EPRI Program 162 HVDC Systems

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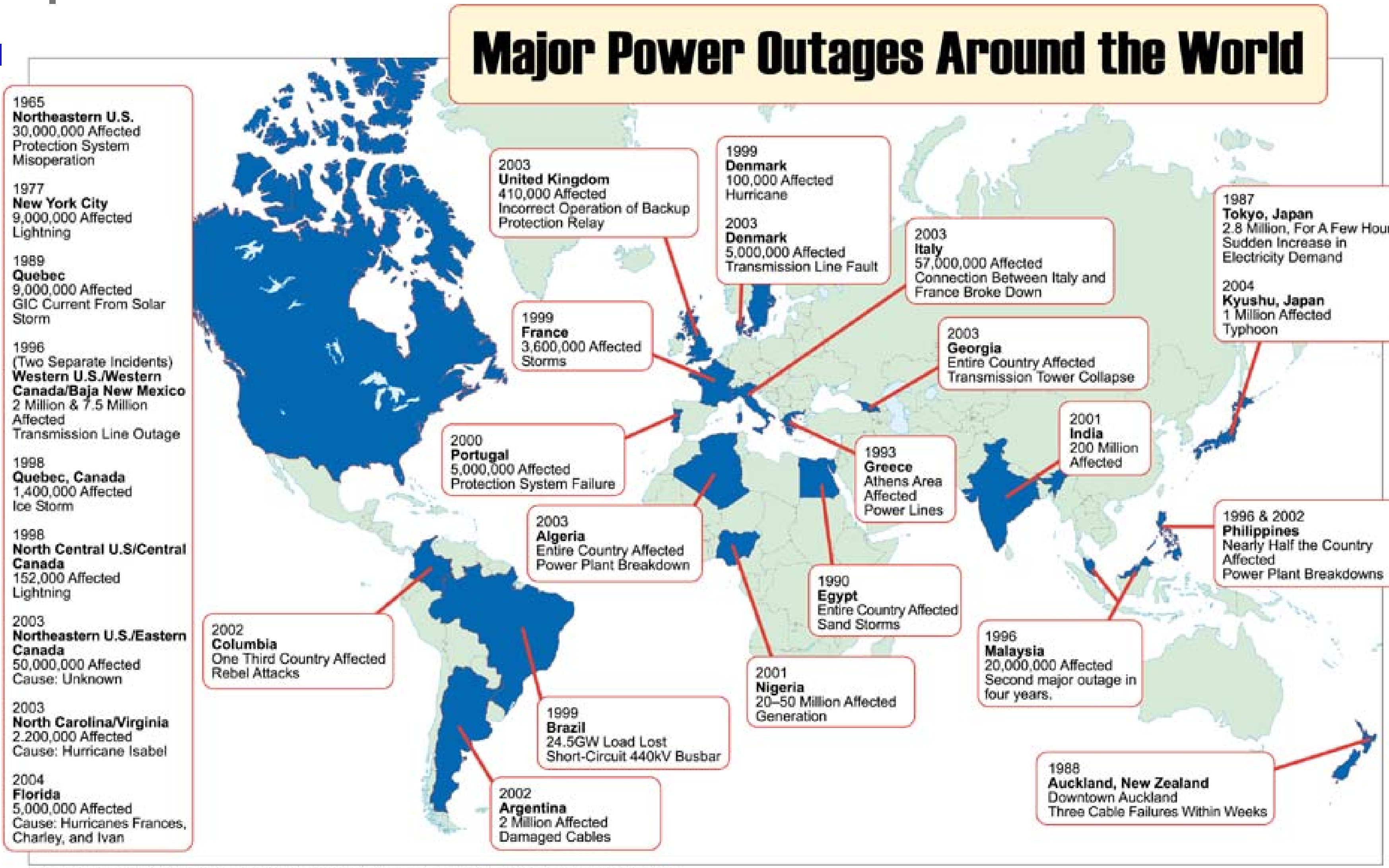
Worldwide Outages



This is not an exhaustive list of all major power outages around the world. There are numerous power outages such as France '78, '87; Belgium '82; Sweden '83; Italy '89, '93, '94; Netherlands '97; and Chicago '99 that are not shown on the map.

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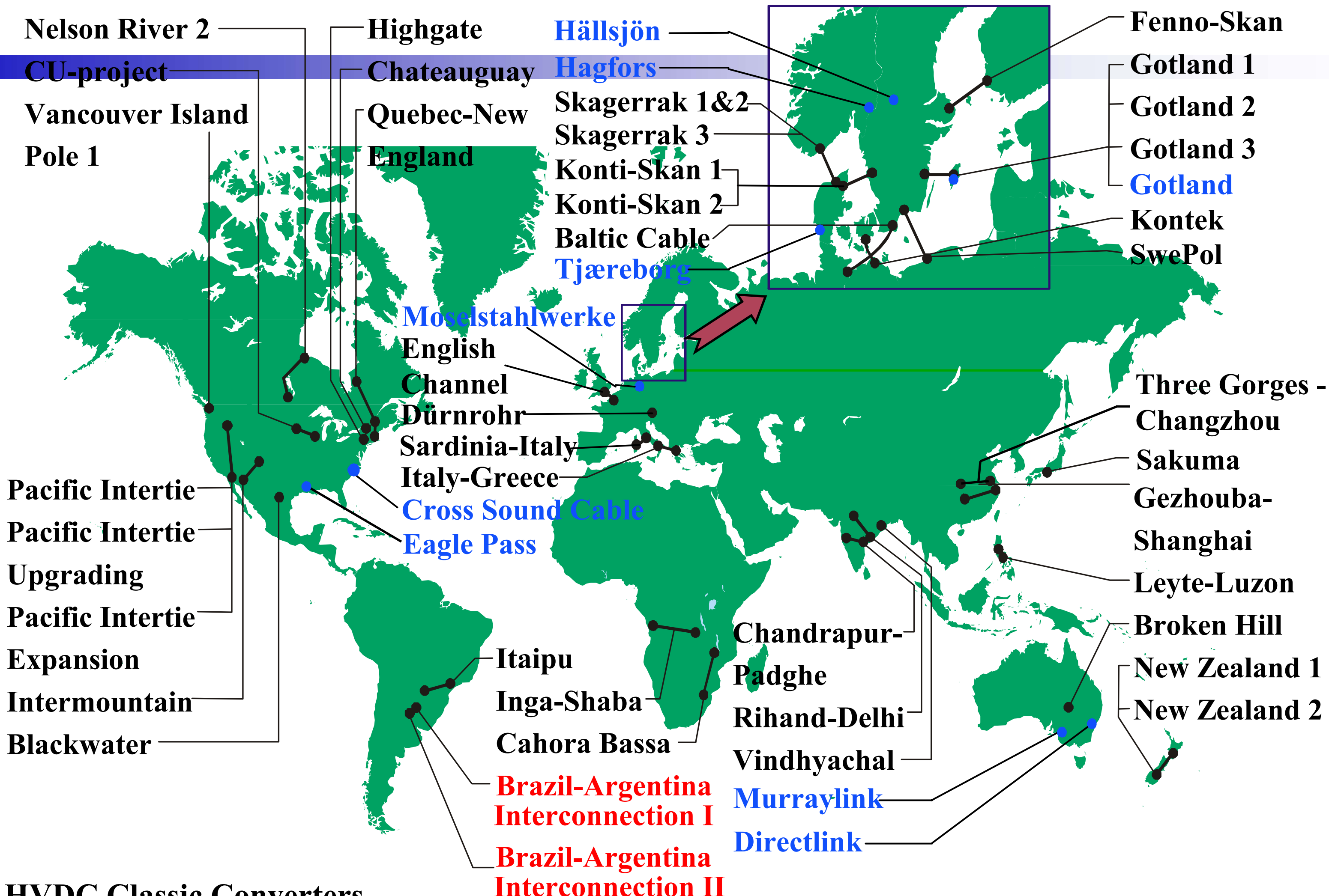
Examples of HVDC Projects Around the World

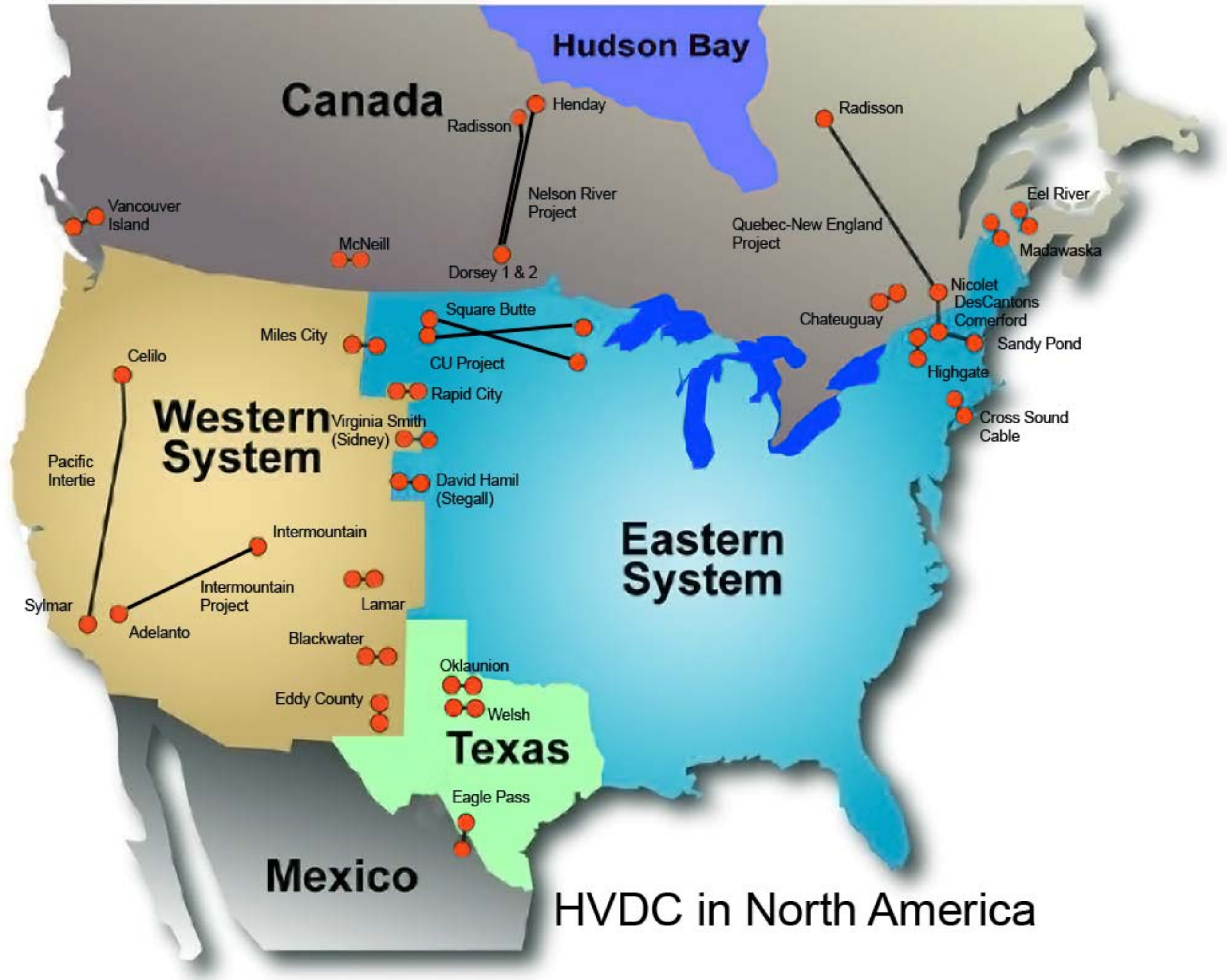


HVDC Classic Converters

CCC Converters

HVDC Light (VSC) Converters

North American HVDC Stations



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HVDC Systems - Technical and Business Drivers

- Aging Infrastructure
- Loss of Institutional Knowledge and Experience in Industry
- Lack of knowledge on Ultra High HVDC Technology for Bulk Power Transfer
- Need for Better Power Flow Management and Reliability

Program 162 – HVDC Systems

Program Objectives

The key objectives of this program are:

- Address Operational concerns of existing HVDC
- Best inspection, assessment, & maintenance programs
- Next Generation HVDC technologies (UHVDC at +/- 800kV and above, VSC DC)
- HVDC Reference Book
- Biennial HVDC conference / Workshop
- AC to DC line conversion technologies

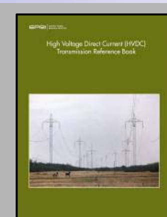
EPRI HVDC Program Structure

- P162.001: Life Extension of Existing HVDC systems - Focus initially on DC converter station life extension, then DC line life extension.
- P162.002: Assessment and Evaluation of Next Generation HVDC Technologies - Focus on UHVDC as well as VSC (Voltage Source Converter) technologies and advanced devices such as IGBT's & IGCT's.
- P162.003: HVDC Reference Book - Update all 24 chapters in a few years. Chapters on HVDC Line and Simulation Tools were updated.
- P162.004: AC/DC Line Conversion - Evaluate DC capability of existing AC structures for upgrade to higher capacity. Demonstration to be done under supplemental funding.

P162 HVDC Systems

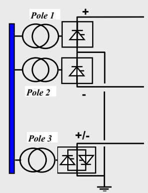
Knowledge Capture & Application Guide

System Life Extension



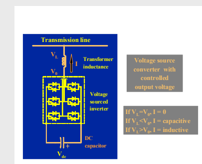
HVDC Reference Text

Concept & Technology Evaluation



Tri-pole Conversion

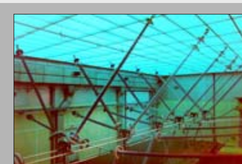
Live Working



Voltage Source Converter

Testing and Assessment

Electrical Effects



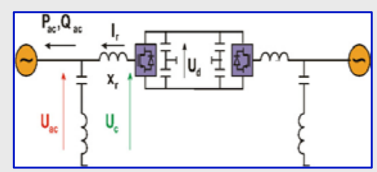
HVDC Insulators

Line & Station Components

Technology Application & Demo

± 800 kV DC

AC to DC Line Conversion



System Performance Enhancement

DC Tap Off

Short Term → **Long Term**

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2008 Task Force Meetings and Webcasts

- Task Force Meetings
  - First HVDC Task Force Meeting was held in Clearwater Beach, Florida, January 23-24, during TIP Week.
  - Second HVDC Task Force Meeting, August 7th, Tri-State G&T, Denver
- Webcasts
  - June 19th
  - November 14th

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Project 162.001: Life Extension of Existing HVDC Systems

Project Objectives and Solutions

- HVDC is 50 years old
- About 100 HVDC systems are in operation in the world
- As these systems age, extension of life is of paramount importance
- Utilities are coming up against the repair-replace decisions
- Also operation and maintenance issues are becoming a challenge
- This project will address life extension of the existing HVDC Systems in a systematic way.

Project 162.001: Life Extension of Existing HVDC Systems

Project Objectives and Solutions

- Develop a suite of practices guiding utilities in line inspection, assessment and life extension by surveying utilities.
- Components covered would include; insulators, conductors, towers, shielding, grounding, converters, substations, transformers, bushings, cables, etc.
- Audible noise, radio and electromagnetic interference (RI & EMI), interference with phone and other systems, will be evaluated.
- Live work practices on HVDC systems will be developed.
- Life extension guidelines will be developed.

162.001 Life Extension of Existing HVDC Systems

Product ID	Deliverable or Task Title	Budget	Scope	Schedule
1013976	Life Extension Guidelines for HVDC Lines			12/31/08

- DC converter station life extension is the initial focus followed by DC line life extension & SVC life extension.
- Similar to EPRI AC Substation Life Extension Guidelines
- Published TR 1013976 - Life Extension Guidelines of Existing HVDC Systems, December 2007

Project 162.002: Assessment & Evaluation of Next Generation HVDC Technologies

Project Objectives and Solutions

- Presently HVDC voltage levels up to +/- 600kV
- During 1980's research was done on HVDC beyond +/- 600kV (+/- 800kV and +/- 1000kV) by EPRI
- This project will address the technology specification for realizing the HVDC Systems at +/- 800kV and above in many areas
  - Conductor Bundles, Corona, Audible Noise (AN), Radio Interference (RI), Insulation, Transformers, Bushing Design, Ground Electrode, Converter configurations, Harmonic Filters
- New focus on Voltage Source Converter based technologies & Advanced Power Electronic Devices for HVDC

Project 162.002: Assessment & Evaluation of Next Generation HVDC Technologies

Project Objectives and Solutions

- Close cooperation with equipment manufacturers will be sought.
- Close cooperation with utilities considering UHVDC (800 kV)
- Technical reports will be written with UHVDC equipment specifications
- Test results will be documented as well
- Utility engineers can make informed decisions while considering the UHVDC Systems at +/- 800kV and above.
- Technical Reports on Voltage Source Converter based technologies and advanced power electronic devices for HVDC

162.002 Assessment & Evaluation of Next Generation HVDC Technologies

Product ID	Deliverable or Task Title	Budget	Scope	Schedule
1013857	VSC based Technologies for HVDC			12/31/08

- Prior research indicates 800 kV DC operation is feasible though some R&D is required.
- 800 kV DC is considered in China, India, South Africa, and possibly in Brazil & will be operational within 3 to 5 years
- Published TR1013857- Advanced HVDC Systems at +/- 800 kV and Above, November 2007
- VSC based technologies for HVDC are increasing and becoming more cost effective

Project 162.003: HVDC Reference Book (Olive Book)

Project Objectives and Solutions

- A decade ago, EPRI has developed two reference books
  - "HVDC Transmission Line Reference Book (TR-102764)"
  - "High-Voltage Direct Current Handbook (TR-104166)".
- Many advances in HVDC technology took place lately
- More operating data is available now
- There is a need for most current HVDC Reference Book (Olive Book as part of EPRI color book series)

Project 162.003: HVDC Reference Book

Project Objectives and Solutions

The objectives of the HVDC Handbook are:

- Guide utilities in specifying an HVDC system
- Lead utilities through each step of the design process
- making sure the implication of trade-offs are well understood
- Guide utilities in the assessment of existing HVDC systems
- Provide options when addressing repair-replace decisions
- Provide strategies for life extension of HVDC

- Information Exchange and Identify future R&D needs
  - Biennial HVDC conference or HVDC workshop cosponsored by EPRI and member utilities.

162.003 HVDC Reference Book

Product ID	Deliverable or Task Title	Budget	Scope	Schedule
1013858	EPRI HVDC Reference Book: Additional Chapters			12/31/08

- TR 1012518 - HVDC Ref Book: Outline of Chapters was developed with 24 chapters, Dec 2006
- Two chapters were published
  - TR 1016071 - Simulation of HVDC Systems, April 2008
  - TR 1013858 - Overhead Lines for HVDC Transmission: Electrical Performance of HVDC Transmission Lines, June 2008
- More chapters will be written in 2008 & 2009

Project 162.004: AC/DC Line Conversion

Project Objectives and Solutions

- Guide utilities in converting some of their AC lines into DC lines for more power transfer on the same transmission corridor

- Develop simulation tools necessary to make economic decisions to convert an existing AC right-of-way to DC

- Develop new technologies to convert AC lines to DC lines
  - (a) using two of the three ac lines as bipolar DC and keeping the third ac line as a spare or use it as a metallic return
  - (b) converting all the three ac lines into a tri-pole DC
  - (c) converting double circuit AC line into 3 bipolar DC lines

Project 162.004: AC/DC Line Conversion

Project Objectives and Solutions

- Develop / adopt design methods necessary to the additional equipment such as converter stations which are needed to convert AC to DC.
- Develop cost versus benefits for each of the technical options for AC to DC conversion
- Demonstrate some of the AC to DC conversion technologies at the utility sites.
- Document the field experience of operating converted DC lines

162.004 AC/DC Line Conversion

Product ID	Deliverable or Task Title	Budget	Scope	Schedule
1013979	Technical Report on AC/DC line Conversion			12/31/08

- AC/DC line conversion options will be studied – 3 phase AC to bipole or tripole, Double circuit AC to 3 bipoles.
- Initial focus will be on studying existing AC tower/line configurations and how they can be used for HVDC
- Published TR1013979 – DC Capability of AC Transmission Lines, December 2007

Power Gain Through Conversion

- Attain higher voltage than AC
- Gain through Tripole
- Maximize use of double-circuit line
- Achieve higher current limit than AC

Power Gain Summary Table

	Single Circuit - Bipole	Single Circuit - Tripole	Double Circuit – 3 Bipoles
DC Voltage = 1.5 * Peak AC l-g voltage DC Current = AC Current	155%	213%	235%
DC Voltage = 1.5 * Peak AC l-g Voltage DC Current = 1.5 * AC Current	233%	320%	353%

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DC Power depends on Maximum DC Voltage

DC Voltage may be limited by:

1. **Conductor gradient**
2. **Earth-level electric field**
3. **Room for insulators at the structure**
4. **NESC clearance to ground**

…Can achieve 1.5 l-g AC Peak Voltage

DC Power also depends on Max DC Current

While AC Current is limited by:

1. **Surge Impedance of Line**
2. **Voltage Drop limits**
3. **Steady State Stability limits**
4. **Thermal Limits**

…DC Current is limited only by Thermal Limits

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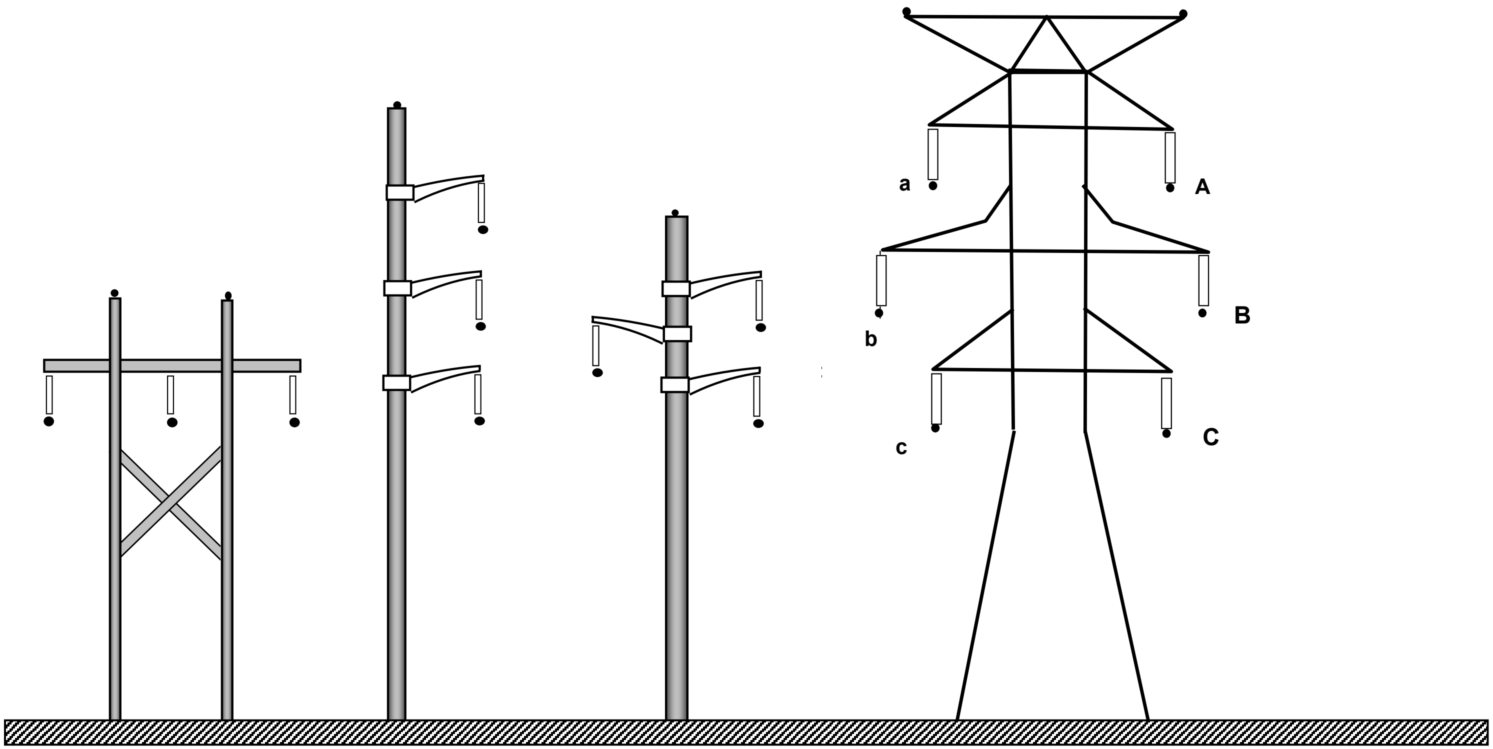
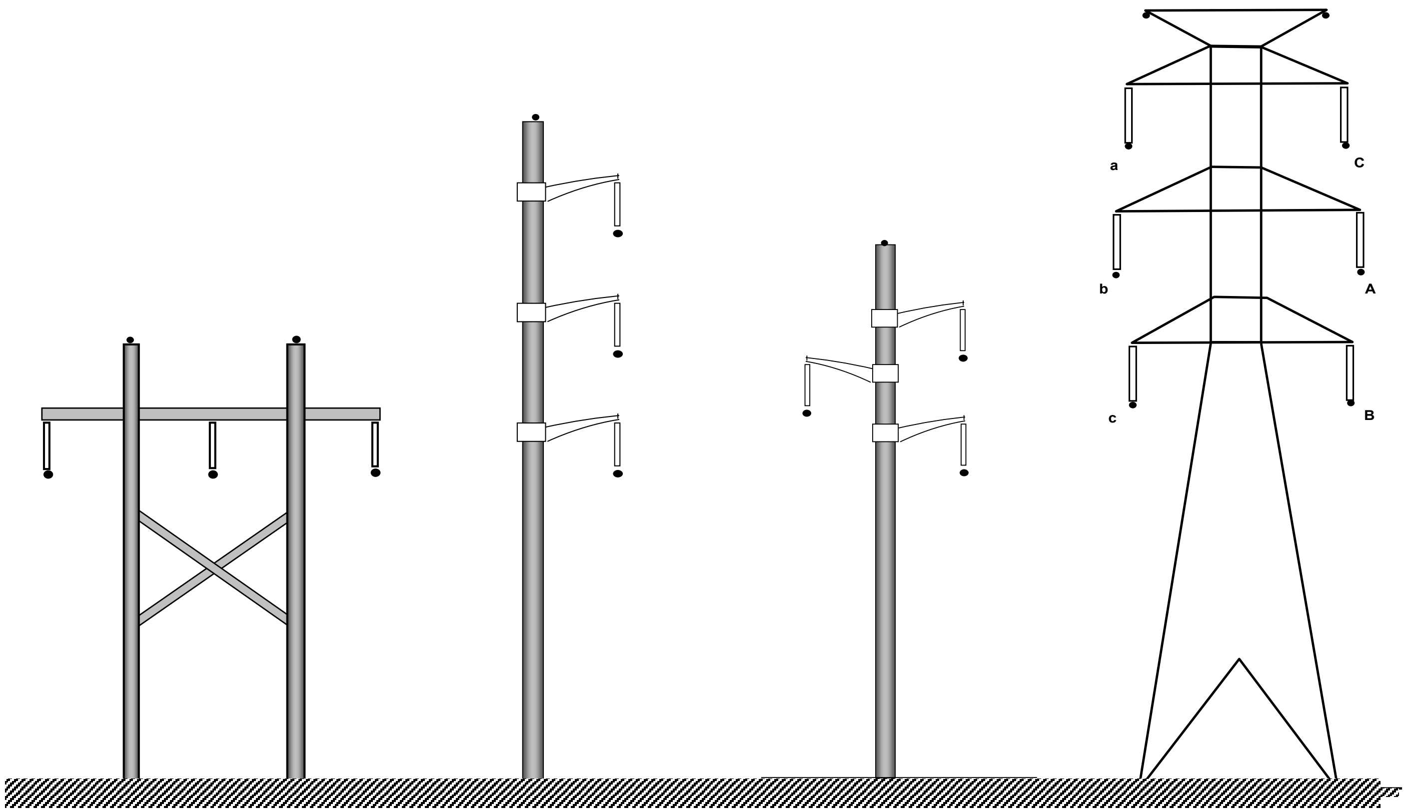
Structures Reviewed: 138 kV



ACSR:	795 kcmil
Diameter	1.106"
Insulators	8

ACSR:	2,156 kcmil
Diameter	1.735
Insulators	9

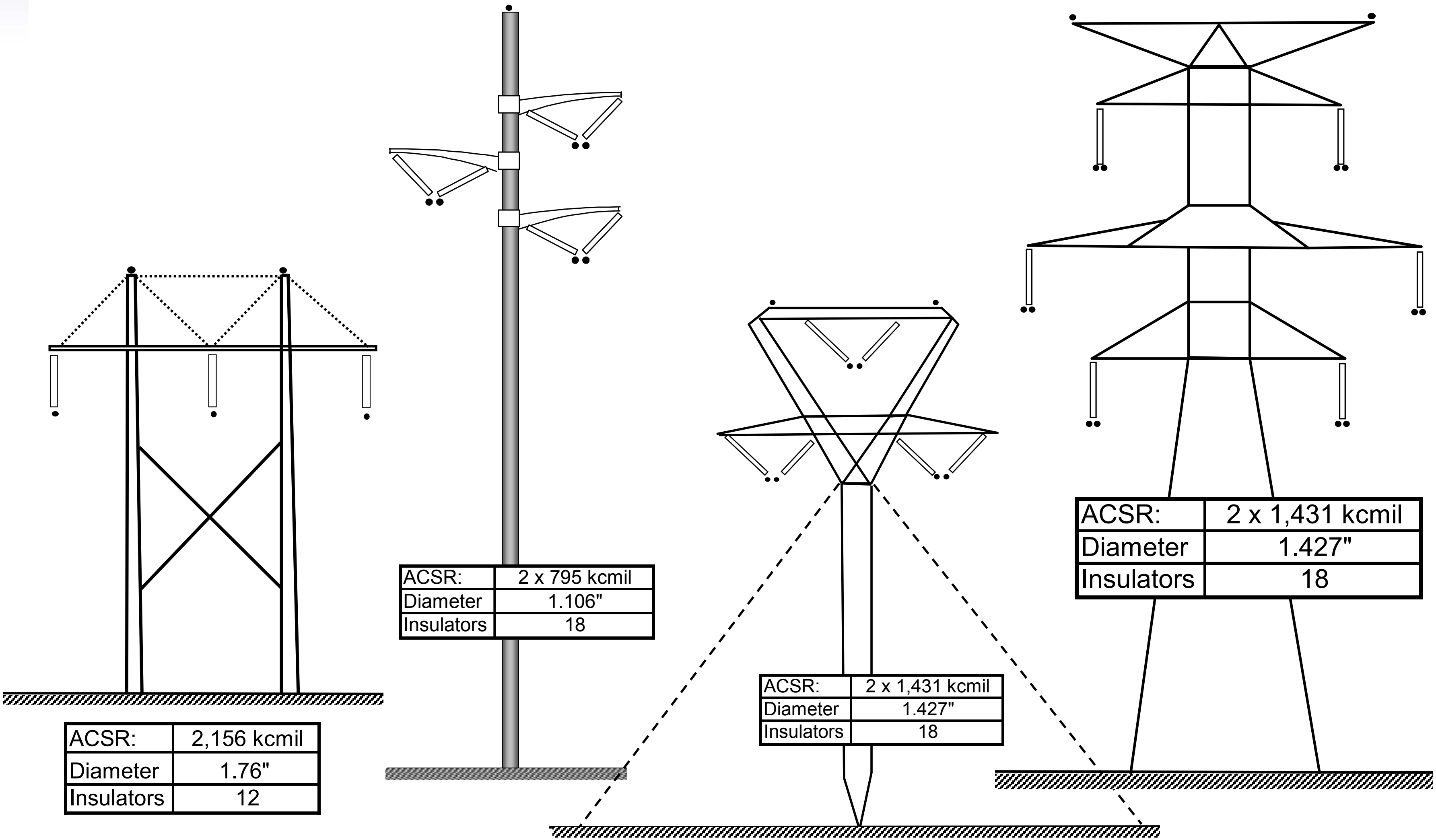
Structures Reviewed: 230 kV



ACSR:	954 kcmil
Diameter	1.196"
Insulators	12

ACSR:	1,590 kcmil
Diameter	1.502"
Insulators	12

Structures Reviewed 345 kV



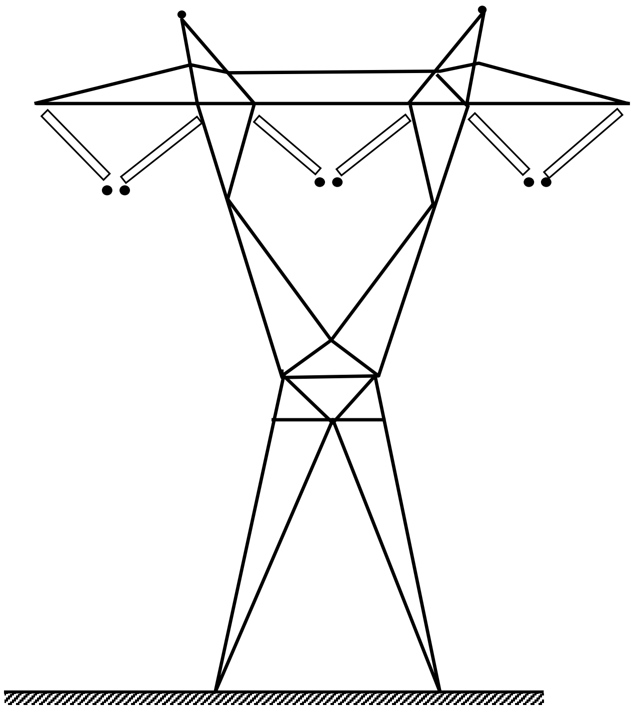
ACSR:	2,156 kcmil
Diameter	1.76"
Insulators	12

ACSR:	2 x 795 kcmil
Diameter	1.106"
Insulators	18

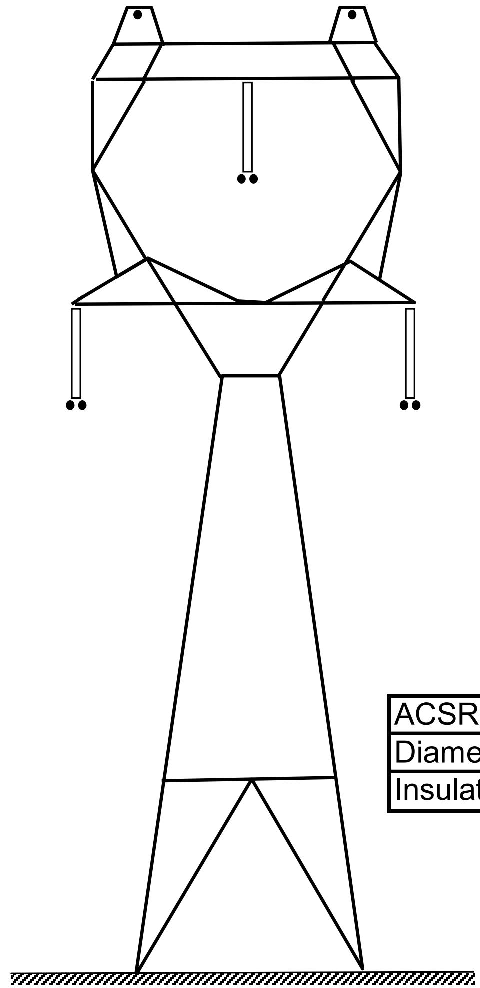
ACSR:	2 x 1,431 kcmil
Diameter	1.427"
Insulators	18

ACSR:	2 x 1,431 kcmil
Diameter	1.427"
Insulators	18

Structures Reviewed: 500 kV

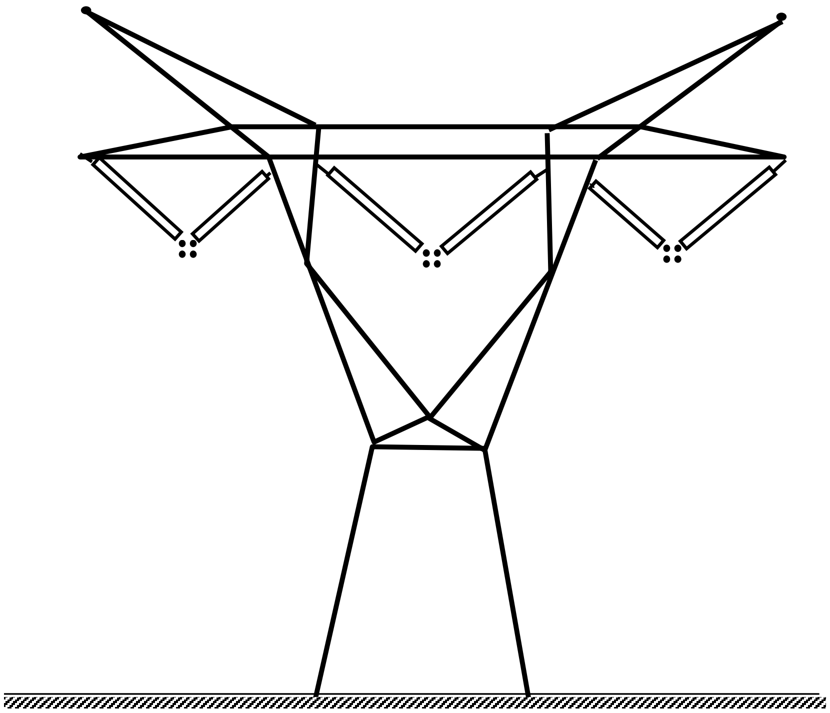


ACSR:	2 x 2,048 kcmil
Diameter	1.65"
Insulators	25



ACSR:	2 x 1,780 kcmil
Diameter	1.602"
Insulators	25

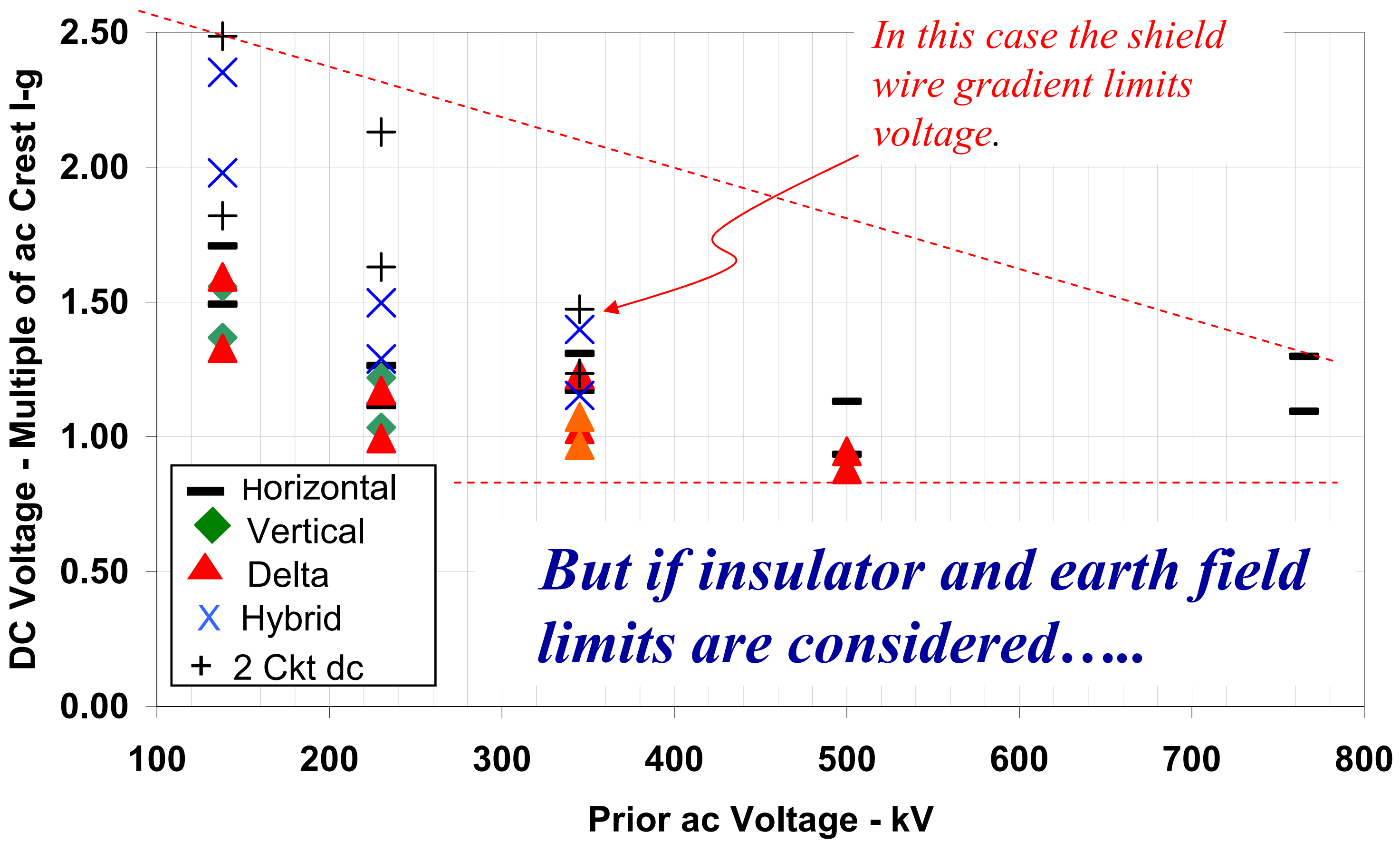
Structures Reviewed: 765 kV



ACSR:	4 x 1,585 kcmil
Diameter	1.602"
Insulators	32

Sustainable dc Voltage

Voltage constrained only by conductor gradient:



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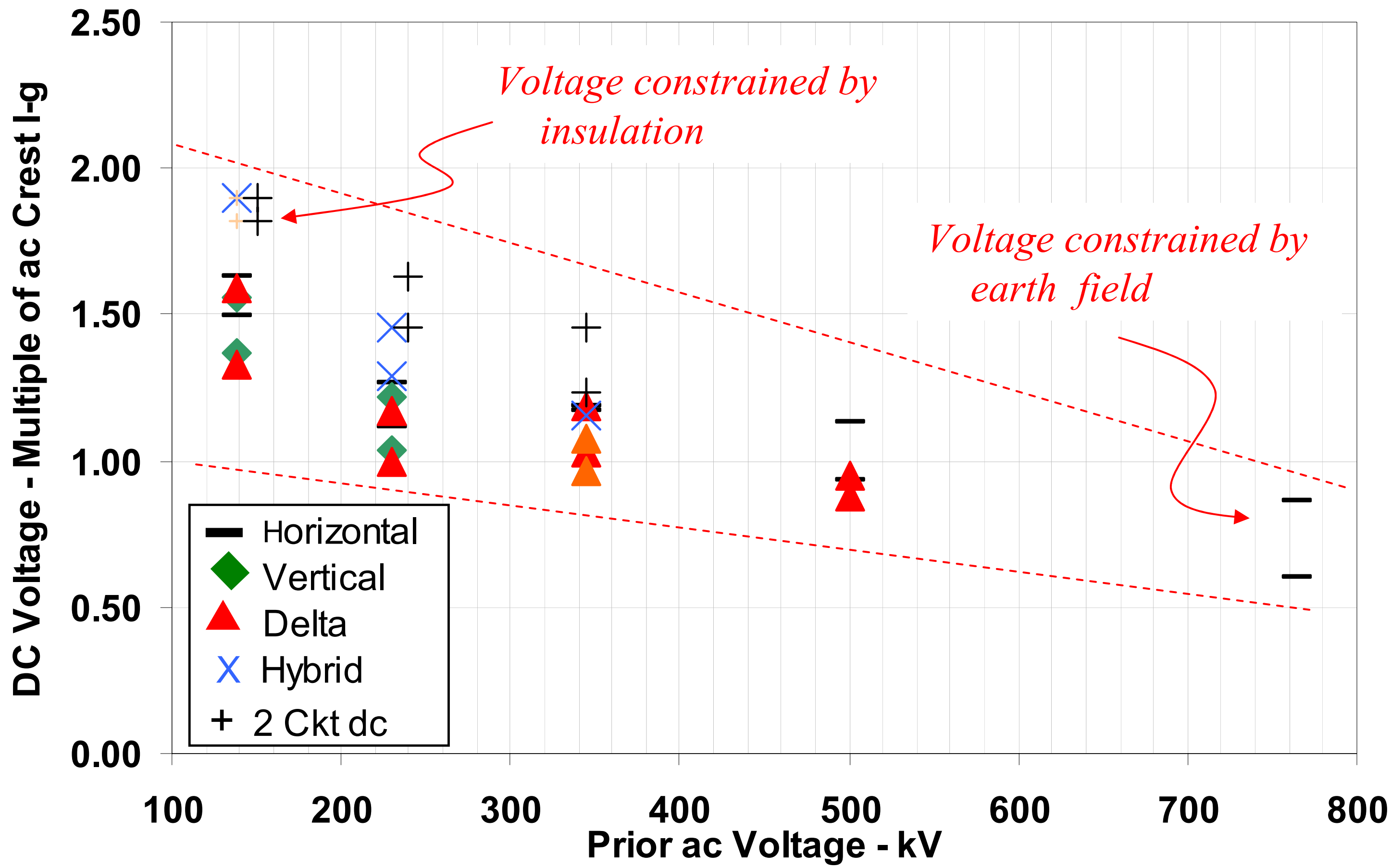
Sustainable dc Voltage

Voltage constrained by insulation and/or earth gradient:



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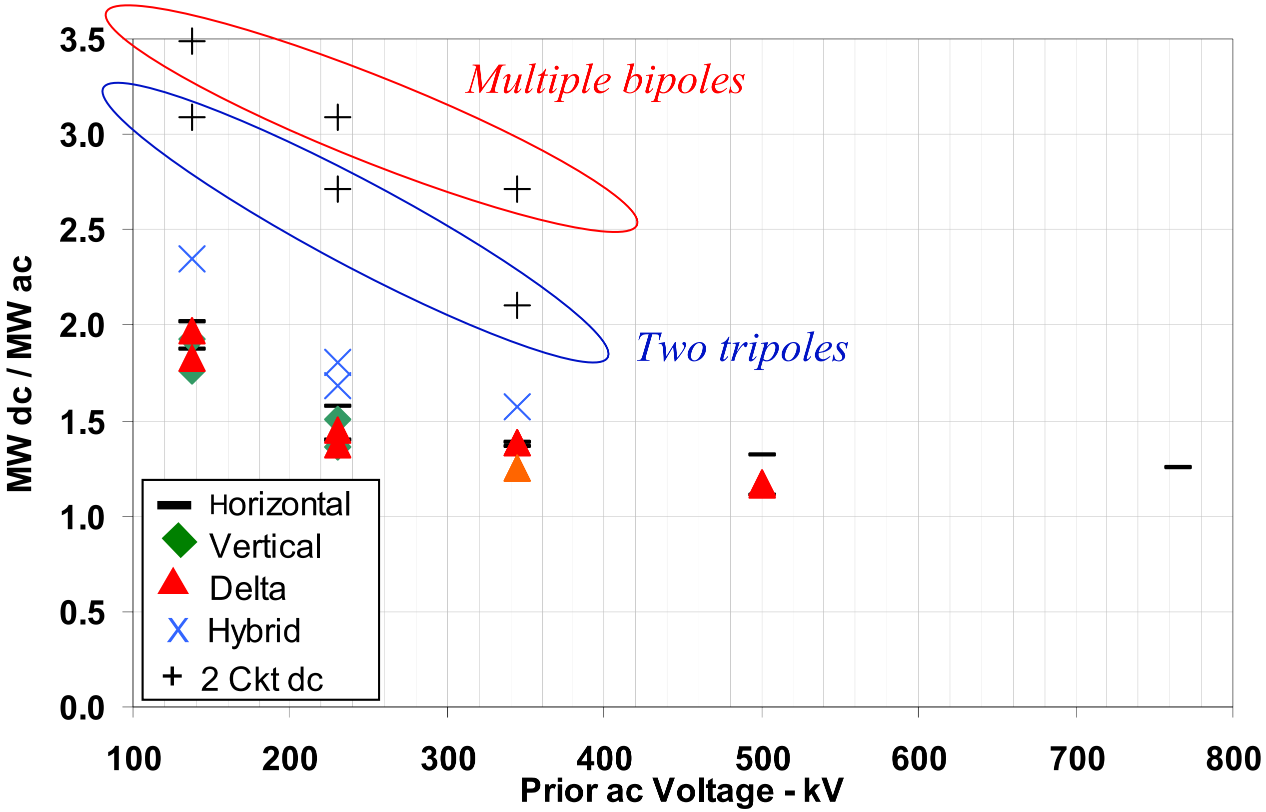
Post-Conversion DC/AC MW Ratio



DC at Max Continuous conductor rating, AC at 80% of maximum rating, pf = 0.95 (Voltage respects all constraints)

Conclusions: AC/DC Line Conversion

- Conversion allows major increase in voltage at low or intermediate voltages.
- Conductor gradient usually limits V_{dc} up to 500 kV, Earth field for 765 kV.
- Where insulation is limiting, there are work-arounds
- Conversion can increase a circuit's contribution to path flow by 2:1 or more… largest gains at lowest transmission voltages.
- Conversion may increase path flow more than an additional ac circuit of like rating.
- Reconductoring along conversion can double ampacity gain

P162: HVDC Systems – 2007 – 2008 – 2009

2007	2008	2009
162.001 Life Extension of Existing HVDC Systems ($100k)	**162.001 Life Extension of Existing HVDC Systems ($125k)**	**162.001 Life Extension of Existing HVDC Systems ($150k)**
Life Extension Guidelines for Converter Stations	Life Extension Guidelines for DC Lines	Update Guidelines with HVDC Line information
	Application of Converter Station Guidelines	SVC Life Extension Guidelines
		Training on Guidelines
162.002 Advanced HVDC Systems at +/- 800 kV and Above ($100k)	**162.002 Assessment & Evaluation of Next Generation HVDC ($125k)**	**162.002 Assessment & Evaluation of Next Generation HVDC ($150k)**
Advanced HVDC Systems at +/- 800 kV	VSC Based Technologies for HVDC	Advanced Power Electronic Devices for HVDC
162.003 HVDC Reference Book ($100k)	**162.003 HVDC Reference Book ($125k)**	**162.003 HVDC Reference Book ($150k)**
HVDC Reference Book: Chapters on HVDC Line & Simulation Tools	HVDC Reference Book: Additional chapters	HVDC Reference Book: Additional Chapters
Biennial EPRI HVDC Conference, Sept 13-14, 2007, Denver, CO		Biennial HVDC Conference / Workshop
162.004 AC/DC Line Conversion ($100k)	**162.004 AC/DC Line Conversion ($125k)**	**162.004 AC/DC Line Conversion ($150k)**
DC capability of existing AC structures	Develop AC/DC conversion technologies	Demo AC/DC Conversion Technologies

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HVDC Systems
Program 162
Supplemental Projects

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Life Extension Guidelines Application to HVDC Converter Stations

- Many converter stations are getting old and repair verses replace decisions have to be made
- Assess service life of the converter station & provide recommendations
- Complements Base Project (Guide) by Demonstration
- The components of the stations to be reviewed include:
  - Converter Station Characteristics such as power transfer capability
  - Environmental assessment – review station environment to determine ways to improve water usage by reducing water consumption and to reduce usage of treatment chemicals.
  - Propose strategies (when & how) to replace Converter Station insulation.
- Deliverables – Converter Station on-site evaluation and a technical report with recommendations
- Status – Base project is developing guidelines which can be applied to real world utility converter stations
- Cost to Participate: $110k ($55k TC + $55k TC match)
- Contact Details: Dr. Ram Adapa, radapa@epri.com, 650-855-8988

Transformerless Converters for HVDC

- In recent past, there have been reports of many converter transformer failures in a number of HVDC projects around the world.
- Novel idea to build a converter without a converter transformer and thus eliminates converter transformer problems
- Converter transformers account for 35–40% of the cost of a converter station
- Project in two phases - First Phase
  - Design & Simulation Studies for a small prototype
  - Economic analysis of the concept
- Second Phase – Field Demonstration
- Deliverables – Technical Report with basic design and economic assessment information
- Status – It is a new project and looking for utility participants
- Cost to Participate: $80k ($40k TC + $40k TC match)
- Contact Details: Dr. Ram Adapa, radapa@epri.com, 650-855-8988

Transformer Saturation Mitigation in Monopolar Ground Return HVDC Operation

Issue

- Monopolar ground return operation can cause transformer dc saturation
- To avoid saturation, current is limited to a small fraction of rated current
- DC Blocking Devices (BDs) in transformer neutrals can mitigate saturation
- BDs only protect transformers to which they are connected & other nearby substation transformers (AC or DC) can saturate

Proposed new system approach

- Converters at each end can be reconfigured to operate as four-quadrant converters - transmit either polarity of current and voltage
- Simultaneously reverse the line voltage and current at periodic intervals
- Power flow remains in the same direction, while the ground current periodically reverses, avoiding transformer saturation

- Deliverables – Technical Report with design and economic assessment
- Status – It is a new project and looking for utility participants
- Cost to Participate: $80k ($40k TC + $40k TC match)
- Contact Details: Dr. Ram Adapa, radapa@epri.com, 650-855-8988

Improved Method For Live Line Reconductoring (either AC or DC) – PON 1015488

- Reconductoring will boost line limits – 50 to 100%
- Two ways to reconductor *live*:
  - *Sequentially transfer load from existing phase positions, to a temporary "outboard" phase position; while the idled phase position is restrung.*
  - *Do the same but use an armored cable laid out along the right of way for the spare phase position.*
- Issues
  - continuous induced current
  - complex grounding challenges
  - transfer busses
  - current transfer switchgear
- Cost to Participate - $80 k ($40k TC + $40k TC match)
- Technical Contacts
  - Dr. George Gela, ggela@epri.com, 413-499-5710, or Dr. Ram Adapa, radapa@epri.com, 650-855-8988

HVDC testing at EPRI Lenox Labs

- Two 1500 kV DC power supplies to provide bipolar voltages up to ±1500 kV
- Large polymer insulator aging chamber
- Presently Testing for ESKOM
  - AC to DC line conversion
- Cost to Participate: $50k to $150k
- Contact Details: David Rueger, drueger@epri.com, 413-448-2452 or Dr. Ram Adapa, radapa@epri.com, 650-855-8988

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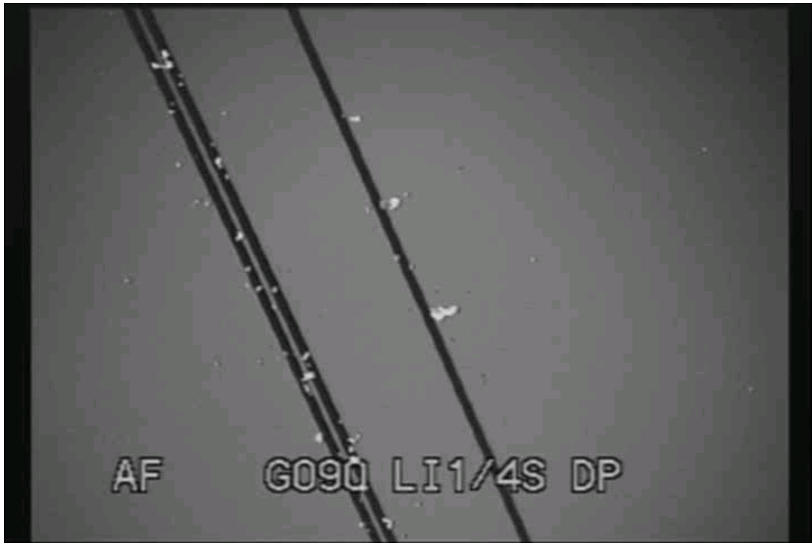
HVAC to DC Testing @ Lenox, MA Eskom

- **Opportunity**
  - 275kV AC → ±400kV DC
  - Potential Power Flow Increase:
    - 1.5 → 1.7
- **Issues**
  - Fair Weather Noise
  - E-field on Ground
  - Insulation
  - Pole to Pole Spacing
- **Approach**
  - Testing @ Lenox, MA
    - E-Field
    - Noise: AN / RI
  - Insulation Under Consideration



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Who should consider joining EPRI's HVDC Research Program?

- Potential participating utilities:
  - With HVDC system
  - Experiencing rapid growth in power demand
  - Encountering transmission capacity shortage
  - Desiring to enhance system stability
  - Contemplating of installing HVDC systems
  - Wanting to know what HVDC can offer
  - Owning or overlooking transmission network
  - Looking for integrating wind & other resources

Program Summary: P162 HVDC Systems

- HVDC Systems is a relatively new program started in 2006
- North American utilities more interested in Life Extension, Next Generation HVDC such as VSC DC transmission, AC/DC Line Conversion, and HVDC Reference Book
- International utilities are more interested in 800 kV HVDC
- Past EPRI products (reference books & reports) and EPRI Lenox labs will be an asset to grow interest in HVDC

For more information

Contact Dr. Ram Adapa, radapa@epri.com

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