CPES

Center for Power Electronics Systems

A National Science Foundation Engineering Research Center

Virginia Tech, University of Wisconsin - Madison, Rensselaer Polytechnic Institute

North Carolina A&T State University, University of Puerto Rico - Mayaguez

Future Electronic Power Distribution Systems

– A contemplative view –

Dushan Boroyevich

Virginia Tech, Blacksburg, Virginia, USA

Keynote presentation at:

PECon 2008

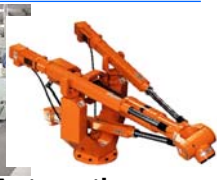
The 2nd IEEE International Power & Energy Conference

Johor Bahru, MALAYSIA

December 1, 2008

Power Electronics Expanding and Emerging Applications

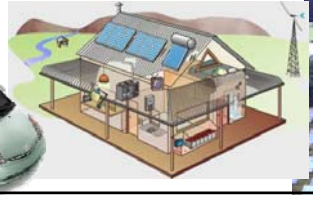
Powering IT



Industry Automation

Most of the Emerging Electric Power Technologies presume
Active Dynamic Control of the Electric Energy Flow (i.e. **Require the Use of Power Electronics**)!

Vehicular Power Systems



Alternative and Distributed Energy Systems

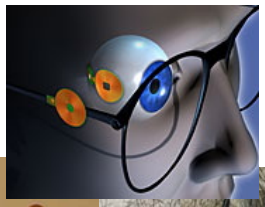
Power Electronics Future?

- **Essential for societal energy needs from:**

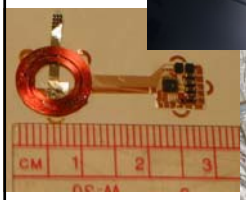
organ implants

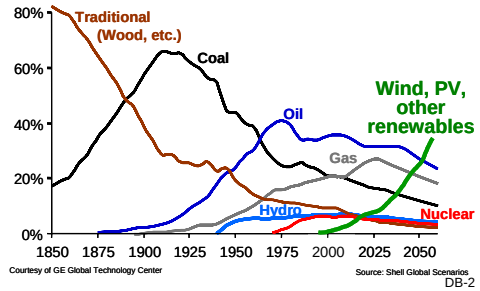
to …

carbon-free energy



Retinal Implant
J. G. Kassakian
IPEC, Niigata,
2005





Electronic Focus of New Electric Power Systems

Emerging and future power systems will have all sources and loads interfaced through power electronics converters:

- **IT Power**: Portable, Server, Telecom, Data Center
- More-electric aircraft, All-electric ship, Hybrid-electric car,
- Sustainable energy, Distributed generation, Future power grid

⇨ **Focus on:** ***Electronic Power Distribution Systems (EPDS) .***

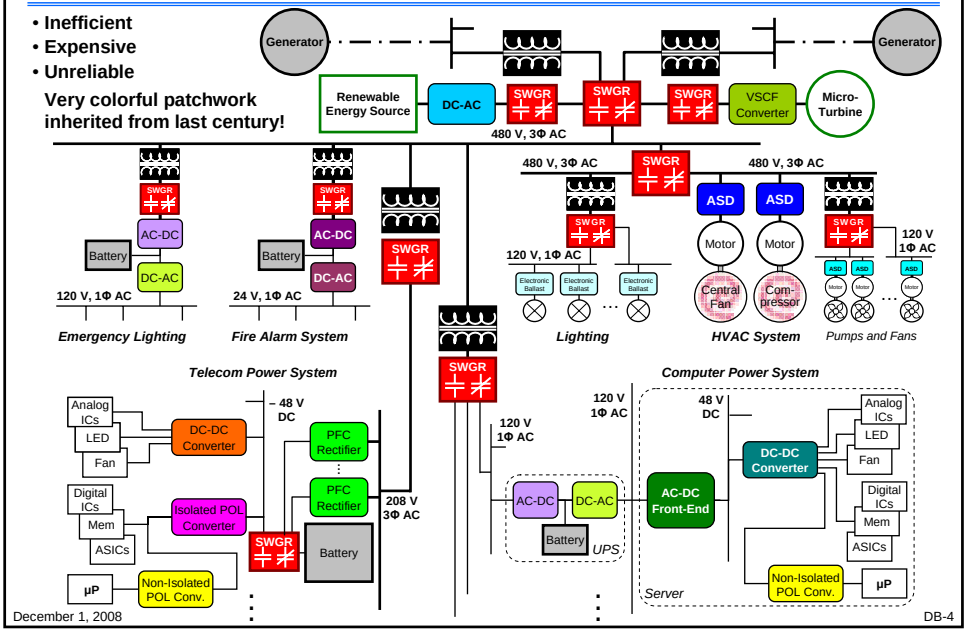
The major opportunities and challenges for synthesis and integration of these systems are in:

- **High-density power converter integration;**
- **System-oriented modeling and analysis;**
- **System architecture design and optimization;**
- **Power management, control, and protection.**

Advanced (?) Electrical Power System of a Large Datacom Center

- Inefficient
- Expensive
- Unreliable

Very colorful patchwork inherited from last century!

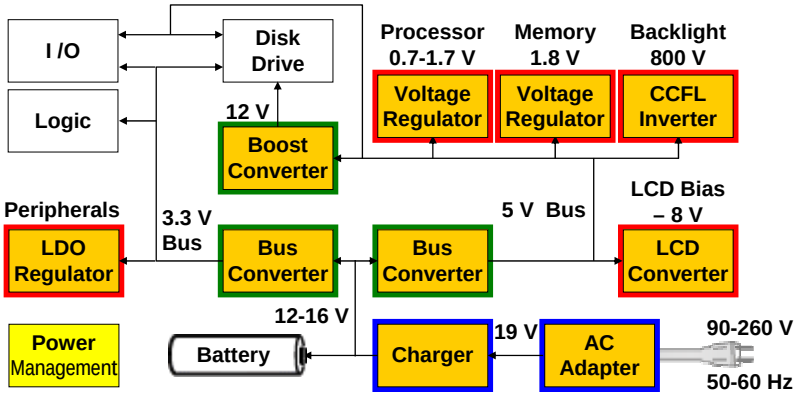


Barriers/Challenge

- **Complexity of traditional power systems:**
  - Fully coupled dynamics of generation, distribution, and delivery.
  - System stability is enabled by imposing an overwhelming, slow, electromechanical or electrochemical dynamics of the sources.
- **Local focus of power electronics:**
  - Concentrated on load dynamics
  - Evolving focus on source dynamics (UPS, distributed generation, fuel cells, alternative energy sources)
  - Until now, only "fixing the problems" of power distribution

Challenge: **Reduce system cost, increase efficiency and availability by decoupling the dynamics of energy sources, distribution system, and loads through the use of power electronics.**

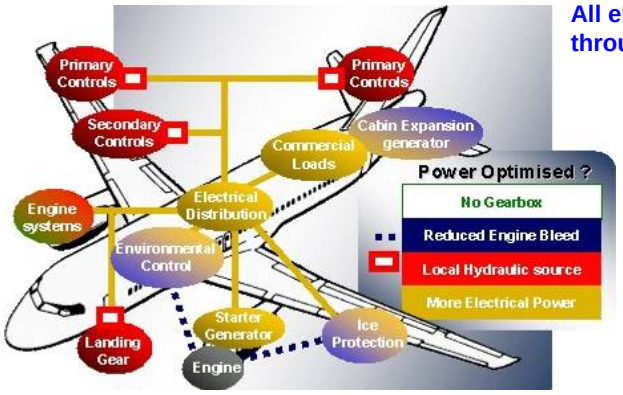
Power-Converter-Based Power Systems *Example*: A Notebook PC



- **Load converters**: Meet dynamic energy requirements of the loads
- **Source converters**: Meet ac line standards; improve battery utilization
- **Power Distribution Converters**:
  - Increase peak-power efficiency ⇔ Improve power density
  - Increase light-load efficiency ⇔ Improve energy efficiency

REDUCE COST !

More Electric Transportation



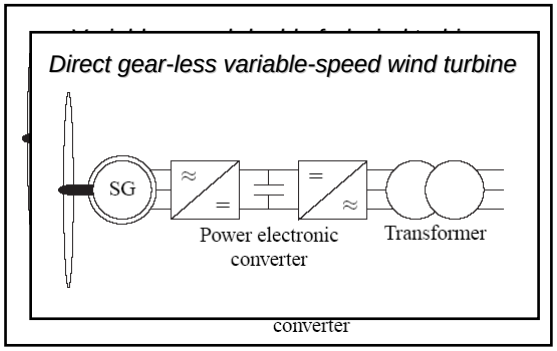
All electrical energy processed through electronic converters

1. **Variable frequency starter/generator**
   ⇒ **Eliminates Gearbox**
2. **Variable speed drives for ECS**
   ⇒ **Eliminates Pneumatics**
3. **High-frequency voltage step-up/down**
   ⇒ **Less Copper & Iron**
4. **Electrical actuation**
   ⇒ **Reduces Hydraulics**

Similar approaches and advantages are being pursued in:

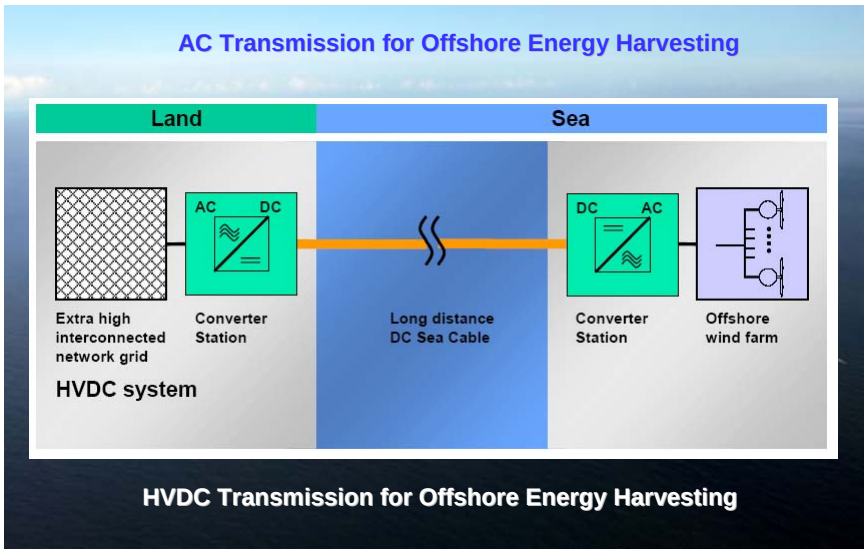
1. **Rail systems and vehicles** (for long time)
2. **All-electric ships**
3. **Hybrid electric cars, trucks, and buses**

Wind Energy: Evolution of Turbine Power Electronics



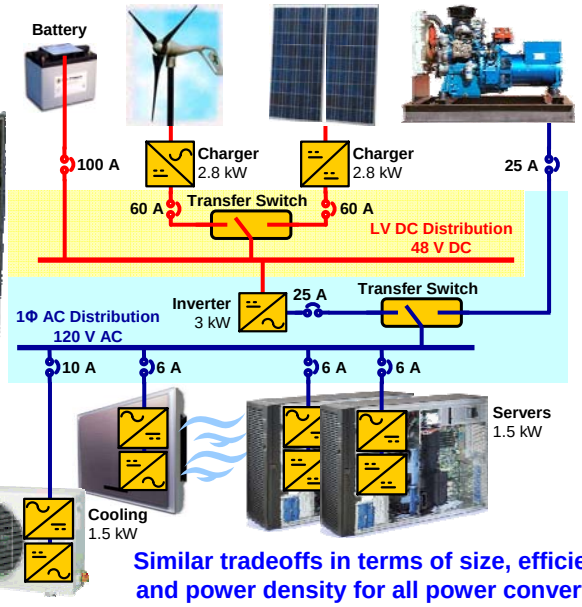
1. Eliminates gear box and need for doubly-fed induction generator
2. Simpler transformer structure
3. Fully decouples wind and grid dynamics

Electronic Power Distribution System: Grid-interface for Offshore Wind Farms



CPES University Testbed: **Hybrid Power System for Remote-site Datacom Centers**

Hybrid Energy Power Sources



Single Enclosure, Self-Contained Unit

Peak-power Efficiency < 50 % !

Similar tradeoffs in terms of size, efficiency, and power density for all power converters.

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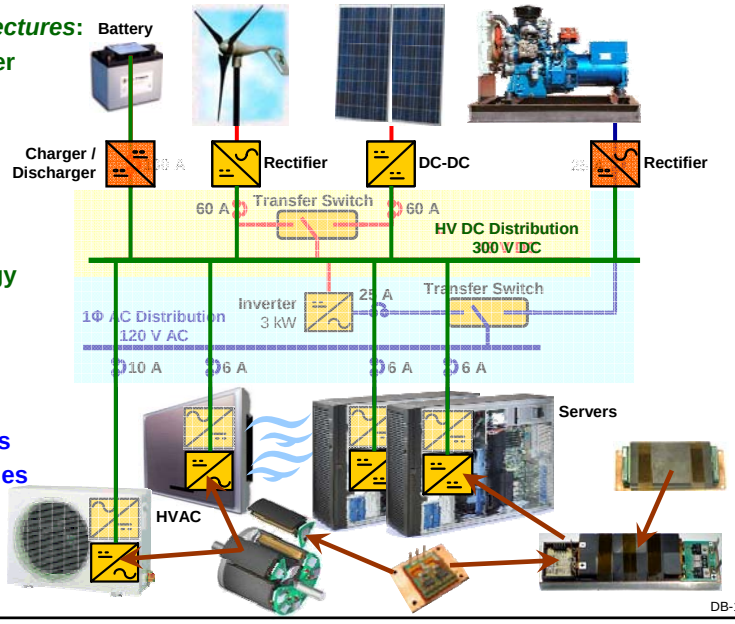
Electronic Power Distribution System (EPDS): An Integrated Testbed

***Improved architectures*:**

- **Reduce number of converters by 30%**
- **Eliminate switchgear**
- **Improve availability**
- **Increase energy efficiency**

System impact evaluation of integrated:

- **Active modules**
- **Passive modules**
- **Converters**
- **Loads and converters**



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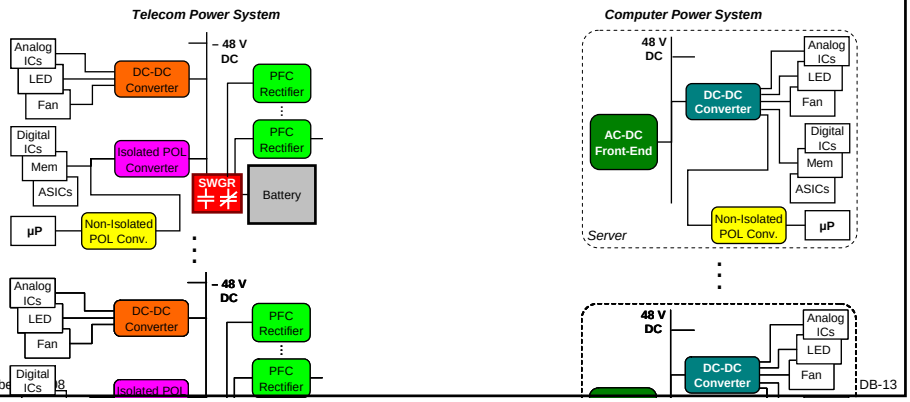
Characteristics of Future Electronic Power Distribution Systems

- **Power electronics converters are used for:**
  - **Source interface**
  - **Load interface** (only "coffee makers" are still non-electronic loads?)
  - **Power flow control and energy management**
- **Advantages:**
  - **High system controllability, flexibility, and responsiveness**
  - **Increased availability**
  - **Reduced size and weight**
  - **Increased energy efficiency**
- **Issues:**
  - **Subsystem interactions (power flow, power quality, EMI, thermal)**
  - **Complexity (not an issue if dynamics is understood & decoupled)**
  - **Reliability and lifetime (not protection)**
  - **Cost (not an issue if system and/or energy costs are reduced)**

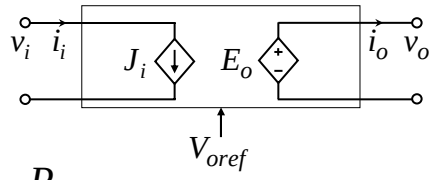
Synthesis of DC Electronic Power Distribution Systems

System Integration is significantly hampered by:

- **Large number of different components**
- **Many different manufacturers**
- **Lack of knowledge of internal converter structures**
- **Lack of information about internal converter parameters**

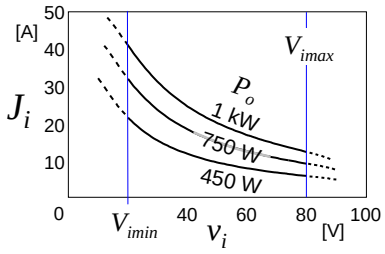


Simplified Power Model of a Regulated DC-DC Converter

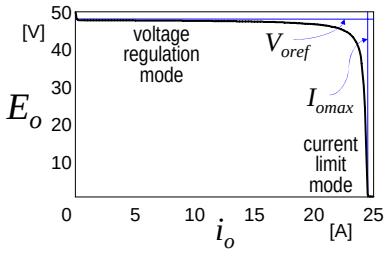


$$J_i = \frac{P_o}{\eta(v_i, i_o) \cdot v_i}$$

$$P_o = v_o \cdot i_o \approx V_{oref} \cdot i_o$$

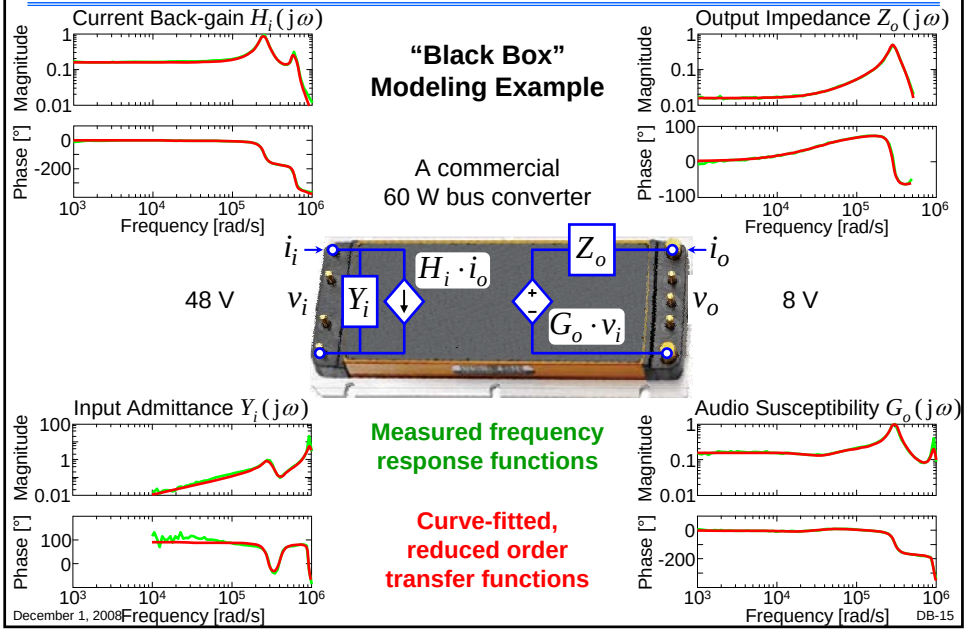


Static Input Characteristic

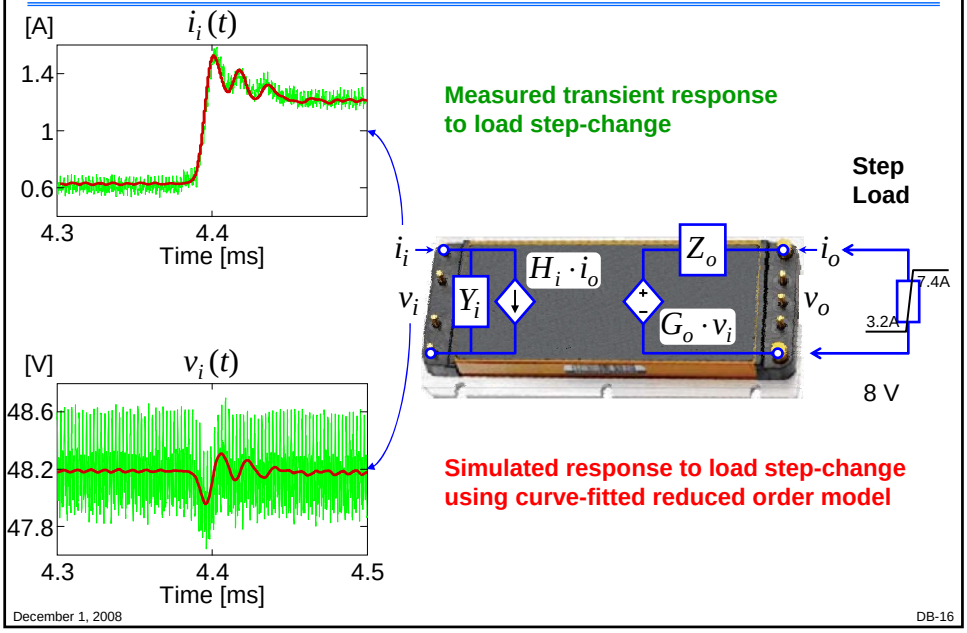


Static Output Characteristic

Modular Terminal Behavioral (MTB) Low-frequency Model of DC-DC Converter

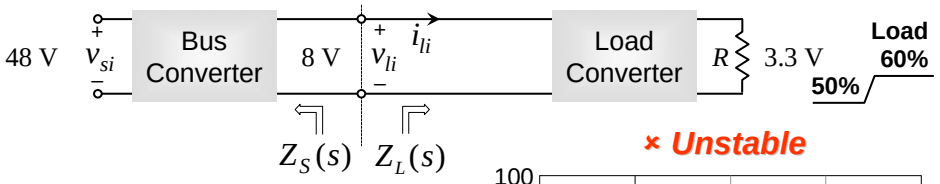


MTB Low-frequency Model Verification: Load Transient



Subsystem Interaction Example

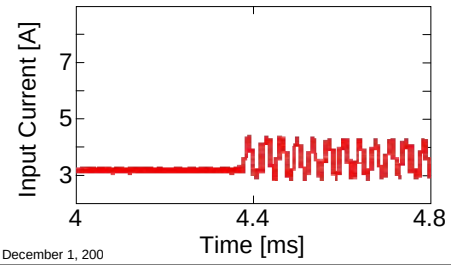
– modeling and experiments with commercial converters –

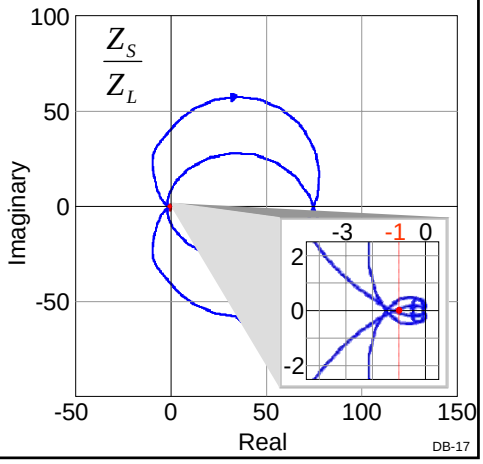


× *Unstable*

- **Interface voltage is:**

$$v_{li} = \frac{Z_L}{Z_L + Z_S} G_{so} v_{si} = \frac{G_{so} v_{si}}{1 + Z_S / Z_L}$$





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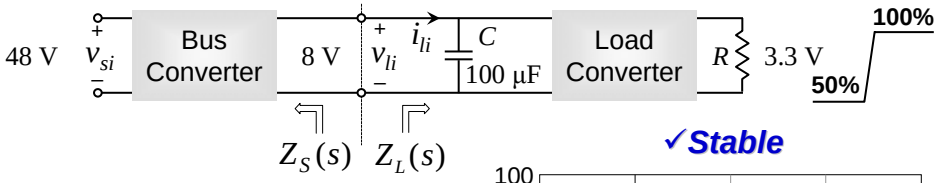

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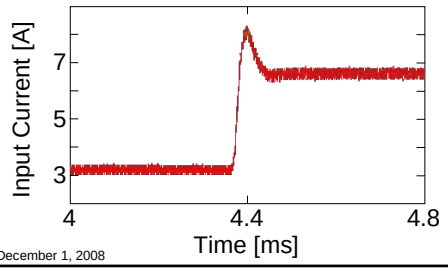
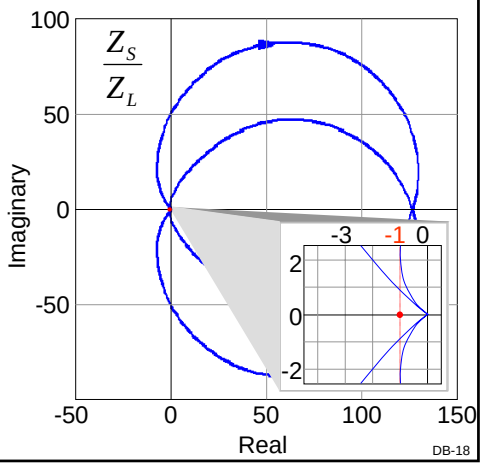
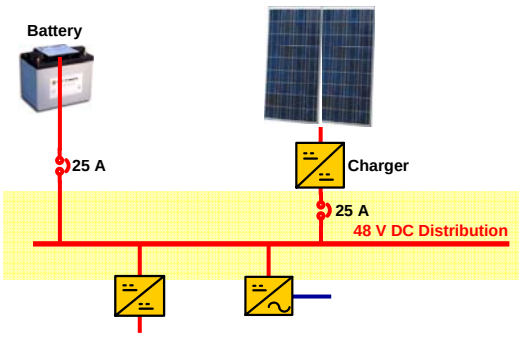


✓***Stable***

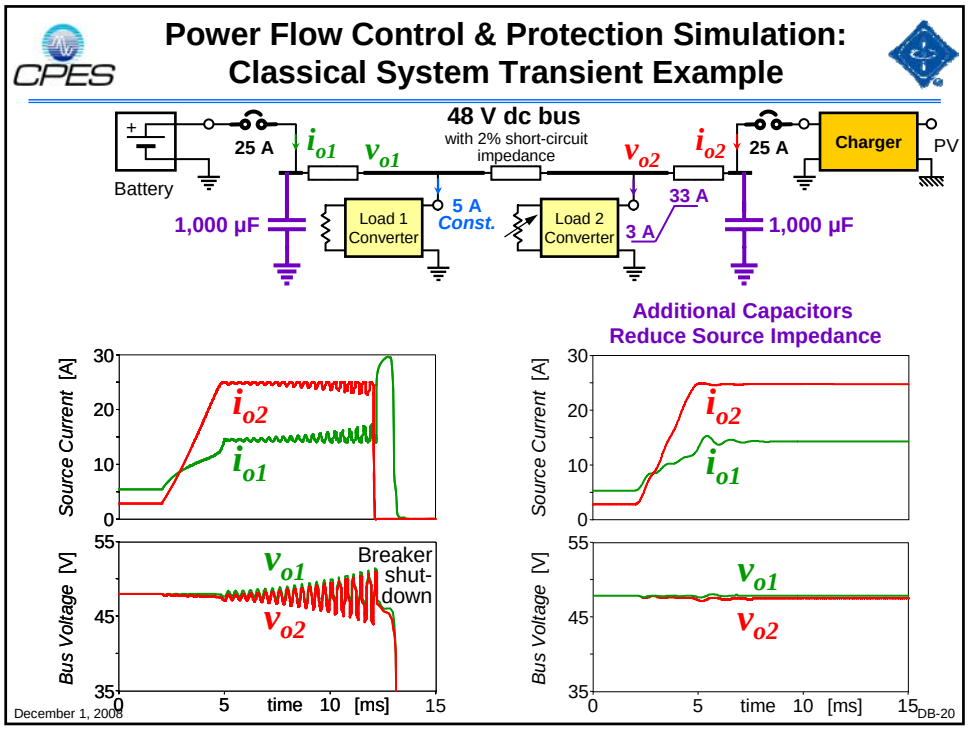


Analysis of Stability, Power Quality, Power Management and Protection



Minimum relevant EPDS example:

- **Two sources**
- **Two loads**
- **DC distribution**


Power Flow Control & Protection Simulation:
Classical System Transient Example
48 V dc bus
with 2% short-circuit impedance
Battery
25 A
i_{o1}
v_{o1}
v_{o2}
i_{o2}
25 A
Charger
PV
1,000 µF
Load 1 Converter
5 A Const.
Load 2 Converter
3 A
33 A
1,000 µF
Additional Capacitors Reduce Source Impedance
Source Current [A]
Bus Voltage [V]
Breaker shut-down
time [ms]
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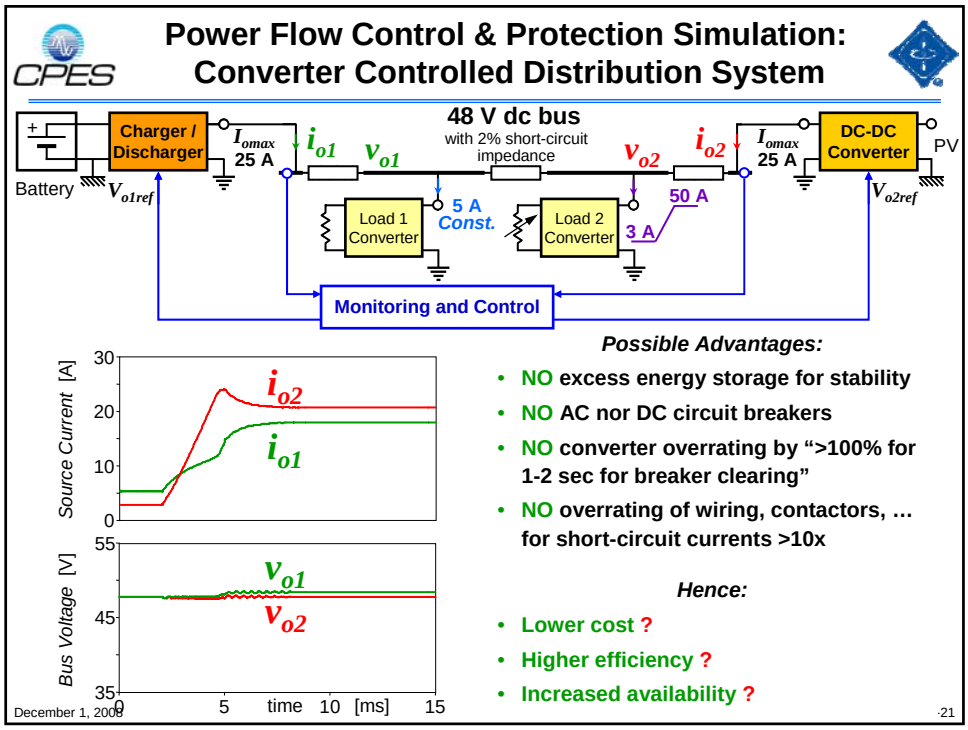
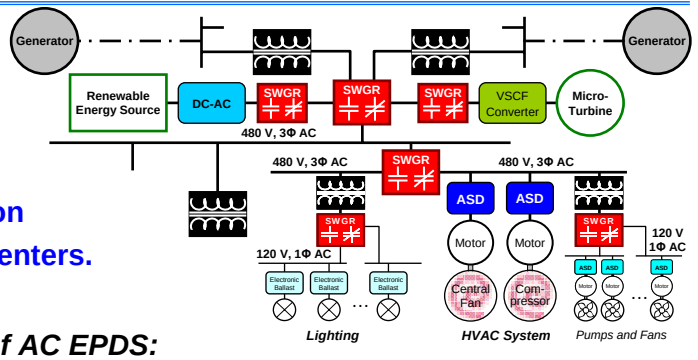

Power Flow Control & Protection Simulation:
Converter Controlled Distribution System
48 V dc bus
with 2% short-circuit impedance
Battery
Charger / Discharger
I_{omax}
25 A
V_{o1ref}
i_{o1}
v_{o1}
v_{o2}
i_{o2}
I_{omax}
25 A
DC-DC Converter
PV
V_{o2ref}
Load 1 Converter
5 A Const.
Load 2 Converter
3 A
50 A
Monitoring and Control
Source Current [A]
Bus Voltage [V]
time [ms]
December 1, 2008
Possible Advantages:
NO excess energy storage for stability
NO AC nor DC circuit breakers
NO converter overrating by ">100% for 1-2 sec for breaker clearing"
NO overrating of wiring, contactors, … for short-circuit currents >10x
Hence:
Lower cost ?
Higher efficiency ?
Increased availability ?
21

AC
Electronic Power Distribution Systems



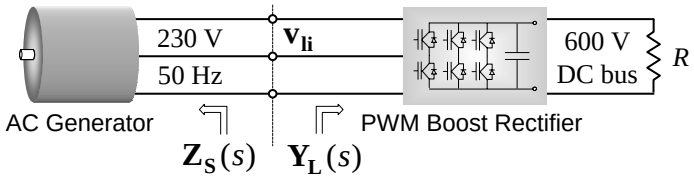
"Electronic"
only recently
in transportation
and datacom centers.

MTB Modeling of AC EPDS:

- **More difficult due to time-varying nature of steady-state**
- **Large disconnect between system and converter modeling**
- **Use of average models in system analysis is uncommon**
- **"Constant-power loads" are being considered only recently**
- **Small-signal frequency-domain modeling still in development**

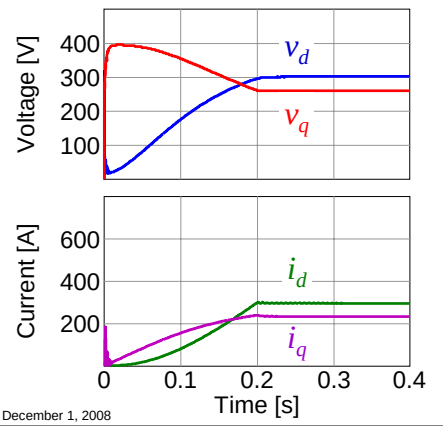
AC Subsystem Interaction Example

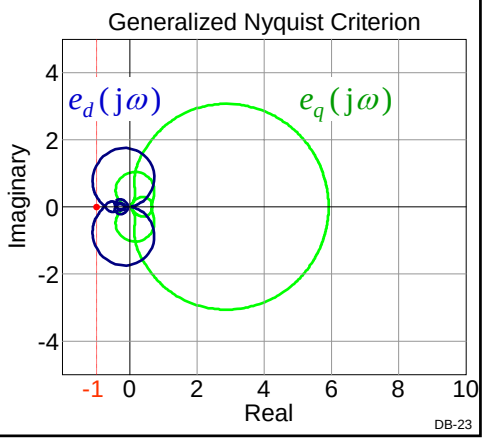
– small-signal and average modeling and simulation –



Start-up to 135 kW

✓***Stable***





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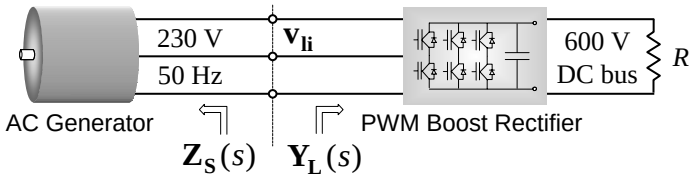
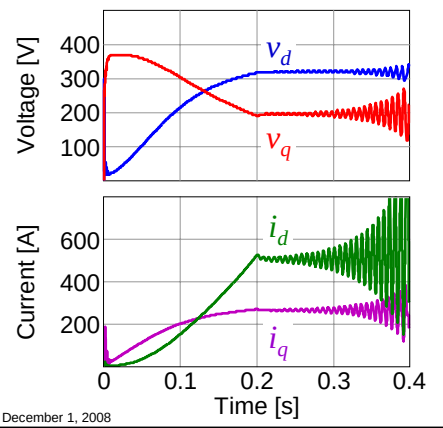
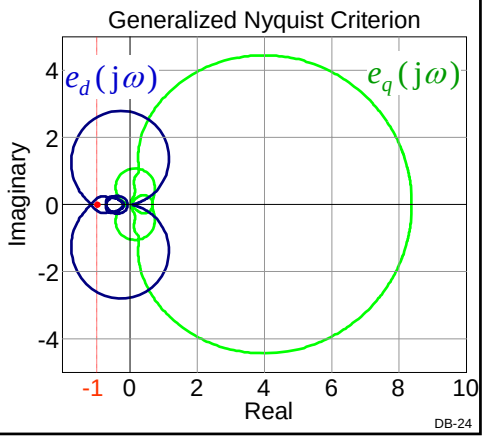


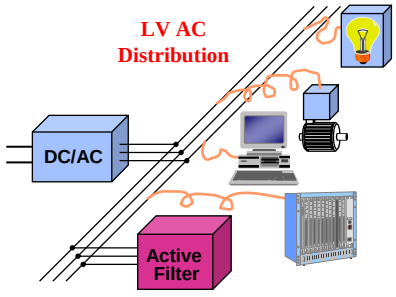
Start-up to 180 kW

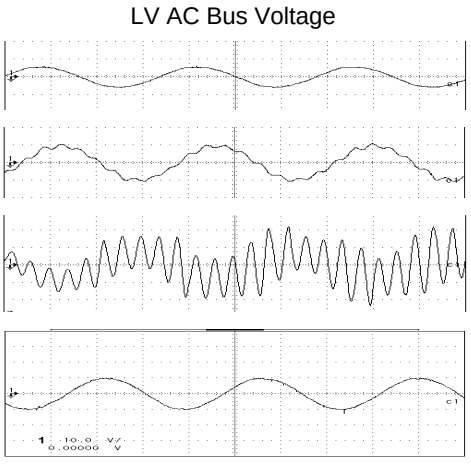
× *Unstable*





Advanced Shipboard Electric Power Systems

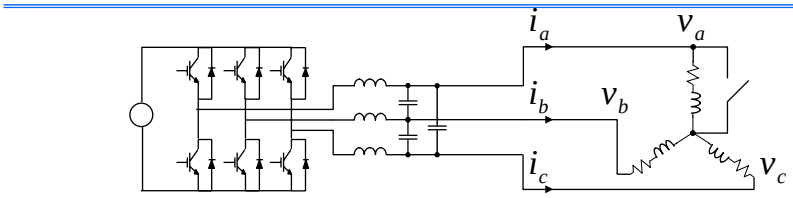




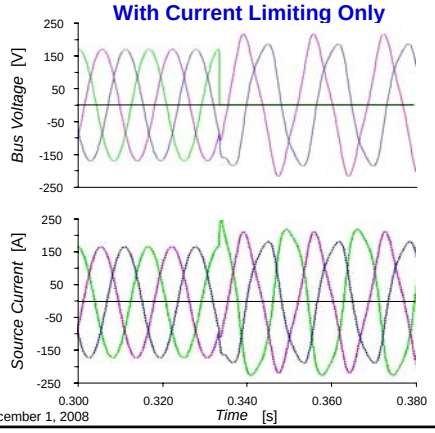
- **Increase in negative impedance loads produces oscillations.**
- **Further increase in negative impedance loads produces instability.**

Using active filter to introduce damping at higher frequencies decouples the load from source dynamics; thence: reduces complexity and stabilizes network !

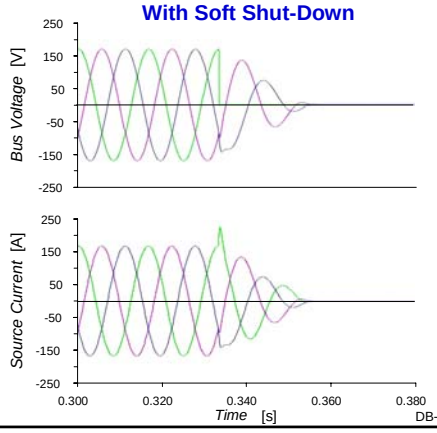
Converter Controlled AC Distribution System
Fault Handling: One-Phase-to-Ground Short



With Current Limiting Only

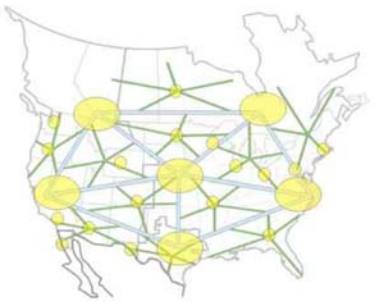


With Soft Shut-Down



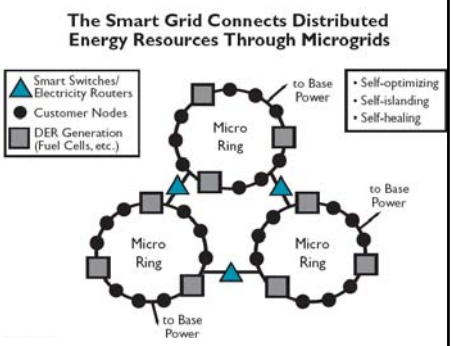
Hypothetical Concepts

- **Dynamically decoupled (asynchronous), hierarchical grid**
- **Consider both AC and DC**
- **Gradual removal of synchronism**
- **Start decoupling from both ends;**
  - **HVDC backbone ⇒ Regional DC interties**
  - **Nanogrids ⇒ Microgrids**
- **Supplant Substations with "Electricity Routers" ("Smart Grid" isn't it!)**



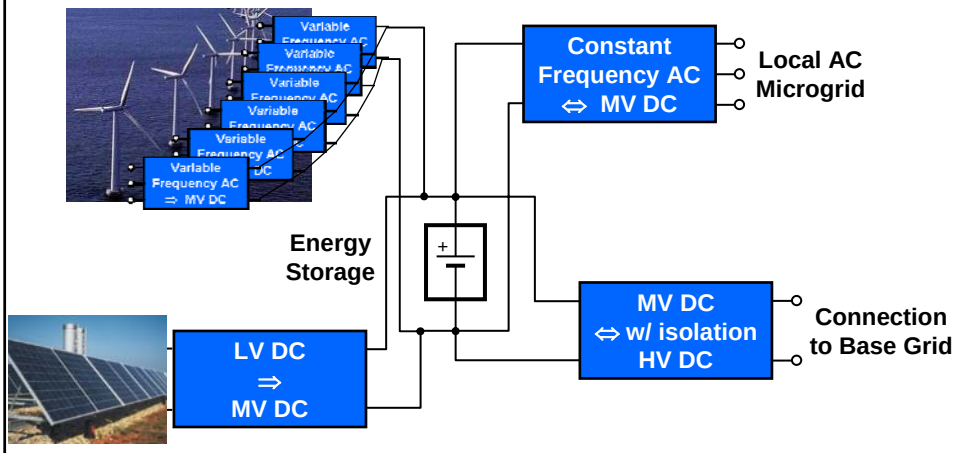
Electricity Backbone, Regional Interconnection, Plus Local Distribution, Mini- and Micro-Grids

DOE: "GRID 2030" VISION



EPRI: 2003 Electricity Technology Roadmap

An "Electricity Router"



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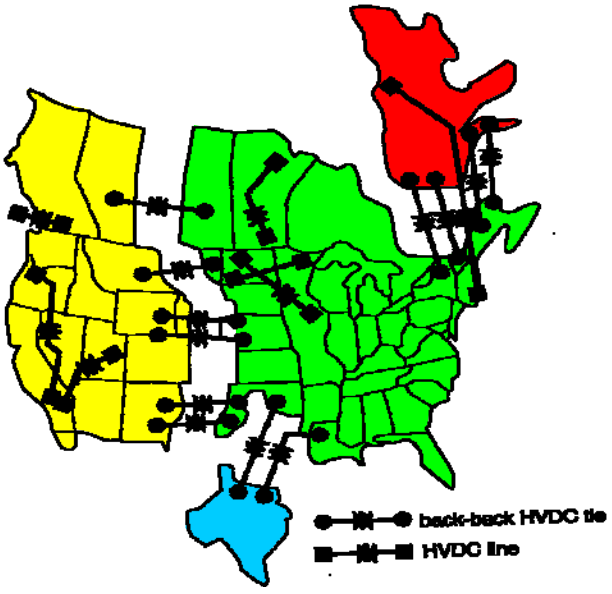
US and Canada Electric Grid

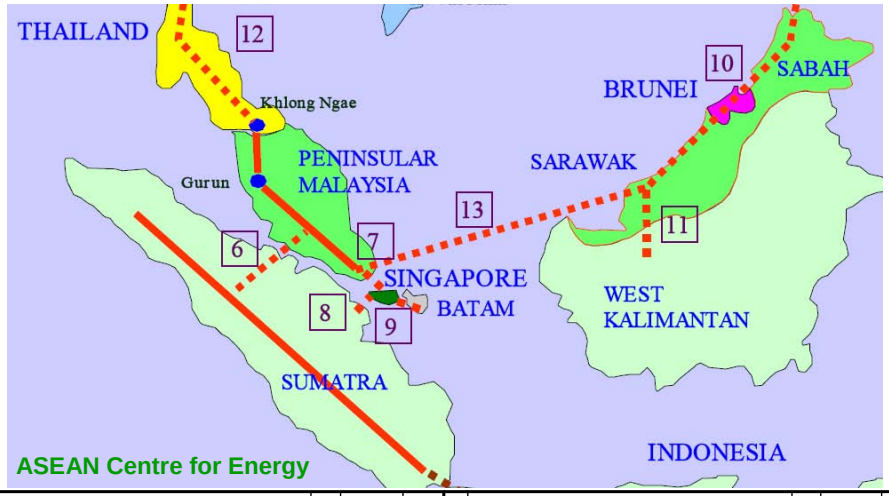
Four major independent asynchronous networks, tied together only by DC interconnections:

1. *Eastern Interconnected Network*
2. *Quebec*
3. *Texas*
4. *Western Interconnected Network*



December 1, 2008 DB-29

Plans for New ASEAN Electric Grid



6	Peninsular Malaysia – Sumatra (Indonesia)	DC	600 MW	2008	10	Sabah/Sarawak (Malaysia) – Brunei Daruss.	AC	300 MW	2019
7	Peninsular Malaysia – Singapore	DC	700 MW	2012	11	Sarawak (Malaysia) – W. Kalimantan (Indo.)	AC	300 MW	2007
8	Sumatra (Indonesia) – Singapore	DC	600 MW	2014	12	Thailand – Peninsular Malaysia	?	?	?
9	Batam (Indonesia) – Singapore	AC	600 MW	2014	13	Peninsular Malaysia – Sarawak (Malaysia)	?	?	?

A Dream of
Electronic Energy Network

that will supplant Electric Power Grid
to enable Carbon-Free Electricity by 2030

- **All electricity could be generated carbon-free:**
  Hydro Wind Solar Nuclear
- **Today's electric power grid cannot handle this due to:**
  - **No ability to absorb high % of distributed generation and storage**
  - **No adequate long-distance energy transport**
  - **No adequate energy storage**
- **Must use electronic networks for electric energy utilization!**
- **Save: bio fuels for some transportation**
  fossil hydrocarbons for chemical products

Research Directions

1. **Network Architectures**
   - Dynamically decoupled, hierarchically interconnected, smart, super-grid and a network of small-, mini-, micro-, and nano-grids, instead of single, constant-frequency ac, grid
   - Distributed generation, storage, loads, and intelligence
2. **Energy Transfer Protocols and Markets**
   - Technology for continuous control of all energy flows
   - Enabling of efficient market mechanisms
3. **Safety and Reliability**
   - Safety & protection
   - Reliability & lifetime
4. **Energy Storage** (minutes, hours, days, seasons)

- **Energy sources, HVDC, superconducting transmission, high-power electronic conversion, …**

Metrics of Success

- **Peak power density**
  - Weight and volume (right-of-way, real estate, … , W/cm^3, W/g)
  - *Related to investment cost*
- **Energy efficiency**
  - High efficiency at light and full load or optimized over load-cycle
  - *Related to operating cost*
- **Life-cycle cost**
  - Based on life-cycle analysis
  - *Related to environmental and societal impact*
- **Reliability and Availability**
  - Critical for economic and societal impact
  - *Related to risk-mitigation pricing*
- **Safety and Protection**
  - More design constraints than metrics of success
  - *Critical for acceptance by community and society*

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