



Power Electronics - Electrical Power Processing

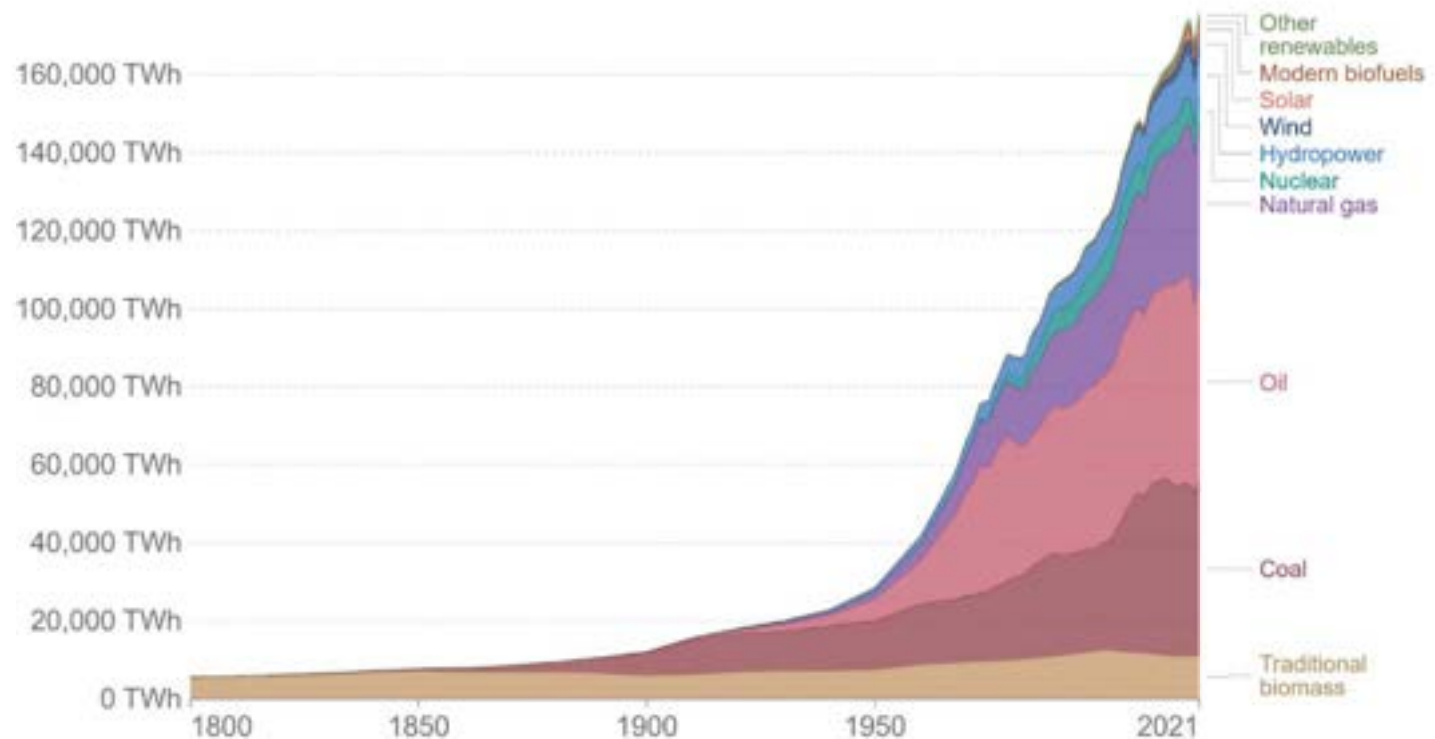
Dr. Bogdan Borowy
Eaton Research Labs

Energy Production & Requirements

Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

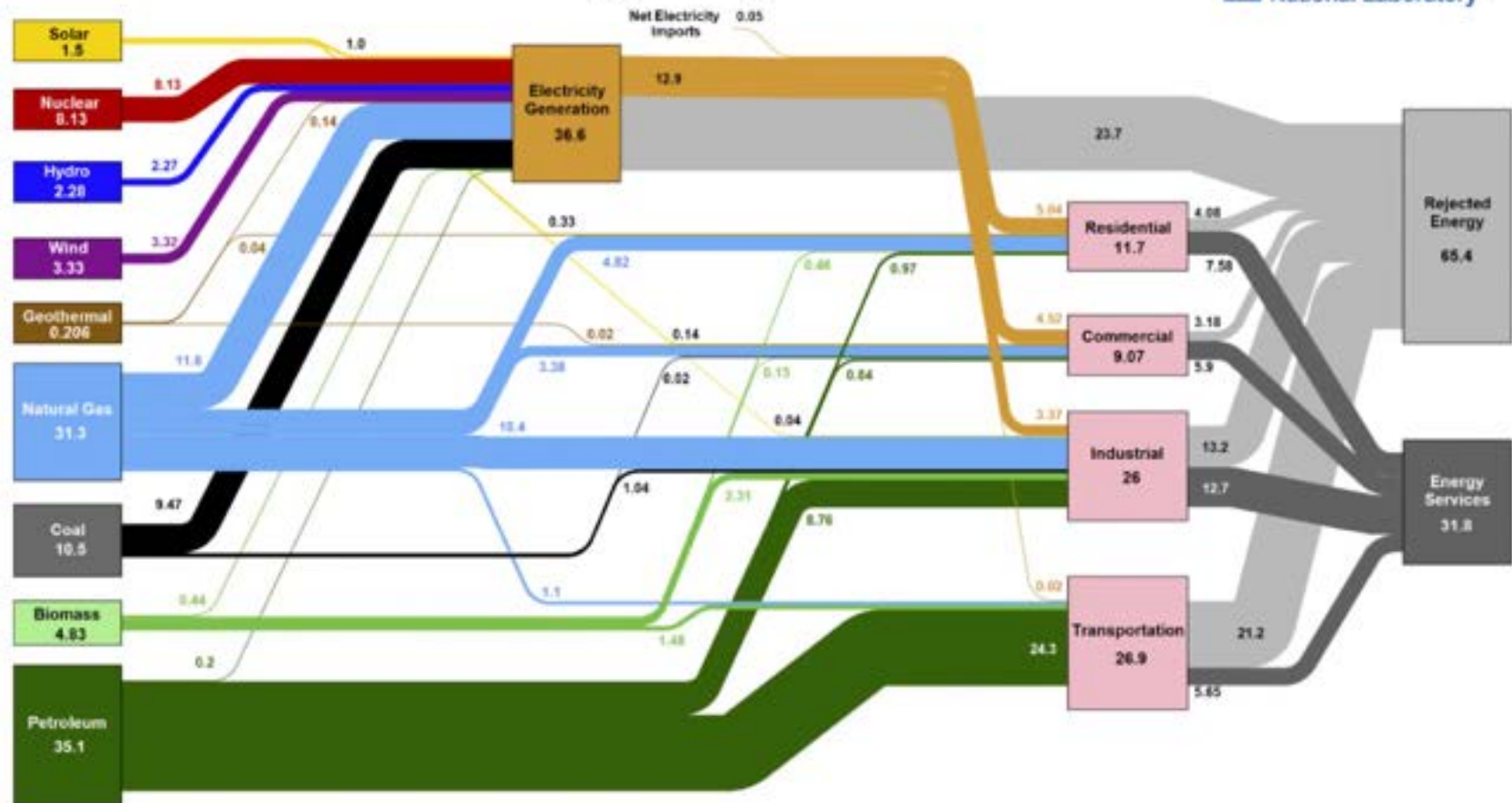
Our World
in Data



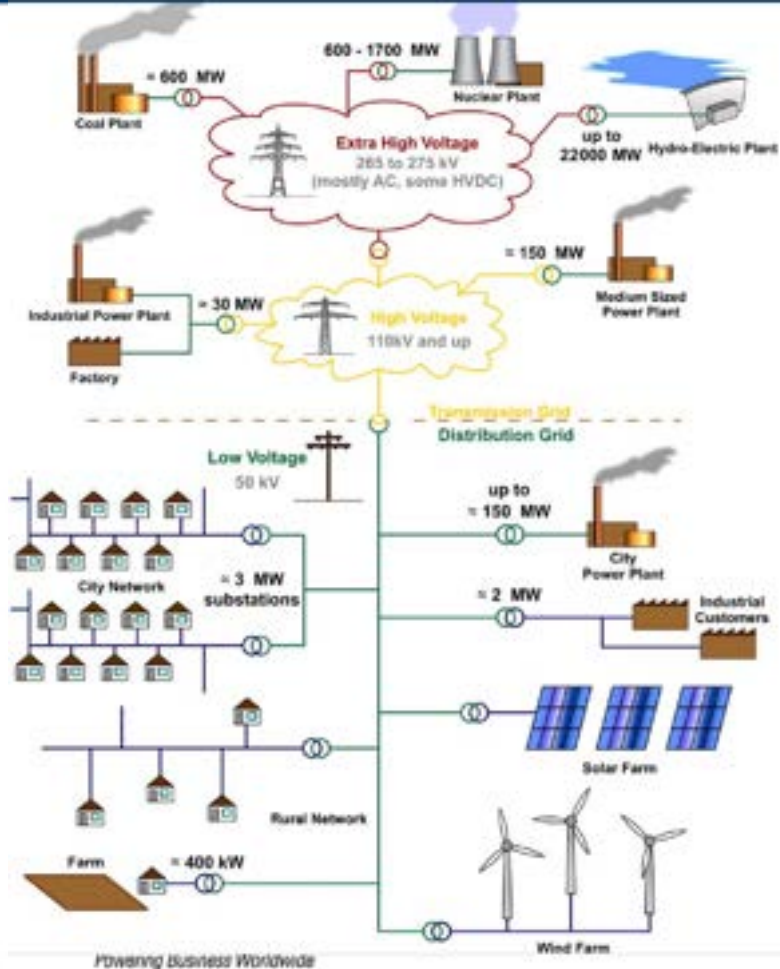
Energy Consumption 2021 in US

Estimated U.S. Energy Consumption in 2021: 97.3 Quads

Lawrence Livermore
National Laboratory



Today's Power AC Grid: Perceptions and Reality



Power Electronics have repeatedly struggled to penetrate the Grid in the past

- -FACTS machines? (~90s)
- -StatComs? (~2000s)
- WHY?
 - Major successes have been in dc Transmission lines and renewables

Electromechanical

Clumsy
Simple
Large
Rugged
Reliable
Slow
Cheap (1-2c/VA)
Overload (fault clearing)
99+% efficiency

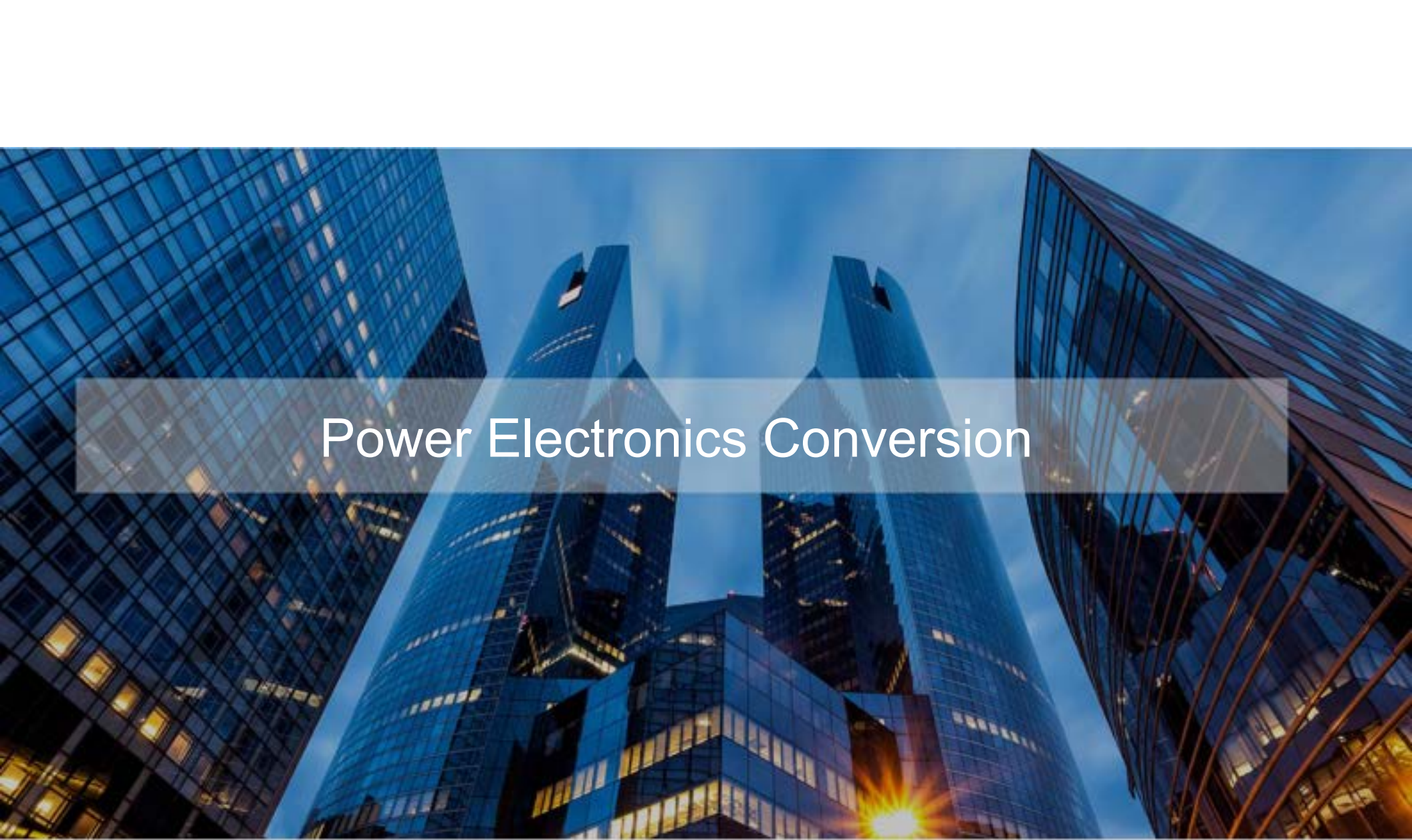
Electronic

Smart
Complex
Compact
Less so?
Less so?
Fast
Expensive (10+c/VA)
Limited Overload
~97% efficiency?

Hybrids?

Grid Challenges

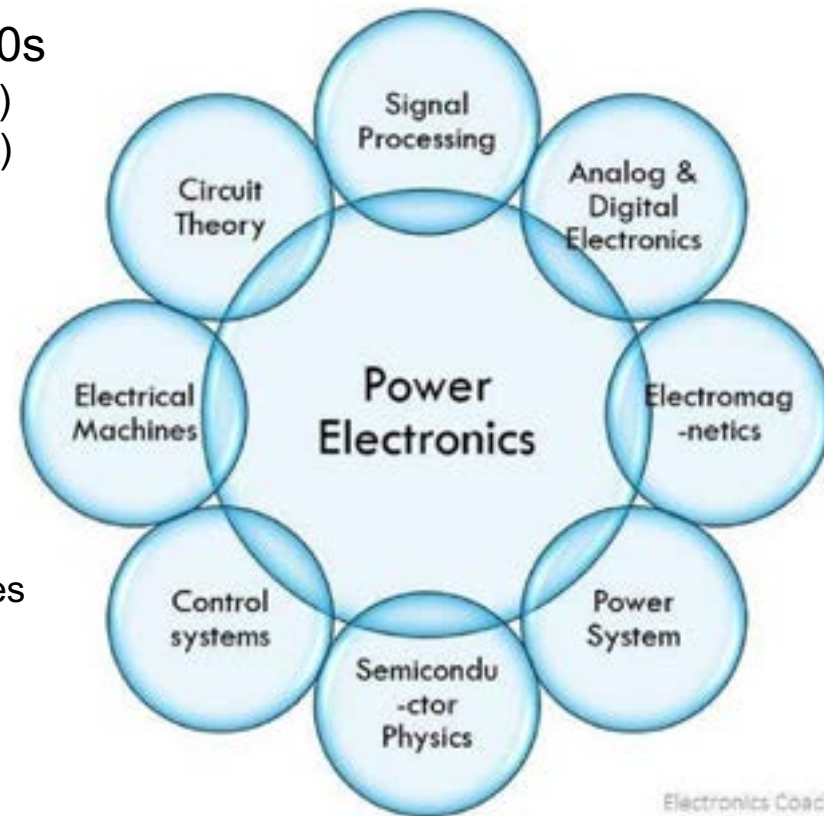
- More Renewables (IBRs)
 - Less predictable generation (non-dispatchable, intermittent)
 - Level
 - Higher Dynamics
- Fast changing loads
 - EV charging
 - Variable speed drives
 - Crushers and mining
- Grid needs highly maneuverable dynamic control
 - Rejection of generation intermittency
 - Improve stability margins without adding “spinning reserves” (inertia)



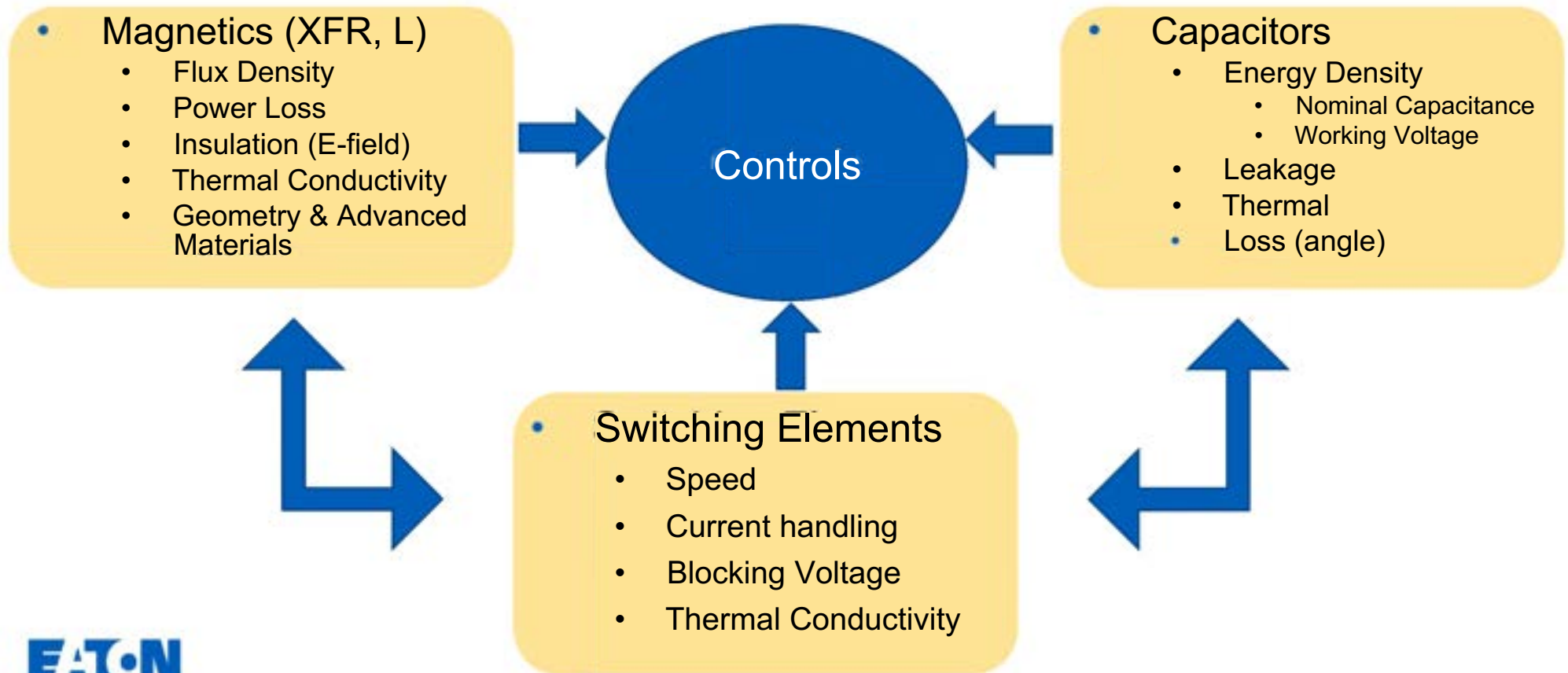
Power Electronics Conversion

Power Electronics: Conversion of Power

- Power Electronics Fundamental Operation since 1930s
 - Transfer Energy Between Source and Load (can be Active)
 - Control Format Characteristics (Steady State, Dynamically)
 - Magnitude
 - Frequency
 - Phase
 - How?
 - By temporarily storing E Energy
 - Inductors (H-Field)
 - Capacitors (E-Field)
 - By switching action
 - Shaping the original (source) voltage / current
 - The unwanted effects (harmonics) – filter through passives
 - Inductors
 - Capacitors
 - Add transformers
 - Gain modification – efficient
 - Adding Insulation



Key Elements of Power Conversion

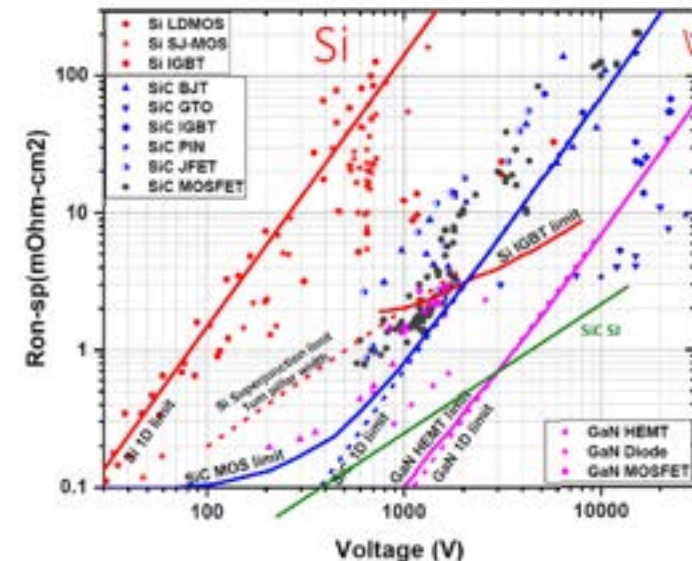
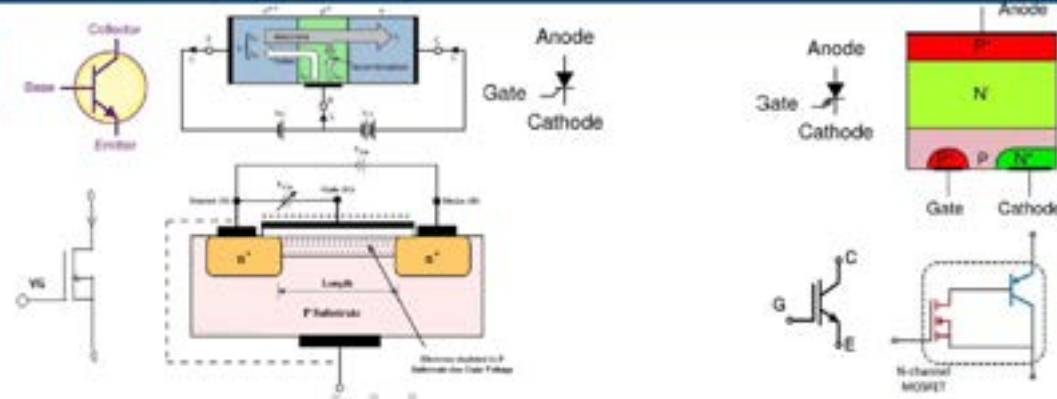


Devices in Power Conversion

Modern Era

- 1946: 1st Transistor
- 1950: 1st BJT
- 1956: 1st SCR
- 1958: 1st GTO (GE)
- Late 1970's: Power BJT; MOSFET
- 1980s: high-power GTO (Japan)
- 1983: IGBT (GE)
- 1990s - : WBG (SiC, GaN, Diamond)

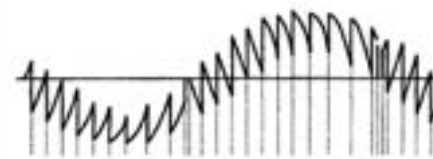
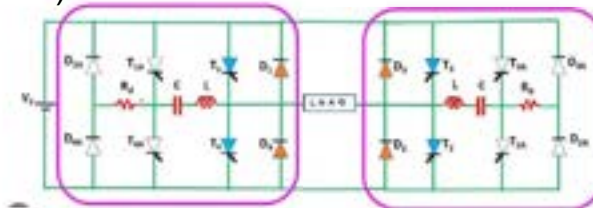
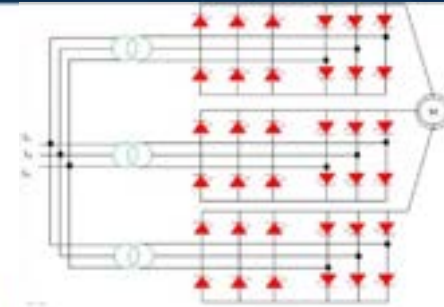
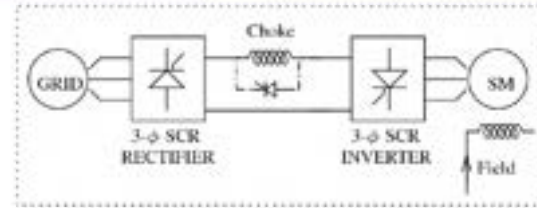
Bell Labs



Power Conversion Topologies

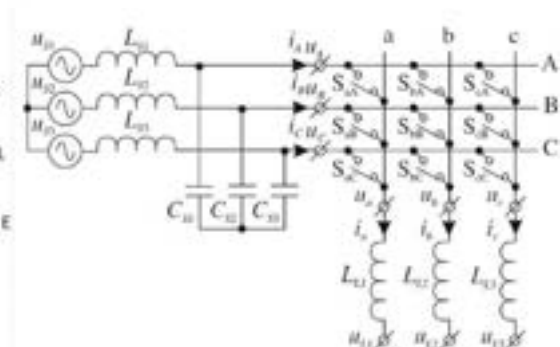
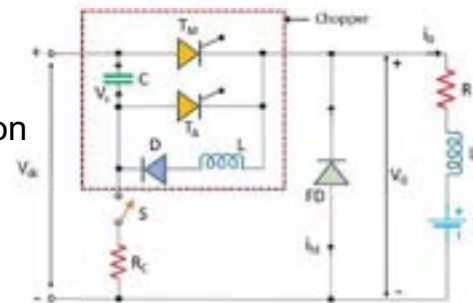
1960-1970s: Thyristor Phase-Control

- Line and Load Commutated Converters
 - Electronic commutator
 - DC Machine Control emulation
 - Vector Control
- Cycloconverters (1960s to 1997 - replaced by multi-level)
- Forced Commutated Converters
 - McMurray Inverter
 - DC/DC Choppers



1980s: Self-Commutated devices available (GTO, MOS, IGBT, IGCT)

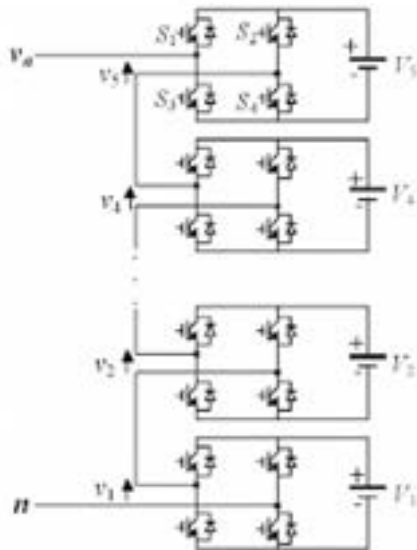
- VCIs with PWM
 - + Active Rectifier
 - 4 Quadrant Operation of Motor Drives
- Soft-switching: a dusted-off Forced Commutation version
 - DC/DC Converters with HF DC link
 - DC/AC motor drives (Deepak Divan UWM 1985)
- Matrix Converters (M. Venturini 1980)
- Resonant Converters (LLC)



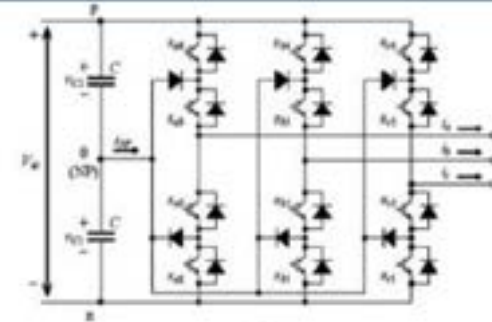
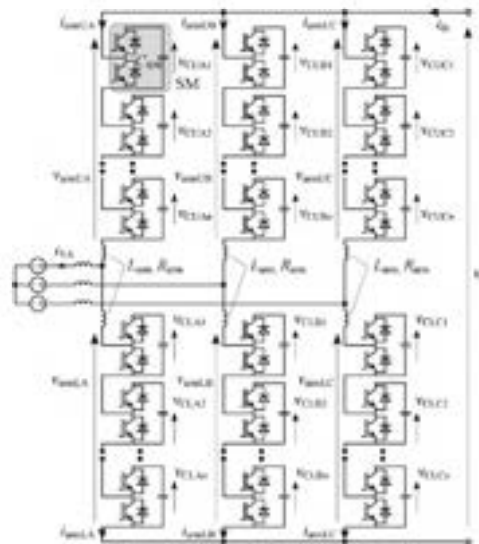
Power Conversion Topologies

- Multilevel Converters
 - 1980s: Neutral Point Clamped Multilevel VCI
 - HV high-power applications
 - Cascaded H-Bridge
 - Modular Multilevel

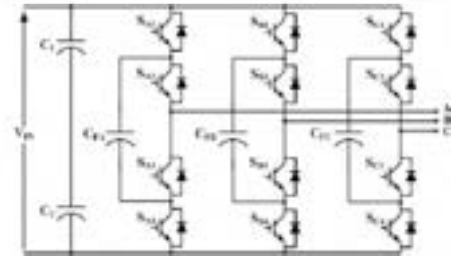
Cascaded H-Bridge



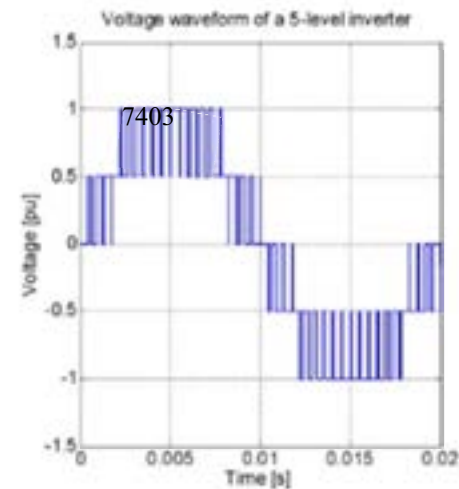
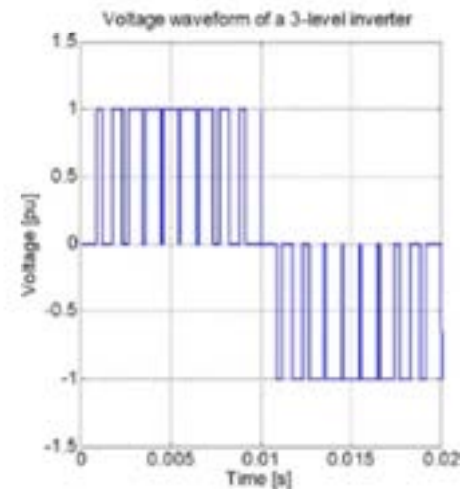
Modular Multi-Level



NPC

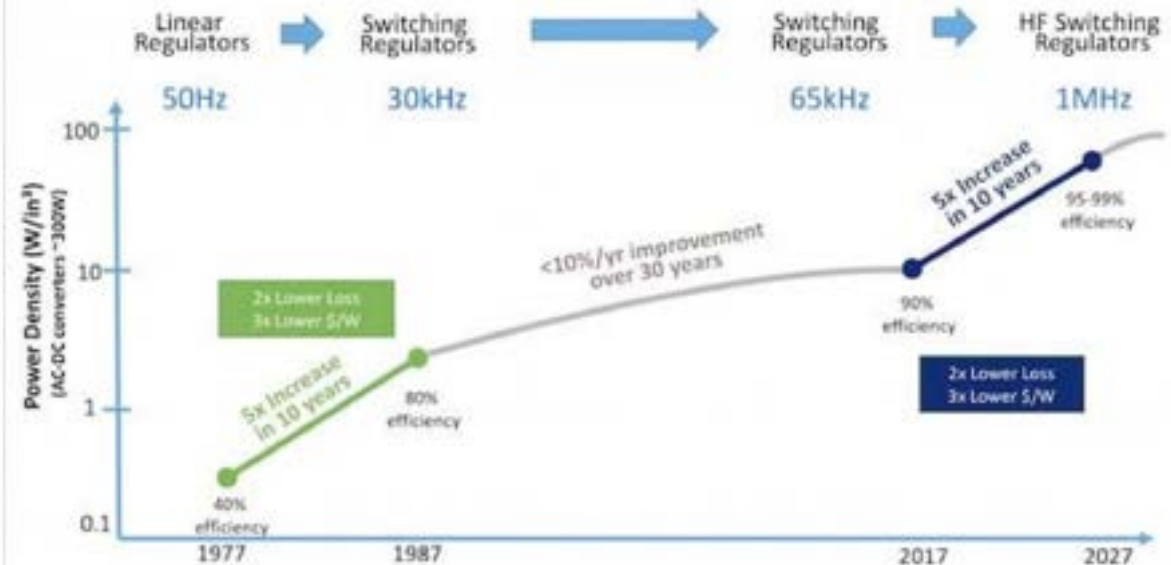
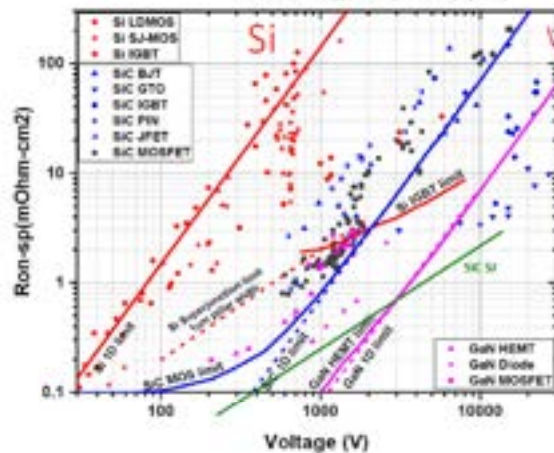
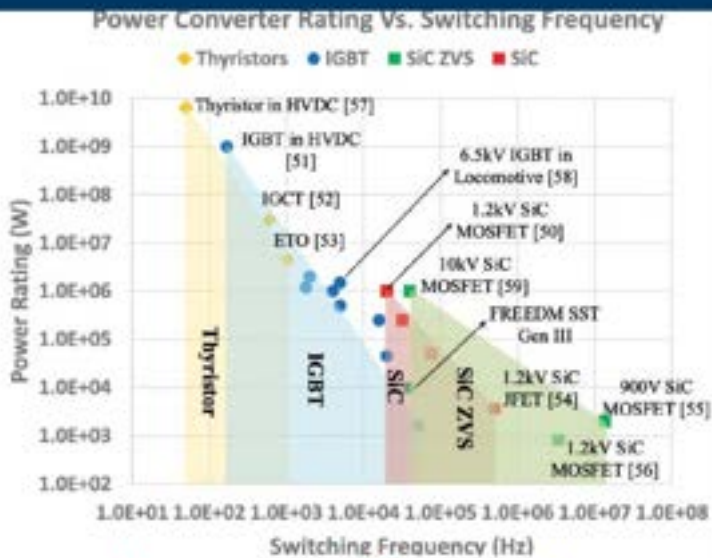


Flying Capacitors



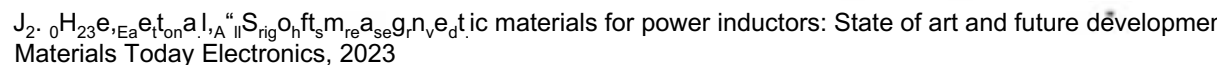
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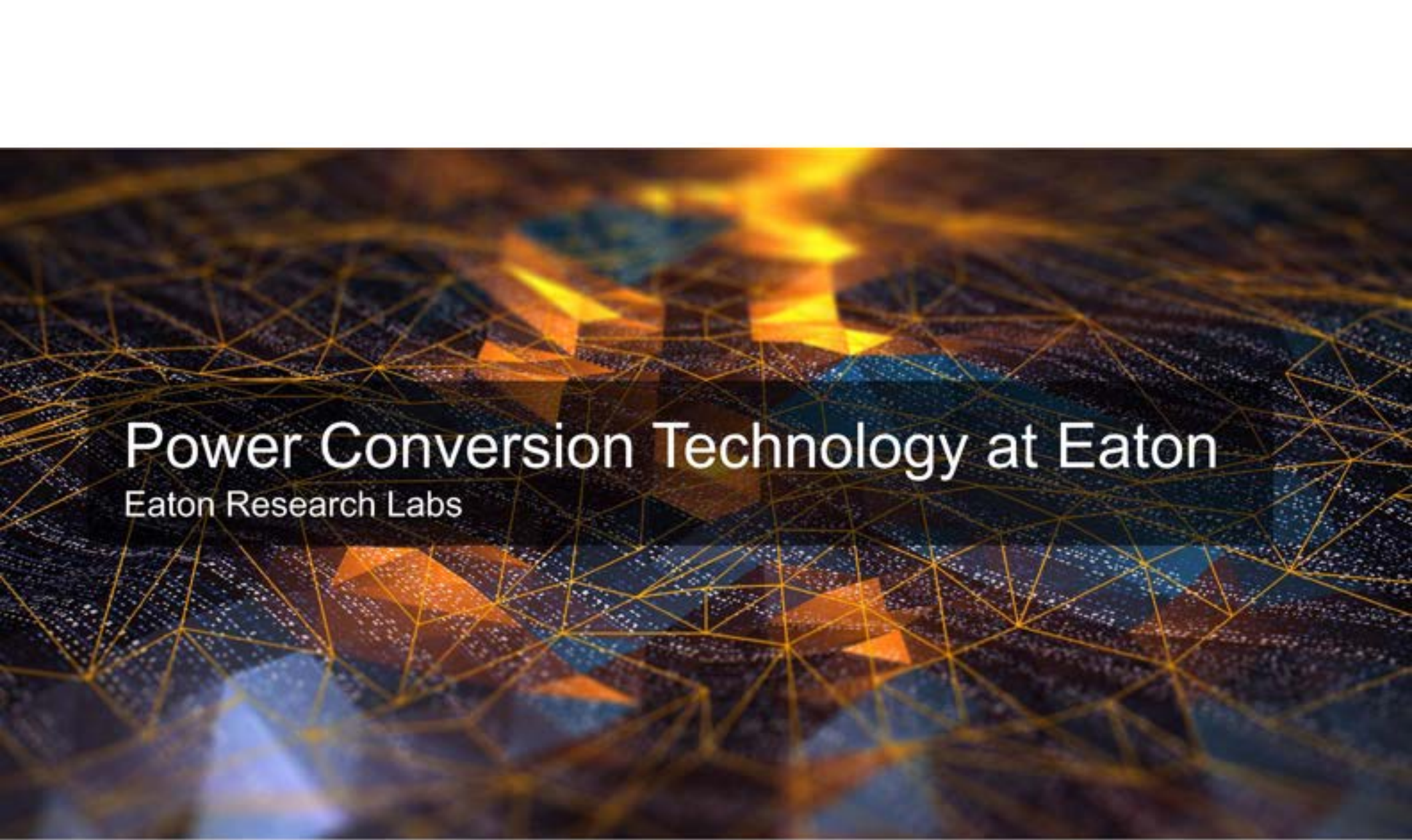
Power Conversion Evolution



- Major Enablers of Power Conversion Progress
- Switching Devices (Si: SCR, BJT, MOS, IGBT; WBG: SiC, GaN)
- Magnetics (Soft M. Materials, Alloys, Material Science, Fabrication)
- Capacitors
- Insulation Materials

Challenges and Opportunities





Power Conversion Technology at Eaton

Eaton Research Labs

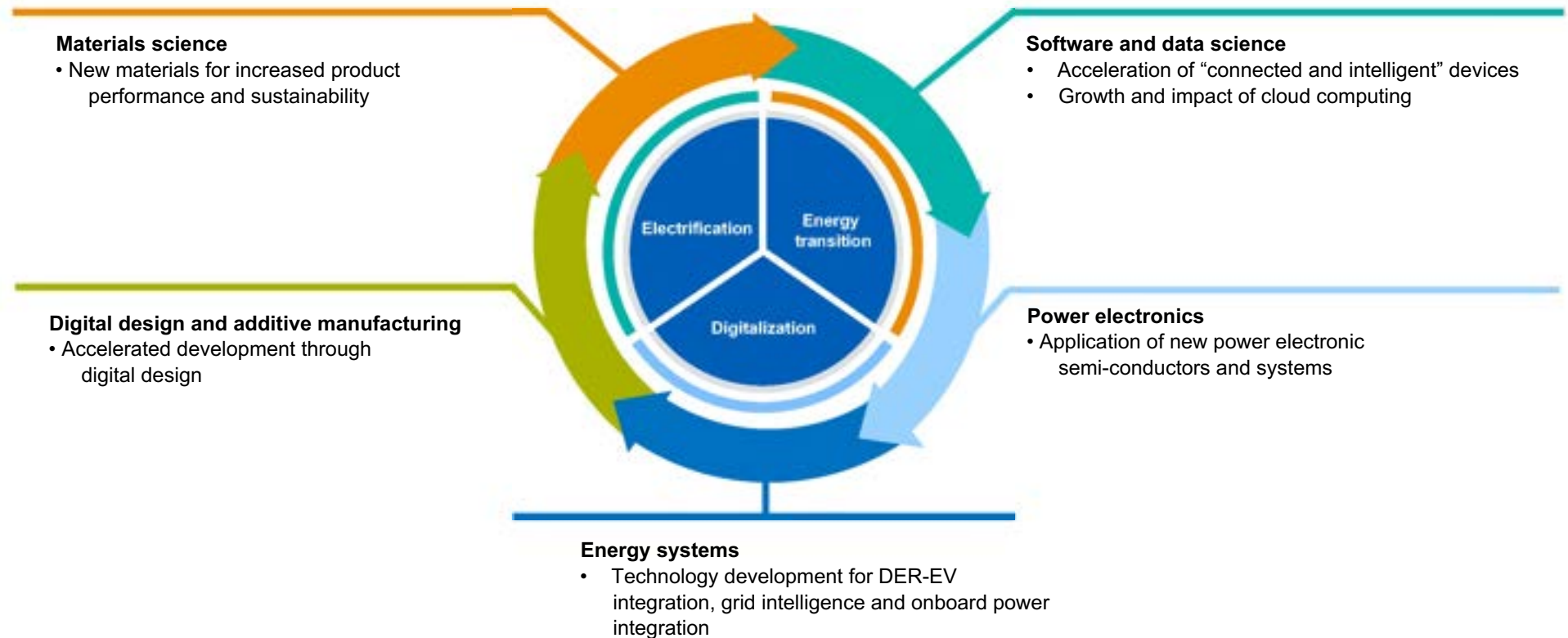
Who is Eaton?

We are an **intelligent power management** company made up of approximately **85,000 employees**, doing business in more than **175 countries** with annual sales of over **\$23 billion USD**.

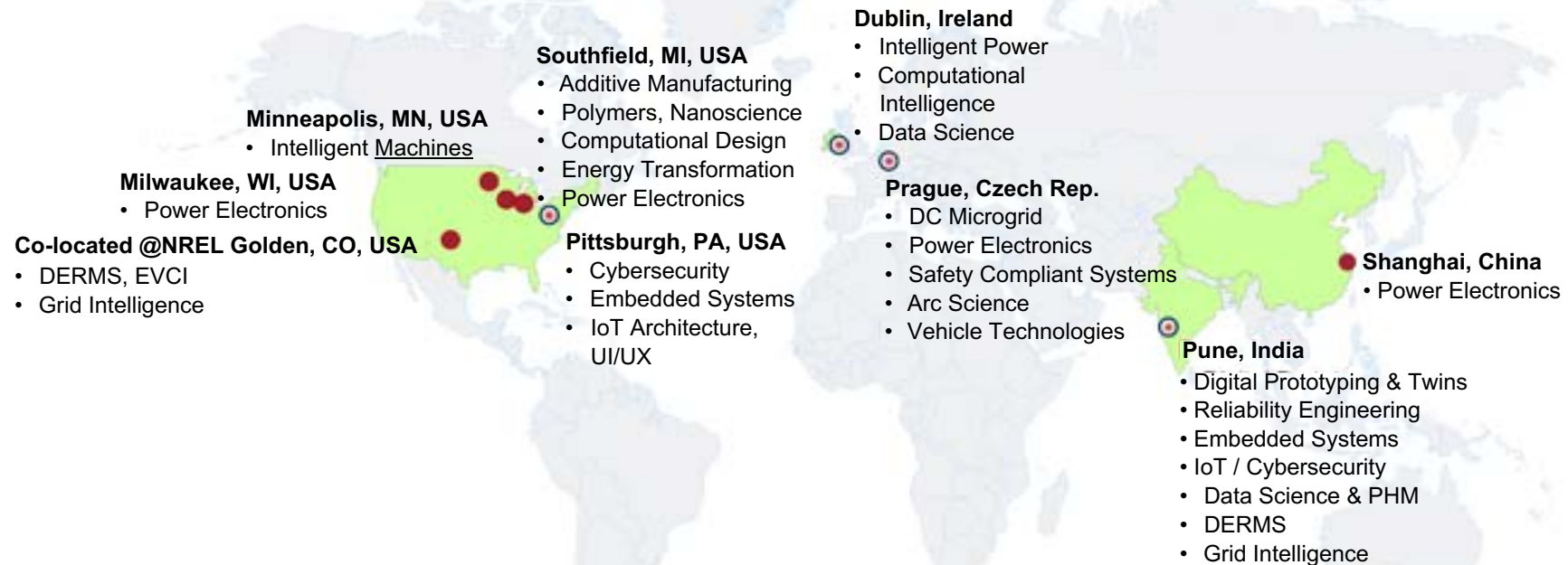
We make what matters work.*



Eaton Research Labs Core Research Platforms



Corporate Research Centers



● **EATON RESEARCH LABS:** Explore, Mature Early Technical and Manufacturing Readiness Levels

⦿ **POWERONE HUB:** Leverage PowerOfOne Eaton Application, Domain Expertise for Speed and Scale of Launches

ERL Energy Systems Technology Themes



Grid intelligence

Grid reliability, resilience and sustainability

Distributed energy resource integration & EV charging

DER Integration, control and optimization
DC Distribution, EVCI and V2X

Electrification

Energy storage technology, More electric vehicle, More electric aircraft

Grid automation and microgrid control

Energy management with DER and EVCI

Energy storage system modeling and battery management

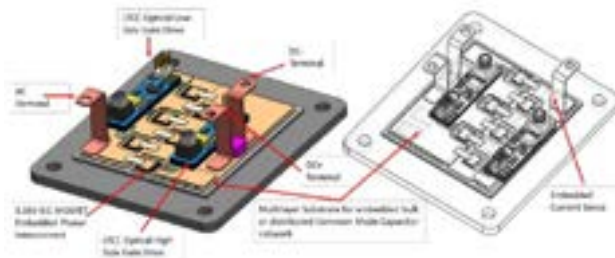
Eaton Research Labs *Power Electronics*

Near term 1-3 years			Mid term 3-5 years	Long term 5+ years
				
Electrical Vehicle DC Fast Charger 20% Cost Reduction	Hybrid and Solid-State circuit protection 10 - 100x faster fault interruption	Power Module for Critical Power 40% more space for servers	Medium Voltage Solid-state Transformer 50% smaller	MEA Drive Train, 40% lighter

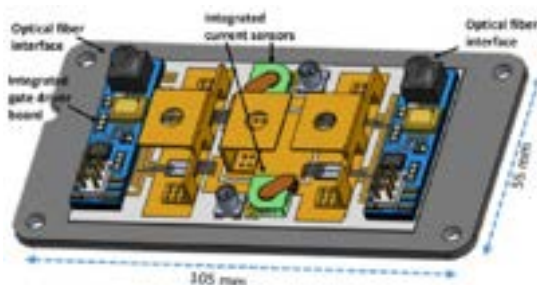
Innovation Drivers: Faster, Smaller, Lighter, Lower Cost, Problem With No Solution

Module Development: ARP Ae ULTRAFast

NextGen Technology



3.3 kV Heterogeneous Integrated Power Module

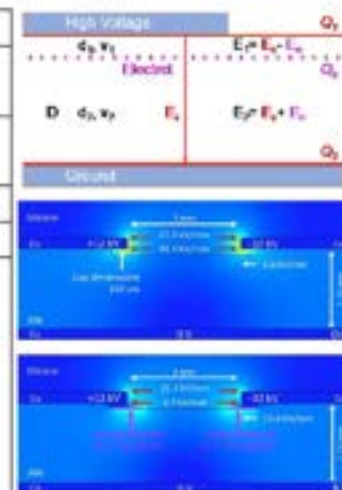


Integrated FO Isolation and Current Sensors



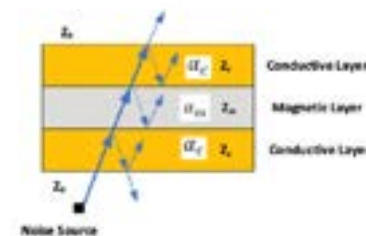
Characteristic	Target	Mitsubishi	Wolfspeed	Inflneon
Current rating (continuous)	$\geq 120\text{ A @}$ $T_c = 90^\circ\text{C}$	750 A (LV100)	800 A (LM3)	1000 A (XHP-2)
Switching frequency	50-75 kHz @ 250 kW	<10 kHz	<10 kHz	<10 kHz
Voltage slew rate	250 V/ns	15 V/ns	35 V/ns	17.5 V/ns
Current slew rate	100 A/ns	6.5 A/ns	10 A/ns	7 A/ns
Integrated gate driving	Yes	No integrated advanced features 	No integrated advanced features 	No integrated advanced features 
Integrated current sensing	Yes			
Integrated Protection	Yes			
Integrated Isolation	Yes			
Integrated Passives	Yes			
Integrated E-Field Dampening	Yes			

- High-Voltage Ceramic Substrate
 - Geometry variations
 - Materials (Alumina, Zirconia, Aluminum Nitride, Silicon Nitride)
 - Metallization (direct bond copper, direct bond aluminum, active metal brazed copper)
- Electret for PD mitigation
- Advanced EMI Shielding – reduction of near fields
- Advanced Gate Drivers
- Current Sensors



Electrets Concept

Electric Field Reduction



Advanced Shielding

Solid State Protection

NextGen Technology



IGBT/MOSFET enabling solid-state DC circuit protection



Ultra-fast vacuum switch with solid-state interruption

End-User Value Proposition

Approach	Speed	Power Capacity	Efficiency
Solid-state	+++	+++	+
Arc-less Hybrid	++	++	++
Hybrid (Arching)	+	+	+++

Solid state and hybrid breakers enable DC power distribution (more than 100 times faster current interruption than conventional breakers)

Leading Applications



Intelligent solid-state breakers (12kV, 2kA)
Next Generation Ships – ONR



Medium voltage circuit breakers (6kV, 200A)
enables MVDC distribution market – ARPA-E

Compact Electric Vehicle Charging Infrastructure (EVCI)

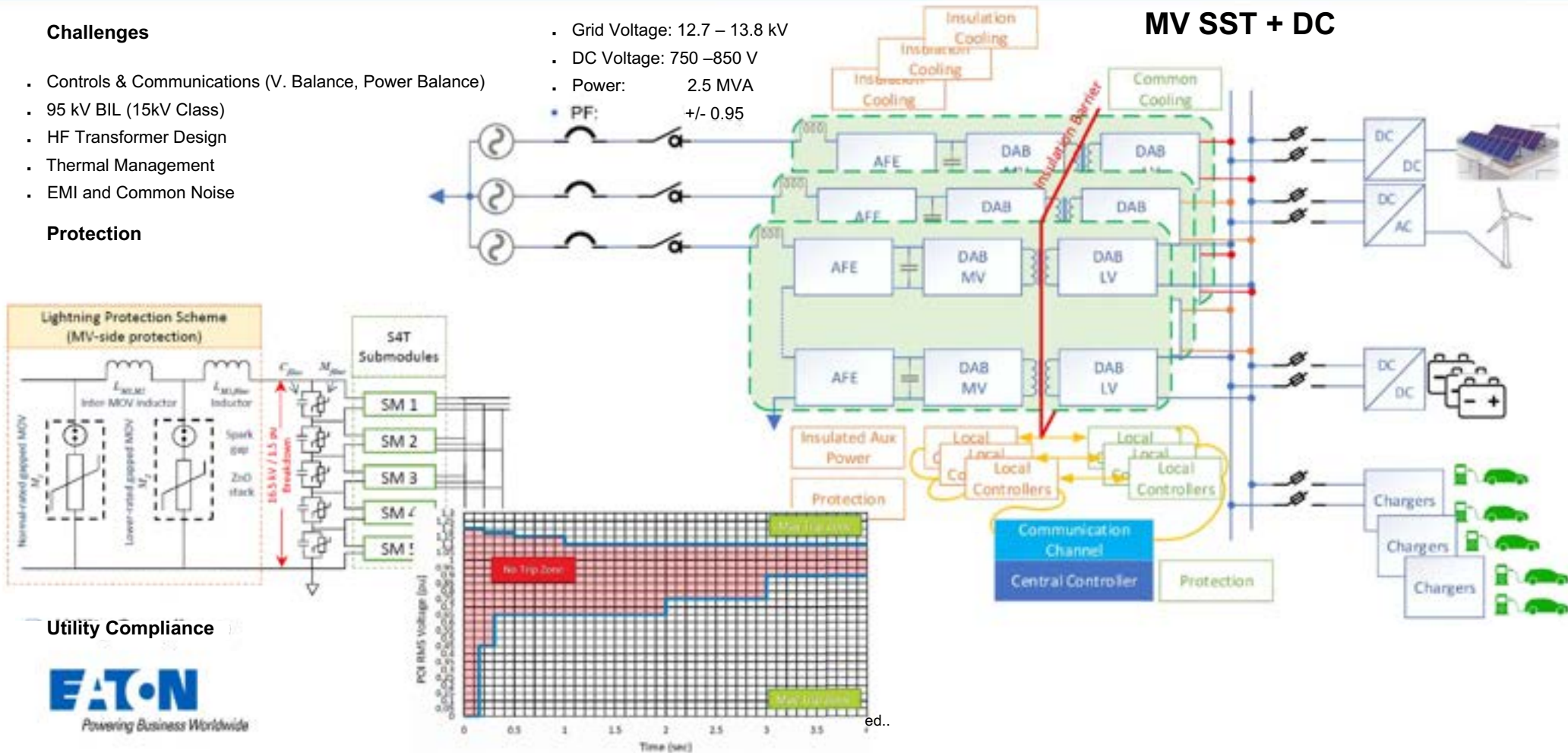
Challenges

- Controls & Communications (V. Balance, Power Balance)
- 95 kV BIL (15kV Class)
- HF Transformer Design
- Thermal Management
- EMI and Common Noise

Protection

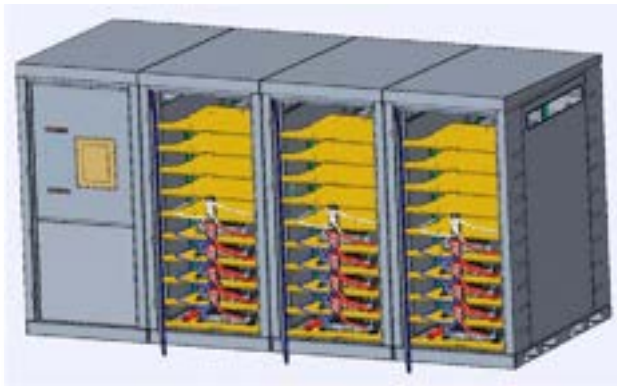
- Grid Voltage: 12.7 – 13.8 kV
- DC Voltage: 750 – 850 V
- Power: 2.5 MVA
- PF: +/- 0.95

MV SST + DC



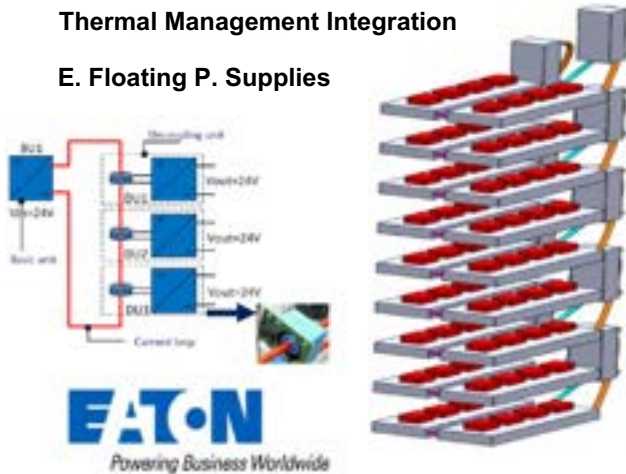
Compact Electric Vehicle Charging Infrastructure (EVCI)

Compactness & Integration



Thermal Management Integration

E. Floating P. Supplies

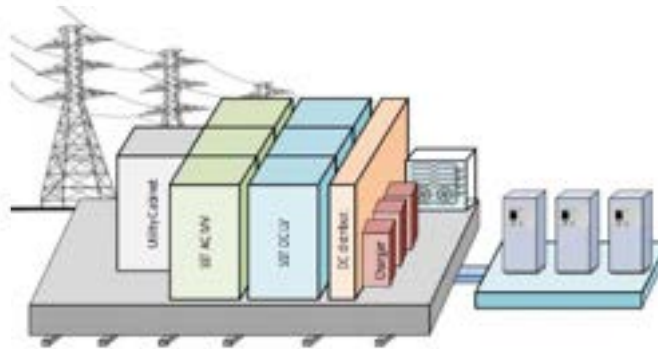


Medium Voltage Grid DC

- Grid Voltage: 12.7 – 13.8 kV
- DC Voltage: 750 – 850 V
- Power: 2.5 MVA
- PF: +/- 0.95

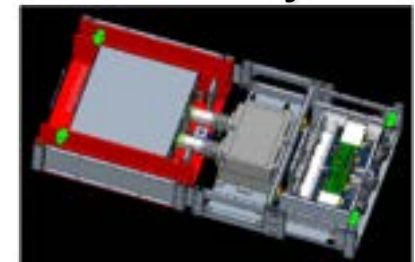
Rapid Deployment (Platform System)

- Utility Interconnection Time/Cost Reduction
- Pre-Installation Factory Acceptance Tests
- DC Distributed Bus (E. sources, Storage, Chargers)



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Modularity



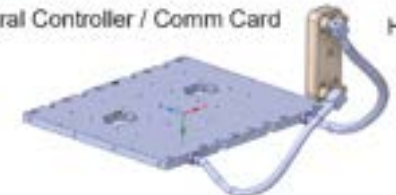
MV+HF XFR + LV Cell



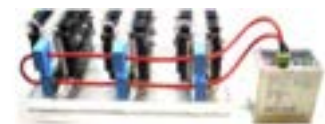
Central Controller / Comm Card



HF XFR



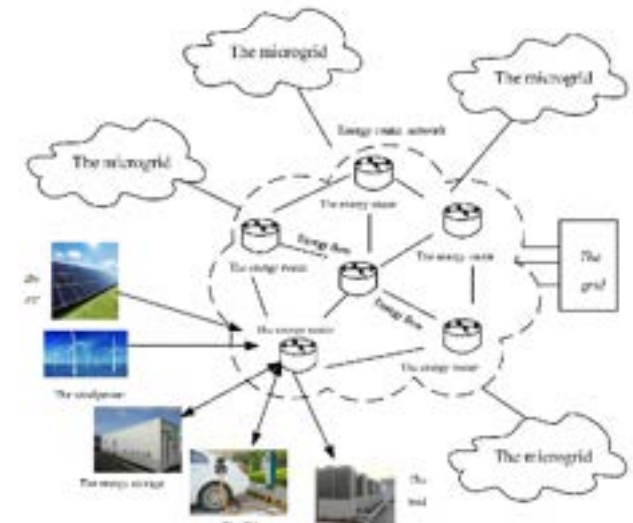
Loop Thermosyphon Adv. Cooling



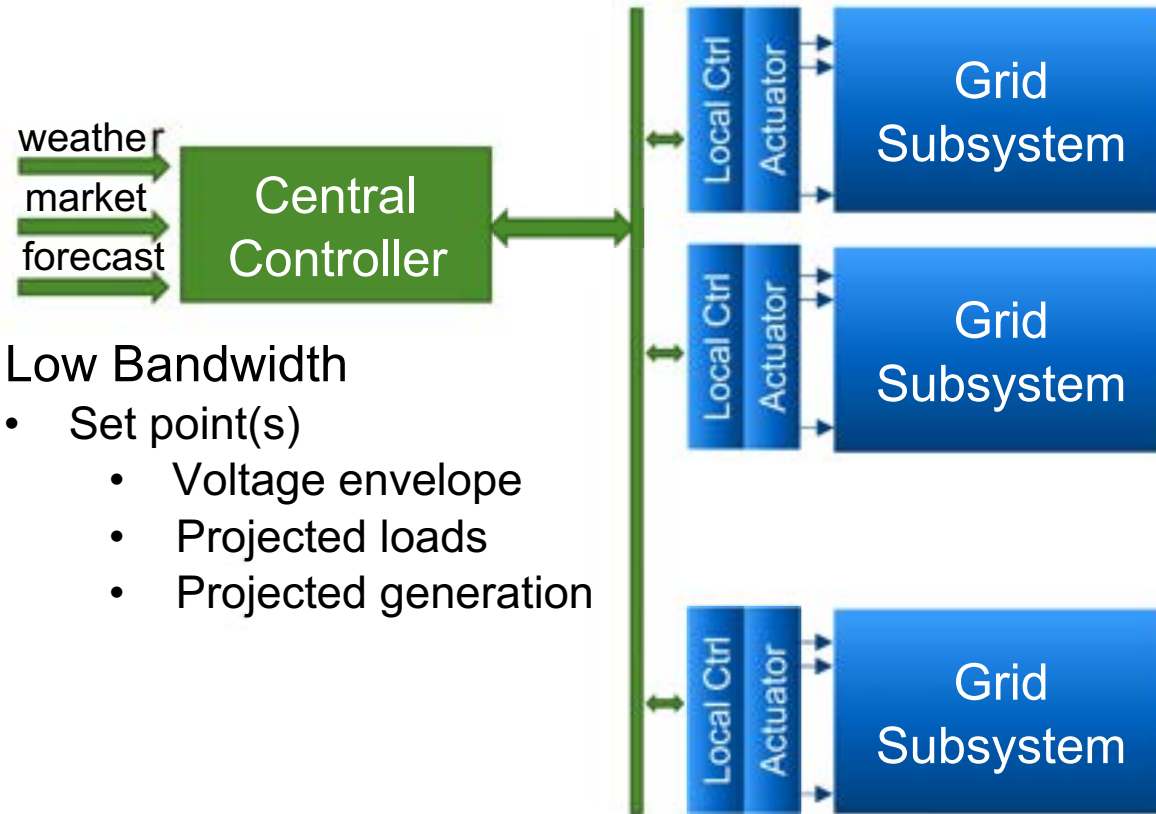
Isolated Power Supply

How Future Grid May Look Like?

- Future Grid Characteristics
 - Island-able Micro-Grids with local resources
 - Adaptable inverters
 - DC distribution
 - MV/HV AC transmission superhighway(s)
- Necessary Conditions
 - Centralized Dispatching / Set-point Ctrl
 - Fast / Agile Physical “Actuators”
 - Disturbance rejection
 - Fast Protection (μS and sub- μS level)
 - Adaptive balancing (power, current, power)
 - Fast Circuit Breakers (100x) – SSCB, Hybrid
 - Availability of advanced magnetics (XFR, L)
 - Materials
 - Fabrication



SST As a High Bandwidth Actuator for Grid Superhighway



Low Bandwidth

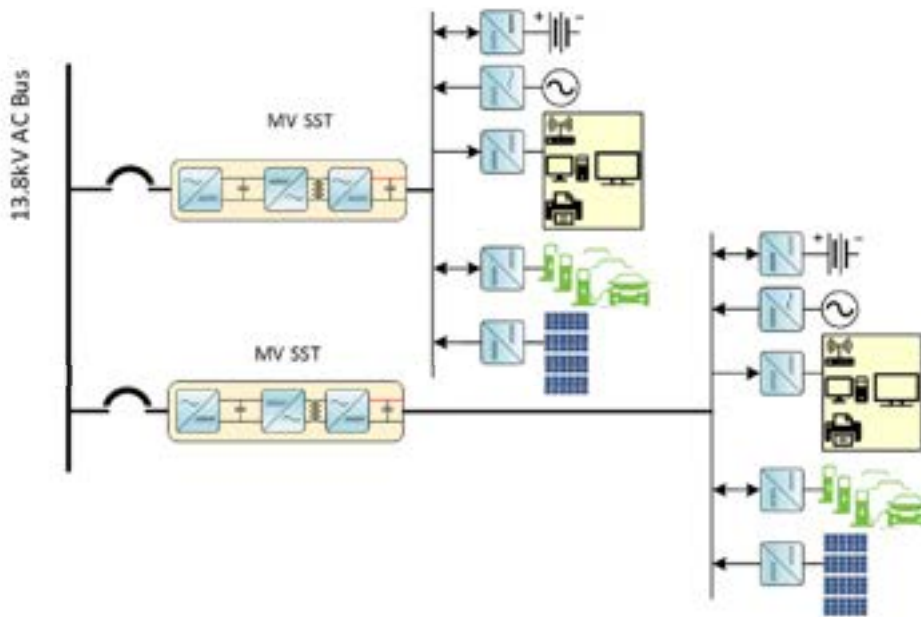
- Set point(s)
 - Voltage envelope
 - Projected loads
 - Projected generation

High Bandwidth “Reflexes” System

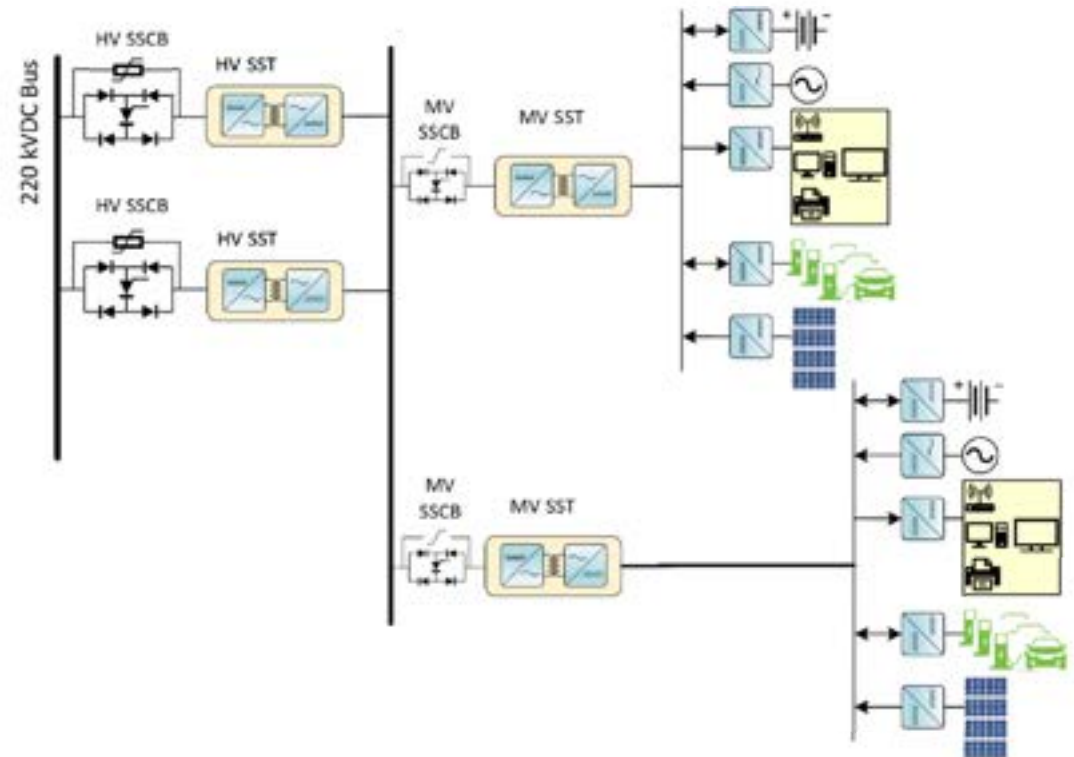
- Follow set point references
- Feed-forwards predicted disturb.
- Reject disturbances
 - from generators
 - from loads
 - Tap changers
 - Switch caps
 - Weather
- Able to “island”

SST: Energy Router for Future Grids (Energy Superhighway)

DC Microgrids with MV Distribution as Energy Highway



DC Microgrids with HV Transmission as Energy Super-Highway



Benefits of SST in Future Grids

- SST Addresses Both Critical Infrastructure Areas
 - Fast Charging (>2MW, >15kV MV Class)
 - Grid Needs
 - High BW Actuation: Controllability
 - Expandable / Modular
 - Grid Forming Inverter – Energy Superhighway
- Acts as High Bandwidth Actuator
- Provides Necessary Autonomous local Controls
 - Module-level fast protection: Reliability
 - Self-Balancing with no need for centralized control

Concluding Remarks

- Power Conversion – Plausible Solution for Future Grid(s)
 - The 4th Industrial Revolution (Cyber-Physical Systems, AI, Robotics)
 - Population Growth Energy Demand
 - Phasing-out of Fossil Fuels
 - Generation
 - Transportation
- Requirements / Challenges
 - Higher Power Density
 - Higher Voltages
 - Fast, Agile, High BW Control Systems
- Immediate Technology Areas Necessary
 - Magnetics
 - Insulation Materials
 - Sensors



Powering Business Worldwide

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