

## Power loss evaluations for long distance transmission lines

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Long distance power transfer is a major problem for renewable energy sources located far away from the major load centres. This issue in particular is more pronounced for the prospective geothermal power plants in Australia. This problem involves analysing the cost of investment and operation and types of interconnection used for transmitting the bulk power from a remote area to a major load centre. As the level of power transfer and the transmission distance increases, the power loss of the transmission line tends to increase. For these reasons, it is essential to carefully analyse the impact of interconnection on the total loss of a power system, subject to changes in operating conditions and varying transmission distances. The typical approach for very long transmission lines is to use high voltage (HV) based on either DC or AC. In theory, the HVAC line has higher resistance and reactance, therefore, it has a high loss in the line compared to the HVDC option. On the other hand, the HVDC scheme has a significant proportion of loss in its converter/inverter stations. Up to a certain distance called the "breakeven distance", HVAC is superior in terms of the total cost, loss and the stability margin. Above this distance, HVDC is the most favourable option. The main task in this paper is determining this "breakeven distance" for a particular electricity system based on static power flow analysis. In this paper we apply a four machine two area test system implemented in the PSS/E software environment to compare the impact of high voltage AC and conventional high voltage DC on total system losses. Further methodology will be developed to make this outcome more generalised for any electricity network..

*Keywords:* interconnection, HVDC, HVAC, loss evaluation.

### Long distance transmission lines

The electricity systems from different areas are being connected by long transmission lines to achieve an economical benefit and to improve reliability. Such interconnections can connect regions in a country, from a country to another country or cover very large continental areas. They can also be used to transfer the power from remote renewable sources, such as off-shore wind farms, solar thermal systems or geothermal power plants in desert areas, etc. to the load centre. The advantages of long interconnections are the flexibility in deciding locations as well as in building larger and more economical power plants; creating the possibility of loss reduction by

optimised system operation [1]. In the expansion of the electricity market all over the world, high voltage transmission lines over a long distance may offer considerable advantages in technical, economical and environmental aspects. In recent years, power industries all over the world supported many interconnections to enable the exchange of power among areas and transfer cheaper electricity over long distance to the customers.

HVAC and HVDC are the two interconnection schemes available for long transmission systems. There have been some publications on technical and economical evaluations for several types of interconnections using HVAC or HVDC technologies.

HVAC has been found to be the better solution for a distance less than the "breakeven distance", which can vary from 400km to 500km, between two synchronous regions [1-3]. However, for long transmission lines, HVAC must be facilitated by Flexible AC Transmission System (FACTS) devices for reactive power compensation.

Longer than the breakeven distance, HVDC becomes more preferable either with an overhead transmission line or an underground cable. Besides, HVDC is also suitable for the submarine cable, interconnections between AC systems of different or incompatible frequencies and for remote renewable energy resource connection.

Paper [4, 5] compared the total system losses due to the impact of HVAC, Line-Commutated Converter (LCC) HVDC and Voltage Source Converter (VSC) based HVDC connected to a large offshore wind farm (from 100 to 1000 MW) with varying distances up to 200km. Paper [4] concluded that the HVAC solution is superior for distances up to 70km. LCC HVDC is preferred in terms of reduced system losses above this distance. The "breakeven distance" for VSC HVDC in a loss point of view is around 200km. According to their results, the combination of different transmission systems never improves the total loss in the system. Paper [5] indicated that the HVDC solution is more expensive than the HVAC option with 100MW, 200MW and 500MW wind farms at the connection a distance of 60km due to higher investment cost and higher power loss. However, the HVDC option appears to be cheaper than the HVAC option while connected to a 100MW wind farm with a distance greater than 90km.

Nevertheless, these conclusions were based on the characteristics of HVAC and HVDC lines and on the experimental measurements data. The loss evaluation was carried within the interconnection, not in the whole system. Up to now, very few technical reports are available to compare the impacts of HVDC and HVAC on large power system performance. This paper will focus on the implementation of HVDC and HVAC options as a long transmission line for interconnecting between 2 large systems.

This paper is organised as follows: the first part of this paper introduces the load flow analysis for a power system using HVDC interconnections. The second part summarises loss evaluation and compares HVDC versus HVAC alternatives. The impacts of transmission length, number of interconnections, power transfer level and the sending end demand on the "breakeven distance" are also presented in this section.

### HVDC analytical model

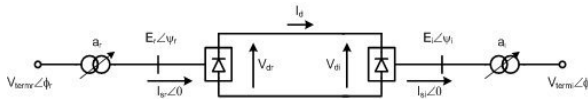


Fig. 1 Single diagram of a conventional HVDC link [1, 6].

The single line diagram of a HVDC system is depicted in Fig. 1. The steady state behavior of a AC-DC power system has been described in details by Arrilaga *et.al* [6]. The state variables for a HVDC system are:  $[x] = [V_d, I_d, \alpha, \phi]^T$  where  $V_d$  and  $I_d$  are the direct voltage and current,  $\alpha$  and  $\phi$  are the firing angle and the terminal voltage angle, respectively. For the inverter side,  $\alpha$  will be replaced by  $\gamma$ , which is called the extinction angle.

The index  $r$  and  $i$  represent the parameters at the rectifier (converter) and inverter side, respectively.

In the PSSE software [7], the relationships between AC and DC voltages and currents at the rectifier side are expressed as:

AC-DC voltage:

$$V_{dr} = N_r \frac{3\sqrt{2}}{\pi} a_r V_{termr} \cos \phi_r \quad (1)$$

$$= N_r \left( \frac{3\sqrt{2}}{\pi} a_r V_{termr} \cos \alpha - \frac{3}{\pi} I_d X_{cr} - 2R_{cr} I_d \right)$$

$$\text{AC-DC current: } I_{sr} = \frac{\sqrt{6}N_r}{\pi} I_d \quad (2)$$

where  $R_{cr}$  and  $X_{cr}$  are commutation resistance and reactance,  $a_r$  is the transformer turn ratio,  $N_r$  is the number of bridges connected in series in a rectifier station.

The DC reactive and active power at the rectifier terminal is determined as follows:

$$Q_{termr}(DC) = V_{termr} I_{sr} a_r \sin \phi_r$$

$$= V_{termr} I_d a_r \sin \phi_r \frac{\sqrt{6}N_r}{\pi} \quad (3)$$

$$P_{termr}(DC) = V_{termr} I_{sr} a_r \cos \phi_r$$

$$= V_{termr} I_d a_r \cos \phi_r \frac{\sqrt{6}N_r}{\pi} \quad (4)$$

In this paper, the commutating resistance and transformer resistance are neglected, resulting in no active power loss in converter stations. Therefore, the DC active power at the rectifier terminal in equation (4) can be calculated as:

$$P_{termr}(DC) = V_{dr} I_d$$

The equations (1-4) can be applied to calculate the DC current, voltage and power at the inverter side, with  $\cos \alpha$  and index  $r$  replaced by  $\cos \gamma$  and index  $i$ , respectively.

The Jacobian matrix for load flow calculation of the HVDC system is determined by solving the following system of equations [1, 6]:

$$\bar{R}(\bar{x}, V_{term}) = 0 \quad (5)$$

$$\text{Where: } R(1) = V_d - \frac{3\sqrt{2}}{\pi} ka V_{term} \cos \phi$$

$$R(2) = V_d - \frac{3\sqrt{2}}{\pi} ka V_{term} \cos \alpha - \frac{3}{\pi} I_d X_c$$

$$R(3) = f(V_d, I_d)$$

$$R(4) = \text{control equation}$$

The relationship between  $V_d$  and  $I_d$ ,  $f(V_d, I_d)$ , in this paper is:

$$V_{di} = V_{dr} - I_d R_d \quad (6)$$

where,  $V_{dr}$ ,  $V_{di}$  is the dc voltage at the rectifier and inverter side respectively.  $R_d$  is the resistance of DC line.

The DC load flow algorithm based on the Fast Decoupled Power Flow method [6], which is used to solve the load flow problem with HVDC is briefly summarised as follows:

$$\frac{\Delta \bar{P}}{\bar{V}} = [B'] [\Delta \bar{\theta}] \quad (7)$$

$$\begin{bmatrix} \frac{\Delta Q}{\bar{V}} \\ \frac{\Delta Q_{term}}{V_{term}} \\ R \end{bmatrix} = \begin{bmatrix} & & \\ B'' & & \\ & BB''_{ii} & AA'' \\ & BB'' & A \end{bmatrix} \begin{bmatrix} \Delta \bar{V} \\ \Delta V_{term} \\ \Delta x \end{bmatrix}$$

$$\text{Where: } [AA''] = \frac{1}{V_{term}} \left[ \frac{\partial Q_{term}(DC)}{\partial \bar{x}} \right]$$

$$[BB''] = \left[ \frac{\partial R}{\partial V_{term}} \right]$$

$$[BB''_{ii}] = \frac{1}{V_{term}} \left[ \frac{\partial Q_{term}(AC)}{\partial V_{term}} + \frac{\partial Q_{term}(DC)}{\partial V_{term}} \right]$$

$$[A] = \left[ \frac{\partial \bar{R}}{\partial \bar{x}} \right]$$

B'' and B'' are susceptance matrix of AC system

## Loss evaluation

The test system used in this paper is a 2-area system shown in Fig. 2, which comprises of 4 generators and 2 large loads [8]. The two areas are connected to each other by two interconnection lines. In the original system, the interconnections are two 220km, 230 kV HVAC lines in parallel. The line parameters are:

$$R = 0.0529 \text{ (Ohms/km)}$$

$$X = 0.529 \text{ (Ohms/km)}$$

$$B = 33.1 \times 10^{-6} \text{ (S/km)}$$

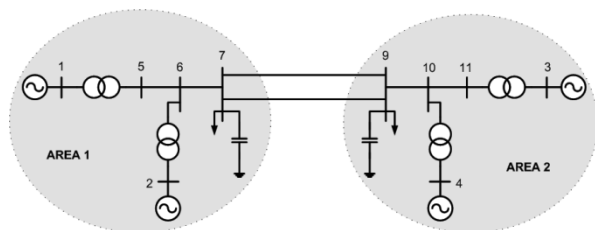


Fig. 2 System diagram [8]

The active and reactive power at system buses are presented in Table 1.

Bus	VM (pu)	V <sub>base</sub> (kV)	P <sub>G</sub> (MW)	Q <sub>G</sub> (MVar)	P <sub>L</sub> (MW)	Q <sub>L</sub> (MVar)
1	1.03	22	700	0	0	0
2	1.01	22	700	0	0	0
3	1.03	22	700	0	0	0
4	1.01	22	700	0	0	0
7	1.00	230	0	200	967	100
9	1.00	230	0	350	1767	100

Table 1. System data bus, including voltage magnitude (VM), base voltage (V<sub>base</sub>), active and reactive power generated (P<sub>G</sub>, Q<sub>G</sub>) and consumed (P<sub>L</sub>, Q<sub>L</sub>) at all buses in the system

We tested the original system with HVAC interconnections replaced by HVDC interconnections. The load flow results for the modified system are compared to that of the original system. The line resistance for the HVDC system is chosen to be the same as that of the HVAC system. In the HVAC case, bus 3 is the slack bus for the whole system; in HVDC interconnection case, bus 1 is the slack bus for area 1 and bus 3 is the slack bus for area 2.

The HVDC rated voltage is 230kV, the data of which is taken from [3]. The rectifier and inverter commutating reactance are 0.07 and 0.055 pu, based on a rated power of 890MW and a rated voltage of 230kV. The tap ratio at the converter transformer is maintained at 1.0 pu. The inverter is operated in constant extinction angle mode with  $\gamma=22^\circ$ . The maximum and minimum firing angle at the rectifier side is  $12^\circ$  and  $8^\circ$ , respectively. Table 2 summarises load flow results obtained from using PSSE with HVAC and HVDC interconnection systems.

Bus	HVAC		HVDC (constant $\gamma$ )	
	VM (pu)	Ang. (deg)	VM (pu)	Ang. (deg)
1	1.03	20.98	1.03	24.79
2	1.01	11.22	1.01	14.9
3	1.03	-6.8	1.03	-6.8
4	1.01	-16.93	1.01	-16.82
5	1.0066	14.51	1.0008	18.27
6	0.9785	4.43	0.9645	8.01
7	0.9618	-3.98	0.9367	-0.68
9	0.9751	-31.33	0.9604	-31.38
10	0.987	-22.98	0.9793	-22.92
11	1.0114	-12.74	1.0086	-12.7

Table 2. Voltage profile of the system, including voltage magnitude and voltage angle of all buses after solving load flow

The active power transfer from bus 7 to bus 9 was kept at 400 MW, resulting in 200MW active power transferred in each line. The load flow results are shown in Table 3 below.

	HVAC		HVDC (constant $\gamma$ )	
	P (MW)	Q (MVar)	P (MW)	Q (MVar)
Gen. 1	700	184.05	635.78	180.19
Gen. 2	700	231.94	700	258.28
Gen. 3	718.74	164.93	772.30	202.10
Gen. 4	700	191.54	700	255.79
<b>Total</b>	<b>2818.74</b>	<b>772.46</b>	<b>2808.07</b>	<b>896.36</b>
L7	967	100	967	100
L9	1767	100	1767	100
<b>Loss</b>	<b>84.74</b>	<b>572.46</b>	<b>74.07</b>	<b>696.36</b>

Table 3. Power flow data, including active and reactive power generated at generator buses and consumed at load buses. See text below for loss calculation

Table 3 gives an initial comparison of the two interconnection options: HVDC and HVAC, with

the same active power transfer level. Both active and reactive power losses are calculated by subtracting the total active/reactive power consumed at the loads from the total generated active/reactive power. The active power loss is directly related to operating cost. The reactive power loss represents the additional reactive power the generators have to provide to the grid for maintaining the system voltage to a desired level. Reactive power generation is an important ancillary service in an electricity power market, and thus, also relates closely to the operating cost. As can be seen in Table 3, the active power loss in the HVDC system is smaller than that of the HVAC system. However, the HVDC system requires more reactive power than the HVAC system. In the following sections, active/reactive power loss of the HVDC and HVAC systems are compared at different power transfer levels and transmission lengths.

### Impact of distance on system loss

The length of both interconnections is varied from 200 km to 350 km. The HVDC is operated in the power control mode. The power transferred from the rectifier station (bus 7) to the inverter station (bus 9) is kept equal to the power transferred in the HVAC case. The voltage magnitude and angle of bus 1 in the HVDC system is maintained equal to that in the corresponding HVAC case. The result is shown in Fig. 3.

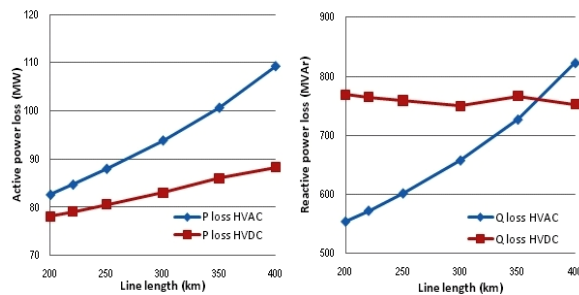


Fig. 3 Total system losses relating to transmission length

It can be seen from Fig. 3 that active and reactive power losses in the HVAC case steadily raise with the increase of the interconnection length. This is to be expected, as active/reactive loss on the interconnection line is an important part of the total AC system active/reactive loss. On the other hand, active/reactive loss in the HVDC system depends mainly on the losses in converter stations. The active power loss in the HVDC system is thus smaller than that in the HVAC system. Besides, the active power loss in the HVDC case does not increase as steeply as does the active power loss in the AC interconnection case when the transmission length increases. The reason is that the voltage profile decreases significantly for the HVAC case while the voltage profile of the HVDC system is slightly improved as the length of the line increases.

The reactive power loss in the HVDC system is slightly decreased with the increase in the length of the interconnection line, since the DC line does not consume reactive power. Moreover, in the HVDC scheme, the inverter is operated in constant  $\gamma$  mode, which keeps voltage at the inverter bus constant at 0.9604 pu (bus 9). As a result, when the transmission length is increased, the bus voltage at the rectifier bus will be increased in order to maintain the bus voltage at the inverter bus due to the relationship in equation (6). The voltage profile of the whole system, therefore, will be improved slightly resulting in lower reactive power loss.

When the line length is increased to 350km, to keep the power transferred on the HVDC line equal to that on the HVAC case, the HVDC needs to be operated in constant extinction angle mode  $\gamma=23^\circ$  in order to increase the dc voltage (voltage at bus 9 is kept at 0.9581 pu). Therefore, we can see a slight increase in reactive loss of the HVDC line. When the length goes up to 400km, the extinction angle was kept at  $23^\circ$ , thus the reactive power loss in the HVDC case continues to decrease slightly and becomes smaller than that in the HVAC case. Therefore, from both active power and reactive power loss points of view, the HVDC would be superior to HVAC after a distance of 360km.

### Impact of power transferred in transmission line on the “breakeven distance”

The power transfer level is gradually increased from 150MW to 300MW per line. This is done by varying the load at the sending end (bus 7), from 1067MW to 767MW. Load flows are calculated for both AC and DC systems at each power transfer level. The results are presented in Fig. 4.

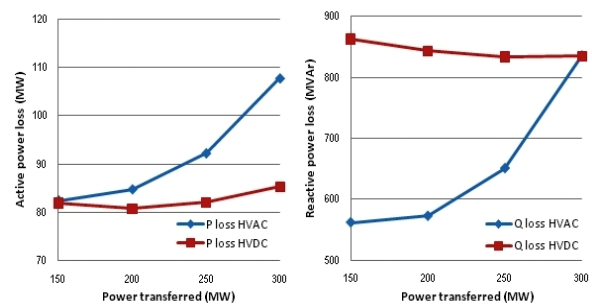


Fig. 4 Total system losses relating to power transferred in the interconnection

The loss in the HVAC system increases significantly as the active power transfer is increased. On the other hand, the reactive power loss in the HVDC system remains relatively unchanged (or even slightly decreases) as the power transfer is increased. In fact the slight reduction of reactive power loss does not relate to the DC link in this case. As the load at bus 7 is decreased, the current on the line 6-7 is reduced, therefore the total reactive power loss in area 1 is reduced slightly.

The “breakeven distance” for this case occurs around 600MW of power transfer (300MW per line). At this power transfer level, the reactive power loss in the AC system starts to surpass the reactive loss in the HVDC system. It should be noted that the two shunt capacitors at bus 7 and 9 help to reduce the reactive power transfer in both areas. The total reactive loss in the HVDC system could be further improved if one optimises the reactive power compensation at the two sending/receiving ends. Overall, reactive power compensation should be done locally, strategically placing shunt capacitors may help to greatly improve the efficiency of the HVDC system.

**Impact of number interconnection on the “breakeven distance”**

Load flow analyses are now carried out for the system with one interconnection line removed. The length of the transmission line is 200km. The HVDC is operated at  $\gamma=22^{\circ}$ . The system loss in this case was compared to the results of previous parts. Fig.5 illustrates the system losses with respect to the number of interconnection lines.

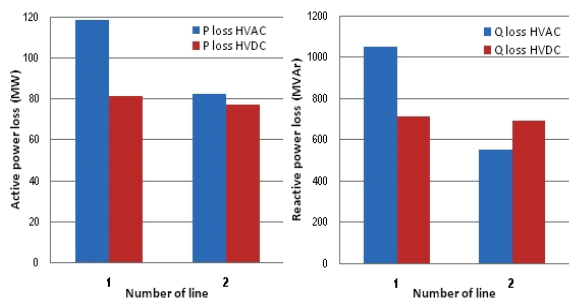


Fig. 5 Total system losses relating to number of interconnections

As is shown by Fig. 5, the loss in the HVAC system is significantly reduced when another interconnection is added. However, the loss in the HVDC system is slightly decreased. Again, one can see that the line loss in the DC link constitutes a very small part in the total system loss compared to the converter/inverter loss. It should be noted that this result is only based on loss evaluation. Adding a new AC line to reduce power loss may not be an overall cost effective solution.

**Impact of receiving end load on the “breakeven distance”**

The active load at bus 9 is gradually increased from 1667MW to 1967 MW. Active/reactive power loss for the AC and DC systems are shown in Fig. 6.

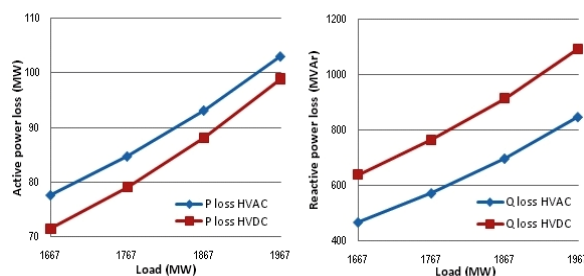


Fig. 6 Total system losses relating to the change in receiving end load

In this case, bus 3 is chosen as a slack bus, which is in the same area as bus 9. Therefore, the increase of active load at bus 9 is balanced by the increase of generating power at generator 3. There is not much difference between how the AC and DC link systems respond to the change in load bus 9. The increase of active/reactive power loss in Fig. 6 indeed comes from the increase of active/reactive power loss in the AC link of area 2. One can conclude that the “breakeven distance” does not depend on the load at the receiving end.

**Conclusions**

This preliminary work compares the DC and AC link options for a simple power system at various transmission lengths, load levels and interconnection strength.

Throughout the case studies, it is observed that the active power loss in the DC link constitutes a negligible part of the total system loss. Furthermore, the required reactive power for the HVDC system is quite independent of the interconnection strength and power transfer level. On the other hand, the AC system losses change considerably with the above parameters. Therefore, as the power transfer level and the interconnection length increase, the DC link gradually shows its superior performance. It should be noted that strategic placement of reactive power compensation can greatly improve the efficiency of a HVDC system. For the studied system in this paper, reactive power locations are obvious as there are only two important loads. For more complicated power systems, a thorough study of optimal reactive power compensation is essential, as it would strongly affect the outcome of the AC/DC comparison.

In this work, the “breakeven distance” is determined by comparing only the reactive/active power loss, which is closely related to the operating cost. If one takes into account the capital cost, the “breakeven distance” would be higher, due to the high cost of building HVDC systems.

One potential advantage of the HVDC system is its capability to enhance the total system dynamic stability. A comparative study of system stability with/without HVDC system is thus needed, and will be the subject of our future research.

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