HVDC Transmission - Program 162

Program Overview

Program Description
The electric power industry is faced with difficulties in acquiring right-of-ways. It is also faced with the challenge of integrating renewable power sources into an ac power system. As well, it is under pressure to improve the reliability of the power grid. High-voltage direct current (HVDC) offers many features to meet these challenges. For example, by converting an ac line to dc, an electric utility is able to raise the power transfer capability of an existing transmission corridor. HVDC technology can be a solution for the integration of renewable power sources such as wind and solar energy into an ac power system. HVDC links could be installed by a utility to isolate its power system from neighboring utilities or to control power transfer between two systems. For these reasons, HVDC technology has been identified as a key component for the future smart grid.

Flexible ac transmission system (FACTS) technology offers an alternative to dc. FACTS can be used to control power flow. Both HVDC converters and FACTS share some common technologies. Therefore, a FACTS supplemental project is included in this HVDC program to provide an alternative option to the industry.

Research Value
HVDC technology is developing and its application has been extended beyond its traditional role of bulk power transfer. The electric power industry has to understand the evolved applications in order to take full advantage of this technology. This program provides the following:

- Technology awareness through technology watch newsletters, conferences, and workshops
- Experience of recent HVDC technologies, integration of HVDC into an ac system, HVDC electrical effects, and system and component performance to members who are considering adopting HVDC for either bulk power transfer, power system performance improvement, and integration of renewable power sources or transmission system flow management
- Options to increase the capability of existing transmission corridors by providing methods to convert high-voltage alternating current (HVAC) lines to HVDC lines, to construct hybrid ac and dc lines, and to enhance power flow management using HVDC or FACTS

The program offers comprehensive information for both owners and non-owners of HVDC systems.

Approach
Electric Power Research Institute (EPRI) research in HVDC yields a variety of data and information that may be beneficial to program members. This information will come in a number of forms and is expected to include the following:

- Evaluate and mitigate impacts of integrating an HVDC system into an AC grid
- Evaluate and test HVDC components and system performance
- Study HVDC electrical effects such as corona, audible noise, electromagnetic interference (in both radio and TV frequencies), and electric fields and ions, so that companies can better understand how dc lines may affect their environment
- Develop strategies and guidelines for converting ac lines to dc lines to increase and manage transfer capability on existing transmission corridors
- Evaluate voltage-source converter (VSC)-based dc transmission and advanced power electronic devices for adoption and identify research and development (R&D) needs to further enhance the use of these technologies at higher voltages
- Provide leadership in theoretical and experimental fronts in HVDC, ac-to-dc line conversion, hybrid ac and dc, and the operation of HVDC systems
- Demonstrate HVDC technology options at utility sites
- Provide HVDC technology awareness by publishing reports and organizing industry-wide conferences and workshops
- Publish HVDC reference guides for the design and operation of HVDC systems

**Accomplishments**

In the past, the HVDC Transmission program has delivered valuable information that has helped its members and the industry in numerous ways. Some examples include the following:

- **HVDC Embedment:** This study investigated some effects of integrating HVDC into an ac grid and resolved some operational concerns of owners and operators of existing HVDC systems and those considering the addition of HVDC to their systems. The study continues.
- **VSC Technology Preferred Option for Connection in a Multi-terminal DC Grid Configuration:** This report looked at the technical challenges that are needed making dc grids feasible, and identified topics that needed to be addressed. It helps members to understand multi-terminal dc lines and options to operate more complex dc topologies and technologies. VSC technology is the preferred option for connection in a multi-terminal dc grid configuration.
- **Life Extension Guidelines for HVDC Converter Stations and Transmission Lines:** The guidelines help utilities extend life spans of individual equipment components, thus improving individual equipment reliability through best-practice operation and maintenance strategies. They help members avoid substantial costs as a result of improved and predictable network performance through an optimized maintenance program.
- **HVDC Reference Book:** The reference book provides state-of-the-art information for planners, designers, and operators.
- **AC-to-DC Line Conversion:** This study assessed the reliability impact when introducing HVDC links to existing transmission systems by converting selected ac lines to dc. Such conversions may increase power transfers on corridors by as much as 50–70%.
- **Testing:** Data from HVDC equipment and component tests at the EPRI Lenox laboratory provides members with valuable information.

**Current Year Activities**

- Provide a technology watch newsletter with the latest developments in HVDC technologies
- Update the leading reference guide for the design and operation of HVDC systems
- Evaluate the impact of integrating HVDC into an ac system
- Resolve operational concerns of owners and operators of existing HVDC systems and those considering the addition of HVDC to their systems
- Evaluate HVDC system performance and conduct component testing
- Evaluate HVDC electrical effects such as electromagnetic interference, fields, and corona in laboratory test settings
- Arrange a demonstration of ac-to-dc line conversion at a utility site

**Estimated 2014 Program Funding**

$1.3M

**Program Manager**

John Chan, 650-855-2452, jchan@epri.com
Summary of Projects

PS162A HVDC Technology Assessment and Evaluation (069266)

Project Set Description
This project set offers technical information to electric power utilities on high-voltage direct current (HVDC) systems. The information covers both new technologies and experience gained in the past 50 years from operating HVDC systems. New applications of HVDC technology are reviewed, investigated, and examined. The impact of a new HVDC system on the existing ac system is studied. This project set is suitable for members who are interested in improving their knowledge of HVDC for traditional and new applications. It will help members in the selection of proper HVDC technologies for their applications. Knowledge transfer will be in the form of technology watch newsletters, reference books, workshops, conferences, and studies.

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<tr>
<th>Project Number</th>
<th>Project Title</th>
<th>Description</th>
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<tbody>
<tr>
<td>P162.003</td>
<td>HVDC Technology Surveillance and Reference Guidelines</td>
<td>This project will periodically publish a newsletter with the latest information on current and new HVDC developments and installations, as well as update the HVDC Reference Book. In addition, an HVDC conference or HVDC workshop will be organized every year to disseminate technical information on latest HVDC technologies.</td>
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<tr>
<td>P162.004</td>
<td>Applications of HVDC Technology and New Developments</td>
<td>This project will address various HVDC applications. One of the applications is connecting renewables to the grid. It also will provide different transmission interconnection options based on technical and economic benefits. Further, it will explore and address issues related to designing and operating dc grids, dc circuit breakers, and dc-to-dc transformers.</td>
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<tr>
<td>P162.009</td>
<td>Integrating HVDC in an AC Grid</td>
<td>This project addresses various system impacts when HVDC interconnections are implemented in a meshed ac grid. Overall transmission capacity can be increased by adding HVDC interconnections with greater flexibility in controllability and increased reliability.</td>
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</table>

P162.003 HVDC Technology Surveillance and Reference Guidelines (062104)

Description
It is important that the power industry has access to the latest developments and advances in high-voltage direct current (HVDC) technology. The Electric Power Research Institute (EPRI) continues to build a comprehensive library of information on HVDC technology for the benefit of the industry. EPRI has been developing reference materials that capture and consolidate related HVDC information and knowledge.

Approach
This project seeks to enhance the knowledge of HVDC technology in the following ways:

Publish HVDC Technology Watch newsletters: To foster new developments in the HVDC area, as well as to disseminate technical developments in a timely manner, a newsletter will be published periodically with the latest information on current and new HVDC installations taking place around the world. The HVDC Technology Watch tracks developments in HVDC technologies such as the following:
• VSC dc transmission for both overhead and underground
• Application of dc for integrating renewables and other new power sources
• Segmentation of ac systems with dc ties
• New cables for dc operation.

Organize HVDC Conference or Workshop: An HVDC conference or workshop will be organized every year to facilitate technical information exchange, and it will be sponsored by EPRI and utility members.

Update the HVDC Reference Book: Information will be developed for the HVDC Reference Book (also known as the Olive Book). Research will help capture the latest information on HVDC technology and operational data for existing HVDC systems. A formal peer review of the existing EPRI HVDC handbooks and related reference books led to recommendations for critical reference book revisions. The handbook will provide the following:

• Guide members in specifying an HVDC system by leading them through each step of the design process and confirming 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 the environmental aspects of these systems, since they differ between HVDC systems and ac systems. This handbook will study these aspects and provide members with insights into 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.

In December 2010, an Interim HVDC Reference Book (1022330) with 12 chapters was published. An additional seven chapters were updated in 2011 (1021954), and the remaining five chapters were updated in 2012. An electronic version of the HVDC Reference Book with all 24 chapters (1024318) was published in December 2012. Additional chapters on new topics such as life extension, ac-to-dc conversion, grounding, live-line work, dc insulators, HVDC embedded into ac grid, ac and dc on the same right-of-way, siting of HVDC, upgrading (voltage and current upgrade) of HVDC, HVDC control interactions with other controllers, fault location in HVDC lines and cables, multi-terminal dc, dc grids, dc circuit breakers, and other relevant HVDC subjects will be added to the HVDC Reference Book in 2013 and beyond. Also some of the chapters, such as VSC dc transmission and electrical effects, will be updated in 2013 and beyond with the latest technology developments. An updated version of the HVDC Reference Book in electronic form will be available at the end of each year. Based on potential demand, a hardcopy version may be published. A tutorial—consisting of a Power Point presentation with course notes—will be developed in 2014 and onwards, and members will be able to use that to train utility engineers in a self-study mode or in a classroom setting. Industry workshops based on the tutorial will be provided in future years.

The technology watch, conference, and reference book provide valuable insights into HVDC technologies for companies presently operating HVDC systems and those contemplating HVDC as a possible transmission option.

Impact
• Increase understanding based on technical information about HVDC technology options
• Enhance dc power system reliability and availability through performance and maintenance improvement strategies
• Enable companies 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 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 managers, planners, and engineers simplify operation, maintenance, and planning decisions in the HVDC area. The technology watch newsletter and the annual HVDC conference or workshop will help members facilitate technology transfer and the generation of future research ideas.

**2014 Products**

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<tr>
<td><strong>HVDC Tech Watch - Newsletter:</strong> This HVDC Technology Watch newsletter will document the latest information on existing and newly planned HVDC installations around the world. In addition, it will highlight the latest technology breakthroughs in this area.</td>
<td>12/31/14</td>
<td>Technical Resource</td>
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<tr>
<td><strong>Updated HVDC Reference Book (Olive Book) &amp; Tutorial for some chapters:</strong> A tutorial—consisting of a PowerPoint presentation with course notes—will be developed for some chapters of the HVDC Reference Book, which could be used for training in the classroom setting or in a self-study mode.</td>
<td>12/31/14</td>
<td>Technical Update</td>
</tr>
<tr>
<td><strong>HVDC Workshop:</strong> An HVDC workshop will be organized along with the HVDC Task Force Meeting to provide technical information on the latest HVDC topics.</td>
<td>12/31/14</td>
<td>Workshop, Training, or Conference</td>
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**P162.004 Applications of HVDC Technology and New Developments (063311)**

**Description**

The electric power industry has to understand different applications of HVDC well in order to take full advantage of the technology. Applications of HVDC technology are evolving beyond its traditional role of bulk power transfer. By converting an ac line to dc, the power transfer capacity of an overhead line could be increased by 50–100%. In certain cases, dc cables may be more compatible with renewable power sources than an ac cable. Voltage-source converter (VSC) technology is improving, and its capacity increasing. Advancements in this technology may lead to new applications. All these developments have to be assessed and evaluated for suitable adoptions. Guidelines are needed in selecting the right application and in selecting between an ac and a dc system.

This project investigates the applications of HVDC technology for conventional power sources and for new sources such as wind and solar, to develop concepts such as ac-to-dc line conversion, dc grids, and dc circuit breakers.

**Approach**

In previous years, an in-depth study was conducted on ac line conversion to dc operation, and a consolidated report, *AC to DC Power Transmission Line Conversion*, was published in 2010 (Product ID 1020114). An arrangement is being pursued to demonstrate the ac-to-dc conversion concept at a utility site.

In 2012, the advantages and disadvantages, both technical and economic, of connecting renewable power sources using a dc cable system were compared with an ac cable system. The development of an ACvsDC Wizard, including methodology and software to assist utility engineers to make ac versus dc decisions, was started in 2012.
In 2013, the ACvsDC Wizard was enhanced with more options and generic data so that utility planners can use it to evaluate ac versus dc options for system expansion. Both underground and overhead transmission options under ac and dc operating conditions can be compared. Conversion of existing ac circuit to dc operation and its merits over ac operation was also added to the Wizard. Case studies with utility system data were developed using the Wizard.

A preliminary investigation on technical and economic studies of various types of dc technologies was completed in 2013.

In 2014, further work on technical and economic studies of various types of dc technologies will be done along with the development of guidelines for different dc applications. Both line-commutated converters (LCCs) and VSCs will be considered for long-distance and back-to-back applications. Applications for renewable integration will be also included. The guidelines will be established for purchasing, testing, and qualification of DC systems for different applications. In addition different ac and dc options to meet power system expansion requirements will be documented.

Investigation of dc grid concepts for distributed renewable generation, including the requirements for dc circuit breakers and dc-dc transformers will be performed with possible demonstration of some new concepts in a laboratory environment.

In the following years, the tasks below will be considered. Utility members will prioritize the order that these tasks will be carried out.

- Demonstrate new dc concepts developed by manufacturers such as the modular multi-level VSCs. In this case, the concept will be studied systematically to determine the optimal number of levels that are needed to achieve the required power level without ac side filters.
- Demonstrate transformer-less VSC concepts in lab and utility environments.
- Lab and Field demonstration of new dc circuit breaker concepts that are developed by either the manufacturers or universities.
- Demonstrate DC grid concepts in a lab and field environment.
- Study the technical requirements for a convertible ac cable for future dc operation, and vice versa.
- Investigate the use of new wide band gap (WBG) materials such as SiC and GaN for HVDC converter applications.
- Perform switching & lightning overvoltage studies for insulation coordination.
- Estimate induced voltages on a parallel un-energized dc line.
- Estimate induced voltages when AC and DC lines are in the same right-of-way - either on the same tower or on different towers in the same corridor.
- Evaluation of field contours for DC insulators and transformer bushings to improve insulator designs.
- Perform real-time digital simulations using RTDS (Real Time Digital Simulator) for evaluating different DC concepts and control strategies.
- Analyze the operational data of existing HVDC converter stations.

**Impact**

High-voltage direct current lines and cables may have a large impact on the reliability and economic performance of an existing power system. This project strives to provide information, engineering approaches, and decision-making support to help companies integrate renewables and other applications using HVDC technology, which may help an owner accomplish the following:

- Reduce the costs of power transmission, potentially reducing electricity rates to end-use customers
- Increase overall system controllability, stability, and reliability
- Make informed decisions based on technical and economic aspects of different technologies
- Help to implement new concepts such as dc grids and dc circuit breakers
How to Apply Results

This project helps planners and engineers select a transmission system for interconnecting renewable generation sources. The project provides multiple technological and economic options, including HVDC lines or cables and HVAC lines or cables, and provides benefit-cost comparisons for different options. In addition, this project will provide methods of designing and operating dc grids, dc circuit breakers, and dc-dc transformers.

2014 Products

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<tbody>
<tr>
<td>Technical and Economic Guidelines for DC Applications &amp; Comparison of Different Options for System Expansion Requirements: Perform technical and economic comparison studies of different dc technologies, considering various applications (including renewable integration), and develop guidelines.</td>
<td>12/31/14</td>
<td>Technical Report</td>
</tr>
<tr>
<td>Design and Operational Challenges of DC Grids and Requirements for DC Circuit Breakers and DC-DC transformers: Provide comparison of different options such as dynamic ratings, voltage upgrade, ac-to-dc conversion, advanced conductors, and superconducting cable for system expansion.</td>
<td>12/31/14</td>
<td>Technical Update</td>
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P162.009 Integrating HVDC in an AC Grid (072082)

Description

The use of high-voltage direct current (HVDC) is increasing. For example, interconnections between regions of an ac grid is being considered to meet the growing reliability challenge of the power system development. For technical and economic reasons, HVDC may be suitable for a long overhead line or cable connection. Difficulties in obtaining approvals to build new overhead lines may lead to underground HVDC connections or conversion of an existing ac line to HVDC operation to achieve increased transfer capacity. In addition, with the growth of on-shore and off-shore wind generation, HVDC lines or HVDC submarine cables are often the most suitable options, particularly for long distances. Applications of HVDC technologies to the existing power grid are thus inevitable. All these new emerging needs will result in an HVDC system embedding in an ac grid.

HVDC connections perform differently than ac connections during steady-state, dynamic, and transient conditions. These differences must be studied. In addition, the coordination between HVDC links and ac lines in parallel should be studied for the most effective utilization of these assets in the entire power network. This project evaluates the impacts of additions of HVDC to an existing power system.

Approach

System planning studies will be performed as a first step before considering HVDC interconnections in the existing ac grid to assess the impacts of HVDC. The impacts of HVDC will be evaluated by using benchmark test systems and the necessary model developments to reflect the latest converter technologies such as modular multi-level voltage source converter (VSC). Additional utility-specific system studies will be conducted using supplemental funding.

Typical studies to be conducted under this project include load flow, transient stability, small signal stability, and voltage stability. Various ac-dc configurations and control strategies will be modeled. The topics listed below have been identified and will be covered, and it is anticipated that all of these topics will be addressed in four years. Other topics that have been identified below and those that will emerge from these studies will be investigated in future years.

In 2012 & 2013, the following topics were studied:

- Power Flow Control Optimization: Adaptive control strategies are to be considered to address the wide range of system operation conditions. This task requires close coordination with HVDC manufacturers who are responsible for the design of HVDC controls.
• Power Oscillation Damping Methods: Alternative methods for power oscillation damping are to be examined using the conventional and phasor measurement unit (PMU) measurements local to converter stations, as well as using PMU data from remote locations such as major power plant locations and transmission inter-ties.
• Wide Area Control Systems: Wide area control system methods are to be developed using local HVDC controls along with the wide area master controls to improve the network’s overall power flow.
• Coordination of DC Control with AC Network Control Devices: Existing methods are to be reviewed and improvements suggested for devices such as phase shifting transformers, series compensation devices, shunt compensation, synchronous condensers, and generator controls.
• Transmission Requirements for Wind Integration: Trade-off analysis are to be carried out for both ac and dc interconnection options, and technical challenges were documented.
• Special Protection and Control Schemes: Special protection and control schemes are to be developed to maximize transmission boundary flows using HVDC fast-ramping techniques under post-fault scenarios.

In 2014, the following topics will be addressed:

• Transient Stability Improvements and Fault Recovery: Studies will be conducted, and the results will be documented for several scenarios.
• Sub-Synchronous Resonance (SSR) Damping Enhancement: Sub-synchronous resonance studies will be conducted using the benchmark test systems with dc, and the results will be documented.

The topics below may be covered in the following years. More topics will be added based on the utility member needs and their input:

• Transmission Loss Optimization: A tool will be developed to optimize overall transmission power flows while minimizing losses for various operating and planning scenarios. This may involve developing a procedure to calculate optimum power flows using existing optimal power flow programs such as TRACE.
• HVDC Models: HVDC models for line-commutated converters and voltage-source converters will be developed for load flow, stability, and transient studies.

Applications of the developed concepts from this project for a specific utility system will be conducted under that utility's supplemental funding during or beyond the duration of this project.

**Impact**

• Lower overall investment cost and, thus, lower rates to end-use customers
• Higher system controllability due to dc control capability
• Increased overall system stability limits
• Increased asset utilization by increasing flows on the ac lines when dc interconnections are present
• Reduced overall system losses

**How to Apply Results**

Members use project findings and deliverables in their transmission capacity expansion efforts using HVDC interconnections to meet increased load demand, as well as to integrate new renewable resources such as wind and solar.
### 2014 Products

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<tr>
<td><strong>SSR Damping Enhancement:</strong> Document sub-synchronous resonance damping improvements with dc control.</td>
<td>12/31/14</td>
<td>Technical Update</td>
</tr>
<tr>
<td><strong>Transient Stability Improvements and Fault Recovery:</strong> Document transient stability improvements and fault recovery improvements with HVDC embedded into an ac network.</td>
<td>12/31/14</td>
<td>Technical Update</td>
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### PS162B HVDC Performance and Effects (069267)

**Project Set Description**

This project set investigates the performance of high-voltage direct current (HVDC) line systems and components, as well as electrical effects from HVDC transmission lines. A benchmark performance index is created for the overall system and each component to identify problem areas that can be improved. Component testing is to be performed. Electrical effects are studied under laboratory and real environments. Through testing and research studies, guidelines will be established for acceptable levels of component performance and electrical effects.

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<th>Description</th>
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<tr>
<td>P162.005</td>
<td>HVDC Line Performance and Component Testing</td>
<td>This project involves approaches to deal with the challenges facing the analysis and determination of the performance level of dc lines and components. Line performance statistics may be developed based on existing HVDC schemes around the world. Different HVDC components such as insulators, conductors, towers, and earth electrodes are to be evaluated through research and testing to help members make informed decisions such as repair versus replacement, or to specify a new HVDC scheme. Live-line studies and testing are to be undertaken to better understand the various factors that influence worker safety. The research provides information to members to improve the performance of existing HVDC systems and to purchase reliable components for new HVDC systems.</td>
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<tr>
<td>P162.006</td>
<td>Electrical Effects of HVDC</td>
<td>The project measures, studies, models, and documents electrical effects associated with HVDC transmission. The underlying physics are studied and guidelines developed. The project will provide guidance as to where mitigation strategies may or may not be needed. Full-scale and reduced-scale experiments for refining measurements and calculations are to be made. Software that incorporates the results is to be developed, validated, and updated.</td>
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P162.005 HVDC Line Performance and Component Testing (069268)

**Description**
Understanding the high-voltage direct current (HVDC) performance of the line and its components is critical to extending the life of an existing HVDC line or building a new HVDC line. Many of the existing HVDC schemes operating in North America and the rest of the world are over 30 years old. As these lines age, benchmarking HVDC line performance becomes important in order to propose remedial measures to optimize and improve line performance. Although there are plans to build several new HVDC schemes in North America and the rest of the world within the next few years, many of the line designers have limited HVDC experience in specifying and applying components on HVDC lines.

The project objective is to develop guidelines for members regarding the selection of various HVDC line components, either for replacements or new installations to meet required performance levels. The guidelines are to be based on experience gained in the past and knowledge to be acquired. This project involves research and testing in dealing with the challenges facing HVDC line performance levels.

**Approach**
This project undertakes research on and testing of HVDC components such as insulators, conductors, towers, earth electrodes, and hardware in order to understand overall line performance. Components used on existing lines need to be tested to assess their integrity and to perform investigations if a failure occurs. Components to be used on new lines need to be evaluated beforehand in order to confirm compatibility and performance levels. The project helps participants develop component specifications for HVDC lines and provides guidance on line designs. For example, accelerated aging tests for components such as insulators are to be performed, to better understand the effects of static electric fields on the performance of insulators in general and composite insulators specifically. In addition to the insulator performance, the corona performance of the entire assembly as well as other relevant components will be studied and guidelines will be developed based on testing.

This project also studies and conducts tests to determine the best practices for HVDC live working. Live working under HVDC conditions is not as widely practiced as under HVAC conditions. The live-line studies in this project are to be coordinated with the live-line research in Program 35 to avoid any overlap.

**Impact**
The research may affect member operations in several ways:

- Line performance benchmarking can lead to better understanding of what needs to be improved and what line components should be selected, which leads to better line performance.
- The life of an HVDC system can be extended by improving system performance.
- Insulator and other line component research can result in better line performance.
- An HVDC component specification guide may help members to specify components properly.
- Live-line studies may result in better live-line maintenance practices, which leads to improved staff and public safety, as well as better line performance.

**How to Apply Results**
The research is structured so that research results may be easy to implement into day-to-day operations using standard procedures. Training courses and seminars are to be held to help members disseminate information into members’ companies so they can apply these results to their own HVDC line operation and maintenance.

The HVDC component specifications developed in this project may be used by utilities to increase confidence and reduce time when specifying components. The HVDC guide will give utilities an overview of the key differences between HVDC and HVAC and the application of components.
2014 Products

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<tr>
<td>HVDC Hardware Corona Performance - Testing and Procedures: Hardware assembly tests will be undertaken to verify and refine the procedures developed in 2013. Guidelines for hardware testing will be developed in future years based on the tests and procedures developed.</td>
<td>12/31/14</td>
<td>Technical Update</td>
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<tr>
<td>HVDC Overhead Transmission Guide: Conductor Optimization (Draft): This year the guide will be updated with a draft chapter on conductor optimization for HVDC lines. The chapter will highlight the factors which influence conductor selection for HVDC lines and also contain some recent examples of the selection process for new HVDC schemes.</td>
<td>12/31/14</td>
<td>Technical Update</td>
</tr>
<tr>
<td>HVDC Live Line Studies: Tools: This task will focus on the effect that a live working tool will have on the insulating strength of an insulator string. Factors affecting the performance of such a parallel combination which could be studied include, space charge accumulation, corona activity and wind.</td>
<td>12/31/14</td>
<td>Technical Update</td>
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P162.006 Electrical Effects of HVDC (062103)

**Description**

High-voltage direct current (HVDC) is a viable technology for long-distance bulk power transmission and other applications that is more efficient than high-voltage alternating current (HVAC) transmission. As electric power companies plan for their power flow needs or higher levels of grid stability, HVDC or hybrid lines (ac-dc sharing the same corridor) may be the most economical and reliable solutions. HVDC lines have special concerns that must be addressed and accounted for during their design and operation. Corona from HVDC lines causes audible noise, electric field interference, ozone production, and spark discharges that may be unique to HVDC lines due to the ejection of electric charge into space (called “space charge”). This space charge results in increased electric fields, the formation of charged ions and charged aerosols, and human sensations. The space charge also results in dc ion currents to ground, and into other objects such as people, distribution lines, other utility lines, or other electrical devices.

The power industry experience with HVDC lines is meager compared to their experience with HVAC lines, and there is a need to make measurements on operating lines, and to develop and validate calculation methods and mitigation techniques. In this project, these electrical effects are to be measured, studied, characterized, and quantified; mitigation measures are to be explored to assist power companies in the assessment and mitigation of electrical effects, and software is to be developed as a tool in HVDC line design and operation.

**Approach**

This project builds upon previous work done by EPRI (and elsewhere) on the subject of electrical effects associated with HVDC and hybrid corridors. Because HVDC is a relatively new technology, regulations and limits of electrical effects have not, in general, been defined. The setting of limits and regulations may become critical criteria for designing and operating HVDC lines. The data and results of the EPRI R&D will help form a basis for establishing reasonable design limits and regulations for the industry.

EPRI uses its laboratory facilities to perform reduced-scale and full-scale experiments to investigate the phenomena, and to develop an understanding of the underlying physics, test theories, and develop mitigation methods. At EPRI laboratory in Lenox, electrical effects from HVDC lines are to be demonstrated for power company personnel. Participants will be able to observe, measure, and immerse themselves in HVDC electrical environments in order to gain firsthand experience about the effects. Measurements are to be made on laboratory test lines, and on operating lines in the field.
All results are documented in EPRI reports, and workshops and conferences are held to provide the necessary technical transfer activities. Software is to be developed and validated for performing calculations of HVDC and hybrid electrical effects, and to explore mitigation strategies. This software provides power companies with a tool to assess electrical effects and design HVDC lines properly.

**Impact**

- Enable power company personnel to understand and manage HVDC and hybrid electrical effects
- Provide information from field measurements and experiences on the magnitude of electrical effects that can be expected from HVDC/hybrid lines
- Guide engineers through reports, workshops, conferences, and software
- Assist in making the critical decision if HVDC is, or is not, a viable technology for specific applications
- Address issues about electrical effects that are brought up in permitting or other public forums
- Optimize the design and operation of lines regarding electrical effects
- Position power companies to meet regulatory requirements and gain public acceptance

**How to Apply Results**

Transmission managers, planners, designers, researchers, and engineers may use the results of this project to help make decisions about whether HVDC/hybrid transmission is a viable option for their transmission needs. The project provides the necessary tools and information to understand where such effects may, or may not, be an issue. The research results and software may be used to optimize the design and operation of HVDC lines from the point of view of electrical effects, and may help with meeting regulatory and public acceptance of HVDC and hybrid transmission. Results may also be used to assess options for mitigation where needed.

**2014 Products**

<table>
<thead>
<tr>
<th>Product Title &amp; Description</th>
<th>Planned Completion Date</th>
<th>Product Type</th>
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</thead>
<tbody>
<tr>
<td><strong>HVDC Electrical Effects: Tests, Measurements, and Software Validation:</strong> EPRI research on the electrical effects of HVDC and hybrid transmission lines will continue. The research activities for 2014 will include measurements, lab tests, and algorithm development and validation for software. The focus will be on the development and calibration of reduced-scale test lines, hybrid lines, and mitigation techniques. The results will be documented in a Technical Update, which will provide results, recommendations, conclusions, and guidance for overhead transmission designers.</td>
<td>12/31/14</td>
<td>Technical Update</td>
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<tr>
<td><strong>HVDC Electrical Effects Version 2.0:</strong> Any utility contemplating or using HVDC transmission will need to have a means of quantifying and calculating HVDC electrical effects for many reasons; including meeting regulations and public acceptance. The HVDC Electrical Effects software will be updated with the algorithms developed in 2013. This software will be a valuable tool for the design of HVDC and hybrid transmission lines.</td>
<td>12/31/14</td>
<td>Software</td>
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Supplemental Projects

HVDC Cable Interest Group (072083)

Background, Objectives, and New Learning

There are considerably more high-voltage alternating current (HVAC) underground and submarine cable installations in the world compared to high-voltage direct current (HVDC) installations, simply because the latter is relatively expensive in comparison. This price difference is mainly because of the high cost of ac/dc converters to transform ac to dc and back again, usually exceeding $100M (~€75M), depending on voltage and power. However, when cable lengths exceed the critical length for effective transmission of ac real power, dc systems become necessary. The choice of a dc power transmission cable system in preference to the more conventional ac cable option would generally be made in cases where the power transfer requirement is greater than 150–300 megawatts (MW), and one or more of the following characteristics apply:

- Long length (typically 25 miles [40 kilometers, km]) submarine cable link or interconnection, with length limits mainly dependent on system voltage and ampacity.
- Intermediate length (typically 5 to 25 miles [8 to 40 km]) submarine cable interconnections between two large ac transmission networks where power transfer control is a potentially serious problem. A dc cable system provides an asynchronous or flexible transmission interconnection.
- Reinforcement of a long-length ac transmission system in areas of high load density (cities) without increasing the interrupting duty of ac circuit breakers.

The relationship of cable length to the choice of an ac or dc transmission voltage lies in the capacitance of the cable. As the ac cable length and voltage increase, the capacitance, and hence the ac charging current, increases in proportion (charging current is equal to the voltage divided by the cable’s capacitive reactance). At the so-called critical length, the capacitance charging current equals that of the thermal current rating of the cable, and no real power can be transmitted. For short- to medium-length ac cable systems, the charging current can be compensated for by the use of shunt reactors at the cable terminations, or in the case of submarine cables, at intermediate islands. For long cable lengths, however, this becomes impractical, and dc power transmission is necessary.

Recently there is a considerable interest in using HVDC cables for renewable energy (for example, wind and solar) integration and power grid interconnections. Submarine HVDC cables are being considered for off-shore wind integration in many parts of the world. Though HVDC cables have been used for some time, there is a need to better understand these technologies for new applications.

Project Approach and Summary

The objective of the Electric Power Research Institute (EPRI) HVDC Cable Interest Group is to address both underground and submarine cable issues for different applications. EPRI will lead this Interest Group, with member participation from electric utilities and manufacturers. This Interest Group can provide information and research results in the following areas:

- Operational experience of existing dc cables
- Mechanical and electrical issues
- State-of-the-art knowledge and economic choices
- DC cable type selection
- Voltage-source-converter-based dc applications
- Challenges and opportunities presented by cable technologies
Initially it is proposed to have a series of conference calls among all participants to identify and prioritize the technical issues. Also depending on participation, one or more technical workshops per year will be organized to exchange information among all participants. This Interest Group also will identify areas for further research that can be separately undertaken using EPRI supplemental funding.

**Benefits**

- Increase understanding about HVDC cable technology applications
- Share the experience with other participants and learning from each other on HVDC cables
- Identify technology R&D needs in HVDC cables
- Reduce the costs of power transmission, potentially reducing electricity rates to end-use customers
- Increase overall system controllability, stability, and reliability
- Make informed decisions based on technical and economic aspects of HVDC cable technologies

**FACTS Application Guidelines and Operating Strategies (072084)**

**Background, Objectives, and New Learning**

Electric utilities around the world are undergoing major transformation, which is redefining the utilization of existing power equipment in the electric transmission network due to limited financial incentives and a lengthy licensing process for new construction. Under such circumstances, utilities are forced to find new ways of quickly increasing power flow through existing transmission corridors with minimal investments. Increased transmission circuit power flows can be achieved by controlling circuit parameters such as current, voltage, phase angle, or timing of current flow. These circuit parameters can be controlled using power electronic controllers known as flexible ac transmission systems (FACTS), which offers distinct benefits such as improved system reliability and performance while increasing transmission capacity. Power utilities need information on how FACTS can be applied to their power systems. In addition, research is needed to reduce the cost of FACTS controllers and increase the proliferation of these controllers in the utility industry. Applications of FACTS for renewable integration and smart transmission grid also need to be explored.

There are presently a number of FACTS controllers installed in the U.S. transmission grid. Owners of FACTS are facing issues in maintaining and operating these controllers, as manufacturers are not able to provide the needed assistance. Fortunately, the issues being faced by these utilities are similar. Through research, EPRI will be able to assist the industry in developing guidelines to address operation, maintenance, and replacement strategies for existing FACTS controllers to improve performance. The research results will benefit utilities with FACTS immediately. Non-owners may also reap the benefits in future purchases.

**Project Approach and Summary**

**Identify opportunities for FACTS applications based on technical and economic benefits:** FACTS controllers can be part of the smart transmission grid to optimize transmission system power flow and improve reliability and efficiency. The benefits of such technology can be demonstrated by applying FACTS technologies at strategic locations in the existing transmission grid. This project will conduct economic and technical studies of FACTS applications in the utility transmission system. Awareness of energy efficiency, including demonstration of green transmission circuits, will provide opportunities for FACTS applications. This project will also compare the option of high-voltage direct current (HVDC) cable versus ac cable with and without FACTS. These comparisons will determine the limit of ac cable distance for long-distance power transfer due to inherent ac capacitances. In light of potential installations of a number of wind farms around the world, results of this type of evaluation will be useful for the power industry.

**Reduce the cost of FACTS so utilities can take advantage of this technology:** Though FACTS controllers have been deployed at some utility sites, widespread application is rather limited because FACTS controllers are still considered expensive by utilities. The Electric Power Research Institute (EPRI) can identify the cost breakdown of these controllers and come up with a research and development (R&D) plan that addresses the development of new power electronic controllers at lower cost so that wider application of these controllers can be achieved.
All components of FACTS controllers such as power electronic devices, converter topologies, control circuits, and cooling systems will be evaluated, and new methods will be proposed to reduce the cost of individual components. This project will investigate the feasibility of applying new concepts such as building block concepts and also advance the power electronic controller technology by proposing new power electronic devices designed with silicon carbide (SiC). It is anticipated that FACTS will be more commonly used if the cost comes down.

**Operation, maintenance, and replacement strategies for FACTS:** There are a number of FACTS controllers installed around the world. These FACTS controllers include the following:

- thyristor-controlled series capacitors (TCSC)
- static synchronous compensator (STATCOM)
- static synchronous series compensator (SSSC)
- unified power flow controller (UPFC)
- interphase power flow controller (IPFC)

In most cases, these controllers are designed for specific utility applications by different vendors. Though many of these controllers are operating at utility sites, utilities are faced with challenges in operation, maintenance, and replacement strategies. As computer technology and hardware is changing rapidly, utilities have difficulty finding spare parts for old equipment and are accordingly forced to change the control circuit boards with the latest technology. Even then it is difficult to find plug-and-play control circuit boards, as vendors are going forward with new projects rather than assisting utilities with existing FACTS controllers.

This project will systematically identify needs in the operation, maintenance, and replacement of FACTS controllers. Initially, utilities with existing FACTS controllers will be surveyed, and their needs will be documented and prioritized. Based on the survey results, best practices in operation and maintenance will be developed. Also depending upon the expected life of each component of the FACTS controllers, replacement strategies will be developed.

Plug-and-play components, which are vendor independent, are necessary to facilitate upgrades of FACTS controllers. This project will identify the requirements for plug-and-play components and define which components of FACTS controllers could be plug-and-play. In addition, life extension guidelines for FACTS controllers will be developed.

**Benefits**

FACTS controllers can provide many benefits that include the following:

- Increase power flow quickly
- Realize additional revenue by increasing power flows using existing assets
- Contribute to improved grid reliability and performance by controlling power flows in transmission and reducing system outages due to overloads
- Reduce overall costs of transmitting power over the grid
- Increase transmission security
- Reduce reactive power flows
- Provide voltage support at strategic transmission buses
- Realize smart transmission grid
- Optimize transmission integration of renewables such as wind and solar
Performance of HVDC Polymer/Composite Insulators (073526)

Background, Objectives, and New Learning

With the increasing use of HVDC transmission lines, the performance and longevity of the components on these lines need to be understood and optimized. One such component is the insulator. Most HVDC lines were built over 20 to 30 years ago prior to the availability of polymer/composite insulators. Therefore, the insulators for HVDC transmission have been traditionally either glass or porcelain.

Polymer insulators offer a few advantages over glass or porcelain insulators. Some of these advantages are:

- More resistance to vandalism such as gunshots.
- Shorter connecting length for the same creepage/leakage distance or longer creepage distance for the same length.
- Lighter weight.

With recent developments and improvements of polymer insulators for HVAC applications, the use of polymer insulators has increased substantially in the last 20 years for ac lines. While these insulators have been used on many ac lines, experience of polymer insulators for use with HVDC lines is limited.

The objective of this research is to improve the knowledge of HVDC polymer insulators on:

- The long-term effect of HVDC electric fields on the polymer material.
- The effect of water droplet corona on the insulators under HVDC conditions.
- The proper application of grading (corona) rings.
- The performance of HVDC polymer insulators under contaminated conditions.

Project Approach and Summary

The following approach is to be undertaken.

- Polymer insulators will be installed on a 500 kV dc test line at a site close to the ocean where the insulators will be exposed to extensive marine contamination.
- Instrumentation will be installed on the insulators to measure leakage current. Ambient conditions will also be monitored continuously.
- Regular visual and ultraviolet (UV) inspections will be conducted. Hydrophobicity of the insulator surface will also be measured regularly.
- Some insulators will be installed with and some without grading (corona) rings.

By assessing the change in insulator parameters from measurements and observations, it may be able to determine the aging effects of HVDC on polymer insulators as well as the effectiveness of grading rings.

Benefits

This project may offer the following benefits:

- Improved understanding of HVDC polymer insulator aging under contamination.
- The need for use of grading (corona) rings on HVDC polymer insulators.
- Proper applications of polymer insulators on HVDC lines.

Thus, enable members to take advantage of a new type of insulators.