# Bulk power transmission at extra high voltages, a comparison between transmission lines for HVDC at voltages above 600 kV DC and 800 kV AC.

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## 1 Introduction

Many of the coming hydro power projects in China are located far away from the load centers, which will require an efficient power transmission in order not to loose to much of the very much need power in the transmission line. The higher the transmission voltage, the lower the transmission losses will be. This is valid both for AC and DC.

In order to bring the power to the load centers in an efficient, cost effective and environmentally friendly way, higher transmission voltages than what are available today have to be developed.

Today the highest voltage for HVDC is 600 kV and a bipolar line can carry 5000 MW and for AC the highest voltage is 800 kV and a line can carry about 2000 MW. None of these voltages are represented in China. The highest DC voltage in China today is 500 kV DC and an 800 kV AC test line is under construction.

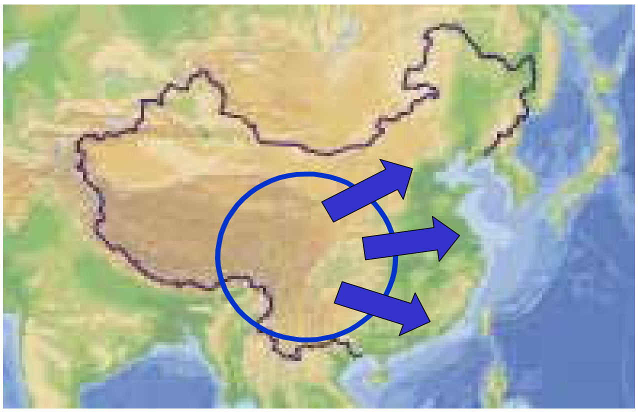


Fig 1. Chinas vast hydro power resources are located in the south-west. Efficient transmission of bulk power over long distances are required in order to meet the demand from fast developing load centers in the east.

The next big hydro power project in China is Xilodu which is rated 18000 MW and located 2000 km from the load center. Some parts of the transmission line will pass altitudes above 2000 meters. This paper will discuss the most feasible alternative and what development that is needed in order to bring the power to the load centers in a way that is the most favorable to the Chinese society.

## 2 Development of EHV transmission systems

### 2.1 EHVAC

The first 735 kV system was commissioned in Canada in 1965. Since then, voltage levels up to 765 kV have been introduced in Russia with neighbouring countries, U.S.A, South Africa, Brazil, Venezuela and South Korea.

The general trend of 800 kV investments is indicated in the diagram, which shows the total capacity of power transformers and generator step-up transformers for 800 kV delivered by ABB.

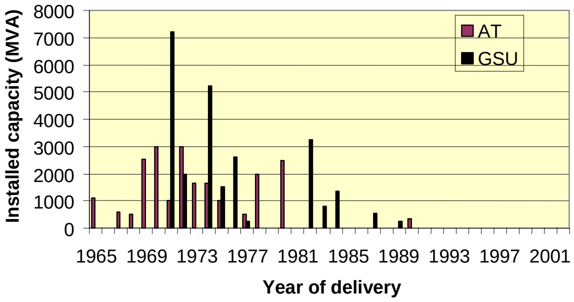


Fig 2. ABB deliveries of autotransformers and generator step-up transformers for 800 kV AC systems.

Since the 90’s, the investments in 800 kV systems have been much lower compared to the 70’s and 80’s. However, plans are under way for future introduction of 800 kV in India and China.

The planned introductions of voltages in the UHV range, i.e. 1000 kV and above, have been cancelled or postponed in several countries. e.g. Russia, Italy and U.S.A. Future 1000 kV lines are only considered in Japan.

## 2.2 HVDC

The first HVDC system for ± 500 kV and above was the Cabora Bassa project, commissioned in 1979. The Brasilian Itaipu project is the only HVDC system operating at ±600 kV so far.

The major HVDC investments at these voltage levels were made in the late 80’s and early 90’s.

However, an increasing interest in high-capacity HVDC links have been noted in recent years, as seen from the diagram, which shows all HVDC projects for ±500 kV and above.

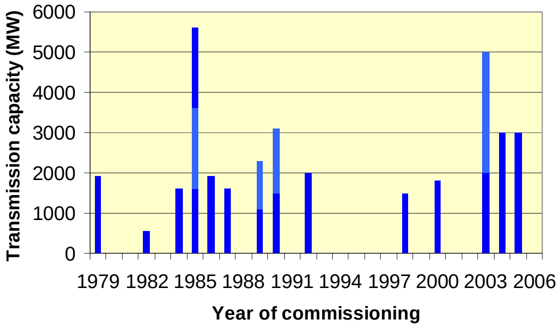


Fig 3. HVDC projects > 500 kV DC. Major investments were done during the 80’s and 90’s. There has been a substantial increase in high-capacity projects since 2000

The need for higher voltage levels can be anticipated for HVDC projects in the near future, especially when the transmission line is more than 1000 km long. From a technical point of view, there are no special obstacles against higher DC voltages. Present solutions are extendable to e.g. ±800 kV when the need arises.

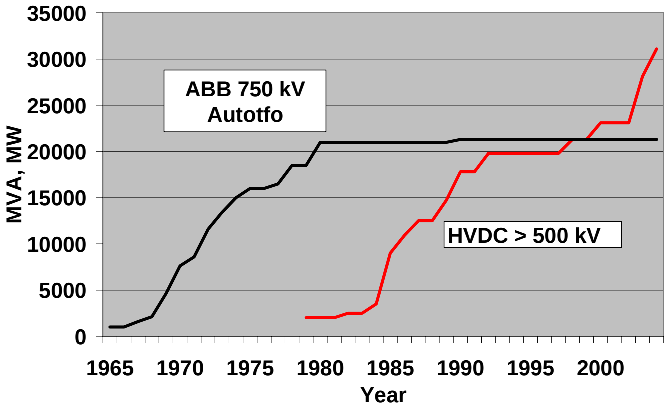


Fig 4. The development of HVAC and HVDC systems for bulk power transmission. The figure clearly shows a heavy increase in HVDC systems while the investment in HVAC almost has halted.

# 3 Design aspects for transmission lines

The general design criteria for AC and DC transmission lines can be divided into electrical and mechanical aspects, both having considerable effects on the investment and operation costs.

The power transmission capacity determines the voltage level and the number of parallel circuits, which has a great influence on the investment costs. Other aspects are emergency loading capability and reactive power compensation of AC lines.

The power losses affects mainly the operating costs and should therefore be optimized with regard to investment cost of the line conductors at the given voltage level.

The insulation performance is determined by the overvoltage levels, the air clearances, the environmental conditions and the selection of insulators. The requirements on the insulation performance affect mainly the investment costs for the towers.

The corona performance influences heavily on the design of the conductor bundles and, subsequently, on the mechanical forces on the towers from wind and ice loading of the conductors. Any constraints on the electromagnetic fields at the ground level will, however, primarily influence the costs for the right-of-way.

The mechanical loading, and hence the investment cost of towers, insulators and conductors, depends mainly on the design of the conductor bundles and the climatic conditions.

Fig 5. Transmission lines for 800 kV AC and 500 kV DC

| | 800 kV AC | 500 kV DC |
|---|---|---|
| Capacity | 2000 MW | 3000 MW |
| RoW | 75 m | 50 m |

# 4 Power transmission capacity

The power transmission capacity of long EHVAC lines is limited by the reactive power consumption of the line inductance, which exceeds the reactive power generation of the line capacitance at load levels above surge impedance loading (which is solely determined by the geometrical configuration of the line). Extensive use of series capacitors may, however, increase the transmission capacity of a line to about 150-200% of surge impedance loading.

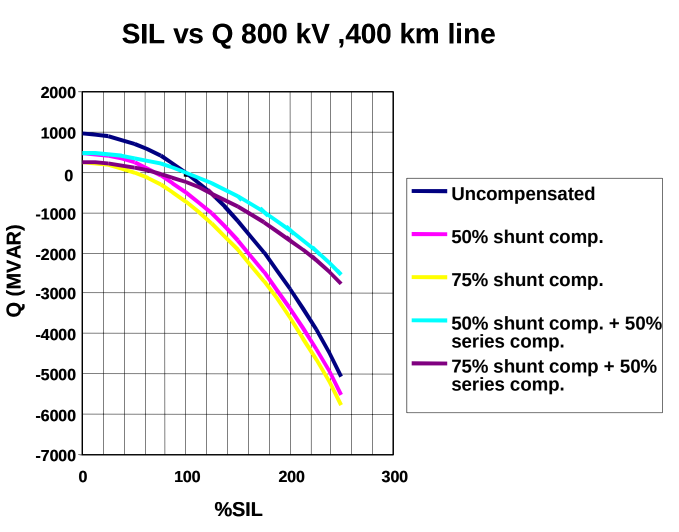


Fig 6. Reactive power consumption vs SIL of an EHVAC line at different degrees of compensation

The thermal loading capability is usually not decisive for long AC transmission lines due to limitations in the reactive power consumption.

The emergency loading capability is dependent on maximum allowable conductor temperature and reactive power constraints. The requirements on emergency loading are determined by the number of redundant lines.

The power transmission capacity of HVDC lines is mainly limited by the maximum allowable conductor temperature in normal operation.

The requirements on emergency loading of HVDC lines depends on the number of redundant lines and the maximum allowable conductor temperature in emergency operation.

When comparing HVDC and EHVAC lines from a transmission capacity point of view, the HVDC lines are principally limited only by the thermal loading capability since there are no reactive power contraints.

## 4.1 Number of lines in parallel

For point-to-point transmission in the 8 to 12 GW range, the table shows the number of lines required when using EHVAC or HVDC at different system voltage levels. The conductor bundle configuration is based on the corona noise requirements at sea level.

| | | **Cond. diam.** | **Thermal limit (line)** | **Thermal limit (s/s)** | **SIL** | **1.5 x SIL** | **Required no. of lines** | |
|---|---|---|---|---|---|---|---|---|
| | **kV** | **mm** | **GW** | **GW** | **GW** | **GW** | **8 GW** | **12 GW** |
| **EHVAC** | **800** | 5 x 35 | 7.5 | 5.5 | 2.5 | 3.8 | **4** | **5** |
| | **1000** | 8 x 35 | 15.0 | 6.9 | 4.3 | 6.5 | **3** | **3** |
| **HVDC** | **±600** | 3 x 50 | 8.0 | 5.8 | n.a. | n.a. | **2** | **3** |
| | **±800** | 5 x 50 | 17.7 | 5.8 | n.a. | n.a. | **2** | **3** |

Fig 7. Number of lines required to transmit 8 – 12 GW

When calculating the required number of lines in parallel, the following criteria were used:

- Emergency operation is defined by the N-1 criterion, which means that one EHVAC line or one HVDC bipole is out of operation.
- A thermal limit of 1.5 A/mm2 may not exceeded for the line conductors
- A thermal limit of 4 kA may not be exceeded for the AC substation equipment. For the HVDC lines, it is assumed that each pole of the HVDC line is connected separately to the 420 kV AC system, yielding a thermal limit of 2.9 GW per pole.
- The loading of the EHVAC lines may not exceed the surge impedance loading in normal operation, or 150% of surge impedance impedance loading in emergency operation.

The effectiveness of HVDC transmission lines at higher voltage levels is clearly demonstrated

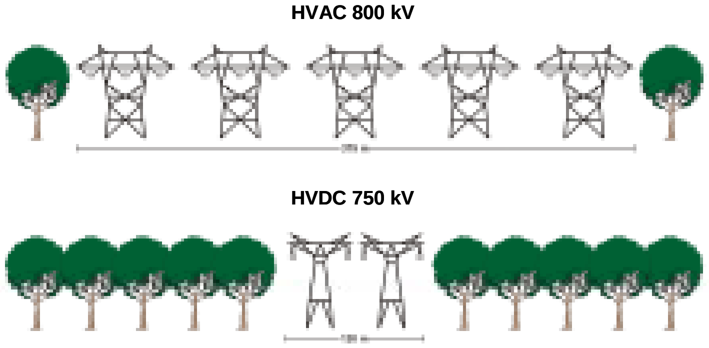


Fig 8. ROW for a 10.000 MW bulk power transmission system with 800 kV AC and 750 kV HVDC

# 5 Line losses

The design of conductors for EHVAC and HVDC lines are optimised with regard to the investments costs for the line and the operation costs for the losses.

For EHVAC lines, the resistive losses determine the conductor cross section.

AC corona losses are important to the design of the conductor bundle. With only a few kW/km of loss in fair weather, the level may increase 10-100 times during conditions of rain or hoarfrost and may reach several hundred kW/km.

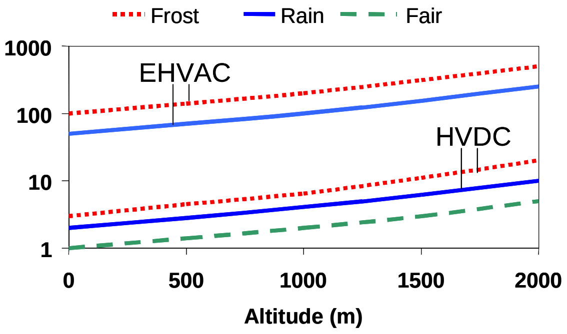
The effect of altitude on corona loss is quite dramatic: at 1800 meters above sea level, the losses at any given weather condition are four times higher than at sea level.

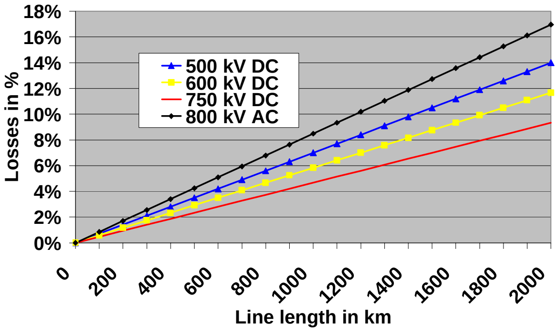
For HVDC lines, the selection of conductor cross section with regard to the resistive losses is done in the same way as with EHVAC.

DC corona losses are, however, of less concern to the design of the conductor bundles, since the increase during rain or hoarfrost is much smaller than with AC, only about 2-3 times.

The effect of altitude on the DC corona loss is similar as with AC.

Typical coronal losses in kW/km are shown in the diagram. When comparing HVDC and EHVAC line with regard to power losses, the main difference is that corona losses of HVDC lines are much less sensitive to variations in weather conditions.





# 6 Insulation design requirements

The insulation performance of transmission lines depends on several factors which are somewhat different for EHVAC and HVDC.

The air clearance requirement is a very important factor for the mechanical design of the tower.

With EHVAC, the switching overvoltage level is the decisive parameter. The diagram shows typical required air clearances at different system voltages for a range of switching overvoltage levels between 1.8 and 2.6 p.u. of the phase-to-ground peak voltage. The required distance shows an exponential behavior with respect to the system voltage.

With HVDC, the switching overvoltages are lower, in the range 1.6 to 1.8 p.u., and the air clearance is often determined by the required lightning performance of the line. Typical clearances are shown in the diagram for different system voltages.

Fig 9. Corona and conductor losses for EHVAC and HVDC lines

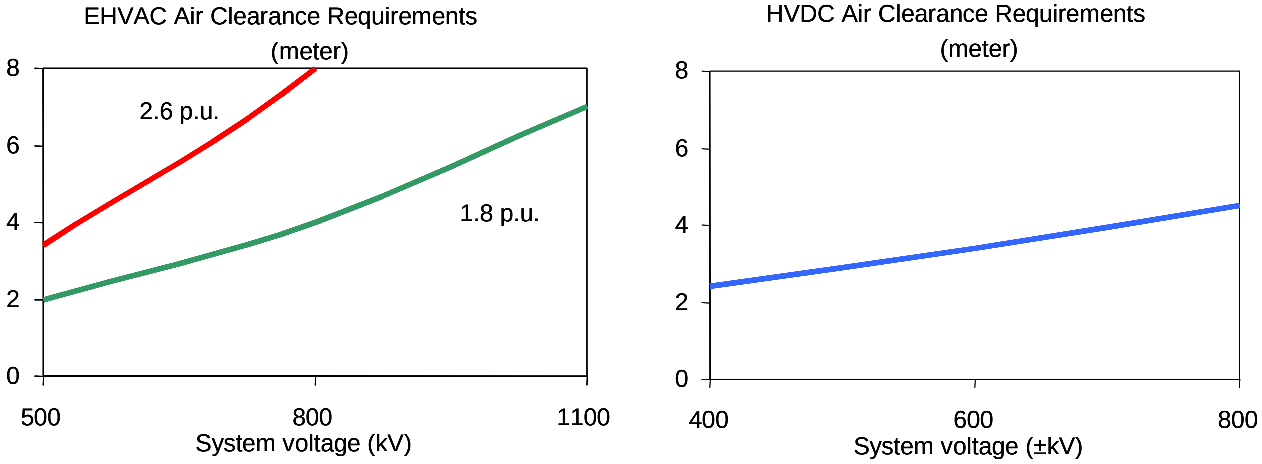


Fig 10. Air Clearance requirements for EHVAC and HVDC for different system voltages

When comparing HVDC and EHVAC line with regard to air clearances, it it is clearly seen that the requirement increases rapidly with the system voltage level for the EHVAC lines. This is due to the close connection between the system voltage and the switching overvoltage levels. With HVDC, on the other hand, the required air clearances at higher system voltages are considerably smaller than with EHVAC

# 7 Line insulator requirements

The selection of insulators for EHVAC systems is relatively straight-forward. The same criteria may be used as for the lower voltage AC systems.

Conventional insulators are still generally used, but composite insulators are considered for polluted areas or for more compact line designs.

For composite insulators, the design of the corona rings is very important to ensure a reliable long term performance. This is due to the effect of the electric field on the hydrophobic properties of the insulating materials.

The requirements on HVDC insulators are higher than for the AC case when compared on the basis of r.m.s. voltage level. This is due to the attraction of pollution particles, which is an effect of the DC electric field surrounding the insulators.

For conventional insulators, there are higher demands on the shape of the HVDC insulators. Material characteristics are also more critical, one example is the need to prevent ion migration in glass insulators.

Composite insulators are becoming an attractive alternative also for HVDC, even in areas with a low pollution level, as more positive service experience are gained. However, the demands with respect to ageing performance of the insulators are more critical than with AC, and the erosion resistance of the polymeric material is an important aspect.

Corona rings will be always significantly smaller for DC than for AC due to the lack of capacitive voltage grading of DC insulators.

When comparing the demands on insulators for HVDC vs. EHVAC, the requirements are more stringent for DC than for AC. This is true for both the flashover performance as well as the ageing effects. Present service experience indicates that composite insulators provide a viable alternative for both EHVAC and HVDC lines. For these insulators, the design of the grading rings is less critical with HVDC.

Examples of actual insulator lengths used on operating lines and test lines for EHVAC and HVDC are shown in the diagrams.

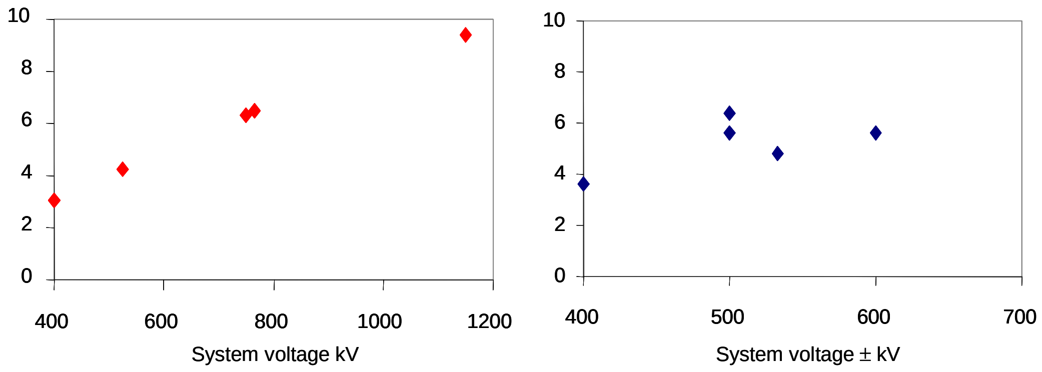


Fig 11. Actual insulator lengths in meter at different system voltages for EHVAC and HVDC

## 8 Effect of altitude

The effects of altitude on the insulation properties are basically the same with AC and DC voltages, however, different kinds of stresses are decisive for the design of EHVAC vs. HVDC lines.

For EHVAC, the dimensioning parameter is the switching performance of the air gaps. For an altitude of 2000 m this means that the air clearances need to be increased by about 15%.

The pollution performance of the insulators is not reduced to the same degree, an increase in insulator length by about 10% is sufficient at 2000 meters.

For HVDC lines, the lightning performance is often the dimensioning parameter for the air gaps. This means that the required increase in air clearance is about 25% at an altitude of 2000 meters above sea level.

The pollution performance of the insulators is reduced in the same way as for AC voltages.

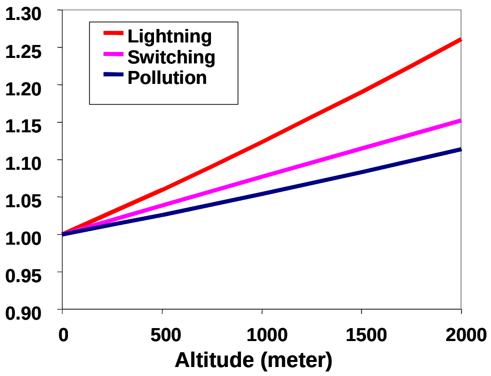


Fig 12. Relative increase in insulation requirements at different altitude.

When comparing HVDC and EHVAC insulation performance with regard to the effect of altitude, it can be stated that HVDC lines need a larger increase in air clearances since the lightning overvoltage withstand is an important design parameter.

## 9 Conductor load on tower

As a result of the different conductor bundle designs used for EHVAC and HVDC lines, the mechanical loading of the towers will also be different. To illustrate this, typical conductor loads under wind and ice were determined for some representative EHVAC and HVDC conductor bundles.

The conductor load is divided into the vertical load, determined by the weight of the conductors and the ice layer thickness, and the transversal load, determined by the wind pressure on the iced conductor. Ice layer thickness, wind speed and all other parameters were selected according to the example case published in Electra No. 132 and based on the IEC standard. The total conductor load on the tower is assumed to increase in proportion to the numbers of conductors and subconductors.

IEC load condition 1 was used for the vertical load, i.e. low wind speed and high ice load, while condition 2 was used for the transversal load. i.e. high wind speed and low ice load.

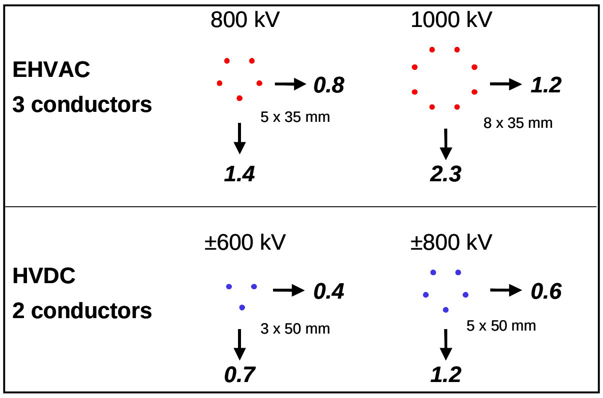


Fig 12. Total conductor load on tower in kN/m

When comparing total conductor loads, it is obvious that the reduced number of subconductors required for HVDC lines is advantageous with regard to the loading of the towers. As seen from theses examples, the HVDC conductor load is roughly only half of the EHVAC conductor load at comparable voltage levels.

## 10 Development work for future bulk power transmission

In general no development is needed for EHVAC substation equipment since 800 kV AC is a mature technology with more than 25 years of operational experience. For HVDC systems above 600 kV work is necessary in order to develop and test converter station equipment.

For the transmission line it is needed  to determine the actual design parameters for both EHVAC and HVDC, although more has to be done on the HVDC line.

With good planning the design criteria for an HVDC system for voltages above 600 kV can be available within 3 years and for an EHVAC line within 1 year.

### 10.1 EHVAC

800 kV AC systems have been in operation since the early 80’s and no development work for sub-station equipment is foreseen. For the transmission line there are limited experience of operation at high altitudes and severe pollution. For that reason is anticipated that some R&D work is necessary in order to have a reliable line design which is relevant for the actual conditions.

### 10.2 HVDC

HVDC converter station equipment for 600 kV DC has been in operation for almost 20 years. The operational experience is today very good. Equipment for voltages above 600 kV is necessary to develop. IEEE working group stated already 1986 : ”Design, construction and operation of 800 kV HVDC are clearly feasible with present knowledge and experience although an R&D effort is highly desirable in order to achieve economy of design and optimum performance.

There is no operational experience of transmission lines for voltages above 600 kV DC. A R&D program is needed in order to determine the design criteria for the line parameters.

## 11 Economical comparison EHVAC and HVDC

The trend of power electronic components, for use in the main circuit of an HVDC transmission, being developed means that the relative cost of HVDC transmissions is reduced as the components become cheaper as a result of continuing innovative technological developments. Thus a large converter station with a cost of 50 USD/kW is today cheaper in current dollars compared with the situation 20 years ago.

The dc line is less costly compared with an 800 kV ac line. On the other hand, the converter station cost offsets the gain in reduced cost of the transmission line. Thus a short line is cheaper with ac transmission, while a longer line is cheaper with dc.

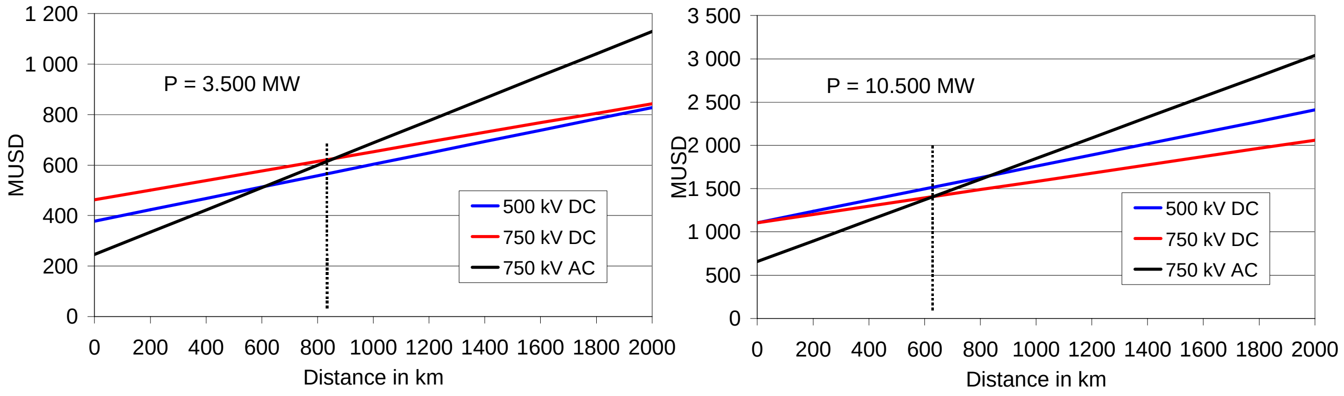


Fig 13. The graphs above show the total cost for stations and transmission lines for 3500 MW and 10.000 MW respectively. The break-even distance decreases with higher power and is about 800 km for 3500 MW and 600 km for 10.000 MW.

An economic study of different transmission alternatives for 10.000 MW and 3.500 MW has been made. As can be seen from the figures, the break-even distance is shorter for high power than for low power transmissions and that it is good economy to have a high line voltage when the power is high.

# 12 Conclusions

In a general comparison of HVDC vs. EHVAC power transmission, the design of the transmission lines and the related investment costs are of great importance. The aim of this paper has been to focus on the differences in the design of line insulation and conductor configuration, and its influence on the mechanical loads.

For the line insulation, air clearance requirements are more critical with EHVAC due to the nonlinear behavior of the switching overvoltage withstand.

The corona effects are more pronounced at AC voltage, therefore, larger conductor bundles are needed at higher system voltages.

The altitude effects are more important to HVDC lines, since the lightning overvoltage withstand is the most sensitive insulation parameter with regard to air density.

The mechanical load on the tower is considerably lower with HVDC due to less number of subconductors required to fulfill the corona noise limits.

The high transmission capacity of the HVDC lines, combined with lower requirements on conductor bundles and air clearances at the higher voltage levels, makes the HVDC lines very cost efficient compared to EHVAC lines. The cost advantage is even more pronounced at the highest voltage levels.