162 HVDC Systems

Program Overview

Program Description
This program offers a comprehensive portfolio on high-voltage direct current (HVDC) technologies for application to existing, new, and future HVDC systems. For owners and operators of HVDC systems, the program offers the best-of-breed operation and maintenance strategies to extend life spans and enhance reliability of individual equipment components. For utilities that do not have HVDC systems, the program offers the most up-to-date HVDC technologies that can be adopted on their power system either for bulk power transfer or system performance improvement by taking advantage of the recent advancement in HVDC technologies. For utilities that wish to increase transmission capacity, the project on AC to DC Line Conversion offers an attractive alternative to achieve such goal. EPRI has been a leader in HVDC technologies and will continue this leadership by offering testing facilities in Lenox, Massachusetts, for HVDC technologies and by updating previously published HVDC reference books.

Industry Needs and Issues Addressed
- To extend the lives of HVDC systems as they continue to age and are further hindered by the limited availability of spare parts and information on design and operation history, owner and operators need guides on operation and maintenance of these systems.
- With knowledge of recent HVDC technologies, operators can consider adopting them for either bulk power transfer or power system performance improvements.
- To address global demand for ultra HVDC systems, information is needed on the development of components that operate at UHVDC levels.
- To increase the capability of existing transmission corridors, utilities need methods to increase power flow, enhance flow management, and convert HVAC lines to HVDC lines.
- To optimize HVDC performance, utilities need a comprehensive reference addressing all aspects of HVDC.

Impact
- Extend life spans of individual equipment components, thus improving individual equipment reliability through best-of-breed operation and maintenance strategies. Enable members to extend life spans of existing HVDC systems. Avoid substantial costs as a result of improved and predictable network performance through an optimized maintenance program.
- Introduce HVDC technologies on existing power systems to enhance their performance. Foster improved grid reliability, reducing total system downtime from HVDC systems that allow full control of power flow and enhanced AC system stability. Avoid widespread outages from better HVDC controls, thus saving millions of dollars in avoided costs.
- Improve ability to meet load growth, since high-voltage DC systems provide more economical long distance power transfer than AC overhead lines.
- Introduce HVDC links in existing HVAC systems through AC to DC line conversion, increasing overall system reliability through reduction of widespread outages.
- Enable increased power transfers on existing assets as much as 50 to 70% by AC line to DC line conversion, increasing owner revenues by millions of dollars.
- Defer construction of new lines with new rights-of-way, saving utilities millions of dollars in avoided costs and lowering environmental impact.

Key Accomplishments
- Maintain the High-Voltage Laboratory in Lenox, Massachusetts, as a unique research and testing resource available to EPRI members. The Lenox Laboratory has conducted pioneering research

for 50 years, first under the direction of General Electric and later as a dedicated EPRI center.
- Provide leadership in theoretical and experimental fronts in HVDC, AC/DC conversion equipment, and operation of HVDC systems.

Current Year Objectives
- Resolution of the operational concerns of owners and operators of existing HVDC systems and those considering the addition of HVDC to their systems
- Development of best-of-breed inspection, assessment, and maintenance programs
- Evaluation of Voltage Source Convertor (VSC) based DC transmission and advanced power electronic devices for adoption and to identify the R&D needs to further enhance the use of these technologies at higher voltages
- Design of the highest HVDC system to date (i.e., +/- 800 kV) to meet the global need to increase voltage and power transfer capacity of HVDC
- Update and preparation of a leading guide for the design and operation of HVDC systems.
- Conversion of AC lines to DC lines to increase transfer capability on existing transmission corridors
- Life extension guidelines for HVDC systems, with emphasis on best O&M practices
- Demonstration of technology options at utility sites

Industry Involvement
- Estimated 2009 funding: $0.6M

Program Technical Lead
John Chan, 650-855-2452, jchan@epri.com

Summary of Projects

Project Number	Project Title	Value
P162.001	Life Extension of Existing HVDC Systems	Life extension guidelines for aging HVDC lines, cables, and converter stations (converters, converter transformers, and ground electrode), enabling members to extend the life of their existing HVDC schemes
P162.002	Assessment and Evaluation of Next Generation HVDC Technologies	Assessment of new technologies such as VSC based DC, EHV / UHV DC, and advanced power electronic devices such as GTOs, IGBTs, and IGCTs for adoption of DC technologies on AC systems
P162.003	HVDC Reference Book (Olive Book)	State-of-the-art *HVDC Reference Book* documenting the most current technological information and developments in the HVDC area
P162.004	AC/DC Line Conversion	Development of AC/DC line conversion schemes to increase power transfer capability on existing transmission corridors

Project Descriptions

P162.001 Life Extension of Existing HVDC Systems (062102)

Issue
High-voltage direct current (HVDC) technology has experienced enormous growth worldwide in the past 50 years, and close to 100 HVDC systems are currently in operation. As these systems age, life extension is critical to ensure their ability to meet increasing utility needs. In addition, utilities are encountering repair or replace decisions for many system components, and operation and maintenance (O&M) issues of these aging systems are becoming a challenge. The situation is further complicated in that utilities typically have very few miles of HVDC network compared to miles of alternating current (AC) lines, as well as very few converter substations. Consequently, the body of knowledge about HVDC inspection, assessment, and maintenance is very limited.

Description
This project will focus on developing life extension guidelines of HVDC systems in a systematic way. Sharing experiences and practices among utilities provides one of the most cost-effective ways of ensuring that best-of-breed field practices permeate the industry globally. With the goal of developing best-of-breed practices for dealing with specific components of HVDC systems, the project will undertake the following tasks:

- An audit of HVDC systems, including collection of maintenance records and field information
- A literature survey covering the documented performance of HVDC
- An analysis of O&M procedures to develop a prioritized list of equipment, with the intent of reviewing the failure modes, examining inspection techniques and instruments, and, if appropriate, pulling equipment from the field for further analysis

The resulting suite of practices will guide members in line inspection, assessment, and life extension. Components covered will include insulators, conductors, towers, shielding, grounding, converters, substations, transformers, bushings, and cables. The study will also address the impact of the HVDC system on the broader public, exploring such issues as audible noise, radio interference (RI), electromagnetic interference (EMI), and interference with phone and other systems. Finally, the project will consider live work on HVDC systems.

The guidelines will be published as stand-alone documents and potentially as a single package at a later time. Members will prioritize the order in which components are addressed. The guides will be drafted to enable a utility maintenance manager to develop an inspection program, assess the results received, and prioritize the maintenance actions required. Finally, the guides will help develop the triggers (time or other factors) that govern field inspections.

The EPRI Technical Report *Life Extension Guidelines of Existing HVDC Systems* (TR-1013976) was published in 2007 to address the converter station components. Life extension guidelines for HVDC overhead lines will be developed in 2008. An update of life extension guidelines, as well as guidelines for SVCs, will be developed in 2009 and in future years.

When both AC and DC lines are present on the same tower, AC and DC line interactions may be an issue. At first, all the possible interactions will be studied, and then mitigation techniques will be developed to deal with this issue. Successful mitigation techniques will be demonstrated at some utility sites.

Value

- Improve overall system reliability and avoid unnecessary system outages through evaluation of operation, maintenance, and reliability performance of existing HVDC systems
- Reduce overall costs of power transmission and lower electricity rates to end-use customers by reducing system outage costs
- Increase customer satisfaction by reducing interruptions and lowering energy rates
- Defer construction of new HVDC systems by extending life spans of existing HVDC assets, and thus gain the benefits of avoided costs
- Generate millions of dollars in new revenue by increasing asset utilization of HVDC equipment

How to Apply Results

The project helps utility engineers and managers design refurbishment strategies for their existing HVDC systems, to extend equipment life, evaluate O&M and reliability performance improvement strategies for their existing HVDC systems, and increase existing asset utilization by extending the life of HVDC systems.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Updated Life Extension Guidelines for HVDC Converter Stations & Overhead Lines: Life extension guidelines for converter stations and HVDC overhead lines will be updated with the new R&D results from other projects and using the information published elsewhere.	12/31/2009	Technical Update
Life Extension Guidelines for SVCs: Life extension guidelines for Static Var Compensators will be developed based on the best utility practices.	12/31/2009	Technical Update
Training Course on Life Extension Guidelines: A training course on HVDC life extension guidelines will be organized so that the utilities can participate and learn the guidelines.	12/31/2009	Workshop, Training, or Conference

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Develop Life Extension Guidelines for HVDC Cables: Life extension guidelines for HVDC cables will be developed using the utility best practices.	2010	Technical Update
Develop Live Work Best Practices for HVDC: HVDC Live Work best practices will be developed using the best utility practices. Also HVAC Live Work best practices will provide some insights into this project.	2010	Technical Update

P162.002 Assessment and Evaluation of Next Generation HVDC Technologies (062103)

Issue

An established technology for bulk power transmission, high-voltage direct current (HVDC) power transmission is being used worldwide, and more than 100 schemes are operating presently. Most of the existing HVDC systems use conventional self-commutated converter technology using thyristors. However advances in voltage source converter (VSC) technologies and power electronic devices such as GTOs, IGBTs, and IGCTs will improve system performance and reliability. Also the present highest operating voltage is +/- 600 kV in Brazil, though China and India are ready to build +/- 800 kV lines. Anticipating the higher voltages, considerable research was conducted in the 1980s on various aspects of HVDC beyond +/- 600 kV, notably +/- 800 kV and +/- 1000 kV. In addition, EPRI had earlier sponsored

research to determine critical problems in developing HVDC converter station equipment for voltage levels greater than +/- 600 kV. These studies, as well as work performed by other organizations, including the International Council on Large Electric Systems (CIGRE), concluded that it is possible to build converter stations at +/- 800 kV, but that further research was warranted in such key areas as external insulation in polluted areas, converter transformers, smoothing reactors, and availability of test labs. While +/- 800 kV systems appear technically feasible, numerous research questions remain unanswered. Hence there is a need for the assessment of next-generation technologies such as VSC DC transmission, Ultra High Voltage DC (UHV DC), and advanced power electronic devices, so that utilities can make cost-effective decisions while considering these advancements.

Description

Though the initial thrust of this project was on +/- 800 kV in 2006 and 2007, the scope of this project is expanded to include the evaluation of advanced HVDC systems such as voltage source converter-based DC transmission. In addition the evaluation of the advanced power electronic devices such as GTOs, IGBTs, and IGCTs (as well as Building Block Concepts for HVDC) will be considered. These advancements will improve the system performance and reliability but there are certain limitations, such as the maximum operating DC voltage. The technology evaluation will include the state of the science in each of these areas, as well as a cost-benefit evaluation.

Electric utilities can achieve improved reliability, power transfer capability, and secure market operations by taking advantage of both AC and DC technologies. In this connection, it is possible to divide large interregional AC grids, such as the Eastern Interconnection of the U.S. grid, with DC links based on advanced concepts such as grid shock absorber (VSC based back-to-back DC) for improving reliability and avoiding cascading outages. This project will assess the feasibility and benefits of such advanced concepts for grid segmentation.

This project will also address technology specifications for realizing HVDC systems at +/- 800 kV and above, with the goal of guiding members as they consider and specify these advanced systems. Areas to be studied include conductor bundles, corona, audible noise (AN), radio interference (RI), insulation, transformers, bushing design, ground electrodes, converter configurations, harmonic filters, environmental conditions, energy tap-off options, and system specifications. In 2007, EPRI published *Advanced HVDC Systems at +/-800 kV* (TR-1013857) to address some of these issues. However there is more research needed in realizing an UHVDC system. Specific attention should be given to the following:

- HVDC system configuration
- Reliability and availability in view of the large amount of power transmitted
- AC system requirements and the interaction with the HVDC system
- Equipment testing levels

This project clearly identifies equipment requirements for ultra HVDC (UHVDC) systems at +/- 800 kV and above and undertakes activities in the development of equipment specifications. Designs will be validated in the laboratory and on paper. Project managers will seek close cooperation with equipment manufacturers.

Technical reports will document UHVDC equipment specifications and test results, so that utility engineers can make informed decisions while considering the UHVDC systems at +/- 800 kV and above.

Value

- Increase power transfer amounts on existing transmission corridors substantially by increasing transmission voltages to 800 kV and above
- Enhance grid reliability with HVDC systems embedded into existing high-voltage alternating current (HVAC) systems
- Reduce overall costs for power transfer from remote generation sites to load centers, potentially lowering end-user electricity rates
- Improve customer satisfaction by reducing interruptions
- Enhance financial performance of member utilities by avoided outage costs and increased revenue opportunities

How to Apply Results

This project provides next-generation HVDC systems and technologies for utility engineers to consider while building new HVDC lines and segmenting the large regional AC grids with DC links. Also the project helps utility managers, planners, and engineers identify the major issues in operating HVDC systems at +/- 800 kV and above, establish technical parameters of equipment exposed to HVDC voltages of +/- 800 kV and above, and gain experience in HVDC equipment performance at +/- 800 kV and above through lab and field demonstration tests—solidifying confidence in building UHVDC systems.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Assessment of Next Generation HVDC Technologies Assessment and evaluation of next-generation technologies such as VSC DC transmission, advanced power electronic devices, AC grid segmentation with DC links, and UHVDC, including a cost benefit analysis	12/31/2009	Technical Report

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Lab testing of next generation HVDC technologies: Test some of the next-generation HVDC technologies in a lab environment to determine operating limitations and gain insights into future developments, to enhance these technologies.	2010	Technical Update
Lab testing and demonstration of next generation HVDC technologies: Lab test and demonstrate in the field some of the next-generation HVDC technologies.	2011	Technical Report
Lab testing and demonstration of next generation HVDC technologies: Lab test and demonstrate in the field some of the next-generation HVDC technologies.	2011	Technical Report

P162.003 HVDC Reference Book (Olive Book) (062104)

Issue

A decade ago, EPRI developed two reference books in the high-voltage direct current (HVDC) area:

- *HVDC Transmission Line Reference Book* (102764), which documented overhead HVDC transmission line research performed at EPRI's Lenox Lab and results obtained at other facilities
- *High-Voltage Direct Current Handbook* (104166), which concentrated on terminal components, operation, modeling, cost estimation, control, and protection, alternating current (AC) filters, DC filters, reliability, and efficiency

Many advances have occurred during the last decade, especially in power electronics device applications for HVDC and Flexible AC Transmission Systems (FACTS). Furthermore, because many HVDC systems have been operating around the world for some time, more operational data is available now than it was a decade ago. It is an ideal time to document new developments in HVDC technology, to help members with future decision making and to summarize operational experiences with existing HVDC systems to guide current HVDC system maintenance.

Description
This project will develop an updated *HVDC Reference Book* (also known as the "Olive–colored" book) with the latest information on HVDC technology and operational data for existing HVDC systems. The project will start with a formal peer review of the existing EPRI HVDC handbooks and related reference books, to highlight areas where revision is critical. The handbook's objectives are as follows:

- Guide members in specifying an HVDC system, leading members through each step of the design process, and ensuring that the implications of tradeoffs are well understood. The book will cover the design of the line, converter, and associated converter substations.
- Guide members in considering environmental aspects, since these differ between HVDC systems and AC lines. This handbook will study these aspects and provide members with insights on the interactions between HVDC systems and the broader society.
- Guide members in assessing existing HVDC systems and the options available when addressing repair or replace decisions, and life extension options.
- Provide tools to help optimize HVDC system design.

To foster future developments in the HVDC area, as well as to disseminate technical developments in a timely manner, a biannual HVDC conference or workshop will be organized, co-sponsored by EPRI and members. The handbook and conference will provide valuable insight to utilities presently operating HVDC systems and utilities contemplating HVDC as a possible transmission technology.

The outline of the HVDC Reference Book was developed in 2006, and two chapters—HVDC Lines and Simulation Tools—were developed in 2007. Remaining chapters will be developed in the future and a final HVDC Reference Book (Olive Book) will be issued with all the chapters.

Value
- Provide unbiased, credible technical information about HVDC technology options
- Reduce system outages by ensuring cost-effective operating strategies
- Enhance grid reliability of the integrated AC/DC power system through dissemination of better maintenance strategies
- Ensure safety of utility personnel by providing effective methods for live line work on HVDC systems
- Enable utilities to reduce transmission costs by fostering construction and maintenance of cost-effective HVDC infrastructures to increase power transfer levels
- Provide a comprehensive resource for members to remain abreast of HVDC technology and ensure that utility engineers have the most current information

How to Apply Results
State-of-the-art information about HVDC technology from the most current *EPRI HVDC Reference Book* will help utility management, planners, and engineers simplify cost-effective operation, maintenance, and planning decisions in the HVDC area. The biannual HVDC conference or workshop will help members facilitate technology transfer and the generation of future research ideas.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Bi-Annual HVDC Conference/Workshop and Proceedings: EPRI will organize a biannual conference on HVDC and will invite utilities, manufacturers, and consultants to exchange ideas. The conference proceedings will be distributed with the presentations.	12/31/2009	Technical Update
EPRI HVDC Reference Book (Olive Book): Some Chapters: Some chapters of the HVDC Reference Book will be published as a technical update. The chapters will be selected using the utility advisory input and will be based on their importance for immediate application.	12/31/2009	Technical Update

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
HVDC Reference Book (Olive Book): Some Chapters: Some chapters of the HVDC Reference Book will be published as a technical update. The chapters will be selected using the utility advisory input and will be based on their importance for immediate application.	2010	Technical Update
Bi-Annual HVDC Conference/Workshop and Proceedings: EPRI will organize a biannual HVDC conference and will invite utilities, manufacturers, and consultants to exchange ideas. The conference proceedings will be distributed with the presentations.	2011	Technical Update
HVDC Reference Book (Olive Book): Complete Draft: All the chapters written in the previous years will be integrated into one final HVDC Reference Book (Olive Book)	2011	Technical Report
Final HVDC Reference Book (Olive Book): All the chapters written in the previous years will be integrated into one final HVDC Reference Book (Olive Book).	2012	Technical Report

P162.004 AC/DC Line Conversion (063311)

Issue

Conversion of alternating current (AC) lines to direct current (DC) lines can increase the transmission capacity of long-distance lines by eliminating some AC system-imposed power flow limitations, such as surge impedance loading, line voltage drop, and power loss. Also, AC/DC conversion may extend the thermal limits by more efficient use of the existing insulation system. Advances in power electronic converters at higher voltage, current, and power ratings make it economically attractive to convert AC lines to DC lines. Also as siting and permitting of new transmission corridors becomes increasingly difficult due to environmental and societal constraints, converting existing AC transmission lines to DC may increase power transfer capabilities to satisfy increasing load growth. While AC/DC line conversion appears feasible, many issues need to be investigated.

Description

This project will address all aspects of AC/DC line conversion, including the establishment of DC voltage and DC current ratings, insulation coordination, converters, converter transformers, filters, and economic analysis. This project will also provide a comprehensive analysis of various technological options for AC/DC line conversion and compare these options technically and economically. Field demonstration of these technologies will be conducted, working closely with participants so that the utilities will gain firsthand experience. The operational experience of such converted DC lines will be documented.

The draft report TR1013979 – DC Capability of AC Transmission Lines was published in 2007. More research work will be done in 2008 and 2009, and a demonstration project will be considered in 2010.

Value

- Defer construction of new transmission lines, avoiding major capital investment costs
- Increase overall system reliability through reduction of widespread outages by introducing HVDC links in the existing HVAC system
- Reduce costs of power transmission, potentially reducing electricity rates to end-use customers
- Increase power transfers as much as 50 to 70% over those of existing infrastructures, creating opportunities for increased revenues

How to Apply Results

The project helps utility planners and engineers convert existing AC lines into DC lines and thus increase capacity throughput on existing corridors. The project provides multiple technological options to convert AC lines to DC lines, provides operational experience in AC/DC conversion, and provides benefit cost comparisons for each type of AC/DC conversion technology.

2009 Products

Product Title & Description	Planned Completion Date	Product Type
Develop AC/DC Conversion Technologies: The technologies needed to convert existing AC lines into DC operation will be developed with the goal of increasing power flows on the existing transmission corridor.	12/31/2009	Technical Update

Future Year Products

Product Title & Description	Planned Completion Date	Product Type
Demonstrate AC/DC Conversion Technologies at Utility Sites: This project will demonstrate the AC line conversion to DC operation at a host utility site.	2010	Technical Update