Superconducting Cable Systems
An aging and inadequate power grid is widely seen as one of the greatest obstacles to the restructuring of power markets in the United States, Europe and elsewhere. Utilities face several converging pressures: Steady load growth, unplanned additions of new generation capacity, rising reliability requirements, sharp price volatility resulting from new competitive forces, and stringent barriers to siting new facilities, particularly extra high voltage equipment. Proposals for conventional grid expansion are facing persistent challenges, just as it is becoming apparent that industry reform cannot succeed without renewed grid investment and new transmission and distribution capacity. Consequently, new technologies that can increase the electrical capacity and flexibility of this vital network are attracting increased attention.

One of the technologies with the greatest promise to address these concerns is the high capacity, underground High Temperature Superconductor (HTS) cable. HTS cables are capable of serving very large power requirements at medium and high-voltage ratings.

**Superconductivity**

HTS cables use tapes made of superconducting materials as current carrying elements. In superconducting materials, the superconducting state exists as long as temperature, current and magnetic field are below their critical values $T_c$, $I_c$ and $B_c$.

$Bi_2Sr_2Ca_2Cu_3O_{10}$ (BSCCO) and $YBa_2Cu_3O_7$ (YBCO) are the commercially available high temperature superconductors that are being used in HTS cables.

**BSCCO:** $Bi_2Sr_2Ca_2Cu_3O_{10}$ (Bi-2223)
- Multifilamentary structure in silver matrix
- Available in km length
- Conductor current densities of 100 A/mm² and above commonly available

**YBCO:** $YBa_2Cu_3O_7$ (Y-123)
- Coated conductor with multilayer structure
- Current densities approaching 100 A/mm² in tape lengths of hundreds of meters
- Current densities and available tape length rapidly improving
- Inherently better price/performance ratio than BSCCO
**Cold dielectric cable**

A cold dielectric superconducting power cable employs concentric layers of HTS wire separated by the high voltage insulation material, commonly referred to as the dielectric. Superconducting tapes (cooled by liquid nitrogen) are both inside and outside the dielectric, and consequently the dielectric itself is also immersed in liquid nitrogen. This ‘cold dielectric’ gives the cable design its name.

The inner, high voltage layer(s) of superconductor tapes are transmitting power while the outer layer(s) are grounded. In the outer layers, currents equal in magnitude but opposite in phase to the inner layers are being induced. These induced currents completely cancel the electromagnetic fields of the inner layers, so that a cold dielectric HTS power cable has no stray electromagnetic fields outside the cable, no matter how high its current (and thus transmission power) rating. This is one of the key benefits of the cold dielectric design. The fact that the electromagnetic field is contained inside the superconducting screen also significantly reduces the cable inductance, another important benefit of HTS power cables.

**Warm dielectric cable**

This simpler design of HTS power cables is the ideal choice when electromagnetic stray fields can be tolerated and a slightly lower transmission capacity than that of a cold dielectric cable is acceptable. Its high voltage phase layer(s), consisting of superconducting tapes, are stranded around a core that also serves as the channel for the liquid nitrogen coolant.

Unlike in the cold dielectric design, there are no superconducting screen layers requiring cooling, and consequently the dielectric is kept at ambient temperature, or warm. As this cable design has higher electrical losses and a higher inductance when compared to a cold dielectric design, it has its place in applications where conventional cables have reached their limits but not all the features of a cold dielectric design are necessary. In such situations, it can be the choice that makes the best economical sense, owing to its simpler overall design, cheaper manufacturing cost, and reduced superconductor length.
Interest in the field of superconducting power cable dates back to the 1960’s, but because conventional metallic superconductors required cooling with liquid helium, these cable system designs were unduly complex and cost prohibitive. Interest in the field was renewed following the discovery of ceramic-based high-temperature superconductors in the late 1980’s, which enabled the use of liquid nitrogen as a cooling medium at about -200 °C. Liquid nitrogen is widely used in a variety of industrial applications and is recognized as a cheap, abundant and environmentally benign coolant.

Nitrogen is an inert gas that constitutes 79 % of the atmosphere.

**Superconducting cable systems**

**HTS cable termination**

The HTS cable terminations as part of the superconducting cable system provide the interface between the cable and the rest of the grid. The superconducting cable termination:

- Manages the thermal gradient from 77 K to 300 K
- Provides electrical field control across the interconnection
- Connects the superconducting cable to the cooling system
- Compensates the thermal shrinkage of the cable during cool down
Nexans is using its extensive experience in high voltage cables and accessories to manufacture superconducting cables using existing industrial processes. With the same flexibility to meet customer demand for conventional cables, we adapted existing machines to meet the technical demands of the superconducting material.

In cold dielectric cables employing PPLP (PolyPropylene Laminated Paper), the lapped dielectric is designed to meet the demands on dry bending properties as well as high voltage insulation once impregnated with liquid nitrogen. For warm dielectric cables, Nexans’ vast experience with extruded XLPE (cross-linked polyethylene) insulation systems also ensures superior performance.

For superconducting cables Nexans is able to produce the cryogenic envelope around the cable core utilizing the UNIWEMA® technology with more than 30 years of experience in cryostat design and manufacturing a long term high quality vacuum can be ensured to prevent thermal losses.

Stranding of superconducting tapes using industrial process
• Existing machines adapted to meet specific requirements of the superconducting material

Dielectric manufacturing on conventional machines
• Specific dielectric design to meet demands on bending properties and high voltage insulation

Cryogenic envelope tube welding using UNIWEMA® technology
• Cryostat manufacturing around the cable core

Benefits of VLI Superconducting Cables

Lower voltages
Because of the higher capacity of VLI (Very Low Impedance) cable - approximately three to five times higher ampacity than conventional cables - utilities may employ lower voltage equipment, avoiding both the electrical (I²R) losses typical of high current operation and the capital costs of step up and step down transformers. High current VLI cables at 115 kV or even 69 kV may solve problems that would ordinarily require a 230 kV or 345 kV conventional solution.

Easier installation
HTS cables are actively cooled and thermally independent of the surrounding environment.

Life extension and improved asset utilization
Over time, thermal overload ages and degrades cable insulation. By drawing flow away from overtaxed cables and lines, strategic insertions of VLI cable can „take the heat off” urban power delivery networks.

Reduced electrical losses
In optimized designs, lower net energy losses occur in VLI cables, than in either conventional lines and cables or unshielded HTS cables with a single conductor per phase, offering a transmission path with high electrical efficiency. Because VLI circuits tend to attract power flow, they will naturally operate at a high capacity factor, reducing the losses on other circuits and further magnifying their efficiency advantage.
Benefits of VLI Superconducting Cables

Indirect and non monetary savings
In addition to these “hard cost” savings, VLI cables may result in other “soft cost” savings. For example, time to install may be shortened because of reduced siting obstacles associated with compact underground installations and less burdensome siting requirements for lower voltage facilities. VLI cables might be routed through existing, retired underground gas, oil or water pipes, through existing (active or inactive) electrical conduit, along highway or railway rights-of-way, or through other existing corridors.

Reduced regional congestion costs
Finally, and perhaps most significantly, the ability to complete grid upgrade projects more quickly will translate into the earlier elimination or relaxation of grid bottlenecks. Solving physical bottleneck problems will sharply reduce the grid congestion costs that, in today’s unsettled, imperfectly competitive marketplace, can impose huge penalties on consumers and the economy at large.

Underground installation
The underground installation of VLI cable eliminates the visual impact of overhead lines.

Environment friendly dielectric
Liquid nitrogen, the coolant/dielectric of choice for VLI cables, is inexpensive, abundant and environmentally benign.

Elimination of EMF
The coaxial design of VLI cold dielectric cables completely suppresses electromagnetic fields (EMF).

Test Field
Nexans tests superconducting power cable systems and their accessories in their one of a kind test field in Hanover, Germany. Combining state of the art high voltage and cryogenic equipment, the test fields is suitable for superconducting power cables and other superconducting high voltage applications, such as fault current limiters.
A 30 m x 12 m x 9 m screened cabin provides ample space to install and test superconducting power cables and their accessories. The cable system is connected to a cooling system outside the cabin.

Liquid nitrogen is circulated through the cable loop and a heat exchanger, which allows adjustment of the liquid nitrogen temperature over a wide range. In combination with variable flow rates, the complete spectrum of operating conditions of superconducting power cables can be evaluated and verified.

Gaseous nitrogen is used to cool down and warm up test objects. An automated temperature control system can provide a constant temperature gradient during cool down and warm up.

All relevant test data is recorded by a computer based measurement system that records temperatures, pressures, voltages and currents during cooling down and the tests.

Making use of a high-voltage transformer, the cable dielectric is evaluated by measuring partial discharges, loss angle and cable capacitances.

### Test equipment data

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<tr>
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<tbody>
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<td>AC Voltage</td>
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<td>Impulse Voltage</td>
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<tr>
<td>AC Current</td>
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<tr>
<td>DC Current</td>
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### Cooling system data

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<tr>
<td>Mass flow</td>
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<tr>
<td>Pressure</td>
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