Solid State Transformer (SST) in Modern Power System

PCIM ASIA 2024, Shenzhen, China

Dianguo Xu
Harbin Institute of Technology

2024-08-29

Outline

– Principle of Solid State Transformer

– Application Scenarios of Solid State Transformer

– Key Technologies and Issues in Solid State Transformer

Principle of Solid State Transformer

Fundamental Principle of Solid State Transformer(SST)

➢ Line frequency transformer

Cons:

① Fixed voltage/current ratio

② Equal input and output active/reactive power

③ Fixed frequency

Pros：

① High efficiency — 99.5%

② Low price

③ High reliability

➢ Solid State Transformer

Pros:

① Capable of AC/AC, AC/DC, DC/DC, DC/AC

② Flexible control of voltage/power

Cons：

① Extra loss in power electronics with 1% reduction of efficiency

② Cost increases by about 5 ~ 10 times

③ High control complexity and failure rate

Outline

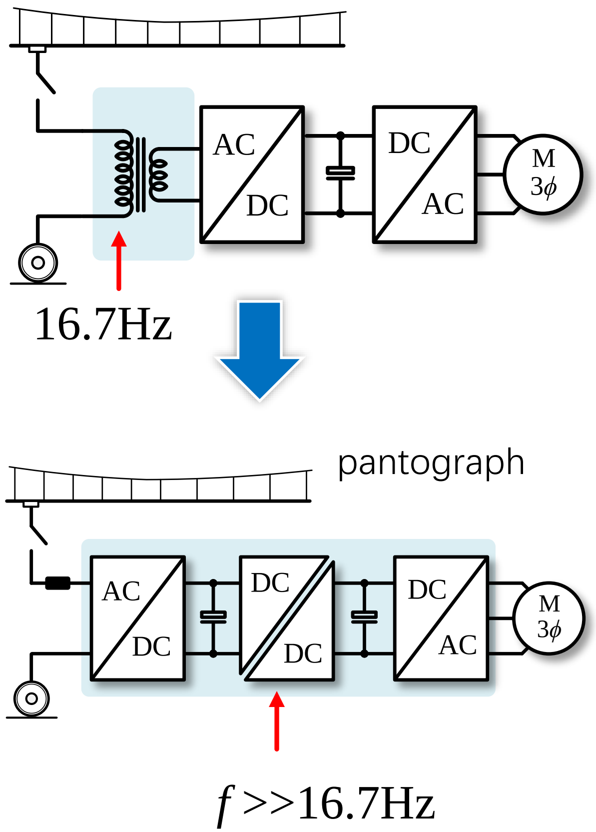
– Principle of Solid State Transformer

– Application Scenarios of Solid State Transformer

– Key Technologies and Issues in Solid State Transformer

Application Scenarios of Solid State Transformer

Traction Power Supply



- **Line-Frequency Traction Transformer (16.7Hz in Europe)**

  ① Weight 12% ~ 18% of the locomotive — 0.25–0.35 kVA/kg

  ② Volume constraint leads to high transformer current density thus low efficiency — 89%~92%

- **SST Solution**

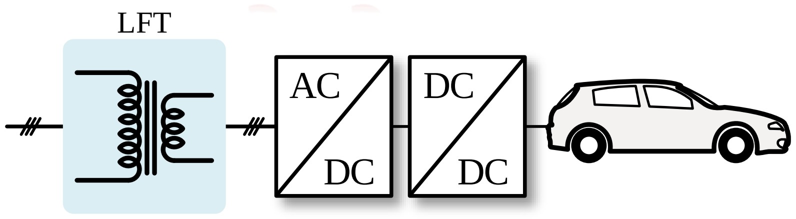
  ① Weight reduction of 50%— 0.5–0.75 kVA/kg

  ② Efficiency improvement of 2% ~ 4%

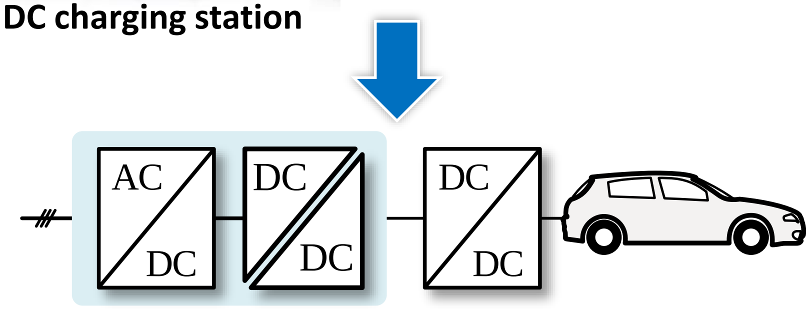
ABB 1.2MW prototype for Swiss Federal Railways with >96% peak efficiency

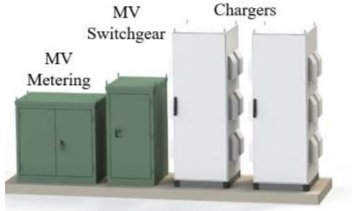
Application Scenarios of Solid State Transformer

■ EV Charging



LFT based DC charging station





SST based DC charging station

Source: Hao Tu (NCS)

➢ Existing DC Fast-charging Station

① LFT+ LV interface cabinet + Charging pile → Large footprint

② Fixed capacity of LFT without scalability

③ High current of LV AC/DC converter increases the loss leads to low G2V efficiency — <95%

➢ SST Solution

① Modular structure with scalable capacity

② 50% reduction in footprint by eliminating LFT and LV interface cabinets

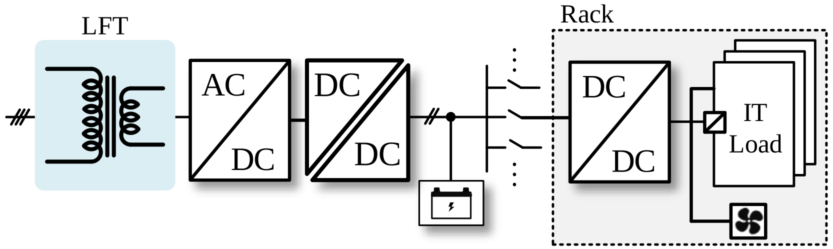
③ High efficiency in AC/DC stage, with around 2% improvement in overall efficiency

15kW Power module

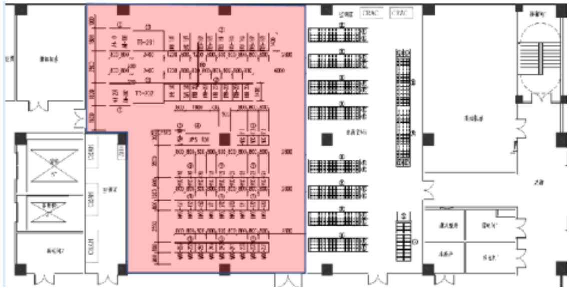
Delta 400kW DC Fast Charging Station with 97.5% Peak Efficiency

Application Scenarios of Solid State Transformer

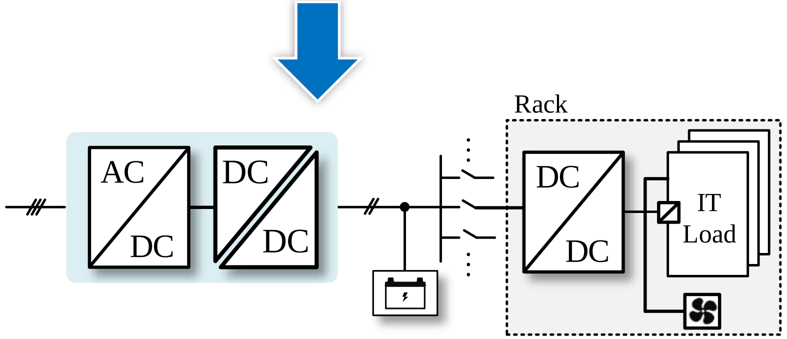
Data Center Power Supply



34 power supply devices
4 Manufacturers
36 Communication interface
$297m^2$ Distribution area



"AC & HVDC power supply" IT device area vs. Power distribution area



LV AC/DC Power Supply Solution

① High no-load loss of LFT

② High number of decentralized power supplies, with power distribution area accounting for more than 50% of the total area

③ LV AC/DC stage limits overall efficiency — 95%~95.5%

SST Solution

① Modular structure with easier deployment and maintenance

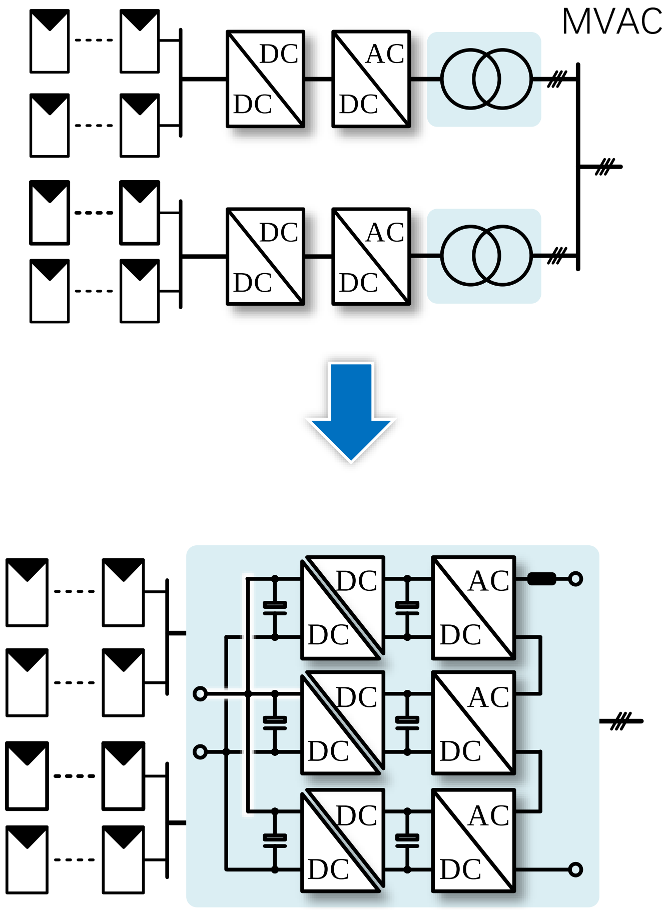
② High integration, significantly reducing the number of power supplies and reducing the power distribution area by 63%

③ Overall efficiency improvement of 2% ~ 3%

XD Power Electronics Corporation 2.4MW data center SST with 98% peak efficiency

Application Scenarios of Solid State Transformer

■ MVAC-Connected PV System



➢ String PV Inverter

① No-load loss of LFT at night

② PV inverter (98.5%)×LFT (98%) — **Only 96.5% overall efficiency**

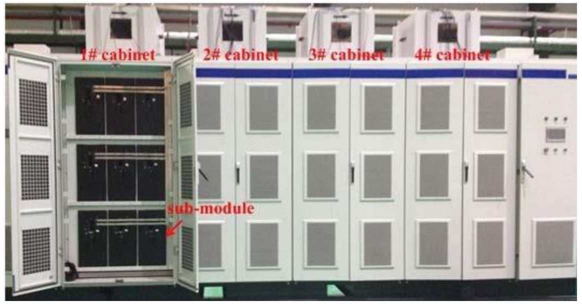
③ Transient instability with parallel connection of extensive inverters

➢ SST Solution

① Lower no-load loss

② High level of integration and high power density

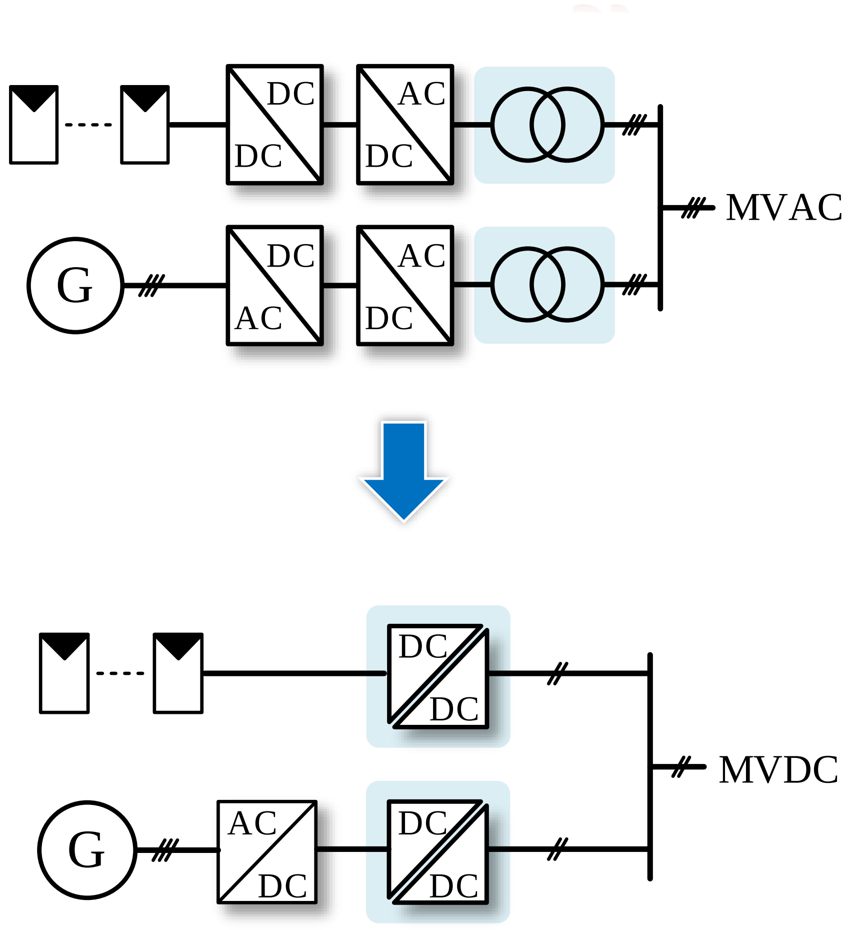
③ **1% improvement in overall efficiency**



TBEA's 1MW SiC based MVAC-Connected PV SST with 98% Peak Efficiency

Application Scenarios of Solid State Transformer

■ Renewable Energy MVDC Collection



➢ **Conventional Collection Solution (AC Collection)**

① Low efficiency due to multiple power conversion stages and high current

② High collection loss in MVAC cables

③ AC is vulnerable to harmonic, resonance, and other power quality issues

➢ **SST Solution (DC collection)**

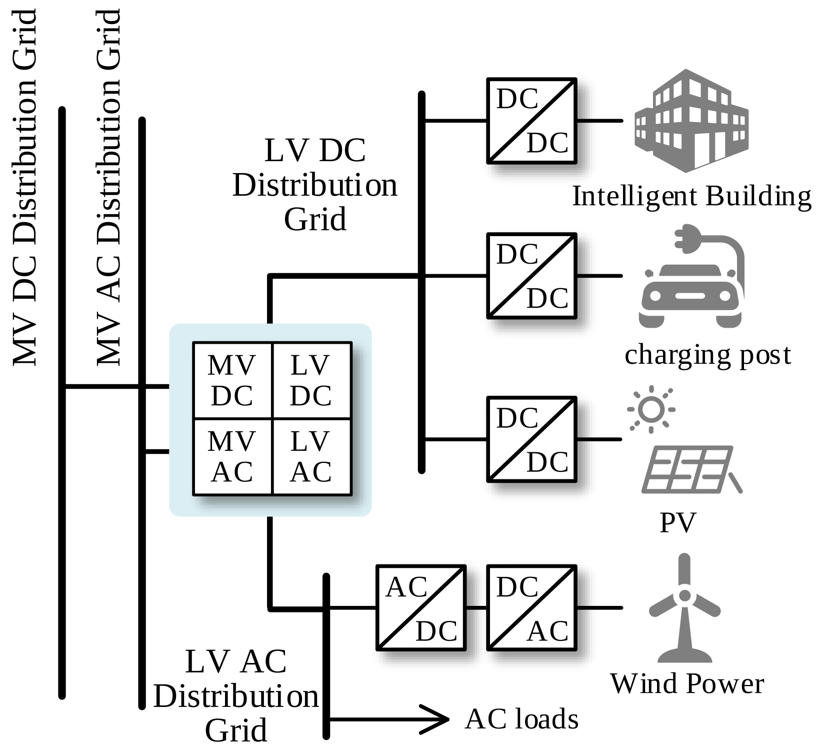
① Loss reduction through integrated power conversion stages and soft switching technique

② MVDC cable features low loss, thus high collection efficiency

IEECAS ±30kV/1MW PV DC Step-up Converter

Application Scenarios of Solid State Transformer

Hybrid AC/DC Distribution Grid



Schematic diagram of AC/DC hybrid distribution grid

Features of Hybrid AC/DC Power Distribution Grid

① Compatible with the existing AC system, flexible access to various types of new energy and new type of loads

② Numerous AC/DC and DC/DC conversion stages

Functionality of SST Solution (Multiport)

① Integrated MVAC/MVDC and LVAC/LVDC ports

② Flexible regulation and energy exchange of each port

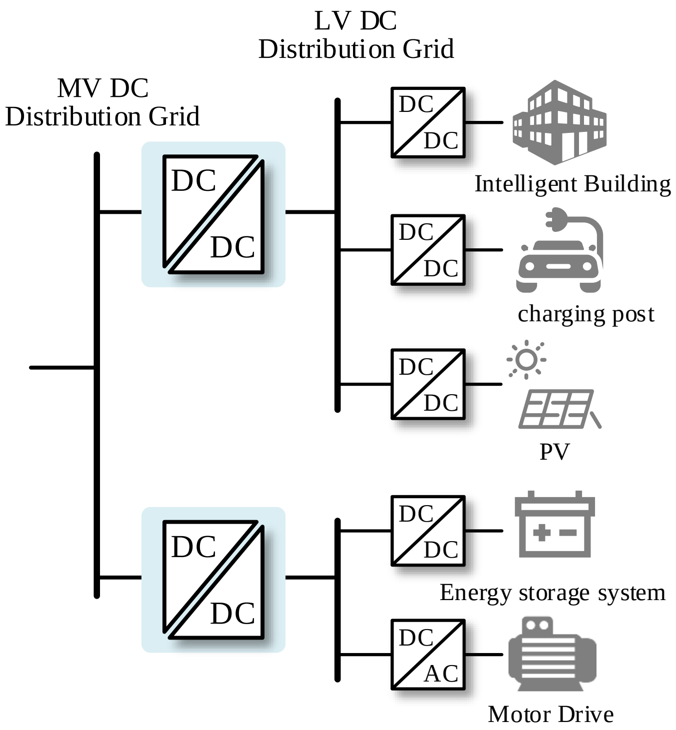
③ Reduction of power conversion stages → Increased efficiency

Suzhou Tongli 3MW multiport SST

Dongguan AC/DC multiport SST

Application Scenarios of Solid State Transformer

DC Distribution Grid



Schematic diagram of DC distribution grid

Features of DC Distribution Grid

① Low cable cost, high transmission efficiency

② Provide high efficient interface to renewable energy and energy storage

Functionality of SST Solution (DC Transformer)

① The only way to realize MVDC and LVDC voltage conversion and energy exchange

Wujiang MVDC/LVDC Power Distribution System Demonstration Project ±10kV/750V 2MW SST

Hangzhou Dajiangdong DC Distribution Network Demonstration Project ±10kV/±375V/500kW SST

Outline

– Principle of Solid State Transformer

– Application Scenarios of Solid State Transformer

– Key Technologies and Issues in Solid State Transformer

Outline

Key Technologies and Issues in Solid State Transformer

- **Efficiency**
- Voltage regulation
- Power density
- Transformer
- Cost
- Fault protection

Solid State Transformer—Efficiency

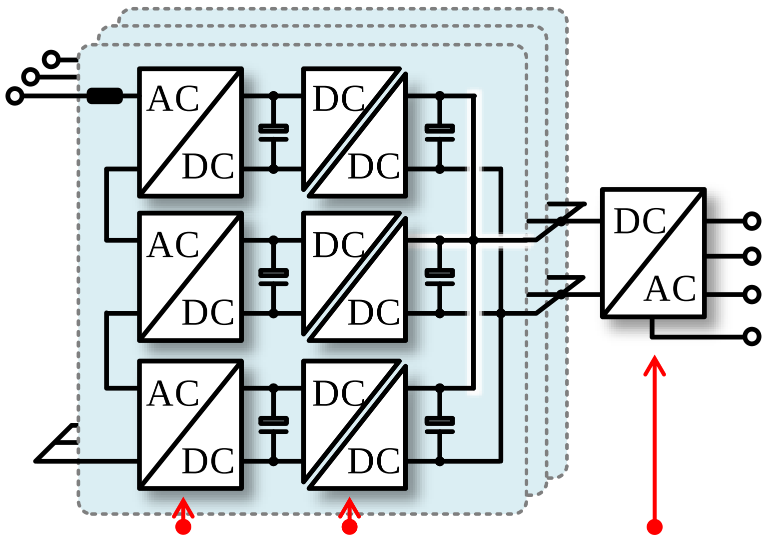
SST Efficiency Analysis

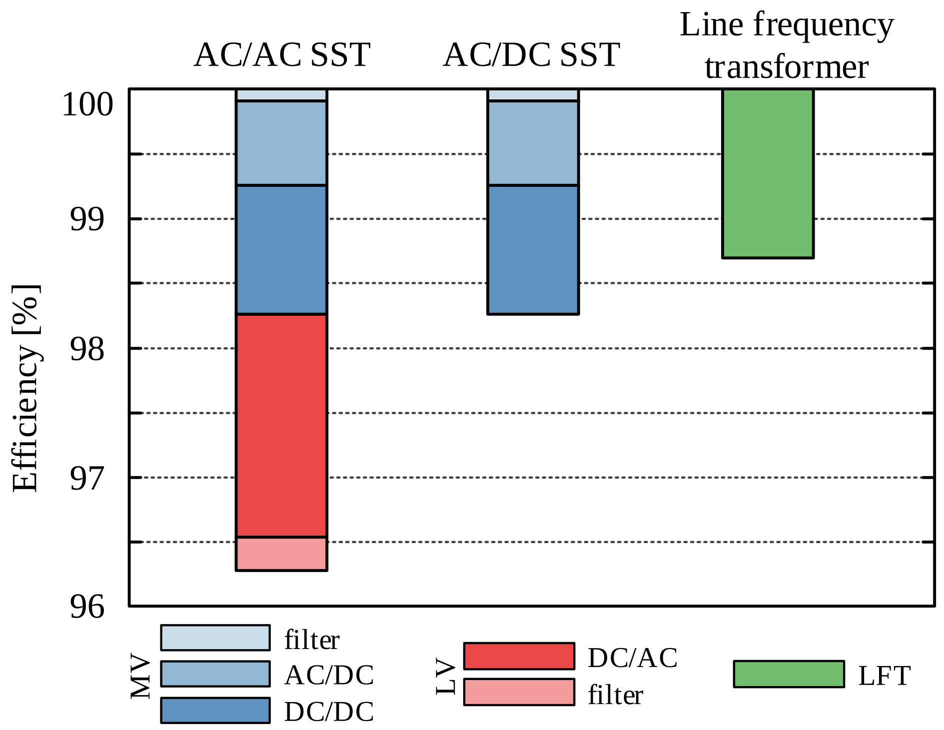
- **SST's efficiency is 1%~2% lower than line frequency transformer**
- **Loss Breakdown**

  ① **AC/DC**: Hard switching, high number of devices

  ② **DC/DC**: losses caused DC/AC+ MFT + AC/DC

  ③ **DC/AC**: Hard switching, high output current, high frequency





Source: J. W. Kolar (ETH Zurich)

Solid State Transformer—Efficiency

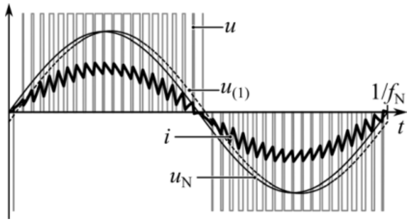
■ Efficiency Optimization of SST

➢ AC/DC Stage (MV side)

① **Switching loss:** Interleaving of the cascaded AC/DC modules → low switching frequency thus low switching loss

② **Conduction loss:** Fixed IGBT on-state voltage limits further optimization

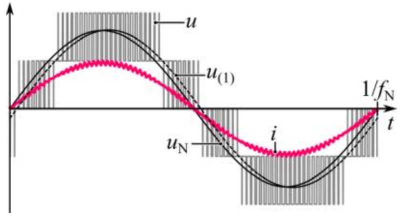
Non-interleaved



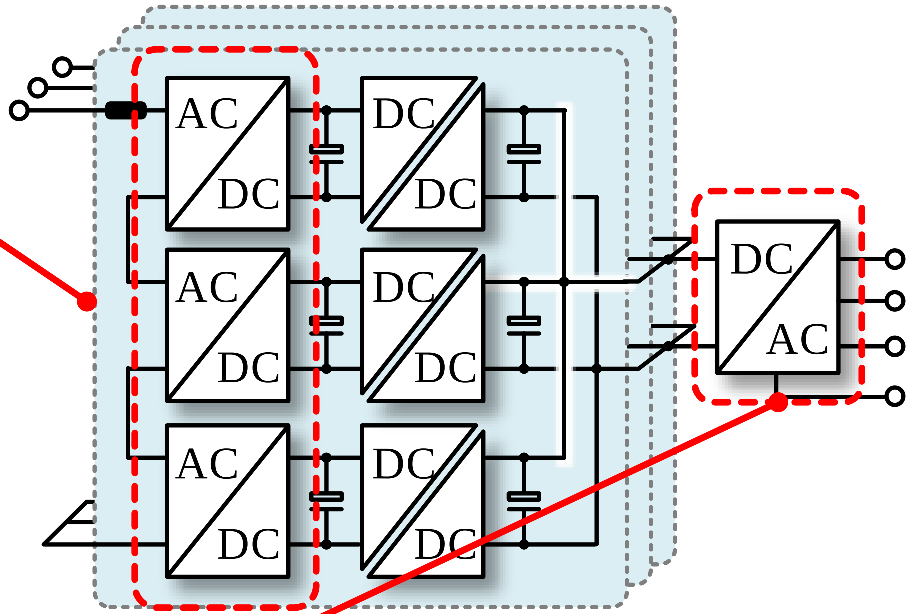
High number of voltage steps
High equivalent frequency

Switching frequency reduced by N^2 times

Interleaved



Source: J. W. Kolar (ETH Zurich)



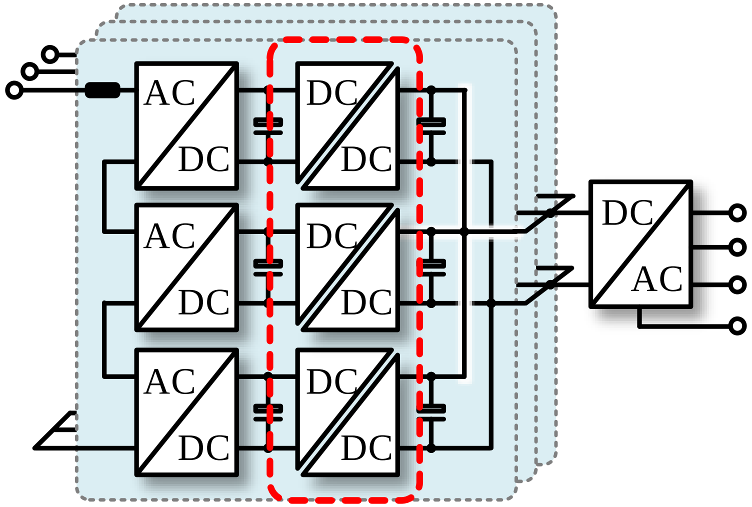
➢ DC/AC Stage (LV side)

① Centralized design with high output current

② High switching frequency is needed to ensure output current waveform quality which causes loss increase

Solid State Transformer—Efficiency

■ Efficiency Optimization of SST

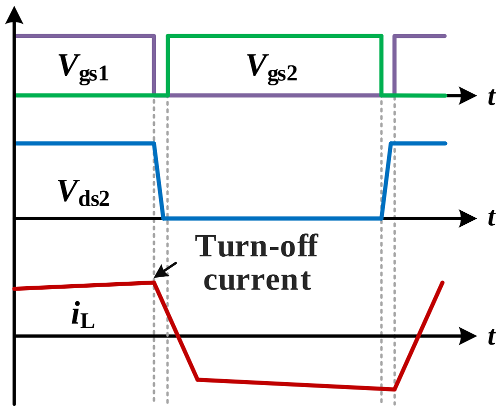


➢ DC/DC Stage

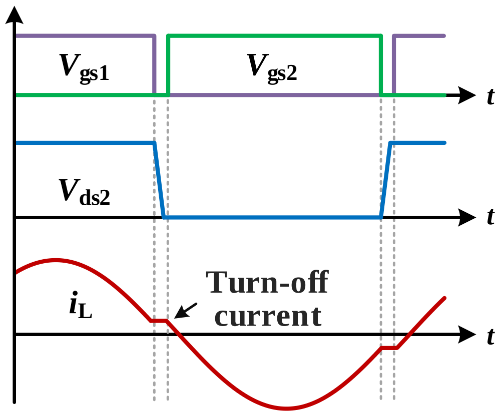
① **DAB:** ZVS of all switches but turn-off at peak current, IGBT trailing current still causes high turn-off loss

② **SRC:** Efficiency increases by 0.5%~1% because of ZVS and QZCS resonance increases current peak which intensifies the conduction loss

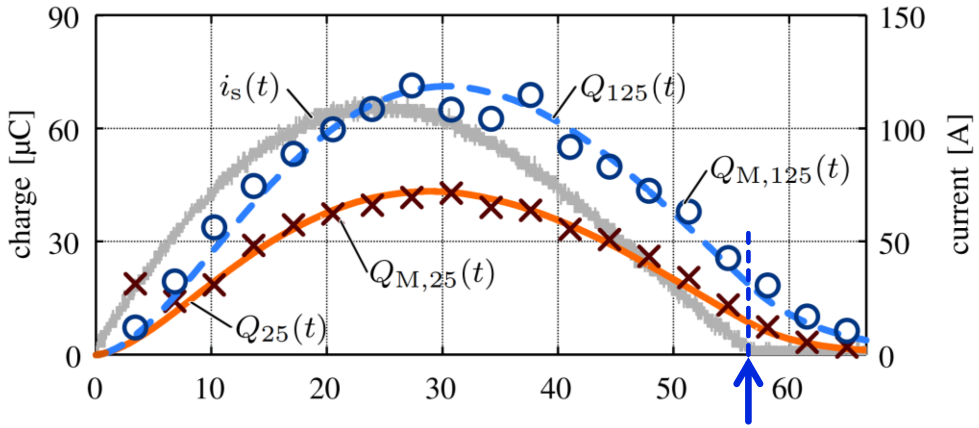
③ IGBT is turned off under ZCS, there are still charge inside, and it takes a long time to be recombined, and the switching loss will be large when the complementary device is turned on



Waveform of DAB



Waveform of SRC



Source: J. W. Kolar (ETH Zurich)

IGBT current is 0 while charge inside is not 0

Solid State Transformer—Efficiency

■ Efficiency Optimization of SST: Employing Wide Band Gap device

➢ **Advantages of SiC:**

① Critical breakdown field strength ×10

→ low on-resistance

② Unipolar device → No trailing process

③ Saturated electron drift velocity ×2

④ Low junction capacitance

} Low switching loss

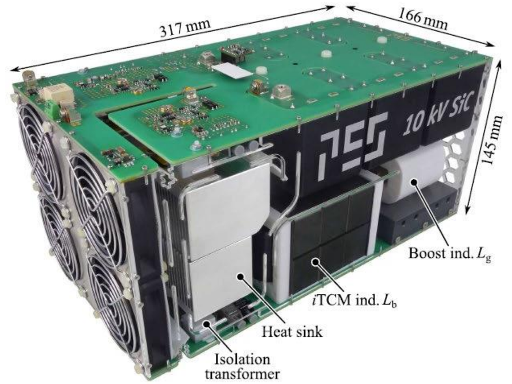
➢ **Limitations:**

① SiC MOS costs 8 times more than Si IGBT

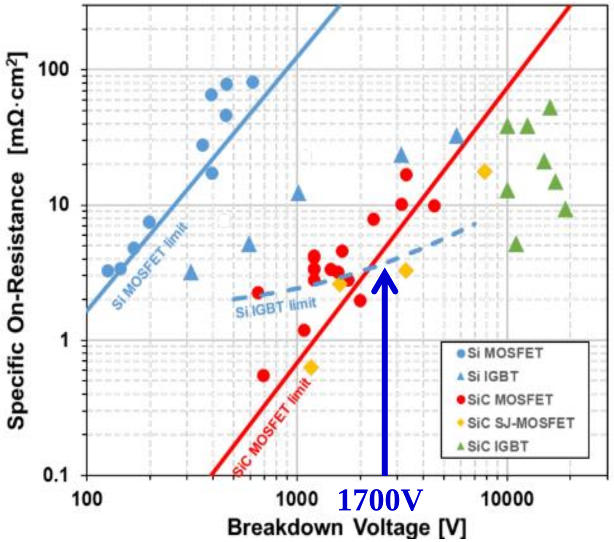
② 1700V SiC on-state voltage is higher than Si IGBT with no improvement of conduction loss!

③ Existing material and technology limit the current carrying capacity, resulting in low capacity of SiC-based SST

NARI 500kW Four-Port SiC SST with 98.5% peak efficiency



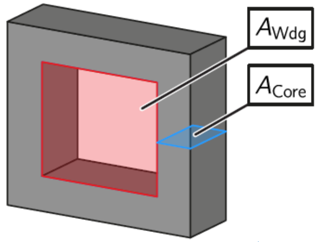
ETH SiC AC-DC power module with peak efficiency up to 99.1% and power density up to 3300kW/m^3



Source: Guangyin Lei (Fudan University)

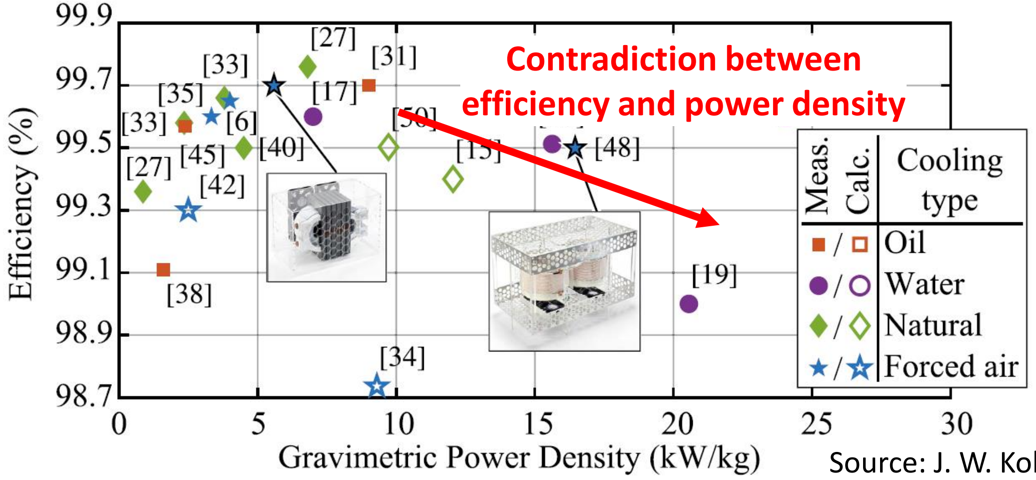
Solid State Transformer—Efficiency

Efficiency Optimization of SST: MFT



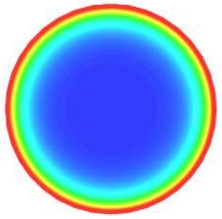
$$\overbrace{A_{Wdg}A_{core}}^{\text{Size}} = \frac{\overbrace{P}^{\text{Power}}}{4\underbrace{K_u}_{\text{Isolation}}\underbrace{B_m}_{\text{Materials}}\underbrace{J}_{\text{Thermal}}\underbrace{f}_{\text{Frequency}}}$$

➢ High frequency → High power density → High loss



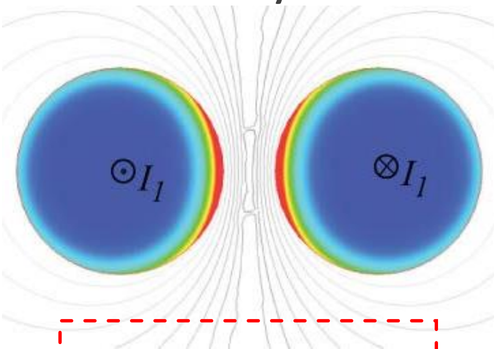
Source: J. W. Kolar(ETH)

➢ Skin effect



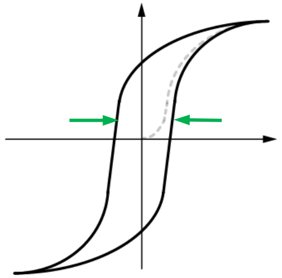
- Thin copper foil / small wire diameter
- Litz wire

➢ Proximity effect



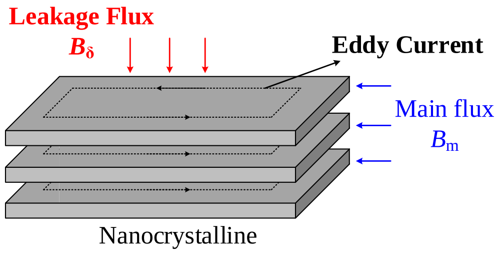
- Litz wire
- Staggered winding

➢ Hysteresis loss



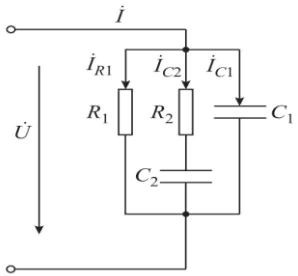
- "Thin and long" materials
- Design of flux density

➢ Eddy current loss



- Reduce leakage flux
- Reduce penetration area
- High resistivity materials

➢ Dielectric loss



Equivalent model of insulating materials

- Low conductivity materials
- Avoid high du/dt waveform

Outline

Key Technologies and Issues in Solid State Transformer

- Efficiency
- **Voltage regulation**
- Power density
- Transformer
- Cost
- Fault protection

Solid State Transformer—Voltage regulation

Voltage Regulation Requirement

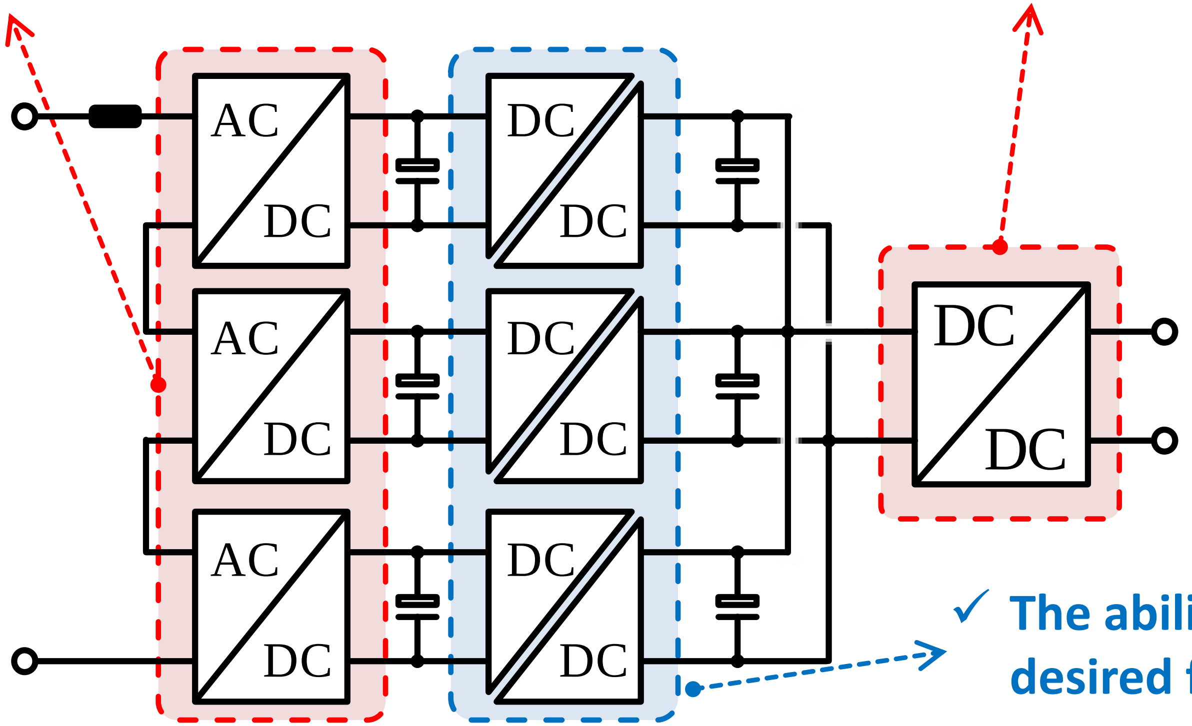
- Application scenarios such as EV charging and PV energy collection require a wide-range DC output voltage regulation capability

① AC/DC voltage regulation

× Reduced modulation index and increased module count

② Additional DC/DC stage

× Extra power devices and conversion loss

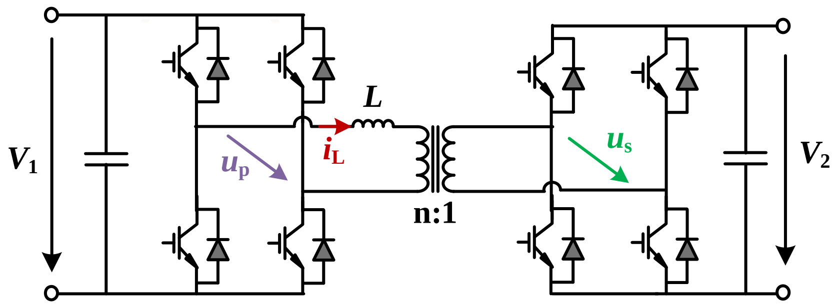


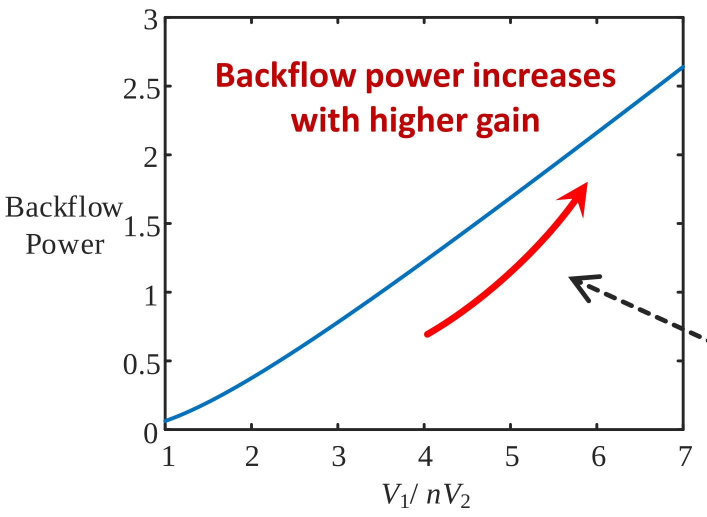
✓ **The ability to regulate voltage is desired for DC/DC stage**

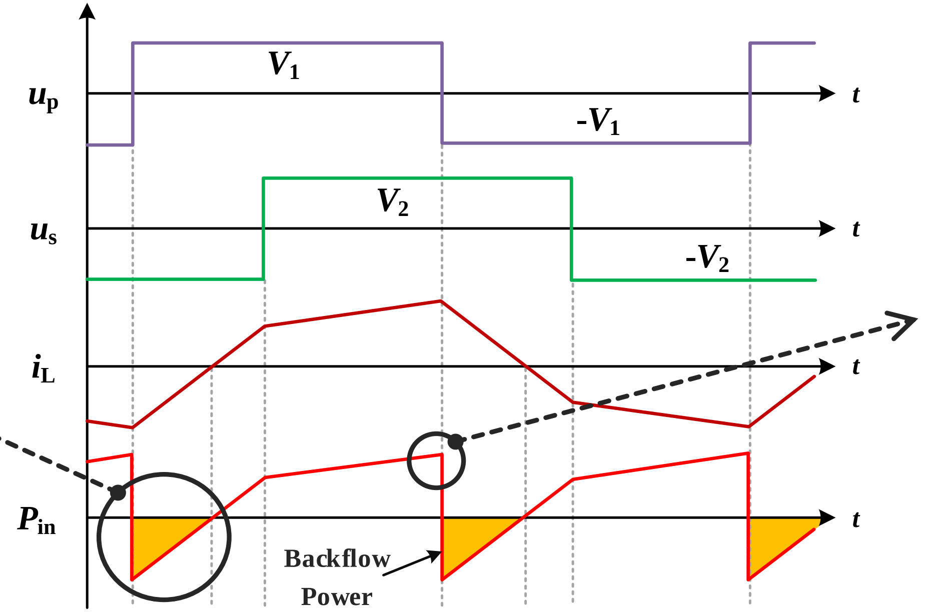
Solid State Transformer—Voltage regulation

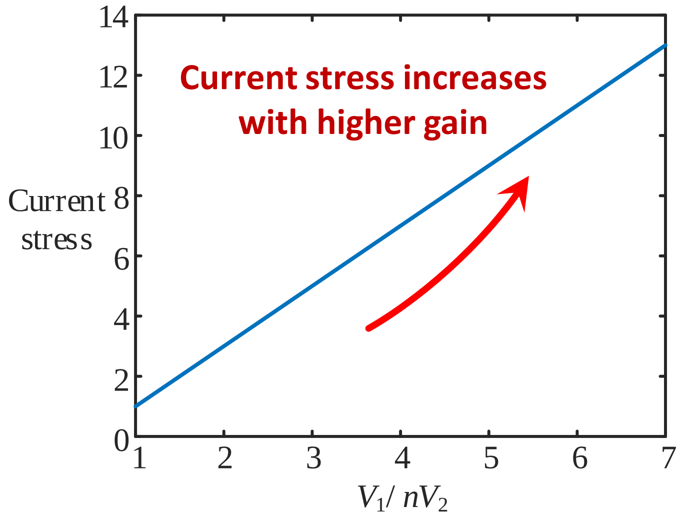
Voltage Regulation of DAB – Single Phase Shift (SPS)

- **Backflow Power:** inductor current is in the opposite phase to primary voltage, the transmitted power flows back into the input side
- Backflow power increases with higher voltage gain, causing higher conduction loss of semiconductors, MFT, and inductor
- Voltage difference on inductor increases with higher voltage gain, imposing higher current stress on the semiconductors





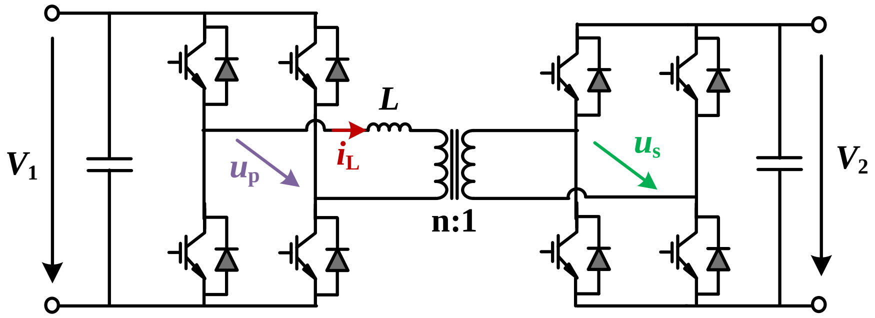


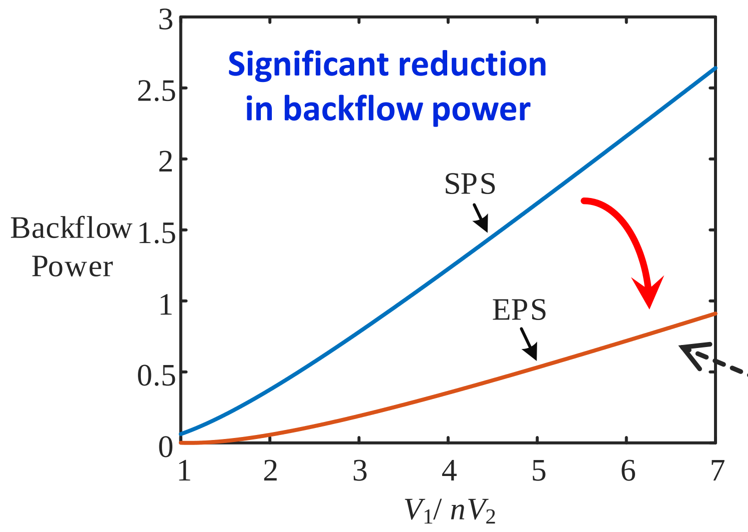


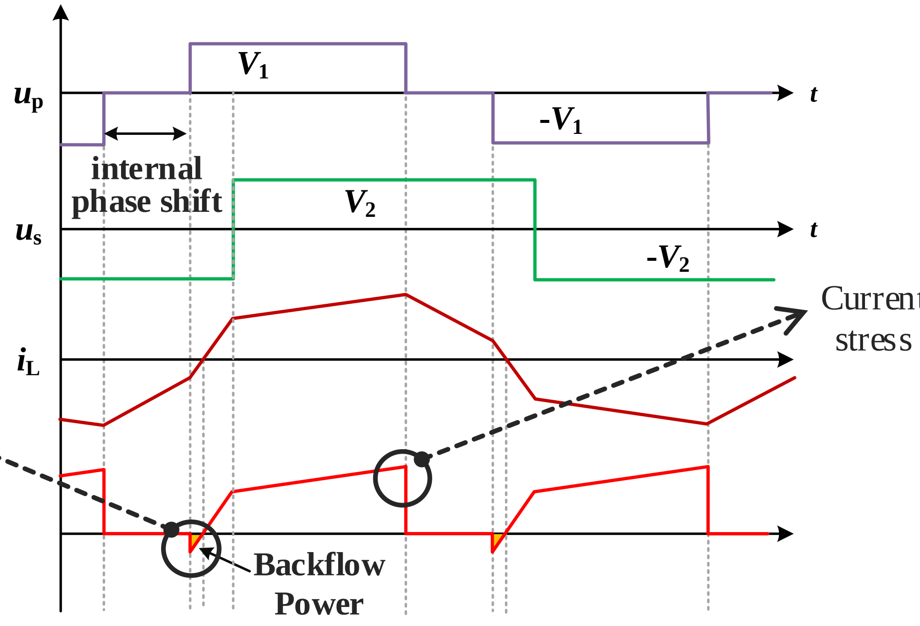
Solid State Transformer—Voltage regulation

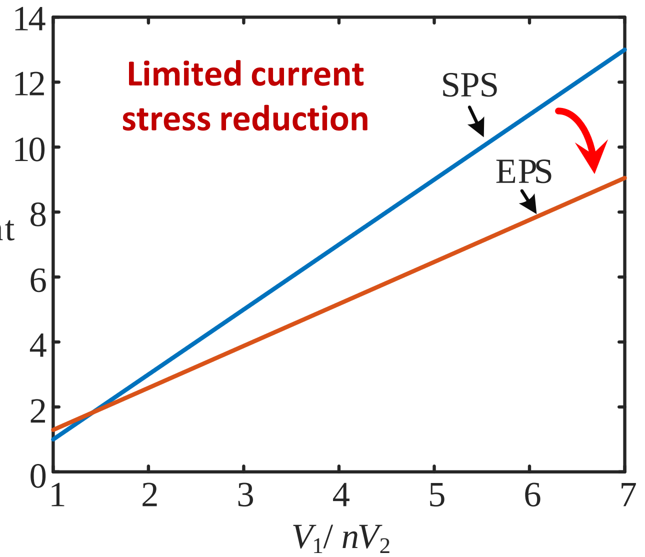
■ Voltage Regulation of DAB – Dual PS/Extended PS/ Triple PS

- ➢ Adding "internal phase shift angle" as an additional control degree to optimize backflow power
- ➢ Limited current stress reduction under high voltage gain







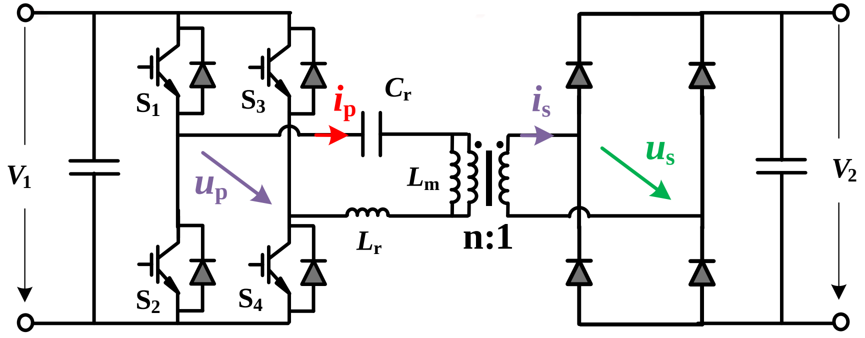


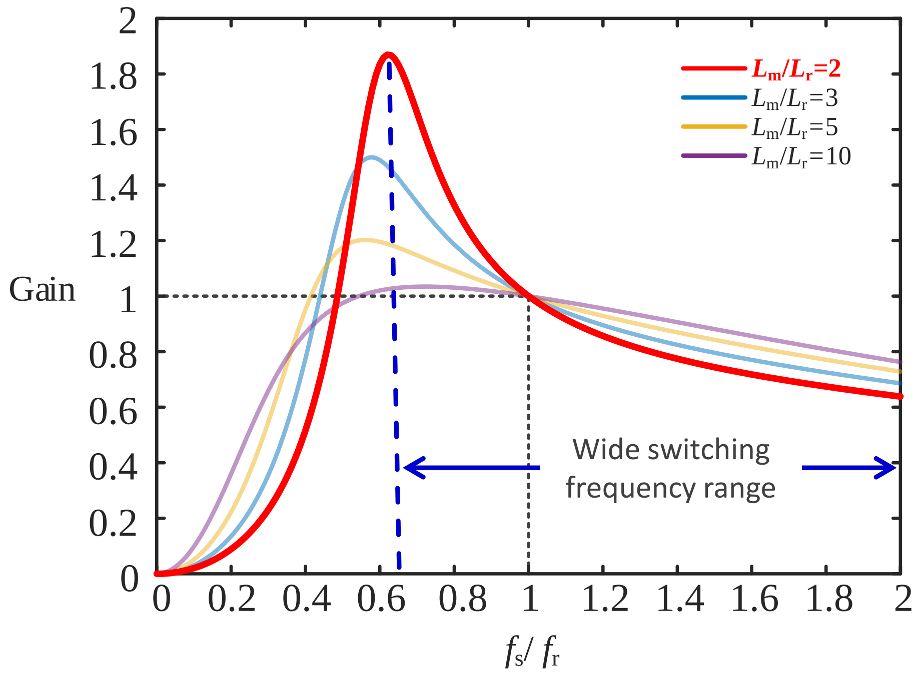
Extended Phase Shift Modulation (EPS)

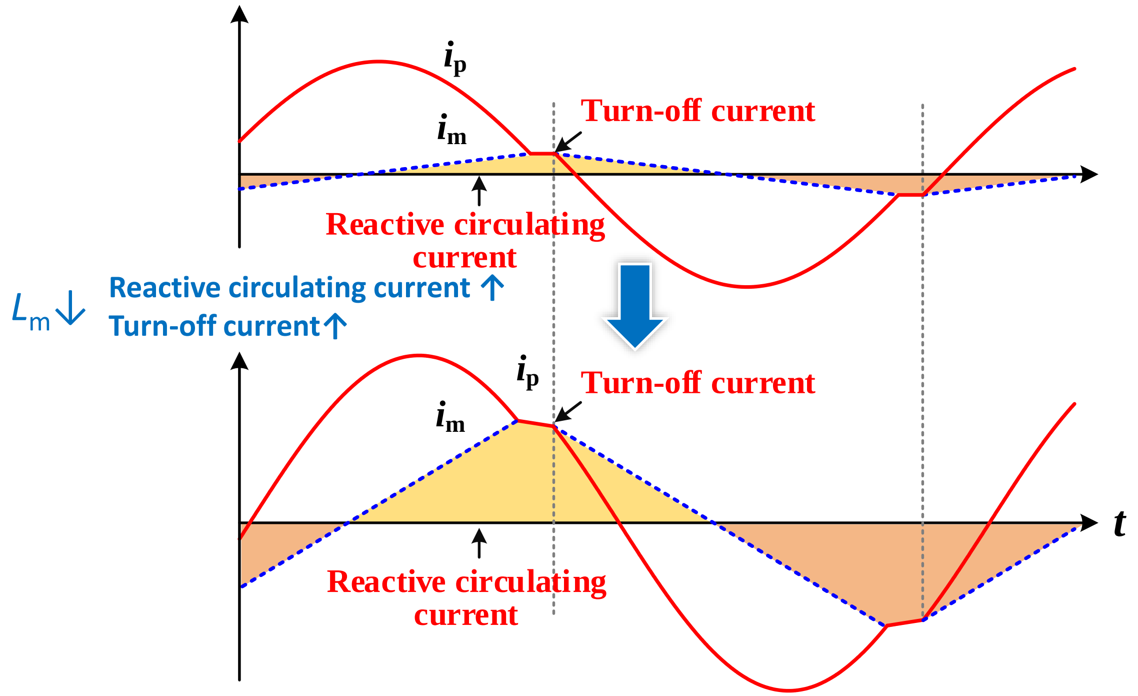
Solid State Transformer—Voltage regulation

■ Voltage Regulation of SRC – Pulse Frequency Modulation(PFM)

- Decrease magnetic inductance→ Steepens the gain curve: increases reactive circulating current, increases current stress and device loss
- Wide-range voltage regulation→ Wide switching frequency range: Increases transformer volume



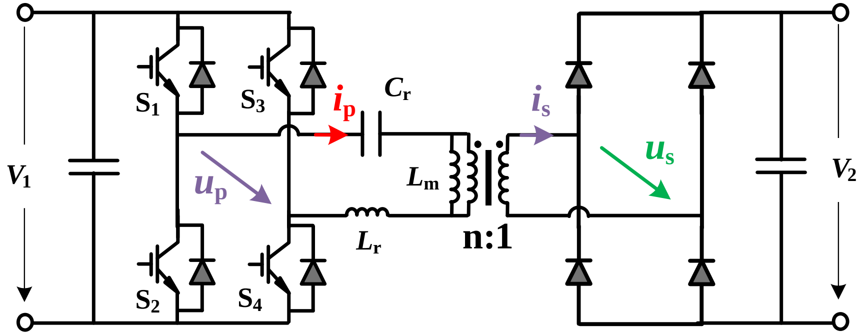


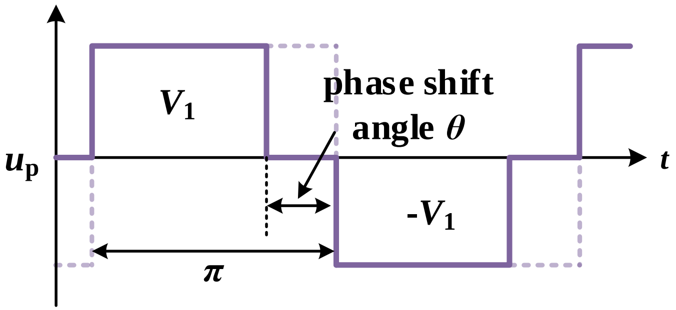


Solid State Transformer—Voltage regulation

Voltage Regulation of SRC – Phase Shift/PWM

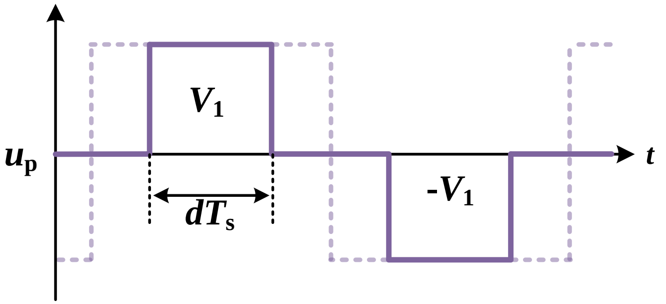
- Adjust the zero voltage duration to change the primary-side equivalent voltage → regulation of the voltage gain
- The turn-off current becomes higher, increasing turn-off loss





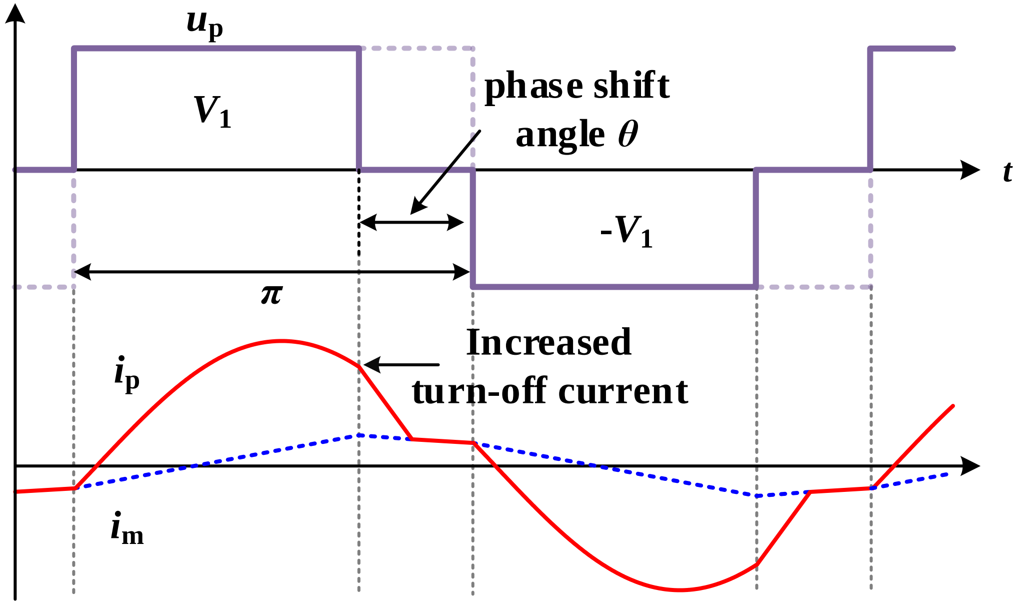
Phase shift control

$$G_{\text{shift}} = \frac{1+\cos(\theta)}{2} G_{\text{PFM}}$$



PWM control

$$G_{\text{PWM}} = \sin(d\pi) G_{\text{PFM}}$$



Outline

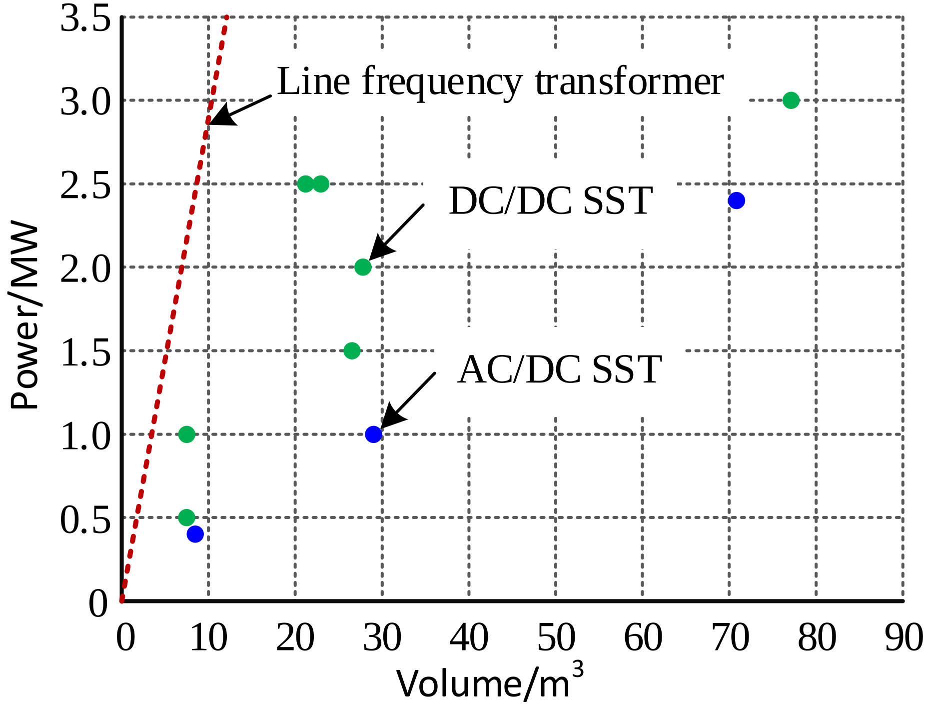
Key Technologies and Issues in Solid State Transformer

- Efficiency
- Voltage regulation
- **Power density**
- Transformer
- Cost
- Fault protection

Solid State Transformer—Power density

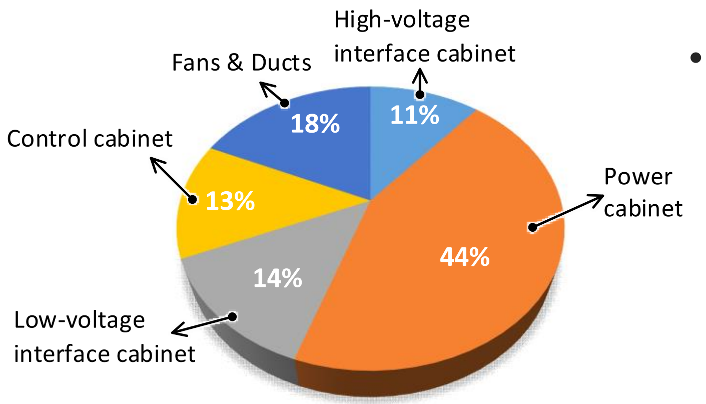
Power density analysis of SST

- The power density of existing industrial SST pilot projects are still 3 to 10 times lower than line frequency transformers



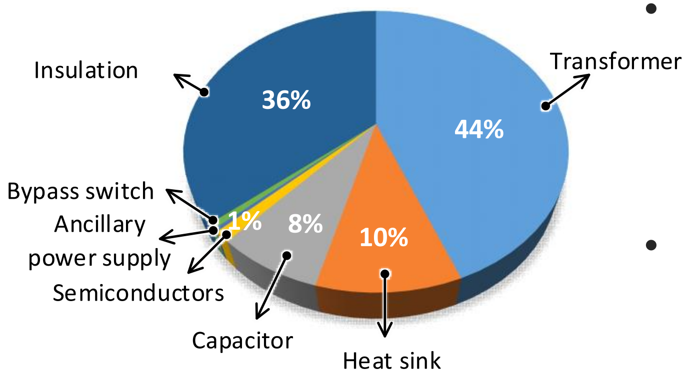
Power density study domestic SST pilot projects

Example of SST overall volume breakdown



- HV and LV interface cabinet, control cabinet, and heat dissipation limit the power density

Example of power module volume breakdown

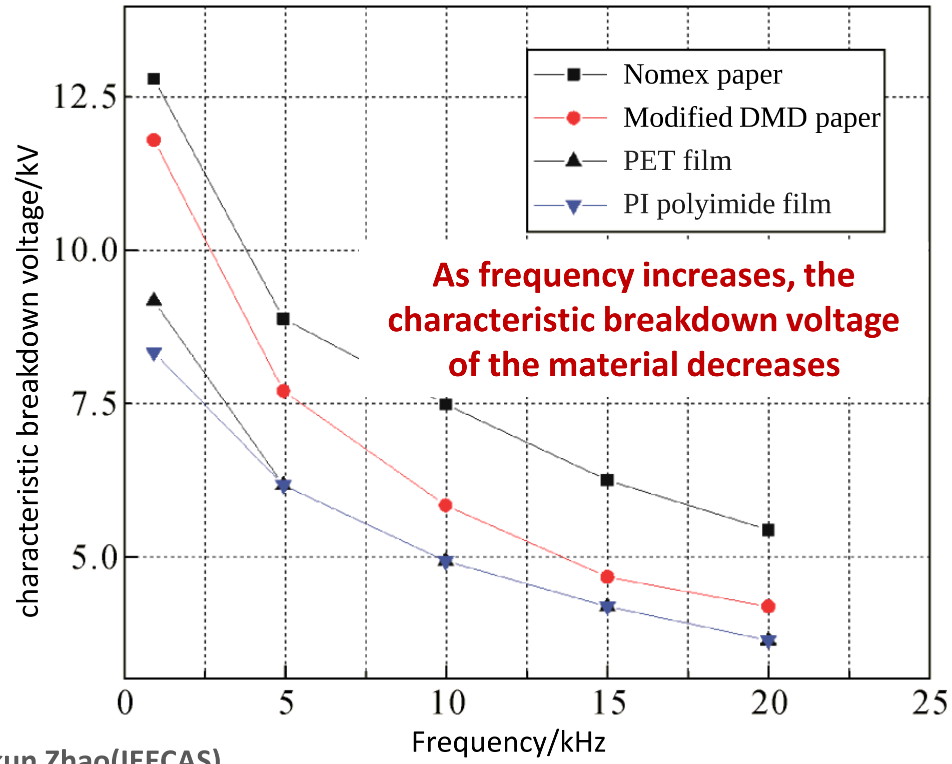


- Passive components (capacitors, transformers) account for more than 50% of the power module volume
- Insulation accounts for 36% of the power module volume

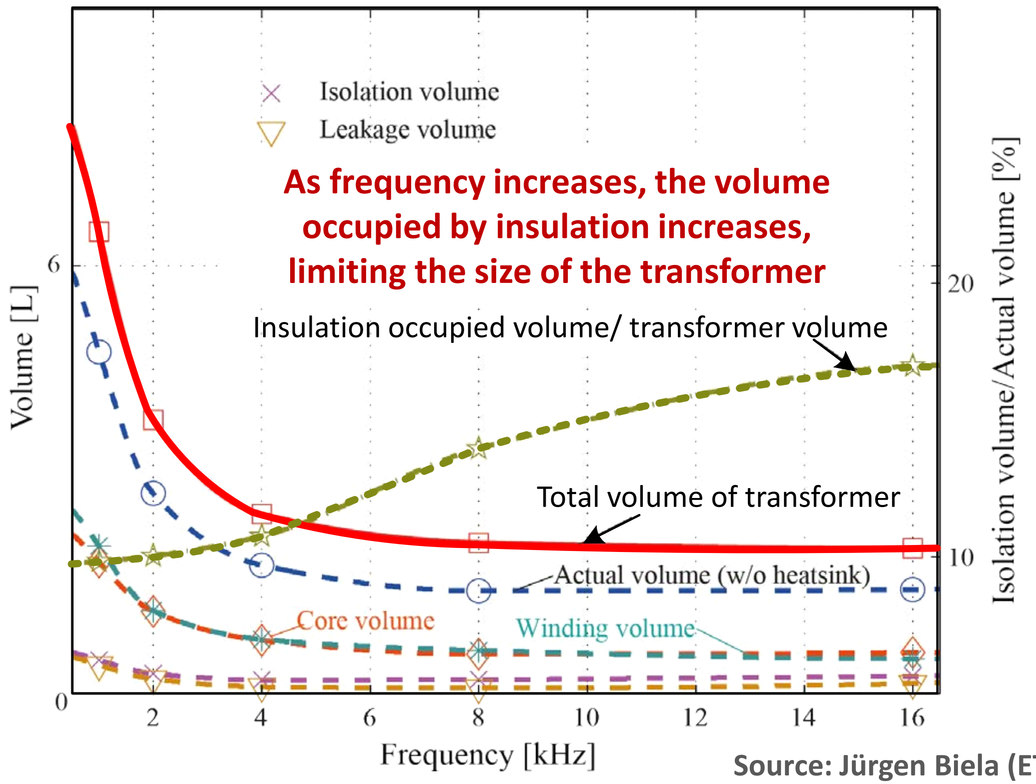
Solid State Transformer—Power density

Power density constraint—Transformer

- To reduce the size of the transformer, increasing the transformer operating frequency is usually considered
- The breakdown voltage of insulation material is inversely proportional to the frequency
- Insulation distance increases at high frequency, which limits reduction of the transformer volume



Source: Yikun Zhao(IEECAS)

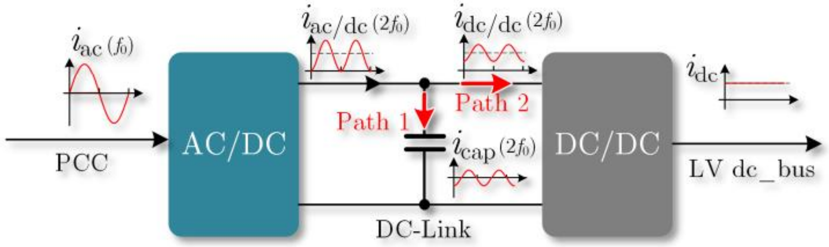


Source: Jürgen Biela (ETH Zurich)

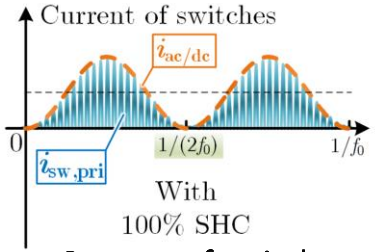
Solid State Transformer—Power density

Power density constraint—Capacitor

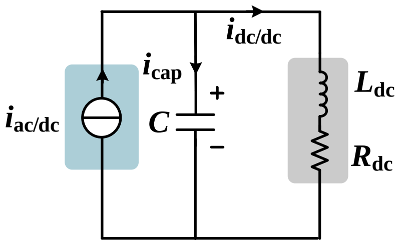
- Secondary harmonic current exists in single-phase AC/DC →increases the current stress by 100%
- Tens of mF capacitor is required to absorb the second harmonic current → significantly reduces the power density!



Source: Jinxiao Wei (CQU)

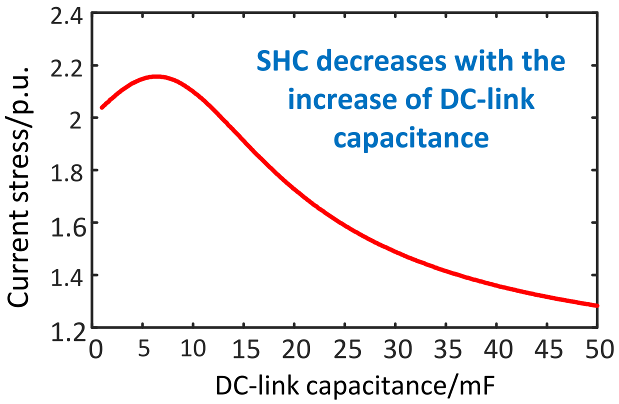


Current of switch



Impedance shunt of DC-link capacitor and SRC

$$\frac{i_{dc/dc}}{i_{ac/dc}} = \frac{Z_C}{Z_C + Z_{L+R}}$$

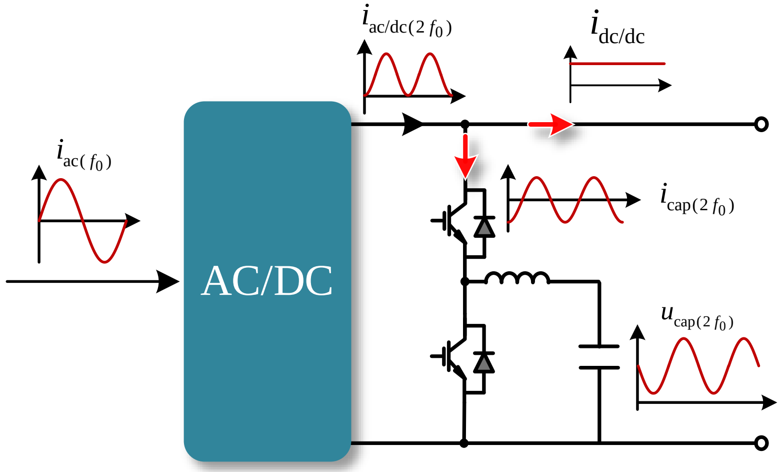


Active power decoupling

① Reducing the DC-link capacitance by actively absorbing the SHC

② Large voltage fluctuation is allowed for decoupling capacitor→ low decoupling capacitance with high switching frequency

③ Adding additional devices and loss, the efficiency is reduced by about 1%!

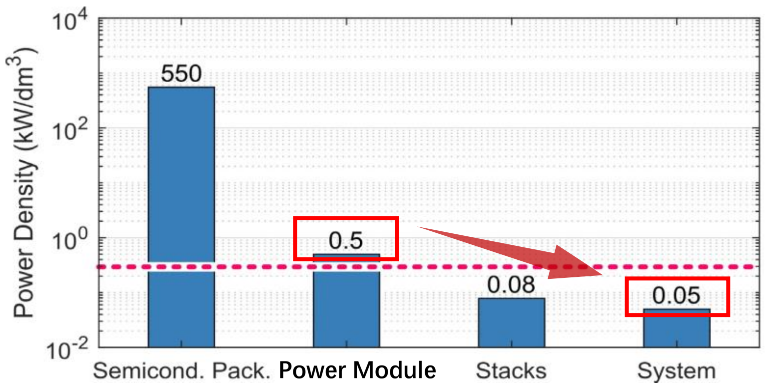


Buck-type Power Decoupling Circuit

Solid State Transformer—Power density

Power density constraint—Module Count

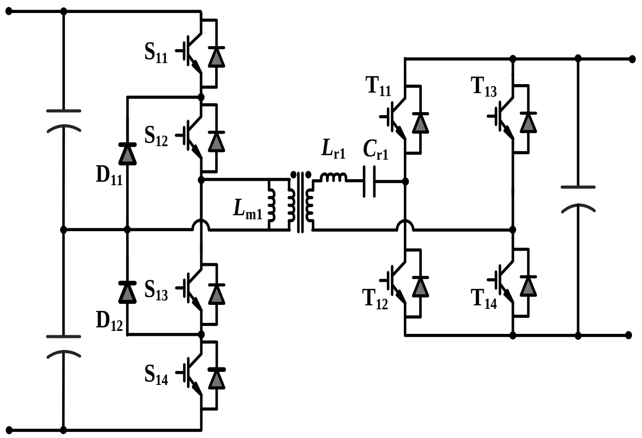
- Due to the limitation of insulation distance between power modules, the power density of overall SST is reduced by an order of magnitude compared to power module!



Source: J. W. Kolar (ETH Zurich)

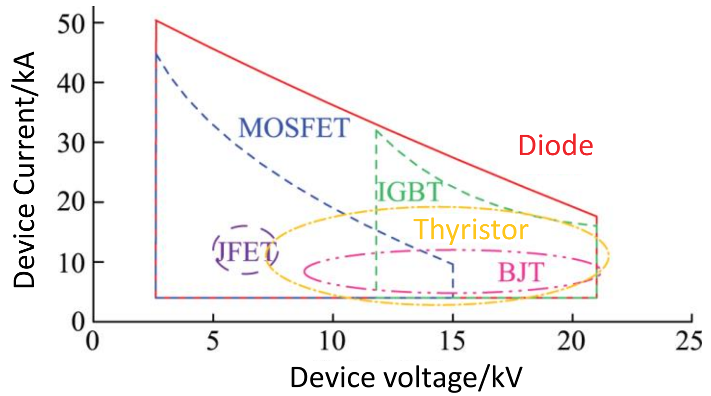
- Increase voltage rating of each module: reducing the power module count

① Multilevel structure → Complex module design and control, Increased transformer capacity



Three-Level Power Module

② High-voltage SiC devices (10kV+)→ Low current-carrying capability and limited capacity



SiC device Types and Voltage and Current Ratings

Source: Shiqi Ji(THU)

Outline

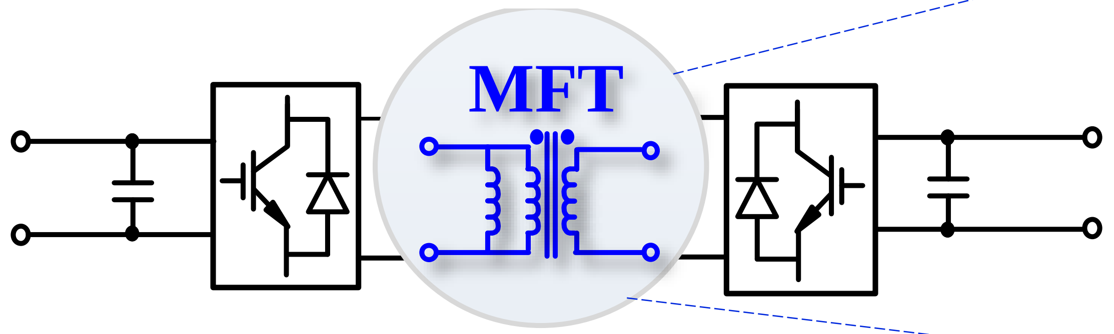
Key Technologies and Issues in Solid State Transformer

- Efficiency
- Voltage regulation
- Power density
- **Transformer**
- Cost
- Fault protection

Solid State Transformer—MFT

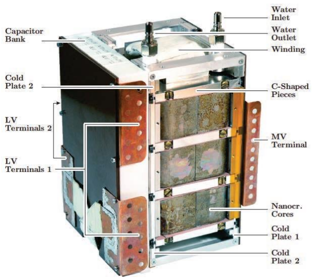
Technical Challenges of Transformer

Solid State Transformer

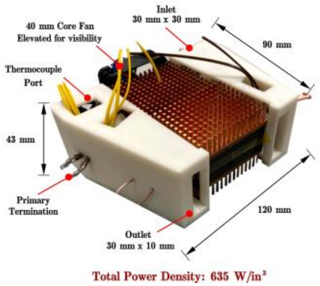


Technical requirements		Technical targets
High power	→	High power density
High voltage	Challenge	High efficiency
High frequency		High reliability

EPFL
300kW，2kHz

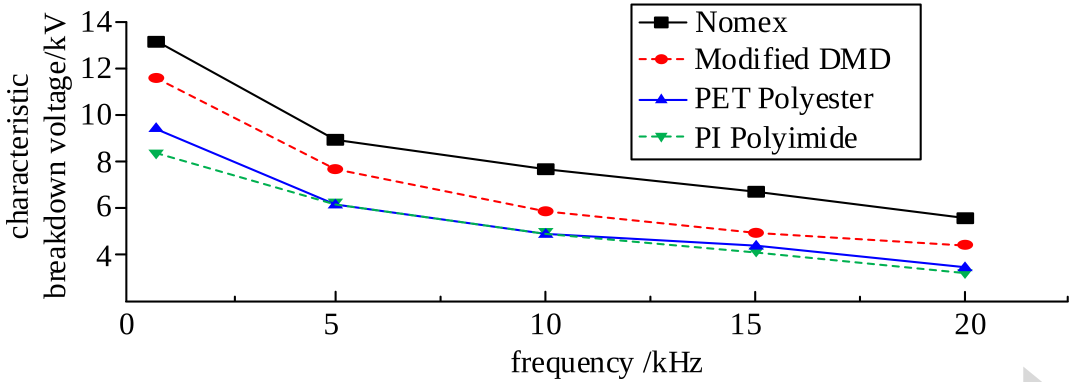


ETH
166kW，20kHz



VT
15kW，500kHz

Challenge 1 Frequency ↑ → Rated power ↓
Loss



Challenge 2 Frequency ↑ → Voltage ↓
Insulation

Wang W, Liu Y, He J F, et al. Research status and development trend of high-frequency transformers in high-voltage and large-capacity power electronic transformers[J]. High Voltage Technology, 2020, 46(10): 3362-3373.

Solid State Transformer—MFT

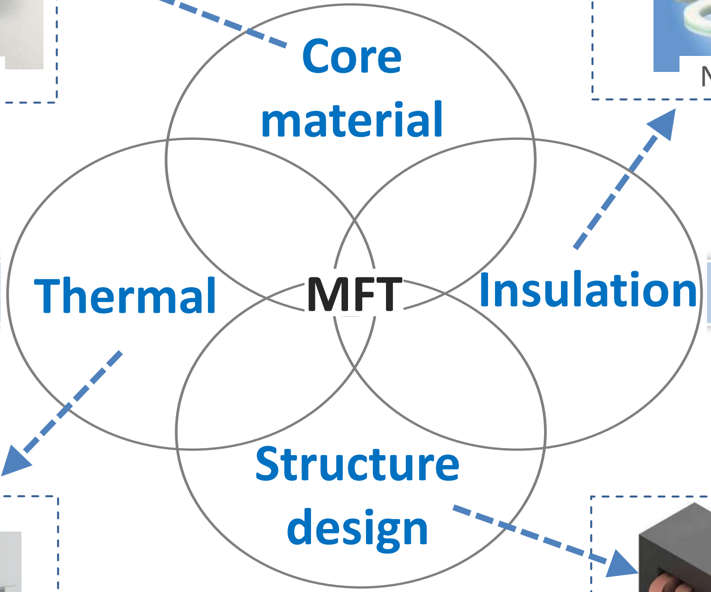
Design of Transformer

Silicon steel sheet | Nanocrystalline | Ferrite

Nomex | Polyester film | Oil

- High power
- High voltage
- High frequency

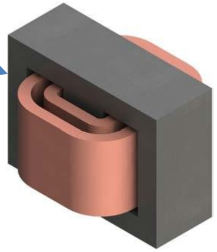
Technical requirements



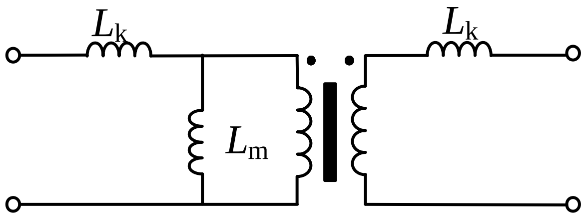
- High power density
- High efficiency
- High reliability

Technical targets

Air cooling | Oil cooling | Water cooling



Core winding structure



Inductance parameters

Sun K, Lu S H, Yi Z Y,et al. A review of high-capacity high-frequency transformer technologies for power electronic transformer applications[J]. Chinese Journal of Electrical Engineering, 2021, 41(24): 8531-8546.

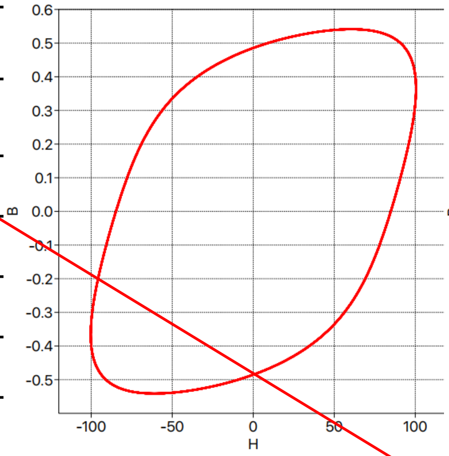
Solid State Transformer—MFT

Core Material

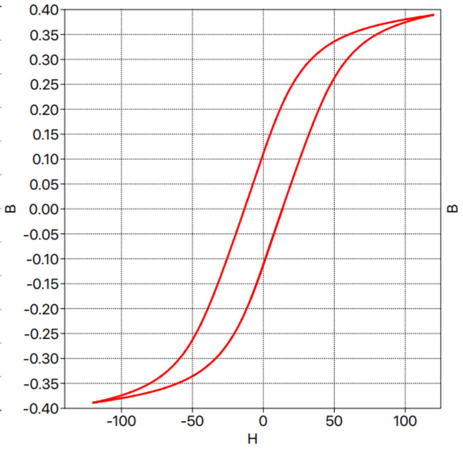
- **Development trend: large capacity (10kW~1MW), ultra-high frequency (1kHz~1MHz) → high power density**
- Large-capacity cores → **high saturation flux density** of the core material to reduce volume
- High frequency → **low coercivity, high permeability, high resistivity** of the core material **to reduce core loss**

Characteristic curve: "thin and long"

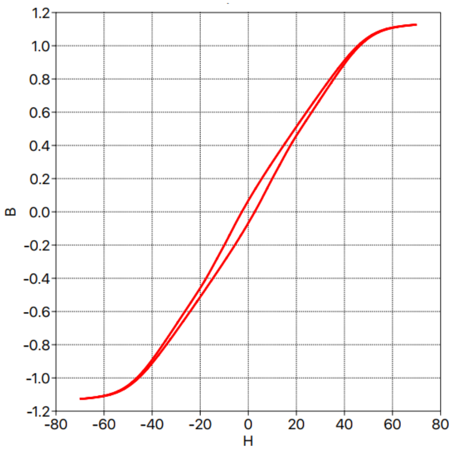
Magnetic material	Alloy Flake		Amorphous alloy strip		Ferrite
	Silicon steel sheet	Permalloy	Amorphous	Nanocrystal	Mn-Zn
B_m/T	1.7	1.55	**1.56**	**1.25**	**0.5**
Coercion/(A/m)	**40**	**12**	**<4**	**<2**	8
$\mu_m/10^4$	**2**	**6**	**5**	**40**	0.6
Resistivity/(μΩ·cm)	**50**	**30**	**130**	**90**	5×10^7
Cost	Low	Very high	High	Very high	Low



Silicon steel sheet B-H curve



Ferrite B-H curve



Nanocrystal B-H curve

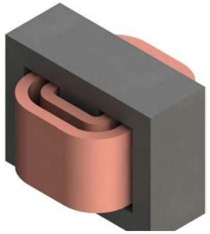
- ✗ Low resistivity causes **high eddy current loss,** low coercivity and low permeability result in **high hysteresis loss** at high frequencies
- ✓ Amorphous, nanocrystalline have **high saturation flux density,** and **almost eliminate hysteresis loss,** suitable for high-power, medium and high frequency transformers
- ✓ Saturation flux density of ferrite is much lower than other materials, with **larger volume,** but it is still widely used due to **cost advantage and high switching frequency**

Solid State Transformer—MFT

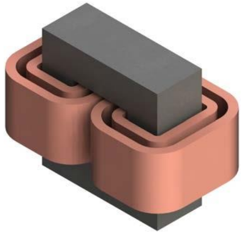
Structural Design

Core structure

Feature \ Structure	Shell (E-type)	Core (U-type)
Capacity	**Small**	**Large**
Insulation distance	**Large**	**Small**
Leakage flux	**Small**	**Large**
Dissipation area	**Large**	**Small**



Shell (E-type)



Core (U-type)

- **Shell type:** small window area limits the winding current under rated current density, suitable for **small and medium power**
- **Core type:** larger window area achieves higher winding current under rated current density, suitable for **high power**

Winding type

Feature \ Structure	Litz wire	Copper foil
Under high frequency	**Good**	**Bad**
Space utilization	**Low**	**High**
Current	**General**	**High**
Process difficulty	**High current**	**High frequency**

Litz wire

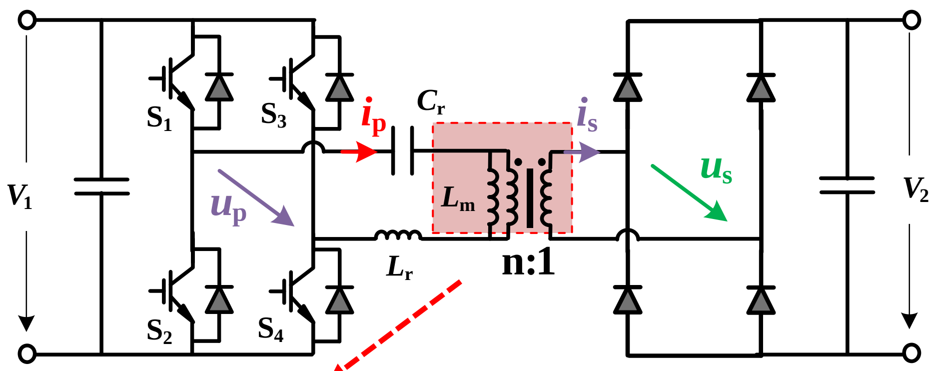
Copper foil

- **Litz wire:** perfect high-frequency characteristics, **low space utilization, more strands under high current**
- **Copper foil:** compact structure, high current, **significant skin effect under high frequency**

Solid State Transformer—MFT

Magnetic Integration

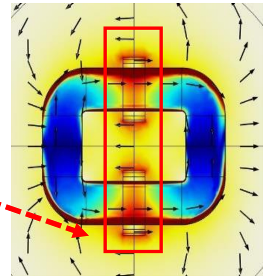
SRC → magnetic inductance design



External paralleled inductor to avoid cutting air gap

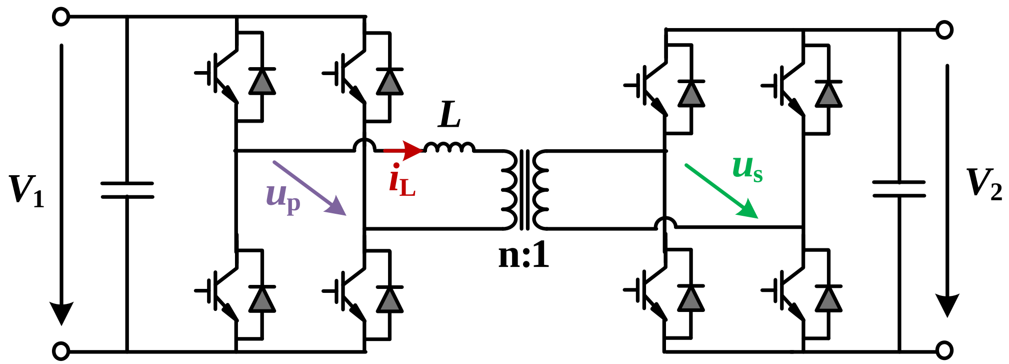
- **Small L_m (several mH) to achieve ZVS**

- **Cut air gap:** main flux at the air gap is directly coupled into the winding, causing high winding eddy current!

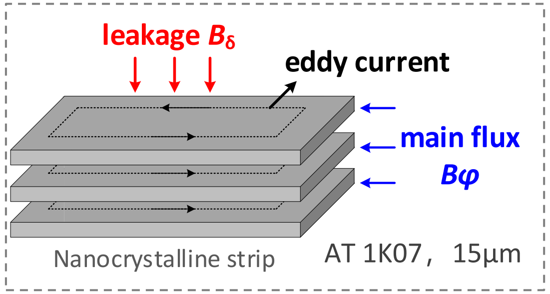


Challenge: difficulty of transformer design with a small L_m

DAB → leakage inductance design



- **Large L (several hundreds μH):** integrated in transformer in form of a **leakage inductance**



- **Adjust winding distance:** leakage flux enters the core surface area, causing high eddy loss on the core!

Challenge: difficulty of integration for large leakage inductance

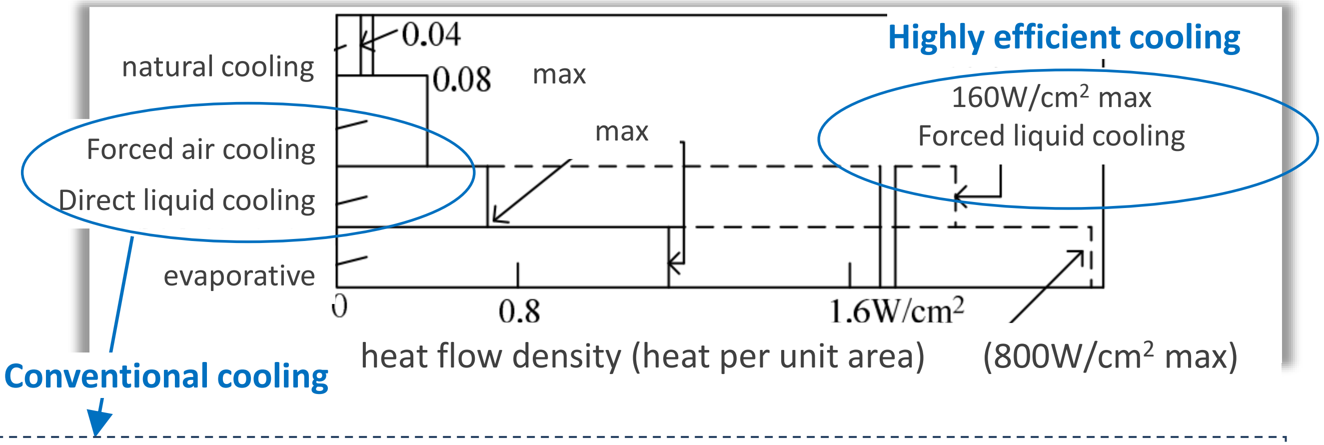
Solid State Transformer—MFT

Thermal Design

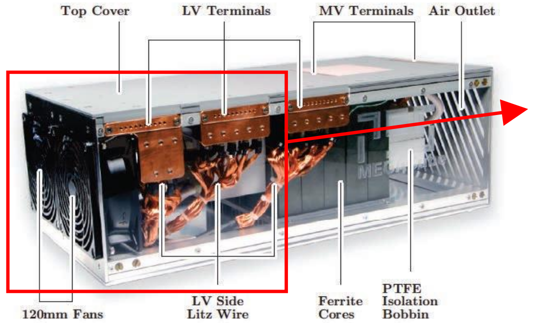
- **Challenge of SST-MFT thermal**
  - Compact design of transformer → heat concentration, difficult to dissipate
  - Good cooling performance → large-scale heat sink

High power density vs. High reliability

Several heat dissipation techniques



ETH: 166kW/20kHz



- **Forced air cooling**
  - × Heatsink + fan takes up about 25% or more of the total volume
  - × High thermal time constant (>500s)
  - × Wind speed over 8~10m/s will significantly increase the back pressure and noise

500kW Oil-immersed transformers

- **Direct liquid cooling**
  - × Large volume weight of fuel tank, oil pillow, shell, accounting for more than 40% of the total weight
  - × Higher thermal time constant (>30s)

- **Conventional cooling: limited cooling capability, bulky, low power density, large thermal time constant**

Solid State Transformer—MFT

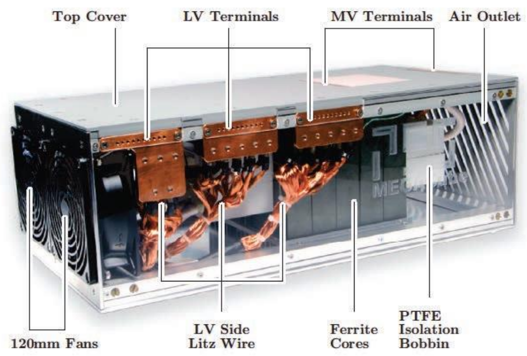
■ Thermal Design

➢ **Forced liquid cooling**

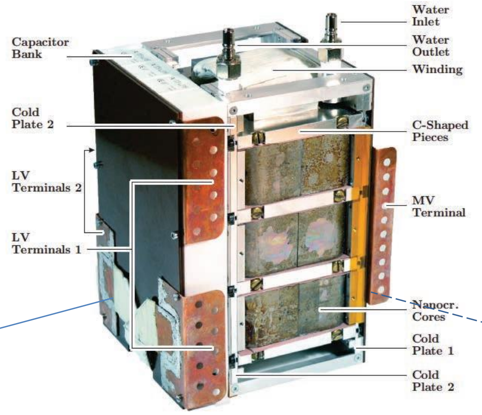
Power density 8.21kW/L

ETH: 166kW/20kHz

(Forced air-cooling)

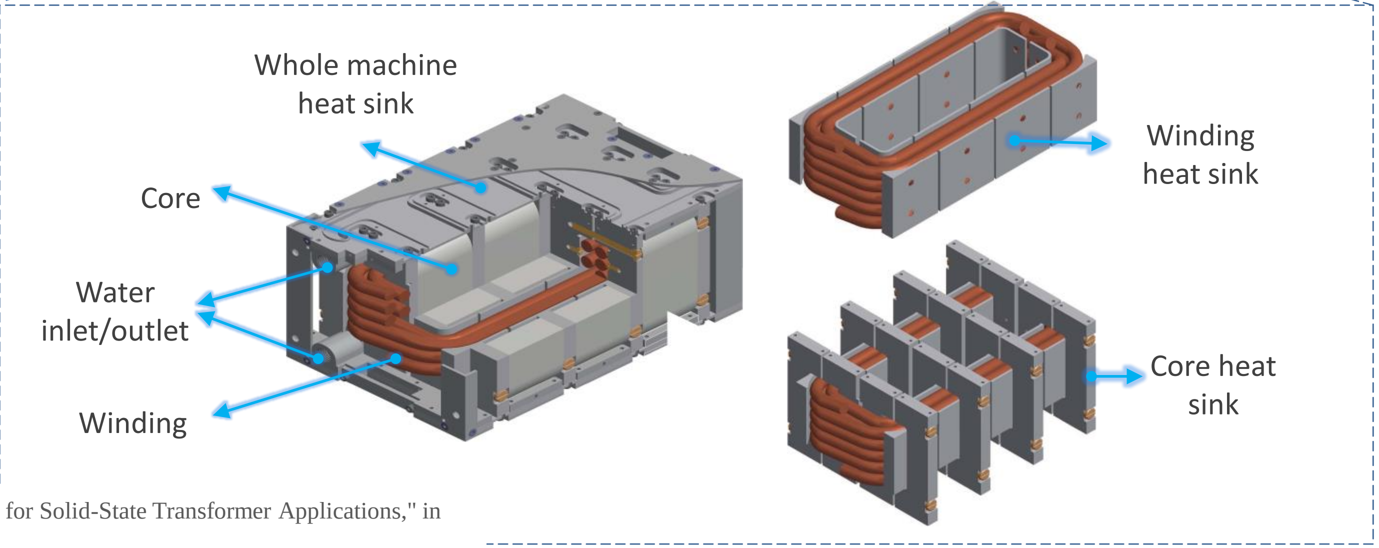


Power density 44kW/L



ETH: 166kW/20kHz

(Forced liquid cooling)



- ✓ Small space for heat sinks: 5 times the power density of forced air cooling
- ✓ Excellent cooling performance: heat flow density up to 160W/cm^2
- × Time constant still large (>30s)

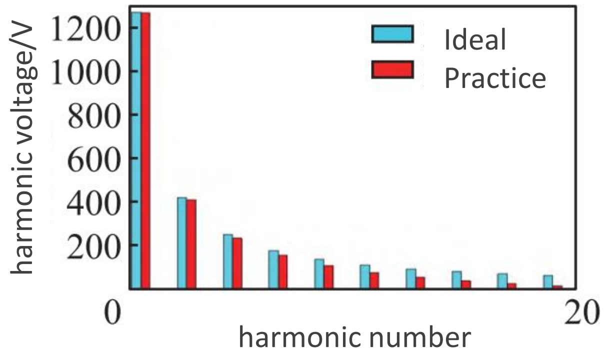
M. Leibl, G. Ortiz and J. W. Kolar, "Design and Experimental Analysis of a Medium-Frequency Transformer for Solid-State Transformer Applications," in IEEE Journal of Emerging and Selected Topics in Power Electronics, 2017, 5(1): 110-123,

Solid State Transformer—MFT

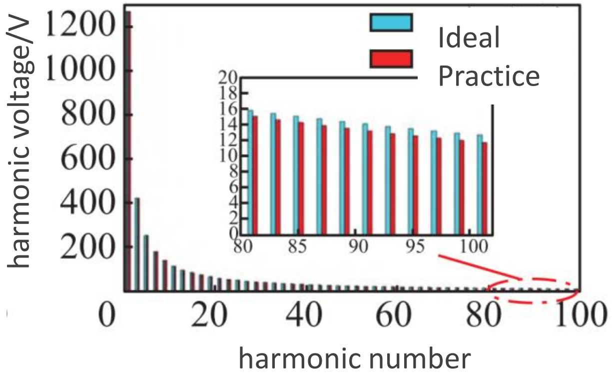
Insulation Design

- **Challenge:** High dv/dt of square wave contains extensive high-frequency harmonics, causing **insulation dielectric loss**

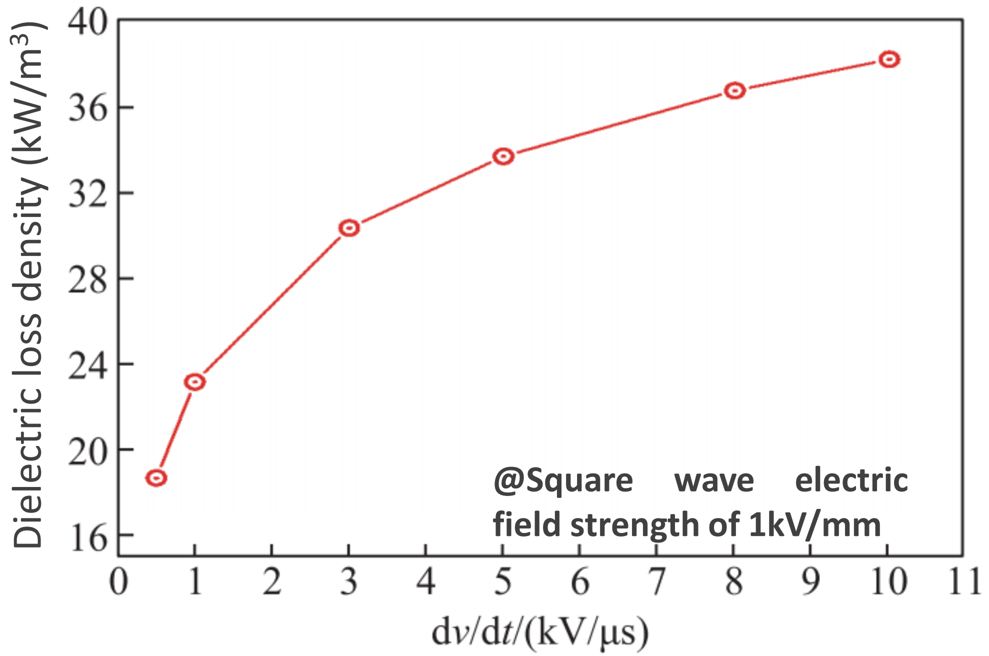
① The higher the dv/dt amplitude, the higher the number of high amplitude harmonics



du/dt=0.5kV/μs



du/dt=10kV/μs



② Compact transformer leads to smaller insulation distances and higher square-wave electric field strength

Insulation dielectric loss density: $$p = \frac{8f_s}{\pi}\ln\left(\frac{f_c}{f_s}\right) r\varepsilon_0\varepsilon'' E_{sq}^2$$

Square-wave electric field strength

Insulation dielectric loss accounts for about 17% of the transformer loss, leading to local temperature rise and degradation of the insulation

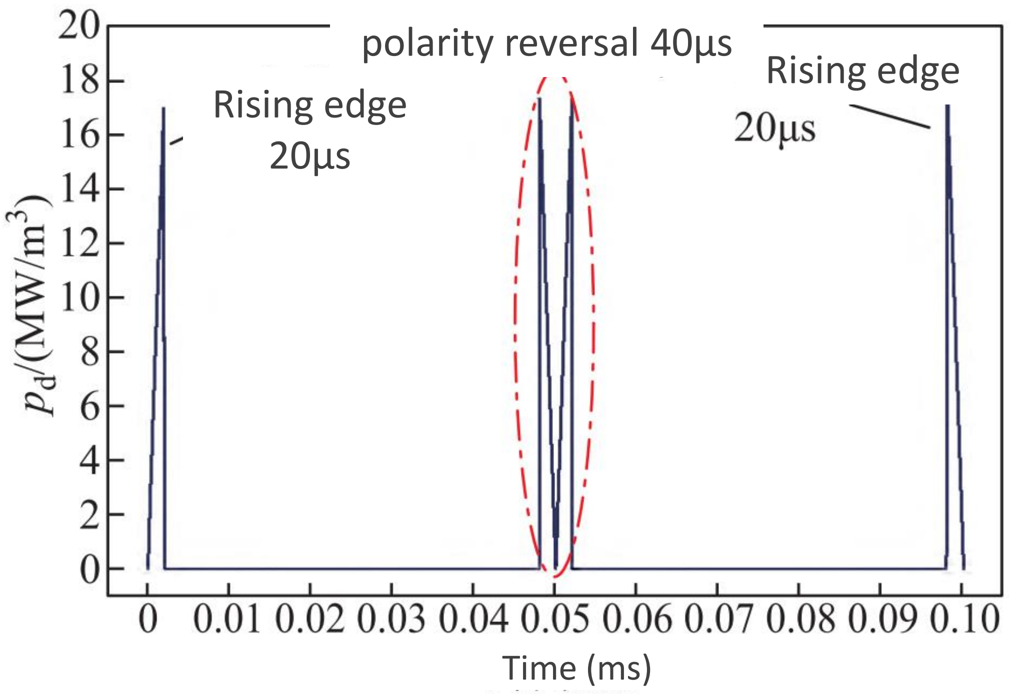
Wang W W, Li R Z, He J F, et al. Characteristics of dielectric loss and impact energy accumulation in high-frequency transformer insulation under fast steep-pulse repetitive electric field[J]. Journal of Electrotechnology, 2023, 38(05): 1206-1216.

Solid State Transformer—MFT

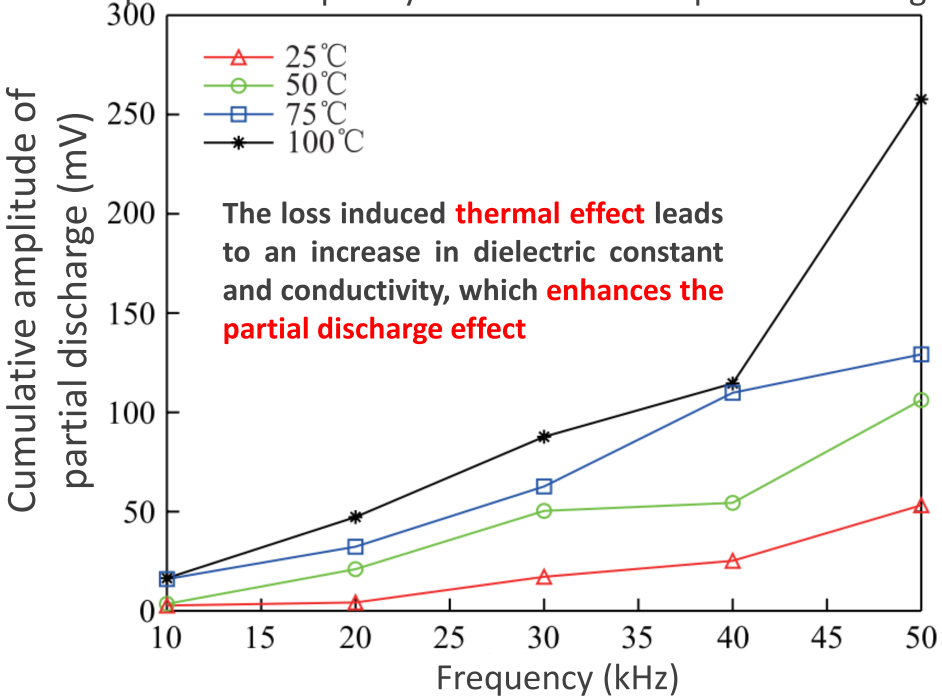
Insulation Design

➢ **Challenge:** High frequency and high dv/dt make the insulation materials suffer electrical stress shocks, and **partial discharge is extremely serious**

Material energy impact density



Temperature-frequency characteristics of partial discharges



- Displacement currents at high dv/dt lead to **high energy**, which **reduce the life of materials**
- Repeated **charging and discharging** of materials under high-frequency causes **relaxation of materials and failure of insulation**

Outline

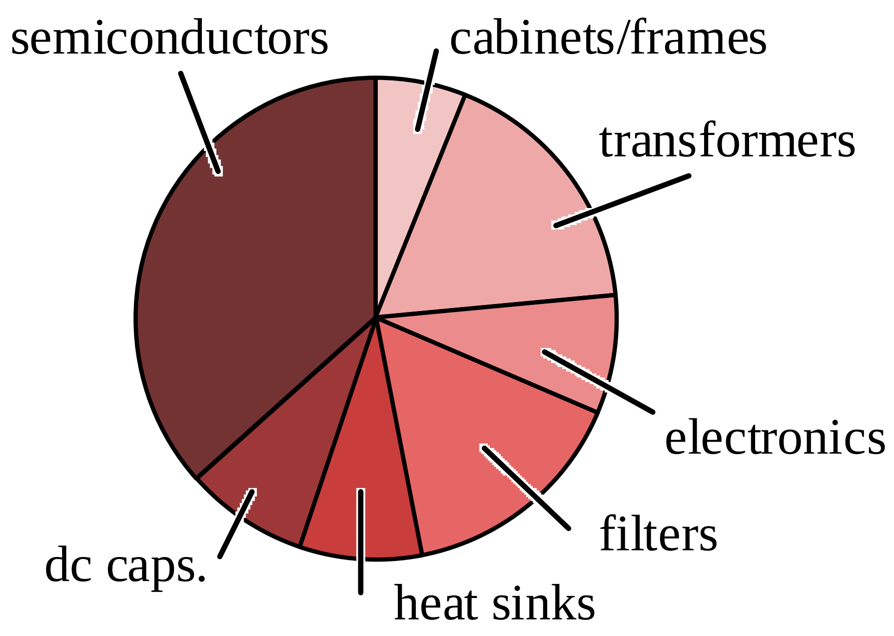
Key Technologies and Issues in Solid State Transformer

- Efficiency
- Voltage regulation
- Power density
- Transformer
- **Cost**
- Fault protection

Solid State Transformer—Cost

Cost Analysis of SST

- **Semiconductors and transformers accounts for a large percentage**

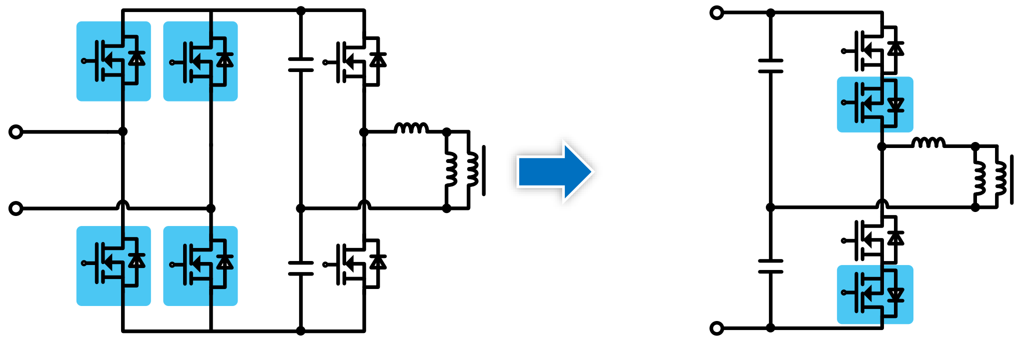


Source: J. W. Kolar (ETH Zurich)

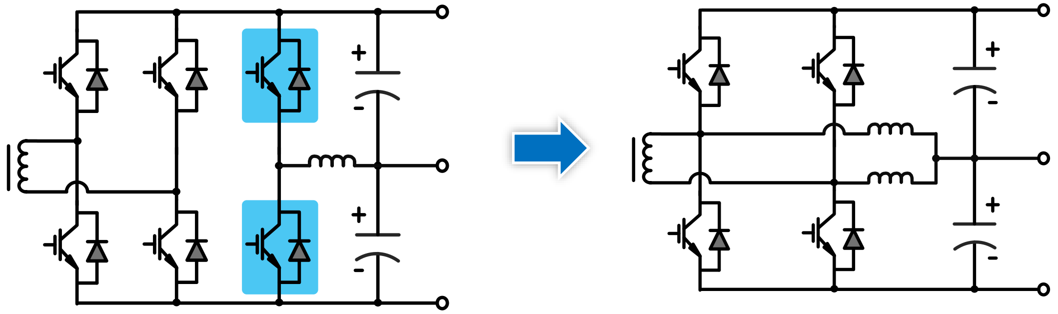
Cost breakdown of AC/AC SST

- **Reducing the number of devices**
  → Integrating power conversion stages

– Coupling between each power conversion stage, increasing the control complexity



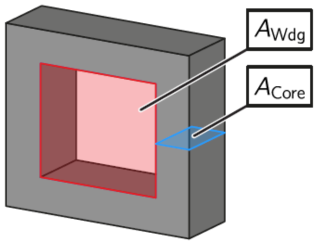
AC/DC with integrated DC/AC



DC/DC with integrated voltage balancer

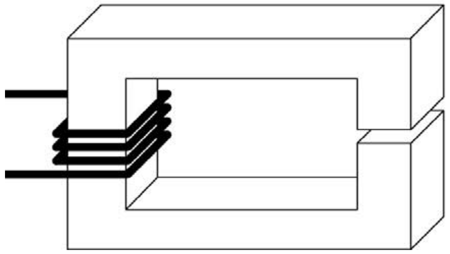
Solid State Transformer—Cost

■ Transformer Cost Optimization



$$\overbrace{A_{Wdg}A_{core}}^{\text{size}} = \frac{\overbrace{P}^{\text{power}}}{4\underbrace{K_u}_{\text{isolate}}\underbrace{B_m}_{\text{material}}\underbrace{J}_{\text{radiator}}\underbrace{f}_{\text{frequency}}}$$

$$\overbrace{N}^{\text{winding turns}} = \frac{\overbrace{U}^{\text{voltage}}}{\underbrace{K_a}_{\text{waveform}}\underbrace{B_m}_{\text{material}}\underbrace{A_{core}}_{\text{size}}\underbrace{f}_{\text{requency}}}$$



Optimization

① Material: high flux density B_m

	Amorphous	nanocrystal	ferrite
saturation flux density/T	1.56	1.25	0.5
cost	high	very high	low

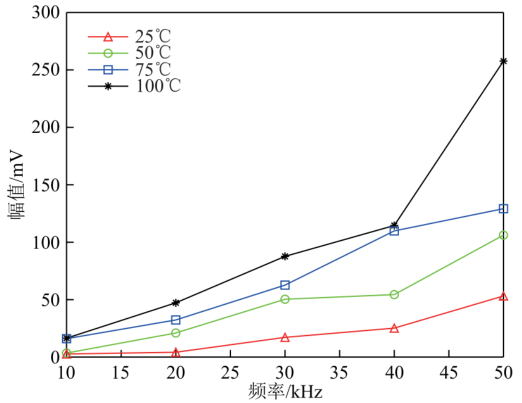
- **Amorphous, nanocrystalline material volume is reduced by 2.5~3 times, and the cost is about 10 times of ferrite**

② Frequency: high frequency f

$$P_c = kf^{\alpha}B_m^{\beta}$$

(AT 1K07， α=1.82)

- Core loss $\propto f^{1.82}$
- Partial discharge intensity $\propto f$



➢ **Using ferrite materials and sacrificing efficiency and power density can optimize cost**

Outline

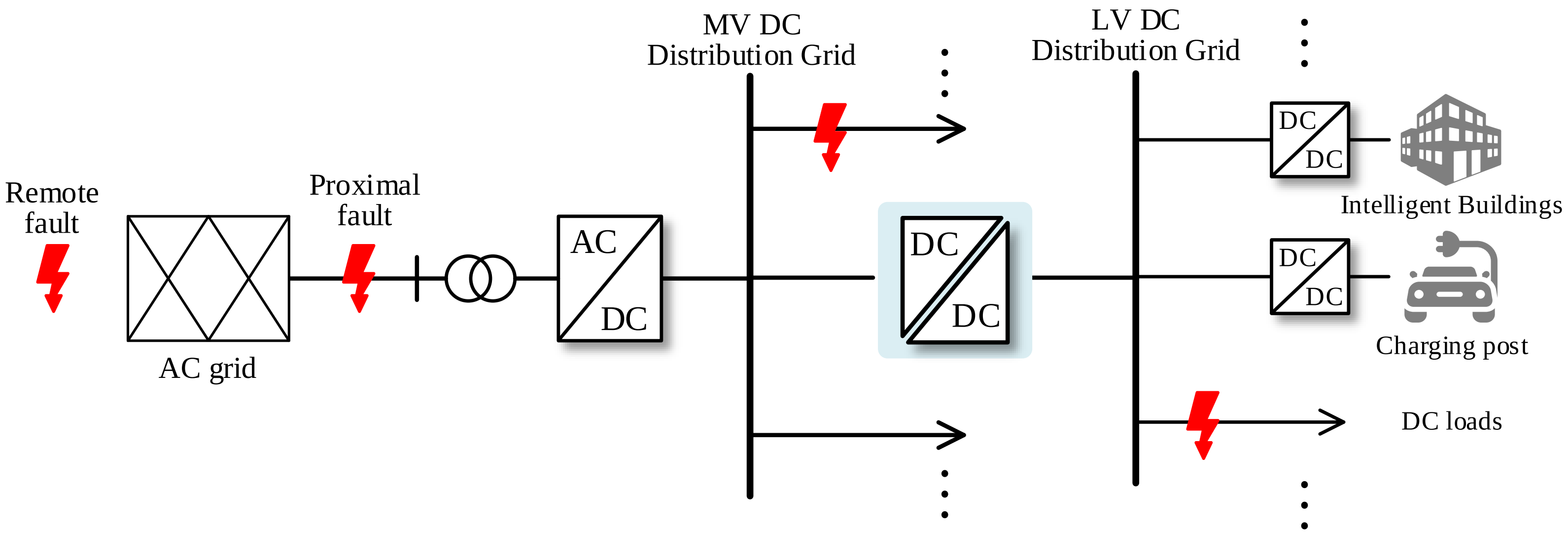
Key Technologies and Issues in Solid State Transformer

- Efficiency
- Voltage regulation
- Power density
- Transformer
- Cost
- **Fault protection**

Solid State Transformer—Fault protection

■ Requirements of Fault Protection

- ➢ **Fault protection on AC (grid) side → Technically mature**
  - − Nearby grid faults: Contributing sufficient fault current to trigger grid protection
  - − Remote grid faults: Performing fault ride-through or providing support to the grid
- ➢ **Fault protection DC side → Challenging**
  - − Fault clearance : Limiting the rise of fault current and realizing fault blocking
  - − Selective protection : Disconnecting the faulty parts and maintaining normal operation of the remaining parts



Solid State Transformer—Fault protection

DC Fault Protection Technology

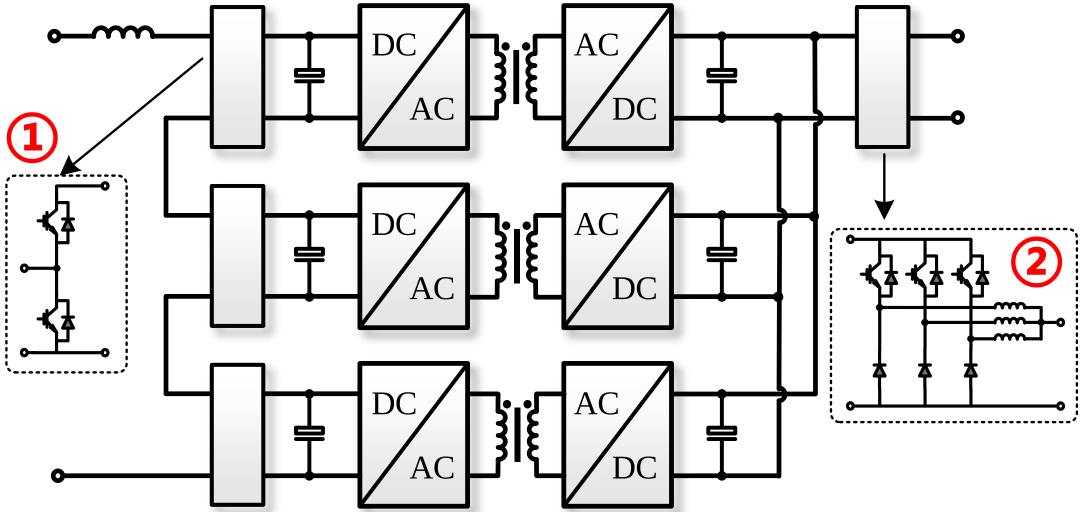
- **DC circuit breaker: Expensive!**
- **Fault current limiting technique based on SST's controllability: ① Configure half-bridge on the MV side ② Configure solid-state switch on the LV side**

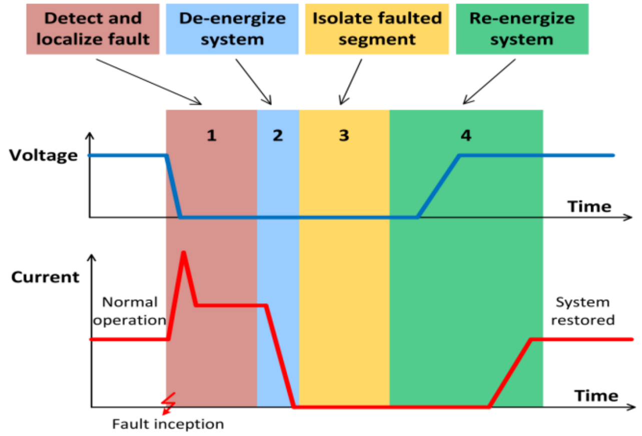
① **For MV side short circuit**, half-bridge module can prevent the capacitor discharging to the fault point, realizing fault isolation

② **For LV side short-circuit**, solid-state switch can inject controllable short-circuit current into the fault point, realizing fault location and selective protection

- **Drawbacks：**

1. Under normal operation, half-bridge module/solid-state switch is still present, resulting in additional conduction loss
2. To handle kA-level current, solid-state switch requires multiple semiconductors or circuitry in parallel, which is costly





Short circuit fault protection procedures

Summary

- **SST** is aimed to replace LFT based AC/DC and DC/AC converters, and fill the gap of MV DC/DC conversion. **High power density, high efficiency, low cost** are the further pursuit
- **Power density and efficiency** are constrained by **high power module count and multiple power conversion stages**. Further breakthrough is expected with **improvement of current capability and cost reduction of wide-band gap devices**
- **The high loss and complex insulation design of MFT** reveal the contradiction among power, voltage, and frequency. Simultaneously satisfying high power density, high efficiency, high reliability, and low cost is still challenging
- **Wide-range voltage regulation and fault protection** are key capabilities of SST. Existing technical solutions come at the expense of lower efficiency and higher hardware expenditure

Solid State Transformer (SST) in Modern Power System

Thanks

Dianguo Xu

2024-08-29