Emerging MV Applications – Data Centers & Superfast EV Charging

Johann W. Kolar et al.

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Dec. 4, 2019

Emerging MV Applications – Data Centers & Superfast EV Charging

J. W. Kolar, F. Krismer, P. Czyz, T. Guillod, P. Papamanolis

Swiss Federal Institute of Technology (ETH) Zurich
Power Electronic Systems Laboratory
www.pes.ee.ethz.ch

Dec. 4, 2019

Outline

- ► Ultra-Fast EV Charging
- ► Motivation
- ► AC & DC Bus Systems
- ► SST Concepts
- ► Next Generation Datacenters
- ► Motivation
- ► Power Distribution Structures
- ► SST Demonstrators
- ► Conclusions

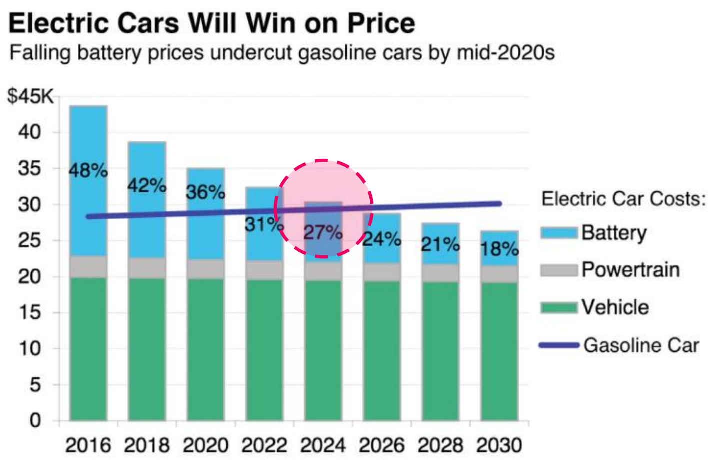
Acknowledgement
D. Bortis
J. Huber
G. Ortiz
D. Rothmund

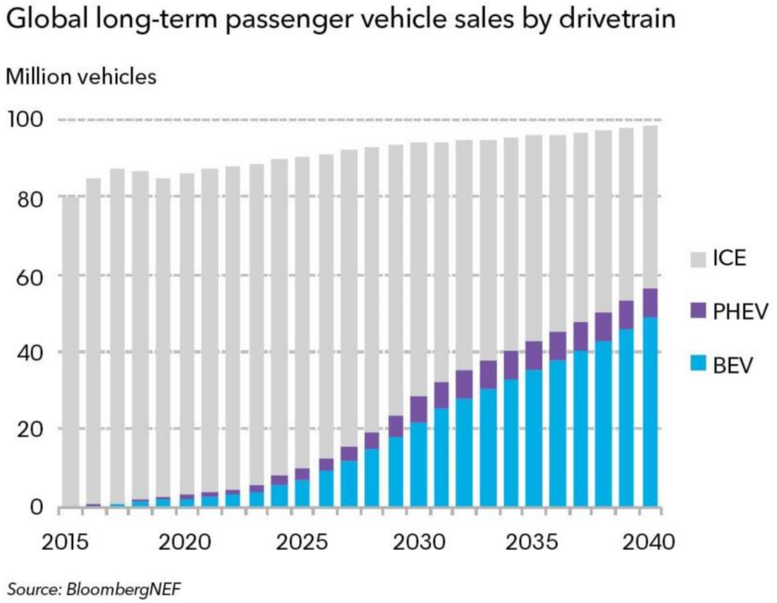
... X-Fast Charging

$$T_{chg} = \frac{E}{P_{chg}}$$

Electric Vehicle Outlook 2019

- Bloomberg NEF — By 2040 — 57% of All Passenger Vehicle Sales
  30% of Global Passenger Vehicle Fleet



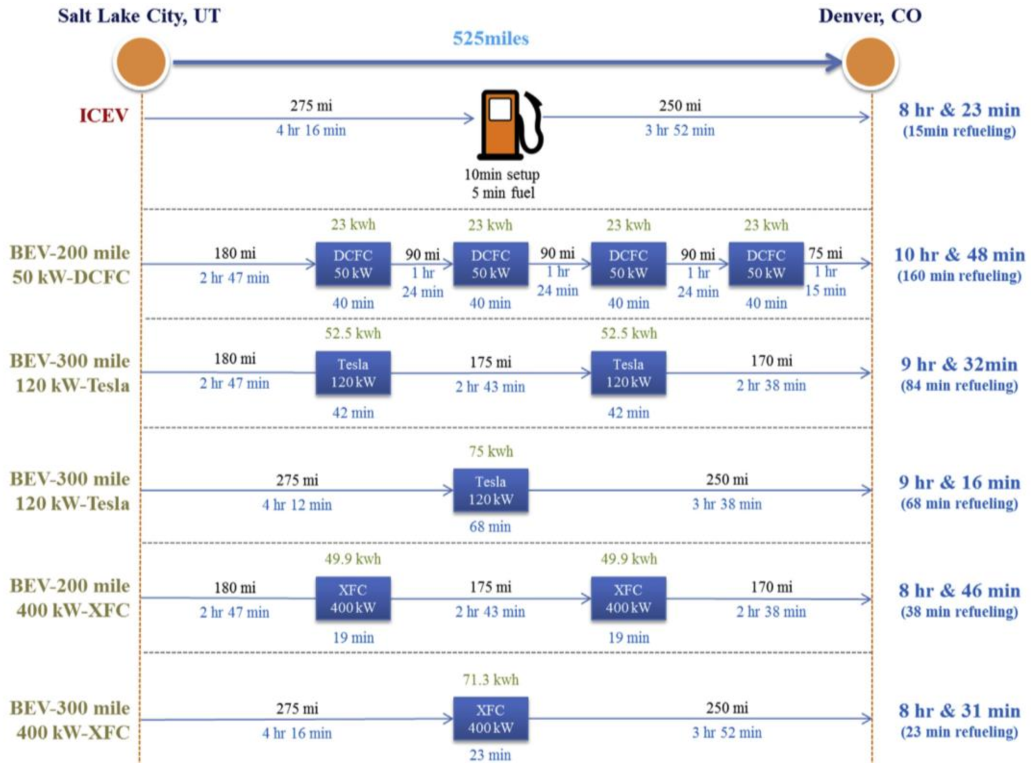


- Falling Battery Costs → Price Parity of EVs and ICE-V by Mid-2020s → Tipping Point for EV Industry

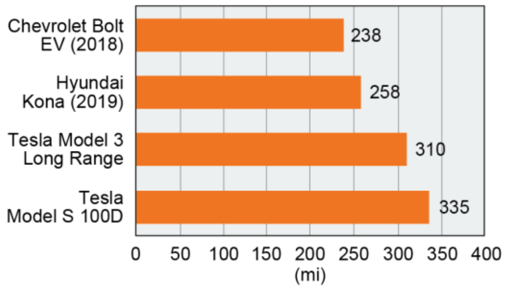
EV Range Anxiety

- *More than 70% of Buyers Want 200+ Miles EV*

Source: A. Meintz et al., 2017, Journal of Power Sources



Source: S. Srdic et al., IEEE Electr. Mag., 2019

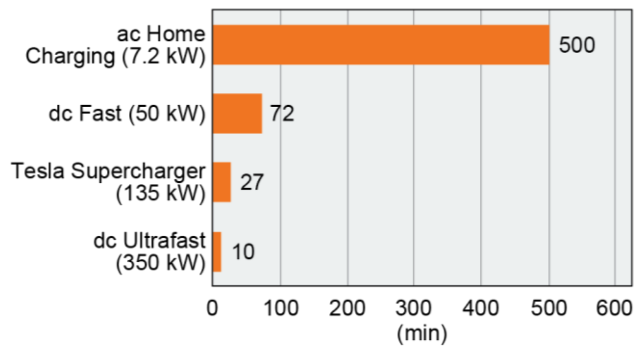


- *Long Distance Travel — BEV vs. ICE-V → Only 8 min Difference for 300-Mile Battery & XFC*

EV Charging Anxiety

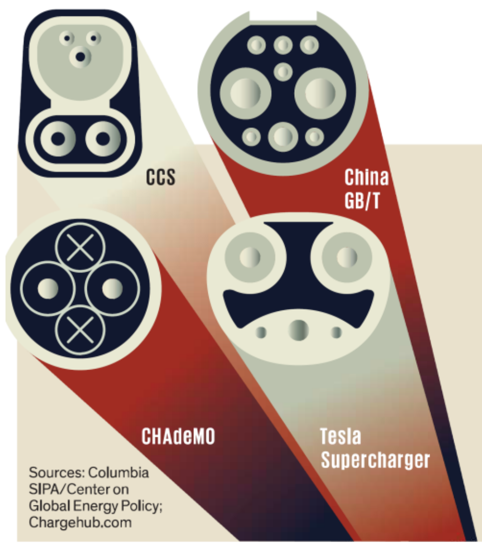
- *200+ Miles EV → 50+kWh*

Source: S. Srdic et al.,
IEEE Electr. Mag., 2019



ChargePoint stations (projected growth)

Source:
ChargePoint



DUELING CHARGERS

System	Public chargers worldwide	Kilowatts	Availability
Combined Charging System (CCS)*	22,000	50–350	United States, European Union, Australia, Korea
China GB/T	330,000	237.5	China, India
Tesla Supercharger	13,000	135	Global
CHAdeMO	25,300	50–100	Global

* North American and European versions are not compatible.

Source: J. Voelcker,
IEEE Spectrum, 2019

- *350kW Extreme Fast Charging (XFC) → Only 10 min Charging Time*

State-of-the-Art Fast Charging

- *Standards — CHAdeMO (global), CCS1 (US), CCS2 (EU), GB/T (China), TESLA (global)*

TABLE Technical specifications of commercially available dc fast chargers

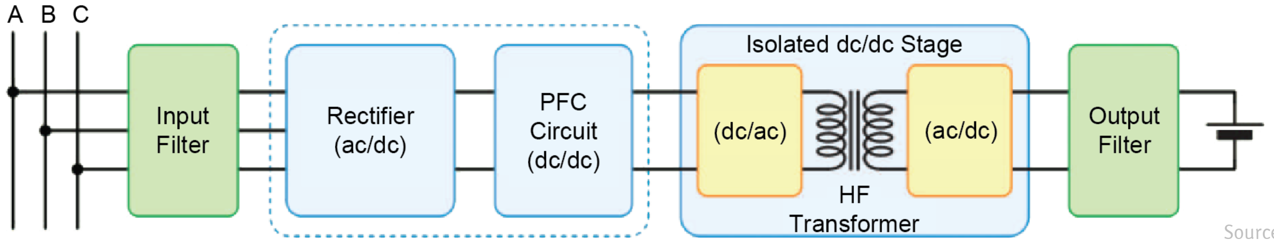
Manufacturer and Model	ABB Terra 53	Tritium Veefil-RT	Tesla Supercharger	EVTEC espresso&charge	ABB Terra HP
Rated power	50 kW	50 kW	135 kW	150 kW	350 kW
Supported standards	CCS Type 1 CHAdeMO 1.0	CCS Types 1 and 2 CHAdeMO 1.0	Supercharger	SAE Combo 1 CHAdeMO 1.0	SAE Combo 1 CHAdeMO 1.2
Input voltage	480 Vac	380–480 Vac 600–900 Vdc	200–480 Vac	400 Vac ± 10%	400 Vac ± 10%
Output dc voltage	200–500 V 50–500 V	200–500 V 50–500 V	50–410 V	170–500 V	150–920 V
Output dc current	120 A	125 A	330 A	300 A	375A
Peak efficiency (charger only)	94%	>92%	92%	93%	95%
Volume	758 L	495 L	1,047 L	1,581 L	1,894 L
Weight	880 lb (400 kg)	364 lb (165 kg)	1,320 lb (600 kg)	880 lb (400 kg)	2,954 lb (1,340 kg)

Source: S. Srdic et al., IEEE Electr. Mag., 2019

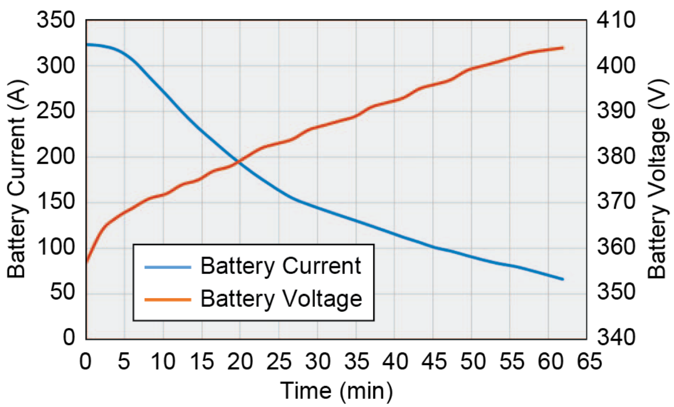
- *Up to 350 kW of Charging Power & Up to 920V DC Voltage*

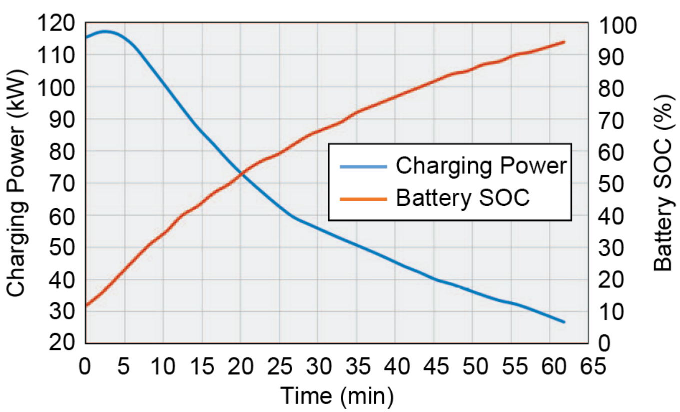
DC Fast Charging

- *State-of-the-Art DC XFC — 400V 3-Φ AC / PFC Rectifier / Isol. DC/DC-Converter*
- *Isol. DC/DC Converter — Simplifies Parallel Connection & Safety Concept*



Source: S. Srdic et al., IEEE Electr. Mag., 2019



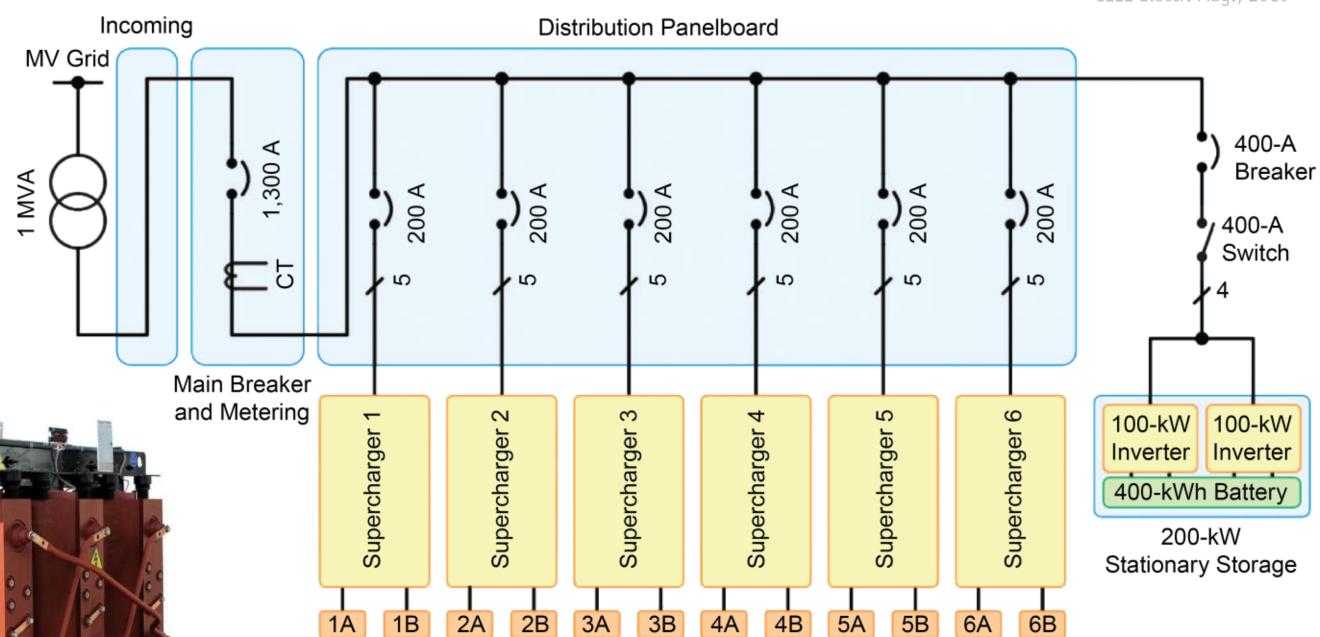


- *TESLA Model S85 — Charging Profile (CC/CV) / SOC / Charging Power*

DC Fast Charging Station

- *TESLA Supercharger Station in Mountain View, California*

Source: S. Srdic et al., IEEE Electr. Mag., 2019

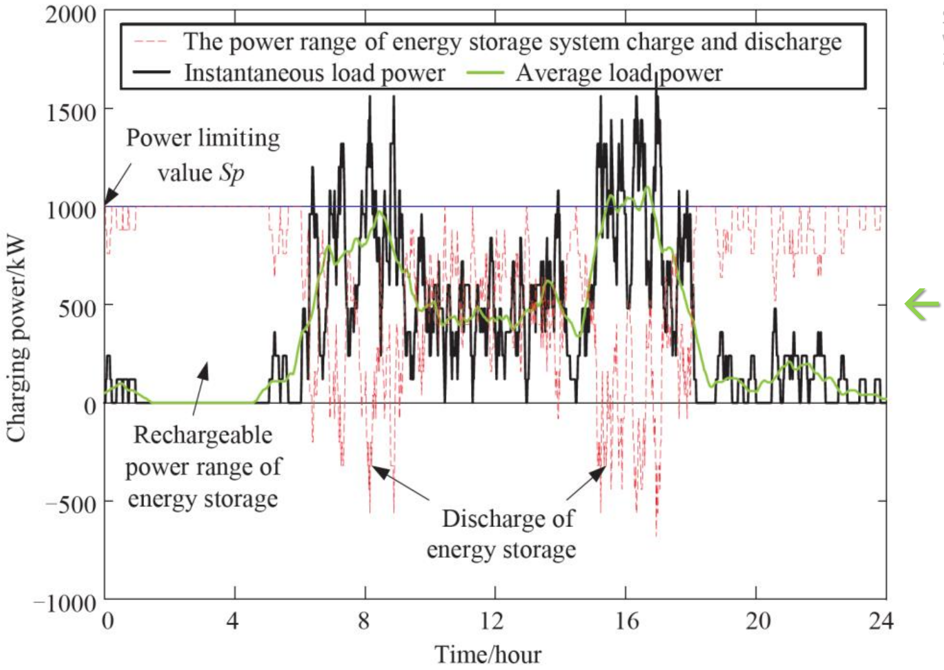


Source: Schneider Electric

- *400kWh / 200kW Battery Buffer*

Charging Station Battery Buffer

- *Large Variation of Power Demand (High Peak Load Tariff etc.) → Energy Buffer*
- *$$$-Model-Based Opt. Sizing incl. Ancillary Grid Services / Overnight Re-Chg / etc.*



Source: Y. Zhang, www.geidco.org, 2018

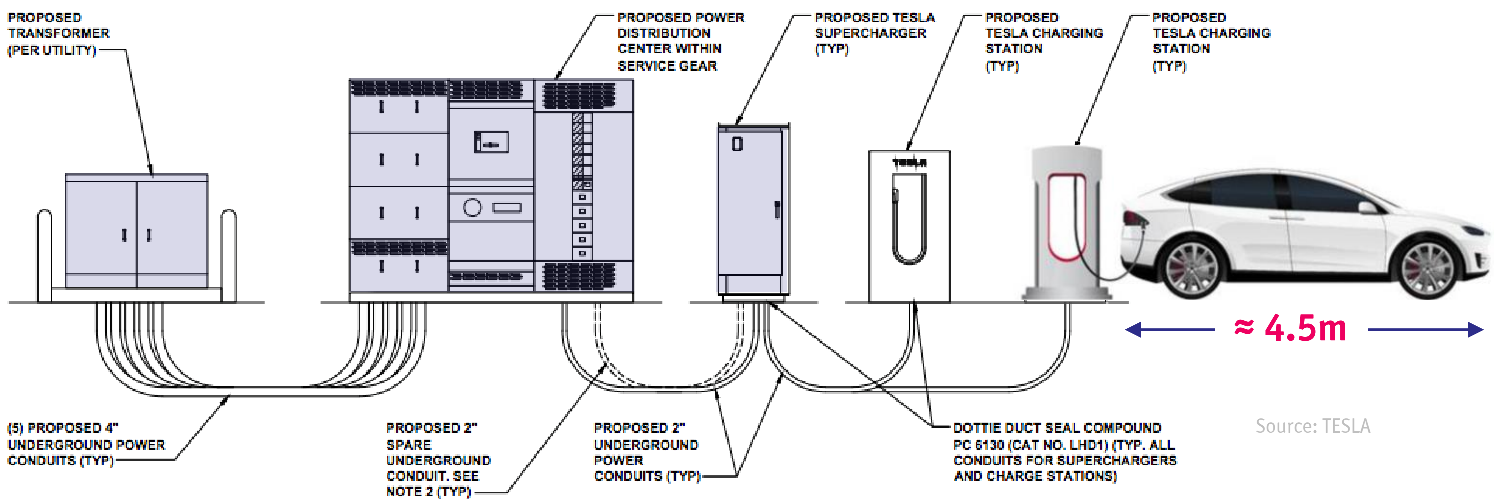
- *Avg. Power < Rated Power & Peak Power → Avg. Power Grid-Tie (!)*

TESLA Charging Station Layout

Source: E. Loveday
INSIDEEVs

NOTES
1. CONDUITS SHALL BE BURIED BELOW FROST LINE AND IN COMPLIANCE WITH LOCAL AND NATIONAL CODE REQUIREMENTS.
2. ONE ADDITIONAL CONDUIT SHALL BE INSTALLED IN PARALLEL OF PROPOSED POWER CONDUITS FOR FUTURE EXPANSION.
3. REFER TO SHEET E-2 FOR CONDUCTOR REQUIREMENTS WITHIN CONDUITS.

"User Interface"



Source: TESLA

- *Supercharger = 12 On-Board Charger Modules in Parallel → 12x10kW = 120kW*

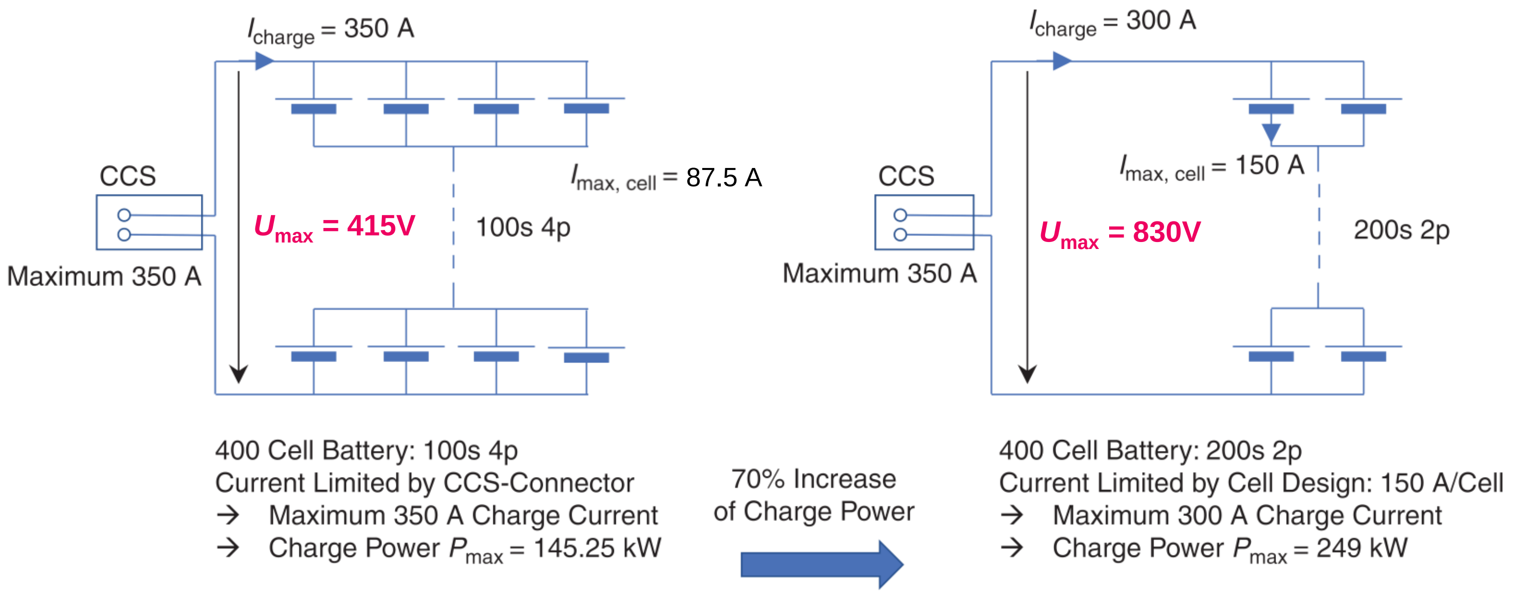
400V → 800V Charging

$$I_{chg} = \frac{P_{chg}}{U}$$

800V vs. 400V Battery Comparison (1)

- **400V — e.g. 100 Cells in Series, 4 Parallel → 300 ... 420V**
- **800V — e.g. 200 Cells in Series, 2 Parallel → 600... 840V**

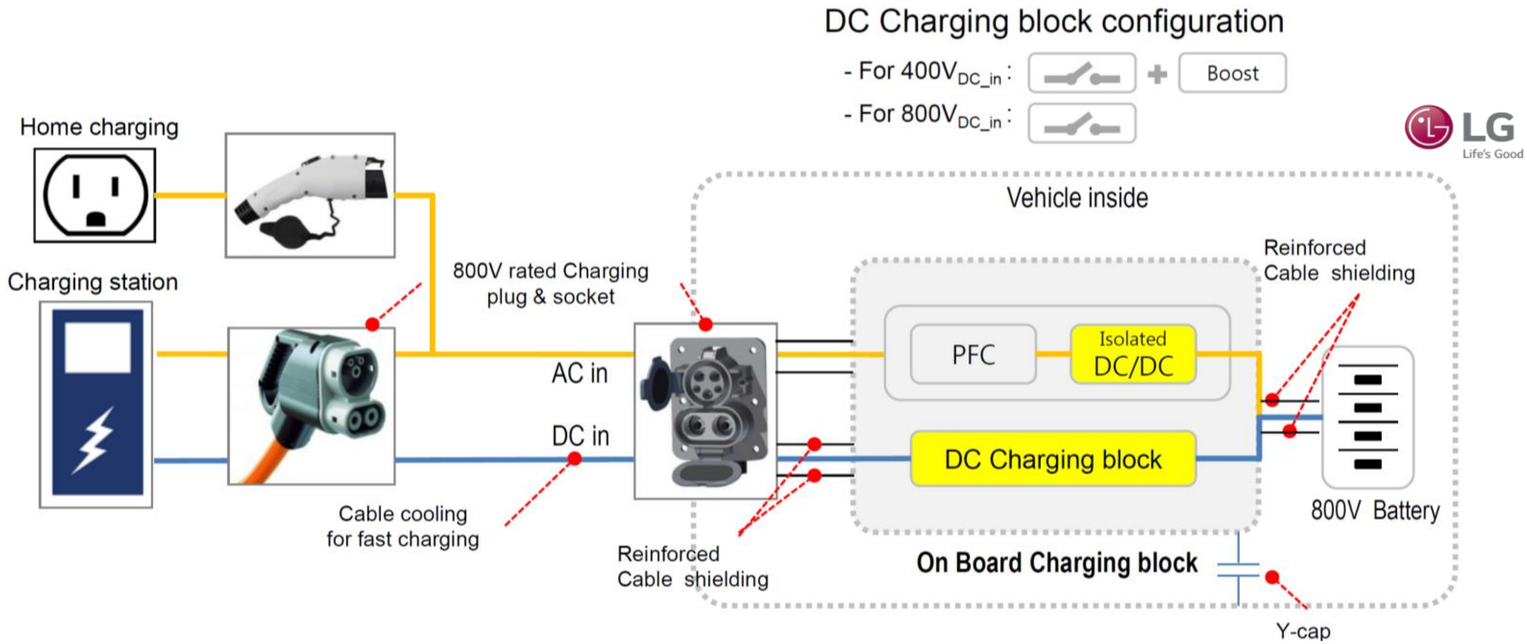
Source: C. Jung, IEEE Electr. Mag., 2017



- **Higher Battery Current → Lower Charging Time BUT Faster Aging**
- **2x I_{chg}/Cell → 4x Loss/Cell (1mΩ/Cell, 3kW → 9kW Thermal Batt. Loss)**

800V vs. 400V Battery Comparison (2)

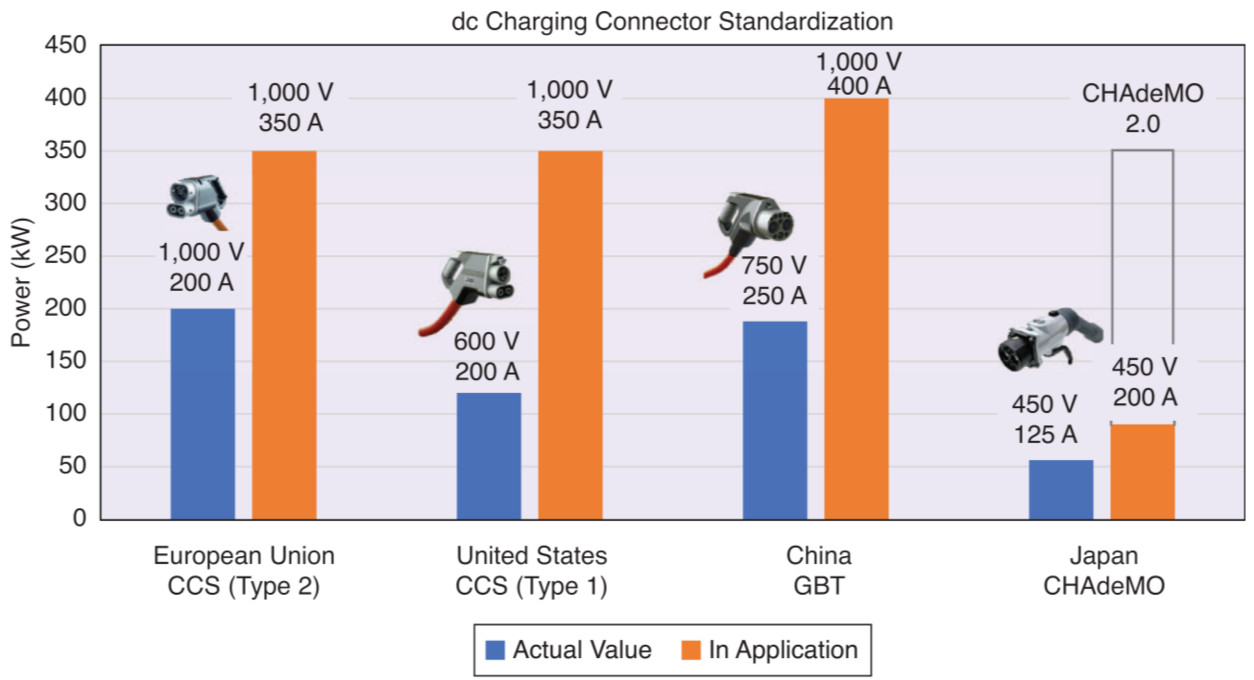
- *10-15kg Lower Cable Weight @ 200kW*
- *0.5 dm³ Lower Connector Volume*
- *Lower IGBT $$$ etc.*



- *800V Standards Not Yet Complete, Necessary Design Modifications, etc.*
- *Higher # of Series Cells → Higher Complexity & $$$ of Batt. Management System*

DC Charging Connectors

- Practical Limit Due to Safety Effort, etc.
- "Low Voltage" Def. as < 1000V AC / < 1500V DC in Standards



Source: C. Jung, IEEE Electr. Mag., 2017

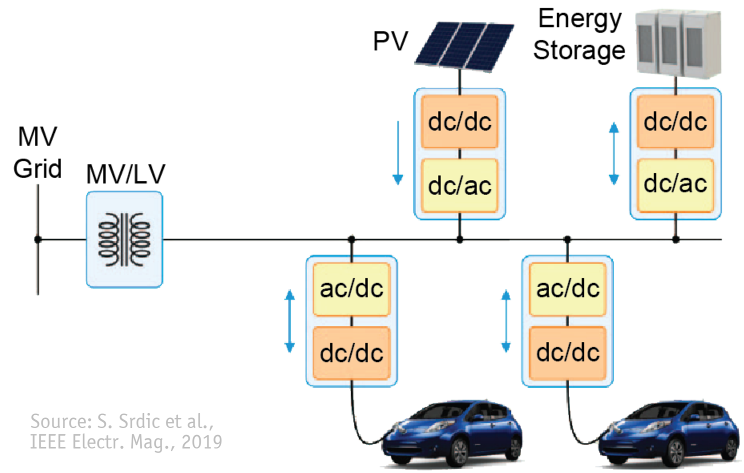
- Typ. Infrastructure Delivers 500V DC (600V IGBTs) & 50kW
- Charging Time Defined by U · I → Current Limited by Connector System

Charging Station Concepts

- *AC-Coupled*
- *DC-Coupled*

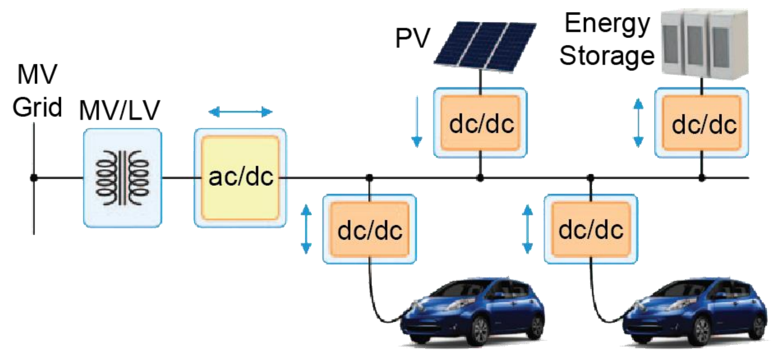
Charging Station Concepts

■ *AC-Coupled*



Source: S. Srdic et al., IEEE Electr. Mag., 2019

■ *DC-Coupled*



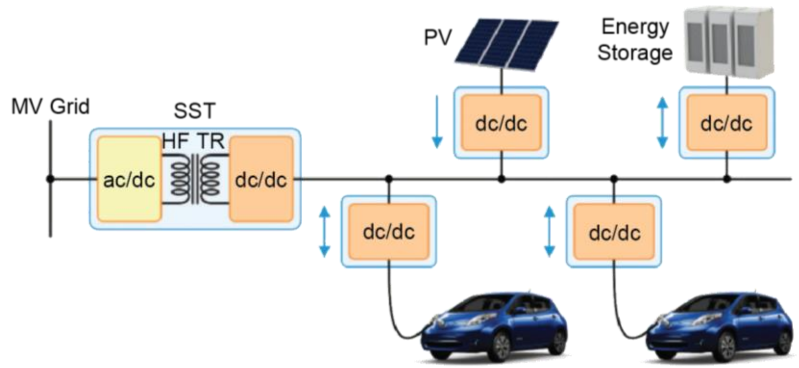
- *Lower # of Conversion Stages*
- *Lower Complexity / $$$ / Losses*
- *DC-Voltage Symmetric to Ground & High-R Gndg*
- *Active Front-End or 12-Pulse Rectifier Stage*

SST-Based XFC

AC/DC Solid-State Transformer (SST)

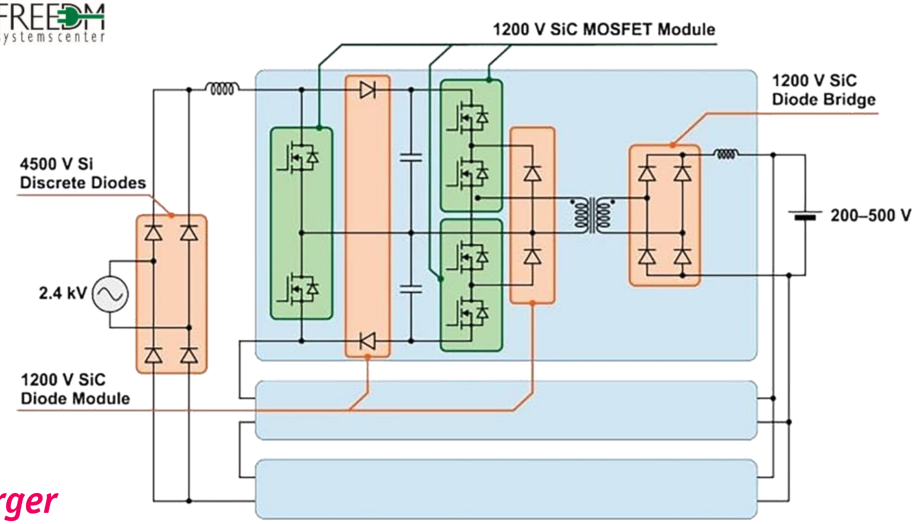
Source: S. Srdic et al., IEEE Electr. Mag., 2019

- Medium-Frequency Isolation
- Low Volume / High Efficiency



→ 50kW Demonstrator System

FREEDM systems center

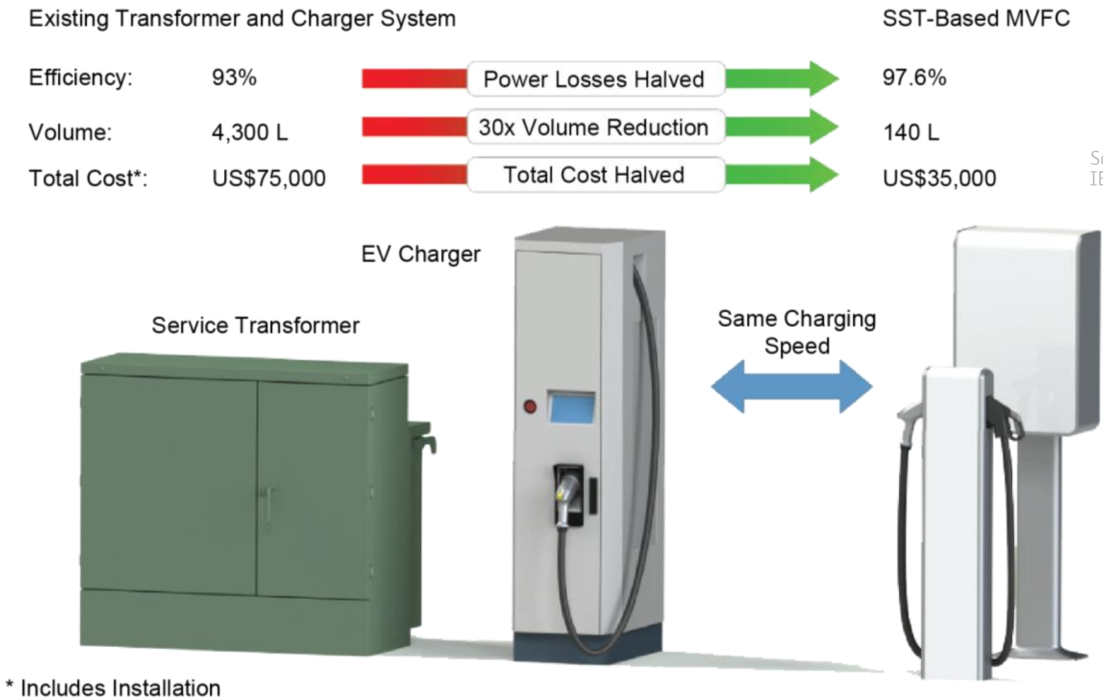


$\eta = 97.6\%$
$\rho = 0.8\text{kW/dm}^3$

- Unidirectional 1-Φ AC/DC SST Charger

SST-Based vs. LFT-Based XFC (1)

- *Exaggerated Expectations in Literature →*

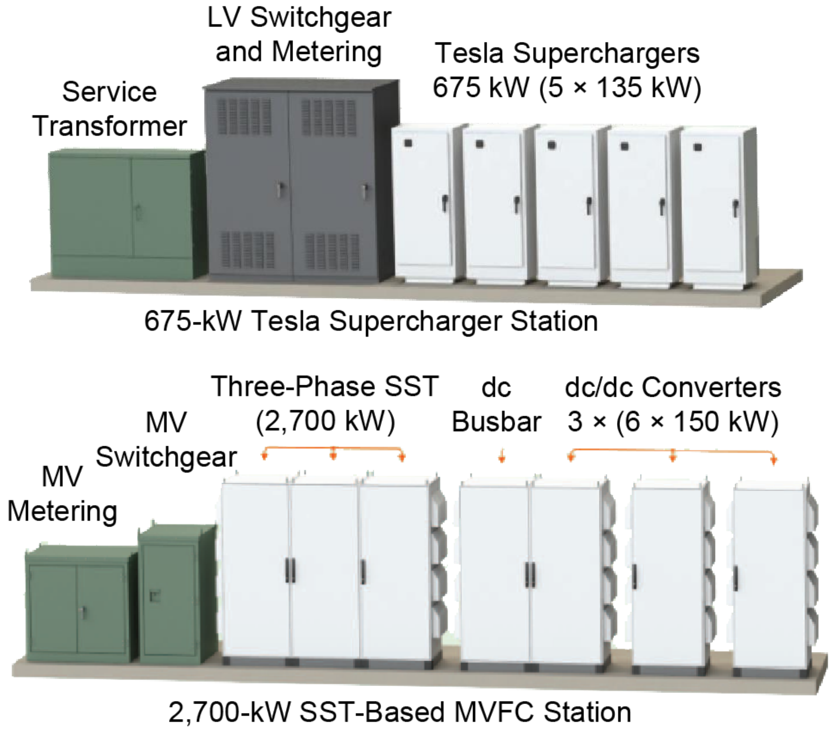


Source: S. Srdic et al., IEEE Electr. Mag., 2019

- ***US DOE \$7m*** ***400kW / 4.8kV or 13.8kV AC-Input SST-Based XFC***
- ***Project Targets*** ***96.5% G2V Efficiency, Weight: 1/4, Footprint: 1/2***
- ***Partners*** ***General Motors, Delta Electronics, DTE Energy, others***

SST-Based vs. LFT-Based XFC (2)

- *State-of-the-Art TESLA XFC Station vs. SST-Based Solution*

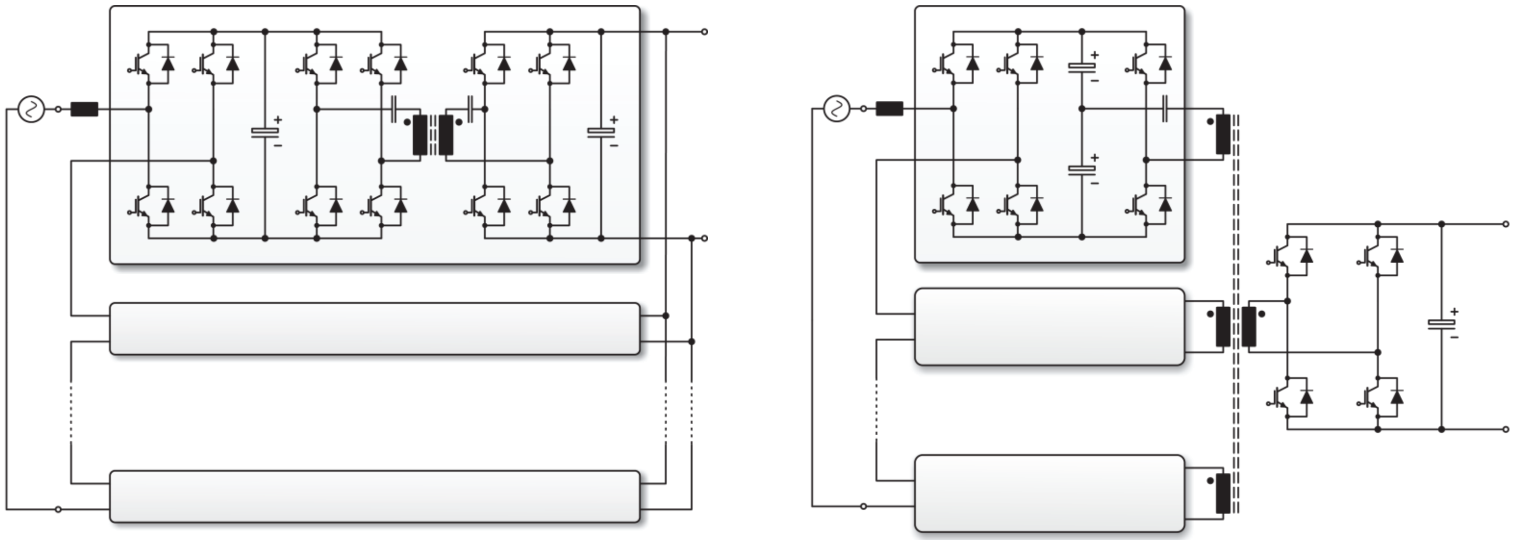


Source: S. Srdic et al., IEEE Electr. Mag., 2019

- *675kW @ 92% G2V Eff. (estimated) → 2700kW @ 97% / Factor 4 @ Same Footprint !*

1-Φ AC/DC SST Topologies (1)

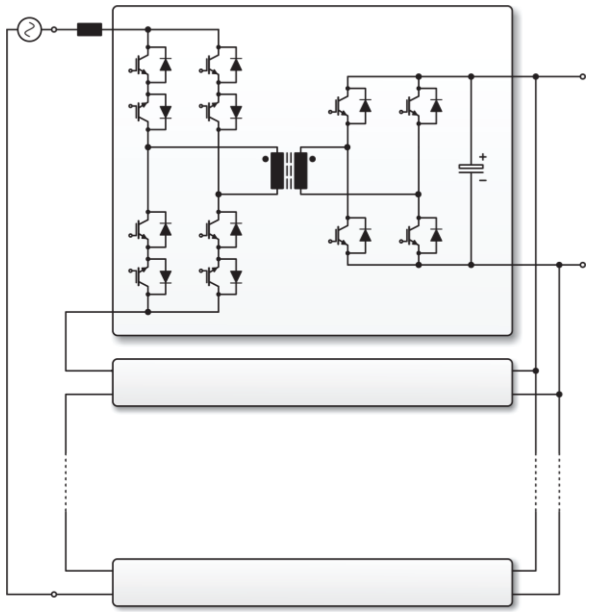
- *PFC Rectifier Stage & Fixed Voltage Transfer Ratio Res. DC-Transformer*
- *Fully / Partially Modular ISOP Structure (Impedance Matching)*

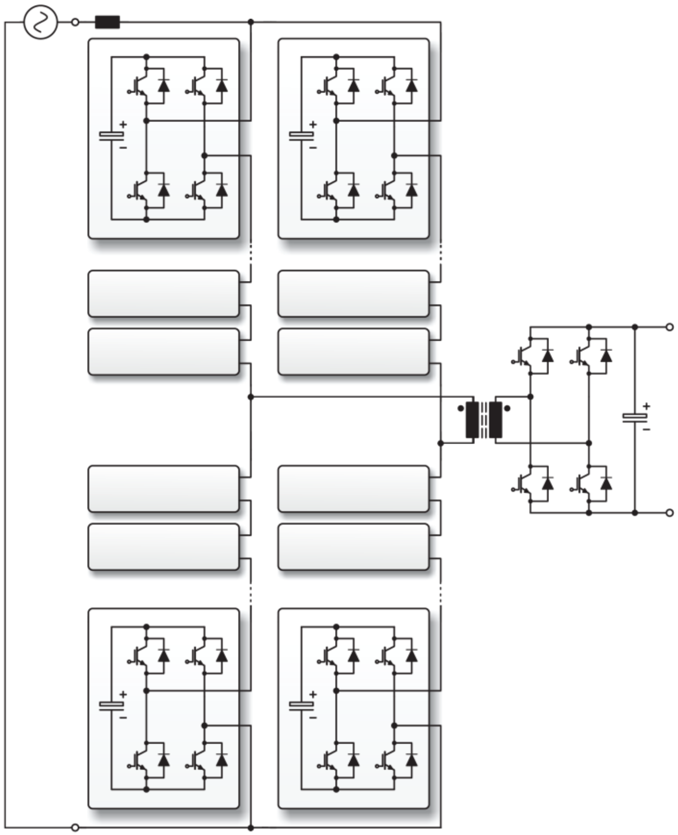


- *Modularity → Redundancy*
- *Multi-Winding Transformer → Risk of Oscillations Between the Modules*

1-Φ AC/DC SST Topologies (2)

- Matrix-Type AC/DC Conversion
- Fully Modular ISOP & MMLC Structure

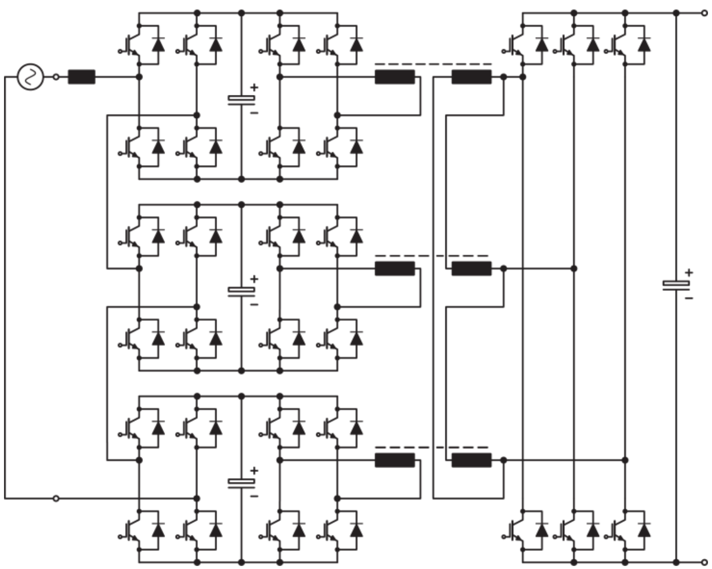




- MMLC Topology → Modularity Limited to Critical System Part / Higher Semiconductors Effort

1-Φ AC/DC SST Topologies (3)

■ *Example of Primary-Modular & Secondary-Integrated ISOP Structure*



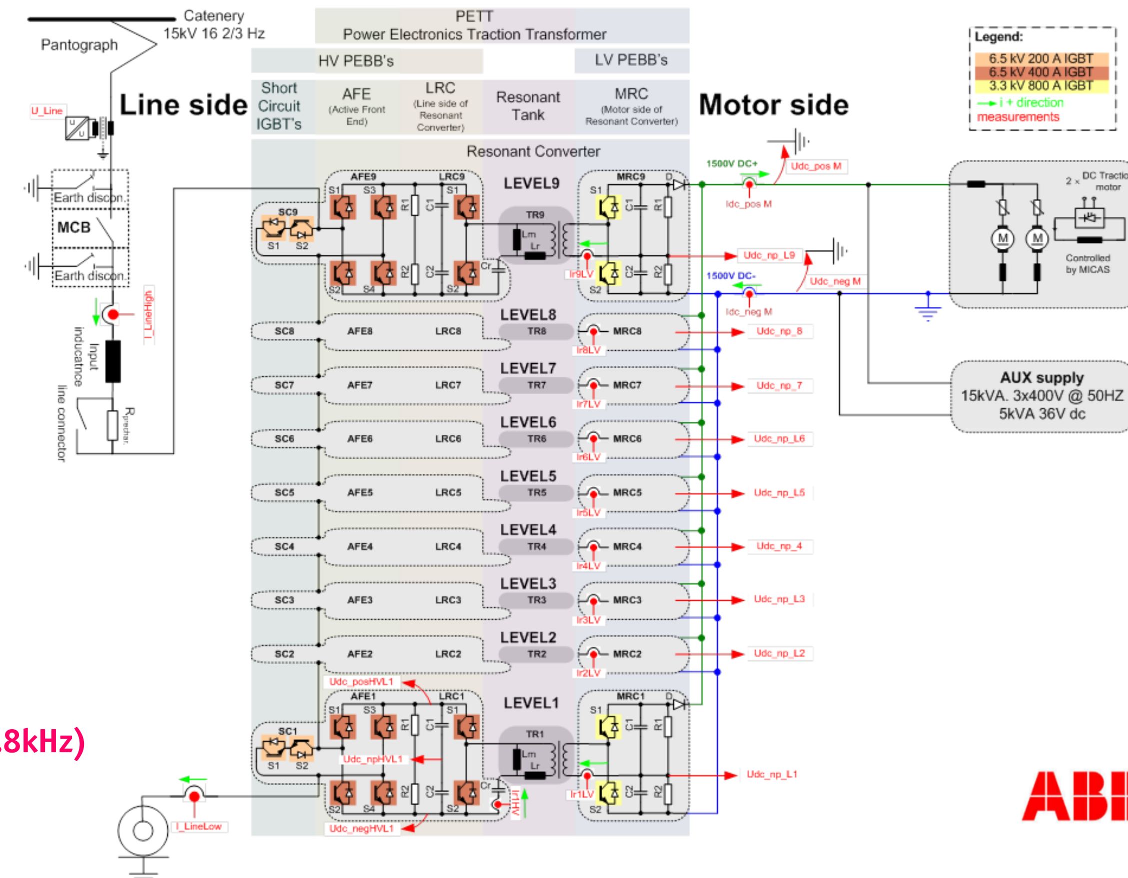
- *Different Partitioning of MV Input & AC/DC Conversion → Very Large # of Possible Conv. Topologies*

Remark

Example of 1-Φ AC/DC SST for Traction (1)

- Dujic et al. (2011)

- Heinemann (2002)
- Steiner/Stemmler (1997)
- Schibli/Rufer (1996)



P = 1.2MVA, 1.8MVA pk
9 Cells (Modular)

54 x (6.5kV, 400A IGBTs)
18 x (6.5kV, 200A IGBTs)
18 x (3.3kV, 800A IGBTs)

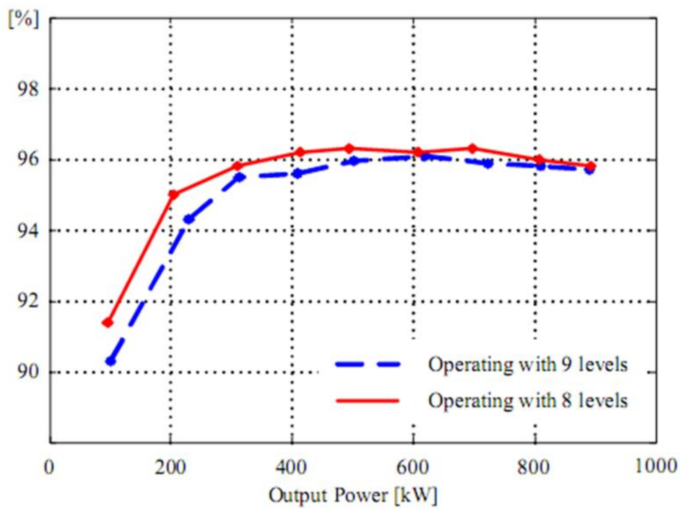
9 x MF Transf. (150kVA, 1.8kHz)
1 x Input Choke

ABB

Remark — Example of 1-Φ AC/DC SST for Traction (2)

- *Cascaded H-Bridges – 9 Cells*
- *Resonant LLC DC/DC Converter Stages*

Efficiency

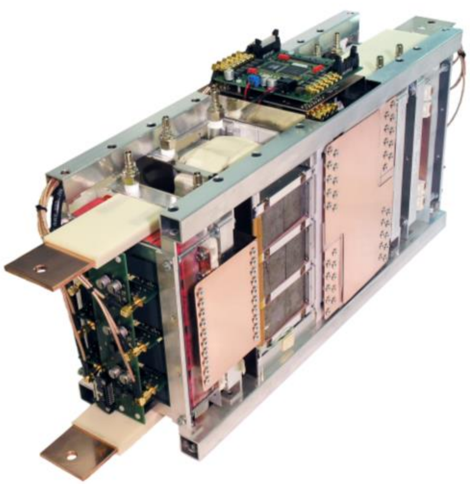


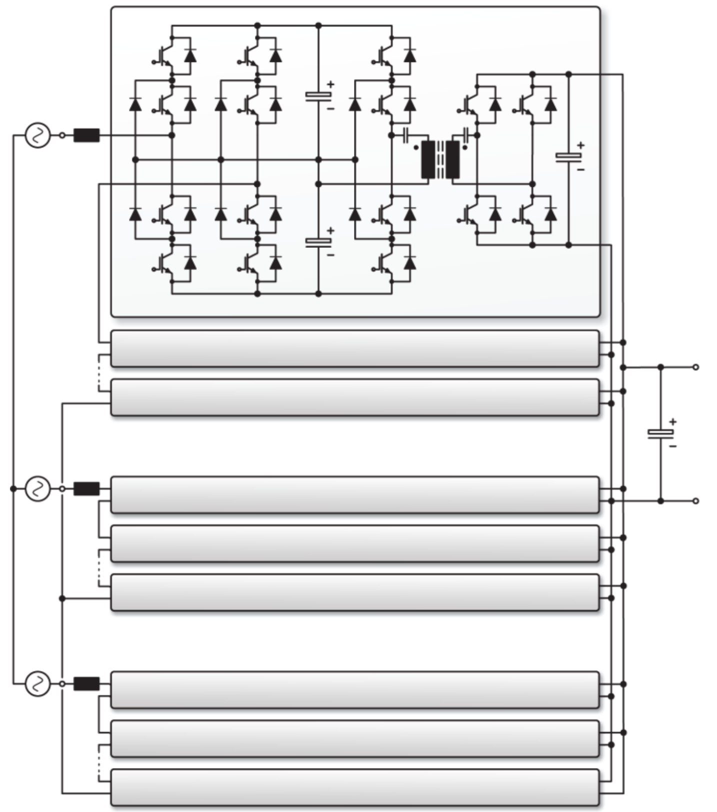
- *Same Overall Volume as Conventional System*
- *Future Development Targets Half Volume*

3-Φ AC/DC SST

3-Φ AC/DC SST Topologies (1)

- *Fully Modular Approach*
- *MEGA-Link @ ETH Zurich*

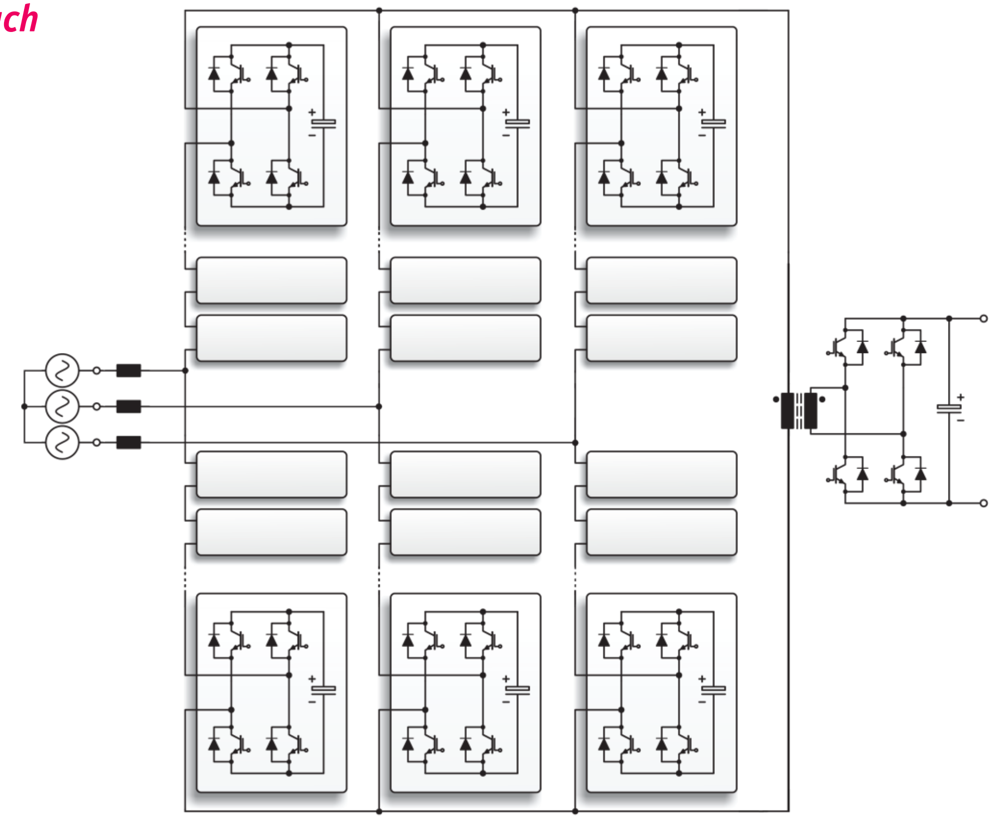




- *166kW / 20kHz Si-IGBT DC/DC Converter Module (±1kV → 400V DC-Transformer) / 98% Eff.*

3-Φ AC/DC SST Topologies (2)

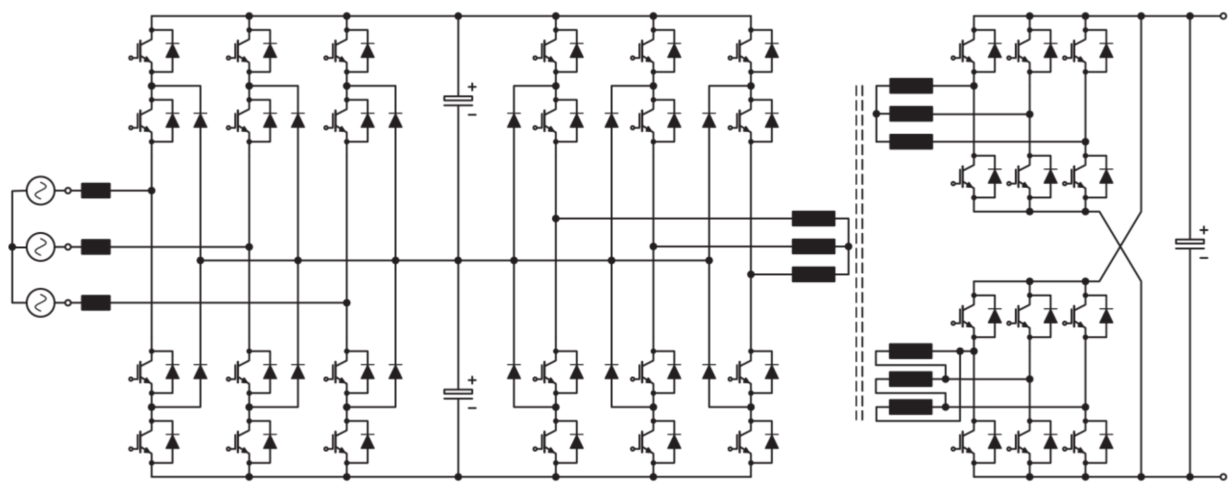
- *Matrix-Type MMLC Approach*



- *Modularity Limited to Critical System Part / Higher Semiconductors Effort*

3-Φ AC/DC SST Topologies (2)

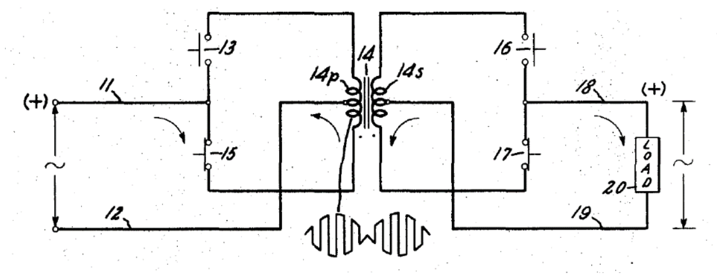
- *Non-Modular Approach*
- *15kV SiC IGBTs Allow Operation @ 13.8kV Mains*



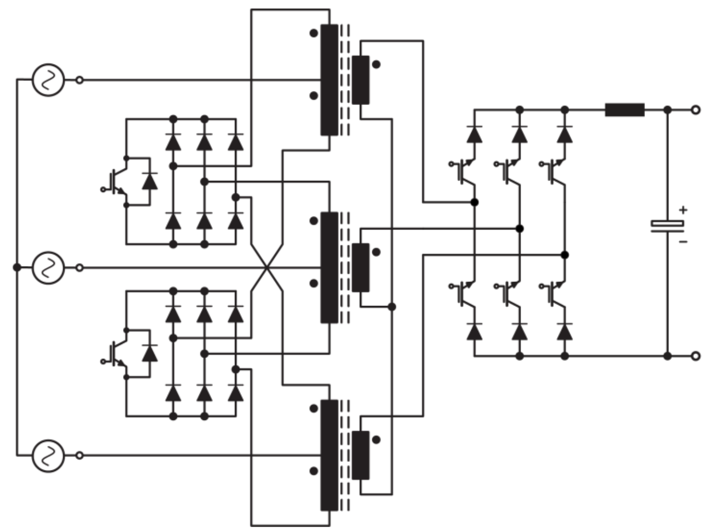
- *No Redundancy (!)*
- *Redundancy Requires Series-Connection of Power Semiconductors (!)*

3-Φ AC/DC SST Topologies (3)

- *Minimum MV-Side Complexity Matrix-Type Approach*



Source: US Patent 3´517´300, W. McMurray, 1970

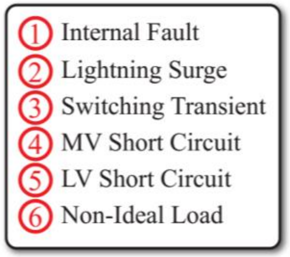


- *3-Φ Extension (N. Mohan) of Basic 1-Φ AC/AC Concept (McMurray, 1968)*

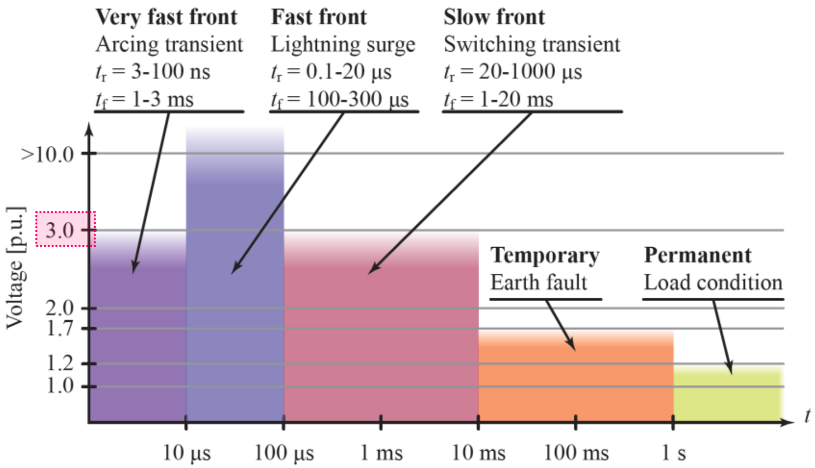
SST Protection

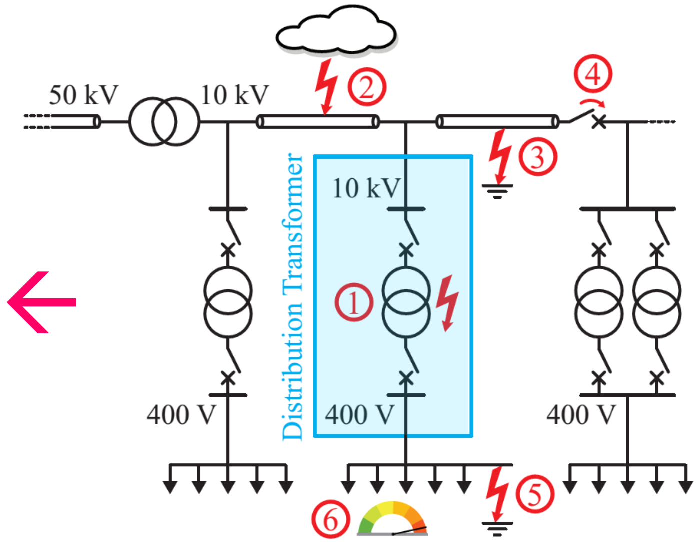
Potential Faults of MV/LV Distribution-Type SSTs

- Extreme Overvoltage Stresses on the MV Side for Conv. Distr. Grids
- SST more Appropriate for Local Industrial MV Grids



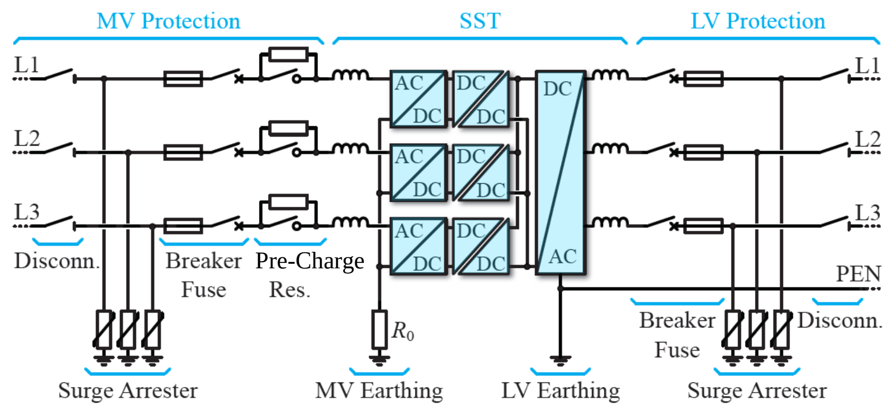
- Conv. MV Grid Time-Voltage Characteristic



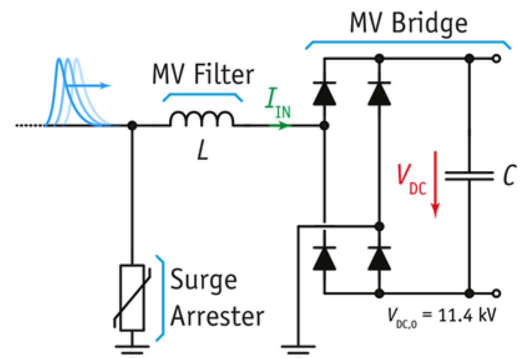


Protection of LF-XFRM vs. SST Protection

- *Missing Analysis of SST Faults (Line-to-Line, Line-to-Gnd, S.C., etc.) and Protection Schemes*



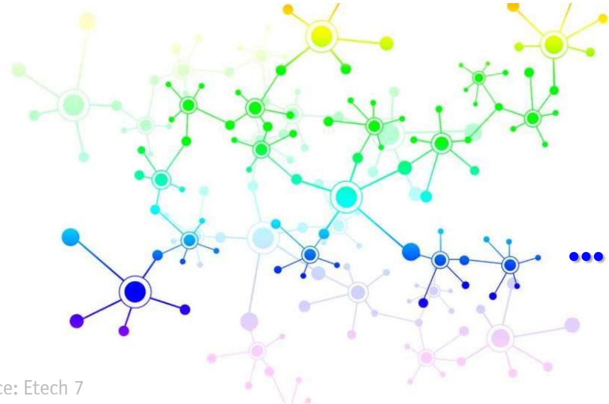
- **Proposed SST Protection Scheme with Minimum # of Protection Devices**



- *Overvoltage Protection (Lightning Strike)*

  * High Arrester Clamping Voltage
  * Filter Inductor > 8% for Current Limiting
  * Min. DC Link Capacitance
  * Sufficient Semicond. Blocking Capability
  * Grounding – Lower Stress if Unearthed

- *Protection Scheme Needs to Consider: Selectivity / Sensitivity / Speed /Safety /Reliability*



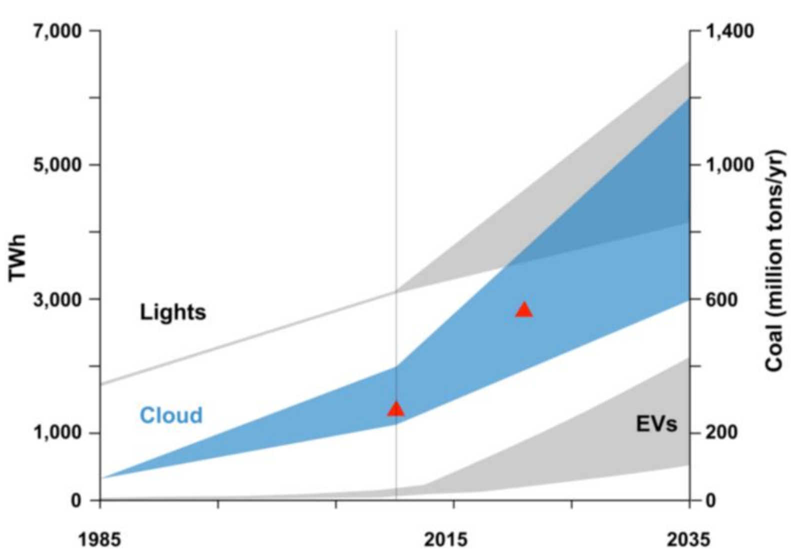
Source: Etech 7

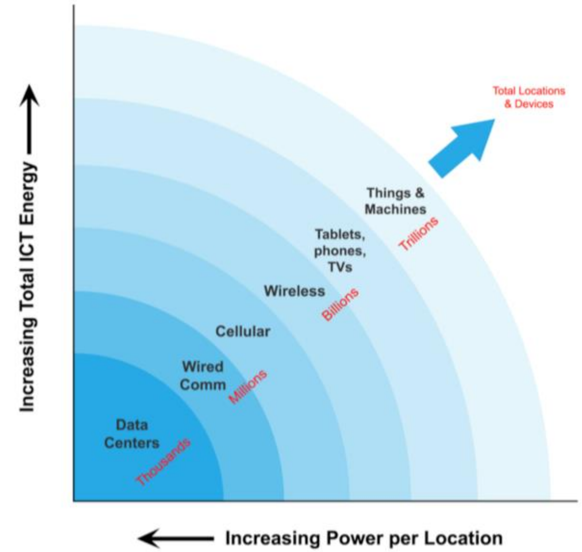
... *Datacenters*

The Cloud / Hyper-Scale Datacenters

■ Global Electricity Demand & Digital Universe (Voice/Video/Internet) Consumption
▲... Greenpeace Estimates for ICT

Source: M.P. Mills, Digital Power Group, 2013





- "The Cloud is Powered By Coal" (40% Share of Electricity Generation)
- 100x Energy Used for i-Phone Charging is Used for Data Processing (1.6GB/Month Avg.)

Hyper-Scale Datacenters

- *MV (kV) → Power-Supplies-on-Chip (0.9V) Power Conversion*
- *Short Innovation Cycles*
- *Modularity / Scalability*

Server-Farms
up to **450 MW**
99.9999%/<30s/a
$1.0 Mio./Outage

Since 2006
Running Costs >
Initial Costs

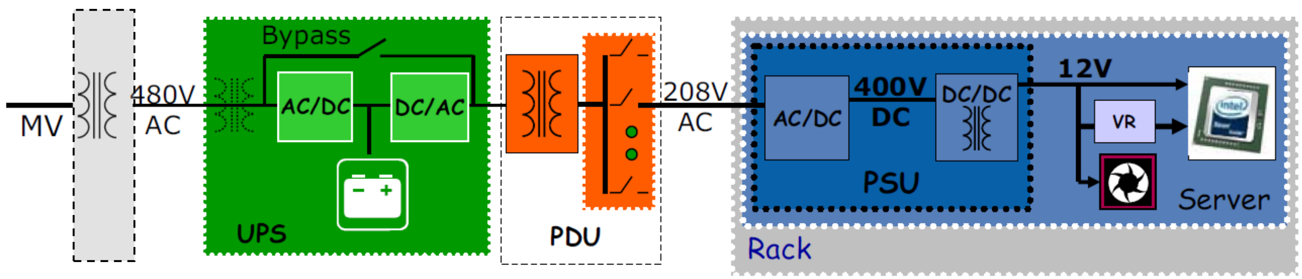
Source: Facebook

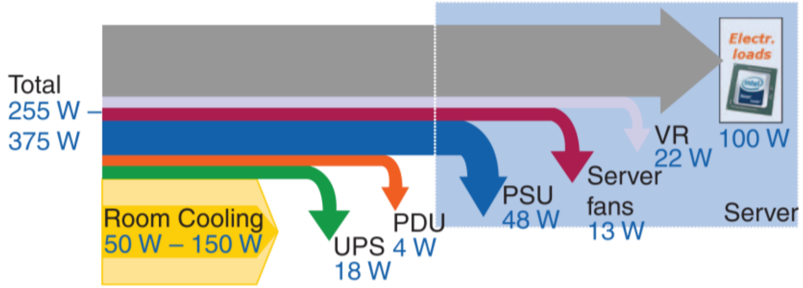
1. *Higher Availability*
2. *Higher Efficiency*
3. *Higher Power Density*
4. *Lower Costs*

State-of-the-Art Datacenters

- *Conventional 480V_{AC} Distribution / Energy Use*

Source: intel 2007





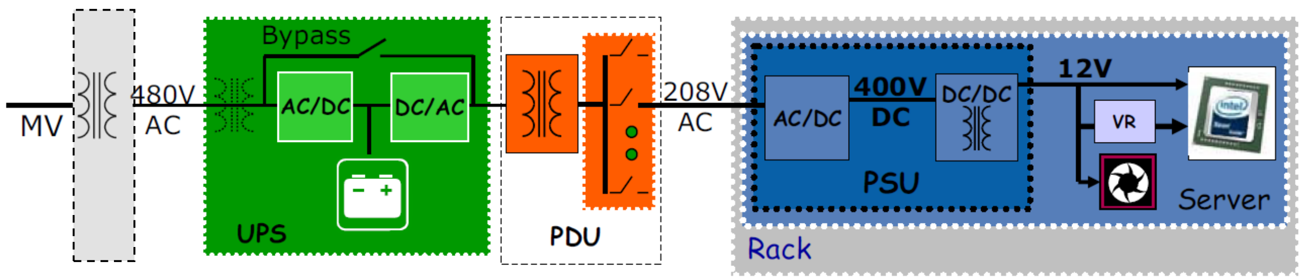
Source: G. AlLee et al., IEEE Power & Energy Mag., 2012

- *Per 100W Compute Load → +200...300W typ. for Infrastructure & Cooling*
- *Eliminate Conversion Stages, Use High Distribution Voltage (Low $$$ → Select UDC of PFC Rectifiers)*

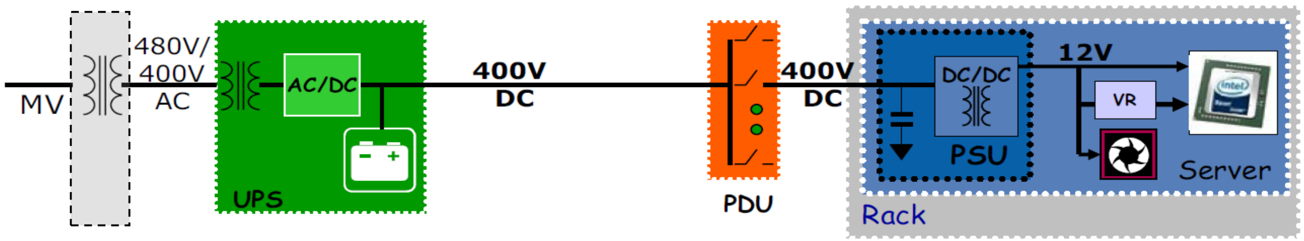
AC vs. 400V DC System

- *Conventional 480V$_{AC}$ Distribution*

Source: intel 2007



- *Facility-Level 400 V$_{DC}$ Distribution; 380V Rated (± 190V), Range: 260V...410V*

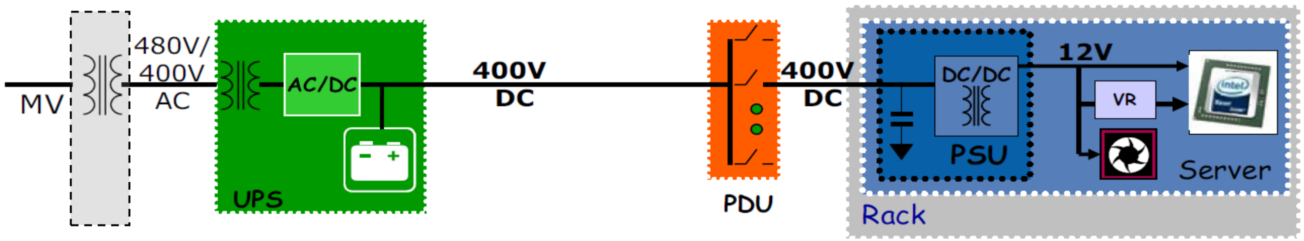


- *+ 5...7% Efficiency & -33% Floor Space & -36% Lifetime $$$ & 0.9999996 Availability*

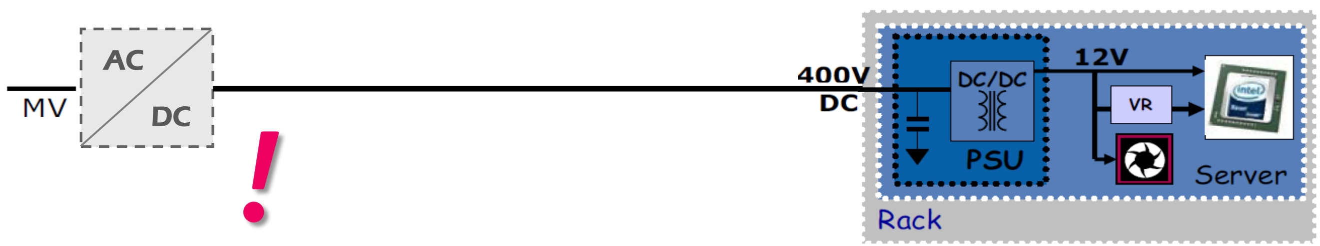
1-Φ Medium-Voltage Grid Interface

- *Facility-Level 400 V_{DC} Distribution*

Source: intel 2007



- *Solid-State Transformer-Based 6.6kV AC → 400V DC*



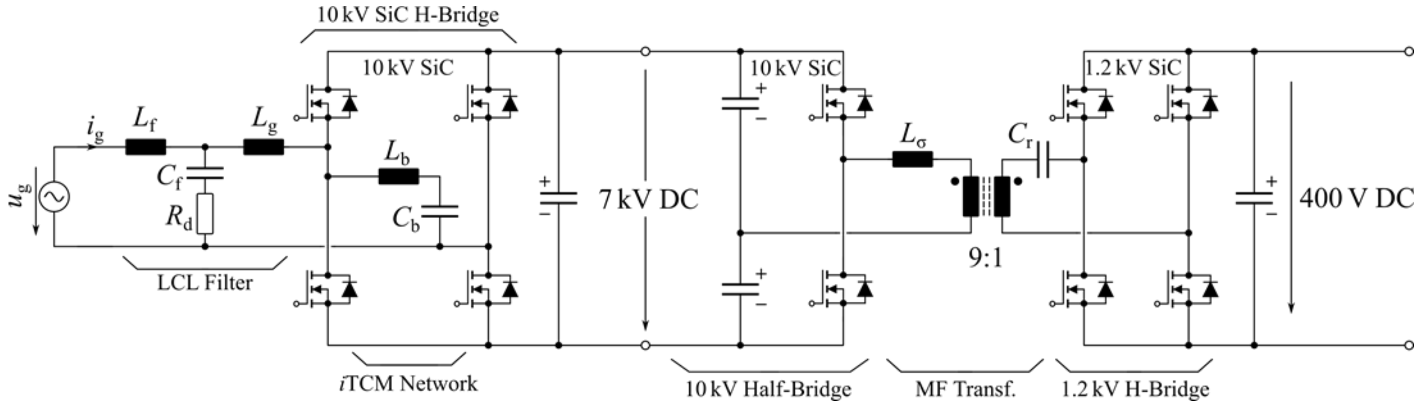
- *MV-Grid (kV) → Chip (0.9V) in 2 Steps → typ. 3% Efficiency Gain, Smaller Footprint, etc.*

Research @ ETH Zurich

25kW SwiSS-Transformer @ ETH Zurich

- *Bidirectional 1-Φ 3.8 kV_{rms} AC → 400V DC Power Conversion*
- *Based on 10kV SiC MOSFETs*
- *Full Soft-Switching*

★ 3.3 kW/dm³



★ 3.8 kW/dm³

▶ *35...75kHz iTCM Input Stage*

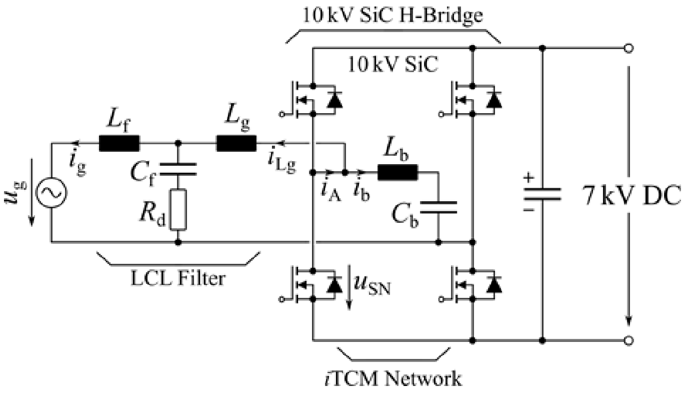
▶ *48kHz DC-Transformer Output Stage*

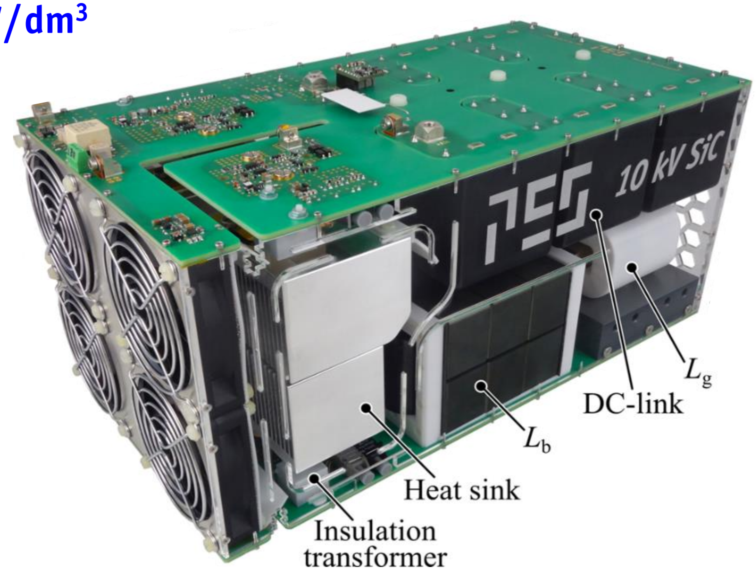
3.8kV → 7kV ZVS AC/DC Converter

- *Full-Bridge iTCM – integrated Triang. Current Mode Operation Enables ZVS*

— ZVS Requires Change of Sw. Current Direction in Each Sw. Period
— Open-Loop Variation of Sw. Frequency for Const. ZVS Current (35...75kHz)
— Separate Optim. of ZVS and Input Inductor Possible
— No Large Ripple Input Current

★ 3.3 kW/dm³





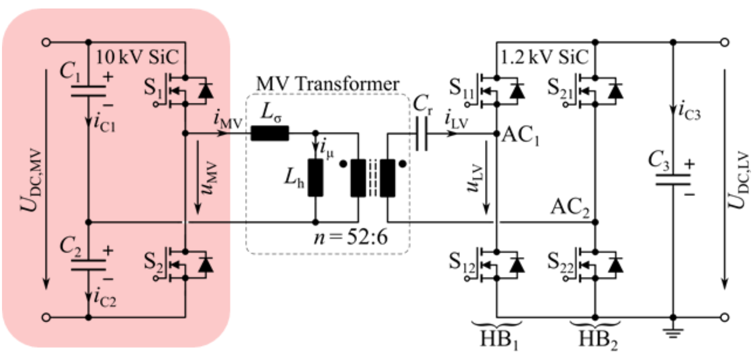
► *Full-Load Measurement (25kW @ 3.8kVrms AC, 7kV DC) - ZVS Over Full AC Cycle (!)*

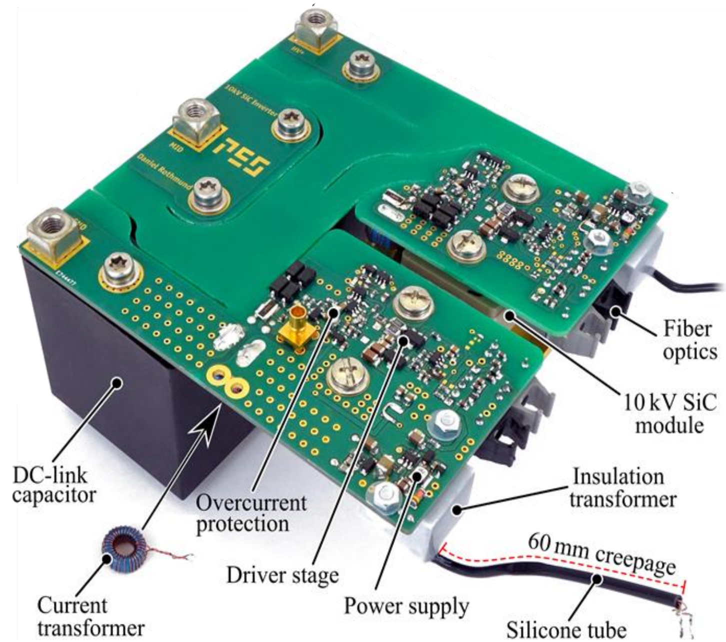
7kV → 400V DC/DC Converter (1)

- *MV-Side Half-Bridge*

— 48kHz Sw. Frequency, ZVS
— Cooling of Power Semicond. by Floating Heatsinks (Not Shown)
— Creepage Distances Ensured by PCB Slots

★ 3.8 kW/dm³



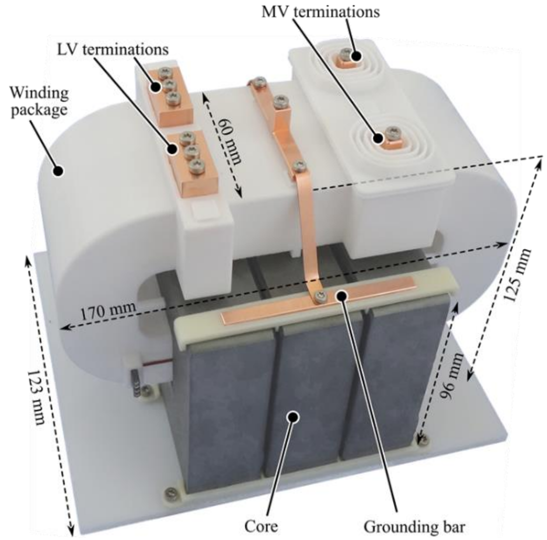


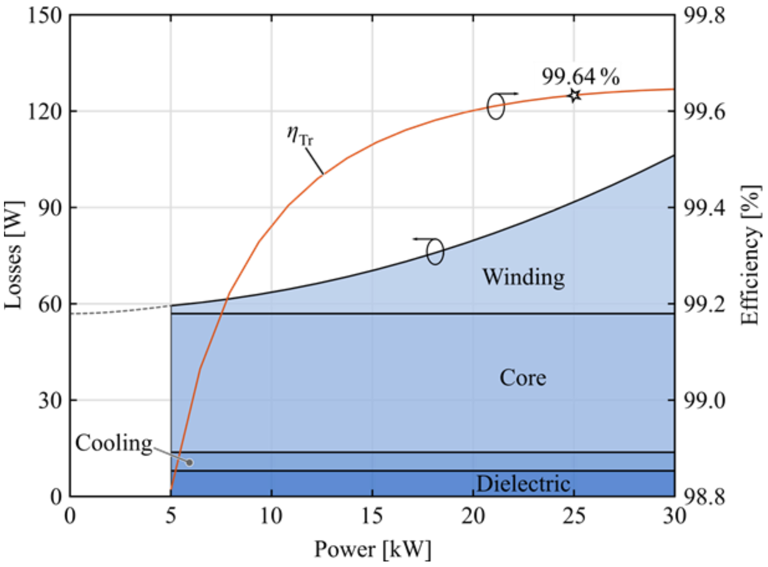
► *Half-Bridge for Cutting Voltage in Half / Lower Switch Count*

7kV → 400V DC/DC Converter (2)

- *MF-Transformer Measurement*

— **Fully Tested @ 25kW / 7 kV**
— **Calorimetric Loss Measurement**
— **99.64% Efficiency**

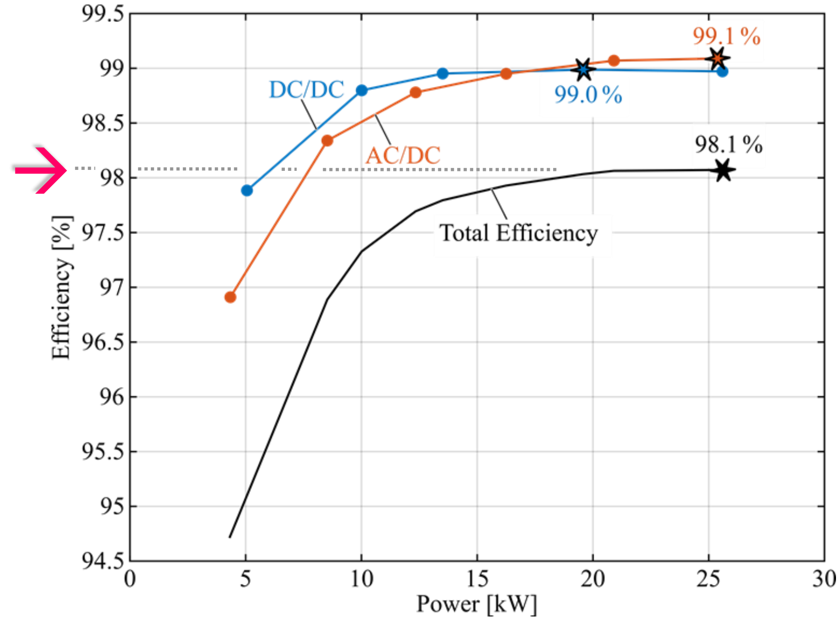




▶ *Transformer Prototype / Loss Distribution / Efficiency*

Overall Performance

- Full Soft-Switching
- 98.1% Overall Efficiency @ 25kW
- 1.8 kW/dm³ (30W/in³)

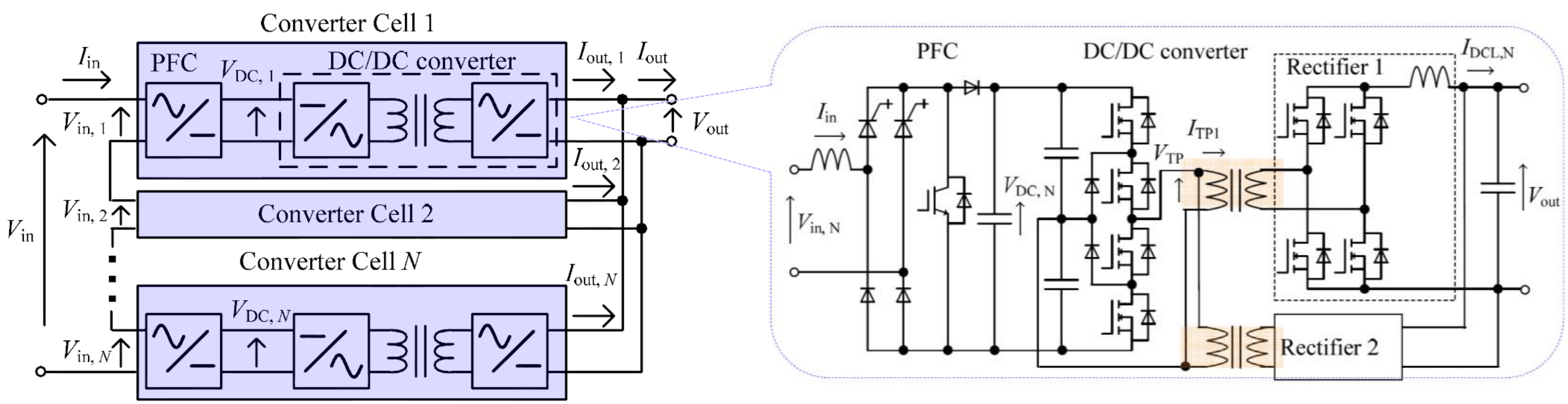


- ► Red. of Losses & Volume by Factor of >2 Comp. to Alternative Approaches (!)
- ► Significantly Simpler Compared to Multi-Module SST Approach

Remark 1-Φ 2.4 kV_{rms} AC → 54V DC

Fuji Electric

- *Published @ IEEE APEC 2017*
- *N=5 Cells @ MV-Side / Cost Optimum*
- *PFC Rectifier → 1.2kV Si IGBTs & SiC Diodes*
- *DC/DC Conv. → 600V SJ & 100V MOSFETs*



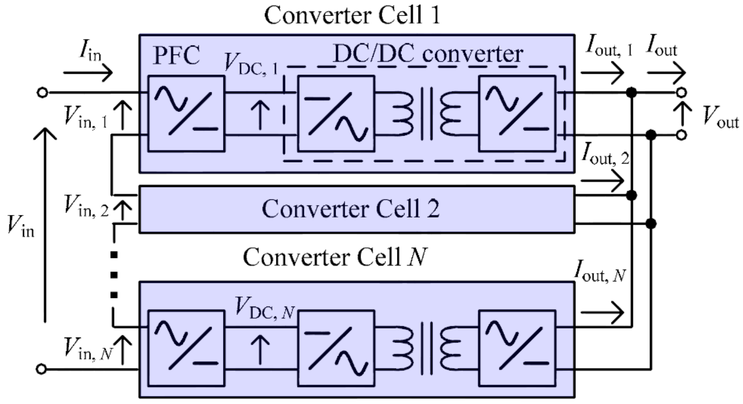
Multi-cell converter.

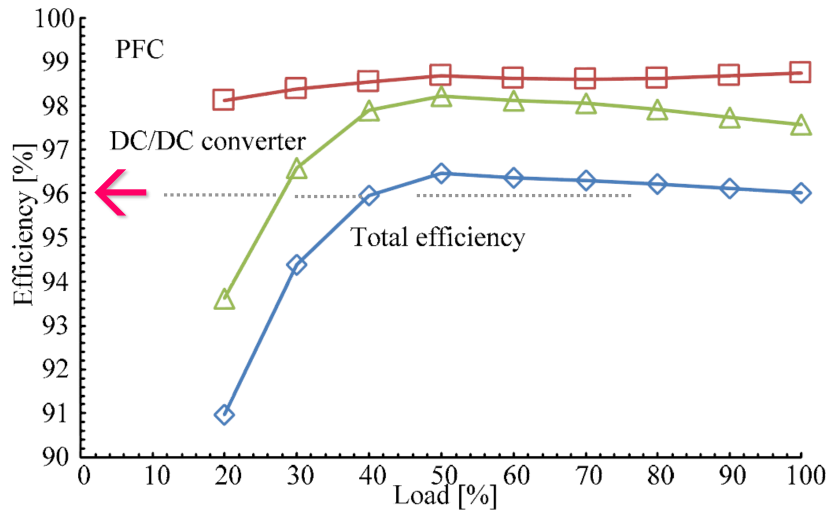
- *Power Density of 0.4kW/dm³ (6.6W/in³)*
- *96% Overall Efficiency @ 25kW*

Remark 1-Φ 2.4 kV_{rms} AC → 54V DC

Fuji Electric

- Published @ IEEE APEC 2017
- N=5 Cells @ MV-Side / Cost Optimum
- PFC Rectifier → 1.2kV Si IGBTs & SiC Diodes
- DC/DC Conv. → 600V SJ & 100V MOSFETs



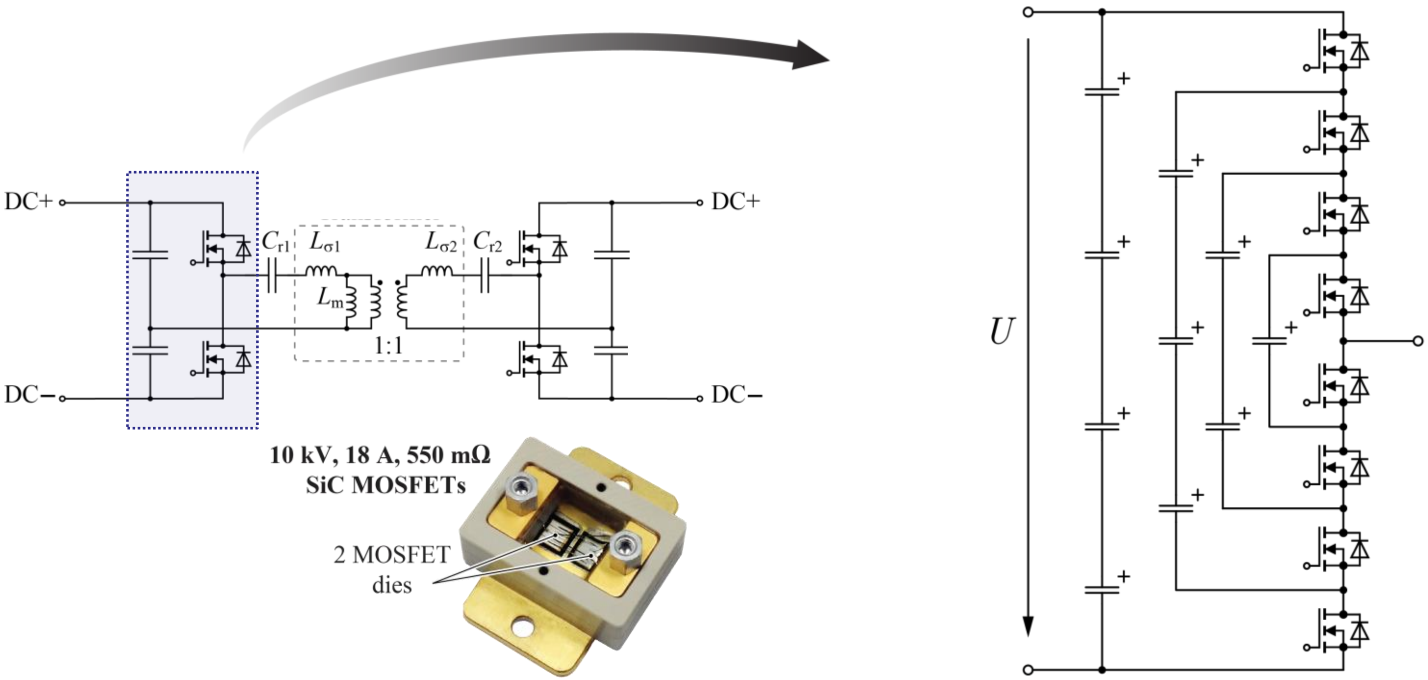


- Power Density of 0.4 kW/dm^3 (6.6 W/in^3)
- 96% Overall Efficiency @ 25kW

10kV
10kV - SiC Super-Switch
10kV
10kV

40kV SiC Super-Switch @ ETH Zurich (1)

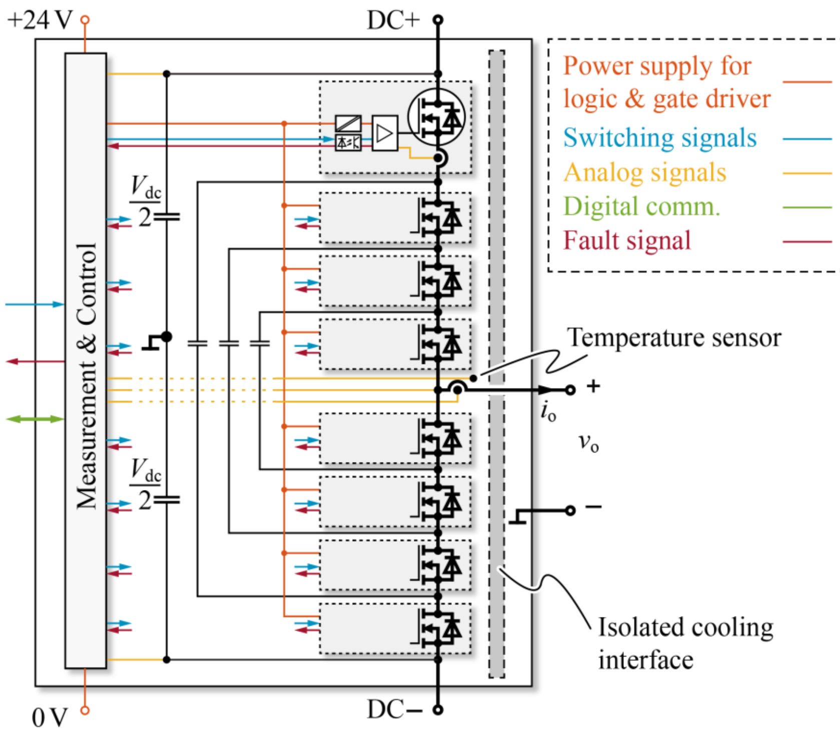
- *4 x 10kV Cascaded SiC MOSFETs*
- *Quasi-X-Level (Staggered) Switching*

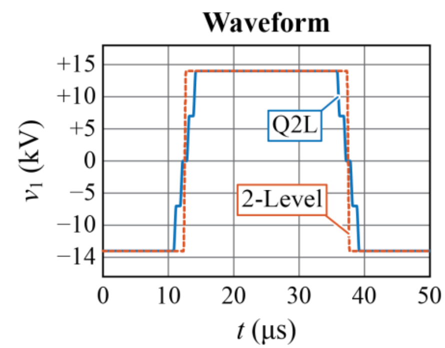


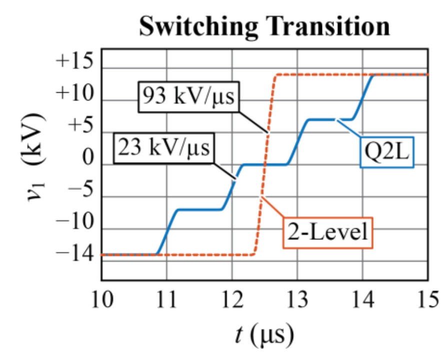
- *40kV Blocking Capability → Up to 28kV DC-Link Voltage / Operation @ 1-Φ 15kV*

40kV SiC Super-Switch @ ETH Zurich (2)

- 300kVA Intelligent Power Module — Two-Level Bridge-Leg Appearance





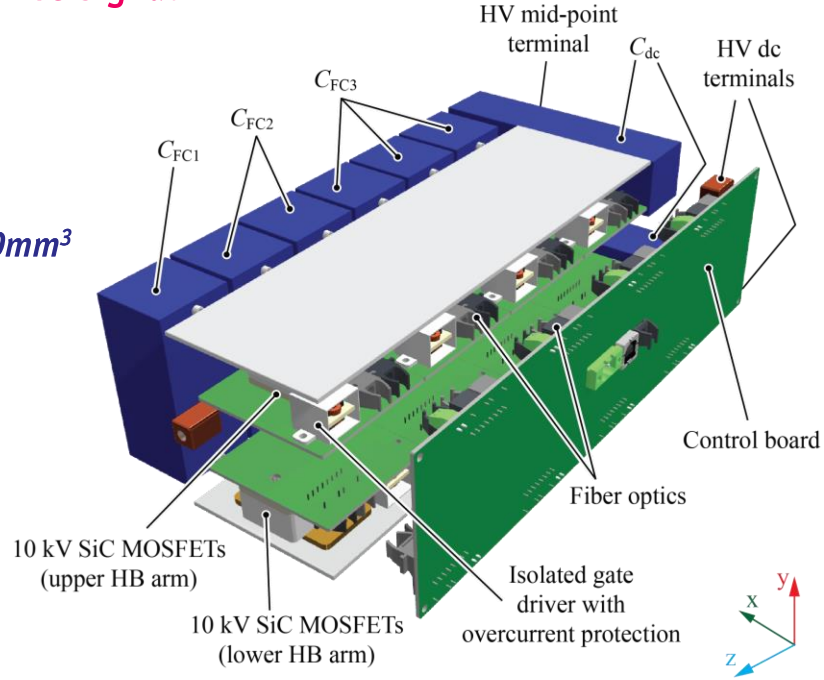


- *Integrated Gate Drive / Voltage Balancing / Protection / etc.*

40kV SiC Super-Switch @ ETH Zurich (3)

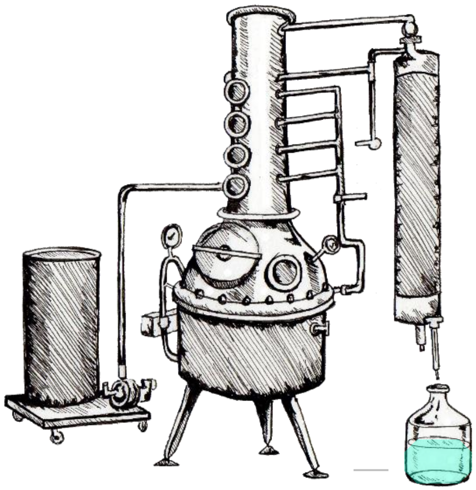
- Based on 2-Chip 10kV SiC Power MOSFET Packages
- Top- & Bottom-Side Isol. Cooling Surfaces
- Single Isol. Drive Signal

250x150x80mm³



★ 100 kVA / dm³

- Integrated Gate Drive / Voltage Balancing / Protection / etc.

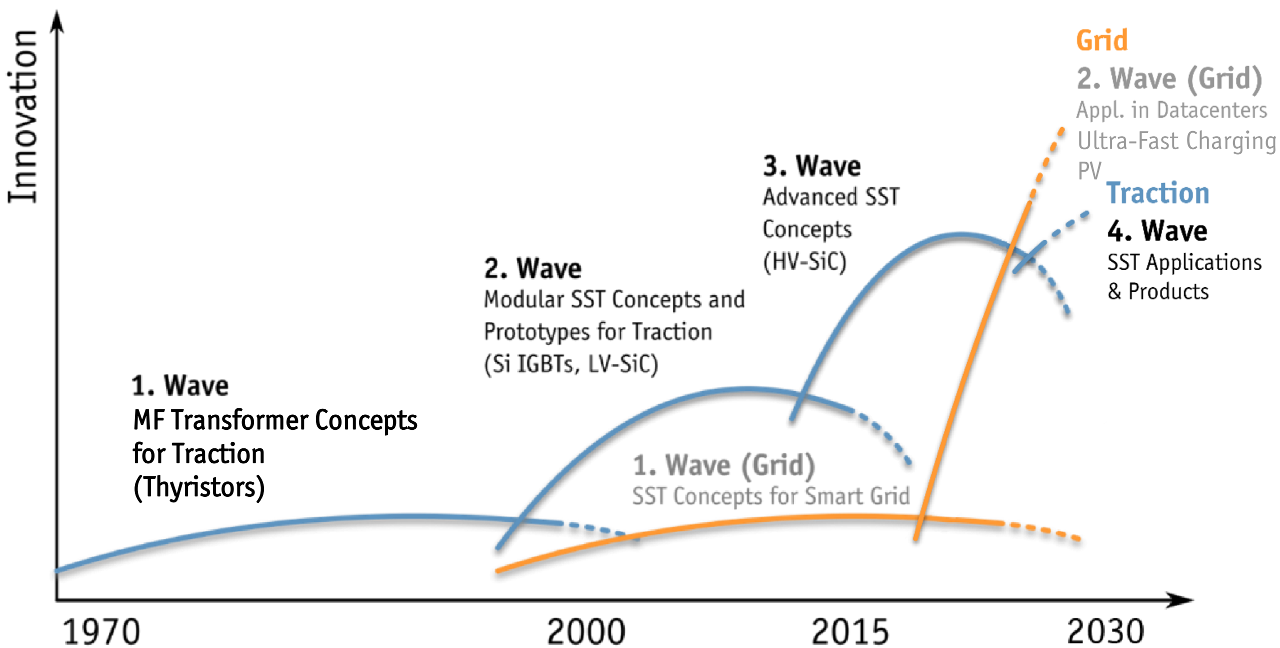


Source: whiskeybehavior.info

Conclusion

Future SST Applications in XFC & Datacenters

- *SST Isolated MV-AC/DC Conversion @ High Efficiency / Compactness*
- *XFC / Datacenters — No Competition Against Existing Infrastructure*
- *Ancillary Services & Connection to Future MV-DC Grid*



- *Realization $$$ & DC-Protection Remain as Challenges (!)*

Thank You !

The ***„Detroit Electric“***
20mph, 80miles/Charge
Anderson Electric Car Company
1907 - 1939