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Superconductor Cables: Advanced Capabilities for the Smart Grid

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The need to make major improvements in the nation's power grid is widely recognized, with Title XIII of the Energy Independence and Security Act of 2007 providing the needed legislative and political support for a "smart grid." The National Energy Technology Laboratory's (NETL) Modern Grid Initiative identifies seven principal characteristics defining the features and functions essential to meeting the performance requirements of such an improved power delivery system. Three of these characteristics are the ability to self-heal, to resist attack, and to improve power quality. "Secure Super Grid" technology, described in this article, is a system-level solution using superconductor cables that addresses all three criteria.

Southwire installing Triax HTS cable at American Electric Power in Columbus, OH. Photo courtesy of Southwire Co.

High temperature superconductivity (HTS) is one of the identified advanced components of the modern grid initiative. Various types of utility equipment leveraging HTS wire are in development, including fault current limiters, synchronous condensers, transformers, motors, and both conventional and wind turbine generators. And, HTS power cables, having already been demonstrated in the power grid, are now ready for commercial deployment. The incorporation of secure super grids technology in HTS power cables provides electric utilities with a powerful tool for dense urban power grids.

Field Experience and New Capabilities Advance HTS Cables

HTS power cables are made with superconductor wire instead of traditional copper or aluminum conductors. Inasmuch as HTS cables are capable of carrying much more current and have significantly lower impedance than conventional cables, they facilitate more efficient AC power flows within the grid. These characteristics allow HTS cables to be strategically placed in the grid to draw flow away from overtaxed conventional cables or overhead lines, thereby relieving network congestion. Lower impedance cables can also ease grid congestion and enable new, more flexible grid configurations. Combined with conventional, proven technology such as series reactors or phase angle regulators, HTS cables provide the opportunity to control power flow directly—a characteristic typically associated with DC transmission.

Various demonstrations over the last several years have documented the range of operational configurations and problem-solving potential of HTS cables. For example, American Electric Power is nearing the end of a two-year field trial of HTS cable at AEP's Bixby Station outside of Columbus, Ohio. About 200 meters (approx. 660 feet) of Southwire's unique Triax HTS cable is reliably serving more than 50 MW of load to approximately 8,600 customers. The HTS Triax cable system at AEP's

Southwire Triax HTS cable termination installed at American Electric Power's Bixby Substation. Photo couretesy of Southwire Co.

substation has worked flawlessly since August 2006.

The Triax HTS cable was developed jointly by Southwire and Germany's nkt cables. The cable's triaxial construction significantly lowers HTS cable costs by placing the three-phase conductors concentrically around a common central core, surrounded by a copper shield. This compact design reduces by up to half the quantity of HTS wire needed. It also reduces what is known as the cable's cold surface area, and with it the energy and cost associated with cryogenic cooling requirements. All of these innovations lower the total cost of HTS systems.

Other HTS cable projects have achieved similar success in the U.S. Long Island Power Authority (LIPA) commissioned the world's first HTS power transmission cable system in a commercial power grid in April 2008. The most ambitious HTS cable project to date, LIPA's 138-kV system, consisting of three single-phase HTS power cables, is now operating successfully in LIPA's Holbrook transmission right of way. Operated at full capacity, LIPA's new HTS cable system can transmit up to 574 MW of electricity. Like the AEP Bixby project, the cable system utilizes HTS wire produced by American Superconductor (AMSC), which also acted as the prime contractor for the LIPA project.

Approximately 40 miles to the west, in Manhattan, Consolidated Edison is spearheading a project that showcases the latest development in HTS technology: cables with inherent fault current limiting capability. Since mid-2007, Con Edison, AMSC, Southwire and the Department of Homeland Security (DHS) have combined their efforts to demonstrate the fault current carrying capability of HTS cables. AMSC is producing the special HTS wire for the project, with Southwire handling the cable's design, fabrication and installation.

Code-named "Project HYDRA," this new technology combines HTS wire's ability to carry very large amounts of power with its unique ability to automatically suppress fault currents. Secure Super Grids utilize customized HTS wires, HTS power cables and ancillary controls to provide high ampacity, low impedance, fault current limiting capability for the grid.

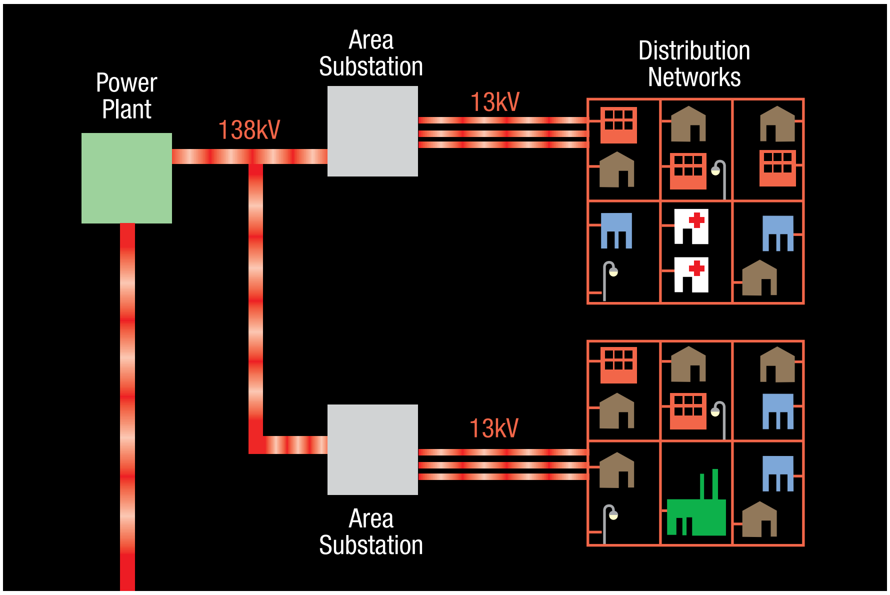
The Modern Smart Grid: Self-healing and Attack-resistant

In the context of urban settings, the Con Edison project illustrates how the flexibility inherent in an HTS cable system can mitigate the historical grid problems common to dense urban areas where large and growing concentrations of load need to be carried in constrained spaces.

Con Edison provides electric service to essentially all of New York City, serving the island of Manhattan over a distribution system organized as shown in Figure 1. Con Edison operates individual load islands using multiple underground feeds from an area substation. Typically, a substation

Figure 1

"Islanded" electric distribution networks serving residential and commercial customers in Manhattan. *(Courtesy of Con Edison)*



consists of five 65 MVA 138-13 kV transformers, serving about 150 MW of load. The utility's security standards mandate N-2 contingency capabilities—that is, no loss of distribution capacity even with two substation transformers off-line. This configuration is common to many urban power grids around the world.

This network carries an implicit drawback: no electrical connections exist between the individual islands. As a result, if one or more transformers are lost at an area substation (or if one or more 13-kV feeds to the distribution network go down), that portion of the distribution network cannot call upon excess load-serving capacity from adjacent distribution networks.

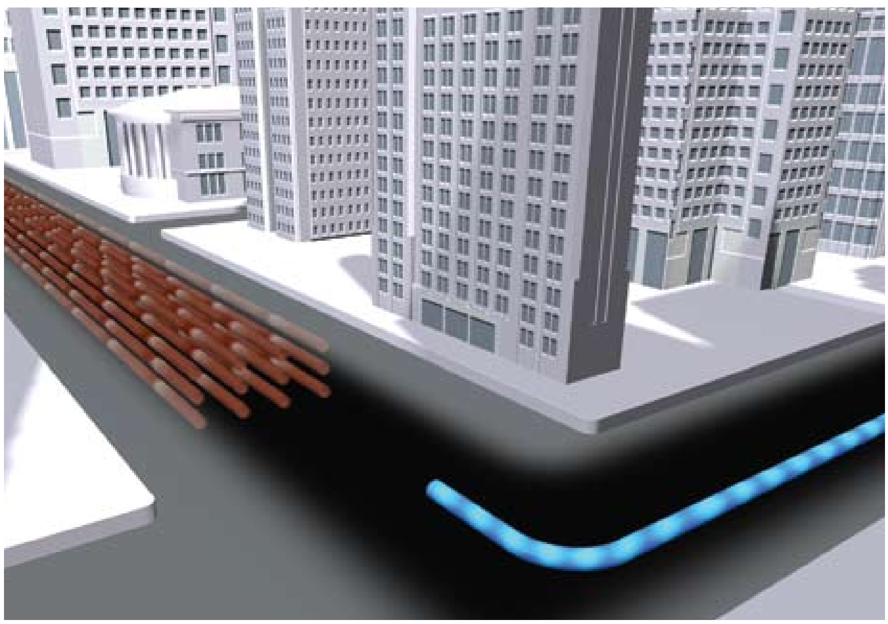
To meet the growing energy need, Con Edison is deploying a novel electric power distribution system that connects area substation secondaries via high-capacity underground "interties." In concert with these changes, Con Edison is splitting its larger distribution networks into smaller ones, each served from multiple 13-kV sources. As depicted in Figure 2 (page 58), the new network architecture enables area substations to share excess capacity in emergencies while decreasing the number of power transformers required at each area substation. Significantly, it also increases overall reliability by sharing transformers across the grid.

For the compact networks to operate as desired, their substation-to-substation interties require a capacity of 3,000 to 5,000 Amps or 68 MVA to 113 MVA. This allows area substations to share excess load-serving capacity while creating more secure delivery paths for critical loads. The cross connections increase the network's reliability and, consequently, reduces its vulnerability to failure or acts of terrorism.

Controlling Fault Currents with HTS Cable

In dense settings such as Manhattan, successful implementation of such an expanded intertie capability faces two critical issues: 1.) how to provide the needed ampacity to interconnect the substations while coping with the limited physical space available under city streets; and 2.) how to thwart the propagation of fault currents.

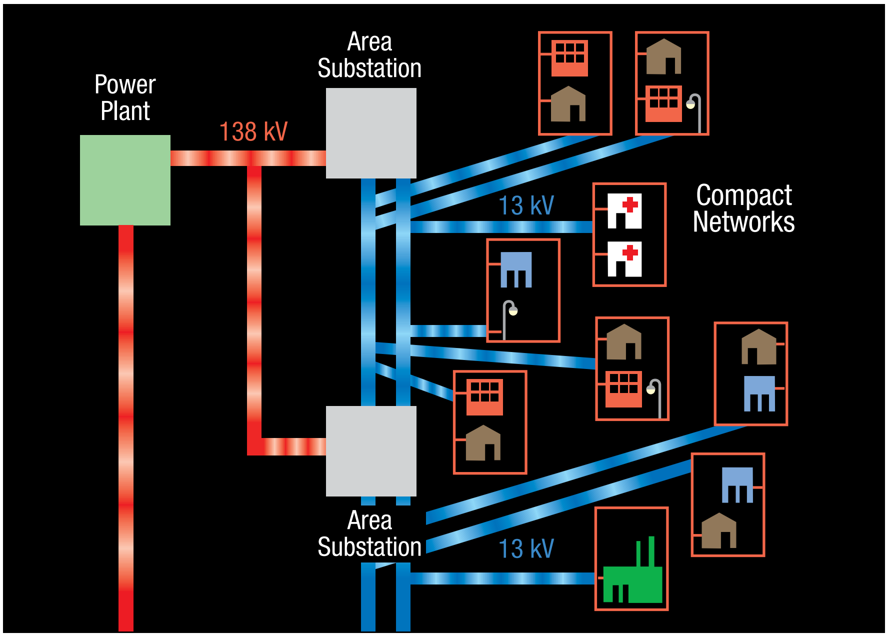
Secondary-side interconnections allow the supply of significant load from adjacent substations. This requires connections that are both high ampacity and low impedance. Low impedance is required to allow power transfer to occur while limiting voltage drop. The low impedance of HTS cables combined with their ability to carry up to five times the current of conventional cables



HTS power cables that require less area and distribute more power can replace over-taxed and aging copper cables in dense urban and metropolitan areas freeing substantial amounts of underground "real estate" that could be used for power, gas, water, sewer and telecommunications networks.

Figure 2

Electric power network using high-capacity substation-to-substation distribution feeders among compact networks. *(Courtesy of Con Edison)*



makes them a logical choice.

Two other characteristics highlight the practicality of using HTS cable where limited physical space is available. The required refrigeration system thermally isolates the cable from the environment; therefore eliminating thermal de-rating considerations as exist with conventional cables. And, HTS cables are essentially free of electro-magnetic field (EMF) radiation. This simplifies siting and health concerns for electric utilities.

Fault current control is often a more challenging issue for grid operators. Generally, distribution interties increase the magnitude of fault currents. A fault current's magnitude is determined by the system voltage divided by the residual impedance of the grid without its load. When additional parallel network connections are made, the impedance drops, and, thus, the magnitude of the potential fault current increases. The momentary voltage drop on the power system that accompanies a fault becomes more pronounced with higher fault currents. Therefore, strengthening the grid with more interconnections may introduce more severe voltage dips when faults occur.

A conventional approach to this problem has been to install additional impedance on the grid, usually in the form of series inductors. Con Edison has instituted such measures in some locations as have other urban utilities, but a high impedance solution has limited effectiveness. As residual series impedance rises and current grows to keep pace with higher loads, voltage drops in direct proportion to both. The consequence is voltage sag—a perpetual power quality issue—and system instability. Since many utilities are rapidly approaching this stability limit, an alternative is needed.

HTS technology offers a unique technical and economic solution to the fault current problem. A fundamental property of HTS materials is that above a critical current level, superconductivity is quenched, meaning they are no longer superconductive. AMSC has developed a special wire that electrically sandwiches a layer of HTS material within layers of resistive material. When a cable is made using this wire, the current flowing through the cable normally is conducted through the very low impedance HTS layer. When a fault occurs that exceeds the HTS material's critical current, the HTS layer quenches and the current is automatically shunted to flow through the higher resistance layer, effectively limiting the fault current's magnitude.

This ability to switch rapidly when a fault current exceeds a critical current is the reason high temperature superconductors have been termed "smart materials." That the laws of physics govern the conductive properties of HTS materials establishes the most important characteristic of HTS-based fault current limiters: They are fail-safe.

A Place for HTS Cables in the Modern, Smart Grid

Both standard and fault current limiting HTS cables offer a unique role in the smart grid by enabling:

- Self-healing properties: Regardless of the method to achieve a self-healing power grid, interconnection points must pre-exist. Constructing these interconnection points by networking urban grids introduces numerous problems ranging from limited right-of-way availability, to the need to control fault current magnitudes, all of which can be addressed by HTS cables.
- Attack-resistance: HTS cables provide the low impedance and high ampacity that allows for simple and easy power transfer between substations to build a tightly meshed urban grid, while also limiting potentially damaging fault current magnitudes caused by intentional acts.
- Improved power quality: HTS cables reduce voltage sag via their lower impedance, and limit voltage dips through their fault current limiting properties. «

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