IEEE PES
HVDC Systems & Trans Bay Cable

AC

DC Cable

AC

March 16, 2005
IEEE PES
HVDC Systems & Trans Bay Cable

- HVDC Transmission
- Project Description Trans Bay Cable
- Principles of HVDC – Controllability, Reliability, Overload Characteristics
- HVDC Control & Protection
- Trans Bay Cable Application - Long Distance HVDC Transmission
- HV DC Submarine Cable Technology and Installation
- Conclusion - HVDC Transmission – GBA Benefits and Operation
Why HVDC Systems?

HVDC is the unique solution to interconnect asynchronous systems, e.g. different grid frequencies. Solution: **HVDC Back-to-Back**

HVDC represents the most economical solution for distances greater than 600 km. Solution: **HVDC Long Distance**

HVDC is the solution for long submarine transmission. Solution: **HVDC Cable**
Portfolio HVDC

- **Up to 800 MW**
  - Long Submarine Transmission
  - AC DC line
  - AC DC cable

- **Up to 3000 MW**
  - Long Distance Transmission
  - AC DC line
- **Up to 800 MW**
  - Back-to-Back Station
  - AC 50 Hz
  - AC 60 Hz

SIEMENS
Siemens has been successful in the HVDC Business for more than 25 years.

2000 to 2005 Siemens Delivered 8 HVDC Systems on 4 Continents
### Basslink HVDC Interconnector 2005/2006

| Customer:          | Basslink PTY Ltd.  
|                   | (NGT Int. Ltd.)  |
| Location:         | Tasmania-Victoria |
| Project Status:   | Under execution  
|                   | Commercial operation |
| Supplier:         | 11/05  
|                   | Tas-Vic Interconnector  
|                   | Consortium |
| Type of Plant:    | Siemens / Pirelli  
|                   | Long Distance |
| Power rating:     | Sea Cable / OHL  
| Transmission dist.: | 500 MW monopolar  
|                   | 286 km DC cable  
|                   | 70 km OHL |
# Neptune RTS 2007

<table>
<thead>
<tr>
<th>Customer:</th>
<th>Neptune RTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>End User:</td>
<td>Long Island Power Authority (LIPA)</td>
</tr>
<tr>
<td>Location:</td>
<td>New Jersey: Sayreville, Long Island: Duffy Avenue</td>
</tr>
<tr>
<td>Supplier:</td>
<td>Consortium</td>
</tr>
<tr>
<td>Type of Plant:</td>
<td>Siemens / Pirelli</td>
</tr>
<tr>
<td>Power rating:</td>
<td>600/660 MW monopolar</td>
</tr>
<tr>
<td>Transmission dist.:</td>
<td>82 km DC Sea Cable, 23 km Land Cable</td>
</tr>
</tbody>
</table>

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[Image showing the map of Neptune RTS 2007 route]
Proposed Neptune – New Jersey to Long Island, NY
<table>
<thead>
<tr>
<th><strong>Customer:</strong></th>
<th>Babcock &amp; Brown</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project name:</strong></td>
<td>Trans Bay Cable</td>
</tr>
<tr>
<td><strong>Location:</strong></td>
<td>San Francisco Bay Area</td>
</tr>
<tr>
<td><strong>Project Status:</strong></td>
<td>Project Development, NTP early 06</td>
</tr>
<tr>
<td><strong>Project Team:</strong></td>
<td>B&amp;B, Siemens, Pirelli</td>
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<tr>
<td><strong>Type of Plant:</strong></td>
<td>Long Distance Sea Cable</td>
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<tr>
<td><strong>Power rating:</strong></td>
<td>400…600 MW monopolar</td>
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<tr>
<td><strong>Transmission dist.:</strong></td>
<td>Approx. 55 miles</td>
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</table>

**Trans Bay Cable Project 2008**

![Map of San Francisco Bay Area showing the proposed route of the Trans Bay Cable project with key locations marked, including Pittsburg.]
Power Electronics - Thyristor
Thyristor Valve Module
Valve Hall
Converter Transformers
Control and Protection System
Cable Laying Ship
Hydro-plow
Trans Bay Cable Project

General Project Description
The Project will be a new High Voltage Direct Current (HVDC) transmission system from the generation rich East Bay (PG&E Pittsburg Substation) into San Francisco (PG&E Potrero Substation)

- Cooperative development with City of Pittsburg

- Significant monetary, reliability and environmental benefits, including retirement of generation in San Francisco

- Provides a long-term energy and capacity solution needed in the Greater Bay Area Grid (SF City Center)

- Schedule: ‘In Service’ for Summer Peak 2008
Trans Bay Cable Project - Summary

- Revenue recovery based on FERC-approved cost-based rates under a PTO tariff with the CAISO
  - Babcock & Brown will provide the financing
  - City of Pittsburg will own the Project assets
  - Transmission rights will be turned over to the CAISO under a negotiated Transmission Control Agreement
Trans Bay Cable Project – Submarine Cable Route
Trans Bay Cable Project – Cable Interconnections

System Data:
Transmission Capacity: up to 600 MW
DC Voltage: 400 - 500 kV

PG&E Potrero Substation < 1 mile San Francisco < 1 mile Pittsburg < 1 mile PG&E Pittsburg Substation

San Francisco – San Pablo – Suisun Bays

AC/DC Converter Station

115 kV substation

Undersea DC Cables

DC AC AC DC

115 kV substation
Trans Bay Cable Project – Typical DC Converter Station

- AC Cable entry
- Valve Hall
- Control Building
- Spare Transformer
- DC Cable entry
- AC, AIS Switchyard
- DC Hall
- Valve Cooling
- Converter Transformer
- Capacitor Bank
- Busbar
- AC Filter
Trans Bay Cable Project – Aerial View of Project Site in Pittsburg – Option 1
Trans Bay Cable Project – Aerial View of Project Site in San Francisco – Option 2
Trans Bay Cable Project

Estimated Project Benefits and Costs
Trans Bay Cable Project – Need Study Results: Plots Showing Greater Bay Area Power Flows – Jefferson-Martin ON, Hunters Point OFF, Potrero (or CCSF Peakers) ON, Trans Bay Cable OFF
Trans Bay Cable Project – Need Study Results: Plots Showing Greater Bay Area Power Flows – Jefferson-Martin ON, Hunters Point OFF, Potrero (or CCSF Peakers) OFF, Trans Bay Cable ON
### Trans Bay Cable Project – Need Study Results: Comparison of Estimated Project Benefits and Costs

<table>
<thead>
<tr>
<th>HVDC Project</th>
<th>1 X 600 MW + No SF Generation</th>
<th>1 X 400 MW + No SF Generation</th>
<th>1 X 400 MW + 4 CCSF Peakers</th>
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</thead>
<tbody>
<tr>
<td><strong>Summary of Estimated First Year (2008) Benefits ($/yr)</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>- Loss Reductions</td>
<td>$19 million</td>
<td>$16 million</td>
<td>$19 million</td>
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<tr>
<td>- Project Deferrals</td>
<td>Negligible</td>
<td>Negligible</td>
<td>Negligible</td>
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<tr>
<td>- RMR</td>
<td>To be determined</td>
<td>To be determined</td>
<td>To be determined</td>
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<tr>
<td>- Economic Dispatch</td>
<td>$55 million</td>
<td>$55 million</td>
<td>$55 million</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>$75 million</td>
<td>$71 million</td>
<td>$75 million</td>
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<tr>
<td><strong>Summary of Estimated Annual Costs of Project ($/yr)</strong></td>
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<tr>
<td>- First Year (2008) Cost</td>
<td>$86 million</td>
<td>$65 million</td>
<td>$65 million</td>
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<tr>
<td>- 30 Year Average</td>
<td>$70 million</td>
<td>$53 million</td>
<td>$53 million</td>
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<tr>
<td><strong>Net Yearly Benefits ($/yr)</strong></td>
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<td></td>
</tr>
<tr>
<td>- 30 Year Average</td>
<td>$5 million</td>
<td>$18 million</td>
<td>$22 million</td>
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</table>
### Trans Bay Cable Project – Need Study Results: Comparison of San Francisco Load Serving Capabilities

<table>
<thead>
<tr>
<th>HVDC Configuration</th>
<th>San Francisco Generation</th>
<th>SF Load Serving Capability (year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 X 400 MW</td>
<td>4, CCSF Peakers</td>
<td>2030</td>
</tr>
</tbody>
</table>
Significant Environmental Benefits

- Significant assistance in **Retirement of Older Generation** in San Francisco

- Clean system power will serve San Francisco; including **Emissions Reduction** from 36 MW peak power production reduction

- If CCSF Peakers installed with Trans Bay Cable Project, **Peakers will Operate Less**
Trans Bay Cable Project – Additional Project Benefits

- **Enhanced Reliability**
  - Pittsburg – San Francisco line “Completes the Greater Bay Area ("GBA") transmission loop”
  - System security increased as buried DC cables will be in a separate corridor from any existing AC lines
  - Reduced power flow on existing Peninsula and East Bay lines, benefiting entire GBA
  - No problems found in N-1, N-2 contingency analyses using std criteria used by California ISO (including special criteria for GBA) and WECC
Basics of HVDC Transmission
Principles of HVDC

Characteristics

- $I_d$ in one direction only
- Magnitude of $P$ or $I_d$ controlled depending on difference in terminal voltages ($U_1, U_2$)
- Direction of $P$ controlled depending on polarity of terminal voltages ($U_1, U_2$)
HVDC Terminal

1 AC Switchyard
2 AC Filters, Capacitor Banks
3 Converter Transformers
4 Thyristor Valves
5 Smoothing Reactor
6 DC Cable
Equipment Tasks

- **AC Switchyard (1)**
  - Connect the terminal to the AC system

- **AC Filters, Capacitor Banks (2)**
  - Reactive power supply
  - Filter harmonic currents

- **Converter Transformer (3)**
  - Provide the AC voltage needed for the required DC voltage
  - Provide 12-pulse operation (star and delta connection)
  - Allow for series connection of 6-pulse bridges
Equipment Tasks

- **Thyristor Valves (4)**
  - Convert AC to DC and vice-versa
  - Connect 6-pulse bridges in series for required DC voltage

- **Smoothing Reactors (5)**
  - Smooth the DC current
  - Avoid resonance with DC line
  - Limit interference caused by DC side harmonics

- **DC Cable (6)**
  - Pure Active Power Transmission
Design / Specification

Main transmission Data
$P_{dc}$, $U_{dc}$, $I_{dc}$ etc.

Main data of converter station (U, I, a, Q)

AC-Network
- Load flow study
- Stability study

Computer
Simulation study

Insulation coordination and arresters

Thyristor valves

Smoothing reactor

DC-Harmonics

DC-Filters

DC-Line

AC-Harmonics

AC-Filters

Converter transformer

Design data for all equipment of the HVDC-system
Main Data of Converter Station

- Basic Control Concept
  - DC-Voltage, DC-Current, ...

- Thyristor Type
  - Short Circuit Current Capability

- Main Data
  - DC Voltage $V_{dc}$ and DC Current $I_{dc}$
  - Reactive Power $Q$
  - Firing Angles $\alpha, \gamma$
  - AC-Bus Voltage (Tap Changers)
Basic Control Functions

Tap Changer Control

ACF

Tap Changer Control

ACF

Tap Changer Control

ACF

Rectifier

Id-Control (Ud-Control)

Closed Loop Control

Inverter

Ud-Control (Id-Control) (Control)

Reactive Power Control

Reactive Power Control

Ud-Control (Id-Control) (Control)

Id-Control (Ud-Control)

Closed Loop Control Rectifier
Control System

\[ U = \frac{3\sqrt{2} E_n}{\pi} \]

\[ \cos \alpha = \frac{3 I_d X_c}{\pi} \]

\[ I_d = \frac{U_{d1} - U_{d2}}{R} \]
Thyristor Valves - LTT Housing and Trigger Cable
Advanced Power Electronics

80 % Less Electronic Components

Flame retardant Valves to UL standards

High Reliability

Valve Group Indoor for HVDC

Module

Thyristor
Thyristors Valves - Principle Circuit of a 12-pulse Group

Valve Tower Arrangement

Valve Branch
Optical Signal Transmission from Ground to Thyristors

VBE : Valve Base Electronic
MSC: Multimode Star Coupler
LG: Light Guide
Fire Protection - Transformers

- Buchholz Relays
- VESDA Detectors
- Air Sampling Tubes
- Ultra Violet Detectors
- Infra Red Sensors
AC Filters and Switchyard
AC Harmonics

- **Calculation of**
  - Characteristic Harmonics
  - Non-Characteristics Harmonics due to
    - AC-Voltage Unbalance (negative sequence)
    - Impedance Unbalance
    - Firing Angle Unbalance

- **Results used for Calculation of**
  - Converter Transformer
  - AC-Filters and C-Banks
AC Filters

Design Basis
- Performance Requirements
- AC Harmonics
- AC System Impedance

Design Criteria
- Adequate Design, also for future AC System Change
- Thermal Capability for Contingency Operation
- Use of same Capacitor Cans (Spare Parts)
- Resonance at Low Frequency
Calculation Method

Step 1: Calculate AC Harmonics, Select Maximal Values
Step 2: Calculate AC System Impedance (Locus)
Step 3: Split up Reactive Power, Define Filter Parameters
Step 4: Check Filter Performance
Step 5: Calculate Filter Performance and Component Stresses for Different Load Conditions
Filter Configurations

AC-Filter Type 1
Single Tuned (ST)

AC-Filter Type 2
Double Tune (DT)

AC-Filter Type 3
Triple Tuned (TT)
Reactive Power of HVDC Converter
Insulation Co-ordination with ZnO-Arresters

- Arrester Arrangement

- AC-Bus Arrester
- Valve Unit Arrester
- Valve Group Arrester
- DC Line Arrester
- Neutral Bus Arrester
- Filter Arrester
Arrester Arrangement
HVDC Control & Protection
HVDC Control and Protection System

Win-TDC*

* SIMATIC WinCC and SIMATIC TDC (Technology and Drive Control)
Win-TDC Control and Protection System Hierarchy

- **Operator Control Level**
  - Master Clock System
  - HMI
  - TFR

- **Control & Protection Level**
  - Station Control System
  - DA
  - Remote Control Interface
  - Inter Station Communication

- **Field/Process Level**
  - I/O Unit
  - AC Filter Switch
  - Valves
  - Measuring System

- **Redundancy** is not shown

- **LAN 100 MBit/s.**

- **Opposite Station**

- **Dispatch Centre**

**Abbreviations:**
- HMI: Human Machine Interface
- SER: Sequence of Events Recording System
- TFR: Transient Fault Recording System
- DA: Data Acquisition Unit

**Other Key Points:**
- Fiber Optic Field Bus
- Measuring Values
Win-TDC Control and Protection System Hierarchy

Typical Configuration (Monopolar HVDC)
Simatic TDC and modules for preprocessing and the transmission of measured values via an Optical Measuring Bus (TDM-Bus), trigger set and redundancy management

Win-TDC / Simatic TDC

- High performance and high speed (64Bit RISC-Processors)
- Systems are used worldwide in various applications
Win-TDC Controller Software

- Only one programming language for all Control and Protection Systems
- More than 250 tested and well proven standard function blocks
- Graphically configurable

Programming language CFC (Continuous Function Chart)
Win-TDC Measuring System
Cross-Redundant TDM Bus

Control and Protection Measuring System 1

Optical TDM Bus System

Pole Control and DC Protection System

System 1

System 2

TDM Bus 1
System 1

TDM Bus 2
System 1

TDM Bus 1
System 2

TDM Bus 2
System 2

TDM Bus = Time Division Multiplexing Bus
Remote Access Connection

- Optional Feature to access the Controls from Remote Locations
- For security, a VPN (Virtual Private Network) encrypted connection
- Can back up Maintenance Personnel
- Speeds up Diagnostic by Assistance from System Experts
Interaction Between AC and DC Systems
Overview

• Steady State Interaction

• Interaction During System Faults

• Enhancements of the Power System using DC Technology

• Specifics of the Trans Bay Cable Project
Steady State Interaction

System 1
- Converter transformer
- DC filters
- Shunt capacitors
- Six pulse converter including the trigger set
- Control & protection system
- Firing angle order to valves

System 2
- Converter
- DC cable
- AC filters
- Control & protection system
- AC System 2
- AC System 1

Telecommunication

Six pulse converter including the trigger set
Steady State Interaction

- Real Power (MW) flow is fully controllable.
- The reactive power (MVAR) depends on the real power output.
- Reactive compensation is required.
Steady State Interaction

- Conversion process from AC to DC generates harmonic currents which flows into the AC system.
- Requires harmonic filters.
Steady State Interaction

- Dispatched like a ‘generator’
  - Power control is much faster than a generator.
  - Reactive power behavior is different from a generator. Real and reactive power of the HVDC converter is not independent.

- HVDC does not contribute to short-circuit fault duty.

- Predicted annual availability of the converter is higher than 96%
  - Minimal scheduled outages required for maintenance - short duration.
  - Fully redundant control and protection system also increases the availability.
Interaction During System Faults

- Solid 3-phase fault near the rectifier
Interaction During System Faults

- Solid 3-phase fault near the inverter
Enhancements of the Power System using DC Technology

• The HVDC real power can be controlled very rapidly, therefore, the converter can be used to improve the power system performance.

• Special Protection Schemes (SPS) can be implemented for:
  • Fast frequency control
  • Power ramping (up or down)
  • Damping of Power Oscillations
  • Improvement of Transient Stability
  • Voltage is kept in a defined ‘bandwidth’ determined by ‘local’ interconnection study
Specifics of the Trans Bay Cable Project

- Interaction with Potrero SVC (-100/ + 240)
  - Control parameters may have to be adapted to avoid control oscillations.

- Conclusion
  - Do not expect any problems between the AC and DC Interaction.
HVDC Submarine Cable Technology and Installation
An impressive track record across the entire product range

- Submarine Systems > than 4,700 miles
- HV/EHV Systems > than 31,000 miles
- HV Accessories > than 34,000 pcs
- MV/LV Accessories > than 400,000 pcs/year
- Power Distribution > than 250,000 ton/year

In service to date

Continuous supply
Submarine Systems

- **Self-Contained Fluid Filled**
  - Paper insulated
  - PPL

- **Mass Impregnated**

- **Extruded**
  - XLPE
  - EPR

- HVDC
- HVAC
- MV
SUBMARINE CABLE SYSTEMS TECHNOLOGY
BASIC REQUIREMENTS OF A SUBMARINE CABLE

• Long continuous jointless shipping lengths
• High level of reliability: full control of manufacturing process to exclude internal defects
• Long design life
• Mechanical resistance to withstand all laying and embedment stresses
• Minimized environmental impact and maintenance
FACTORS TO BE CONSIDERED WHEN SELECTING A SUBMARINE CABLE

• Power to be Transmitted and Network requirements
• Route Selection - Seabed Geology, Thermal Resistivity
• Route Length / Water Depth profile
• Protection Requirements - Burial Depth, Fishing Activity, Marine Activity
• Security of Supply
• Environmental Considerations
• Economic Viability
THE CHOICE OF THE POWER TRANSMISSION SYSTEM

ROUTE LENGTH km
A.C. one 3-phase system  D.C. one bipole

A.C. Extruded Insulation Cable Systems
A.C. Extruded or Fluid Filled Cable Systems
A.C. Fluid Filled Cable Systems
D.C. Fluid Filled Cable Systems

Mass-impregnated D.C. Cable Systems
Mass-impregnated D.C. or XLPE Extruded D.C. Cable Systems (150 kV)

2400 MW
1250 MW
1000 MW
750 MW
500 MW
200 MW

2030 MW
1580 MW
1130 MW
780 MW
430 MW

1250 MW
1000 MW
750 MW
500 MW
200 MW

No Theoretical limit for D.C.
TYPICAL MASS IMPREGNATED SUBMARINE CABLE

CABLE CONSTRUCTION:

- Conductor of copper or aluminium segmental strips
- Semiconducting paper tapes
- Insulation of paper tapes impregnated with viscous compound
- Semiconducting paper tapes
- Lead alloy sheath
- Polyethylene jacket
- Metallic tape reinforcement
- Polypropylene yarn bedding
- Single or double layer of steel armour (flat or round wires)
- Polypropylene yarn serving
Cable System - HVDC 400 kV Cables

Submarine HVDC Cable
- Copper Conductor: 1500 mm²
- Insulation: Mass impregnated paper
- Armour: Galvanized steel
- Overall diameter: 121 mm
- Weight of cable: 43 kg/m

Land HVDC Cable
- Copper Conductor: 2000 mm²
- Insulation: Mass impregnated paper
- Overall diameter: 121 mm
- Weight of cable: 38.5 kg/m
Cable System – Metallic Return MVDC 12/20 kV Cables

**Submarine MVDC Cable**
- Copper Conductor: 1400 mm²
- Insulation: XLPE compound
- Armour: 50% galvanized steel, 50% HDPE
- Overall diameter: 90 mm
- Weight of cable: 20.2 kg/m

**Land MVDC Cable**
- Copper Conductor: 1400 mm²
- Insulation: XLPE compound
- Overall diameter: 71 mm
- Weight of cable: 15.0 kg/m
ARCO FELICE FACTORY

• Year in which activity started 1954
• Total Area 70,000 sq.m
• Covered Area 48,288 sq.m
• Workers 316
• Staff 43

PRODUCTION RANGE

• HV Submarine Power Cables (Paper, Mi, Fluid Filled)
• Submarine Optical Fiber Cables
• Land Optical Fiber Cables
• L.V./M.V Power Cables (EPR & XLPE)
PAPER IMPREGNATED SUBMARINE CABLES

Manufacturing Flow Chart

- Stranding
- Impregnation
- Paper Lapping
- Lead Extrusion
- PE Sheath Extrusion
- Armouring
Submarine Cable Laying
Main features

- Length Overall 133 m
- Molded Breadth 30 m
- Draft 8.5 m
- Gross Tonnage 10,617 tons

- Dynamic Positioning Control
- Total propulsion Power 5,710 kW
- Capstan 6 m diameter, 50 tons pulling tension
- Linear laying machine 10 tons pulling tension
- Turntable, external dia. 25 m, capacity 7,000 tons
The cables will be simultaneously installed in a Bundle configuration, fastened together with ropes and straps applied before approaching the laying sheave.
Hydro-plow Lay & Burial Method

- Simultaneous lay & burial → cable immediately protected (no cable exposure)

- Very effective burial method using Hydro-plow
  - Jetting power focused on excavation only
  - Jetting power is not used for machine propulsion
  - Minimum trench cross-section

- Cable is taken to the trench bottom by stinger
- Single pass → low installation time
- Simple machine → low contingencies
Simultaneous Lay & Burial Operation

C/S Giulio Verne
PIRELLI BURIAL EQUIPMENT

Hydroplow-3
Power Cable Embedment Sled
Shore Crossings - Horizontal Directional Drilling

Drilling the pilot hole

Hole reaming

Duct installation

10 m

Bore Hole

Duct

F.O. cable

HVDC cable

Electrode cable

Duct
Cable Protection - Alternative methods
Cable Protection - Alternative Methods
HVDC Transmission – GBA Benefits and Operation
HVDC System Attributes for the GBA

- Energy and Capacity Transmission - for SF City Center
- Robust Technology - Proven in Systems Worldwide
- Controllable Power - Exact power flow - Generation to Load
- Operational Flexibility – ability to “dial in a flow”
- Invisible Transmission - Energy exchange via Sea Cable
- Firewall Protection – AC system disturbances kept isolated
- Enhancement of AC system stability
- Reduced System Line losses
THANK YOU!!

AC

DC Cable

AC