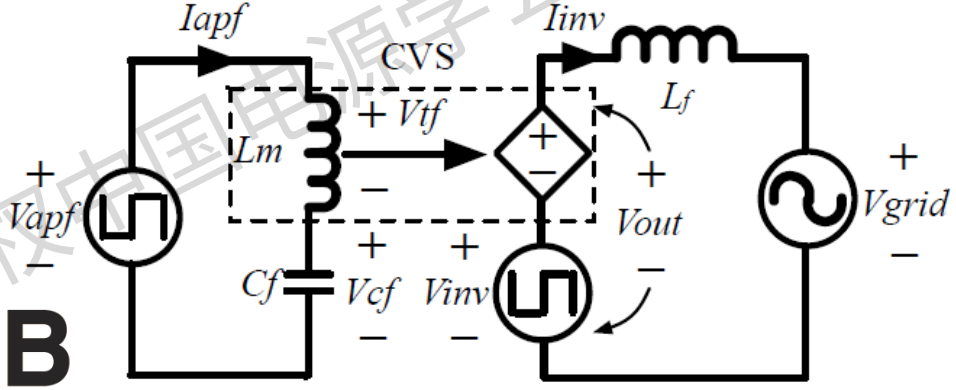
The cost, volume and weight are **80.6%**, **68.6 %** and **70.7 %** of the passive solution, respectively.



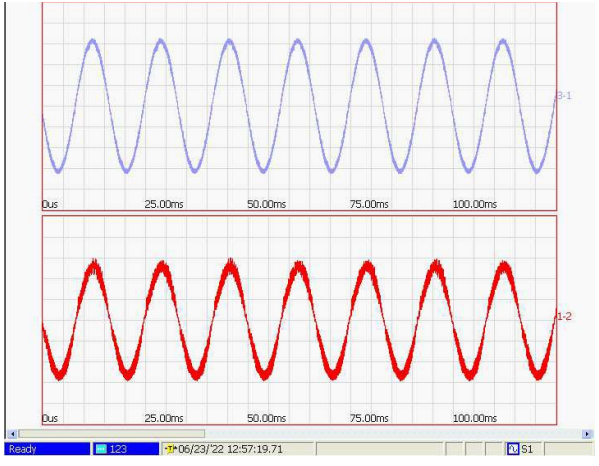
Source: Haoran Wang and Huai Wang, "A Two-terminal Active Inductor with Minimum Apparent Power for the Auxiliary Circuit," IEEE Transactions on Power Electronics, pp. 1013 – 1016, Feb. 2019.

Bridge Inverter with Active Power Filter

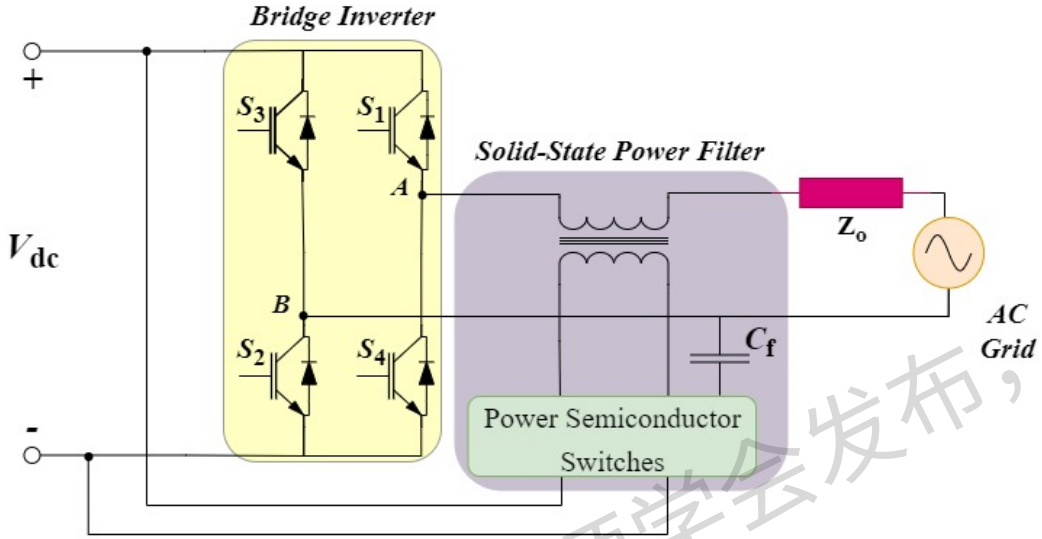




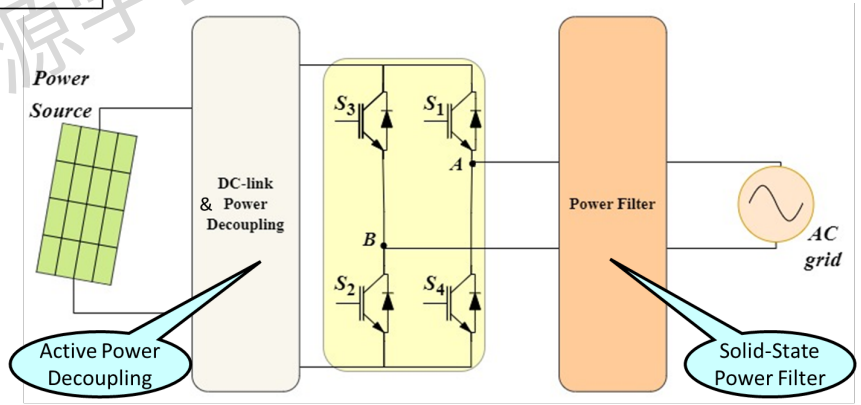
General Parameter	Value
Grid voltage V_{grid}	240 Vrms
Nominal grid frequency	60 Hz
DC-link voltage V_{dc}	400 V
Switching frequency	10 kHz
Control interval	10 μs
Operation Current Reference	18.18 Arms
Parameter of Proposed Inverter	
Transformer mutual inductance L_m	0.2 mH
Transformer primary-side leakage inductance L_{lp}	10 μH
Transformer secondary-side leakage inductance L_{ls}	10 μH
Transformer turn ratio $N1$:$N2$	1:1
Capacitor C_f	4 μF
Grid filter L_f	0.2 mH
Parameter of Reference Inverter	
Grid filter L_f	1.0 mH



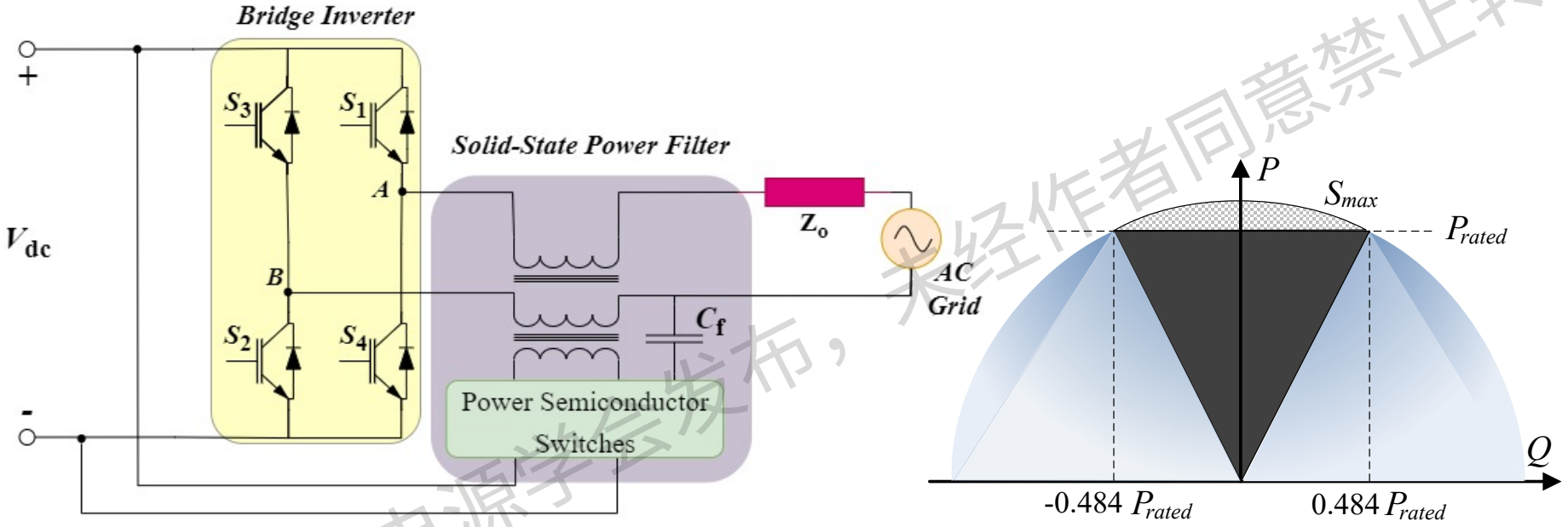
Solid-State Power Filters



- Significantly reduced passive components → PCB-based power inductors
- Fast dynamics
- Programmable characteristics
- Adaptive to grid parameters
- PCB-based inverters at kW level
  - Lowering manufacturing costs
  - Reducing volume and weight
  - Improving reliability and life span



Solid-State Power Filters – extended functions



- Filtering out harmonics – primary SSPF function
- Reactive power control – mitigating power curtailment
- Common-mode filtering
- Grid interactions – mitigating power quality issues

Closing Remarks

- DER market is growing, potentially providing more functionality and flexibility for grid operation.
- New power electronic technologies are being developed for DERs, driven by the pursuit of high performance and additional functionality
  - Passive components are being (gradually) replaced by active power components, which presents opportunities for WBG, topological and control technologies
- Solid-state power filters may be developed as an integral part of converters with programmable parameters
  - Power converters at several kWs can be manufactured on PCBs with significantly reduced size and weight

Thank You Very Much!

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