Transforming the Grid with Superconductivity

A. P. Malozemoff
American Superconductor Corp.

Basic Research Needs for Superconductivity
APS March Meeting
Denver CO, March 6, 2007
US Electric Power System is under Severe Stress

The underlying problem: Under-investment in electric power grid while demand for electric power steadily increases

Under-investment has spawned a host of technical problems
Grand Challenges in Electric Power

- Demand growing relentlessly, doubling by 2050, tripling by 2100, plus need to reduce dependence on foreign oil and to cut CO₂ emissions
  - Need a major enhancement in overall electric energy efficiency
    - Increasing grid efficiency
    - Electrification of transportation
    - Reurbanization

- Power outages and disturbances cost >10B$ per year
  - Need a secure and ultra-reliable grid

- Environmental issues growing
  - Assure an environmentally clean energy infrastructure
Superconductors: In the Right Place at the Right Time for Major Role in Upgrading the Electric Energy System

Production:
- coal
- gas
- nuclear fission
- heat

Delivery:
- electrical generators
- electricity
- power grid

Use:
- lighting, heating, refrigeration
- transportation
- industry
- information technology
- fuel cells
- solar
- hydro
- wind

Superconductivity
First Round: Low Temperature Superconductors 
(Max \( T_c \) 23 K): NbTi, \( \text{Nb}_3\text{Sn} \)

- Widely and successfully used for high energy physics, MRI, laboratory magnets...

- For electric power? - many LTS demonstrations
  - Ac cable - Brookhaven Nat’l Lab
  - Dc cable - LANL
  - Motors, generators - Westinghouse, Siemens, GE, Alstom, Super-GM (Japan)
  - Fault current limiters - ABB, Toshiba, Alcatel-Alsthom

- Only commercial LTS electric power product - AMSC’s 2.6 MJ SMES (Superconducting Magnetic Energy Storage)
  - Units installed in northern Wisconsin, Texas
  - Utility, industrial power quality focus now on reactive power

**Key barriers: cost, cooling complexity, stability, contingency limit**
Present Round: High Temperature Superconductors (BSCCO, YBCO, etc. – $T_c$ up to 135 K)

HTS wire - 150x current and power density of copper

1000 m reel of HTS wire commercially available

Pancake coil for motor rotor

Coil for magsep solenoid magnet

HTS facilitates first generation of commercial superconductor power equipment
The Future: New Superconductors?

- **MgB$_2$** – low cost, low anisotropy
  - Superconductivity discovered in 2001
  - Higher T$_c$ ($\leq$39 K) and H$_{c2}$ than Nb$_3$Sn

- Future discoveries?
  - Ultra-high T$_c$
    - As $\xi \sim \hbar v_F/kT_c$ gets smaller
      - Flux creep barrier $\sim \xi^n$ drops
      - Practical J$_c$ drops
      - Grain boundaries barriers grow
    - *How can one design ultra-high T$_c$ superconductors to be useful?*
  - Low anisotropy
  - Deformable materials

New discoveries will continue, opening new opportunities in energy


**Enhancing Efficiency in the Electric Power Grid**

- 7-10% of 1 Terawatt US electric power now lost in grid
  - Superconductor equipment could cut this by half, save 50 Gigawatts!
  - Reducing delivery bottlenecks even more impactful
    - *E.g. superconductor cables bringing 50%-efficient generation to cities, replacing 30%-efficient “reliability-must-run” generators*

- Dc supergrid: a radical leap in grid efficiency
  - Westinghouse’s ac grid won out over Edison’s dc grid
    - *Reduced $I^2R$ loss by efficient transformers, high voltage*
  - Superconductors break this paradigm
    - $I^2R = 0$ enables high dc current, low voltage
  - Can we do even better in a hydrogen economy?
    - *Liquid hydrogen as cooling medium for supergrid (Grant-Starr)*
**Enhancing Energy Efficiency by Electrification of Transportation**

- Electric vehicles ~2x more energy efficient than gas in original BTU content of oil
  - ‘A 5% penetration of plug-in vehicles in Manhattan will create a 50% increase in rate of demand growth’
  - ConEd, 11/15/05
  - Superconductors key in enabling urban grids to handle this demand

- Maglev an efficient alternative to intracontinental aviation

- Military ship propulsion with HTS motors - 15% efficiency gain at half speed over conventional motors

Japanese Maglev flies with HTS coils, (courtesy CJR)
**Enhancing Efficiency by Opening the Urban Power Bottleneck**

- Reurbanization driven by rising energy costs
- Requires more power capacity in dense urban areas
- But overhead lines near impossible to permit, underground infrastructure clogged

**New York then**

**New York now: it only gets worse!**

Lower Manhattan underground infrastructure (Courtesy of Con Edison)
Getting Power in to Our Cities

Need underground power cables which are

- High capacity
- Compact, light – easy to install by retrofitting existing ducts or boring
- Non-interfering (no EMF or heat)
- Low voltage for easy permitting

Superconductors - the ideal solution!

Detroit Edison cable installation (Courtesy, Pirelli)

HTS cable for Albany installation (Courtesy, SEI)
HTS Cable Driver: 3-5x Power of Conventional XLPE Copper Cables at Lower Voltage

HTS enables more capacity at lower voltage; simplifies permitting
Major HTS Cable Demonstrations Underway

Bixby substation, AEP, Columbus OH
13.8 kV, 2400 A 200 m cable system
by Ultera (Southwire/nkt cables)
In-grid operation since July 2006
Establishing Secure, Reliable Grid: Overcoming Kirchoff’s Laws

Grounded HTS cable shield conductor
- Full shielding – no EMF

Low inductance enables economic ac current control with phase angle regulator

\[ \text{PowerFlow} = \frac{(V_s)(V_R) \sin \theta}{Z} \]

Ac power flow control can revolutionize grid reliability

PAR (courtesy, Mitsubishi)
Establishing a Secure and Reliable Grid: Controlling Fault Currents in Urban Grids

- Every added power source adds parallel output impedance
  - increases fault current
- In large urban grids, fault currents can exceed 60,000 A
  - approaching maximum breaker capability!

Faults short out resistive loads, leave grid primarily reactive!

Need a solution, or must drastically reconfigure and break up the grid
Superconductors Enable “Resistive” Fault Current Limiters

- Superconductors - “smart” materials, switch to resistive state above critical current

- Many FCLs prototyped around the world; challenge to make them scalable or economic

- New opportunity to design a practical FCL using 2G HTS wire (YBCO coated conductor)

2.25 MVA, 13 kV class, resistive FCL, 28 kA short circuit current reduced to 3 kA (Siemens/AMSC, 2007)
Components for Cost-Effective Commercial Fault Current Limiter

Bifilar Coil

HTS Wire

Insulation (Green)

Stabilized

Low-cost laminated stabilizer (stainless steel)

2G HTS wire cross-section

Low Inductance

Module

Coils connected in series and parallel to meet utility voltage and current specs

Basic Energy Sciences

BES Report on Basic Research Needs for Superconductivity
http://www.sc.doe.gov/bes/reports/abstracts.html#SC
Example of Resistive FCL Switching Response

Why is limited current so much larger than $I_c$?
Need study of dynamics in flux flow state

$>1$ kA short-circuit current
limited to $\sim 200$ A$_{rms}$

$L_{total} = 57$ m
three coils in series

$I_c = 70.7$ A

$I_{nom} = 50$ A

$U_{nom} = 2400$ V$_{rms}$

$P_{nom} = 120$ kVA
Establishing a Secure and Reliable Grid: an Urgent Need

Significant power blackouts becoming all too frequent
"…the blackout on August 14, 2003 was preventable. It had several direct causes and contributing factors including:

#1. Failure to maintain adequate reactive power support…”

- Reactive power measured in “VARs”
- Think VARs
Voltage Collapse from Inadequate Reactive Power: "Nose Curve"

a) Simple model:

\[ I \rightarrow jX \rightarrow V \rightarrow R \]

b) Real case (courtesy of D. Bradshaw, TVA)

Need dynamic compensation of VARs for grid stabilization
HTS Dynamic Synchronous Condenser for Grid Stabilization

- Synchronous condenser: rotating machine - generator without prime mover
  - Injects either capacitive or inductive VARs into grid for
    - Power factor correction
    - Instantaneous mitigation of voltage disturbances

- HTS system solves key limitations of conventional copper-based synchronous condenser
  - Compact rotor coils enable high VAR output in small frame: lowers $/kVAR
  - Compact system, easily sited
  - Superconductors eliminate thermal fatigue from cycling rotor coil current – main source of failure of conventional systems
**HTS Rotating Machinery Progress**

- Synchronous condenser builds on rapidly progressing HTS motor technology

- ±8 MVAR AMSC synchronous condenser successfully tested at TVA substation
- Two ±12 MVAR commercial units on order

36.5 MW AMSC ship propulsion motor in assembly at Navy facilities

8 MVAR synchronous condenser

*Synchronous condenser - world’s first commercial HTS product for power grid*
Assuring an Environmentally Clean Electric Power Infrastructure

- Superconducting power equipment avoids use of oil
  – a contaminant and fire hazard

- Closed cycle liquid nitrogen and/or cryocoolers
  - Non-contaminating
  - Non-flammable

- Superconductor’s high efficiency reduces unnecessary pollution and CO₂ emission at energy source

Superconductivity – basis for a green and clean technology
If HTS is Already Moving to Commercialization, What Basic Research Remains to be Done?

- Most desired superconductor functionalities (high current density, robust mechanical properties) have already been achieved,
  - But still at too low a temperature
  - With processes which could be simplified

- The main challenge is:

And cost translates quickly into a host of fundamental research challenges
Basic Research Needs

- Lowering cost by reducing $/kAm: lower cost processes, higher $I_c$
  - 1G HTS wire now $150/kAm$
  - Copper in cable:$30-65/kAm$
  - DOE goal: $10/kAm$
  - 2G HTS wire (YBCO coated conductor) – on path to beat copper

- Lowering cost by reducing cryogenic requirements
  - Higher temperature operation
    - Enable YBCO 65-77 K operation in field
      - Improved pinning
      - Reduced grain boundary current limitation
    - Higher temperature superconductors
  - Lower ac loss

- Assuring reliability through electrical, thermal stability to overcurrents, defects
  - Conducting buffer layers in 2G HTS wire architectures
  - Understanding high current, flux flow behavior, hot spots
Complex Field-Angle-Dependent Pinning Phenomena in YBCO Coated Conductors

Basic research needed to understand and control pinning

“Nanodots” – oxide precipitates

124 intergrowths

Critical Current (A/cm-w)

Angle (degree)

YBCO + nanodots

YBCO

77K, 1T

H//c-axis

H//ab-plane

Basic Energy Sciences

BES Report on Basic Research Needs for Superconductivity
http://www.sc.doe.gov/bes/reports/abstracts.html#SC
2G HTS wire (YBCO coated conductor) architectures have many layers!

**Basic Research Needs: Lowering Wire Cost by Fundamental Process Improvements**

Must simplify architectures, invent new and simpler texturing approaches.
Summary

- Superconductivity is in the right place at the right time to address grand challenges of energy delivery and use:
  - Major increase in energy efficiency and capacity
    - Higher efficiency grid equipment
    - Electrification of transport
    - Breaking power bottlenecks for reurbanization
  - Secure and ultra-reliable grid through
    - Power flow control
    - Fault current control
    - VAR management
  - Environmentally green and clean technology

- HTS electric power equipment revolution is starting, but full impact hinges on enhanced performance and cost reduction facilitated by basic research

Superconductivity research critically needed to fully meet the grand challenges