ETH
Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

NPERC-J
3rd Workshop

# Next Generation Power Electronics Infrastructure System

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# The EEnergy Internet

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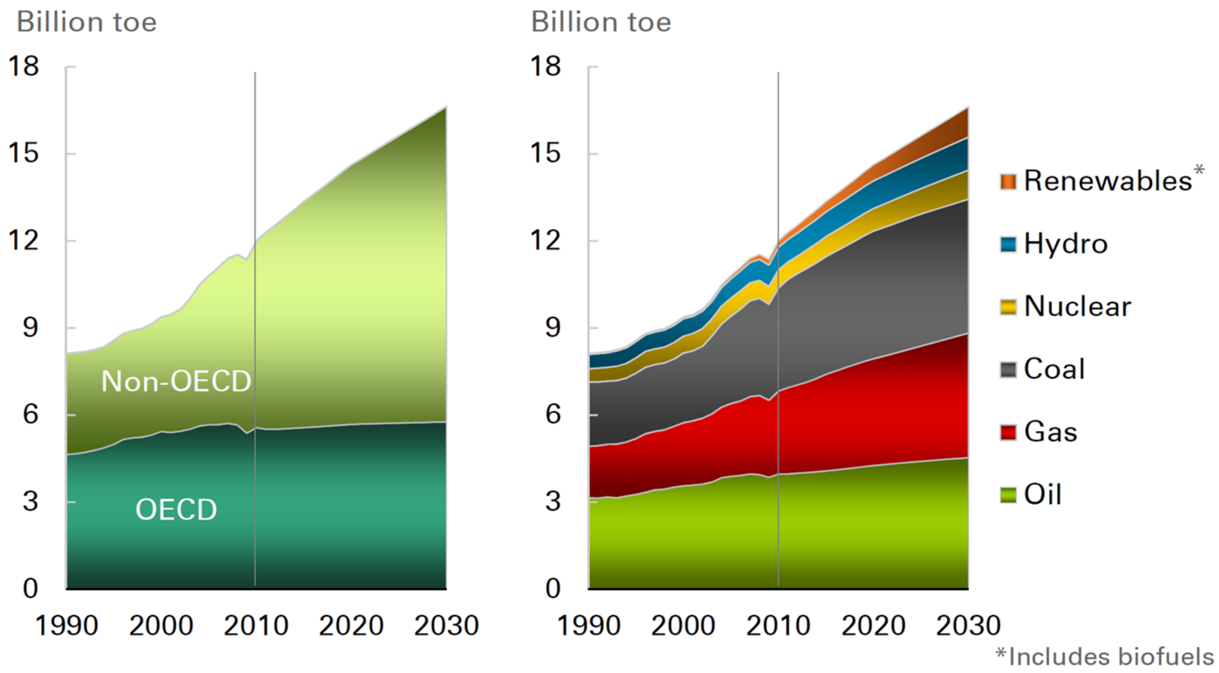
# Outline

- Introduction
- Demands on Future EE Infrastructure
- Fractal Smart Grid
- Smart Grid Power Electronics - SST
- Conclusions / Challenges

# Energy Consumption Growth

→ Consequences / Countermeasures

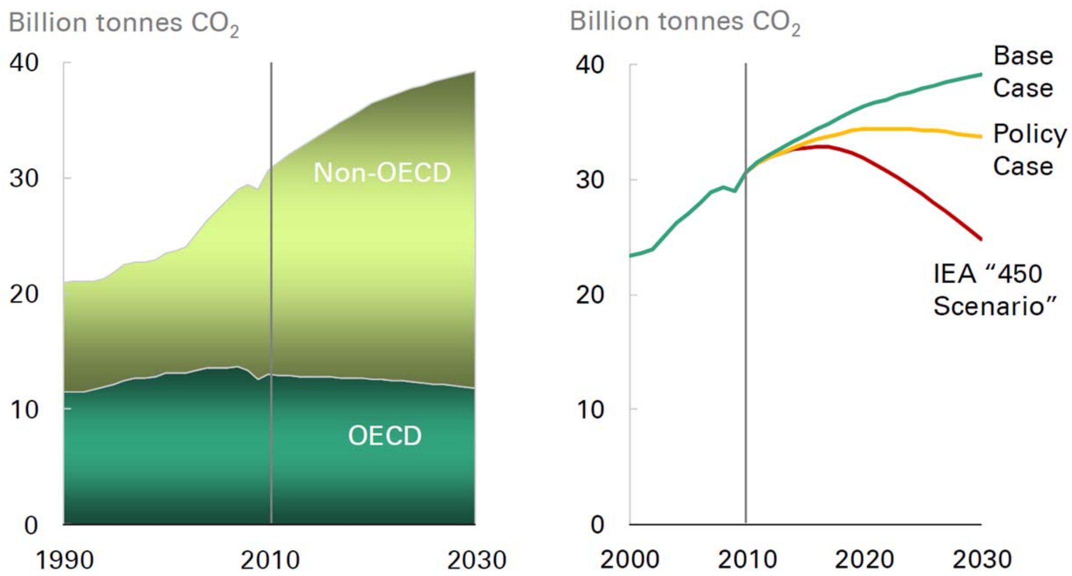
# ▶ Global Energy Consumption Growth




- **Not a Sustainable Path !**

Source: Energy Outlook 2030 / BP 2012

# ▶ Global $CO_2$ Emissions from Energy Use



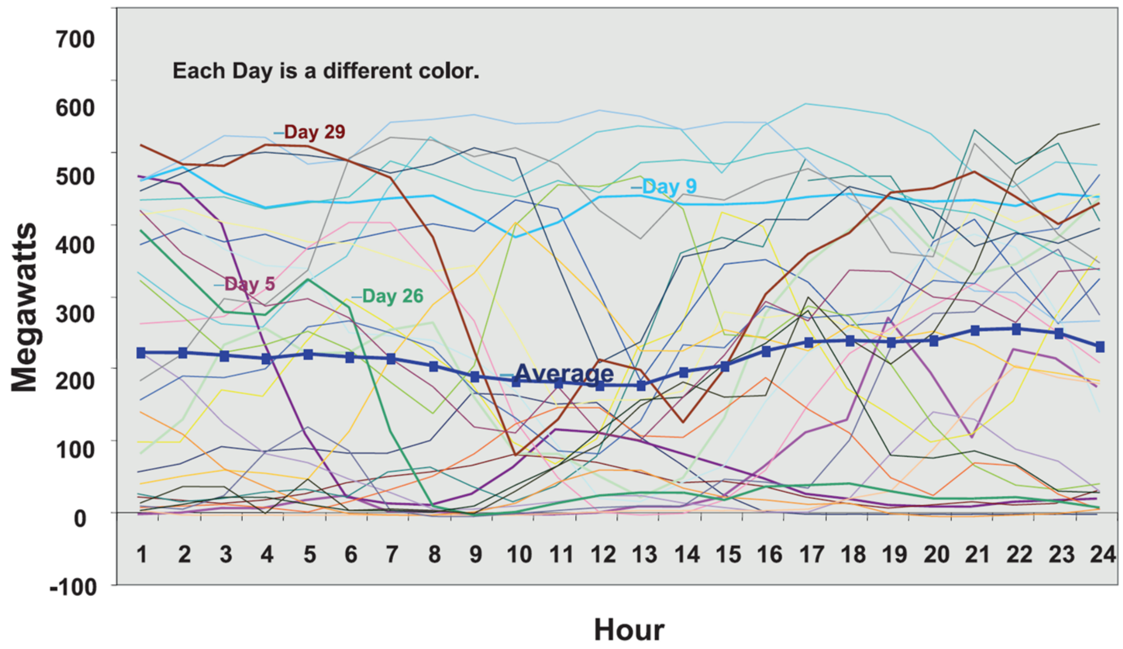

Source: Energy Outlook 2030 / BP 2012

- Risk to Exceed Recommended Emission Limit → Global Warming
- "Policy Case" → (1) Renewable Energy, (2) Increase Prices, (3) Increase Efficiency ("Negawatts")

# Renewable Energy

→ Characteristics / Grid Integration

# Characteristics of Renewable Energy Sources I



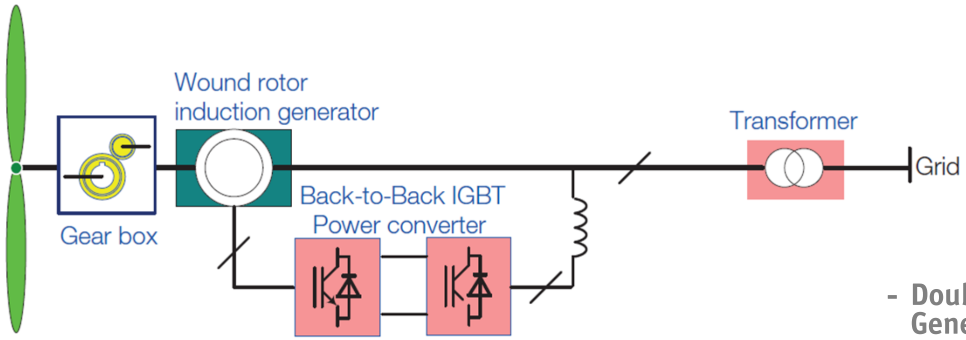

- Hourly Output of Wind Plant in Calif.

Source: IEC White Paper 2012

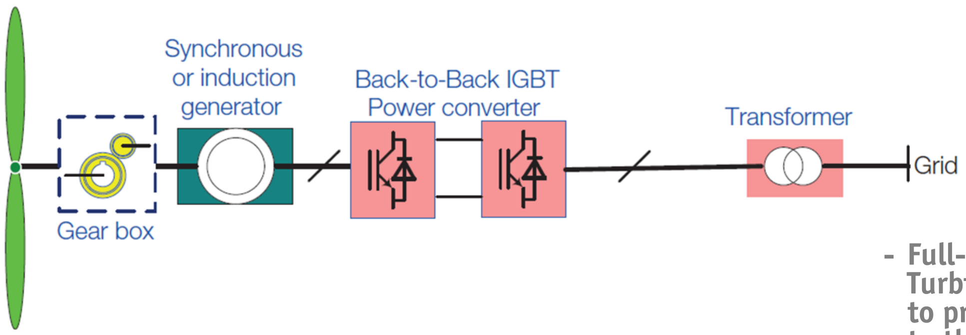
- Fluctuating (Partly Unpredictable) → Storage (all Scales) and/or Demand Management

# ▶ Characteristics of Renewable Energy Sources II

Source: IEC White Paper 2012



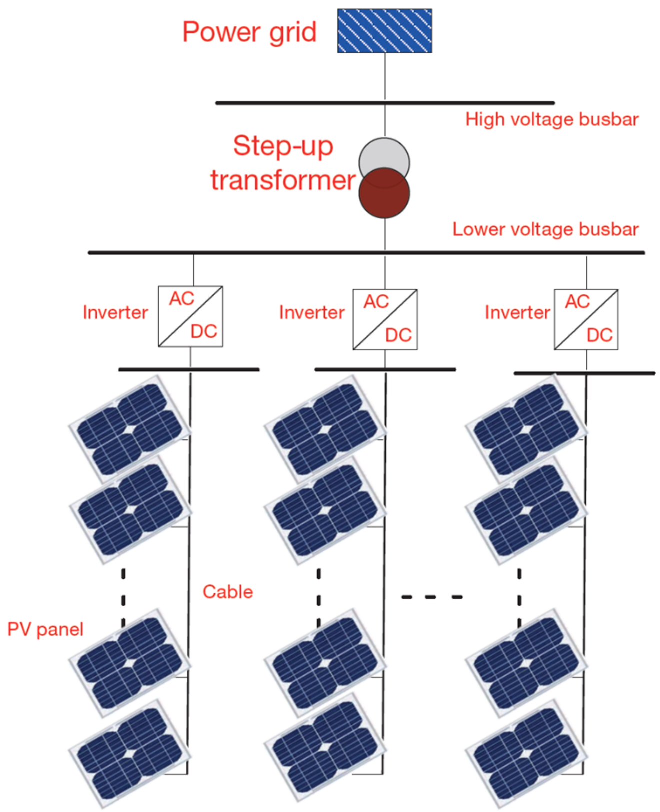

- Doubly Fed Induction Generator




- Full-Power Conv. Wind Turbine Generator (allows to provide Ancillary Services to the Grid)

■ Variable Frequency AC Output → Power Electronics Interface for Grid Integration

# Characteristics of Renewable Energy Sources II

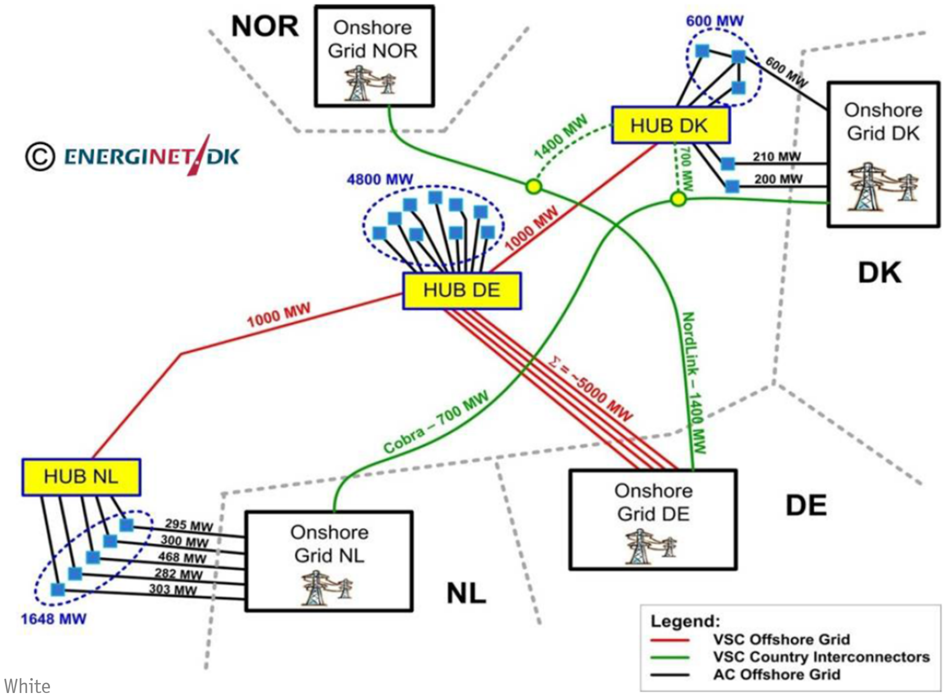



Source: IEC White Paper 2012

- Structure of a PV Power Station

- **DC Output** → **Power Electonics Interface for Grid Integration**

# ▶ Characteristics of Renewable Energy Sources III

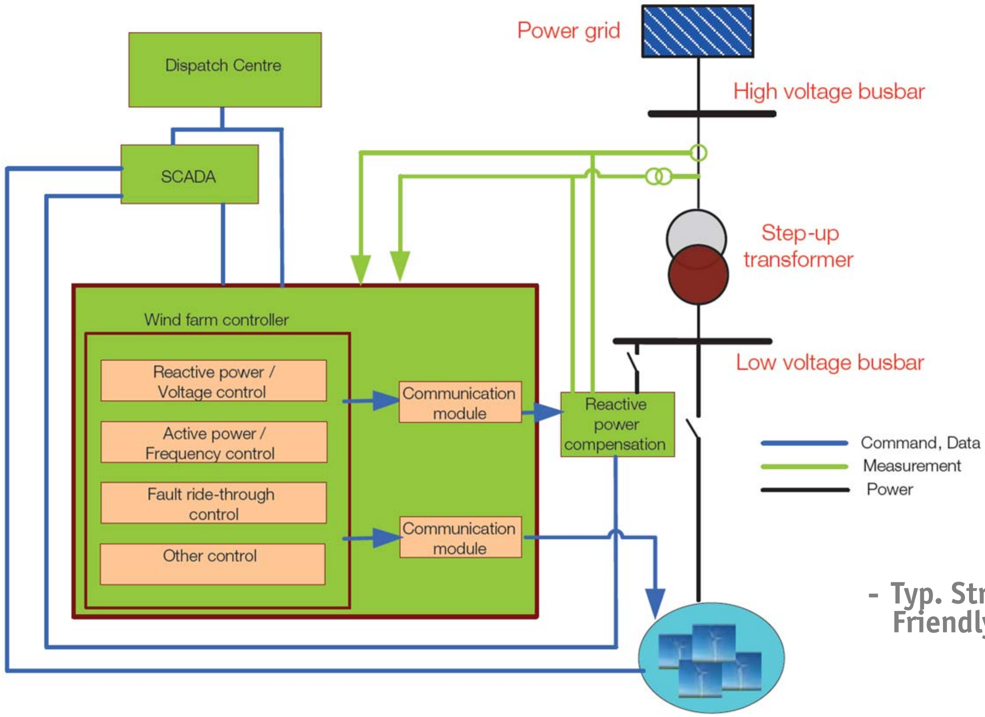



Source: IEC White Paper 2012

- Simulation Benchmark Test System for EU Transnational Off-Shore Grid

■ Decentralized / Remote (e.g. Off-Shore) → (Multi-Terminal) HVDC Transm. / EU Super Grid

# ▶ Local "Grid-Friendly" Integration of Renewable Sources

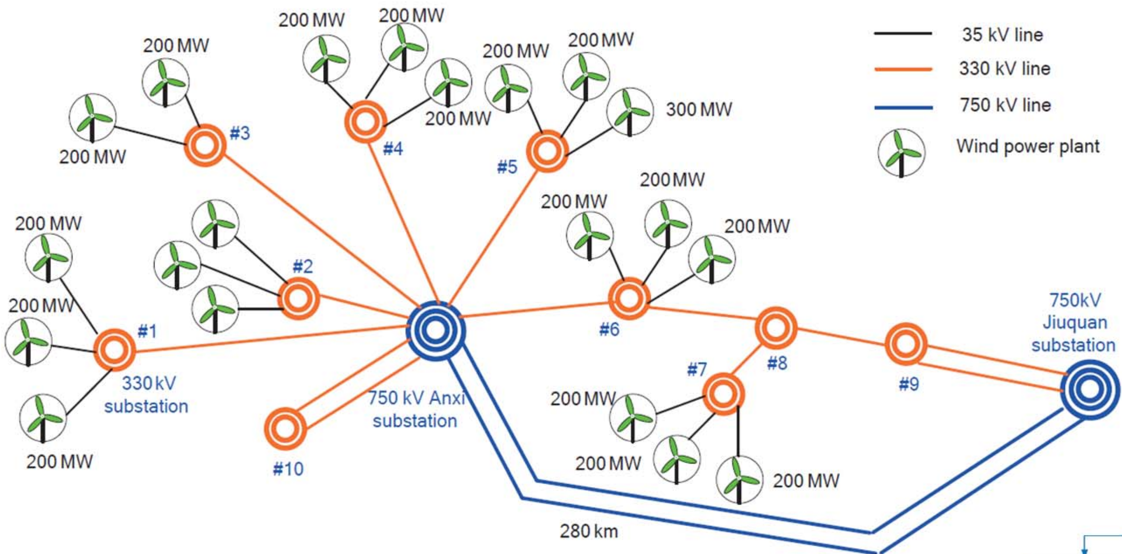



Source: IEC White Paper 2012

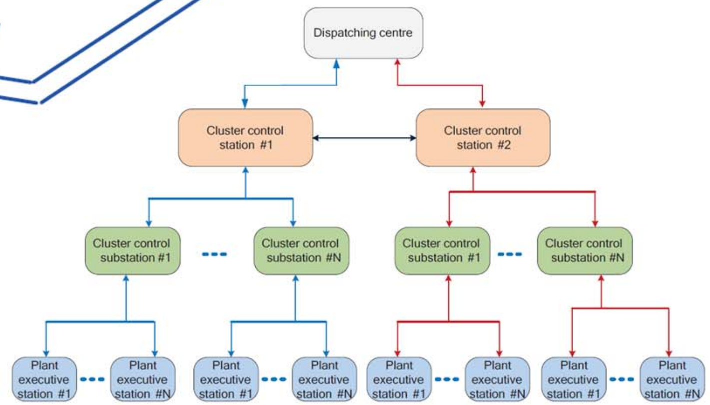
- Typ. Structure of "Grid-Friendly" Wind Power Plant

■ Contribution to Power System Reliab. / Stability → Short-Circuit Current Control
Voltage/ VAr Control (VSC or FACTS Equipm.)
Fault Ride Through (Fault: Low/High *V* or *f*)

# ▶ Grid-Integration of Distributed Renewable Energy




Source: IEC White Paper 2012



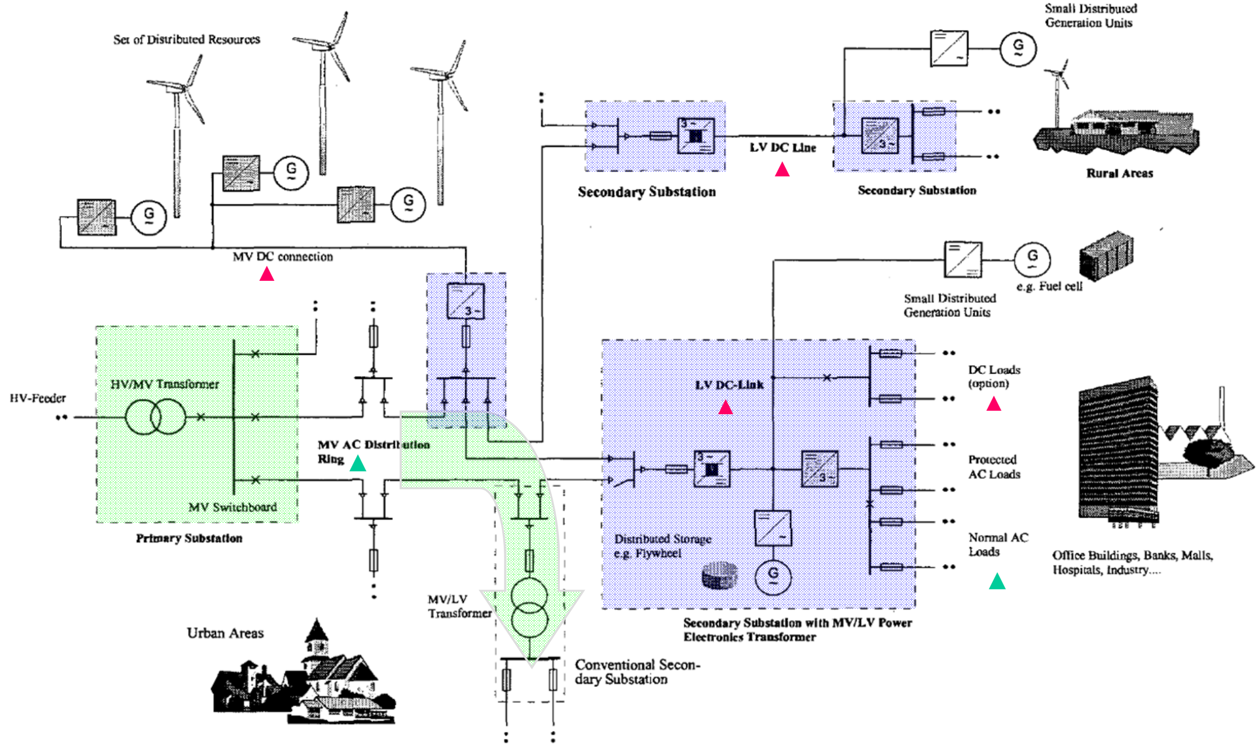

- **Multi-Layer Centralized Control of Renewable Energy Plant Cluster**

→ **NEW Approach Required to Allow Integration of (also Small Scale) Renewable Energy Sources / Storages & Load Control etc. All Over the Grid**

# Future *Fractal Smart* Grid

→ Fractal Grid Structure
→ Convergence of IT & Energy Systems

# ▶ Advanced (High Power Quality) Grid Concept




Source: ABB / Heinemann 2001

- MV AC Distribution with DC Subsyst. (LV and MV) & Large Number of Distributed Ren. Resources
- MF AC/AC Conv. with DC Link Coupled to Energy Storage - High Power Qual. for Spec. Customers

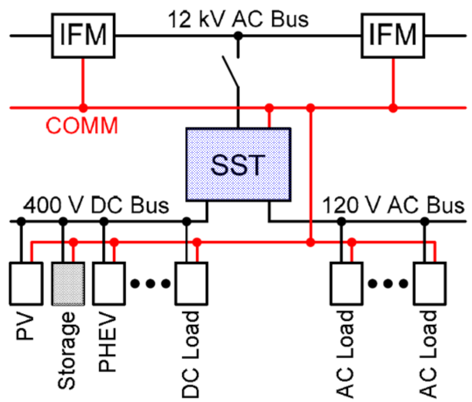
# ▶ Future Ren. Electric Energy Delivery & Management (FREEDM) Syst.

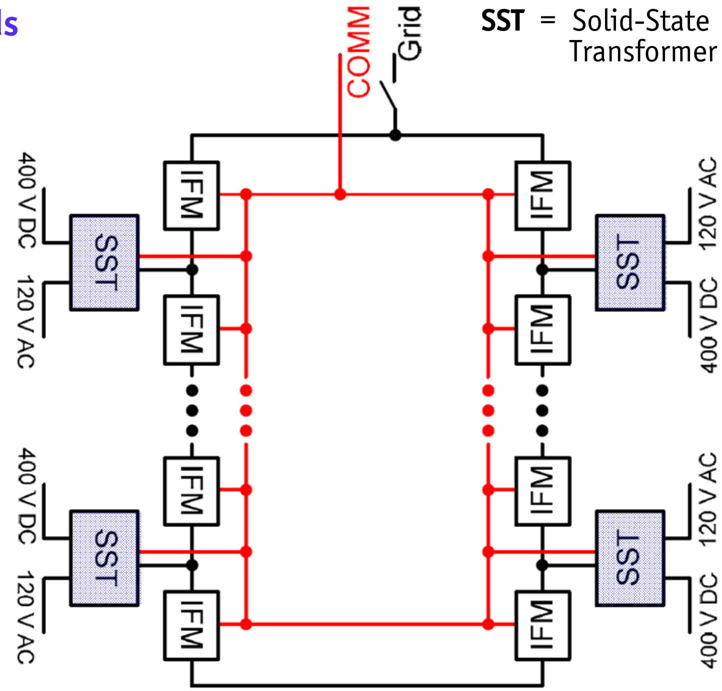
"EEnergy Internet"

- Integr. of DER (Distr. Energy Res.)
- Integr. of DES (Distr. E-Storage) + Intellig. Loads
- Enables Distrib. Intellig. through COMM
- Ensure Stability & Opt. Operation

IFM = Intellig. Fault Management
SST = Solid-State Transformer

Source: Ayyanar / Huang 2008




■ Bidirect. Flow of Power & Information / High Bandw. Comm. → Distrib. / Local Autonomous Cntrl

# ▶ Smart Grid Concept

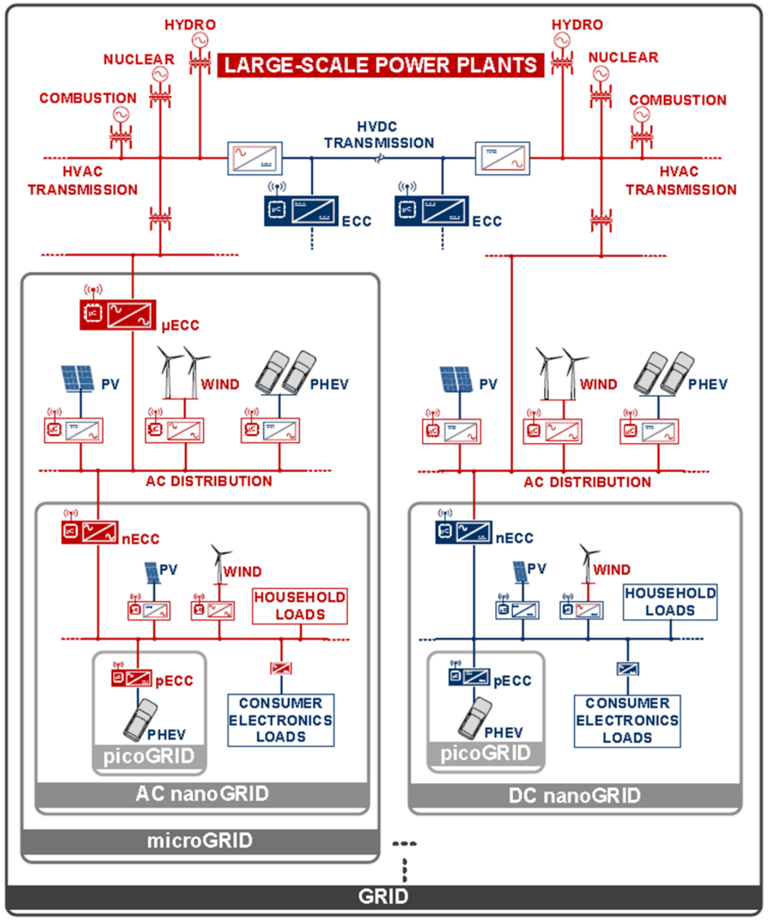
Source: Borojevic 2010

- Hierarchically Interconnected Hybrid Mix of AC and DC Sub-Grids

  - Distr. Syst. of Contr. Conv. Interfaces
  - Source / Load / Power Distrib. Conv.
  - Picogrid-Nanogid-Microgrid-Grid Structure
  - Subgrid Seen as Single Electr. Load/Source
  - ECCs provide Dyn. Decoupling
  - Subgrid Dispatchable by Grid Utility Operator
  - "Virtual Power Plants"
  - Integr. of Ren. Energy Sources

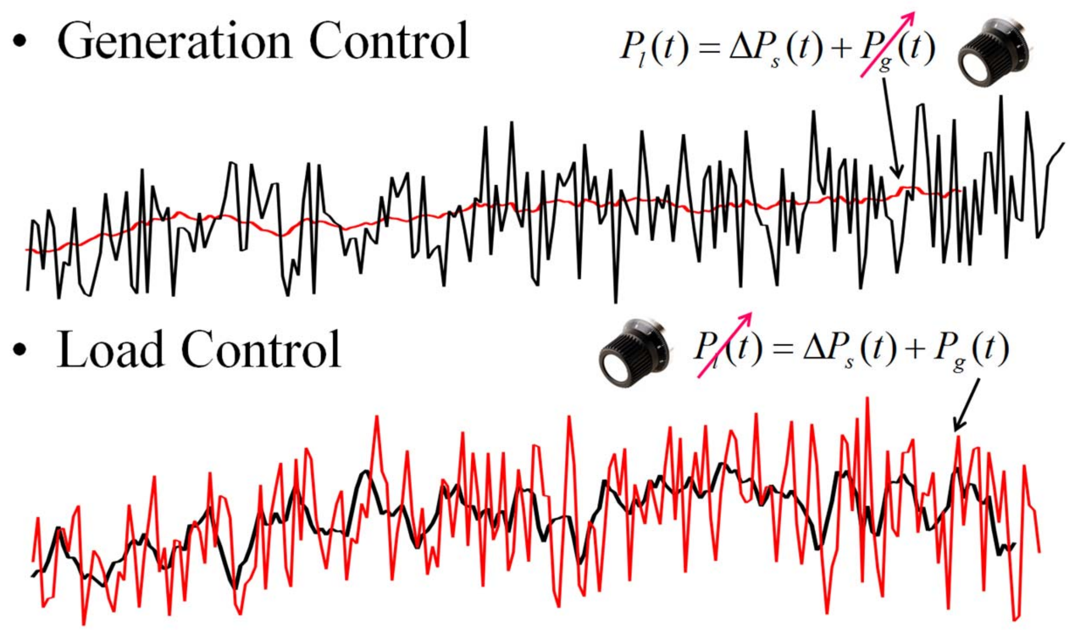
- ECC = Energy Control Center

  - Energy Routers
  - Continuous Bidir. Power Flow Control
  - Enable Hierarchical Distr. Grid Control
  - Load / Source / Data Aggregation
  - Up- and Downstream Communication
  - Intentional / Unintentional Islanding for Up- or Downstream Protection
  - etc.



# ► Smart Grid Control Challenge I

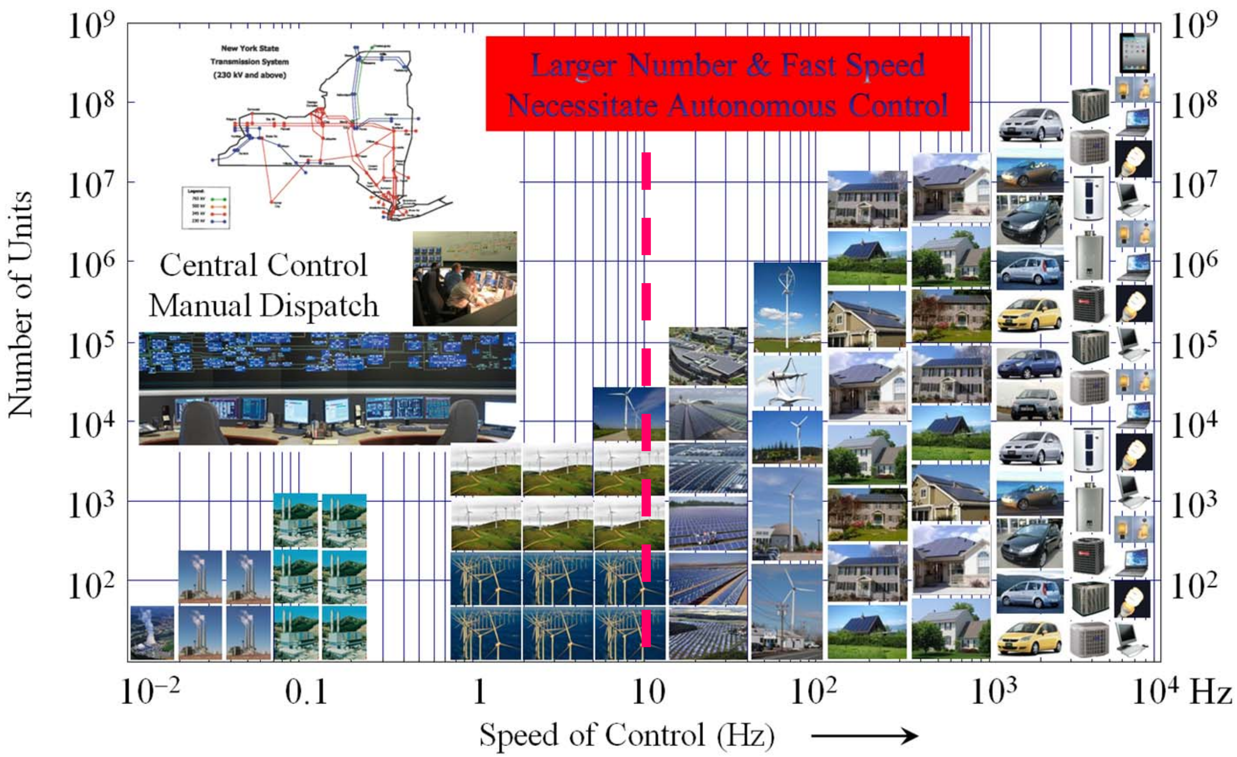
Source: J. Sun, EPRI-PSMA Workshop 2013




- Constant Power Loads
- Ren. Energy = Variable / Distributed Sources
- Red. Kinetic Energy Storage in Future Grids → Provide other Storage & Control for Power Balance

# ▶ Smart Grid Control Challenge II

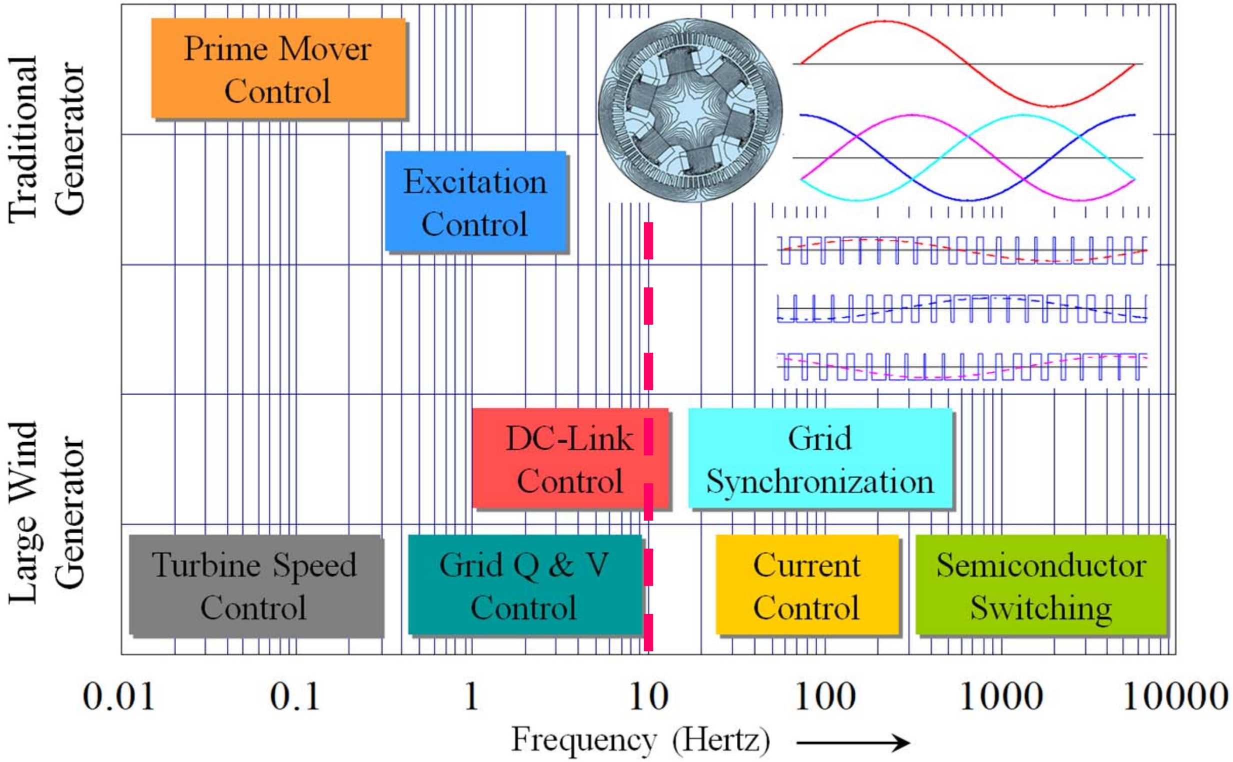
Source: J. Sun, EPRI-PSMA Workshop 2013




■ Large Number & Low / High Dynamics → Clustering and Decentr. / Autonomous Contr. or Response

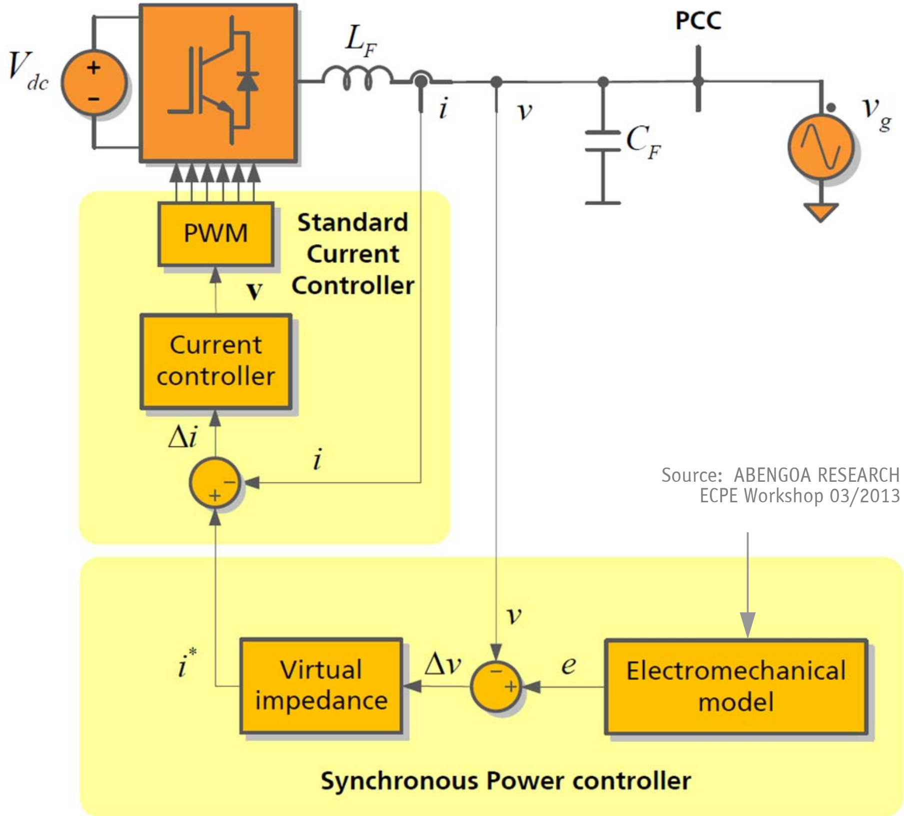
# ▶ Smart Grid Control Challenge III

Source: J. Sun, EPRI-PSMA
Workshop 2013




- Dynamics → from Transient Balance by Kin. Storage (No Cntrl) to ms-Active Power Flow Control

# ▶ Example of Autonomous Response




Source: ABENGOA RESEARCH
ECPE Workshop 03/2013

- Grid Connection Based on "Virtual Impedance" →

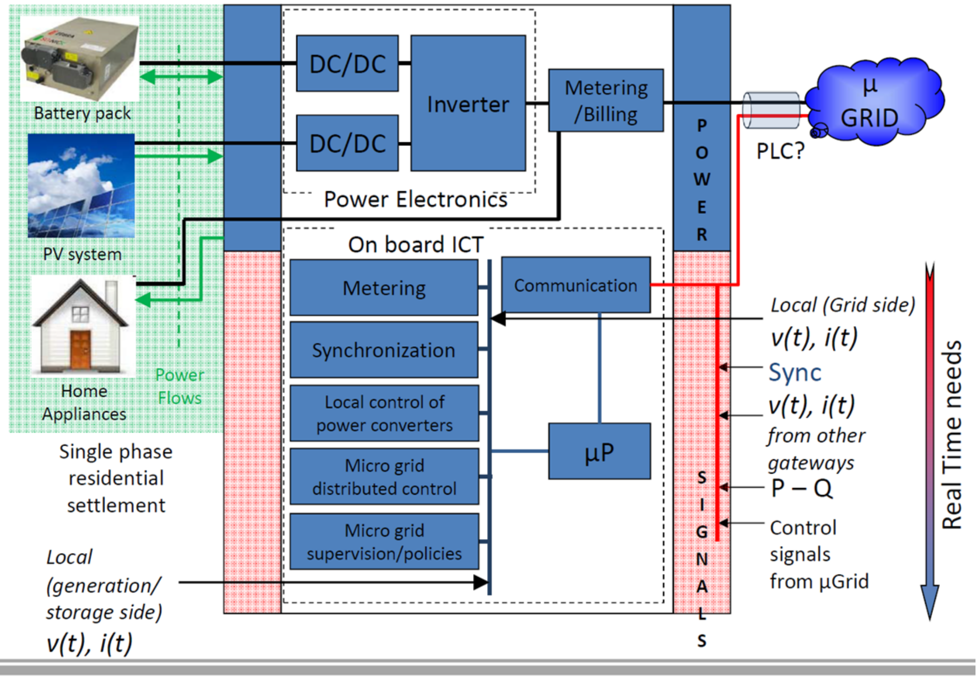
Power Converter Emulates Synchronous Generator Behavior (according to EM Model)

# ▶ Smart Home / Microgrid

Source: P. Tenti ECPE Workshop 03/2013

→ **Energy Trading (Scheduling of Power Supply / Consumpt., Operating Reserves, Power Quality Services, Energy Storage / Balancing etc.; Smart Meters**

→ **Smart Picogrid (Smart Homes, Smart Buildings etc.)**




Energy Gateway – Functional diagram

■ **Distributed Control of Power Electronic Interfaces in Smart Picogrids**

# Smart Grid Power Electronics

→ Solid State Transformer

# Classical Transformer - Basics

- Advantages

- Relatively Inexpensive
- Highly Robust / Reliable
- Highly Efficient (98.5%...99.5% Dep. on Power Rating)

- Weaknesses

- Voltage Drop Under Load
- Losses at No Load
- Sensitivity to Harmonics
- Sensitivity to DC Offset Load Imbalances
- Provides No Overload Protection
- Possible Fire Hazard
- Environmental Concerns

- Construction Volume

$$A_{Core} A_{Wdg} = \frac{\sqrt{2}}{\pi} \frac{P_t}{k_W J_{rms} \hat{B}_{max} f}$$

$P_t$ .... Rated Power
$k_W$ .... Window Utilization Factor (Insulation)
$B_{max}$ .... Flux Density Amplitude
$J_{rms}$ ... Winding Current Density (Cooling)
$f$ ..... Frequency

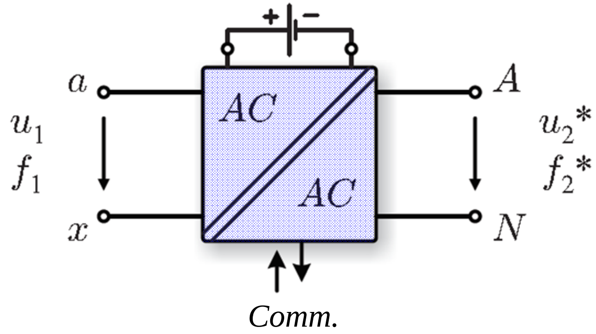
- No Controllability
- Low Mains Frequency Results in Large Weight / Volume

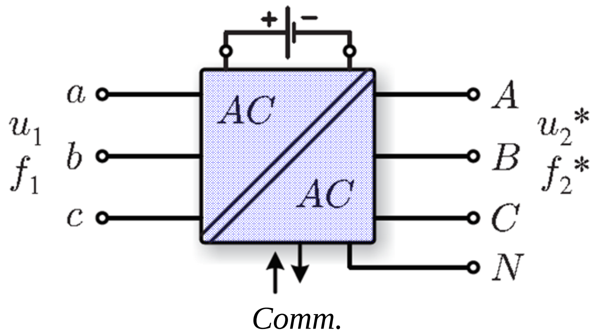
# ▶ SST Functionalities

- Protects Load from Power System Disturbance
  - Voltage Harmonics / Voltage Sag Compensation
  - Outage Compensation (UPS Functionality)
  - Load Voltage Regulation (Load Transients, Harmonics)

- Protects Power System from Load Disturbance
  - Unity Inp. Power Factor Under Reactive Load
  - Sinus. Inp. Curr. for Distorted / Non-Lin. Load
  - Symmetrizes Load to the Mains
  - Protection against Overload & Output Short Circuit

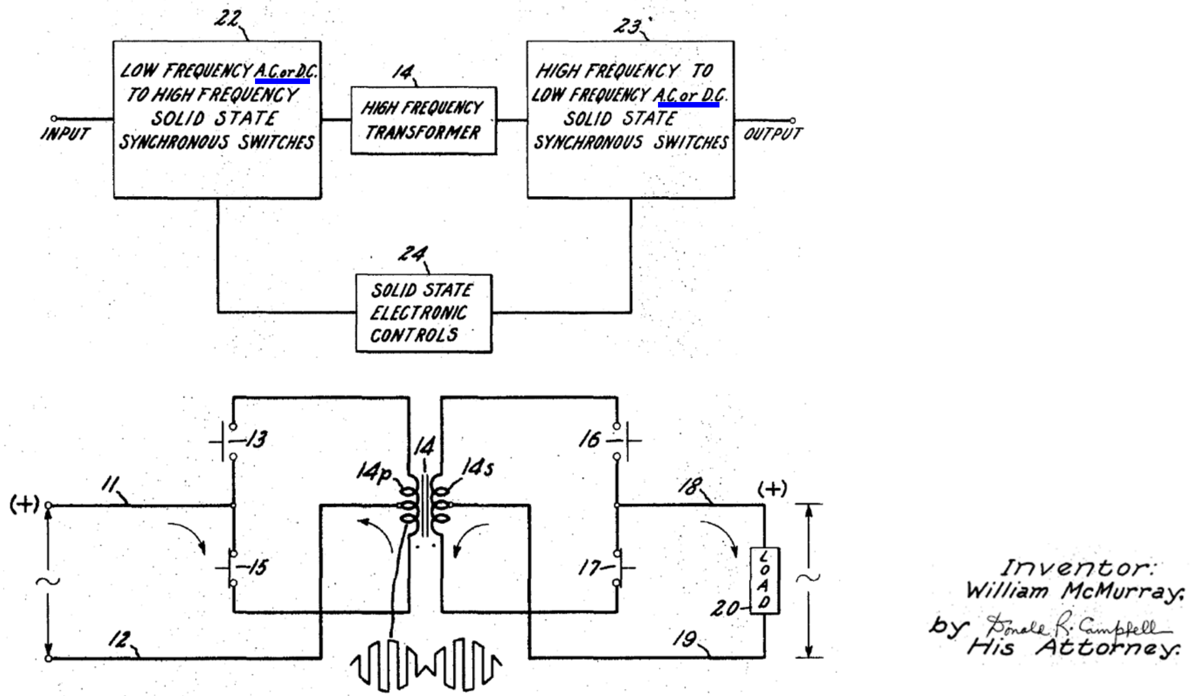
- Further Characteristics
  - Operates on Distribution Voltage Level (MV-LV)
  - Integrates Energy Storage (Energy Buffer)
  - DC Port for DER Connection
  - Medium Frequency Isolation → Low Weight / Volume
  - Definable Output Frequency
  - High Efficiency
  - No Fire Hazard / Contamination



# ▶ Electronic Transformer - McMurray 1968

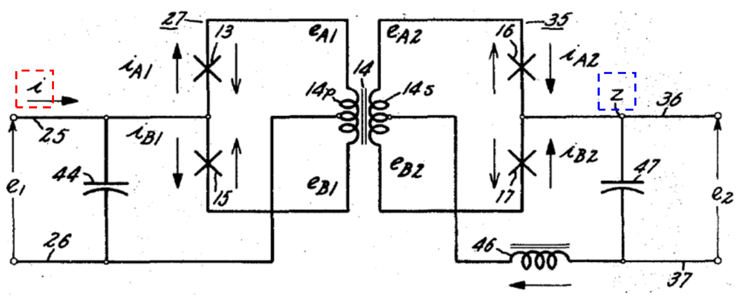
■ Matrix-Type $f_1$=$f_2$

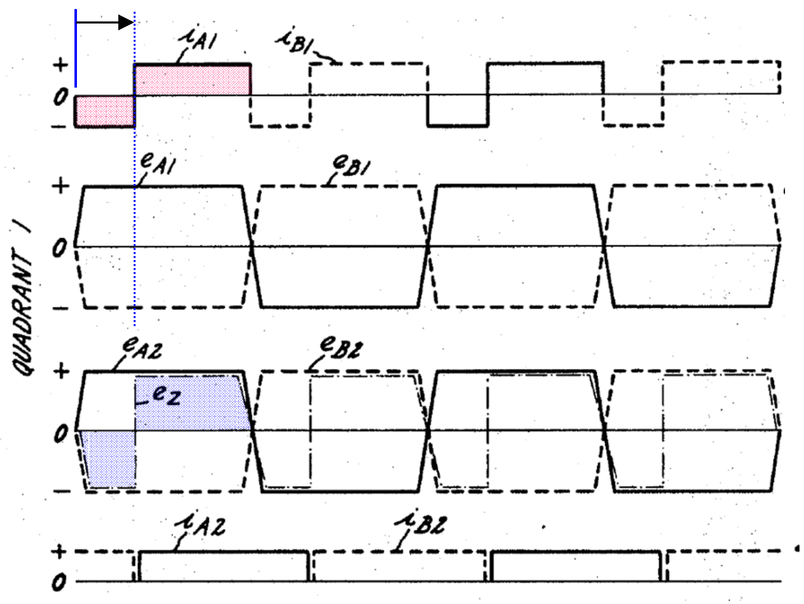



- Electronic Transformer = HF Transf. Link & Input and Output Sold State Switching Circuits
- AC or DC Voltage Regulation & Current Regulation/Limitation/Interruption

# ▶ Electronic Transformer - McMurray 1968

■ Matrix-Type $f_1$=$f_2$

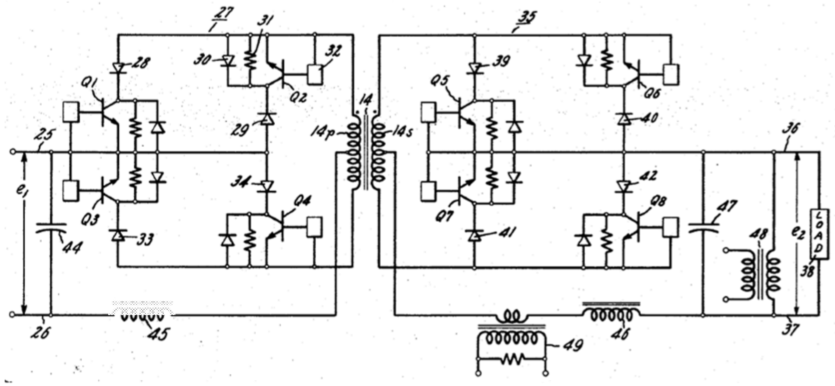


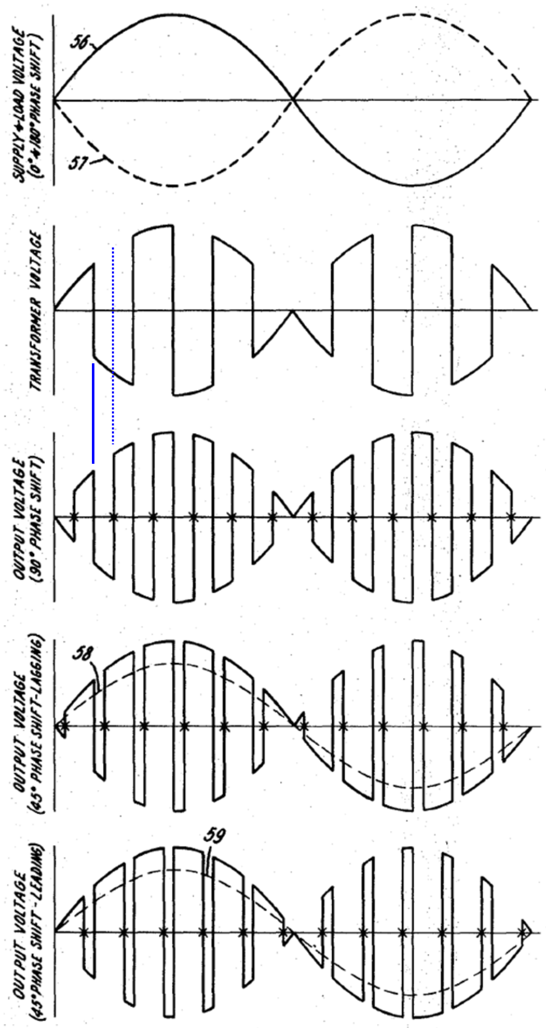



- 50% Duty Cycle Operation @ Primary and Secondary
- Output Voltage Control via Phase Shift Angle

# Electronic Transformer

## Matrix-Type $f_1=f_2$





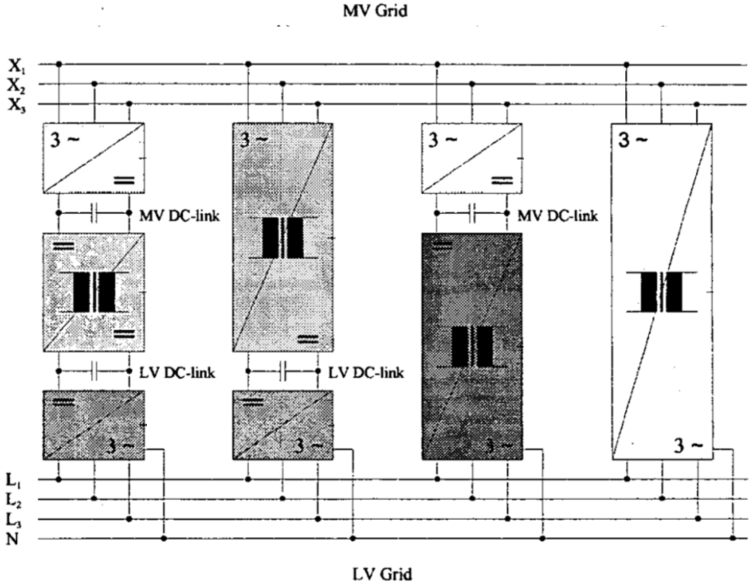

- Inverse-Paralleled Pairs of Turn-off Switches

# ▶ Basic Solid-State Transformer (SST) Structures

- Power Conversion

- Three-Stage Power Conversion with MV and LV DC Link
- Two-Stage Concept with LV DC Link (Connection of Energy Storage)
- Two-Stage Concept with MV DC Link (Connection to HVDC System)
- Direct or Indirect Matrix-Type Topologies (No Energy Storage)

Source: ABB / Heinemann 2001




- Realization of 3ph. Conversion

- Direct 3ph. Converter Systems
- Three-Phase Conn. of 1ph. Systems
- Hybrid Combinations

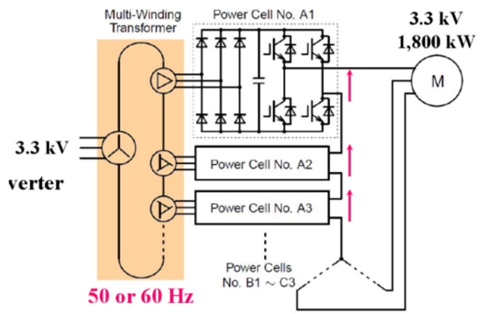
- Handling of Voltage & Power Levels

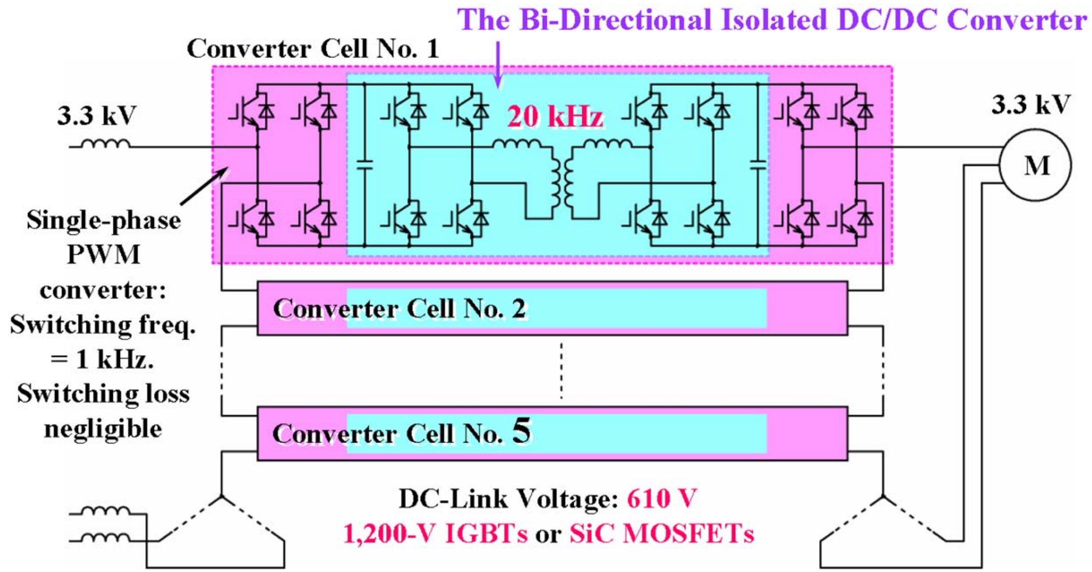
- Multi-Level Converters / Single Transf.
- Cascading / Parallel Conn. of Conv. Modules
- Series / Parallel Connection of Semicond.
- Hybrid Combinations

■ Medium Freq. Required for Achieving Low Weight (Low Realiz. Effort) *AND* High Control Dynamics

# ▶ DC-Link Based *Fully Phase-Modular* SST Topologies

- Akagi (2005/2007)

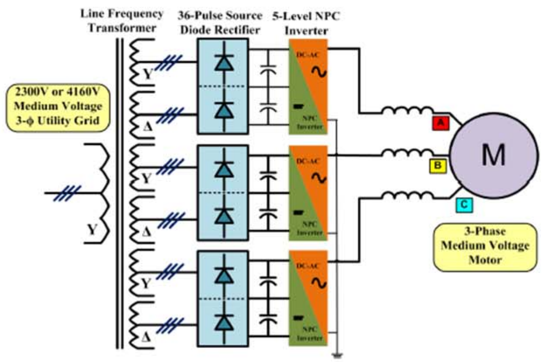


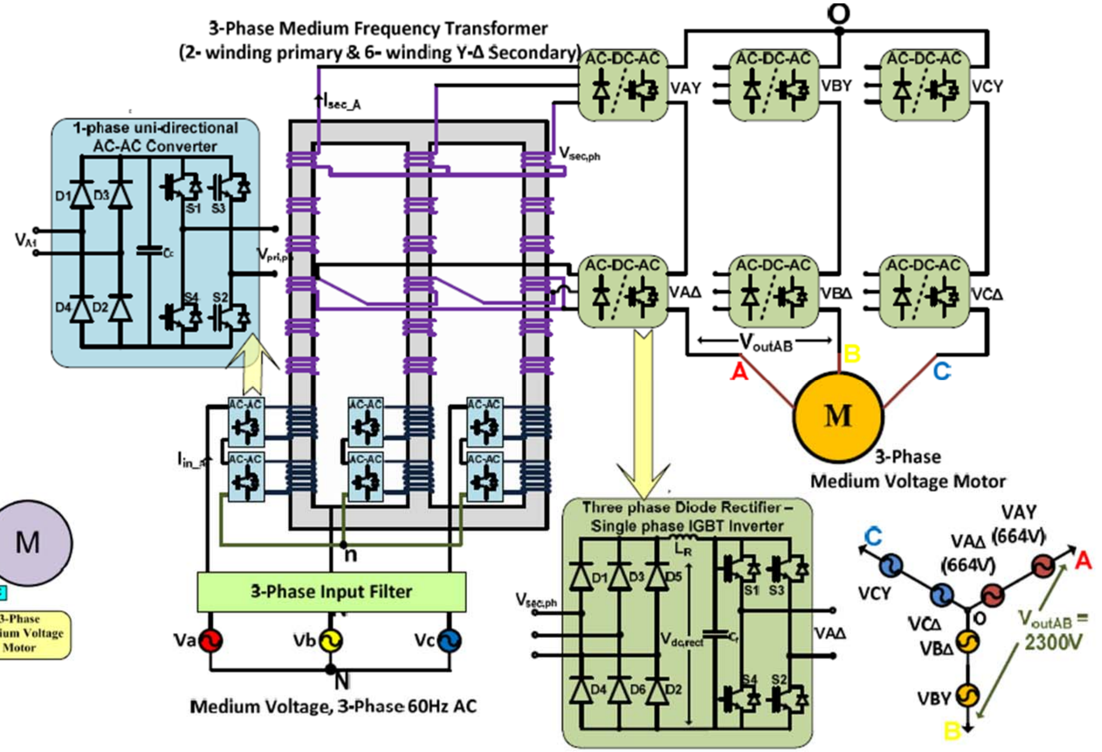




■ Application for MV Motor Drives Replacing the 50/60 Hz Transformer

# ▶ Unidirectional DC-Link Based SST Structures

- Enjeti (2012)

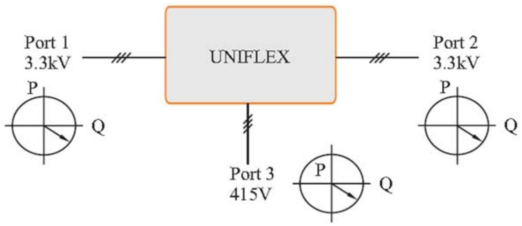


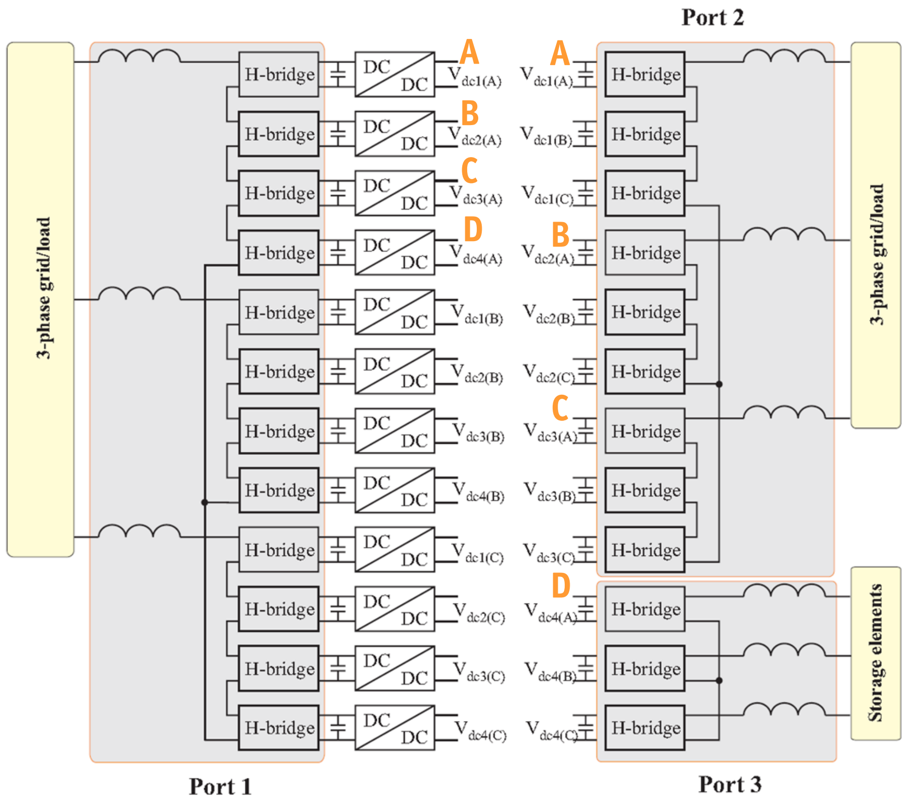




- SST Appl. for MV Adjustable Speed Drive (Unidir. AC/AC Front End / Cascaded 2L 1ph.-Inverters)
- Avoids Bulky LF Transformer / DC Link and Mains Current Harmonics (Active Filter)

# ▶ UNIFLEX Project

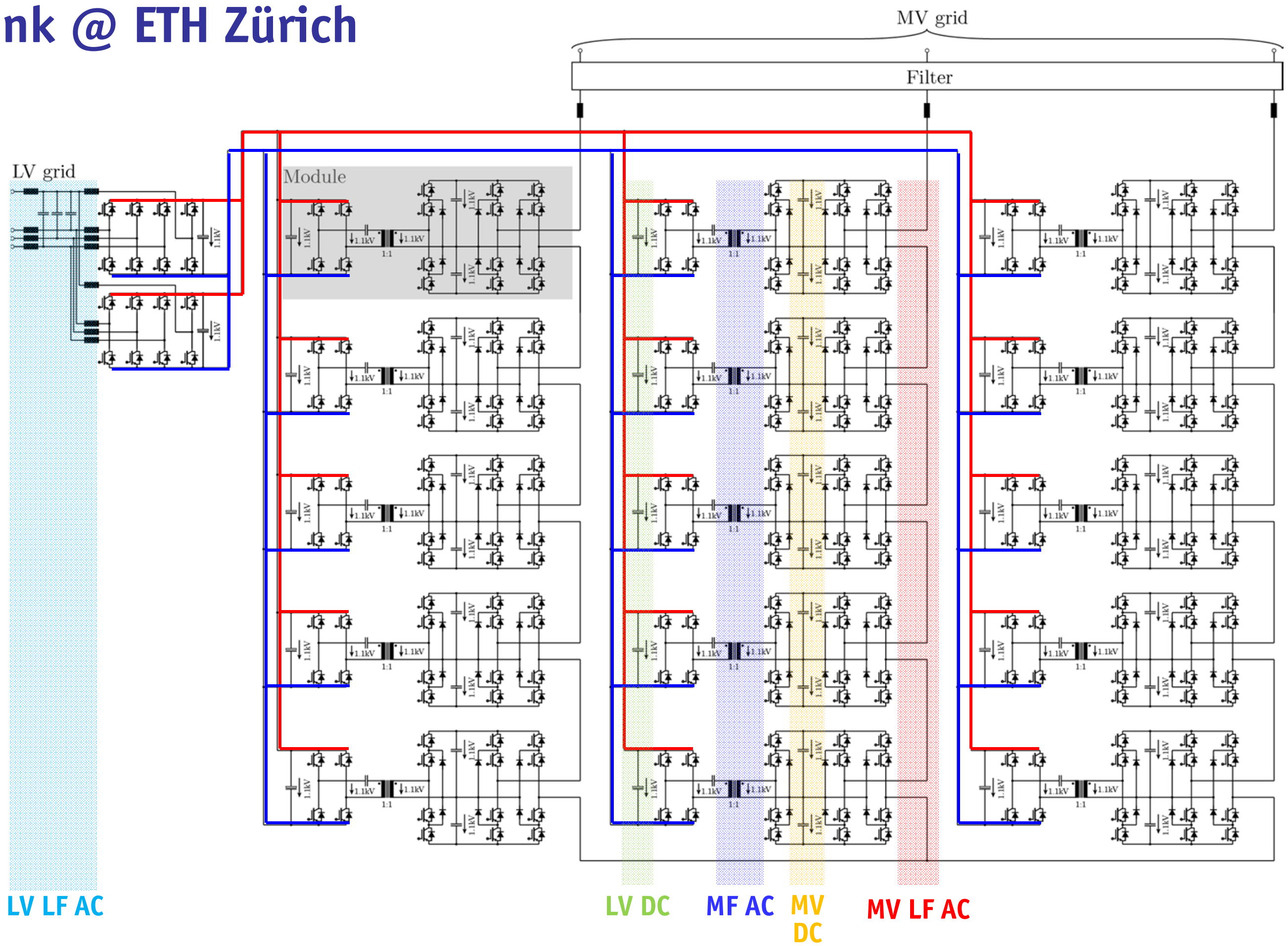
- EU Project (2009)




- Advanced Power Conv. for Universal and Flexible Power Management (UNIFLEX) in Future Grids
- Cellular 300kVA Demonstrator of 3-Port Topology for 3.3kV Distr. System & 415V LV Grid Connection

# ▶ MEGALink @ ETH Zürich




$S_N$ = 630kVA
$U_{LV}$ = 400 V
$U_{MV}$ = 10kV

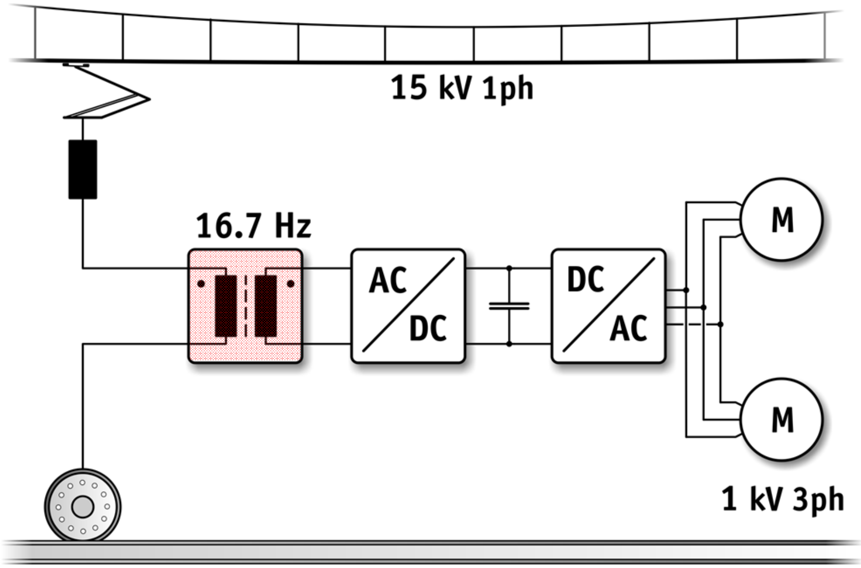
- 2-Level VSI on LV Side / HC-DCM-SRC DC-DC Conversion / Multilevel MV Structure

# Examples of SST Applications

→ Future Traction Vehicles
→ Subsea Power Systems

# ▶ Electric Railway Systems – Today's Drive Scheme

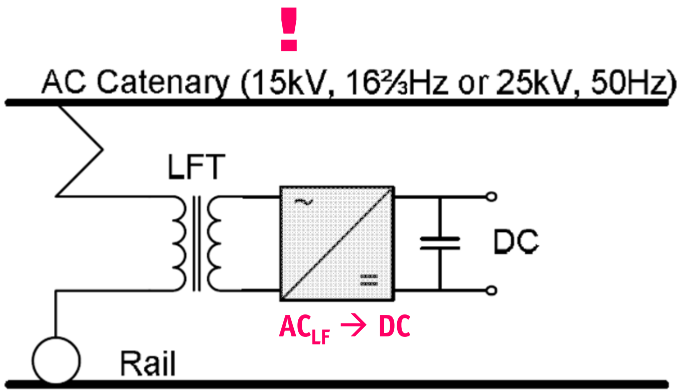
- 16.7Hz 1ph.-Transformer Required to Step-Down the Catenary Voltage to the Drive's Operating Voltage



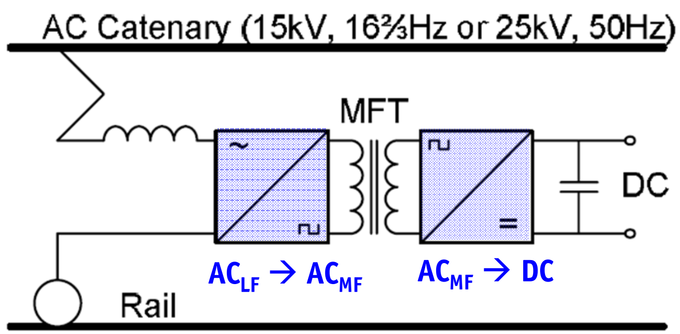

- Low Frequency Transformer
  - 15% Weight of Locomotive
  - e.g. for 2MW ca. 3000kg
  - 90-92% Efficiency

# ▶ SST Application I - Next Generation Locomotives

- Trends
  * Distributed Propulsion System → Weight Reduction (pot. Decreases Eff.)
  * Energy Efficient Rail Vehicles → Loss Reduction (would Req. Higher Volume)
  * Red. of Mech. Stress on Track → Mass Reduction (pot. Decreases Eff.)




*Conventional AC-DC conversion with a line frequency transformer (LFT).*

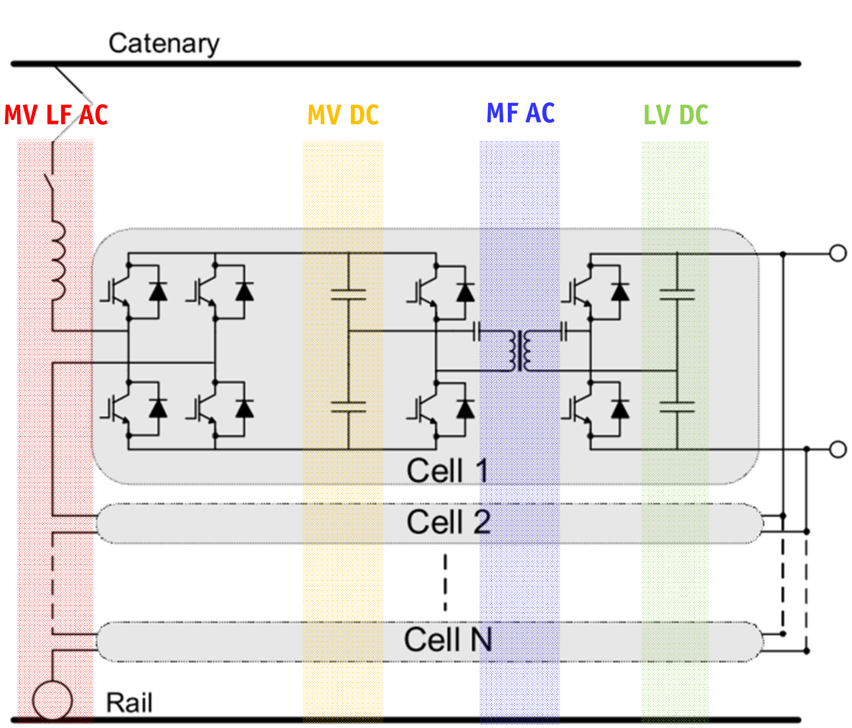


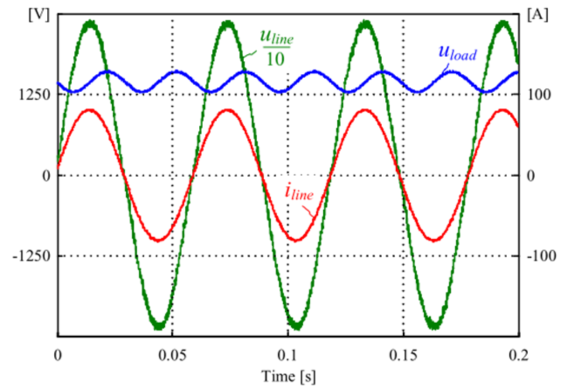

*AC-DC conversion with medium frequency transformer (MFT).*

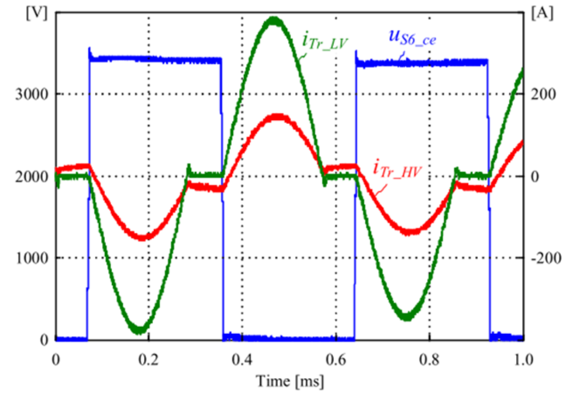
- Replace Low Frequency Transformer by *Medium Frequ.* (MF) Power Electronics Transformer (PET)
- Medium Frequ. Provides Degree of Freedom → Allows Loss Reduction *AND* Volume Reduction
- El. Syst. of Next Gen. Locom. (1ph. AC/3ph. AC) represents Part of a 3ph. AC/3ph. AC SST for Grid Appl.

# ▶ ABB 1ph. AC/DC Power Electronic Transformer I

- Dujic / Zhao (ABB, 2011)

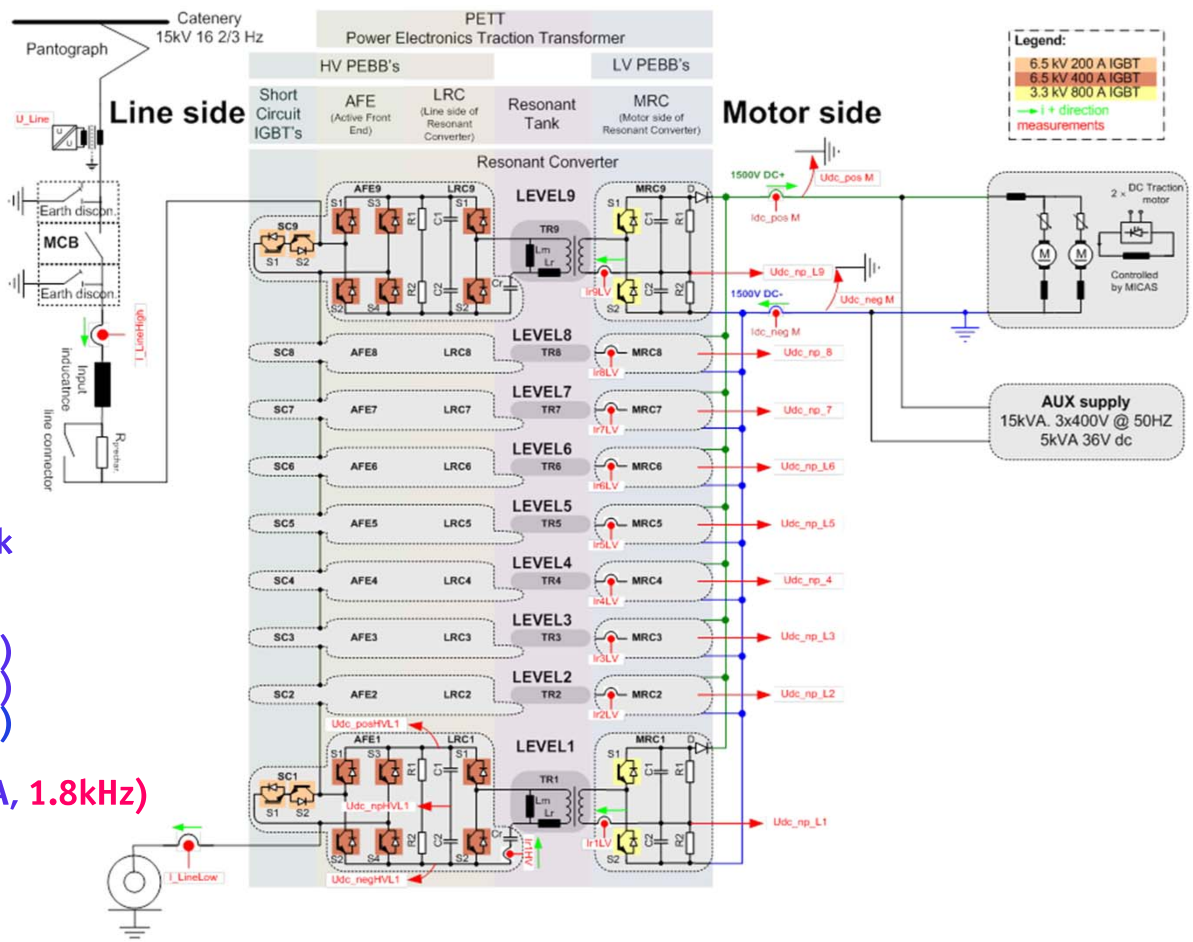



- Cascaded H-Bridges & Resonant LLC DC/DC Converter Stages

# ▶ ABB 1ph. AC/DC Power Electronic Transformer II



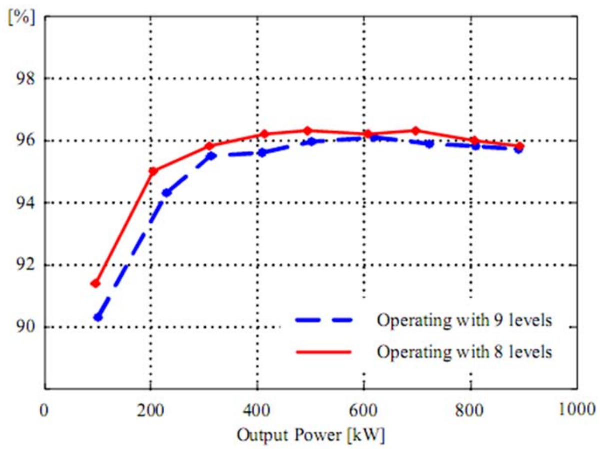

**P = 1.2MVA, 1.8MVA pk**
**9 Cells (Modular)**

**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 1.2 MVA 1ph. AC/DC Power Electronic Transformer III

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




# ▶ SST Application II - Subsea Oil and Gas

Source: ABB
Devold 2012

- ABB Future Subsea Power Grid → "Develop all Elements for a Subsea Factory"

# ▶ SST Application II - Subsea Oil and Gas

Source: ABB
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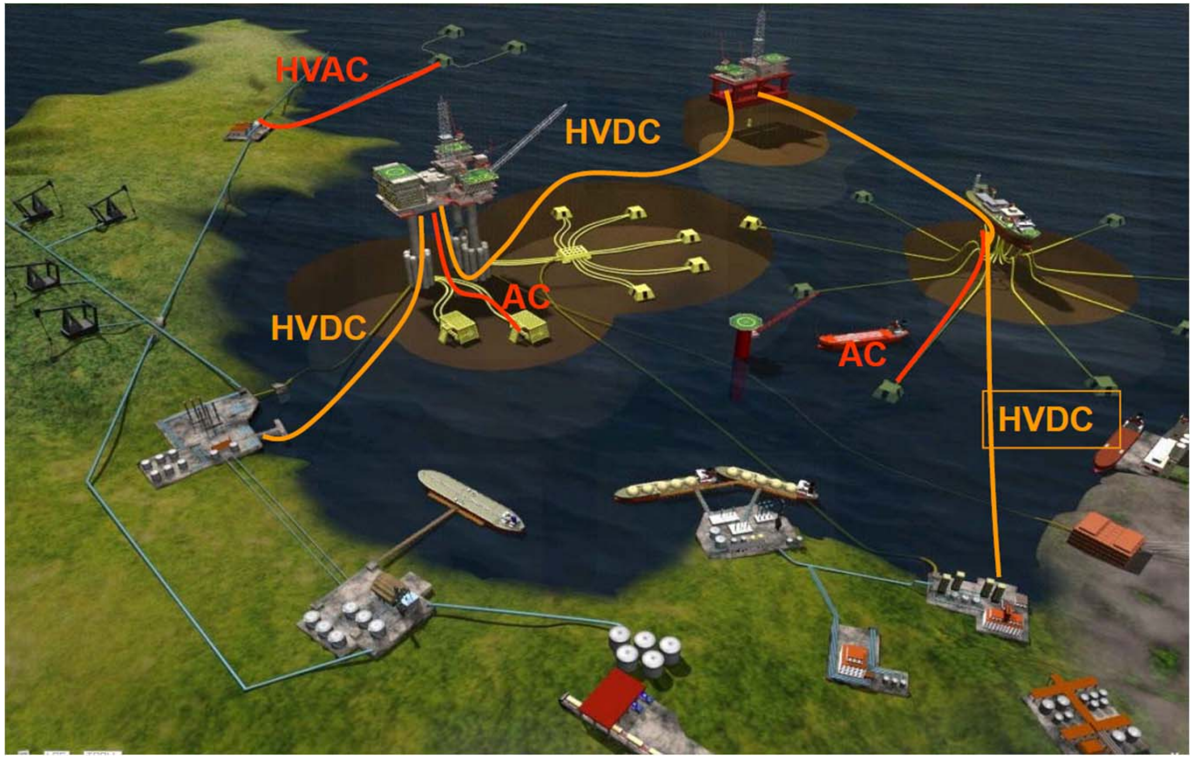
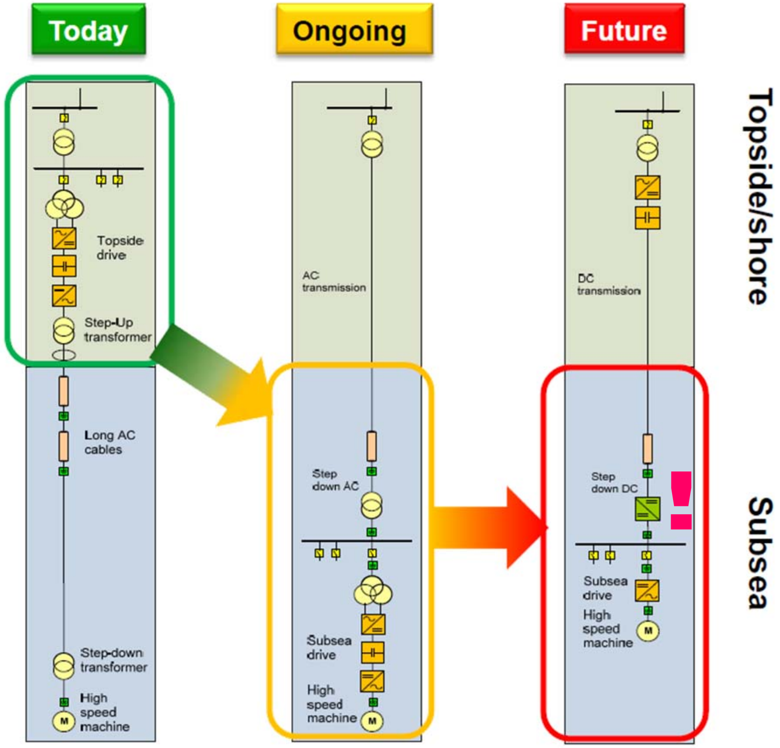



■ ABB Future Subsea Power Grid → "Develop all Elements for a Subsea Factory"

# ▶ SST Application II - Subsea Oil and Gas

Source: ABB / Devold 2012

- Future Subsea Distr. Network for Oil & Gas Processing




- DC Transmission, No Platforms/Floaters
- Longer Distances Possible

■ Weight Opt. / Pressure Tol. Power Electronics

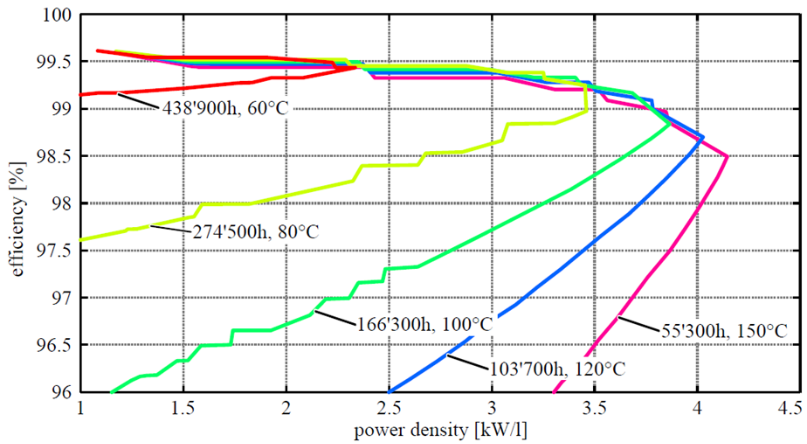
# SST Reliability / Protection

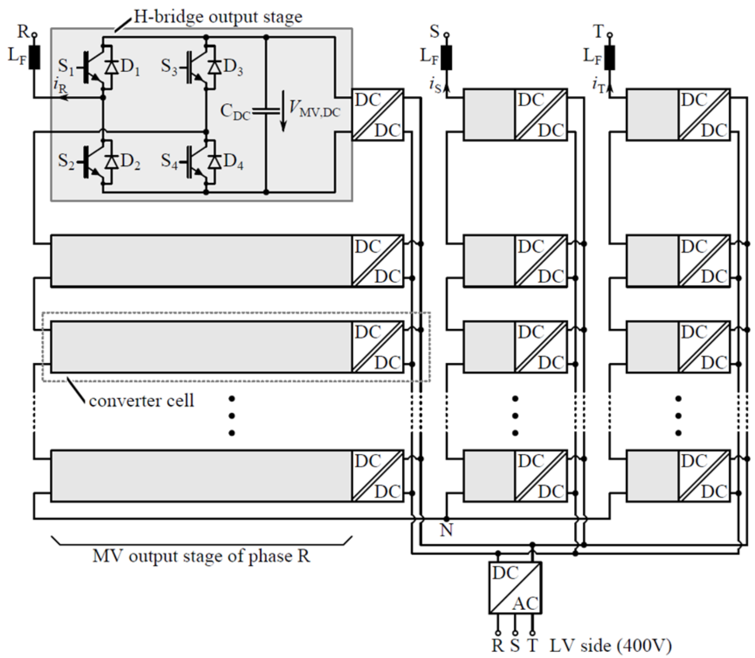
→ Multi-Level vs. WBG Semiconductors
→ Overcurrent Requirements

# ▶ Trade-Off - Reliability / Power Density / Efficiency

## - Reliability / Power Density Pareto Front

(5 Casc. H-Bridges, 1700V IGBTs, No Red.,
FIT-Rate calculated acc. to *Tj*, 100FIT Base)

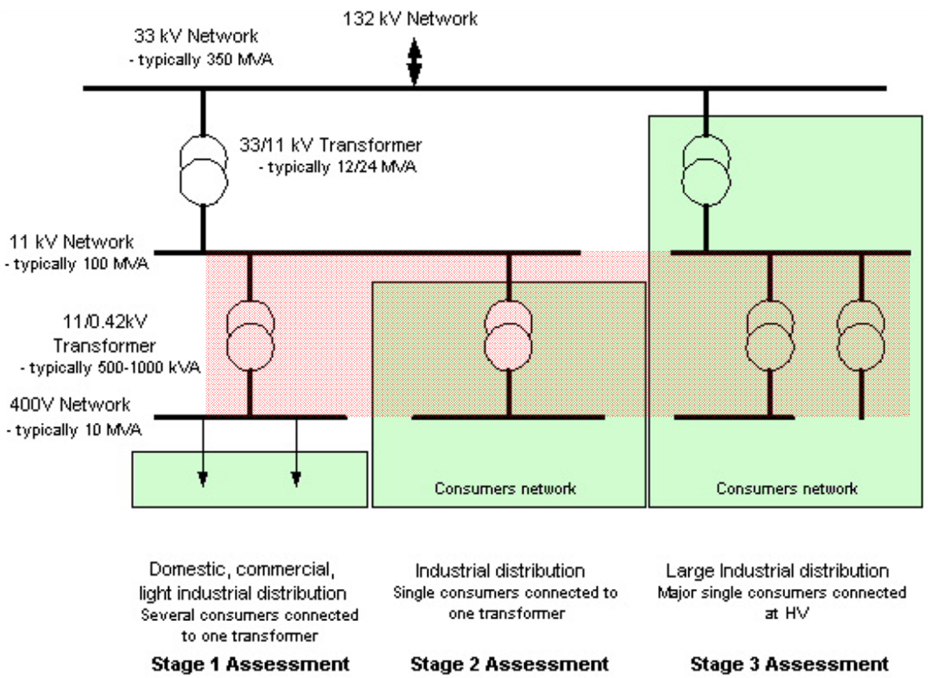



- Equivalent 2-Level SiC Converter → 15.5kA/us & 1.1MV/us (!) for Equal Switching Losses

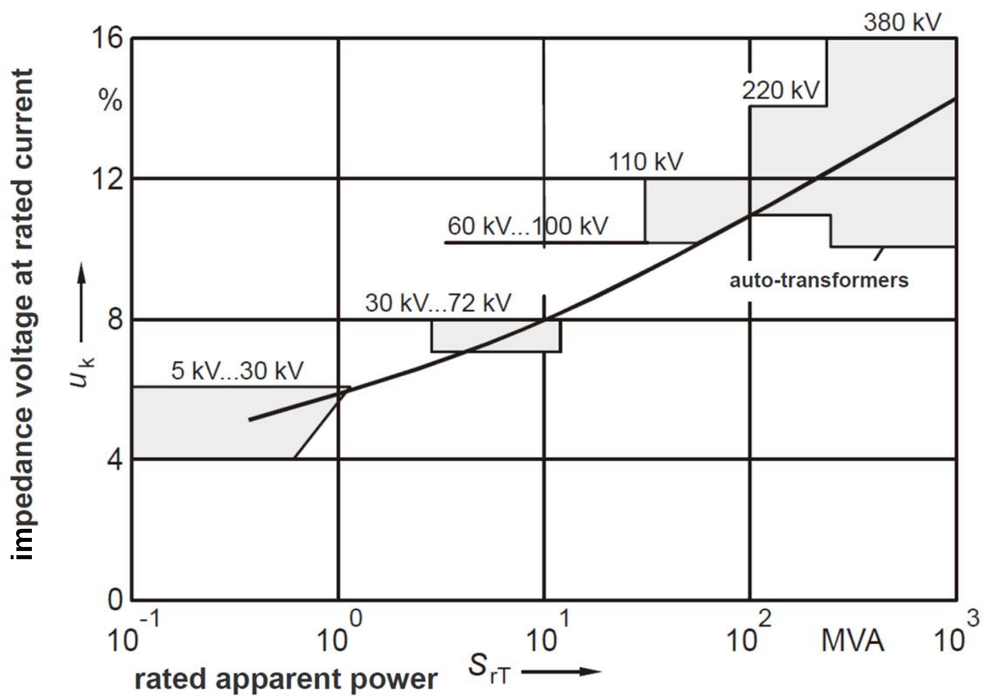
# SST Protection Challenge – Overcurrent Requirements I

- MV Transformers must Provide Short-Circuit Currents of up to 40 Times Nominal Current for 1.5 Seconds (EWZ, 2009)
- Traction Transformers: 150% Nominal Power for 30 Seconds (Engel 2003)
- Power Electronics: Very Short Time Constants !



# ▶ SST Protection Challenge – Overcurrent Requirements II

Source: Oswald
Uni Hannover



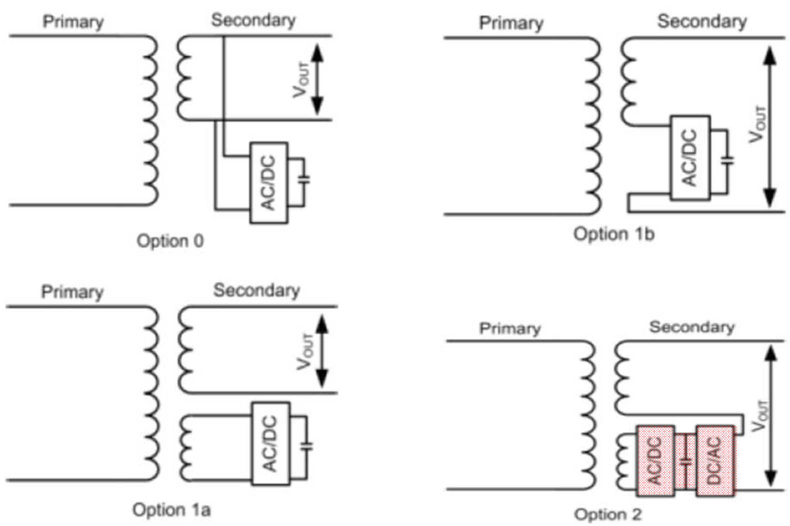

■ Lower Grid Voltage Levels → Higher Relative Short Circuit Currents

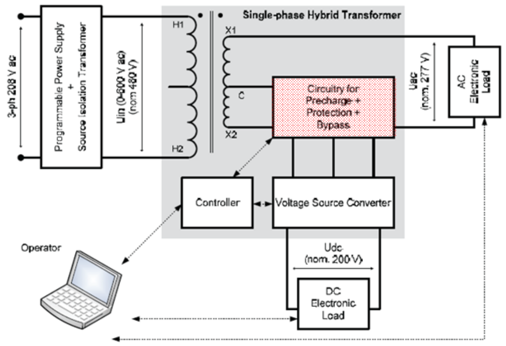
# Hybrid SST Concepts

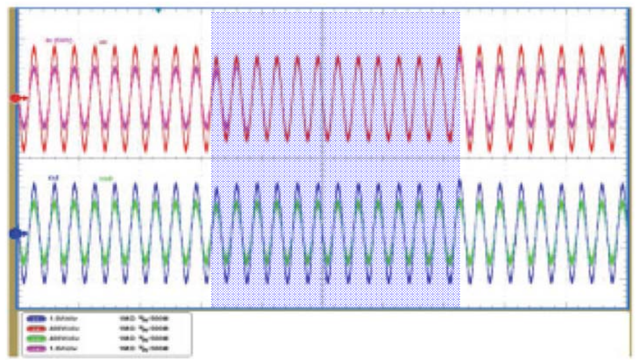
→ LF Transformer (!)
→ Power Quality Enhancement

# ▶ Hybrid Distribution Transformer

Source: ABB/Bala 2012



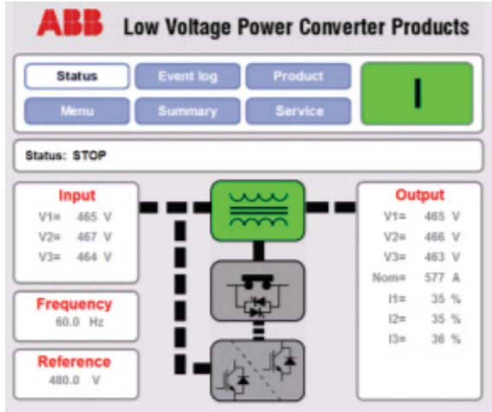



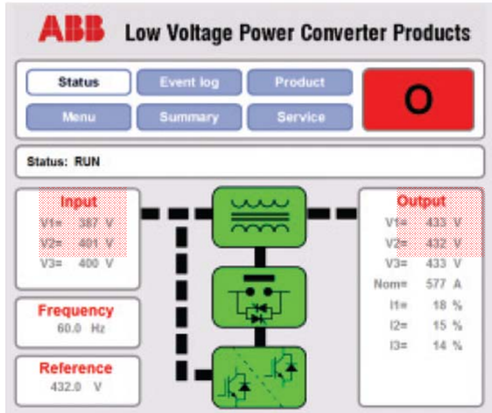



- Reactive Power Compensation (Power Factor Correction, Active Filter, Flicker Control)
- $5^{th}$ and $7^{th}$ Harmonics Compensation by proper Selection of Vector Group
- Available DC Port (Isolated in Option 1a)
- Option 2: Controlled Output Voltage

# ▶ Hybrid Distribution Transformer

Source: ABB/Bala 2012

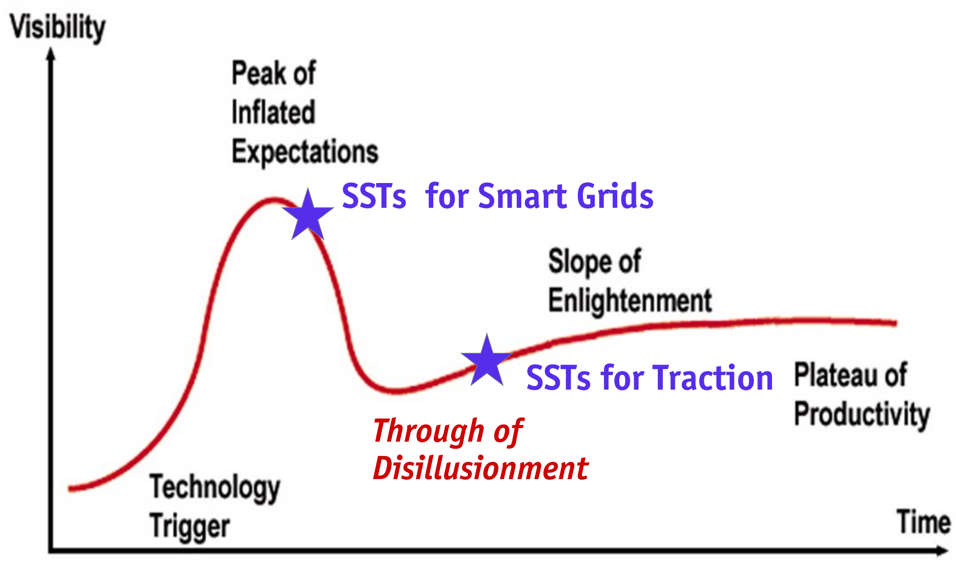




- Commercial Product (ABB)
- Direct Connection of Input to Output (Bypass) or
- Compensation of Inp. Voltage Sag (Contr. Output Voltage)

# ▶ Critical Remark I - Technology Hype Cycle

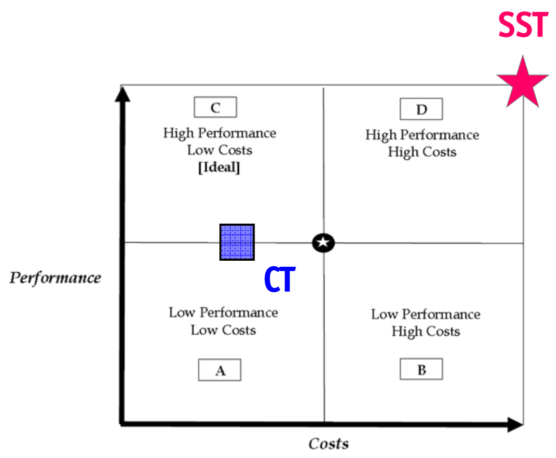
- Different States of Development of SSTs for Smart Grid and Traction Applications



# ▶ Critical Remark II - Limitations / Applications

## ■ SST Limitations

- Efficiency (Rel. High Losses 3-6%)
- High Costs (Cost-Performance Ratio still to be Clarified)
- Limited Volume Reduction vs. Conv. Transf. (Factor 2-3)
- Limited Overload Capability
- (Reliability)



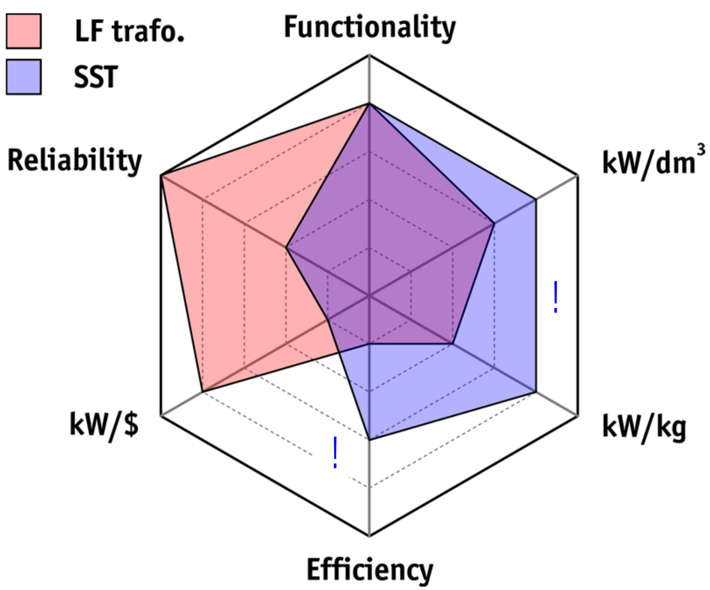

## ■ Potential Application Areas

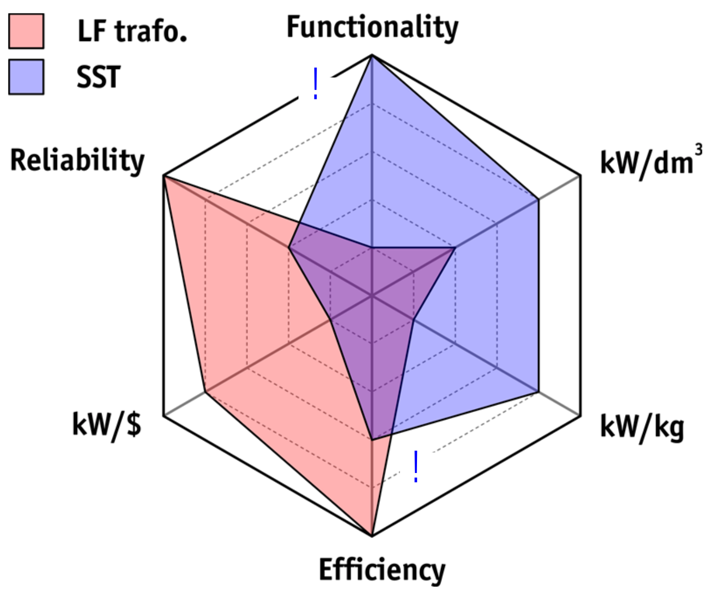
▶ Replacement of Multi-Stage Conversion System (Efficiency Margin) or DC Grids

▶ Applications for Volume/Weight Limited Systems where 3-4 % of Losses Could be Accepted

- Traction Vehicles
- UPS Functionality with MV Connection
- Temporary Replacement of Conv. Distribution Transformer
- Parallel Connection of LF Transformer and SST (SST Current Limit – SC Power does not Change)
- Military Applications

# ► Application Areas → SST Advantages /Weaknesses




■ Traction - LF Transf. vs. SST

■ Distribution - LF Transf. vs. SST

## ▶ Main SST Optimization Potential

- Cost & Complexity Reduction by Functionality Limitation (e.g. Unidirectional Power Flow)

## ▶ Future Research Topics

- Insulation Materials under MF Voltage Stress
- Low Loss High Current MF Interconnections
- MF Transformer Construction featuring High Insulation Voltage
- Thermal Management (Air and $H_2O$ Cooling, avoiding Oil)
- "Low" Voltage SiC Devices for Efficiency Improvement

- Multi-Level vs. Two-Level Topologies with SiC Switches → "Optimum" Number of Levels
- Multi-Objective Cost / Volume / Efficiency/ Reliability Optimization (Pareto Surface)
- SST Protection (e.g. Overvoltage)
- SST Reliability

- Hybrid (LF // SST) Solutions
- SST vs. FACTS (Integration vs. Combination of Transformer and Power Electronics)
- System-Oriented Analysis → Clarify Benefits on System Level (Balancing the Low Eff. Drawback)

# Challenges of Smart Grid Realization

→ Technologies
→ Reliability
→ Costs

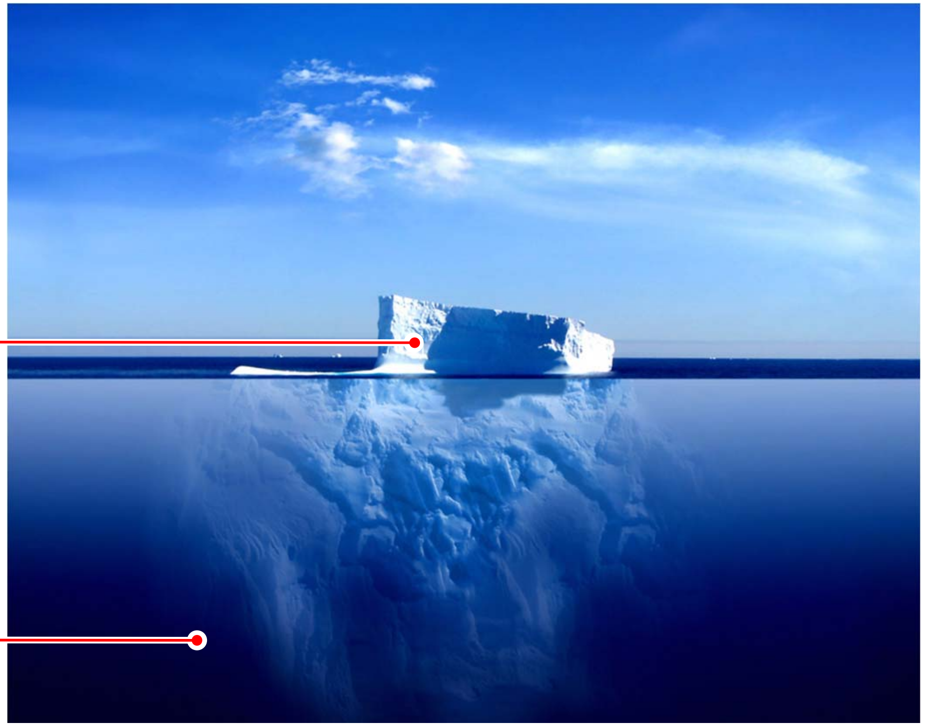
# ▶ Challenges of Smart Grid Realization I

- **Engineering Challenge** → Competence in
  - Power Systems
  - Power Electronics
  - ICT
  - etc.
- **Technological Challenge**
  → Power Converters (WBG, Modular, Scalable)
  → Control Concepts (Autonom. Cntrl etc.)
  → New Protection / Monitoring Concepts
  → etc.
- **Economic Challenges**
  → Standardization (Power Electr., ICT)
  → Forecasting / Planning
  → Establish Business Models
  → etc.
- **Operation Challenge**
  → Grid Stability
  → Reliability
  → Data Security (!)
  → etc.

## ▶ Challenges of Smart Grid Realization II

Done !

To be Done...



- Huge *Multi-Disciplinary* Challenges / Opportunities (!) are Still Ahead

# Questions ?