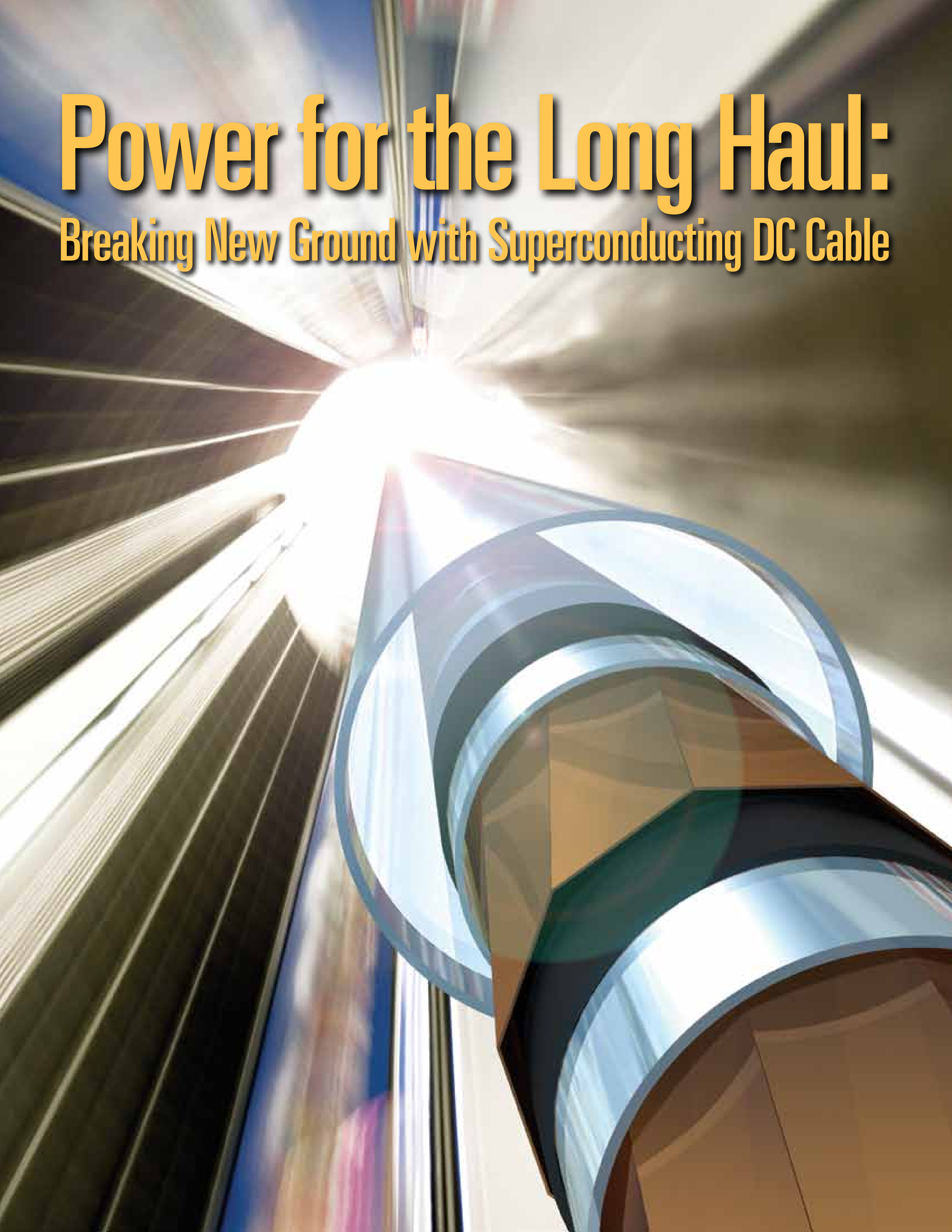
Power for the Long Haul:
Breaking New Ground with Superconducting DC Cable



THE STORY IN BRIEF

Building on decades of ac superconductor R&D, EPRI has designed a first-of-its-kind dc superconducting cable that could be built with currently available materials. The new cable, which incorporates the best features of traditional and advanced bulk power transfer technologies, could be just what is needed to handle the changing transmission demands of the future.

EPRI researchers have developed a conceptual design for a superconducting direct current (dc) cable that could carry 10 gigawatts (GW) of power over 1500 kilometers (km) with near-zero losses and could be built with today's technology. The next steps would be to optimize the design, develop prototypes, and then apply the cable in shorter-length applications such as interconnecting high-power, back-to-back dc converters. With further engineering, the cable could operate effectively as part of the existing grid—enhancing its safety, reliability, and efficiency and enabling a level of bulk power transfer that is not conceivable with today's conventional technology.

Superconducting dc cable systems offer several potential advantages. They can:

- Move massive amounts of power over long distances with lower energy losses, greater reliability, and better stability and security than conventional high-voltage alternating current (ac) or dc systems, increasing the system's efficiency;
- Require smaller rights of way and fewer siting restrictions;
- Carry higher current at lower voltages; and
- Carry large amounts of remotely generated renewable energy over long distances.

"Should large, 5- to 10-GW generation facilities, such as large wind farms or nuclear facilities, become the norm in the next few decades for supplying energy to distant urban areas, new methods of transmitting this level of power over long distances will be needed," said Arshad Mansoor, vice president of Power Delivery and Utilization for EPRI. "On a long-range view, the superconducting dc cable is a promising means to that end."

A series of EPRI reports describe the cable design, further development options, and the practical issues of integrating cable into existing systems by using advanced power electronic converters. The EPRI reports are offered to increase awareness and understanding of the technology and its benefits, and to stimulate further engineering design and optimization.

Reinventing Transmission

A key challenge facing the North American transmission grid is the need to move power over longer distances, noted Steven Eckroad, EPRI program manager for underground transmission.

"Superconducting dc cable systems are inherently suitable for long-distance, high-power bulk energy transfer," said Eckroad. "Moreover, superconducting dc cable offers benefits that are simply not obtainable with the conventional transmission technologies—overhead high-voltage ac lines, overhead high-voltage dc lines, and underground high-voltage dc cables."

Each of the conventional transmission technologies has advantages and disadvantages.

Overhead high-voltage ac transmission is the backbone of today's grids. Increasing ac transmission voltage is the norm for increasing power flow in the near term. Overhead ac transmission accommodates multiple "local" connections but is less suitable for point-to-point, long-distance power transfers. Controlling power flows can be an issue, which may lead to the potential for serious voltage problems and system instability. For long lines, the need for reactive power compensation is a significant cost and operations burden.

Overhead high-voltage dc lines are generally more efficient than ac lines for long-distance, high-power point-to-point transmission and are increasingly used worldwide to carry remotely generated energy over long distances to population centers. To interconnect with the ac grid, high-voltage dc lines require power electronic converters, which add significant cost. As a result, dc lines become cost-competitive with ac only beyond a break-even distance, where the dc line's lower cost per unit length compensates for the converter cost. Unlike ac lines, overhead dc lines typically carry power along a single corridor without connections that deliver power to local loads.

Underground high-voltage dc cables avoid visibility and siting issues of overhead lines and offer greater reliability because they provide better protection from natural and man-made catastrophic events. High-voltage dc cables can deliver power at multiple off-ramps by using advanced voltage source converters, which make it possible to change the direction of power flow at many different nodes, providing the ability to feed power into and extract power from the system at many locations. However, voltage ratings for dc underground cables have not reached the levels of their overhead counterparts, and underground cables generally take longer

Building on Progress in AC Cable

The EPRI superconducting dc cable design builds on advances in superconductivity, innovative dc cable technology, and a series of demonstrations and in-grid projects with ac superconducting cables.

Superconductivity—the ability of some materials to carry electricity with zero resistance—was discovered in 1911. Although its potential for carrying power was recognized, the technology was uneconomical because materials had to be cooled with expensive liquid helium to extremely low temperatures (approximately –269°C) before they could superconduct. A lower-cost option emerged with the 1986 discovery of ceramic-based high-temperature superconductors, which are superconductive when cooled with liquid nitrogen to about –205°C.

Today, superconductivity is being put to use in power systems around the world. Projects to demonstrate ac superconducting cables in power grids have increased internationally as the technology improves and utilities seek to ease urban power congestion.

Superconducting cables provide three to five times the power capacity of conventional cables in the same physical space, enabling utilities to serve growing demand by using existing underground cable ducts. Superconducting cable systems also may be an effective option where rights of way are difficult to obtain.

In a pioneering 1999 demonstration project catalyzed by funding from EPRI and the U.S. Department of Energy (DOE), Detroit Edison installed the world's first high-temperature superconductor cables in a utility network to upgrade its downtown distribution system. Shortly before commissioning, project engineers discovered leaks in the system's vacuum thermal insulation, preventing the cable from operating as intended. Nevertheless, the project provided lessons for several additional in-grid demonstrations supported by DOE's Superconducting Power Equipment Program.

In one DOE-sponsored demonstration, American Electric Power has been operating a 200-meter high-temperature superconductor ac cable for more than three years. The 13.2-kilovolt (kV) cable provides a link between the secondary of a 138-kV/13.2-kV step-down transformer and the 13.2-kV bus. In a second demonstration, Long Island Power Authority in 2008 commissioned the world's first and only high-voltage transmission cable based on high-temperature superconductors. At 600 meters, the underground 138-kV system is the longest in-grid cable to date, linking a Long Island substation to overhead lines.

A proposed Entergy project in New Orleans, La., involves delivering power to growing residential and commercial areas where space constraints make new substation construction costly and problematic. Superconducting cable enables utilities to bring in transmission levels of power at distribution voltages, avoiding the need for substation transformers to step down voltage. The project will feature a 1.1-mile-long superconducting cable connecting a 230-kV/13.8-kV substation to a neighborhood site that is not large enough for high-voltage transformers.

Superconducting ac cable demonstrations also are planned or under way in Korea, China, Japan, Russia, and the Netherlands.

EPRI tracks these projects and reports on them in a series of annual Technology Watch reports that, like the superconducting cable reports, are available free as an educational service. The reports (1017792, 1015988, 1013990, and 1012430) offer tutorials on cable construction, technology, and operations, as well as status updates on cable demonstrations.

to repair because they require excavation.

"As with every other technology, the superconducting dc cable will have its pluses and minuses," said Eckroad. "But we think the design of the cable achieves some of the best features of all the options for moving bulk power."

Superconducting dc cable offers the following features:

- The massive power transmission capability of conventional high-voltage ac and dc lines;
- The efficiency and cost advantages of high-voltage dc lines, with even lower losses;
- The multiple off-ramp capability of high-voltage ac lines and of underground dc cables with voltage source converters;
- The unobtrusiveness and higher reliability of underground dc cables;
- The system control characteristics of dc transmission lines and links; and
- The potential to avoid electric and magnetic field (EMF) radiation.

"The key to the advantage of a superconducting dc cable is that the cable itself, excluding the converters, has no electrical losses," said Eckroad. "With other technologies, losses increase with the amount of power transmitted and with distance, especially with overhead ac. Of course, the superconducting cable must be kept cold, and the refrigerator power must be counted as a loss—but the loss is more or less constant and not proportional to the power transmitted on the cable. As a result, the percentage losses in a superconducting cable will be substantially lower than those with other transmission technologies. The more power transferred and the longer the distance, the more attractive this technology becomes."

The absence of electrical loss enables superconducting cables to carry high current at low voltage, in contrast to conventional aluminum or copper conductors, which require higher voltage to carry more current while minimizing losses.

"Superconducting cable changes the paradigm when it comes to increasing power," said Eckroad. "Instead of going to higher voltage to move more power, with superconducting cable you go to lower voltage and higher current—essentially providing transmission-level power at distribution voltages, which may reduce the need for large substation transformers to step down voltage to distribution levels."

Design Concepts and Grid Integration

EPRI researchers decided to pursue an interregional cable that would carry 10 GW over 1000 km or more, with nominal current and voltage of 100 kiloamperes and 100 kilovolts. Such a system could connect large power grids, transporting power from remote energy facilities to urban load centers with minimal environmental impact and without requiring transformation from transmission- to distribution-level voltages. This superconducting superhighway would serve multiple, distributed generators and loads, using voltage source converter technology for the power on- and off-ramps.

To ensure reliability and availability, EPRI designed for full redundancy in the cable system. Each circuit would have two cables in parallel, each with full 10-GW power capability. During normal operation, each would carry approximately half of the power. If there were a limitation of one cable, the other could carry the total load.

To address potential cable failure, modeling studies tested the assumption that loss of a dc transmission line carrying many gigawatts could cause voltage instability or frequency transients in the ac system. Results showed the ac system to be resilient to loss of the superconducting cables. Findings for long-distance cable routes in the eastern and western United States indicated that the eastern grid can accommodate the loss of a 10-GW superconducting dc cable and that the western grid can accommodate an 8.5-GW loss. These studies represent possible scenarios and are not necessarily prescriptive for all possible transmission paths.

Sharing Results, Reducing Costs

The three recently released EPRI reports are expected to stimulate interest and further development of the technology. American Superconductor, which manufactures high-temperature superconductor wire, is already using EPRI results to design a dc superconductor cable system for a proposed project to link the three U.S. electricity grids.

The three grids (the Western Electric Coordinating Council, the Eastern Interconnect, and the Electric Reliability Council of Texas) operate asynchronously, making it necessary to use back-to-back dc converters to move power from one region to another. The project, proposed by New Mexico startup company Tres Amigas, LLC, aims to link the three grids by means of three ac-dc-ac converter terminals linked by 5-GW superconducting dc cables.

"This project, if it goes forward, would help advance superconducting dc technology," said Eckroad. "Increased production of superconducting wire could help bring costs down and make long-distance superconducting cable more cost-competitive."

Next Steps and Future Work

Superconducting dc cable has been taken to a level of engineering design at which EPRI is confident of the concept's practicality and readiness for optimization and commercial development. Considerable work remains to be done before a final system can be fabricated and installed. EPRI researchers recommend a phased program to systematically develop the commercial prototype.

"The next step is to test the concept on a model cable system," said Eckroad. "A scalable model cable of approximately 60 to 100 meters, incorporating all the electrical and mechanical components, would provide a critical, early evaluation of a superconducting cable system. The model testing could be performed in a laboratory and then scaled up to a demonstration at a utility substation. This early testing and evaluation will provide information to guide future activities in design optimization and detailed engineering solutions."

This article was written by David Boutacoff. For more information, contact Steven Eckroad, seckroad@epri.com, 704.595.2717.

Further Reading

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Steven Eckroad is a senior technical manager and program manager for EPRI's Underground Transmission program. He also manages power delivery applications for superconductivity and supports the Institute's Energy Storage program. Before joining EPRI in 1992, he worked at EnerTech Energy Technology Consulting, which he founded, and earlier at Bechtel Group. Eckroad received a B.A. in physics from Antioch College and carried out postgraduate studies in electrical engineering at the University of Missouri at Rolla.