



**SuperPower<sub>INC.</sub>**

A Subsidiary of InterMagnetics General Corporation

OAK RIDGE NATIONAL LABORATORY  
U. S. DEPARTMENT OF ENERGY



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# Development of High Temperature Superconducting Power Transformers

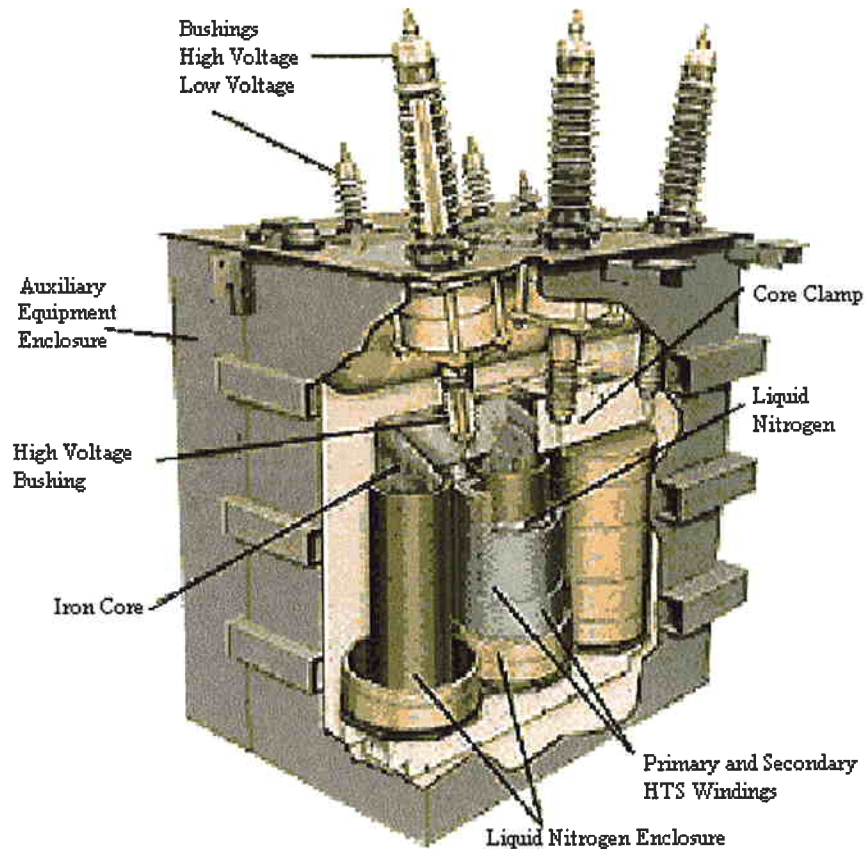
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## HTS Transformers offer economic, operational, and environmental advantages.



- **Higher efficiency.**
- **2X rating overload capability without insulation damage.**
- **Lower impedance and better voltage regulation.**
- **Potential for fault current limiting capability.**
  - Reduced cost for associated switchgear, breakers, etc.
- **Lower environmental hazard due to lack of oil.**
- **Lighter and more compact than conventional units.**

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## Higher Efficiency (Lower Operating Losses)

- Core losses
  - Core losses in HTS transformer are comparable to core losses in conventional transformer
- Winding losses
  - No  $I^2R$  losses
  - Load losses generated are on the order of hundreds of Watts at cryogenic temperatures
    - Cryocooler compressor power needed to remove at low temperatures on the order of tens of Watts per Watt of loss
    - Present day compressors run continuously and must be sized for peak load
  - For a 30/60 MVA HTS transformer
    - winding losses are like no-load losses
      - due to power needs of cryocoolers
      - around tens of kilowatts at room temperature vs. one to two hundred kilowatts of load loss for conventional transformer

## Emergency Overload Capability

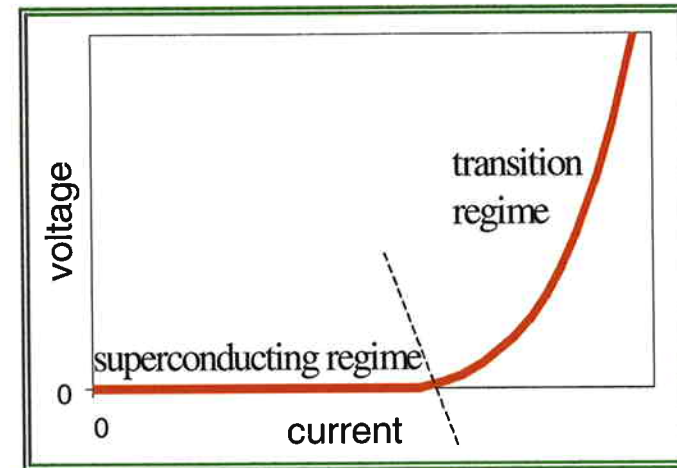
- Emergency overload capability up to twice the normal rating can be built into the design
  - Very little heating even during this overload condition
    - Remain in the cryogenic condition
    - No thermal degradation of insulation
  - Designed to handle the added overload mechanical forces.
  - Run for extended periods at overload conditions
    - AC losses are proportional to operating current cubed
      - Refrigeration costs are directly proportional to ac losses
      - Operation in this mode tends to be inefficient
      - Operation above the design limit is not practical

## Lower Leakage Reactance

- Lower leakage transformers can be designed because:
  - AC fields are already minimized to reduce ac losses and refrigeration costs
  - Compact windings allowed by high current density
    - May be desirable to incorporate fault current limiting capability so as not to increase system short circuit currents
- Specific benefits to power systems operation are:
  - Improved voltage regulation
  - Reduced impact of faults elsewhere in the system
  - Reduction in required static and dynamic VAR capability
    - Increased reactive power availability from generators
    - Increased availability of real power from existing generators
  - Transformer designs that separate transformer impedance requirements from specific system short circuit current requirements

## Fault Current Limiting

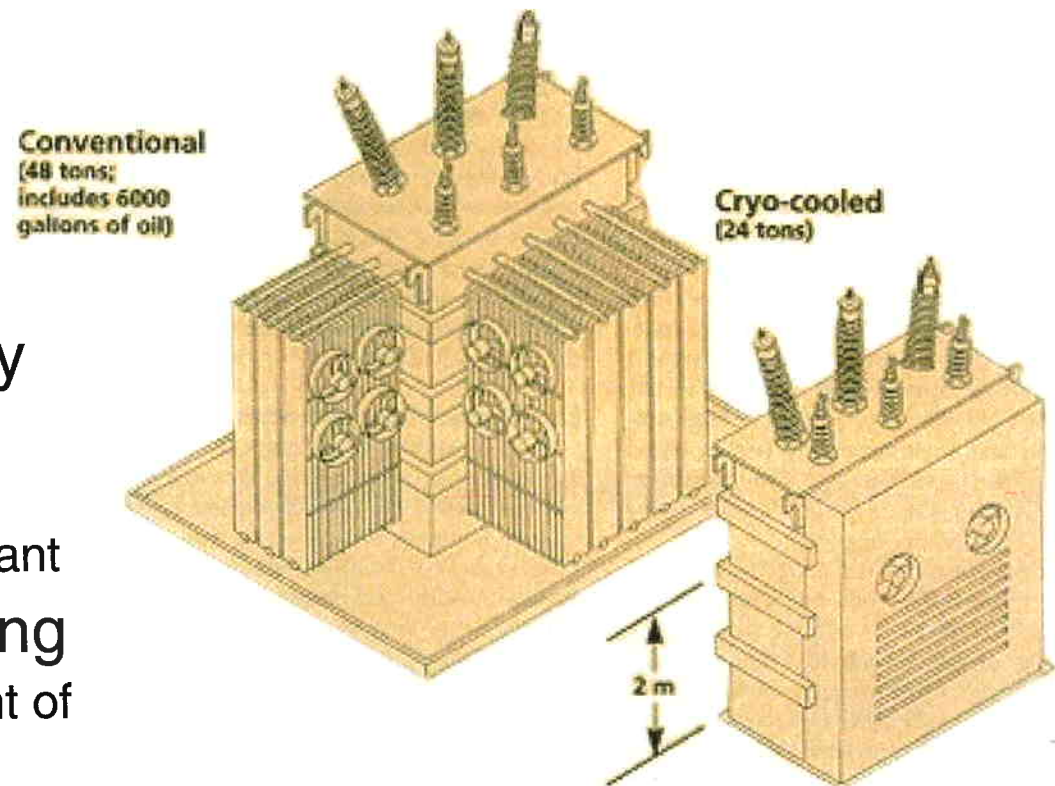
- The current-voltage characteristics of a superconductor lend themselves to the possibility of designing the windings to also operate as an intrinsic fault current limiter



- Feasibility of fault current limiting:
  - Depends on rapidly achieving a uniform transition of the entire length of superconductor to the resistive state
- Benefits to the power system include:
  - Reduction of current interruption ratings for circuit breakers and reclosers
  - Elimination of the need for other current limiting devices

## Siting Benefits

- **Compact Design**
  - Lighter weight
  - Smaller footprint
    - no heat exchangers
    - compact windings
- **Environmentally friendly**
  - Oil free
  - Non-flammable
  - Benign liquid nitrogen coolant
- **Possibility of indoor siting**
  - limited mainly by the weight of tank and core



**30 MVA Transformers**

external package of HTS transformer very similar to conventional transformer

## High Power Density

- Expected factor-of-two size and weight reductions for a 30/60 MVA HTS transformer compared to a conventional transformer

### Example: 60 MVA substation

#### • Conventional Transformers

- **two 27/36/45 MVA units.**
  - Each nominally operates at 30 MVA
- Either handles full 60 MVA load in emergency
  - only for a short time
  - with significant loss of transformer life

#### • HTS Transformers

- **two 30/60 MVA HTS units**
  - Each nominally operates at 30 MVA
    - half the footprint
  - Either handles full 60 MVA load in emergency
    - prolonged time
    - no loss of life during overload
- Two more HTS transformers can be added in original footprint
  - double the capacity of substation



## Design Approaches

### • Liquid Nitrogen Bath Cooled

- Windings immersed in LN<sub>2</sub> bath
  - Use cryocoolers to re-condense, or periodically replenish, boiled-off LN<sub>2</sub>
- Advantages
  - LN<sub>2</sub> provides thermal & electrical insulation
  - Very similar to oil
  - Possible to air cool the core
- Disadvantages
  - Operation limited to between 77K (-320F) and 64K (-345F)
  - More of the (relatively expensive) superconductor is needed
  - Vacuum-tight, non-metallic, donut-shaped enclosures for the liquid nitrogen that surround each core leg

### • Cryocooled

- Use cryocoolers to directly cool the windings
  - Can run at optimal operating temperature
- Advantages
  - Less conductor needed
  - Reduce conductor cost
  - Only tank wall is vacuum tight dewar
- Disadvantages
  - Energy required for cryocoolers
  - Must have very low ac loss winding design and efficient cryocoolers

## Design, Operation and Cost Issues, Dielectrics

- Penetrations through vacuum space
  - surface creep in vacuum, cold temperatures
- Cryogenic temperature operation
  - Desired Properties
    - High dielectric strength
    - Low partial discharge
    - Low dissipation factor
    - Thermal compatibility
    - Mechanical strength for solid materials
    - Thermal conduction
  - LN<sub>2</sub> impregnated paper can be designed to be comparable to oil/paper
  - Measurements underway or completed

*however*

**Standard solutions for good cryogenic performance  
are often incompatible with high electric field**

