Power Interconnector
Economic Justification and Financing Methodology

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(Presenter Gratefully Acknowledges Sources Accessed)
Presentation Structure

• Power System Planning
• Regional Power Market Expansion
• Economic Analysis Methodology
• Specific Results
• Typical Financing Structures
• Illustrative Examples
POWER SYSTEM PLANNING

• Objective
• Choice from Feasible Options
• Simple Economic Comparison
• Generation Planning Models
• Transmission Planning Models
WASP MODEL FOR GENERATION PLANNING

• Load Modeling
• Fixed System Definition
• Various Options Permitted
• Configuration Generation
• Probabilistic Simulation
• Dynamic Optimization
POWER TRANSMISSION PLANNING

• AC Power Flow Analysis
• Transient Stability Analysis
• Short Circuit Analysis
• Linearized Power Flow
• Integrated Generation and Transmission Planning
Regional Power Market Expansion

• Optimal exploitation of energy resources
• Reduction in generation reserve requirements
• Reduction in overall cost of supply
• Improved system reliability, energy security
• Incentives to resource rich countries to accelerate power development
• Cross-border connectivity, a prerequisite
Regional Power Market Expansion ..... 

- Undertake power system studies for short, medium and long term to identify possible quanta of power transfer, transmission system requirements
- Review regulatory provisions including grid codes to ensure reliable interconnected operation
- Pricing of traded power and transmission and payment security mechanisms
- Adopt broad agreement at governmental level for multi-lateral power exchange
IND-BHU Power Interconnections
Proposed IND-SRI HVDC Power Link
NEP/IND and BAN/IND Power Transfer
Proposed IND-PAK Power Link
Energy Transfers from CA/WA
SETTING OF CASA 1000 PROJECT

Existing Facilities
- Toktogul HPP
- Existing Surplus
- Nurek HPP
- Existing Surplus

Facilities Under Construction
- 500 kV OHL South-North
  Financing: China Exim bank
- Sangtuda 1 HPP
  Financing: Russia
- Sangtuda 2 HPP
  Financing: Iran
- 220 kV OHL SS Sarban – Tajik/Afghan border
  Financing: ADB/IsDB

Perspective Facilities
- 220/500 kV Uzbek by pass
  SS Datka (Kyrgyz) – SS Hojent (Tajik)
- Cascade of Zarafshan HPPs
  (Yavan and Oburdon HPP)
  Annual generation 1680 GWh
- Rogun HPP
  Annual generation 13000 GWh
- Coal TPP
  Annual generation 3900-6400 GWh
- 500 kV OHL “CASA 1000”
  Nurek HPP – Kabul - Peshawar
## ADB SA Regional Power Exchange Study
### Interconnections Considered

<table>
<thead>
<tr>
<th>No.</th>
<th>Interconnection</th>
<th>Description</th>
<th>Capacity (MW)</th>
<th>Cost (USD million)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>India-Bhutan</td>
<td>Grid reinforcement to evacuate power from Punatsangchhu I &amp; II</td>
<td>Total grid reinforcement of 2,100 MW</td>
<td>140-160 (2010 estimate)</td>
</tr>
<tr>
<td>2</td>
<td>India-Nepal</td>
<td>Dhalkebar-Muazaffarpur 400 kV line</td>
<td>1,000 MW</td>
<td>186 (2010 estimate) including internal transmission upgrade</td>
</tr>
<tr>
<td>3</td>
<td>India-Sri Lanka</td>
<td>HVDC line with sub-sea cable</td>
<td>500 MW in the short-term</td>
<td>339 (2006 estimate) 600 (Current)</td>
</tr>
<tr>
<td>4</td>
<td>India-Bangladesh</td>
<td>HVDC back-to-back asynchronous link</td>
<td>500 MW</td>
<td>192-250 million (2011 estimate)</td>
</tr>
<tr>
<td>5</td>
<td>India-Pakistan</td>
<td>220 kV in the short term, 400 kV in the long term</td>
<td>250-500 MW</td>
<td>50-150 million (2012 estimate)</td>
</tr>
<tr>
<td>6</td>
<td>CASA 1000 and India-Pakistan interconnection</td>
<td>HVDC and 500 kV HVAC for CASA</td>
<td>1300 MW</td>
<td>Approx 1 billion (2011 estimate)</td>
</tr>
</tbody>
</table>

* Cost of these projects are likely to escalate with delay and also depend heavily on specific design options. The estimates presented are derived from various planning documents and discussions with Member State representatives.
Methodology: Overview

- Transmission Resources
  - Capex/Opex, MW, Location of Resources
- Generators
- Optimal Mix of Generation using Investment Optimisation with DC power flow constraints
  - Probability distribution of uncertain parameters
  - Selected Generators given a transmission configuration
- Performance of Selected Resources using Monte Carlo Simulation with DC-PF. Perform two runs with and without a transmission line to assess the benefit of the line
Methodology: Monte Carlo

Demand variation (by node and block of LDC)

Uncertain fuel costs (SRMC of generation)

Random outage of generators and lines

Combined set of parameters for each Monte Carlo sample

Investment and dispatch optimisation model – all samples

Distribution of flows, costs etc created using all samples
Methodology: Implementation

• NATGRID model is essentially a stochastic investment and dispatch optimisation model with DC approximation of load flow embedded in the optimisation.

• We obtained PSS/E load flow dataset for 2016 for the Indian power grid.

• Indian power demand to reach over 230 TW of peak demand and 1300 TWh of energy by 2016.

• We have used CEA’s generation expansion plan for the study.
Methodology: Implementation

- The NATGRID methodology allows us to calculate all of the components of benefits and marginal costs maintaining any constraints related to investment, dispatch and transmission flows. The objective function of NATGRID consists of costs that include:
  - Capital cost of new power stations,
  - Fixed operation and maintenance (O&M) costs of existing and new power stations,
  - Variable O&M costs of existing and new power stations,
  - Fuel costs, and
  - Costs of unserved energy
Methodology: Implementation

• The model is set up with more than 700 generating units and over 160 inter-regional links to run the DC-OPF across 500 random Monte Carlo samples

• Benefit of an interconnector may vary greatly depending on demand and other factors
  – One must look at the full range of possibilities rather than rely on a point estimate specific to a single set of assumptions
  – A set of random samples is a useful way to capture uncertainties in demand growth, outage of generation and interconnectors, and fuel costs
Methodology: Implementation

• Benefits are calculated as follows:
  – NATGRID is run with and without the link

• Difference in total system cost represents the benefit of the link. It comprises
  – Capacity costs because the link can defer/avoid the need for part of the new capacity
  – Fuel costs because the link obviates the need to dispatch expensive diesel plants
  – Cost of unserved energy because the link would better meet peak
Methodology: Implementation

• Benefits depend on a number of parameters such as demand, generation availability, fuel costs, that are uncertain

• We estimate the benefit by running the model 500 times each time using a different demand configuration, set of available plants and transmission capacity and fuel costs

  – Results in 500 estimates of benefits that can be used to develop a distribution of flows on the link and also associated benefits (see Detailed Results)
## Results: Benefit estimates

<table>
<thead>
<tr>
<th>Case study</th>
<th>Key assumption</th>
<th>Total and annualised cost of transmission USD million</th>
<th>Annual benefit in 2016/17 (USD million)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>India-Sri Lanka HVDC link</strong></td>
<td>Puttalam Stage 2 and 400 MW in new hydro is added by 2016. But Trinco (1,000 MW) coal station is not considered.</td>
<td>Total cost USD 339 million (2006 estimate) Annualized cost USD 50 million pa (2010 estimate)</td>
<td>USD 186 million pa comprising 96 million in unserved energy reduction, and 90 million in fuel/capacity benefits.</td>
</tr>
<tr>
<td><strong>India-Bangladesh HVDC link</strong></td>
<td>Three scenarios around demand growth in Bangladesh that range between 9,000 MW to 12,000 MW in 2016/17.</td>
<td>Total cost range between USD 192 million to USD 250 million. Annualised cost of USD 25 million pa assumed for cost/benefit analysis.</td>
<td>Annual benefits range between USD 145 million to USD 389 million, depending upon demand-supply assumptions.</td>
</tr>
</tbody>
</table>
### Results: Benefit estimates

<table>
<thead>
<tr>
<th>Case study</th>
<th>Key assumption</th>
<th>Total and annualised cost of transmission USD million</th>
<th>Annual benefit in 2016/17 (USD million)</th>
</tr>
</thead>
</table>
| **India-Bhutan grid reinforcement**      | Puntsanchhu I & II (2100 MW)          | Total cost USD 140-160 million. Annualized cost USD 18-20 million pa. | Up to USD 1,954 million pa including  
• USD 350 million in opex benefit and  
• USD 1,604 million in unserved energy reduction benefit |
| **Nepal-Bihar 400 kV link**               | Two scenarios:                        | Total cost USD 63 million. Annualized cost USD 8 million pa | (a) Surplus state benefit of USD 105 million pa (71 million in unserved energy reduction and 34 million in opex benefits)  
(b) Deficit state benefit of USD 215 million (173 million in unserved energy reduction and 42 million in opex benefits) |
|                                           | Surplus state:  
(2000MW added) |                                                       |                                                       |
|                                           | Deficit state:  
650 MW delayed |                                                       |                                                       |
Detailed Results: IND-SRI

- Distribution of benefits

The link is likely to be beneficial with USD 186 million in annual benefit on average. This is likely to yield a benefit to cost ratio of over 3.
Detailed Results: India-Bangladesh

- Distribution of benefits for three cases

![Graph showing annual benefit in USD million against probability for Case 1, Case 2, Case 3, Avg Case 1, Avg Case 2, Avg Case 3.](image-url)
Detailed Results: India-Nepal
Nepal in Deficit (650 MW less capacity)

Average benefit in deficit state increases to $215m pa ($173m of USE benefits)

Negative fuel cost savings
Detailed Results: India-Bhutan

- Distribution of fuel & opex benefits

On avg USD 350m ($21/MWh on avg), bottom quartile of USD 183m can also recover interconnection costs of USD 140-160m **in a single year**
India-Pakistan Link (500 MW)

Potentially very high benefits due to a combination of USE and fuel cost savings
Very significant upside through the ability of these projects to largely eliminate shortage in Pakistan. Also, the bottom end of the distribution shows the total benefit rarely dips below USD 500 million.
FINANCING OPTIONS

Government Budget

Official Borrowing

Multilateral and Bilateral

Public Utility

Project 1

Project 2

Project 3

Equity Financing
- Sponsor Capital
- International Stock Markets
- Investment Funds / Multilateral

Debt Financing
- Commercial Banks / Bond Markets
- Export / Supplier Credit
- Energy Funds / Multilateral
Structure of a BOT Power Project

- National Electric Utility
- Insurers
- Fuel Suppliers
- Contractors
- Plant Operator
- Power Purchase Agreements
- Insurance Agreements
- Fuel Supply Contracts
- Construction Contracts
- Operating Services Agreement
- Project Company
- Project Implementation Agreement
- Escrow Agreements
- Loan Agreements
- Sales Contracts
- Equity Agreements
- Shareholders Agreements
- Sponsors
- Investors
- Plant Suppliers
- Contractors
- Plant Operators
- Host Government
- Senior Lenders
- Escrow Agent
- All Lenders
- Private Investors
- Plant Suppliers
MULTILATERAL CREDIT ENHANCEMENT

- Complementary Financing

- Guarantee Operations
  - Increase commercial co-financing
  - Attract better terms and conditions, particularly longer maturities
  - Only partial guarantees offered
  - Must have stake in the project
COMPLEMENTARY FINANCING
(ADB)
Main Loan From ADB
Complementary Loan From Commercial Bank(s)
ADB Becomes Lender of Record For Commercial Bank Loan
Share ADB Preferred Creditor Status (eg. No Debt Rescheduling)
PARTIAL CREDIT GUARANTEES
- to cover nonpayment for designated part of debt service (principal or principal plus interest for later maturities)

PARTIAL RISK GUARANTEES
- to cover specific risks of nonperformance of government obligations (e.g., payment for output by state-owned entities, foreign exchange availability for profit repatriation)
• Joint venture between the Tata Power Company Limited (51%) and Power Grid Corporation of India Limited (49%) – a pioneering PPP
• Set up 3000 MW 400 kv double cct line from Siliguri in West Bengal to Mandaula in Uttar Pradesh (near New Delhi), covering 1166 km
• Project completed within schedule and cost estimate and commercial operation since September 2006.
• Total project cost was $265m- financed by equity of $79.5m and debt of $185.5m.
• IFC provided a loan of $75m and Asian Development Bank provided a loan of $66.3m and domestic financing institutions and banks provided loans of $44.2m
• Entire transmission capacity was assigned to Power Grid Corporation under a Transmission Service Agreement for a regulated transmission fee.
• PTL constructed the line and maintains it to ensure its availability at contracted levels.
SUCCESS FACTORS

- **Strong political and stakeholder commitment is needed** to advance large projects at the bi-lateral and multi-lateral level. Need strong, capable utilities to engage.

- **Technical and Financial Support provided by the external stakeholders** such as the IFIs (e.g., World Bank and ADB) can be crucial to initial project development and resolution of common issues.

- **Legally enforceable agreements.** This may be by multi-country treaty or by bilateral inter-governmental agreements, or multi-lateral government agreements.

- **The creditworthiness of the main buyer** is a prime consideration to enable project financial closure.

- **Private sector participation can speed development** both for funding and operational expertise. This also improves the confidence of commercial lenders to the project.

### Table 1: Project Cost Summary

($ million)

<table>
<thead>
<tr>
<th>Item</th>
<th>Total</th>
<th>AFG</th>
<th>TAJ</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>A. Base Cost</strong>&lt;sup&gt;a&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Transmission Line</td>
<td>45.7</td>
<td>25.7</td>
<td>23.0</td>
</tr>
<tr>
<td>2. New Substations</td>
<td>12.5</td>
<td>12.5</td>
<td>–</td>
</tr>
<tr>
<td>3. Generation Upgrading/Rehabilitation</td>
<td>14.8</td>
<td></td>
<td>12.4</td>
</tr>
<tr>
<td>4. Bulk Metering</td>
<td>1.5</td>
<td>–</td>
<td>1.7</td>
</tr>
<tr>
<td>5. Implementation Consultant</td>
<td>3.3</td>
<td>1.3</td>
<td>2.0</td>
</tr>
<tr>
<td>6. Others</td>
<td>3.6</td>
<td>3.2</td>
<td>0.4</td>
</tr>
<tr>
<td>7. Taxes and Duties&lt;sup&gt;b&lt;/sup&gt;</td>
<td>1.3</td>
<td>3.3</td>
<td>0.0</td>
</tr>
<tr>
<td><strong>Subtotal (A)</strong></td>
<td>82.7</td>
<td>44.0</td>
<td>41.9</td>
</tr>
<tr>
<td><strong>B. Contingencies</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Physical Contingencies&lt;sup&gt;c&lt;/sup&gt;</td>
<td>9.8</td>
<td>5.5</td>
<td>4.7</td>
</tr>
<tr>
<td>2. Financial Contingencies</td>
<td>5.4</td>
<td>2.9</td>
<td>2.4</td>
</tr>
<tr>
<td><strong>Subtotal (A+B)</strong></td>
<td>97.9</td>
<td>54.4</td>
<td>49.0</td>
</tr>
<tr>
<td><strong>C. Interest During Construction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total (A+B+C)</strong></td>
<td>109.5</td>
<td>55.5</td>
<td>54.0</td>
</tr>
<tr>
<td>%</td>
<td>100</td>
<td>50.7</td>
<td>49.3</td>
</tr>
</tbody>
</table>

*AFG=Afghanistan, TAJ=Tajikistan.*

<sup>a</sup> 2006 prices.

<sup>b</sup> Taxes and duties under the Project are not payable in Tajikistan.

<sup>c</sup> Ten percent physical contingencies for most items.

<sup>d</sup> Based on 2% escalation (annual disbursements 20%, 39%, 31%, 10%).

<sup>e</sup> Assuming 5.5% used for relending to Barki Tajik (Tajikistan) and 1% for relending to DABM (Afghanistan).

Source: Asian Development Bank estimates.
**ADBAFG-TAJ 220KV (2006)**

Table 2: Financing Plan
($ million)

<table>
<thead>
<tr>
<th>Source</th>
<th>Total</th>
<th>AFG</th>
<th>TAJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADB</td>
<td>56.5</td>
<td>35.0</td>
<td>21.5</td>
</tr>
<tr>
<td>OFID Fund</td>
<td>8.5</td>
<td></td>
<td>8.5</td>
</tr>
<tr>
<td>IsDB</td>
<td>10.0</td>
<td></td>
<td>10.0</td>
</tr>
<tr>
<td>ARTF/Other</td>
<td>16.5</td>
<td>16.5</td>
<td></td>
</tr>
<tr>
<td>Equity (Government of</td>
<td>18.0</td>
<td>4.0</td>
<td>14.0</td>
</tr>
<tr>
<td>Afghanistan/BT)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Total Project</strong></td>
<td><strong>109.5</strong></td>
<td><strong>55.5</strong></td>
<td><strong>54.0</strong></td>
</tr>
</tbody>
</table>


Source: Asian Development Bank estimates.
PROPOSED CASA 1000

Interconnected Tajikistan/Afghanistan/Pakistan System
Table 9-5  EPC Cost Estimate for HVDC Tajikistan-Afghanistan-Pakistan and HVAC Kyrgyz Republic-Tajikistan Interconnections (US $ Million)

<table>
<thead>
<tr>
<th>Countries</th>
<th>HVDC Component</th>
<th>HVAC Component</th>
<th>HVDC HVAC Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Converter Substations +</td>
<td>Electrodes</td>
<td>Transmission Line</td>
</tr>
<tr>
<td>Tajikistan</td>
<td>128</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Afghanistan</td>
<td>71</td>
<td>5</td>
<td>162</td>
</tr>
<tr>
<td>Pakistan</td>
<td>128</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>The Kyrgyz Republic</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total EPC Costs</strong></td>
<td><strong>558</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Estimates include EPC costs only.

In order to estimate the total project costs other costs such as Owner’s Engineer, Contingency, country network reinforcements, environmental and social mitigation measures were added to the EPC costs shown in Table 9-5 above. These costs were calculated as follows:

- Owner’s Engineer – 2% of EPC Costs
- Contingency – 10% of EPC plus Owner’s Engineer Costs
Creating an Enabling Environment for Cross Border Power Trade

- Develop a SAARC Regional Energy Trade and Cooperation Agreement
- Harmonise the Legal and Regulatory Frameworks
- Build a comprehensive/reliable energy database
- Develop a regional energy trade treaty similar to the Energy Charter Treaty
- ADB can provide TA support for SAARC accepted regional projects and build on analysis
AC and DC Transmission for Power System Interconnection
Presentation Structure

• Regional Power Transmission Needs
• HVAC Power Transmission
• Power Flow Analysis
• Flexible AC Transmission
• HVDC Power Transmission
• Illustrative Examples
Regional Power Market Expansion

- Optimal exploitation of energy resources
- Reduction in generation reserve requirements
- Reduction in overall cost of supply
- Improved system reliability, energy security
- Incentives to resource rich countries to accelerate power development
- Cross-border connectivity, a prerequisite
Energy from WA and CA to SA
NEP/IND and BAN/IND Power Transfer
IND-BHU Power Interconnections
Proposed IND-SRI HVDC Power Link
ROW for 10,000 MW Bulk Power Transfer with 800 kV AC and 750 kV HVDC
AC Power Transmission Line Parameters

- Resistance: Ohm/mile * length (R)
- Inductance: Henry/mile * length (L)
- Capacitance: Farad/mile * length (C)

Characteristic Impedance $Z_c$ is given by:
$$\sqrt{\frac{(R+jwL)}{jwC}} = \sqrt{\frac{L}{C}} \times (1-j\frac{R}{2wL})$$

When $R << wL$, $Z_c=\sqrt{\frac{L}{C}} = $ Surge Impedance (SI)

Surge Impedance Load (SIL) = ($V_{\text{rated}}$ **2)/SI watts (natural load)
Transmission Line Pi Equivalent

Figure 6.3 Equivalent $\pi$ circuit of a transmission line

From the equivalent circuit, the sending end voltage is

$$\tilde{V}_s = Z_e \left( \tilde{I}_R + \frac{Y_e}{2} \tilde{V}_R \right) + \tilde{V}_R$$

$$= \left( \frac{Z_e Y_e}{2} + 1 \right) \tilde{V}_R + Z_e \tilde{I}_R$$
VOLTAGE RATING AND POWER CAPACITY

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>132</th>
<th>230</th>
<th>345</th>
<th>500</th>
<th>700</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural load (MW)</td>
<td>43</td>
<td>130</td>
<td>300</td>
<td>830</td>
<td>1600</td>
</tr>
</tbody>
</table>

The power flow in an AC system and the power transfer in a transmission line can be expressed as

\[ P = \frac{E_1 E_2}{X} \sin \delta \]

\( E_1 \) and \( E_2 \) are the two terminal voltages, \( \delta \) is the phase difference of these voltages, and \( X \) is the series reactance. Maximum power transfer occurs at \( \delta = 90^\circ \) and is

\[ P_{\text{max}} = \frac{E_1 E_2}{X} \]
Transmission Cost for Received Power

![Graph showing the transmission cost for received power with different voltage levels: 230 kV, 345 kV, and 500 kV. The graph plots Mills/kWh against MW at receiving end for distances of 200 miles and 600 miles.](image-url)
Power Flow Analysis

- Used to design the power system
- Used to upgrade the power system
- Used to study the power system in real time for secure operation
- By far the most useful calculation used by power system engineers
- HVDC convertors and links can be incorporated
IEEE 14 BUS SYSTEM

[Diagram of an IEEE 14 BUS SYSTEM with generators and synchronous condensers labeled.]

ABP 14 BUS TEST SYSTEM BUS CODE DIAGRAM
Power Flow Analysis

The Power Flow Problem

- Compute voltage magnitude and phase angle at each bus
- Calculate real and reactive power flow through equipment

Input Data

- Transmission line data
- Transformer Data
- Bus Data

<table>
<thead>
<tr>
<th>Bus Type</th>
<th>Known Parameters</th>
<th>Unknown Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swing Bus</td>
<td>V=1&lt;0°</td>
<td>P, Q</td>
</tr>
<tr>
<td>Load Bus</td>
<td>P+jQ</td>
<td>V, delta</td>
</tr>
<tr>
<td>Gen Bus (Voltage Control)</td>
<td>V, P</td>
<td>Q, delta</td>
</tr>
</tbody>
</table>
Load Flow Problem

For load flow calculations, the system buses are classified into three types:

The slack bus: There is only one such bus in the system. Due to losses in the network, the real and reactive power cannot be known at all buses. Therefore, the slack bus will provide the necessary power to maintain the power balance in the system. The slack bus is usually a bus where generation is available. For this bus, the voltage magnitude and phase angle are specified (normally the voltage phase angle is set to zero degrees). The voltage phase angle of all other buses is expressed with the slack bus voltage phasor as reference.

The generating or PV-bus: This bus type represents the generating stations of the system. The information known for PV-buses is the net real power generation and bus-voltage magnitude. The net real power generation is the generated real power minus the real power of any local load.

The load or PQ-bus: For these buses, the net real and reactive power is known. PQ-buses normally do not have generators. However, if the reactive power of a generator reaches its limit, the corresponding bus is treated as a PQ-bus. This is equivalent to adjusting the bus voltage until the generator reactive power falls within the prescribed limits.
## Power Flow Standard Printout

<table>
<thead>
<tr>
<th>BUS</th>
<th>1 Bus 1</th>
<th>345.0</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
<th>% 1.0000</th>
<th>0.00</th>
<th>2 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERATOR 1</td>
<td>141.16</td>
<td>-14.21R</td>
<td>141.9</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOAD 1</td>
<td>100.00</td>
<td>0.00</td>
<td>100.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 2 Bus 2</td>
<td>1</td>
<td>-36.75</td>
<td>8.09</td>
<td>37.6</td>
<td>25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 3 Bus 3</td>
<td>1</td>
<td>77.91</td>
<td>-22.30</td>
<td>81.0</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BUS</th>
<th>2 Bus 2</th>
<th>345.0</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
<th>% 1.0000</th>
<th>3.51</th>
<th>1 Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>GENERATOR 1</td>
<td>363.00</td>
<td>100.22R</td>
<td>376.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOAD 1</td>
<td>200.00</td>
<td>100.00</td>
<td>223.6</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>TO 1 Bus 1</td>
<td>1</td>
<td>37.18</td>
<td>-5.83</td>
<td>37.6</td>
<td>25</td>
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<tr>
<td>TO 4 Bus 4</td>
<td>1</td>
<td>125.86</td>
<td>6.05</td>
<td>126.0</td>
<td>50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BUS</th>
<th>3 Bus 3</th>
<th>345.0</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
<th>% 1.0083</th>
<th>-3.73</th>
<th>1 Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD 1</td>
<td>100.00</td>
<td>15.00</td>
<td>101.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SWITCHED SHUNT</td>
<td>0.00</td>
<td>81.33</td>
<td>81.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 1 Bus 1</td>
<td>1</td>
<td>-76.92</td>
<td>27.55</td>
<td>81.7</td>
<td>27</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>TO 4 Bus 4</td>
<td>1</td>
<td>-23.15</td>
<td>38.71</td>
<td>45.1</td>
<td>23</td>
<td></td>
<td></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>BUS</th>
<th>4 Bus 4</th>
<th>138.0</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
<th>% 0.9813</th>
<th>-2.33</th>
<th>1 Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>TO 2 Bus 2</td>
<td>1</td>
<td>-123.48</td>
<td>6.66</td>
<td>123.7</td>
<td>49</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 3 Bus 3</td>
<td>1</td>
<td>23.45</td>
<td>-37.11</td>
<td>43.9</td>
<td>22</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 5 Bus 5</td>
<td>1</td>
<td>100.04</td>
<td>30.44</td>
<td>104.6</td>
<td>10 0.9625TA 0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>BUS</th>
<th>5 Bus 5</th>
<th>34.5</th>
<th>MW</th>
<th>MVAR</th>
<th>MVA</th>
<th>% 0.9946</th>
<th>-7.99</th>
<th>1 Home</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOAD 1</td>
<td>100.00</td>
<td>20.00</td>
<td>102.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TO 4 Bus 4</td>
<td>1</td>
<td>-100.04</td>
<td>-19.92</td>
<td>102.0</td>
<td>10 0.9625NT 0.0</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Linear Power Flow Analysis

- Ignore bus Voltage Magnitude (only be concerned with bus phase angle)
- Ignore reactive power flows and loads (only be concerned with MW flow)
- Ignore transmission line resistance and charging capacitance

Less Accuracy, but enables linear expression of line power flow in terms of the terminal bus angles – hence can be used as linear constraints in combined generation and transmission planning
St. Clair Line Loadability Curve

1. 0–80 km: Region of thermal limitation
2. 80–320 km: Region of voltage drop limitation
3. 320–960 km: Region of small-signal (steady-state) stability limitation
Flexible AC Transmission System (FACTS) No Compensation on Lossless Line
FACTS – Series Compensation
FACTS – Shunt Compensation

\[ \frac{X}{2} \quad \frac{X}{2} \]

\[ V_s \quad I_c \quad V_m \quad V_r \]

\[ V_s = V_m = V_r = V \]
Static VAR Compensation (SVC) Example

**Series Compensation**

![Diagram of Series Compensation](image)

- TCSR / TSSR
- TCSC / TSSC

Examples of FACTS series compensation
Static VAR Compensator (SVC)

• Most common SVCs are:
  – Thyristor-controlled reactor (TCR): reactor is connected in series with a bidirectional thyristor valve. The thyristor valve is phase-controlled. Equivalent reactance is varied continuously.
  – Thyristor-switched reactor (TSR): Same as TCR but thyristor is either in zero- or full-conduction. Equivalent reactance is varied in stepwise manner.
  – Thyristor-switched capacitor (TSC): capacitor is connected in series with a bidirectional thyristor valve. Thyristor is either in zero- or full-conduction. Equivalent reactance is varied in stepwise manner.
  – Mechanically-switched capacitor (MSC): capacitor is switched by circuit-breaker. It aims at compensating steady state reactive power. It is switched only a few times a day.
AC SUBSTATION COMPONENTS
## Estimated Installed Costs

<table>
<thead>
<tr>
<th>Type of Equipment</th>
<th>Cost ($/)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circuit breaker</td>
<td></td>
</tr>
<tr>
<td>345 kV</td>
<td>700–800K</td>
</tr>
<tr>
<td>500 kV</td>
<td>1400–1600K</td>
</tr>
<tr>
<td>765 kV</td>
<td>1800–2000K</td>
</tr>
<tr>
<td>Bulk power transformer</td>
<td></td>
</tr>
<tr>
<td>345 kV</td>
<td>3–4/kVA</td>
</tr>
<tr>
<td>500 kV</td>
<td>4–5/kVA</td>
</tr>
<tr>
<td>765 kV</td>
<td>5.50–6.50/kVA</td>
</tr>
<tr>
<td>Shunt capacitors</td>
<td>6–6.50/kVA</td>
</tr>
<tr>
<td>Series capacitors</td>
<td>7–9/kVA</td>
</tr>
<tr>
<td>Static var systems</td>
<td>20–40/kVA</td>
</tr>
<tr>
<td>Shunt reactors</td>
<td>12–14/kVA</td>
</tr>
</tbody>
</table>
AC and DC transmission principles

\[ p = \frac{E_1 E_2}{X} \sin \delta \]

\[ p = \frac{U_{d1} (U_{d1} - U_{d2})}{R} \]
HVAC / HVDC SOME COMPARISONS

- Intermediate reactive components cause stability problems in HVAC
- HVDC line has no stability problem (frequency absent), thus no distance limitation.
- Cost per km of HVDC line lower than for HVAC line (same power)
- Cost of terminal equipment for HVDC line is higher than for HVAC
- Breakeven distance between AC and DC overhead line is from 500 km to 800 km (higher KV - lower km)
- The HVDC has less effect on the human and the natural environment in general
- high transmission capacity of HVDC lines, combined with lower requirements on conductor bundles and air clearances makes the HVDC lines cost efficient compared to EHVAC lines
HV Power Transmission Towers

Tower configuration

3,000 MW

800 kV AC

500 kV DC

41m

40.5m

16m

41m

a) b)
HVDC Long Distance Transmission Systems

- **Monopolar**
  - Terminal A
  - Transmission Line
  - Terminal B

- **Bipolar**
  - Terminal A
  - Transmission Line
  - Terminal B
  - Pole 1
  - Pole 2
Typical Converter Station

AC bus

Shunt capacitors or other reactive equipment

AC filters

Converter

Smoothing reactor

DC filter

Transmission line or cable

Telecommunication

Control system
BIPOLAR HVDC SYSTEM

Diagram showing the components of a bipolar HVDC system, including AC bus, Converter, DC smoothing reactor, Bridge, Electrodes, DC filter, Transformer, DC line, AC filter, Reactive power source, and Circuit breaker (CB).
NELSON RIVER BIPOLE 1 HVDC
MANITOBA - CANADA
NELSON RIVER BIPOLE 1 - AC/DC COMPARISON
500 KV AC Vs +/- 450 KV DC
1600 MW OVER 556 MILES
NELSON RIVER BIPOLE 1

D.C. SYSTEM COSTS AS A PERCENTAGE OF TOTAL PROJECT COST

Converter transformers
20-25

Valves (including control and cooling)
20-30

Filters and var supply
5-20

Miscellaneous (communications, dc reactor, arresters, relaying etc.)
5-15

Engineering (system studies, project management)
2-5

Civil work and site installation
15-30
Nelson River Bipoles 1 and 2

Bipole 1

- 895 km from Radisson to Dorsey ±450 kv 1620 MW 1800 A
- six, 6-pulse converter groups at each end (three in series per pole) rated at 150kV dc, 1800A.
- built between March 1971 and October 1977 with mercury arc valves
- between 1992 and 1993 the mercury arc valves replaced with thyristors

Bipole 2

- 937 km from Henday to Dorsey 1800 MW ±500 kV.
- four 12-pulse thyristor converter groups at each end (two in series per pole) in two stages
- first stage in 1978 with maximum power 900 MW at 250 kv
- increased to 1800 MW when completed in 1985.
IND: Ballia-Bhiwadi HVDC
## IND: Ballia-Bhiwadi HVDC

<table>
<thead>
<tr>
<th>Customer</th>
<th>Powergrid Corporation of India Ltd.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Project name</strong></td>
<td>Ballia–Bhiwadi</td>
</tr>
<tr>
<td><strong>Location</strong></td>
<td>Uttar Pradesh province to Rajasthan province</td>
</tr>
<tr>
<td><strong>Power rating</strong></td>
<td>2,500 MW, bipolar</td>
</tr>
<tr>
<td><strong>Type of plant</strong></td>
<td>Long-distance transmission, 800 km</td>
</tr>
<tr>
<td><strong>Voltage levels</strong></td>
<td>± 500 kV DC, 400 kV, 50 Hz</td>
</tr>
<tr>
<td><strong>Type of thyristor</strong></td>
<td>Direct-light-triggered, 8 kV</td>
</tr>
</tbody>
</table>
**Setting of CASA 1000 Project**

**Existing Facilities**
- Toktogul HPP
- Nurek HPP

**Facilities Under Construction**
- 500 kV OHL South-North
- Sangtuda 1 HPP
- Sangtuda 2 HPP
- 220 kV OHL SS Sarban – Tajik/Afghan border

**Financing**
- China Exim bank
- Russia
- Iran
- ADB/IsDB

**Perspective Facilities**
- 220/500 kV Uzbek by pass
  - SS Datka (Kyrgyz) – SS Hojent (Tajik)
  - Cascade of Zarafshan HPPs (Yavan and Oburdon HPP)
  - Annual generation 1680 GWh

- Rogun HPP
  - Annual generation 13000 GWh

- Coal TPP
  - Annual generation 3900-6400 GWh

- 500 kV OHL “CASA 1000”
- Nurek HPP – Kabul - Peshawar

**Annual generation**
- Rogun HPP: 13000 GWh
- Coal TPP: 3900-6400 GWh
- 500 kV OHL “CASA 1000” Nurek HPP: Unknown
CASA 1000 Power Transmission
## CASA 1000 Cost Structure

<table>
<thead>
<tr>
<th>Countries</th>
<th>HVDC Component</th>
<th>HVAC Component</th>
<th>HVDC HVAC Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Converter Stations + Substations</td>
<td>Electrodes</td>
<td>Transmission Line</td>
</tr>
<tr>
<td>Tajikistan</td>
<td>128</td>
<td>5</td>
<td>33</td>
</tr>
<tr>
<td>Afghanistan</td>
<td>71</td>
<td>5</td>
<td>162</td>
</tr>
<tr>
<td>Pakistan</td>
<td>128</td>
<td>5</td>
<td>20</td>
</tr>
<tr>
<td>The Kyrgyz Republic</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Total EPC Costs</strong></td>
<td><strong>558</strong></td>
<td><strong>-</strong></td>
<td><strong>-</strong></td>
</tr>
</tbody>
</table>
## Generic Cost Comparison Elements

<table>
<thead>
<tr>
<th>AC</th>
<th>DC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right-of-way</td>
<td>Right-of-way</td>
</tr>
<tr>
<td>Load density per acre of right-of-way</td>
<td>Load density per acre of right-of-way</td>
</tr>
<tr>
<td>Transmission voltage</td>
<td>Transmission voltage</td>
</tr>
<tr>
<td>Line—Conductors</td>
<td>Line—Conductors</td>
</tr>
<tr>
<td>Towers</td>
<td>Towers</td>
</tr>
<tr>
<td>Substations or switching stations</td>
<td>HVDC converter stations</td>
</tr>
<tr>
<td>Breakers and disconnects</td>
<td>Breakers and disconnects</td>
</tr>
<tr>
<td>Transformers</td>
<td>Transformers</td>
</tr>
<tr>
<td>Reactive power (capacitive and inductive)</td>
<td>Filters and var supply</td>
</tr>
<tr>
<td>Shunt capacitors and reactors</td>
<td>Valve assembly and smoothing reactor</td>
</tr>
<tr>
<td>Series capacitors</td>
<td>Ground electrode and metallic return transfer breaker</td>
</tr>
<tr>
<td>Static var systems</td>
<td>Protection</td>
</tr>
<tr>
<td></td>
<td>Control</td>
</tr>
<tr>
<td></td>
<td>Station civil works</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Comparison HVDC-Classic and HVDC-Light®

HVDC Light has fewer components and most equipment indoors
VSC HVDC Control
<table>
<thead>
<tr>
<th>Conventional LCC HVDC</th>
<th>VSC HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High power capability - 6000 MW</td>
<td>Lower power capability -1200 MW</td>
</tr>
<tr>
<td>• Good overload capability</td>
<td>• Weak overload capability</td>
</tr>
<tr>
<td>• Requires stronger AC systems</td>
<td>• Operates into weaker AC systems</td>
</tr>
<tr>
<td>• Generates harmonic distortion, AC &amp; DC harmonic filters required</td>
<td>• Insignificant level of harmonic generation, hence no filters required</td>
</tr>
<tr>
<td>• Coarser reactive power control</td>
<td>• Finer reactive power control</td>
</tr>
<tr>
<td>Large site area, dominated by harmonic filters</td>
<td>• Compact site area, 50 – 60% of LCC site area</td>
</tr>
<tr>
<td>No ‘black start’ capability</td>
<td>“Black” start capability</td>
</tr>
<tr>
<td>• Requires converter transformers</td>
<td>• Only conventional transformers</td>
</tr>
<tr>
<td>• Lower station losses ( ~1.5% for both terminals)</td>
<td>• Higher station losses (~ 2% for both terminals)</td>
</tr>
<tr>
<td>• Lower cost</td>
<td>• Higher cost by 10 – 15%</td>
</tr>
<tr>
<td>• Higher reliability</td>
<td>Lower reliability</td>
</tr>
<tr>
<td>• More mature technology</td>
<td>• Less mature technology</td>
</tr>
</tbody>
</table>
Development of HVDC converter capacity

Transmission capacity
HVDC Classic (MW)

Transmission capacity
HVDC VSC (MW)
HVDC Benefits

- No limits in transmitted distance - valid for OH line and sea or underground cables.
- Direction of power flow can be changed very quickly (bi-directionality).
- No increase in short-circuit power – retain circuit breakers in the existing network.
- VSC allows independent control - good to connect alternative energy sources
- HVDC transmission - high availability and reliability
- With VSC and new extruded polyethylene DC cables, lower power (upto 200 MW) over just 60 km economic
THANK YOU
VERY MUCH!