Five steps are involved in the design of an HVDC link as follows:

- Load flow modelling of an HVDC link
- Dynamic modeling of an HVDC link
- Planning an HVDC link
- HVDC links in weak AC systems
- Specifications for an HVDC link

This article describes the third step above, the planning process of such a link. For completeness, however, we will elaborate on all five steps.

Load flow modeling of an HVDC link
The converters, converter transformers and filters, DC lines, the AC system plus any associated AC reactive support devices and nearby generators need to be modeled with accurate positive and zero sequence data for load flow and fault level modeling purposes (although DC does not contribute to fault level strength, fault levels of the surrounding AC networks are necessary and will determine the basic design of the link). Fig. 1 is an example of the Cigré HVDC benchmark model as it is presented in a common power system modeling package [10].

Dynamic modeling of an HVDC link
The DC system, nearby generators, exciters, governors, stabilisers and reactive devices e.g. static var compensators (SVCs) and synchronous condensers (SCOs) should be modeled in RMS and EMT software. Conventional/generic HVDC controls can be used in the RMS and EMT studies since in most cases the planning studies are carried out to test the feasibility of transmission options and for costing purposes. Further, detailed models from possible suppliers are unlikely to be known at this early stage. The generic controls should include all the major control functions necessary for the study. Suitable contingencies should be modeled on the DC system and the adjacent AC systems. The link controllers can be designed to improve the dynamic operation of the integrated DC/AC system.

Planning an HVDC link
This section (the subject of this article), investigates the high-level planning issues required before making a final decision on a transmission solution for a 2000 MW 1400 km link. AC and DC solutions are explored with their associated capital costs and life-cycle costs. Reliability issues are investigated e.g. (n-0), (n-1), (n-2), etc. and additional circuits are evaluated using the principle of cost of unserved energy (COUE). The least cost option over a designated period with the appropriate performance is chosen using present value (PV) techniques.

HVDC Links in weak AC systems
In applications where one or both terminals of the DC links are to be connected at very weak locations in the AC systems, e.g. where short circuit to power ratio (SCR) is less than two (< 2), particular care is required in the modeling of the DC scheme. Large system EMT type analysis should be undertaken, taking into account the design requirements and potential interactions with possible SVCs, SCOs, machines and power electronic controls in the AC network.

Specifications for an HVDC link
The specifications for an HVDC Link need to address the scope of the HVDC project, standards to be applied, system parameters
under normal and abnormal conditions, performance requirements and guarantees under all conditions, studies required by the contractors, operational requirements of the overall scheme, functional specifications of the different components of the scheme including the converters, the converter transformer, the DC line, associated AC substation equipment, earth electrodes, secondary plant, SVCs, SCRs, civil works etc. Over and above the technical specifications, commercial conditions are also required.

The following covers the basic planning process associated with a line commutated converter (LCC) HVDC link. At present, this technology is more suitable for transmitting large amounts of power over long distances than the more modern voltage source converter (VSC) technology. Also, although DC transmission at 800 kV is being considered internationally e.g. China, a maximum DC voltage of 600 kV has been considered in this study. DC transmission at 600 kV has already been successfully implemented in Brazil (Itaipu 1 & 2, 3150 MW each, 800 km) [11].

Planning of an HVDC link
Why consider HVDC?
HVDC should be considered for power transmission because of the following reasons:

- An overhead DC transmission line with its towers can be designed to be less costly per unit length than an equivalent AC line designed to transmit the same level of electric power [7]. However, the DC converter stations do contribute significantly to the total cost of an HVDC link, which means that HVDC is normally only viable over long distances (600 km+). This is illustrated in Fig. 3.
- It is possible to connect systems of different frequencies/asynchronous systems
- Active power transfer can be controlled. The HVDC link can regulate the transfer of active power to a set level i.e. the transfer is not dependent on AC system voltages and impedances. Active power can be exchanged bi-directionally.
- Fast control of active power. This is useful for power, frequency or voltage oscillation damping.
- The magnitude of power transfer is not limited by stability margins as is the case with ac transmission.
- HVDC lines are not prone to reactive losses and surge impedance loading (SIL) constraints.
- Corona and radio interference are less with DC transmission than conventional AC [5]
- Environmental impact of an HVDC line is normally less than that of an AC line
- The HVDC link does not contribute to fault levels on the AC system, where high existing fault levels may be a problem
- AC resistance is higher than DC resistance because of skin effect, hysteresis, eddy currents and proximity effect [5]
- Certain HVDC technologies (e.g. the VSC) can enable the transmission scheme to be connected to a very weak or even passive AC network, since it is self-commutating and can provide AC voltage support and/or AC voltage reference [8]. VSCs have higher losses than LCCs.

Disadvantages of DC transmission:
- HVDC transmission is normally not cost effective over short distances (except where an asynchronous link is required, e.g. because of different frequency or requirement for independent control of the two networks)
- The converter stations occupy significantly more space than the equivalent AC substations
- Additional power losses in converter stations, however, for long distance transmission the overall power loss may be lower than for an AC line
- HVDC infeeder do not add fault level strength to a network
- Converters can require up to 60% of their power transfer in shunt reactive support, this is normally supplied by the harmonic filters
- Converters create harmonics and these harmonics require filtering
- HVDC transmission systems are usually more technically complex than AC transmission systems and can be more expensive to maintain and operate

Assumptions and general comments
- The link is to transmit 2000 MW over 1400 km at 100% utilisation
- Preliminary feasibility load flow and dynamic studies have proven AC and DC transmission options to be technically feasible
- The link is a greenfields transmission system i.e. there are no existing AC lines available for conversion to HVDC operation e.g. by using current modulation techniques [9]
- Fault levels on both sides of the link are above the minimum requirement of twice the maximum power transfer of the link

The following assumptions were made to estimate costs:

- Line cost:
  - Cross-rope design used for 400 kV AC lines:
  - V-guided design used for 765 kV AC lines:
  - Mono-mast used for monopole- and bipole HVDC lines:

- Fig. 3: AC and DC breakeven distance
- Fig. 4: AC options life cycle cost
Table 1: Transfer capability and power losses

<table>
<thead>
<tr>
<th>Option</th>
<th>Line description</th>
<th>Number of lines</th>
<th>Transfer capability (MVA)</th>
<th>Total transfer capability (MVA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>765 kV 6xZebra</td>
<td>1</td>
<td>2822</td>
<td>2822</td>
</tr>
<tr>
<td>2</td>
<td>765 kV 6xZebra</td>
<td>2</td>
<td>5644</td>
<td>(N-0)</td>
</tr>
<tr>
<td>3</td>
<td>400 kV 3xTern</td>
<td>3</td>
<td>2160</td>
<td>(N-0)</td>
</tr>
<tr>
<td>4</td>
<td>400 kV 3xTern</td>
<td>4</td>
<td>2880</td>
<td>(N-1)</td>
</tr>
</tbody>
</table>

Table 2: Possible AC solutions

<table>
<thead>
<tr>
<th>Option</th>
<th>Line description</th>
<th>No of lines</th>
<th>Transfer capability</th>
<th>Total transfer capability</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>765 kV 6xZebra</td>
<td>1</td>
<td>2822</td>
<td>2822</td>
<td>(N-0)</td>
</tr>
<tr>
<td>2</td>
<td>765 kV 6xZebra</td>
<td>2</td>
<td>5644</td>
<td>(N-0)</td>
<td>(N-0)</td>
</tr>
<tr>
<td>3</td>
<td>400 kV 3xTern</td>
<td>3</td>
<td>2160</td>
<td>(N-0)</td>
<td>(N-0)</td>
</tr>
<tr>
<td>4</td>
<td>400 kV 3xTern</td>
<td>4</td>
<td>2880</td>
<td>(N-1)</td>
<td>(N-1)</td>
</tr>
</tbody>
</table>

Table 3: Reliability of AC solutions

<table>
<thead>
<tr>
<th>Option</th>
<th>Reliability</th>
<th>Configuration</th>
<th>Number of circuits</th>
<th>Power Transfer Rating (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Normal</td>
<td>Monopole with earth/metallic return</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>N-0.5*</td>
<td>Bipole with earth/metallic return</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>N-1</td>
<td>Bipole with earth return</td>
<td>1</td>
<td>200</td>
</tr>
<tr>
<td>4</td>
<td>N-1</td>
<td>Bipole with earth return</td>
<td>2</td>
<td>66</td>
</tr>
</tbody>
</table>

Fig. 5: Monopole with earth or metallic return

Fig. 6: Bipole with earth or metallic return

Fig. 7: Bipole without earth or metallic return

Conductor cost:
Conductor cost is proportional to conductor cross section

Converter Cost
Converter cost includes all filter and reactive compensation devices costs

AC voltage support
Neglected

Operating and maintenance costs
Neglected

The following assumptions were made in the Present Value (PV) analysis:

Time frame: 20 years
Discount rate: 10%

COUE was treated as a cost and not as an income i.e. non-firm solutions were penalized with additional COUE costs. Therefore, the financial treatment is a present value (PV) analysis and not a net present value (NPV) analysis.

In order to compare DC with conventional AC transmission, it is necessary to analyze a number of AC solutions as well. Because this article focuses on DC, the AC analysis will be brief.

Although a basic method is used in this article, the line optimization process should consider load forecast considerations, power quality constraints, voltage collapse studies, corona and audible noise, induction and transposition studies, line performance studies, and life cycle cost of maintenance for the different options [4].

Also, the choice of a conductor affects the capital cost, life cycle cost of losses, insulation, hardware, structures, foundations and towers for a specific line [4].

AC analysis
Power transfer over 1400 km using AC transmission is limited to the levels shown in Table 1.

Therefore, supplying 2000 MW over 1400 km can be achieved by the AC solutions as shown in Table 2.

Option 1 can only transfer the power under system normal conditions (N-0), whereas options 2 and 4 can transfer full power under system abnormal conditions (N-1). To account for this superior design, the COUE is calculated over its lifespan of 20 years. Taking a COUE of US$2/kWh (or R12/kWh at an exchange rate of R6/ US$) and assuming an availability of 98% for a single line, the annual COUE of a single line transferring 2000 MW is: R12/kWh x 2 000 000 x 8760 x 0,02 = R4.2-billion/year. The improvement of a second line is calculated to be 1% i.e. an improvement from 98% to 99%. Therefore, the COUE is reduced to R12/kWh x 2 000 000 x 8760 x 0,01 = R2.1-billion.

Table 3 shows the reliability for the different AC solutions.

Calculation of the life cycle cost of the 4 options shows that option 2 is the optimal AC solution. This is shown in Fig 4.

HVDC analysis

Basic design
The following are typical HVDC configurations (a DC line with connected converters is referred to as a pole):

- Monopole with earth return or metallic return (with monopole designs, the earth electrode or metallic earth return conducts full current during normal operation) (Fig. 5)
- Bipole with earth return or metallic return (Fig. 6)
- Bipole without earth return or metallic return (Fig. 7)

In a bipole configuration, the converter stations are arranged to operate at equal but opposite line voltage, so that the current in the earth return path is very small under normal operation.

Modes of monopole operation
Monopole with earth return – 100% power is possible under normal conditions. When the single pole converter is out or the DC line or earth return is not operational, no power transfer is possible

Monopole with metallic return - 100% power is possible under normal conditions. When the single pole converter is out or the DC line or metallic return is not operational, no power transfer is possible
Modes of bipole operation

Bipole rated at 100% of link transfer with earth return – This arrangement can be used to supply 100% of the power under system normal conditions. When any one of the pole converters is out, the link can supply 50% of the power by using the unhealthy pole as a metallic return. (A small delay will be necessary for link switching). No power transfer is possible when one of the pole DC lines is out.

Bipole rated at 100% of link transfer with earth return – This arrangement can be used to supply 100% of the power under system normal conditions. It can also supply 50% power when either one of the converter stations or DC lines is out. (however earth return can be rated to 50% of full link power)

Bipole rated at 200% of link transfer with earth return – This arrangement can be used to supply 100% of the power under system normal conditions. It can supply 100% power when either one of the converter stations or DC lines is out (as the system is rated at twice the design power transfer). The earth return would need to be rated to full link transfer. Another advantage of this arrangement is that the power losses under normal conditions are much lower because of the large conductors used to enable a 200% power rating.

Double Bipole with earth return (133% rating) – This can be used to supply 100% power when one DC line or converter pole is out. A common earth electrode could be designed to support both bipoles. The topology of this configuration would be essentially four poles, each rated at 33%, so that if any one pole blocks/opens, the remaining poles are still able to transfer 100% power.

The basic design chosen could depend on a number of factors such as environmental requirements, earth resistivity, reliability, availability of servitudes, etc.

DC options

From the above basic designs, the following options were evaluated based on different levels of reliability (again, superior reliability is accounted for in the techno financial evaluation by including COUE, similar to the AC analysis):

Conductor selection

Although corona is less on DC lines than on AC lines, it is still necessary to have a minimum number of sub-conductors to ensure that corona levels are acceptable, as below.

In this analysis the sub-conductor guideline as above, is used.

Fig. 8 portrays the varying DC resistance values in Q/km and the varying conductor thermal ratings in KA for conductors ranging from Tem and Wolf to Lapwing and Zebra.

As mentioned above, power transfer using DC is not limited by a power transfer stability (angle) limit as in the case of AC. Power transfer and conductor selection is limited by thermal capacity and inverter DC voltage only. (Converter transformers have a finite tapping range, normally 30%. In practice, large DC voltage excursions are unlikely to be designed for, due to the associated high losses).

Table 6 shows varying thermal requirements between monopole and bipole transmission options with voltages varying from 400 kV to 600 kV.

The minimum number of conductors necessary to obtain the link rating of 2000 MW depends on the type of conductor used. For this analysis the following three conductors were used as per Table 7.

The calculations were automated using a spreadsheet based on the following parameters: voltage, corona and thermal capacity.

Power losses over 1400 km at 2000 MW for the four options at different voltage levels are shown in Table 8.

Financial evaluation

The same cost of unserved energy that was used for the AC analysis will be used for the DC analysis i.e. USD 2/kWh (ZAR 12/kWh).

The graphs (Fig. 9, 10 and 11) depict the Total PV Costs, which includes capital costs, the life-cycle costs and COUE of the different link options.
monopole is not shown as it had the highest PV cost due to the lack of redundancy/firmness in its design.

Tables 9 and 10 show the relationship between Capex, Losses, COUE and Total PV Cost for the best AC and DC options (by configuration).

The spreadsheet model was also used to determine the AC/DC break-even distance. This distance was calculated to be close to 600 km for a 2000 MW transfer. The tables show the different AC and DC configuration results for this break-even distance.

From the above, it can be seen that the 200% Bipole and 2 x 66% Bipole options have a lower total PV cost compared with the AC option for the 2000 MW and 1400 km case.

The 100% Bipole option has the highest total PV cost due to its inferior reliability which is quantified in the higher COUE cost.

For the 2000 MW 600 km case, the AC option has the lowest total PV cost. (600 km is close to the breakeven decision distance).

**Conclusions**

For a 2000 MW, 1400 km link, 200% Bipole and 2 x 66% Bipole options were found to have the lowest total PV costs

For a 2000 MW, 600 km link, the AC option was found to be the lowest PV cost option

The above analysis has not included the dynamic benefits to the AC systems as a result of an asynchronous DC connection.

Further techno-financial comparisons could be investigated using staged implementation of AC/DC lines/poles.

These results are preliminary i.e. extensive tower and conductor configuration optimisation could alter the results.

**References**


[10] Cigré HVDC Benchmark Model as modeled in DigsILENT.


**Table 9: 2000MW at 1400km**

<table>
<thead>
<tr>
<th>Line (conductor type &amp; kV)</th>
<th>No of Conductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x AC</td>
<td>8982 802</td>
</tr>
<tr>
<td>100%BP</td>
<td>3739 2017</td>
</tr>
<tr>
<td>200%BP</td>
<td>3826 1917</td>
</tr>
<tr>
<td>2 x 66%BP</td>
<td>4853 1709</td>
</tr>
</tbody>
</table>

**Table 10: 2000MW at 600km**

<table>
<thead>
<tr>
<th>Line (conductor type &amp; kV)</th>
<th>No of Conductors</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x AC</td>
<td>2966 687</td>
</tr>
<tr>
<td>100%BP</td>
<td>2812 1421</td>
</tr>
<tr>
<td>200%BP</td>
<td>2833 1166</td>
</tr>
<tr>
<td>2 x 66%BP</td>
<td>3233 1166</td>
</tr>
</tbody>
</table>

**Fig. 11: 2 x 66% Bipole**