Center for Power Electronics Systems
The Bradley Department of Electrical and Computer Engineering
College of Engineering


Virginia Tech, Blacksburg, Virginia, USA

Advanced High-Megawatt Converters for New Grid Architectures

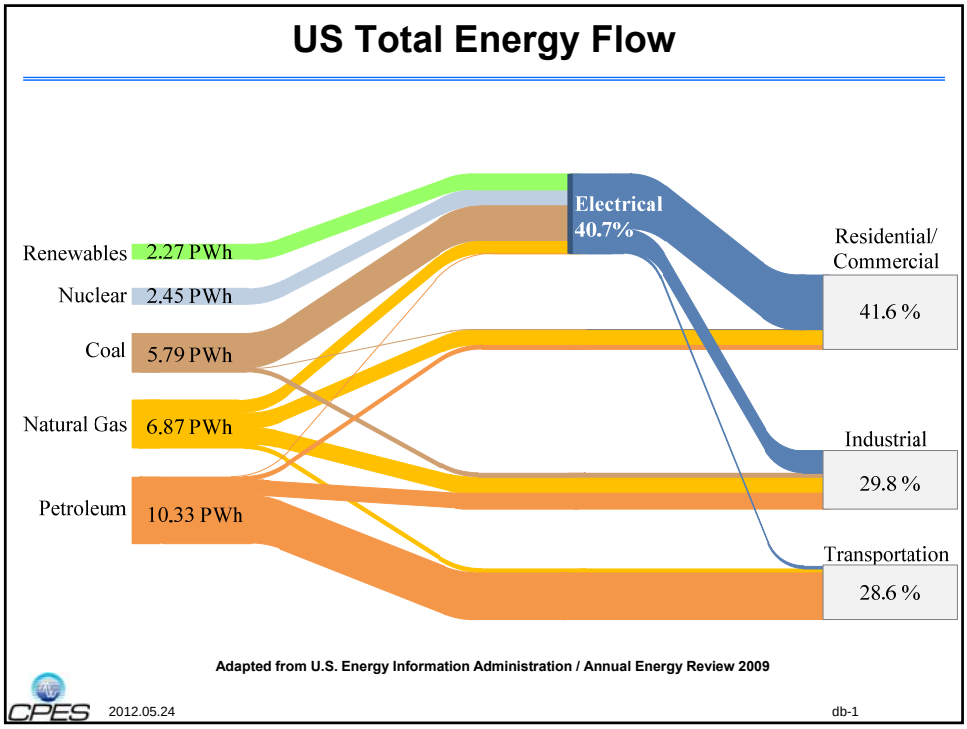
Dushan Boroyevich

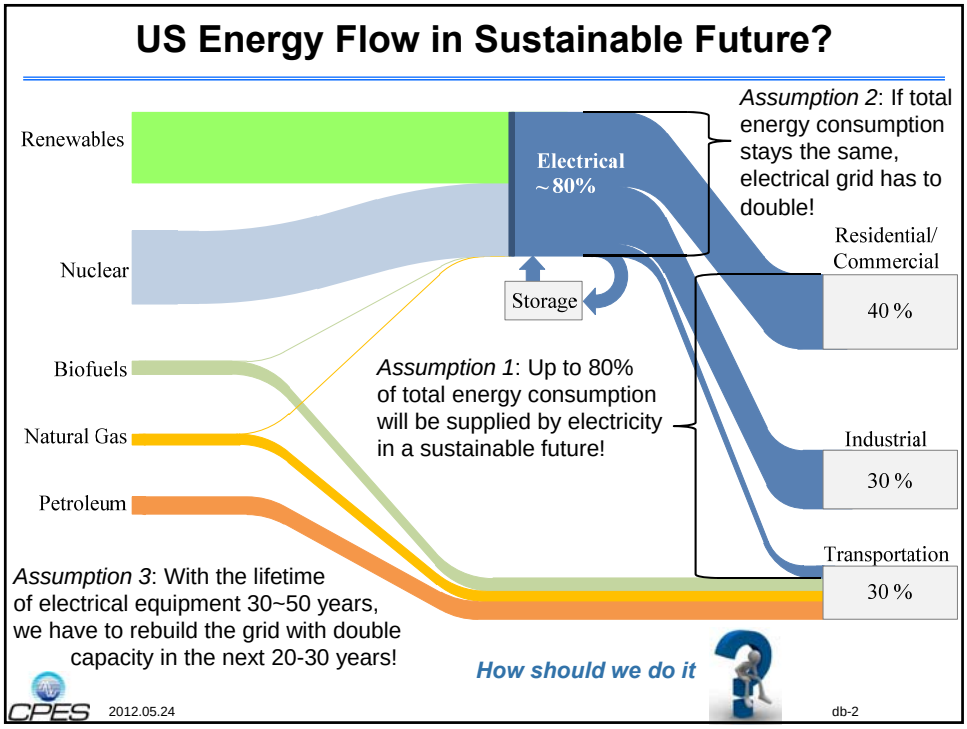
Presentation at
High Megawatt Power Conditioning System Workshop

Technology Roadmap
for Increased Power Electronic Grid Applications and Devices

NIST
Gaithersburg, Maryland

2012.05.24


US Total Energy Flow
Renewables 2.27 PWh
Nuclear 2.45 PWh
Coal 5.79 PWh
Natural Gas 6.87 PWh
Petroleum 10.33 PWh
Electrical 40.7%
Residential/ Commercial
41.6 %
Industrial
29.8 %
Transportation
28.6 %
Adapted from U.S. Energy Information Administration / Annual Energy Review 2009
CPES
2012.05.24
db-1


US Energy Flow in Sustainable Future?
Renewables
Nuclear
Biofuels
Natural Gas
Petroleum
Electrical ~80%
Storage
Assumption 2: If total energy consumption stays the same, electrical grid has to double!
Residential/ Commercial
40 %
Industrial
30 %
Transportation
30 %
Assumption 1: Up to 80% of total energy consumption will be supplied by electricity in a sustainable future!
Assumption 3: With the lifetime of electrical equipment 30~50 years, we have to rebuild the grid with double capacity in the next 20-30 years!
How should we do it
CPES
2012.05.24
db-2

Most of Electricity is Consumed by Electronic Loads

Residential/Commercial

Industrial

Transportation

CPES 2012.05.24

Electronic loads are constant-power loads.

db-3

More Electricity is Supplied by Electronic Sources

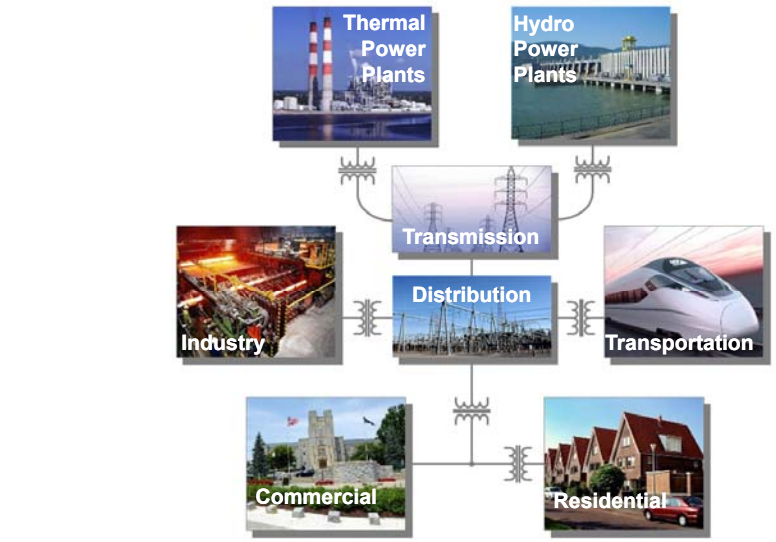
Renewable Generation

Energy Storage

CPES 2012.05.24

db-4

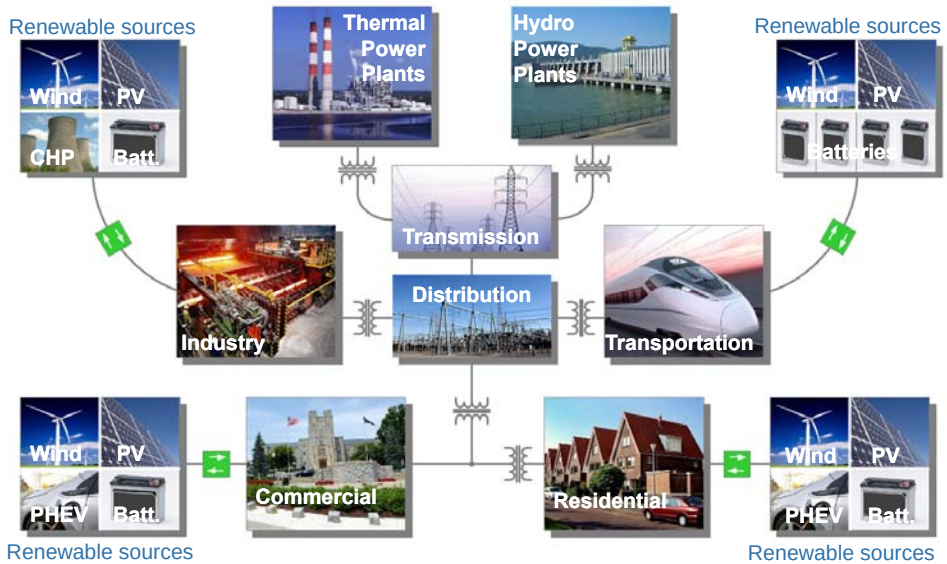
20th Century Grid



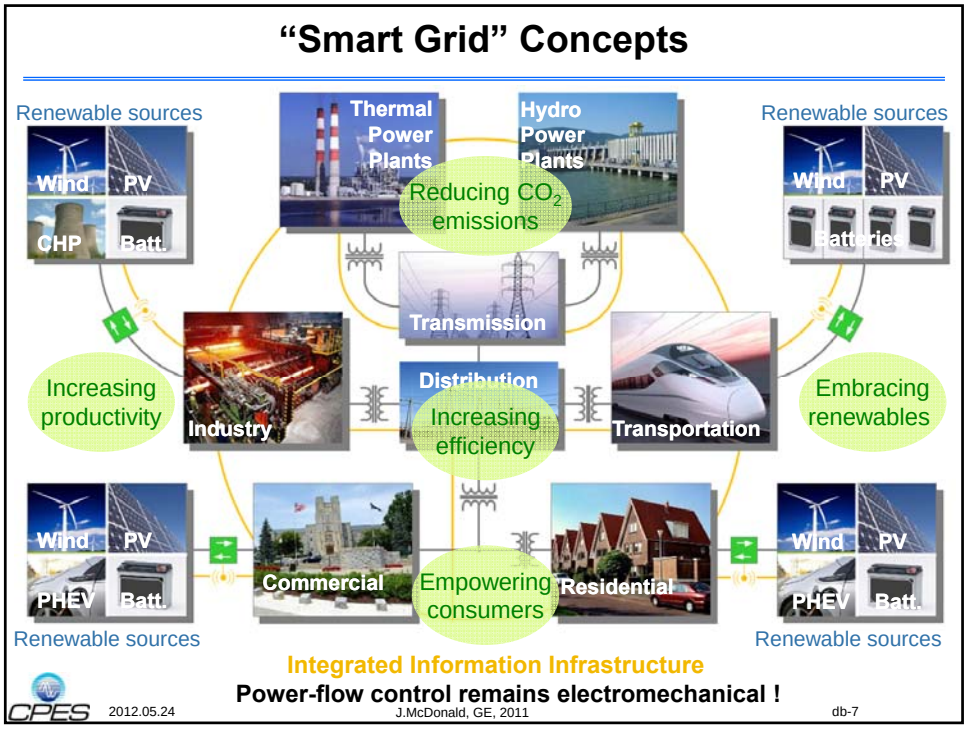
Generation (Centralized)
Transmission (Mesh)
Distribution (Radial Network)

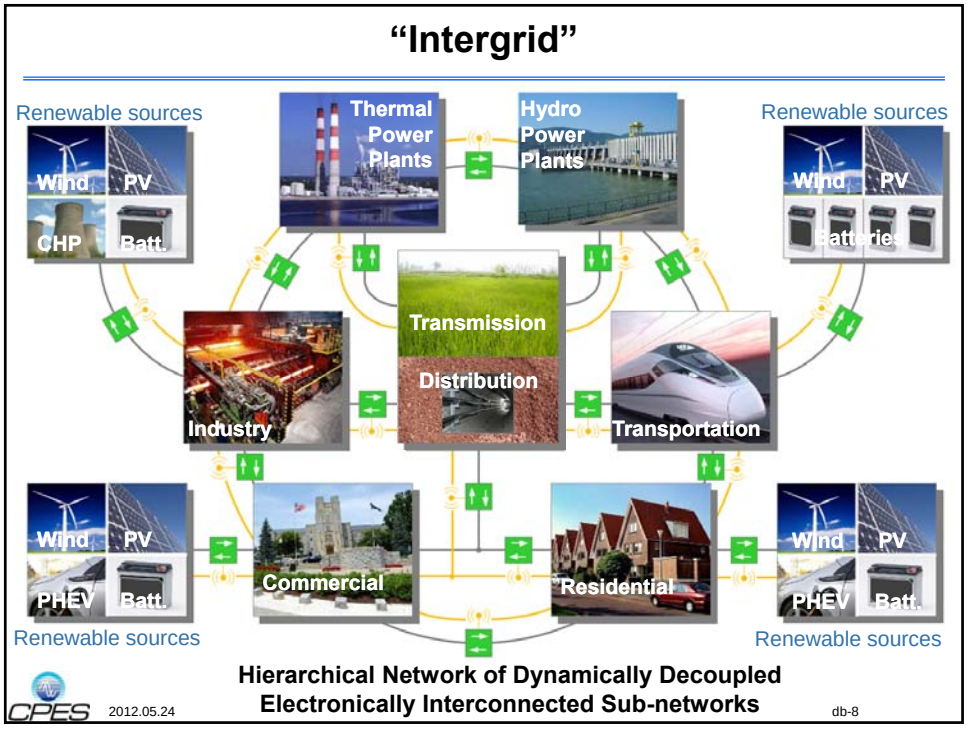
CPES 2012.05.24 db-5

21st Century Grid?

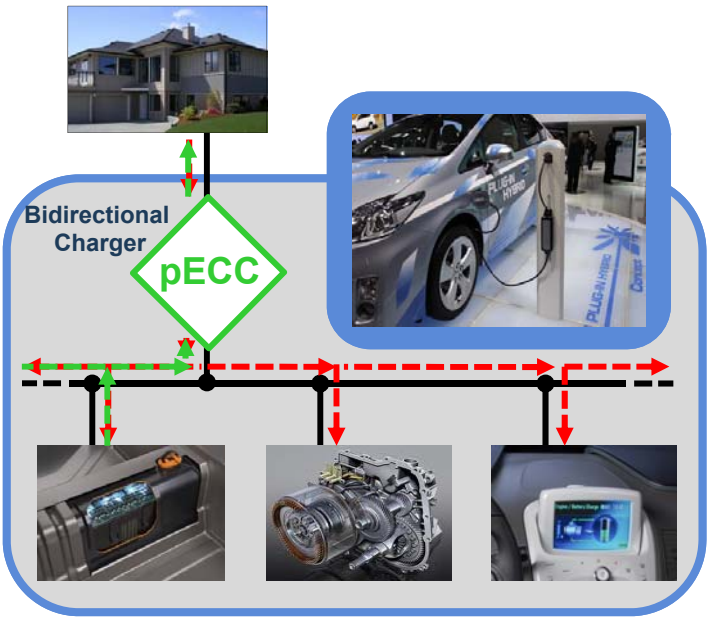


CPES 2012.05.24 db-6

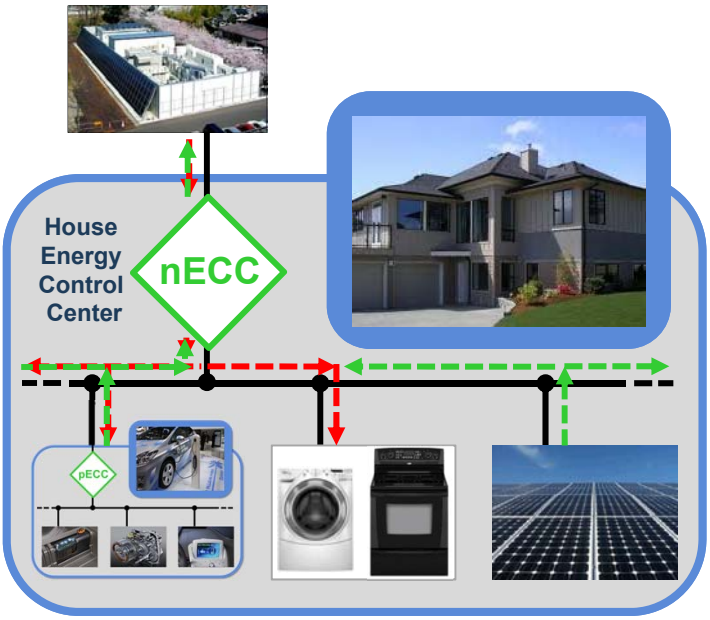

"Smart Grid" Concepts
Renewable sources
Wind
PV
CHP
Batt.
Thermal Power Plants
Hydro Power Plants
Reducing CO_2 emissions
Renewable sources
Wind
PV
Batteries
Transmission
Distribution
Increasing productivity
Industry
Increasing efficiency
Transportation
Embracing renewables
Wind
PV
PHEV
Batt.
Commercial
Empowering consumers
Residential
Wind
PV
PHEV
Batt.
Renewable sources
Renewable sources
Integrated Information Infrastructure
Power-flow control remains electromechanical !
CPES
2012.05.24
J.McDonald, GE, 2011
db-7


"Intergrid"
Renewable sources
Wind
PV
CHP
Batt.
Thermal Power Plants
Hydro Power Plants
Renewable sources
Wind
PV
Batteries
Transmission
Distribution
Industry
Transportation
Wind
PV
PHEV
Batt.
Commercial
Residential
Wind
PV
PHEV
Batt.
Renewable sources
Renewable sources
Hierarchical Network of Dynamically Decoupled
Electronically Interconnected Sub-networks
CPES
2012.05.24
db-8

Plug-in Hybrid Electric Vehicle (picoGrid)



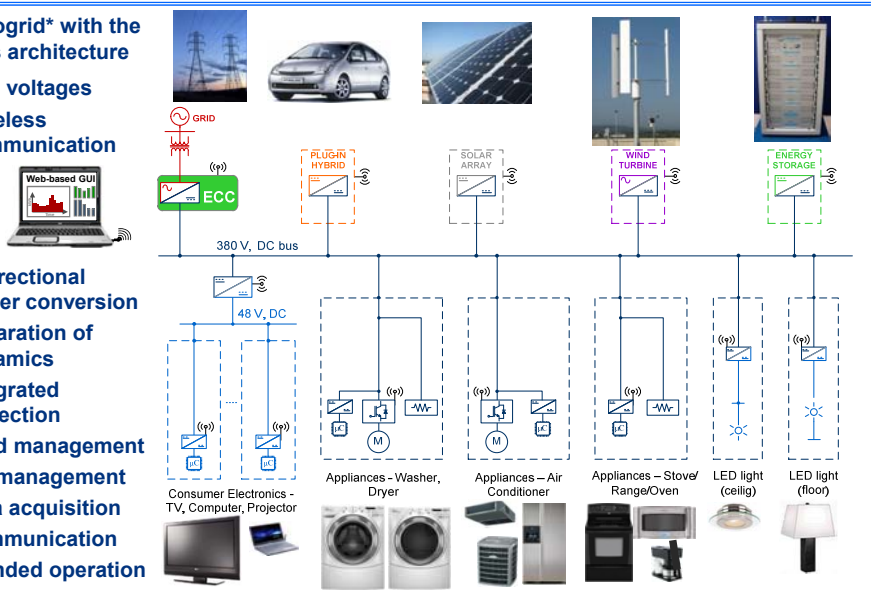
A house (nanoGrid)



Home DC nano-Grid Experiment at CPES

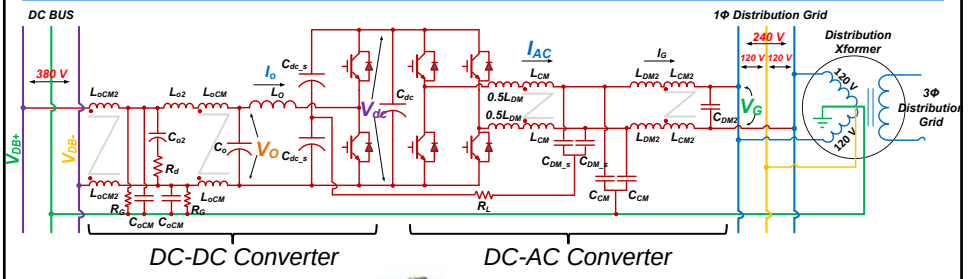
Nanogrid* with the bus architecture

- Two voltages
- Wireless communication
- Bidirectional power conversion
- Separation of dynamics
- Integrated protection
- Load management
- DG management
- Data acquisition
- Communication
- Islanded operation



CPES 2012.05.24 * J. Bryan, R. Duke, S. Round, 2003 db-11

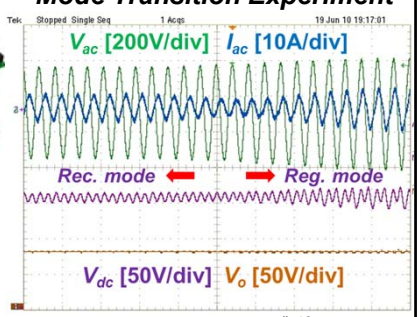
Single-phase nano - Energy Control Center



10 kW, 20 kHz CPES Prototype

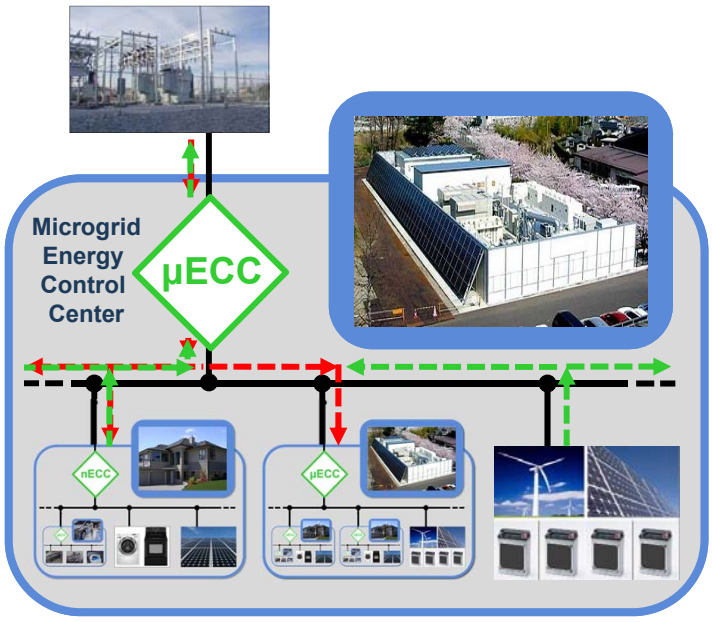
- Bi-directional topology
- Bi-dir. control system
- Bi-dir. current limit
- Bi-dir. EMI compatibility
- Low dc leakage current
- Low cost, high density

Mode Transition Experiment



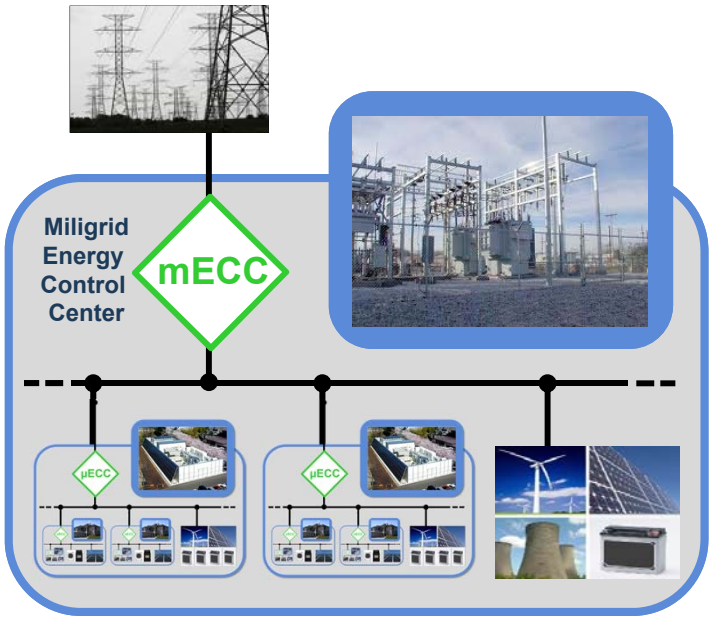
CPES 2012.05.24 db-12

Microgrid



CPES 2012.05.24 db-13

Miligrid

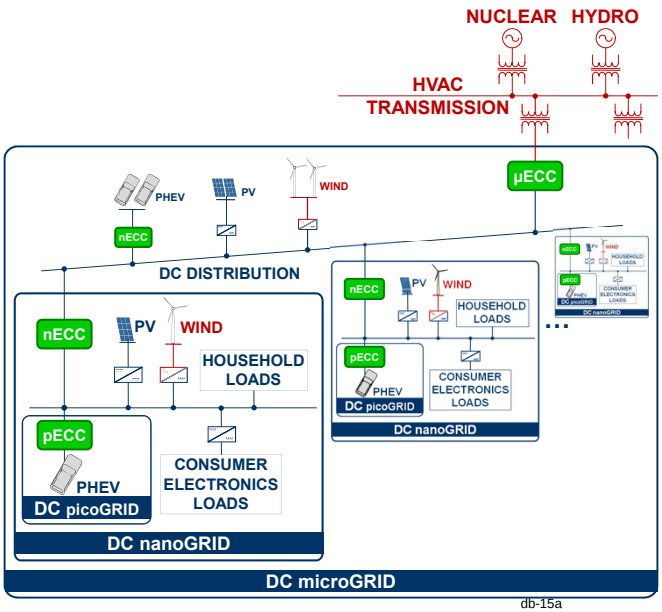


CPES 2012.05.24 db-14

¿ Intergrid ?

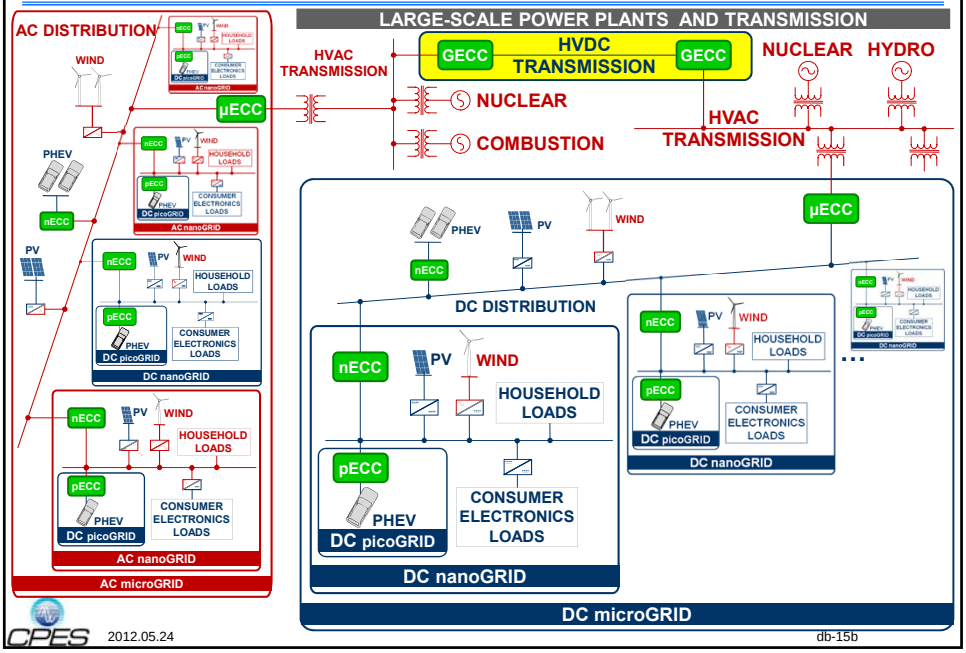
Main features:

- At least minimal level of local energy generation and storage;
- Interfaces to the higher-level system through bidirectional power converters;
- Ability to operate in islanded mode;
- Extensive communication and control capabilities;
- No thermo-mechanical switchgear;
- Step-up/down and isolation functions provided by the power converters (no low-frequency transformers);



CPES 2012.05.24 db-15a

Intergrid: Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks

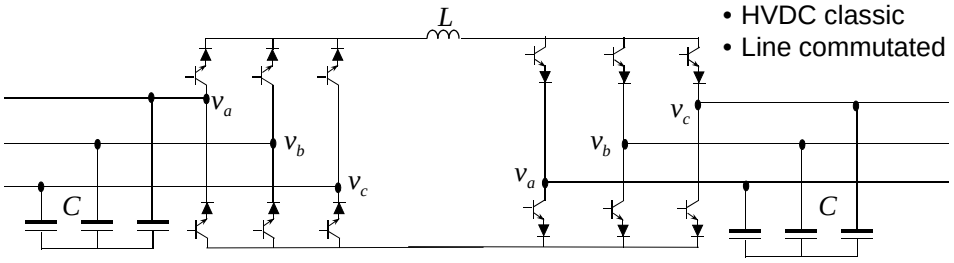


CPES 2012.05.24 db-15b

Basic Topologies for High-Power ECCs

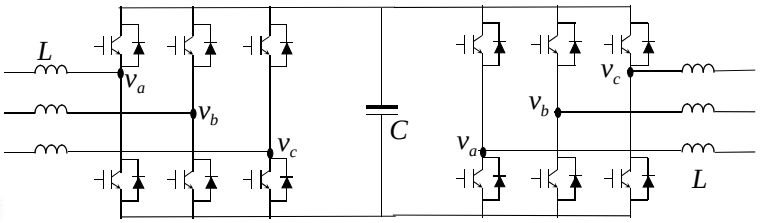
Current Source Converter

- Thyristor-based
- HVDC classic
- Line commutated



Voltage Source Converter

- IGBT-based
- HVDC light



CPES 2012.05.24 db-16

Recent Paper in *Proceedings of the IEEE*

Vol. 100, No. 2, February 2012 *

INVITED PAPER

State of the Art in Ultrahigh-Voltage Transmission

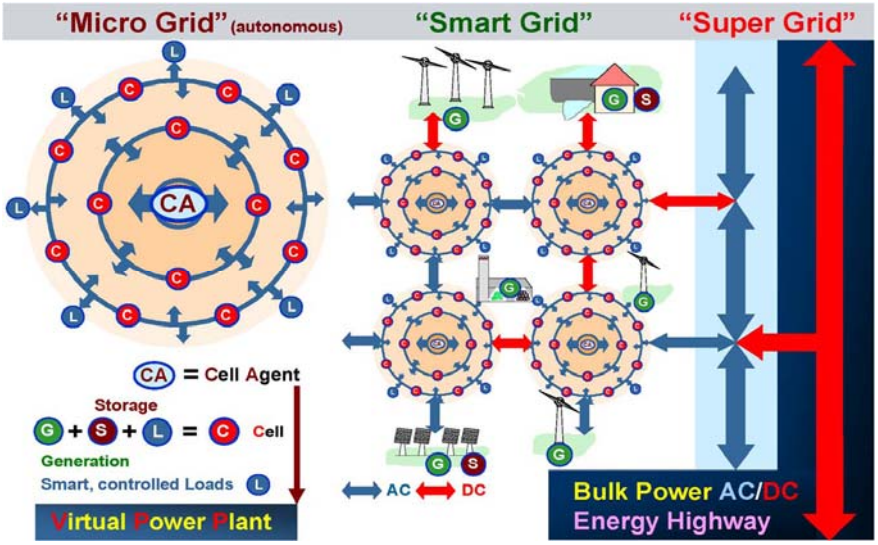
This paper discusses ultrahigh-voltage (UHV) DC as an efficient solution for bulk power transmission, especially of renewable energy.

By Thomas James Hammons, *Fellow IEEE*, Victor F. Lescale, *Life Member IEEE*, Karl Uecker, Marcus Haeusler, Dietmar Retzmann, *Member IEEE*, Konstantin Staschus, *Senior Member IEEE*, and Sébastien Lepy

CPES 2012.05.24 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. db-17

Fig. 10. Prospects of grid developments.

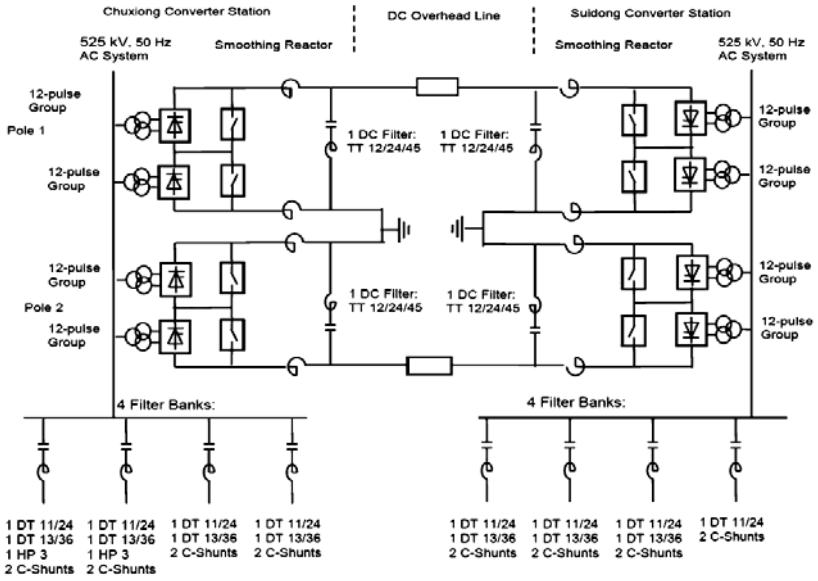
Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.



CPES 2012.05.24 db-18

Fig. 23. Single line diagram of Yunnan-Guangdong UHV DC system.

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.



CPES 2012.05.24 db-19

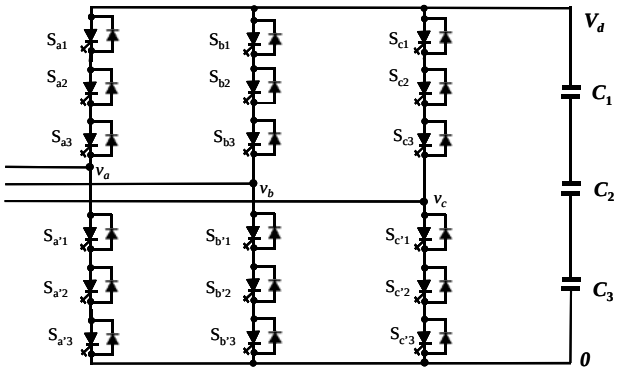
Fig. 26. ***A view of the thyristor valve towers in the 800-kV valve hall.***

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.

Fig. 27. ***800-kV converter transformer (single-phase two winding).***

Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012.

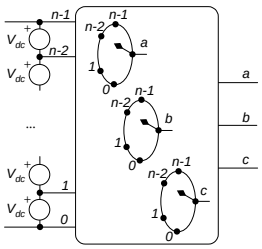
Two-Level Converter for High-Voltage Applications

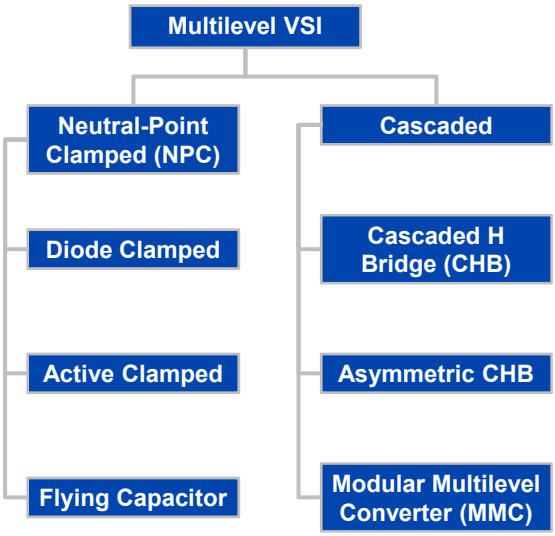


- Difficulty in voltage sharing among devices, especially the voltage sharing during switching transients.
- Needs complex active gate-drives to achieve voltage sharing.

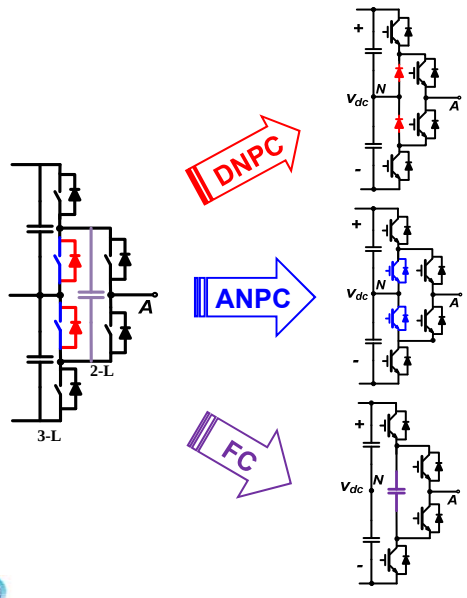
Multilevel Converters for High-Voltage Applications

Functional diagram of Multilevel converter





Multilevel Structures – Capacitor Clamped



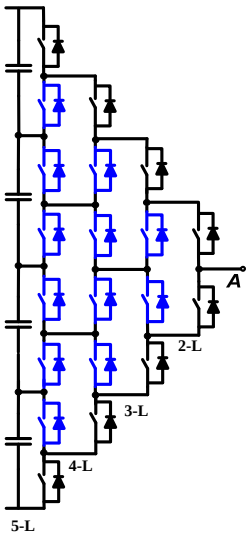
Diode Clamped
- Uneven device losses
- Neutral point voltage balance

Active Clamped
- Even device losses with control
- Neutral point voltage balance

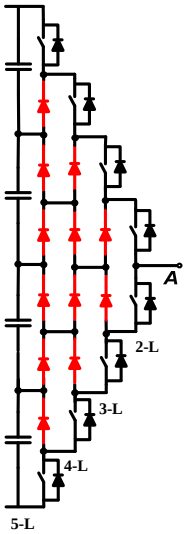
Flying Capacitor
- Uneven device losses
- Neutral point voltage balance
- Clamping cap voltage control

Multilevel Structures – Capacitor Clamped

5-level AC



5-level DC



m-level NPC

DNPC
- Switches: 2× (m-1)
- Diodes: (m-1)×(m-2)

ANPC
- Switches: m×(m-1)

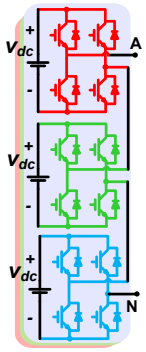
Large number of devices

Complex structure

Cap. Voltage balancing

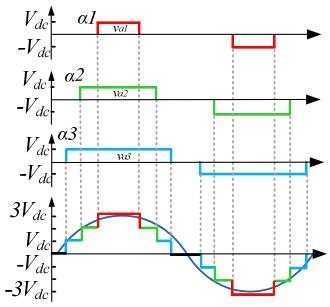
Multilevel Structures – Cascaded H Bridge

Symmetrical CHB



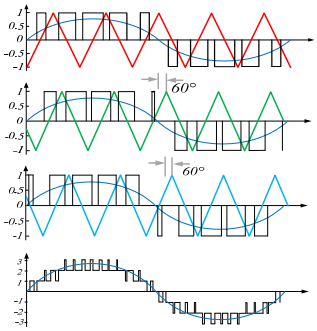
- Module: N
- Level: 2N+1

Low Freq. Modulation



- Loss reduction
- Four commutations
- Uneven conduction

Phase Shift Modulation



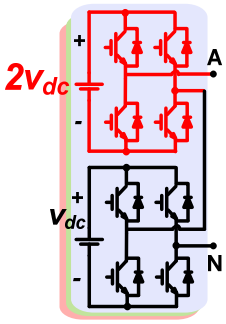
- THD reduction
- Uni-polar modulation
- Even Switching pattern

Highly Scalable Structure

Need Isolated DC Sources

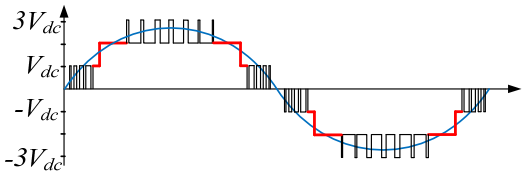
Multilevel Structures – Cascaded H Bridge

Asymmetrical CHB



- Module: N
- Level: $2^{(N+1)}-1$

Hybrid Modulation



- Low freq. for high voltage module: loss reduction
- High freq. for low voltage module: THD reduction

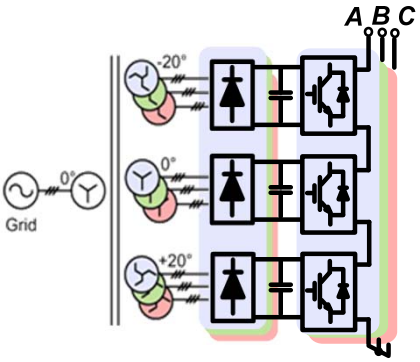
More levels produced

Uneven loss & stress

Loss of some modularity

System Configurations for CHB

Phase Shift Transformer for CHB

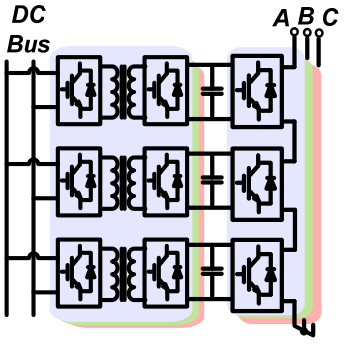


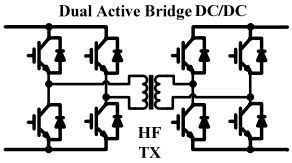
Line frequency magnetics **Good input power quality**

Size, weight, cost issues **Unidirectional operation**

System Configurations for CHB

High Freq. Isolation for CHB

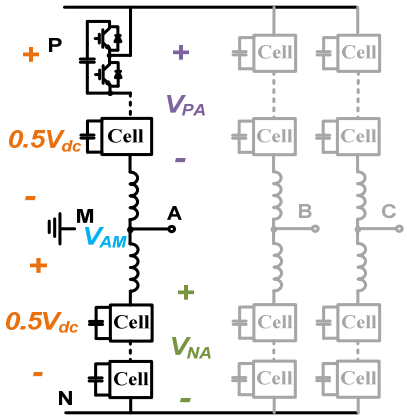




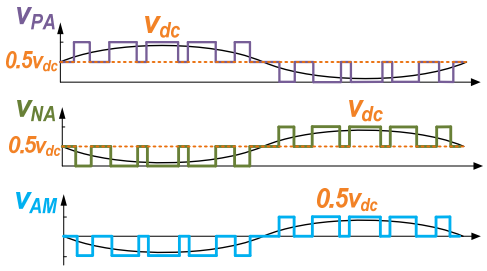
High freq. magnetics **Smaller Size** **Bidirectional Operation** **Highly Scalable**

Extra switches & circuits **High switching loss**

Modular Multilevel Converter (MMC)



Arm Voltage Waveform



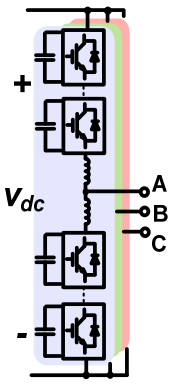
$$V_{AM} = \frac{V_{dc}}{2} - V_{PA} = -\frac{V_{dc}}{2} + V_{NA}$$

$$V_{AM} = \frac{V_{NA} - V_{PA}}{2}$$

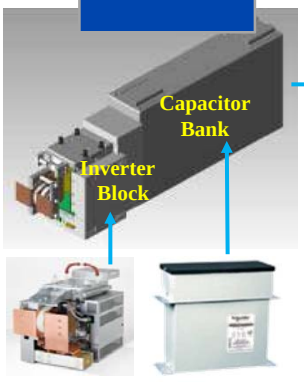
Arm voltage anti-phase

0.5 DC link voltage bias

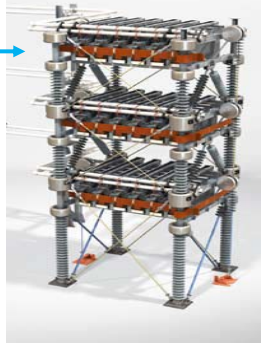
System Configurations for MMC



MMC Module



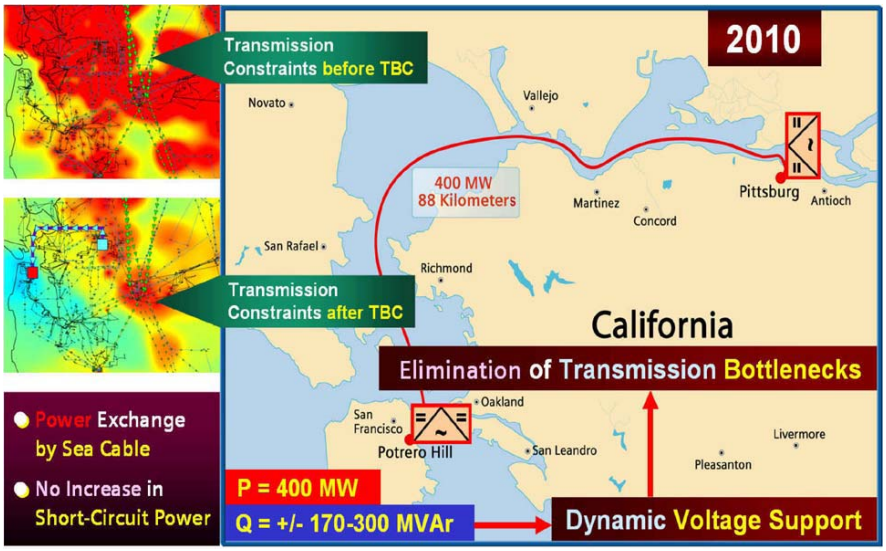
MMC based HVDC



Single DC Source

Large line freq. cap.

Fig. 14. ***The "Trans Bay Cable" project in the United StatesVworld's first VSC HVDC with MMC technology and þ=200-kV XLPE cable. ****



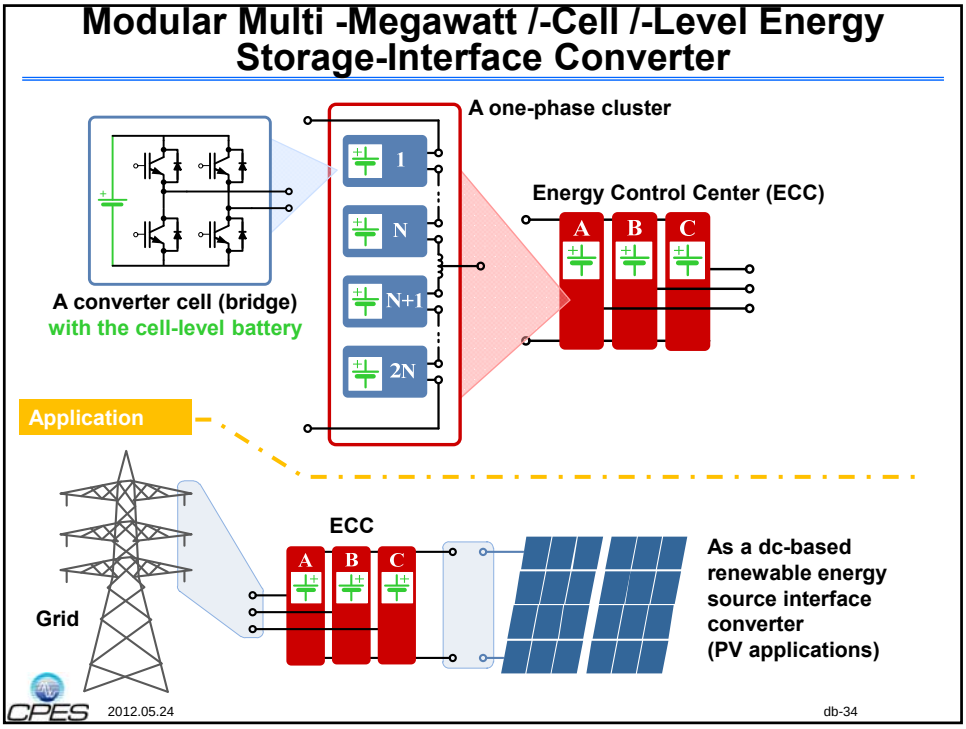
CPES 2012.05.24 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. db-32

Fig. 21. ***Bulk Power Corridor with GILV400-kV installation at Kelsterbach, Germany. ****

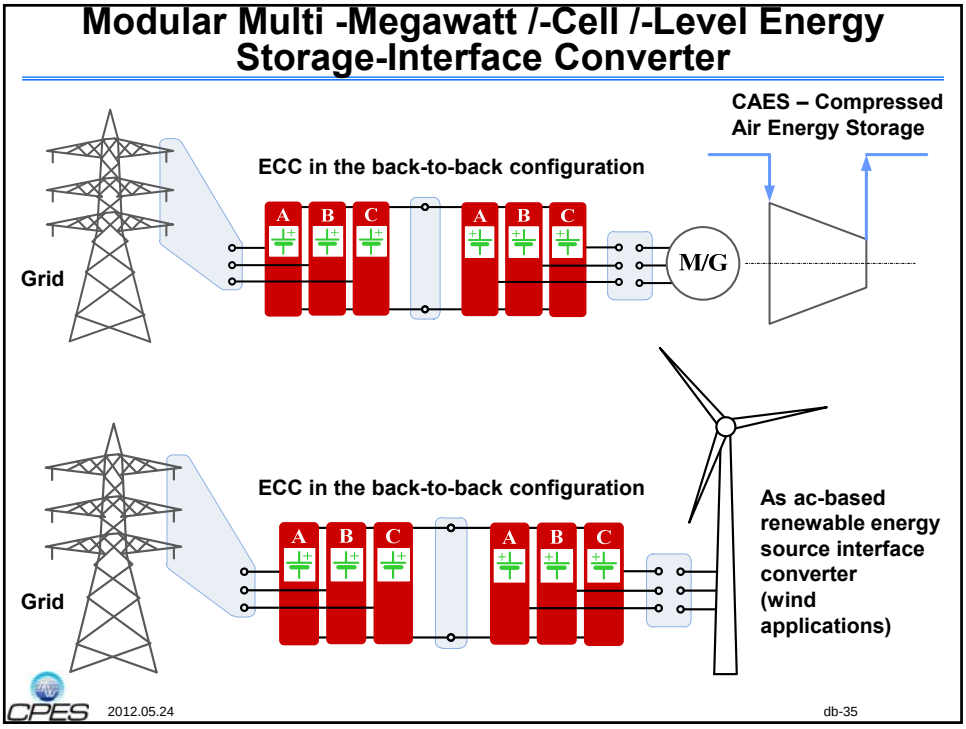
- Customer: Amprion
- Location: Airport Frankfurt
- Award of Contract: July 2008
- Installation: first directly buried GIL
- Transmission Capacity: 2 x 1,800 MVA
- Length of GIL: appr. 1 km
- Gas for Insulation: 80% N2, 20%SF6

CPES 2012.05.24 * Hammons, T. J. et al., "State of the Art in Ultrahigh-Voltage Transmission," *Proc. IEEE*, Vol. 100, No. 2, Feb. 2012. db-33

Modular Multi -Megawatt /-Cell /-Level Energy Storage-Interface Converter



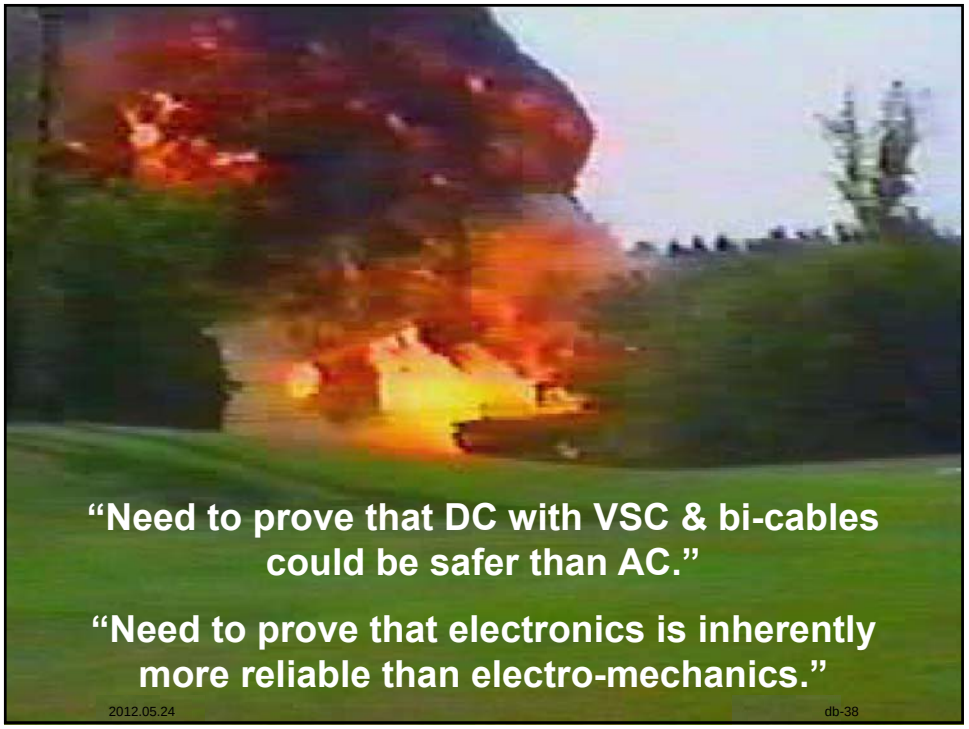
Modular Multi -Megawatt /-Cell /-Level Energy Storage-Interface Converter



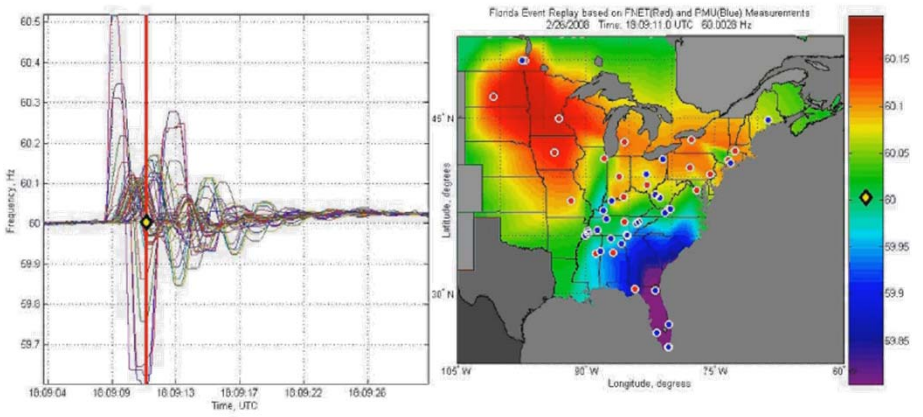
Research Needed to
Replace Electric Energy "Railways" with "Highways"

1. **Network Architectures and Control**
   - Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks
   - Distributed generation, storage, loads, and intelligence
   - Continuous control of all energy flows
   - Enabling of efficient market mechanisms
2. **High-Power and High Power-Density Converters**
   - New materials, active and passive devices, thermal management
   - High-density integration and packaging, especially HIGH-VOLTAGE technologies and UNDERGROUND transmission / distribution
3. **Safety and Reliability**
   - Safety & protection (need to prove that DC with VSC & bi-cables could be safer than AC)
   - Reliability & lifetime (need to prove that electronics is inherently more reliable than electro-mechanics)
   - Security and availability (need to prove that decoupled networks are inherently more robust and resilient)

CPES 2012.05.24 db-36



Frequency Variations during 2008 Florida Blackout



"Need to prove that decoupled networks are inherently more robust and resilient."

Education Needed to Instigate Innovative Intellectual "Ecosystem"

1. **Network Architectures**
   - Hierarchical network of dynamically-decoupled, electronically-interconnected, sub-networks
   - Distributed generation, storage, loads, and intelligence
2. **Energy Transfer Protocols and Markets**
   - Continuous control of all energy flows
   - Enabling of efficient market mechanisms

Computational infrastructure for hierarchical, multidisciplinary, multiscale modeling, analysis, design, and optimization

3. **High-Power and High Power-Density Converters**
   - New materials, active and passive devices, thermal management
   - High-density integration and packaging
4. **Safety and Reliability**
   - Safety & protection
   - Reliability & lifetime

Experimental infrastructure for Hierarchical low- to high-power validation of electronic control of energy traffic

Need new engineers = power + electronics