ECONOMIC EVALUATION
OF
HVDC TRANSMISSION SCHEMES

by

Jaspal Singh

A thesis
presented to
the Faculty of Graduate Studies
the University of Manitoba

In partial fulfillment
of the requirements for the degree of
Master of Science
in
Electrical Engineering

Winnipeg, Manitoba
Canada
April 1987 ©

ISBN 0-315-37366-0

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ABSTRACT

This thesis is concerned with the economic evaluation of HVDC transmission schemes. The economic, technical, reliability and operational aspects of ac and dc transmission design are described and evaluated.

The criteria for comparison between ac and dc transmission alternatives is described. Economic evaluation is illustrated by an example to transmit 2200 MW of electric power over a distance of 1000 km by three alternatives.

ACKNOWLEDGEMENTS

The author wishes to express his appreciation and deepest gratitude to Professor M. Z. Tarnawecky for suggesting the thesis topic, his esteemed guidance, unflinching encouragement, financial support and kind assistance throughout the entire course of his graduate study.

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LIST OF SYMBOLS

α	Converter firing angle
β	Advance angle of firing of converter
γ	Angle of extinction for inverter
μ	Angle of commutation or angle of overlap
f	Frequency
F	Peterson empirical function
δ^o	Power angle in degrees
ΔI_d	Current margin
dB	Decibel
dB(A)	Average A–weighted audible noise level in decibel
I_d	Direct current
V_d	Direct voltage
V_o	No load ideal voltage
PWL	Acoustic power level for bundle, dBpW
PWL_o	A weighted acoustic power level
g	Average maximum gradient, kV/cm
n	Number of subconductors in bundle
h	Line height, m
D	Direct (radial) distance between transducer and phase, m
Z_o	Surge impedance

LIST OF ABBREVIATIONS

ac	Alternating current
ACSR	Aluminum Cable Steel Reinforced
AN	Audible noise
ASEA	Allmamma Svenska Elektriiska Aktiiebolaget
BBC	Brown Boveri Corporation
BPA	Bonneville Power Administration
CIGRE	Conference Internationale des Grands Reseaux Electriques a Haute Tension, Paris
dc	Direct current
EHV	Extra High Voltage
HVAC	High Voltage Alternating Current
HVDC	High Voltage Direct Current
MCM	Thousands of circular mills
RI	Radio interference
ROW	Right of way
SIL	Surge impedance loading
SNR	Signal noise ratio
TVI	Television interference
UHV	Ultra high voltage

Chapter I

Introduction

Attempts have been made over the years to establish "break-even" criteria [1,2,3] of transmission distance and power for choice of ac and dc systems as shown in Fig. 1.1 [4] . Estimates of the "break-even" distance of overhead lines, published in literature, range from 500 km.(310 mi) to 1500 km.(930 mi). An economic comparison between ac and dc transmission made by an international working party of CIGRE [3] and based on 1965 costs showed an average "break-even" distance of 1000 km (600 mi) for transmitting 1080 or 2160 MW on two overhead circuits and 77 km (48 mi) for transmitting 1080 MW on two shunt compensated underground cable circuits.

These general comparisons could be influenced by costs which vary from one country to another or by a variation in the basis for comparison. In particular ac overhead line costs vary by a factor as high as 2.5 . In addition, there are other factors which can vary greatly between practice of various utilities such as the amount a utility charges for load and fixed losses.

These relatively simple comparisons of alternative ac and dc transmission arrangements did not properly evaluate the technical, reliability and operational aspects and different but very unique properties and characteristics of dc technology.

Therefore, when making a comparison of ac and dc transmissions it is important to establish the proper criteria to be used in the conceptual designs of each alternative system. The ac and dc system do not behave in the same way for either normal operating condition or under system disturbances. The difference in operation should be recognized and advantage taken wherever possible of particular characteristic.

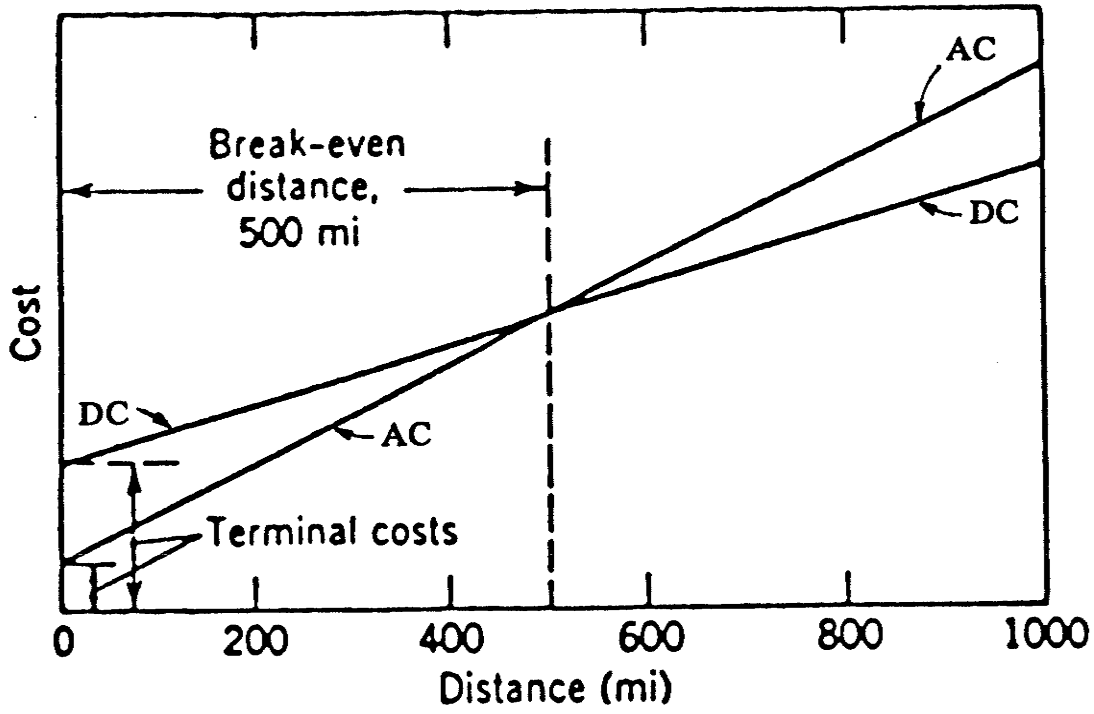


Fig. 1.1 Comparative Cost of AC & DC Overhead Lines vs. Distance

1.2 Development of HVDC Systems

In recent years there has been a significant increase of interest in HVDC transmission as shown in Fig. 1.2 [5]. This increased interest results from the following considerations:

1. Economic advantages.
2. Functional advantages.
3. Environmental advantages.

HVDC systems can often provide a more economical alternative than an HVAC system, as for the following:

1. Submarine or underground cable system.
2. Long distance point to point transmission of bulk power.

Similarly, HVDC systems offer functional characteristics and performance not achievable with ac systems alone. Examples include asynchronous interconnection, control of power flow, and power modulation to increase stability limits [20] .

From an environmental vantage point, an HVDC system provides less operational difficulties than a comparable HVAC system. Examples include more power per right of way, reduced radio and audible noise.

For the above reasons, and in view of the dramatic increase in fuel costs and cost of spinning reserves, the past few years have seen a tremendous increase in the number of HVDC systems under study or construction as shown in Fig. 1.2 .

In Table 1.1, all the North American HVDC Schemes in operation, scheduled or active consideration are numbered and listed in chronological order by year of completion [5] . Figs. 1.3 and 1.4 show the geographical location of these schemes.

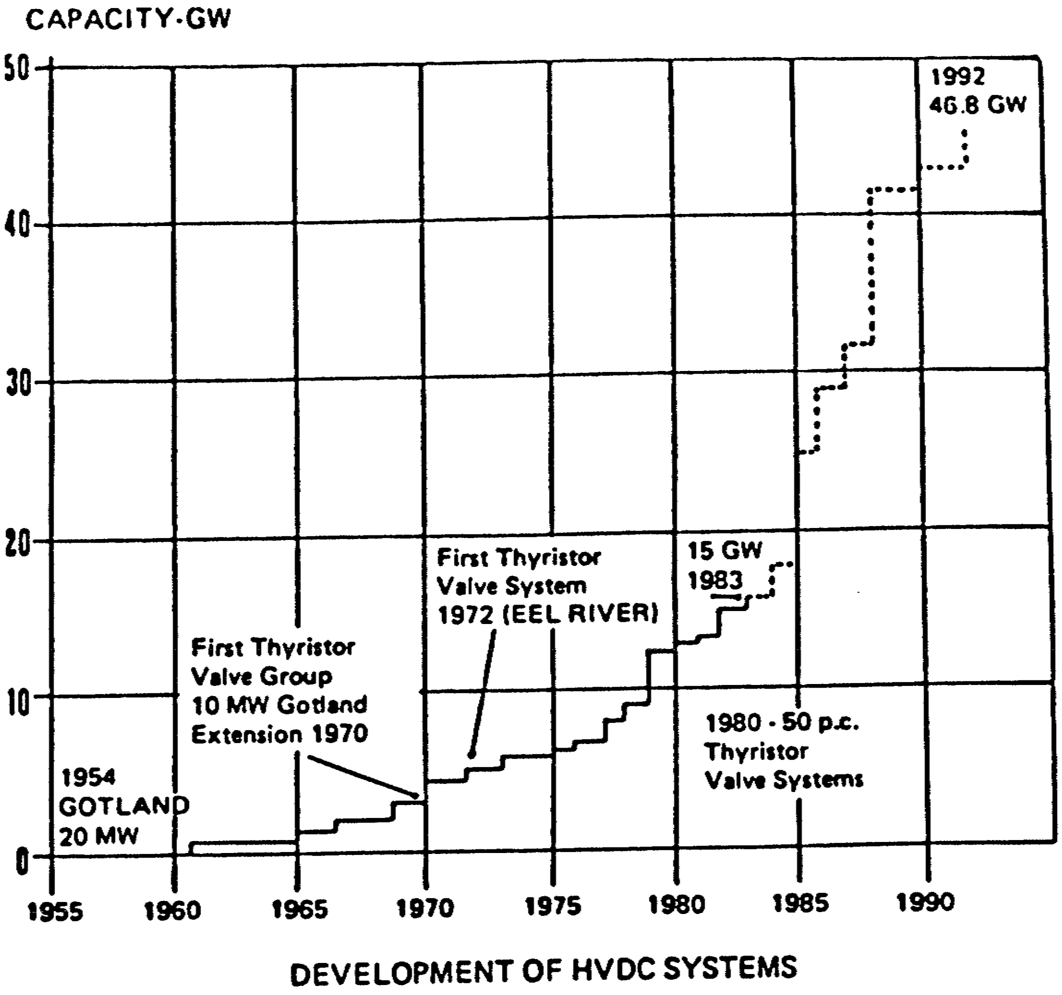


Fig. 1.2 Development of HVDC Systems

Table 1.1 North American HVDC Schemes

REF.	NAME OF SCHEME	MW	KV	LENGTH km	COMPLETION	MAIN PURPOSE
1	Vancouer Island 1	312	+260	41 O/H, 28 Cable	1968/9	U/W Trans.
2	Pacific Intertie 1	1440 1600	±400	1360	1970 1977	O/H Trans.
3	Eel River	320	2x80	Back-to-Back	1972	Async. Tie
4	Vancouver Island 2	470	-280	41 O/H 33 Cable	1977/8	U/W Trans.
5	Nelson River 1	1620	±450	895	1977/8	O/H Trans.
6	Nelson River 2	900 1800	±250 ±500	930	1978 1985	O/H Trans. O/H Trans.
7	Square Butte	500	±250	735	1977	O/H Trans.
8	David A. Hamil	110	50	Back-to-Back	1977	Async. Tie
9	Co-op Power(CU)	1000	±400	687	1978	O/H Trans.
10	Astoria	1000	100 biased to 400 kV	0.6 Cable Monopole	1981/4	
11	Eddy County	200	83	Back-to-Back	1984	Async. Tie
12	Chateauguay	2x500	140	Back-to-Back	1984	Async. Tie
13	Oklaunion	200	83	Back-to-Back	1984	Async. Tie
14	Miles City	200	83	Back-to-Back	1985	Async. Tie
15	Madawaska	350	140	Back-to-Back	1985	
16	Pacific Intertie	2000	±500	1360	1985	Voltage Upgrade
17	Blackwater	200	56	Back-to-Back	1985	
18	Highgate	200		Back-to-Back	1985	
19	Intermountain	1600	±500	800	1986	O/H Trans & Stability
20	Des Cantos - Comerford	690	±450	175	1986	
21	Walker County	520	400 Monopole	240 (Poss. delay)	1986	Async. Tie
22	Sidney	200		Back-to-Back	1988	
23	Yukatan-Mexico city	900	500			
24	Salt River	1600 2200	±314 ±500	385	1988	
25	Pacific Intertie	200 A to 3000A	±500	1360	1988?	Current Upgrade
26	Comerford - Sandy Pond	1400		200	1990	
27	Alaska					
28	Gull Island	1800	±400	1095	Proposed	O/H Trans.
29	Western DC Grid					Man/Sask/Alb Tie

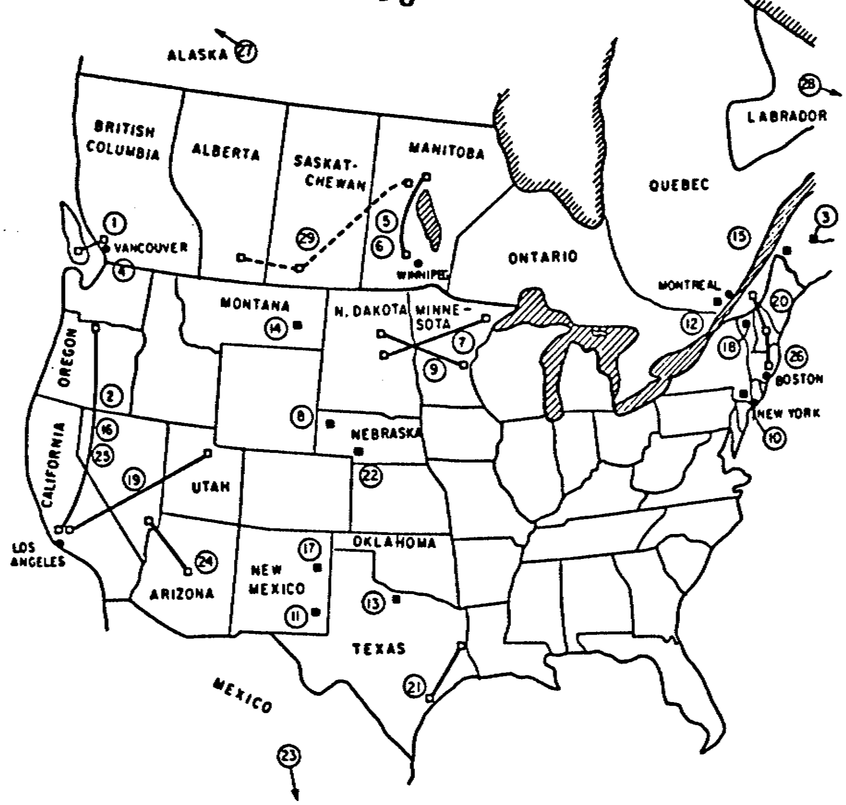


Fig. 1.3 Geographical Location of North American HVDC Schemes

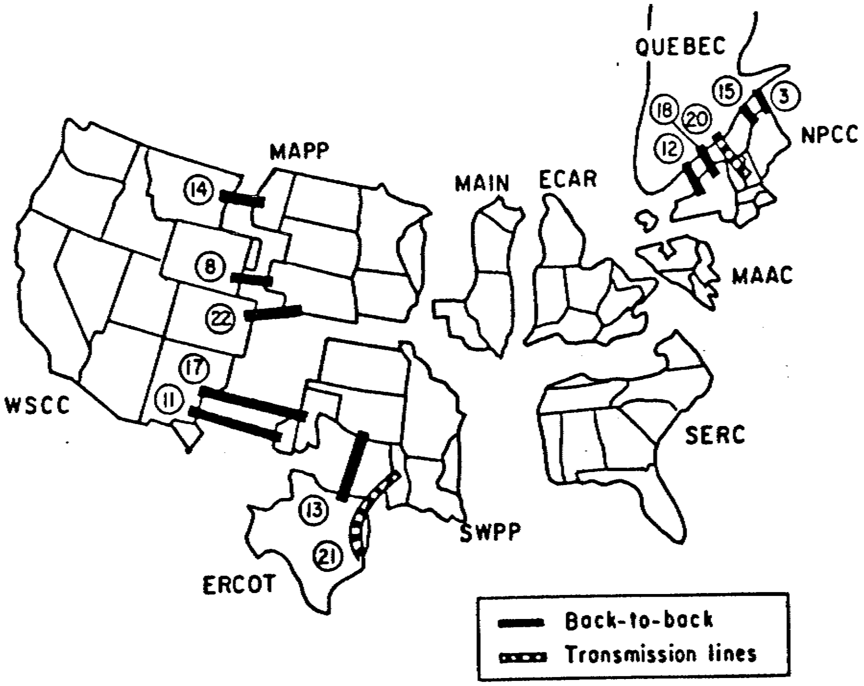


Fig. 1.4 DC Interconnection Western Coordinating Council (WSCC), Electric Reliability Council of Texas and Quebec to the Other Regions

1.2.1 HVDC Application Trend

Traditionally, the economics of HVDC transmission have been concerned with "break-even" distances for long distance transmission. That this is an oversimplification is evidenced by the fact that the majority of early schemes throughout the World were for submarine interconnections for which there was no feasible ac alternative

Exception to the "break-even" concept continue to predominate in North America. Selected from Table 1.1 [26], distances range from back- to-back (zero transmission distance) up to 841 mi (1353 km) for the Pacific DC Intertie.

The schemes shown in Table 1.2 [26], all involve overhead dc transmission that might previously have been considered uneconomic for a dc transmission that might follow simple text-book "break-even" evaluation of dc versus ac.

Table 1.2 Typical Transmission Distances of HVDC Schemes.

REF	SCHEME	DISTANCE KM	COMPLETION
20	Des Cantons - Comerford	175	1986
26	Comerford - Sandy Pond	200	1990
21	Walker County	240	1986
24	Salt River	385	1988
9	Co-op Power (CU)	687	1978

Thus the trend has been towards strategic interchange of controllable power via back-to-back and short / median transmission distances. It is evident that utilities, in examining alternative transmission strategies, have increasingly exploited aspects other than lower transmission losses - such as controllability and asynchronous power transfer.

The purpose of this thesis is to carry out an economic evaluation of HVDC schemes with due consideration to economic, reliability, technical and operational aspects. A general criteria for comparison is described in Chapter II. Design of HVAC and HVDC transmission are discussed in Chapter III and Chapter IV respectively. Chapter V compares the technical and reliability aspects and chapter VI describes costing of ac and dc schemes. Chapter VII describes economic evaluation of ac and dc schemes which is illustrated by an example in Chapter VIII. Conclusions are presented in Chapter IX.

Chapter II

Criteria For Comparison.

2.1 Introduction

The traditional method applied in the past when comparing ac and dc transmission alternatives resulted in calculating the "Break-Even-Point" of cost versus distance. This method of comparison is inadequate as technical, reliability and operational aspects are not properly evaluated and included in the comparison.

Thus the evaluation of technical, reliability and operational aspects along with tangible and intangible performance benefits must be included in the comparison. The economic evaluation by this approach may lead to the conclusion that HVDC transmission proves to be economical also in case of shorter distances.

The economic advantages of HVDC over HVAC for long distance bulk electric power are generally well understood. Since there are both technical and operational differences between the two technologies, care must be taken when making comparison. System operational requirements must first be defined. This allows the inherent capabilities of HVAC and HVDC systems to be properly identified so that operationally equivalent ac and dc systems will be compared.

However some features do not lend themselves to ready or easy comparative evaluations. For example to achieve the same performance as a relatively small inter-regional HVDC link might well require an extremely large high capacity ac intertie or application of other expedients to support stability.

Thus meaningful economic evaluation should consider systems of equivalent performance if at all possible. Failure to do so, for example, can lead to decisions derived from sub-optimal analyses only to find later that important but unrecognized system operating requirements must be addressed at additional cost. Such considerations would have been important to the earlier decision.

This chapter describes a general criteria for comparison. The items described in this criteria should be examined and evaluated when choosing between two options for electric power transmission, ac or dc. Consideration of applicable items should yield a comprehensive picture of the total life-cycle cost benefits flowing from either choice and thus permit an informed comparison of the two technologies.

2.2 Distance of Transmission

System planners sometimes speak of a "break-even-distance" when comparing ac and dc transmission. It is the distance at which the lower cost per kilometer of the dc line cancels the higher cost of the converter terminals at either end of the dc line. For example, for a 1000-MW line with the cost of losses fixed at 400 US dollars per kilowatt-year the break-even-distance is about 500 to 600 miles (800 to 960 km), according to a study done for the U.S. Dept. of Energy and the Oak Ridge National Laboratory [15]. The study indicates that the "break-even-distance" increases with the amount of power transmitted as shown in Fig. 2.1.

Break-even-distance is, however, only one of several factors that should be considered by the system planners.

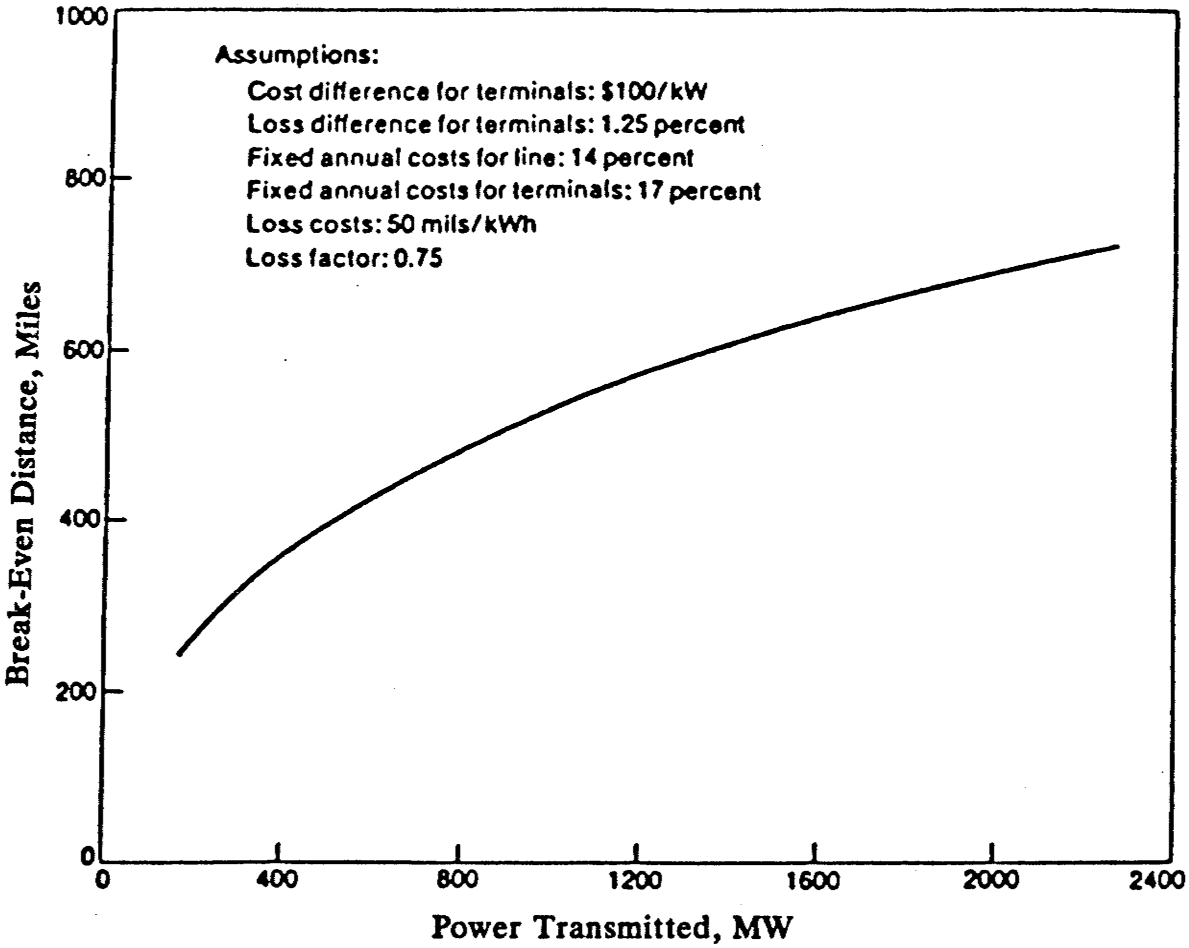


Fig. 2.1 Break–even Distance Versus Power Transmitted

2.2.1. Long Distance Transmission

On long HVAC overhead lines the production and consumption of reactive power by the line itself constitutes a serious problem. Series and shunt compensation is used to overcome this problem. Also the line is sectionalized by means of intermediate switching stations for the following reasons :

a) Limiting the overvoltage when a line is energized from one end.

b) Limiting the decrease in stability power limit attributable to switching out one circuit to clear fault or for line maintenance.

c) For connection of intermediate loads or generation, shunt reactors and series capacitors.

On the contrary HVDC line itself requires no reactive power, and the voltage drop on the line itself is merely due to line resistance. The converters at both ends of the dc line, however, draw reactive power from the ac system. It varies with the transmitted power and is approximately 60% of the active power at each end. It is independent of the length of line.

There is no limit to the length of transmission by dc due to the absence of line reactance and consequently intermediate switching stations are not required.

Thus series and shunt compensations are required on long ac lines and they add to the cost and complexity of these lines. Whereas reactive compensation is not required on a dc line itself, but only on the ac side of the converters. This fact gives an advantage to long dc lines over long ac lines.

Fig. 2.2 shows that dc link requires less reactive power than ac line for distances of more than 250 miles [4].

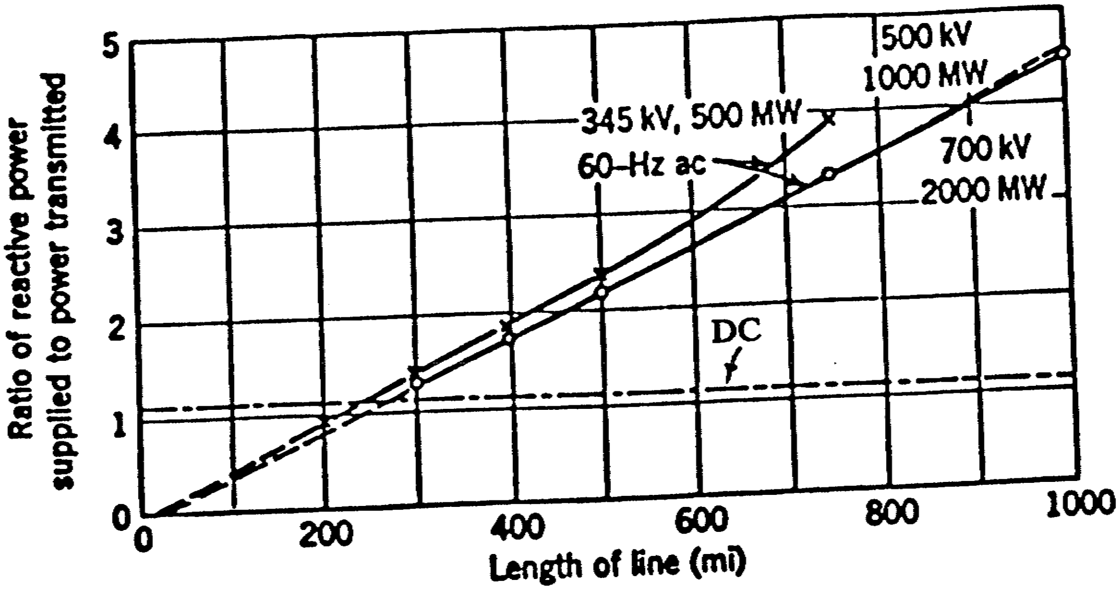


Fig. 2.2 Reactive Power Requirements of Long Overhead AC and DC Lines

2.2.2. Short Distance Transmission

In some circumstances the question of economic distance is irrelevant and transmission by dc is the only or better solution for the following cases :

a) To interconnect ac systems of different frequencies or where asynchronous operation is desired.

b) To interconnect ac systems with minimal increase in existing short circuit capacity.

c) For submarine cable.

d) In congested urban areas where it is difficult to acquire right of way for overhead lines and where the lengths involved makes ac cable impractical.

Six of the first seven HVDC installations, beginning with Gotland, involved submarine cables. In the English Channel crossing and the Konti-Scan scheme asynchronous operation was preferred because of simplicity and economy of control.

2.3 Overhead vs. Cable Transmission

Electrical power may be transmitted by means of overhead lines or underground and submarine cable or a combination of both overhead lines & cables. It is useful to compare the relative merits of ac and dc transmission for these cases.

2.3.1. Overhead Lines

A dc overhead line is cheaper than an ac overhead line for the following reasons :

- a) Fewer conductors are required (although the total cross-section area may be the same).
- b) Fewer insulator strings are required.
- c) Transmission towers for the same voltage are smaller and lighter in weight.

In addition a long ac line may have to be compensated by series capacitor and shunt reactors, and the stability limit may not allow the line to be used to its full thermal capability.

The dc line cost is generally taken to be 2/3 rd of the ac line cost.

2.3.2. Cable Transmission

Unlike overhead lines, a cable can transmit about *three* times the power [3] if used for direct current than it could transmit if used for ac because of higher insulation stresses which can be employed. Hence fewer cables are required with a narrow right-of-way.

Due to unidirectional field there is practically no charging current in case of dc. In case of ac, the steady state charging current is shown in Table 2.1 [16] .

Table 2.1 Steady State Charging Current for a 3-ϕ AC Cable.

Transmission Voltage (kV)	Charging Current (3-ϕ Cable) (kVA/circuit/mile)
132	2000
220	5000
400	15000

There is thus a distance limit beyond which it is necessary to supply the charging current at intermediate points which is as follows :

40 miles for 132 kV

25 miles for 220 kV

15 miles for 400 kV

Fig. 2.3. shows approximate weights of a 3 ϕ ac cables and dc cables at different voltages for a current capacity of 500 A.

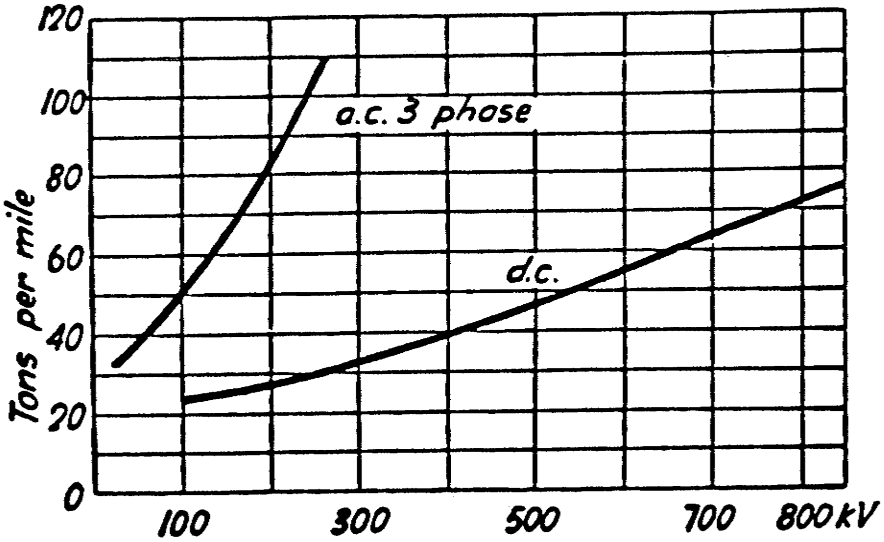


Fig. 2.3 Comparison of Weights Per Mile of AC and DC Cables

2.4 Right-of-Way (ROW) Requirements

The comparison of right-of-way required for transmission of power by HVAC and HVDC should be considered. HVDC requires narrow ROW as compared to HVAC to transmit the same amount of power. Metropolitan areas are centers of high load growth and new right-of-ways are hard to obtain in such areas. In such situations the power capability of existing corridors can be increased by conversion of ac facilities to dc or hybrid ac/dc.

2.4.1 New Right-of-Way (ROW)

There are many situations particularly in European countries where the availability of ROW is limited. In such cases HVDC can be used to advantage. As an example the ROW requirement of the ± 600 kV HVDC line is about 160 ft (48 m) as against 280 ft (85 m) required by the 765 kV AC line to transfer the same 2000 MW of power [14] . Table 2.2 compares the right-of-way requirement for HVAC & HVDC transmission to transmit the same amount of power [14].

Table 2.2 Comparison of ROW of HVAC vs. HVDC

TYPE OF TRANSMISSION	RIGHT-OF-WAY WIDTH	ACREAGE PER MILE
Bipolar HVDC	120 ft (36 m)	14.5
Double-Circuit HVAC	250 ft (76 m)	30.3

2.4.2 Old Right-of-Way.

Part of the system planning is to study means to increase the power transfer capability from one point to another. Conventionally this has been done by:

a) Adding an ac circuit.
b) Adding compensation to an existing ac line.

There is a need to increase the power capability of existing lines supplying metropolitan areas where new right-of-ways are not available. HVDC can be used to advantage in such cases either by:

i) Converting the existing ac lines to dc lines.
ii) Converting one circuit of a double-circuit ac line to dc.

Jones & Kennedy give an example where the use of existing ac line with dc can increase the transfer capability five fold [17]. The obvious savings by this conversion is that a new line does not have to be built.

2.5 Reliability Requirements

The reliability of an electrical system is a very important element of system design. Duplicate circuits are used to permit continuity of supply for large power levels.

The level of firmness of supply is determined by the amount of power to be transmitted and the impact of its loss to the system. Duplicate circuits would be required for the higher ratings to permit transmission at half power with one circuit out. In some countries, such as Canada, in view of the high risk of damage to overhead line tower circuits over long distances, firm circuits are used which permit transmission of full power with one circuit out. This level of firmness is achieved at an increased cost of transmission line.

2.5.1 Interruptible Supply

If the type of delivery is interruptible, duplicate circuits may or may not be required depending on the power level and the design criteria. If required, the duplicate circuits at higher ratings would be designed to permit transmission at half power with one circuit out.

2.6 Stability Considerations.

Before one can make economic comparison of alternative facilities, one must have alternates, which are truly comparable. While the resulting alternates may not be technically equivalent in every respect such as reliability and flexibility of operation, they should all be technically acceptable and therefore amenable to economic comparison so that their technical differences can be evaluated in terms of dollars.

The main problem, therefore, is to determine this criteria and this in turn evolves from the nature of the system itself. The behavior of the system under various disturbances should be evaluated. Particularly the operational behavior including flexibility and security of operation must be fully evaluated.

2.6.1 Stabilization of an AC Link

A rapidly growing application of HVDC is the coordinated control of parallel ac/dc systems which makes it possible to increase the power transfer capabilities of parallel ac lines [22]. Since ac lines are normally designed with relatively high thermal capability compared to stability limits, the increase of stability limits is a performance benefit which deserves cost evaluation.

The above stabilizing feature has been used in the Pacific Intertie to damp the steady-state oscillation in the parallel ac lines, which permitted an increase in the transmission capability by 400 MW [14]. The cost evaluation of this benefit was 48 million in US dollars.

2.7 Environmental Impact

Environmental impact, which mainly comprises corona, electric field and ion effects is an important consideration in line design. Corona considerations make it necessary to use multiple conductor- bundles. The choice of the actual number and size of conductors in the bundle is based on economic as well as environmental considerations.

2.7.1 Corona Performance.

Corona discharges on the conductors of a transmission line give rise to several effects:

a) Corona loss (CL)
b) Radio Interference (RI)
c) Television Interference (TVI)
d) Audible Noise (AN)

The impact of corona loss is mainly economic while the RI, TVI and AN have a potential impact on the physical environment of the line and should be limited to acceptable levels under various weather conditions.

2.7.2 Electric Field Effects.

There are a number of effects associated with the installation and operation of transmission lines which are not directly related to power carrying function of the line. There is public opposition to installation of new high-voltage transmission lines due to possible health hazards resulting from electric fields in the proximity of overhead transmission lines [13].

Therefore, environmental impact should be properly evaluated and compared for both HVAC & HVDC alternatives.

2.7.3 Visual Impact.

HVDC bipolar line requires smaller transmission towers and just two conductors which results in reduced visual impact. This is an intangible benefit which can not be translated in monetary terms.

Chapter III

Design of EHV/UHV Overhead Transmission.

3.1 Introduction.

The decision to build an EHV/UHV line will result from system planning studies to determine how best to meet system requirements. At this stage, the voltage level, load capability and points of connection to the line will have been established. There then remains the problem of designing the line to meet these requirements at the lowest cost consistent with the required reliability and technical aspects and acceptable audible noise, radio noise and television noise levels and total line and corona losses.

3.2 Conductor Selection.

Conductor size is one of the most important considerations in line design. The conductor size is often established by I^2R losses and corona performance. Bundle conductor configurations are usually necessary to attain satisfactory corona performance. The ac transmission conductors are usually designed to operate in the range of 15 to 20 kV/cm [7].

Conductor selection, clearance to ground, and phase spacing are dictated largely by corona and field constraints. The basic acceptable criteria [34] are :

1. Audible Noise Level of 53 dB(A) at 1200 kV, 30 meter from centerline during rain (Right-of-Way edge).
2. Electric field strength 9 kV/m maximum under the line, 1 meter above ground.

3.3 Environmental Impact

The evaluation of environmental impact which mainly comprises corona performance and electric field performance is an important consideration in line design. Corona considerations make it necessary to use multiple conductor bundle.

3.3.1 Corona Performance

The effects related with corona performance are corona loss (CL), audible noise (AN), radio noise (RN), television interference (TVI), corona loss and ozone. The corona loss has economic impact while AN, RI, and TVI relate with the physical environment. The ac transmission line is designed so that these effects are limited to an acceptable level.

3.3.1.1 Corona Loss

Corona loss is an important economic parameter and should be limited to an acceptable level under various weather conditions. The magnitude of fair-weather corona loss is insignificant in comparison with foul weather loss. However, fair-weather losses occur for a large percentage of time and their consideration will affect the value of the total energy consumed by the line.

The bad weather corona loss is of the order of 50 to 1000 times of the fair weather loss and it is of economic significance in line design [7].

Eqn. 3.3, as described in appendix 1, gives the fair weather ac corona loss [51] .

$$P_C = \frac{33.7(10^{-6})\, f\, E^2\, F}{\left(\log_{10} \frac{S}{r}\right)^2} \quad \text{kW / mile of conductor.} \tag{3.3}$$

3.3.1.2 Radio Interference.

One of the possible consequences of transmission line corona discharges is radio noise. Radio noise (RN) is rather a general terminology which refers to any unwanted disturbance within the radio frequency band extending from 3 kHz to 30,000 MHz. The terminology radio interference (RI) refers to interference in the AM broadcast band (535 - 1605 kHz) .

The radio interference should be limited to tolerable levels. The tolerable level of signal to noise ratio (SNR) is 24 dB [7] .

The bad weather RI from ac lines is many times the fair weather RI level. Thus the RI of a transmission line is dependent on the prevailing weather conditions and can vary over a wide range.

The RI at 15 meter from outer phase, can be calculated from Eqn. 3.4 [8].

$$RI = RI_0 + 120 \log \frac{g}{g_0} \; 40 \log \frac{d}{d_0} + 20 \log \frac{h}{h_0} \frac{D_0^2}{D} \qquad (3.4)$$

3.3.1.3 Television Interference.

Television interference (TVI) is mostly a foul weather phenomenon is a practically unexplored problem. The average measured TVI levels at 75 MHz during foul weather is 28 to 29 dB(μV/m) [8].

The "tolerable reception" corresponds to a signal to noise ratio (SNR) of 17 dB measured by a peak detector. For this design criteria, a noise of 57 dB (peak) above 1 μV/m, referred to a 3 MHz bandwidth, should not be exceeded. The Eqn. 3.5 can be used to calculate TVI .

$$TVI = TVI_0 + 120 \log \frac{g}{g_0} + 40 \log \frac{d}{d_0} + 20 \log \frac{D_0}{D} \qquad (3.5)$$

3.3.4 Audible Noise.

Audible noise from transmission lines has become of increasing concern in recent years and is very important limiting factor in the design of lines.

Transmission line audible noise has two characteristics:

1. Broadband Noise, described as frying, or cracking, or hissing.
2. Pure tone components at frequencies of 120 Hz and multiples.

The pure tone are superimposed on the broadband noise. The most noticeable tone is the 120 Hz "hum".

The audible noise has wide variation depending on weather condition. For ac line audible noise is primarily a foul weather phenomenon.

A subjective evaluation of annoyance [9] indicates maximum desirable limit of 55 dB(A) day time and 45 dB(A) night time in residential areas.

The Bonneville Power Administration (BPA) comparative formula [8] in Eqn. 3.6 can be used to calculate acoustic power level for bundle conductor at 15 meter from outer phase.

$$PWL = PWL_0 + 120 \log \frac{g}{g_0} + 55 \log \frac{d}{do} + 10 \log \frac{n}{n_0} \qquad (3.6)$$

3.4 Insulation Coordination.

The insulation of the transmission line is designed to withstand switching surges, impulses caused by lightning, and the reduction of electrical strength caused by contamination of the insulators.

At EHV/UHV levels switching surges determine the insulation design. For ac lines insulation level is generally based on overvoltages of 2.5 p.u. of the operating rms value.

3.5 Surge Impedance Loading.

The concept of surge impedance loading (SIL) is a convenient way of comparing the approximate load carrying capability of different voltage levels. Eqn. 3.7 gives the surge impedance load that the line would carry to if each phase is terminated in a surge impedance $Z_o = \sqrt{L/C}$.

$$\mathrm{SIL} = \frac{V^2 \ (\mathrm{kV})}{Z_o \ (\mathrm{ohm})} \quad \text{, in MW} \tag{3.7}$$

Fig. 3.1 shows line capability in terms of SIL. The curve in the figure represents per unit surge impedance loading of uncompensated ac lines as a function of line length. As shown, the line loading in SIL decreases with the increase in line length.

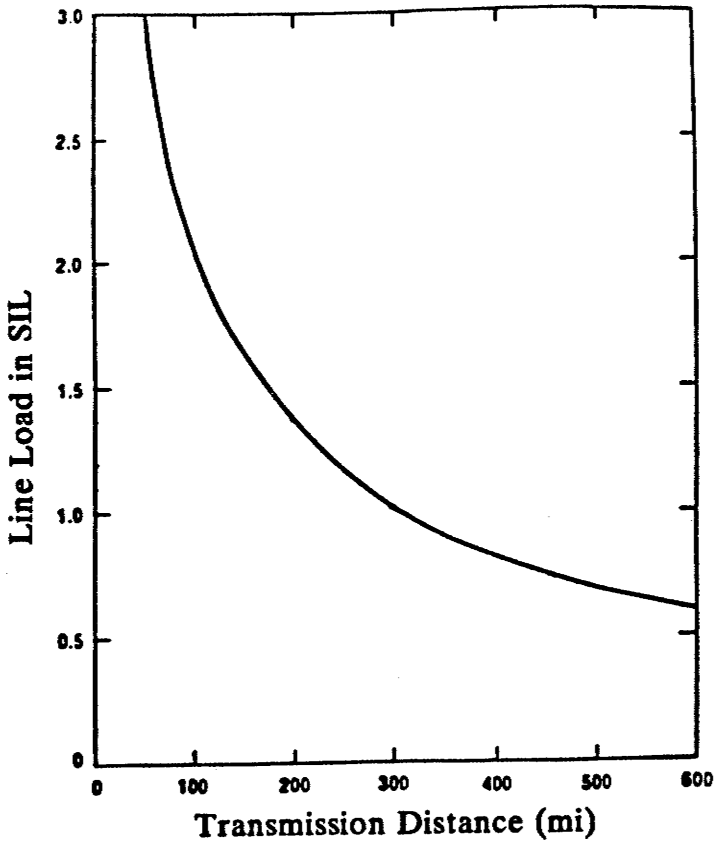


Fig. 3.1 Line Capability in Terms of Surge Impedance Loading

The curve in Fig. 3.2 shows the line loadability and also three regions of concern with an ac line.

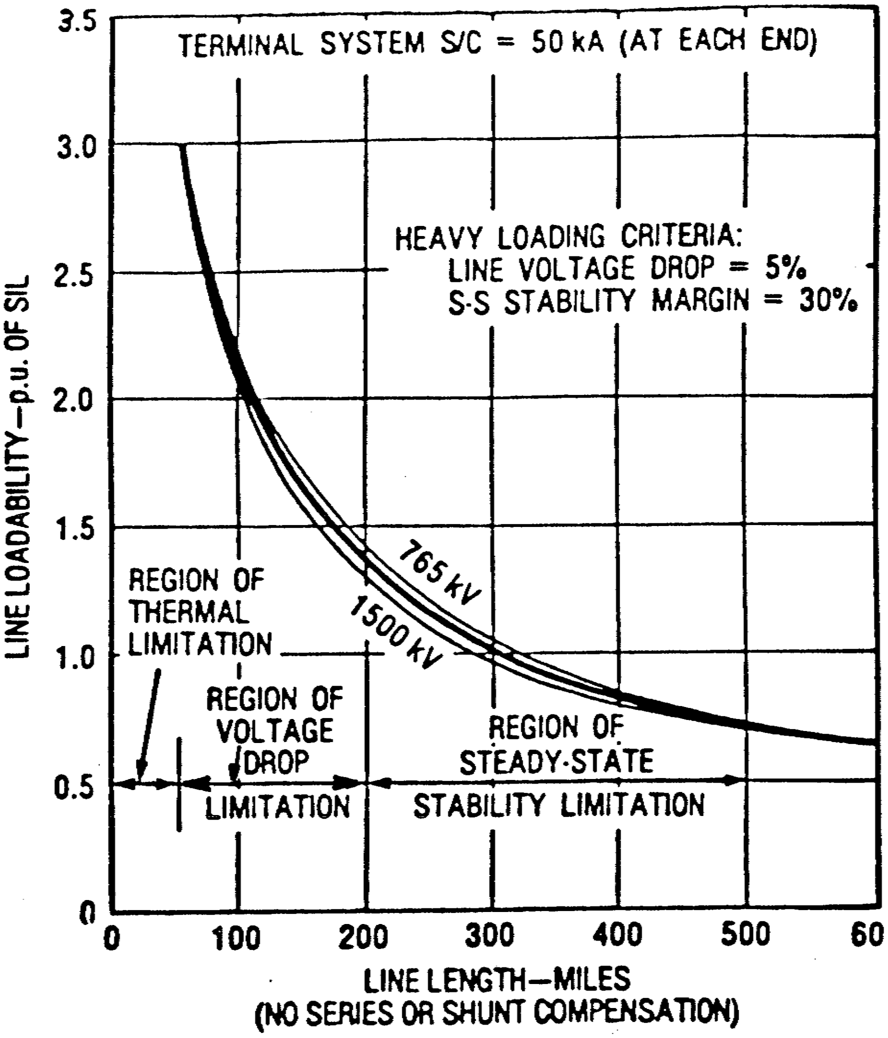


Fig. 3.2 Line Loading and Three Regions of Concern

Therefore, as shown in Fig. 3.3, an ac line needs series compensation and shunt compensation and is sectionalized in order to achieve an acceptable voltage profile along the whole length of line independent of load variations.

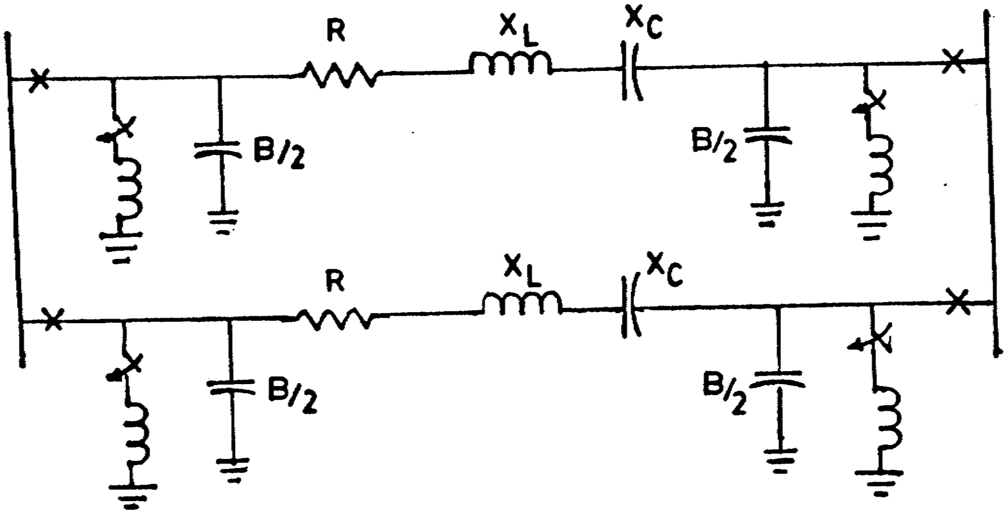


Fig. 3.3 Typical Series and Shunt Compensated Line Section

3.6 Stability Considerations.

An ac system is designed so that all the generators remain in synchronism under steady state and transient conditions Eqn. 3.8 gives the power which can be transferred over an ac transmission line.

$$P_{transfer} = \frac{V_S V_R}{X_L} \sin \delta^{\circ} \qquad (3.8)$$

The ac transmission system must be able to withstand without loss of stability the sudden changes in generation, load , and faults. All of these produce transients on the system voltage and power angle. And the transient stability criteria limits the line loading below steady state stability limit which results in operation at $\delta = 30°$.

The stability of an ac system can be improved by various methods as listed below :

1. Excitation system control.
2. Fast governor control.
3. Use of braking resistors with generators.
4. Additional ac transmission lines.
5. Series compensators.
6. Higher voltage lines or overlays.

The first three methods are relatively low cost and the last three methods are more expensive. All these methods result in synchronous solutions.

3.7 Subsynchronous Resonance.

Subsynchronous oscillations occur in ac systems operating with long, highly compensated transmission lines. This is an electrical power system condition where the electrical network exchanges energy with a turbine-generator at one or more frequencies below the synchronous frequency of the system. Subsynchronous resonance was found to be the reason for the shaft damage of the Mohave Plant generator in California [43] .

Chapter IV

Design of HVDC Transmission.

Since the change in HVDC converter technology in the 1970's, when mercury arc valves were replaced by series strings of high power thyristors in all new schemes, the rate of progress has been rapid. Over the last 17 years, the surface area of the silicon slices has increased by 20 times, from 380 mm^2 to 785 mm^2 [27]. This has resulted in the increase of current carrying capability of thyristors and currents as high as 4000 A can easily be handled without parallel connection of thyristors.

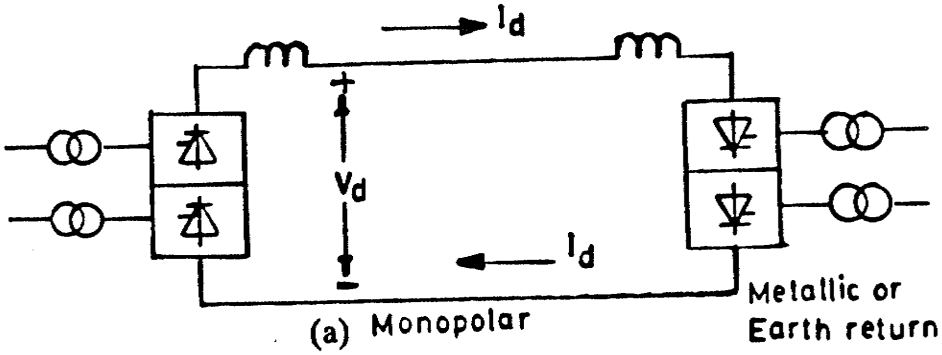
The design of HVDC valves is optimized for each scheme in terms of technical and economic performance. In order to take full advantage of the rapid progress in semiconductor device technology, it is unlikely that thyristor types can be standardized for any substantial period of time.

The design of a HVDC system requires coordinating performance characteristics of a great number of components.

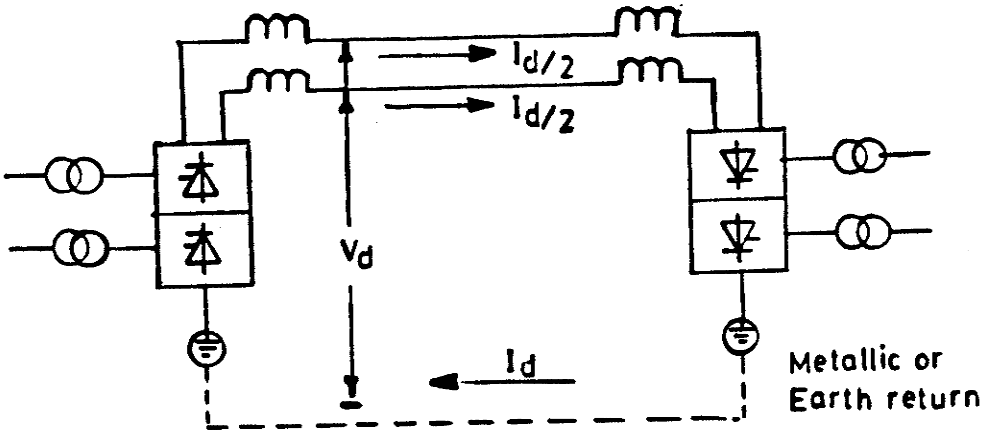
4.1 Kinds of Transmission

There are three kinds of dc transmission links as shown in Fig.4.1.

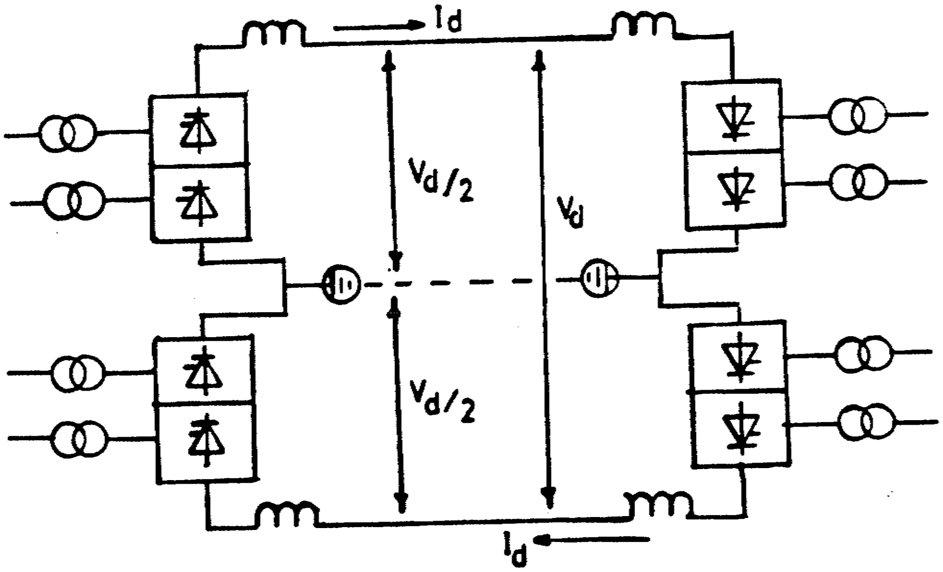
a) Homopolar
b) Monopolar
c) Bipolar



(a) Monopolar



(b) Homopolar



(c) Bipolar

Fig. 4.1 Kinds of DC Links

4.1.1 Homopolar Link

This link has two conductors, single or double, operating at the same polarity (usually negative) and uses earth as return. This mode of transmission has following characteristics :

- i) It uses earth as return
- ii) High reliability
- iii) Low corona power losses and low radio interference

4.1.2 Monopolar Link

This scheme has two modes of transmission.

- a) Monopolar with earth return - This scheme uses only one conductor at a high voltage and the earth return.
- b) Two conductor monopolar - In this case metallic return is used. In this mode of transmission problem of subsurface corrosion of other utilities, such as gas pipes etc., is eliminated.

4.1.3 Bipolar Link

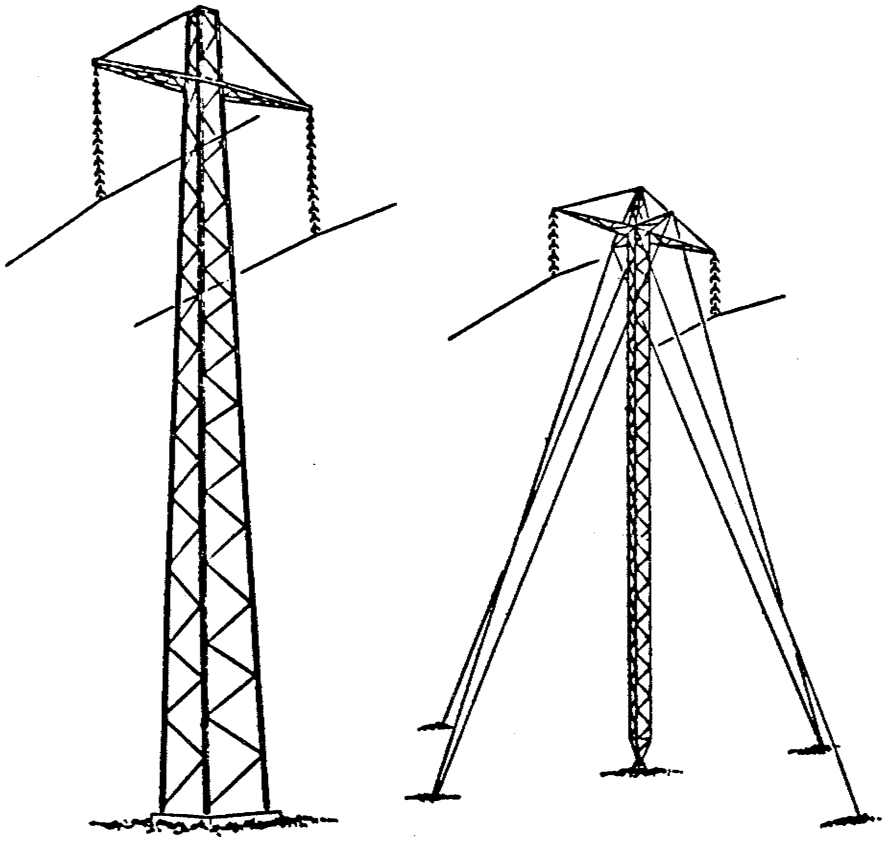
This kind of transmission is mostly used in HVDC schemes and it has two poles at positive and negative polarities respectively. From a reliability point of view, it is considered equivalent to that of an ac double circuit.

A bipolar link can operate in monopolar mode if one of the poles fails. In such an event the healthy pole can transmit 50% of rated power or even more depending on pole capability.

Bipolar 12 pulse mode operation eliminates 5 th, 7 th, 17 th, 19 th,... order current harmonics on the ac side and 6 th, 18 th, 30 th,... order harmonics on the dc side.

4.1.3.1 DC Transmission Towers

The transmission towers required for dc are simple in construction. Mostly self supporting tangent tower and guyed tangent towers are used as is shown in Fig. 4.2.



(a) Self Supporting Tangent Tower (b) Guyed Tangent Tower

Fig. 4.2 DC Overhead Line Towers

4.2 Characteristics of DC Link.

In a HVDC link the inverter is generally operated at constant current control and the inverter is operated at constant extinction angle control. The control and V-I characteristics of a dc link [4] is shown in the Fig. 4.3.

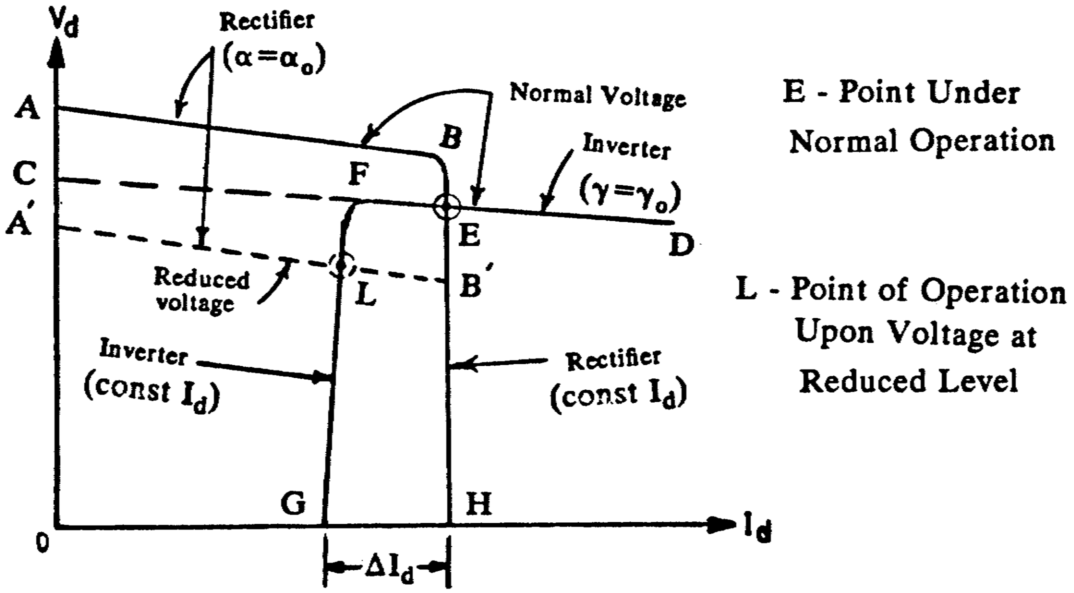


Fig. 4.3 Actual Characteristics of Control Scheme

The rectifier voltage at the end of dc transmission line is given by the Eqns. 4.1 and 4.2

$$V_d = V_o \cos\alpha - I_d \left(\frac{3\,\omega\,L_1}{\pi} + R\right) \tag{4.1}$$

$$V_d = \frac{V_o}{2}\left[\cos\alpha + \cos(\alpha + \mu)\right] \tag{4.2}$$

Whereas for the inverter the voltage is given by the following Eqns. 4.3 and 4.4

$$V_d = V_o \cos\gamma - \frac{3\omega L}{\pi} I_d \tag{4.3}$$

$$V_d = \frac{V_o}{2}\left(\cos\gamma + \cos\beta\right) \tag{4.4}$$

4.3 Choice of Voltage of Transmission

In a dc link, the transmission line voltage can be chosen freely to meet the economical optimum of the dc transmission system. For a given rated power to be transmitted, the optimum line voltage must be calculated mainly considering converter station costs, line costs, and total loss costs. The calculations follow the same rules as for an ac lines, but limitations set by corona phenomenon for ac lines are much less pronounced for dc lines.

Any desired transmission voltage can be realized by connecting the required number of thyristors in series to best meet the individual project requirements.

It is practical to study cost relations for the line and the terminals separately and thereafter to make a total optimization, considering transmission distance and other factors which may be of importance, for instance, environmental requirements.

In some earlier designs parallel connection of thyristors had to be used to meet the current requirements. However, with the thyristors available today, having a silicon wafer up to 100 mm dia, the current capability of each thyristor is so high that a rated converter current of about 4000 A can easily be handled without parallel connection of thyristors.

4.3.1 DC Line Costs

The dc line cost varies [33] according to Fig. 4.4, where each voltage level corresponds to a specified creepage distance and flashover clearance.

For a dc voltage, below 400 kV, the voltage level has only minor influence on the costs, but for higher voltages the cost increases rapidly owing to the nonlinear withstand characteristics for switching surges.

From these curves, line costs for a given rated load and including capitalized loss costs are calculated according to Fig. 4.5 [33].

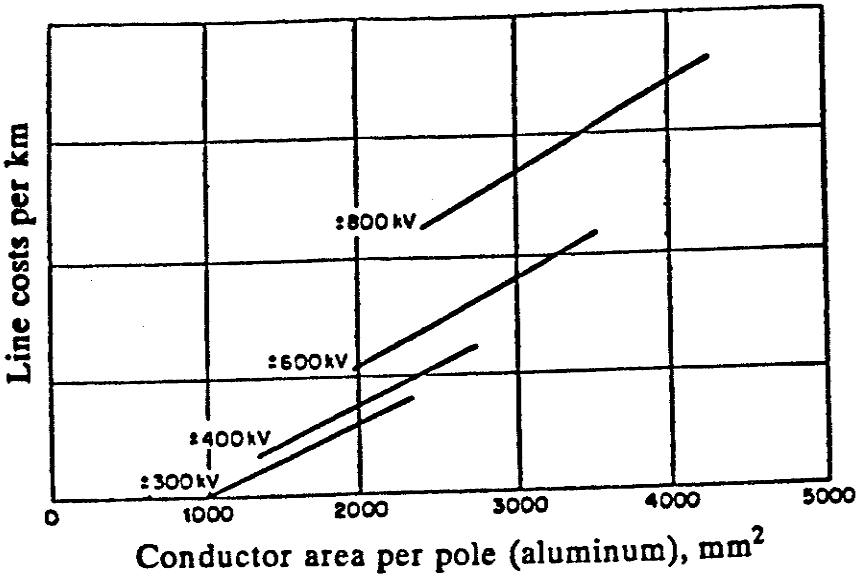


Fig. 4.4 HVDC Line Cost as a Function of Conductor Cross–Section for Different System Voltage Levels

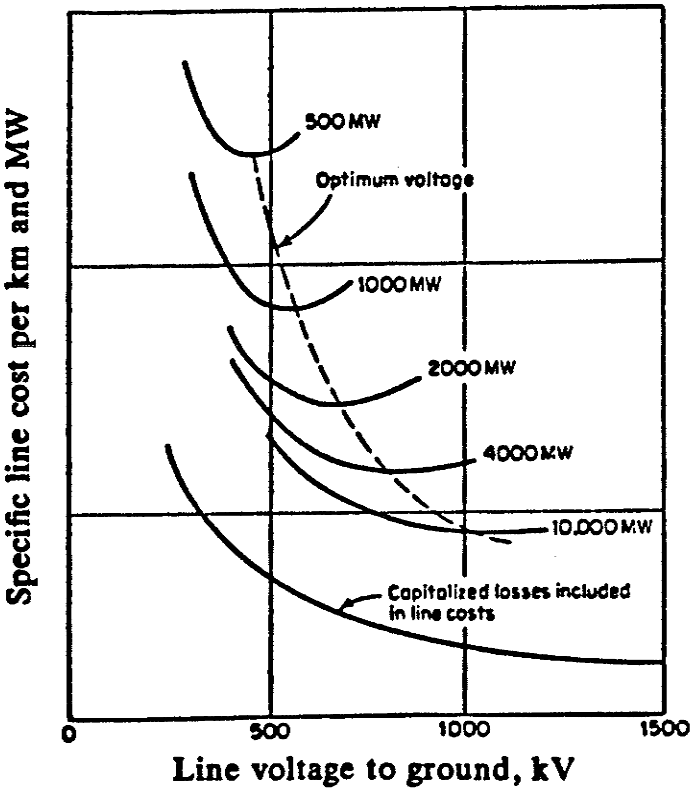


Fig. 4.5 Bipolar HVDC Line Costs for Different Rating

The lowest curve in Fig. 4.5 gives the capitalized loss cost separately, which in fact is the same for all curves and is included in the total cost curve. The optimum voltage curve indicates the highest voltage which should be considered. In practice a value of about 75 to 85% of the optimum voltage will be found reasonable considering line length, station-voltage dependent costs, load utilization of the line, etc.

4.4 Conductor Selection

The choice of conductor for HVDC transmission lines depends to a large extent on I^2R losses and corona and field effect considerations. The dc corona effects are less pronounced as compared to ac.

4.5 Environmental Impact

Environmental impact which mainly comprises corona, electric field and ion effects is an important consideration in HVDC transmission line design. For transmission voltages higher than about ± 300 kV, corona considerations make it necessary to use multiple conductor bundles. The choice of the actual number and size of conductors in the bundle is based on economic as well as environmental considerations.

In fair weather, the electric fields and ion currents vary with the season from a minimum value during the winter to a maximum value near the end of September [52].

The highest level of electric field and ion current occur during frost conditions followed by rain, fog, fair weather during spring to fall (insect season), snow, andfair weather during the winter.

4.5.1 Corona Loss

Direct current transmission lines usually exhibit a much smaller change in corona loss than comparable ac lines in the transmission from fair to rain weather. Typically, dc losses may increase by 10 to 1 while ac losses may increase by 50 to 1 [11]. Thus from economic considerations the dc line is designed for fair weather corona losses. The corona loss is mainly dependent on pole spacing [52].

The average annual corona losses can be calculated if the corona loss characteristics and the weather conditions during an average year are known. This is illustrated in Table 4.1.

Table 4.1 Comparison for Corona Losses ±400 kV & 500 kV AC

Corona Losses, kw/km		
Item	±400 kV DC	**500 kV AC**
Average Losses in Fair Weather	1.3	1.3
Minimum Losses in Fair Weather	0.6	0.1
Maximum Losses in Short Section Under Worst Weather Conditions	10	130
Maximum Losses for the Whole Line Under the Worst Worst Weather Conditions	6	20
Annual Mean Losses for the Whole Line	2.3	5.6

As shown in the table, both the annual mean losses and the maximum losses are considerably lower for dc than for ac.

For bipolar lines corona loss current can be predicted by using the Annberg Eqn. 4.5 given below and described in Appendix 2.

$$I_C = K_C\,(K+1)\,n\,r\,2^{0.25\,(g_{max} - g_o)}\;10^{-3}\ \text{Amp/km} \qquad (4.5)$$

4.5.2 Radio Interference

Radio interference from corona on the conductors is considerably less with negative voltage than with positive. For bipolar dc line the radio interference should be the same as as for a similar monopolar line, as only the positive conductor will significantly contribute to the radiation. The existence of two poles with opposite polarity will increase the nominal electric field strength, however causing a raise of the radio interference by a few decibles, depending upon the distance between the poles [33].

In bipolar operation, the positive polarity is the principle source of radio interference. The radio interference produced by negative conductor is approximately one half (-6 db) that from the positive conductor [45].

The radio interference levels are decreased by rain, wet snow, and other atmospheric conditions which thoroughly wet the conductor. However, RI may increase slightly during the initial conductor-wetting period. Thus dc lines are designed for fair weather RI.

The acceptable signal to noise ratio (SNR) for fair weather RI from dc lines is lower than that from ac lines. The subjective evaluation indicates a dc radio interference tolerance level SNR of about 10:1 whereas for ac transmission lines, the SNR for acceptable reception is variously reported as 15:1 to 25:1 [11]. Thus the dc line has a lower nuisance value than ac line noise.

For ac the radio interference during rain is higher than for the fair weather value. This increase is dependent on both the rain intensity and the conductor surface voltage gradient. For dc just the opposite occurs as as illustrated by Fig. 4.6 [33]. This reduction is also present during snow. Wind, in most cases, increases the interference level, but in a very irregular manner.

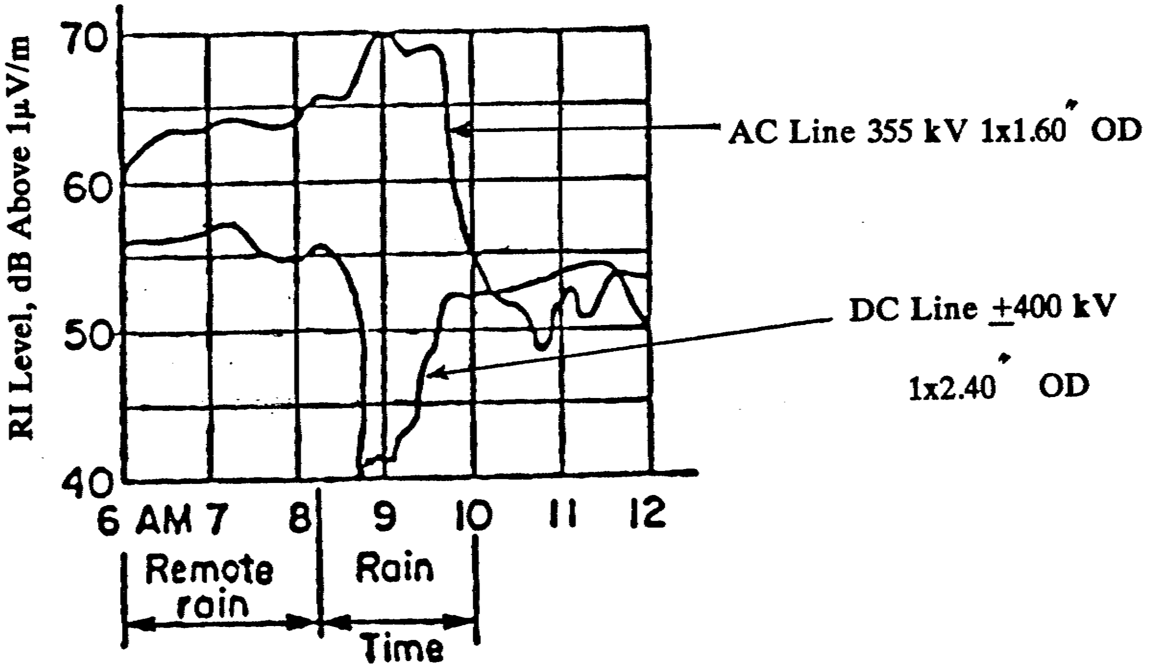


Fig. 4.6 Comparison of Radio Interference of Bipolar DC and AC Line

4.5.2.1 Influence of Conductor Bundling on RI

For ac lines, the use of bundled conductors with the same cross-sectional area as the single conductor can reduce the radio-interference. This is because the interference strongly depends on the electric field strength at the conductor surface, which is reduced for a bundled conductor.

In case of dc lines, the presence of surface charge around the conductor will counterbalance the effect of an increasd number of bundle conductors. Although an increased number of bundle conductors for a constant total cros-sectional area will slightly decrease the radio-interference also for dc lines. Radio interference considerations should normally not be decisive for the choice of number of bundle conductors.

4.5.3 Television Interference.

Television interference (TVI) associated with dc transmission lines is attributable to hardware noise, sparking on insulators, corona discharges on metallic fittings and ionic current. The noise level in the television frequency range, that is, above 50 MHz is dominated by the insulator corona. In this case, the interference during fair weather conditions is very small but increases during bad weather conditions. Generally, the noise level in this frequency range is very low and can be ignored in most practical cases.

Subjective tests for acceptable black and white reception close to the dc test line showed a minimum SNR requirement of 60:1 as compared with the generally accepted standard of 100:1.

TVI was found to be of little concern at distances greater than 25 meter from the right-of-way center-line [11].

4.5.4 Audible Noise

The positive polarity conductor is the primary source of dc transmission line audible noise [11].

Rain causes a very slight reduction of dc line audible noise. Noise levels during snow are not noticeably different than during fair weather.

DC line audible noise is attenuated approximately 2.6 db(A) for each doubling of the radial distance from positive conductor [11].

The acceptable noise level for dc line is in the range 45-50 db(A) [50].

4.6 DC Terminal Station

A dc terminal station consists of converters acting as rectifiers at the sending end and as inverters at the receiving end of the transmission. Normally 12-pulse converters are used to eliminate 6th order voltage harmonic on the dc side and 5th & 7th order current harmonics on the ac side. Fig. 4.7 shows a typical bipolar system [33].

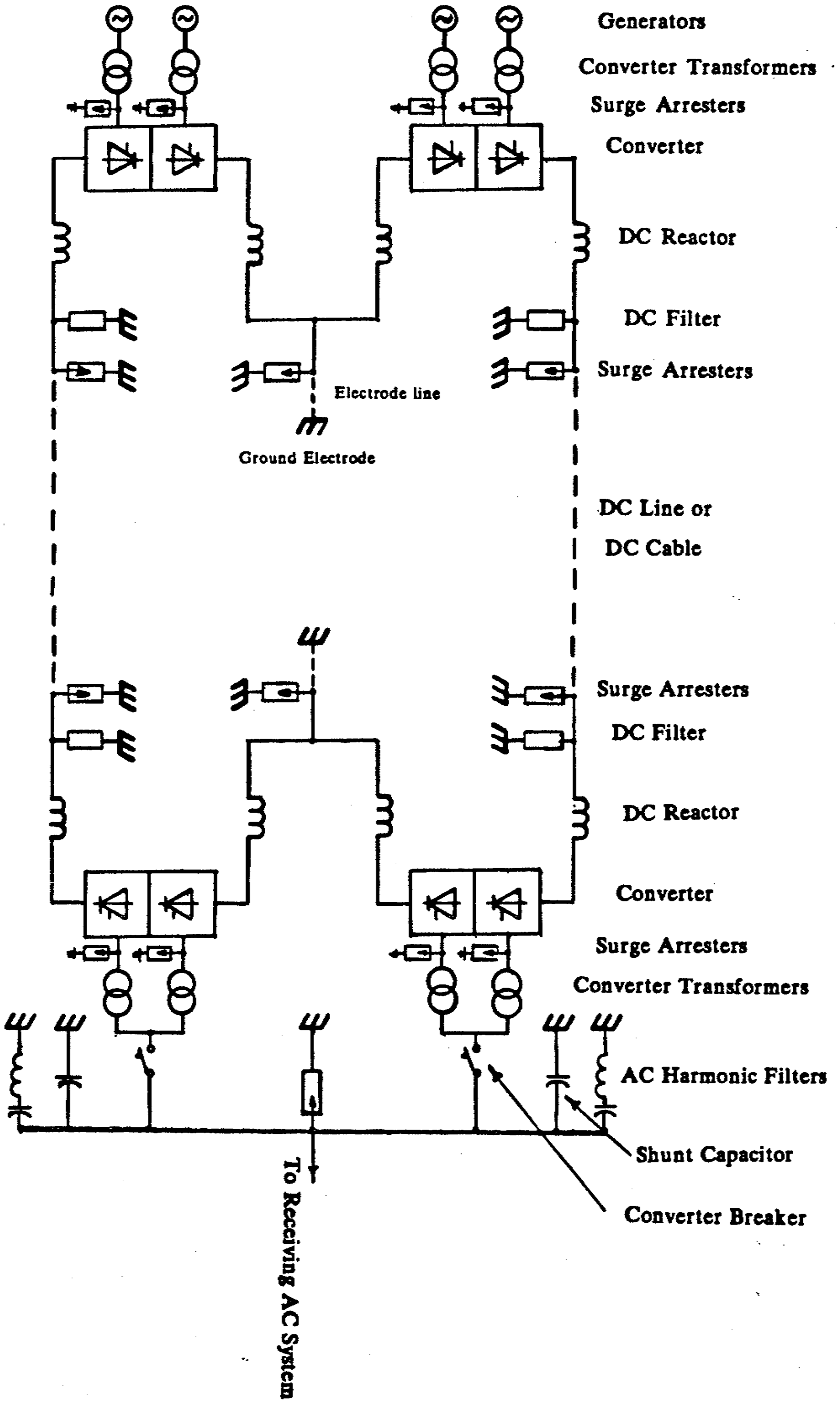


Figure 4.7 A Typical Bipolar HVDC System using Unit–Connection method

4.6.1 DC Converter Terminal Cost

The specific converter terminal cost curve [33] given in Fig. 4.8 is referred to bipolar converter station with one 12-pulse converter per pole.

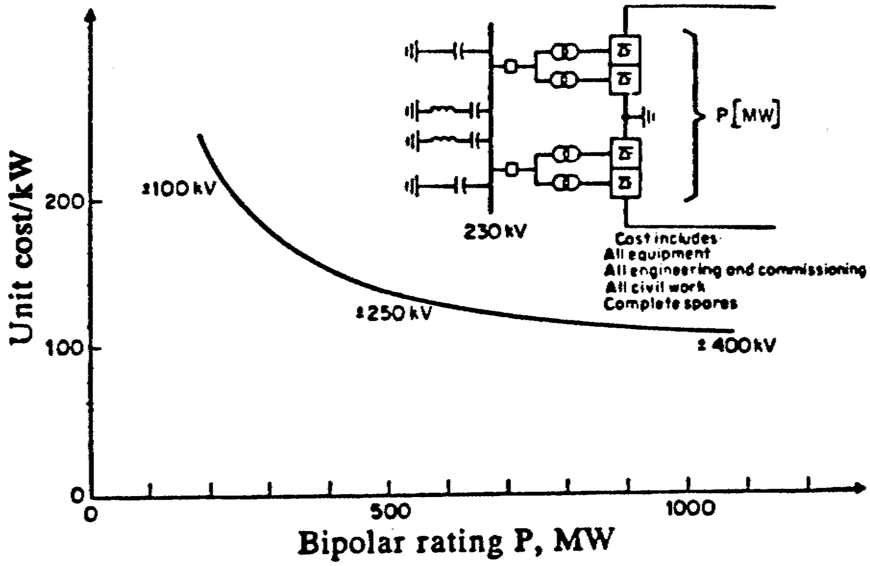


Fig. 4.8 Specific Converter Station Cost vs Bipolar Rating

As the converter itself makes up the largest portion of the terminal equipment, the specific cost is mainly dependent on the size of the converter.

The influence of the ac voltage in the connected network on the cost of the dc terminal station is shown in Table 4.2 [33].

Table 4.2 Influence of AC Voltage on HVDC Terminal Cost.

AC Network Voltage (kV)	Relative Converter Terminal Cost.
130	98%
230	100%
400	103%

4.7 Insulation Coordination

Just as in case of ac, the aim of HVDC insulation coordination is to establish the required electric strength of the various components of the transmission system on the basis of overvoltage stresses and overvoltage protection. But there are some fundamental differences between ac and dc insulation coordination. An ac system consists of parallel connected circuits and the requirement is to establish the insulation levels phase to earth and phase to phase. Throughout the system these levels are of a comparable order.

HVDC converter stations on the other hand consist of series connected bridges, each bridge requiring different insulation strengths and within each bridge the electric strength is different for the various components such as transformers, valves etc.

Overvoltages on the ac side may originate from lightning, switching faults and load rejection. For converters the overvoltages may originate from either ac system or the dc line and/or cable, or from in-station flashovers.

4.7.1 Overvoltages

Basically, the overvoltages, can be categorized as :

1. Those which originate from within the converter terminal.
2. Those which originate from outside.

The the externally generated overvoltages can be grouped as to whether they are impressed on the terminal from the ac network or from the dc line.

4.7.1.1 External Overvoltages

If a flashover occurs on a dc line, sustained outage can be prevented by de-energizing the dc line and re-energizing it after some hundred milliseconds. The control system permits re-energizing at a somewhat reduced voltage thus minimizing the re-occurrence of pollution flashover.

Also, there is a smoothing reactor between the line terminal and the converter station, slowing down any steep-fronted surges.

Overvoltages entering from the ac system are :

i) Overvoltages from load rejection and generator overspeed.

ii) Switching surges originating on the ac system including effects of ground faults and transmitted through the converter transformers.

iii) Lightning surges.

Overvoltages on the ac side of the converter transformers may be transferred to the dc side. The temporary overvoltages of fundamental and harmonic frequencies require particular attention. Due to the large capacitor banks required for reactive compensation and harmonic filtering, substantial power frequency overvoltages can arise on load rejection.

The temporary overvoltages appear on both sides of the converter transformers and the surge diverters on the valve side.

Overvoltages entering from the dc line are from :

i) Lightning surges
ii) DC line faults
iii) Malfunction in controls of the other terminals
iv) Persistent misfire or arc-through in inverter valve
v) Load rejection

These types of overvoltages are caused by disturbances in the functioning of the valves, fault in the converter station or on the dc line.

4.7.1.2 Internal Overvoltages

Both in normal operation and also under abnormal conditions, a large variety of direct voltages, together with alternating and/or transient voltages may arise on the various components of a dc transmission scheme.

Due to series connection of converter bridges, the dc transmission line is subjected to the sum of voltages arising on the cascaded bridges.

Overvoltages are generated in the converter station from :

i) Ground faults within the station
ii) Arrestor operation

4.7.2 Protection of Converter Station

Extensive use is made of gapless zinc oxide (ZnO) arresters to protect the converter stations. The use of zinc oxide surge arresters results in more consistent protective levels than was possible with prior technology. The starting point is to protect the thyristor valves against excessive overvoltages and further surge arresters provide protection for all the major components of the converter station representing a large variety of protective levels.

4.7.3 Insulation Level of DC Transmission Line

The insulation of a transmission line involves the following basic considerations :

i) Ability to withstand the operating voltage under abnormal weather conditions.

ii) Ability to withstand transient overvoltages arising from faults and switching operations.

iii) The insulation should be such as to reduce the likelihood of outage due to lightning strokes to an acceptable figure.

The dc transmission lines are designed for an overvoltage factor of 1.7 p.u. [16].

4.7.4 Overvoltage Protection System

The overvoltage protection system depends upon the configuration of the HVDC station and the HVDC transmission line. For a two-terminal bipolar HVDC scheme with overhead lines and with two 12-pulse converters connected in series in each pole, a possible arrester scheme is shown in Fig.4.9 [49].

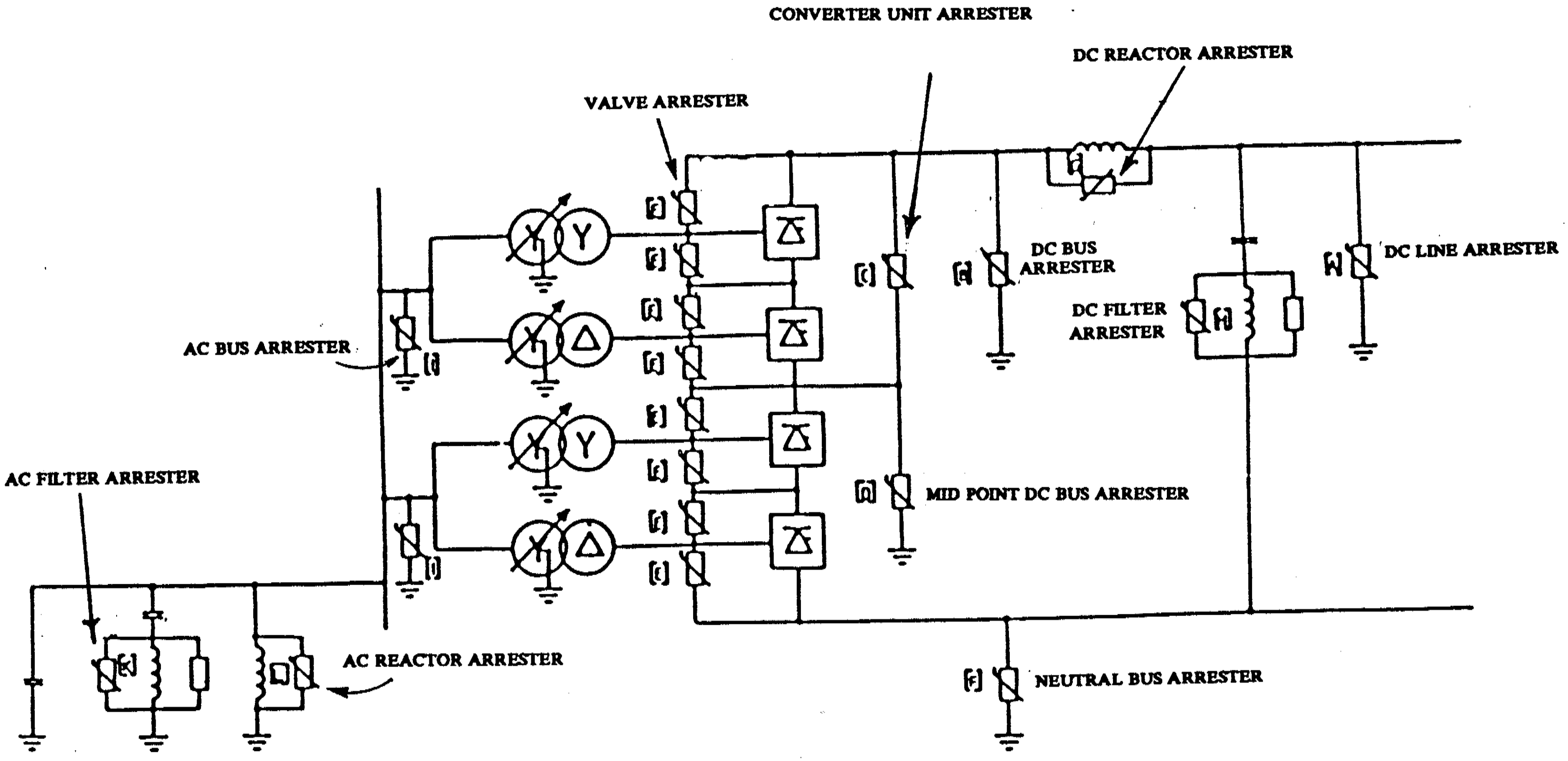


Fig. 4.9 Typical Arrester Locations in HVDC Converter Station Pole With two Series Connected 12 Pulse Converters

4.8 Electric Field Effects.

The uncertainty of human risk from exposure to high-voltage electric system has become an area of public concern [13]. The corona generated electric field and ion environment in the vicinity of dc transmission is rather difficult to characterize either analytically or experimentally. In recent years increased consideration has been given to a category of harmful health effects for which an objective evaluation appears elusive [13]. In spite of the lack of evidence of harmful effects resulting from transmission line electric fields, the subject has been used in emotional debates over certification of many of transmission lines. A number of studies are underway in order to characterize the electric field and ion environment and possible health hazards [13].

There are basic differences between electric field effects of HVAC and HVDC lines, because :

i) In case of ac fields, current and voltages are generated by the capacitive coupling through air between line and objects, whereas in dc fields currents and voltages are caused by ionic conduction through the air.

ii) The ions produced by corona on line conductors remain constrained close to the conductors when the voltage is alternating, while they flow from conductors to ground or to the conductors of the opposite polarity if direct voltages are applied to the conductors.

Fig. 4.10 shows both the electric field at ground calculated for the case of a 765 kv ac line and the ion current density at ground measured at Project UHV for a ±600 kv dc line.

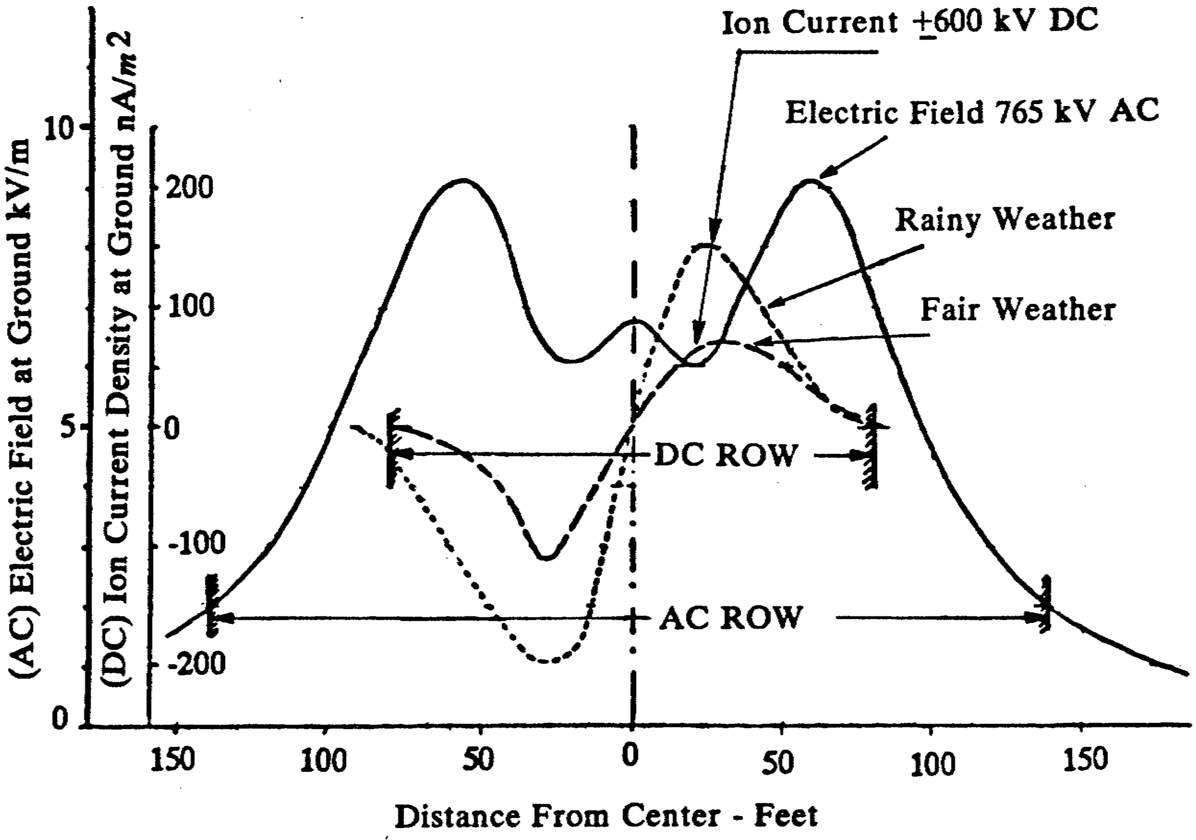


Fig. 4.10 Electric Field for 765 kV AC and Ion Density for ±600 kV DC Line in Fair and Foul Weather

DC ROW = 280 ft (85 m)

AC ROW = 160 ft (49 m)

The existence of ion currents under the lines is a distinguishing feature of dc transmission. However, the magnitudes of shock currents which may be produced under dc lines are much lower than those in the ac case, while at the same time corresponding perception and let-go currents are much higher for dc than ac.

Although further research needs to be done to establish precise criteria for electric fields and ion currents produced under dc lines, they do not constitute a serious problem in the design of dc transmission lines [14].

4.9 Biological Effects.

Further research needs to be done in order to show threshold levels below which health risk is determined to be within acceptable limits. Specific needs in this area include :

i) Identification of biological effects.

ii) Determination of the applicability of the biological effects identified to humans and development of a methodology to analyze human risk.

4.10 Harmonics and Filters

Converters generate harmonic voltages and currents on both ac and dc sides. A converter of pulse number P generates harmonics on dc and ac sides given by Eqns. 4.7 and 4.8 respectively.

$$h = pq \tag{4.7}$$

$$h = pq \pm 1 \tag{4.8}$$

Most HVDC converters have pulse number 6 or 12 and thus produce harmonics of the order given in Table 4.3.

Table 4.3 Order of Characteristic Harmonics.

Pulse no. p	DC side pq	AC side pq ±1
6	0,6,12,...	1,5,7,...
12	0,12,24,...	1,11,13...

The amplitude of the harmonics decreases with increasing order. Unless measures are taken to limit the amplitude of the harmonics entering the ac network and dc line, some of the following effects may occur :

1. Overheating of capacitors and generators.
2. Instability of the converter control.
3. Interference with telecommunication systems, especially noise on telephone lines.
4. Corrosion of subsurface service pipes.

The principle means of diminishing the harmonic output of converters are:

a) Increase of the pulse number.
b) Installation of filters.

Most of the HVDC schemes use 12 pulse valve groups which eliminate harmonics of order 6 th, 18 th, 30 th,... on the dc side and of order 5 th, 7 th, 17 th, 19 th,... on the ac side.

Chapter V

Comparison of Technical Aspects.

The differences in the transmission characteristics of the ac and dc transmission are based on the fact that in steady state with ac the inductances and capacitances of the lines have an effect, while with dc this is not so. Also there are differences in the control characteristics. The asynchronous nature of the dc link helps in the improvement of ac system stability. Faster dc controls facilitate scheduled power flow , power modulation, system assistance during disturbances in electrical network and many other performance benefits.

5.1 Stability Considerations

An ac transmission line, as opposed to a dc line, is a synchronous tie between two points, tying together two networks containing rotating machinery . Disturbances in one system will affect the other system too.

Therefore, requirement for ac transmission is that stable operation be maintained under normal and fault conditions. This problem can be explained by studying the well known equation

$$P = \frac{V_1 V_2}{X} \operatorname{Sin} \delta^{\circ} \qquad (5.1)$$

The power transfer capability depends on power angle δ, reactance X and the voltage. The power angle is maintained at about 30° due to transient stability considerations

In order to improve the stabilizing capacity of an ac line it is necessary to reduce the line reactance or else choose a higher transmission voltage. The line reactance can be reduced in either of the two ways :

1. Compensation with series capacitor within practical limits.
2. Paralleling of two or more lines.

Whereas with dc, there is no concern for frequency or phase angle of the interconnected system, as it is an asynchronous link. No stability problems will arise in case of dc link and the ac systems can be operated independently without regard to their relative phase, frequency or voltage. The power transferred over a dc link can be changed very fast by dc controls. This feature can provide system support during disturbances in ac systems.

5.2 Short Circuit Capacity Level.

Interconnections of systems by ac transmission results in increase of short circuit currents, which may exceed the capability of existing circuit breakers or cause unacceptable high electrical and mechanical stresses on the system equipment.

In case of dc link, as no transmission of reactive power occurs via the dc link, there is no contribution to the short-circuit level of the interconnected systems and the existing switchgear can remain in service.

5.3 Length of Transmission.

There is no technical limit to the length of transmission in case of ac, but series and shunt compensation is used in order to increase the line capability and for acceptable voltage profile. Also the line is sectionalized to locate the compensation equipment and improve stability, reliability and performance.

In case of dc, there is no limit to length of transmission due to absence of line reactance and there is no reactive power flow in the line. The reactive power flow is confined to the converters. Thus dc line is simple in design and there is no need for intermediate stations.

5.4 Reactive Power Management

On long ac lines and cables the production and absorption of vars is a serious problem. The reactive power characteristic of long overhead ac lines is capacitive for loads below the surge impedance level [44] as shown in Fig. 5.1. This necessitates shunt compensation by reactors for no load and light loading condition. For heavy loading condition series capacitors are required.

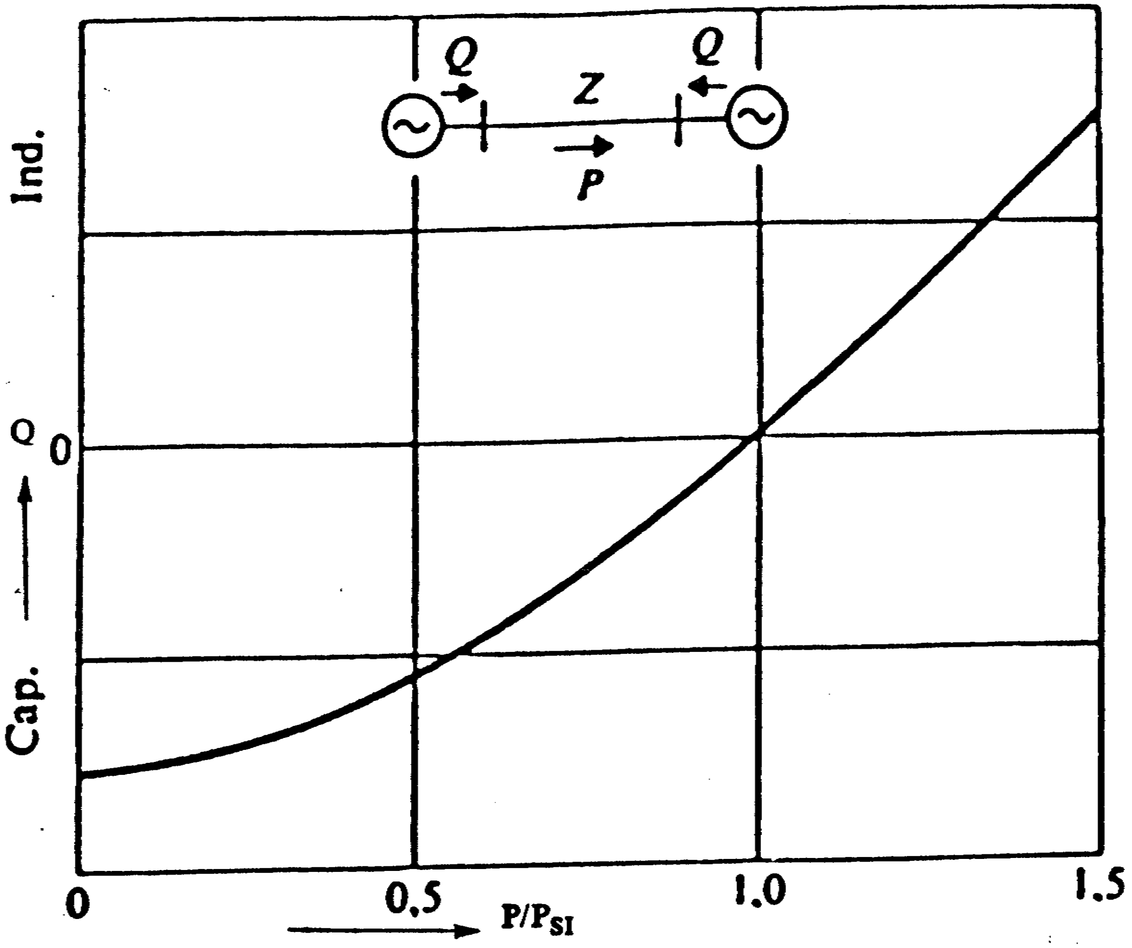


Fig. 5.1 Reactive Power Characteristics of an AC Line

P_{SI} = Surge-impedance load

DC transmission lines do not require reactive power. Converter terminals absorb vars from the ac system. The var requirement is 60 % of the transmitted dc power and is independent of line length.

Although both ac and dc transmission systems require reactive power, it is worth noting that ac lines require more reactive power above the length of 250 miles as shown in Table 5.1 [4].

Table 5.1

Ratio of Reactive Power Transmitted at Rated Load as a Function of Line Length

Line Length Miles	HVDC Transmission	345kV 500 MW	765 kV 2000 MW
250	1.15	1.2	1.1
400	1.15	1.9	1.8
600	1.15	2.9	2.75

In ac cables the vars produced by charging the shunt capacitance greatly exceeds that consumed by the series inductance. In 20-25 miles of ac cable the charging current equals the rated current, and, even if supplied from ends, severely limits load carrying capacity.

DC cables do not encounter this problem and therefore become increasingly attractive to transmit power beyond 20 miles [14] .

5.5 Reduced Voltage Operation

A unique characteristic of HVDC transmission system can be a major factor in maintaining service continuity. If line insulation is partially damaged as a result of a lightning stroke or other incident, the pole with the damaged insulation can be returned to service with reduced voltage.

Reduced voltage operation can be achieved in steps by turning off discrete 12 pulse converter groups in a series connected system or by continuously lowering the dc voltage by firing angle control.

In an ac system such a voltage reduction is not possible and therefore insulation if damaged the entire ac circuit must be removed from service.

5.6 Flexibility of Controls

The flexibility of control systems associated with HVDC transmission presents a large number of possible solutions to power interchange control.

The control modes can be categorized in two major areas :

1. Controls independent of ac system variation.
2. Controls responsive to ac system conditions.

5.6.1 Controls Independent of AC System Variation

In this case the objective is to deliver constant power to the receiving terminal even in the presence of small disturbances with related phase shifts and ac voltage variations. This classical mode of operation utilizes the unique characteristics of the HVDC control system which allows the most efficient generating units to be used for base loading.

5.6.2 Controls Responsive to AC System Condition

The controls responsive to ac system condition deserve much deeper investigation. The closed loop control system of HVDC transmission can suitably respond to various ac system conditions and modulate the transfer of dc power in such a way that it will enhance dynamic stability with a substantial increase in power transfer limits on coordinated parallel ac and dc transmission systems [41].

Thus the performance of the connected ac system can be enhanced by controlling the dc power flow to changes in various parameters of the ac system such as frequency of the system , voltage and phase angle at a given bus. This technique has been successfully employed on Eel River, Nelson River, Square Butte and Pacific Intertie DC Schemes with economic benefits to the systems and improved ac system stability.

5.6.3 Enhancement of Controls

HVDC offers advantage in flexibility of enhancement of controls with ac/dc system changes . Many supplementary controls required with system changes have been added to existing HVDC schemes [41] as system developed over the years.

5.7 Programmable Controllers

In recent years there has been an increased use of microcomputers based programmable systems in HVDC control equipment [47] as shown in Fig. 5.2.

The programmable systems allow easier adaptation to individual project requirements since no hardware needs to be developed. Programmable adjustments can be made for current and future system needs.

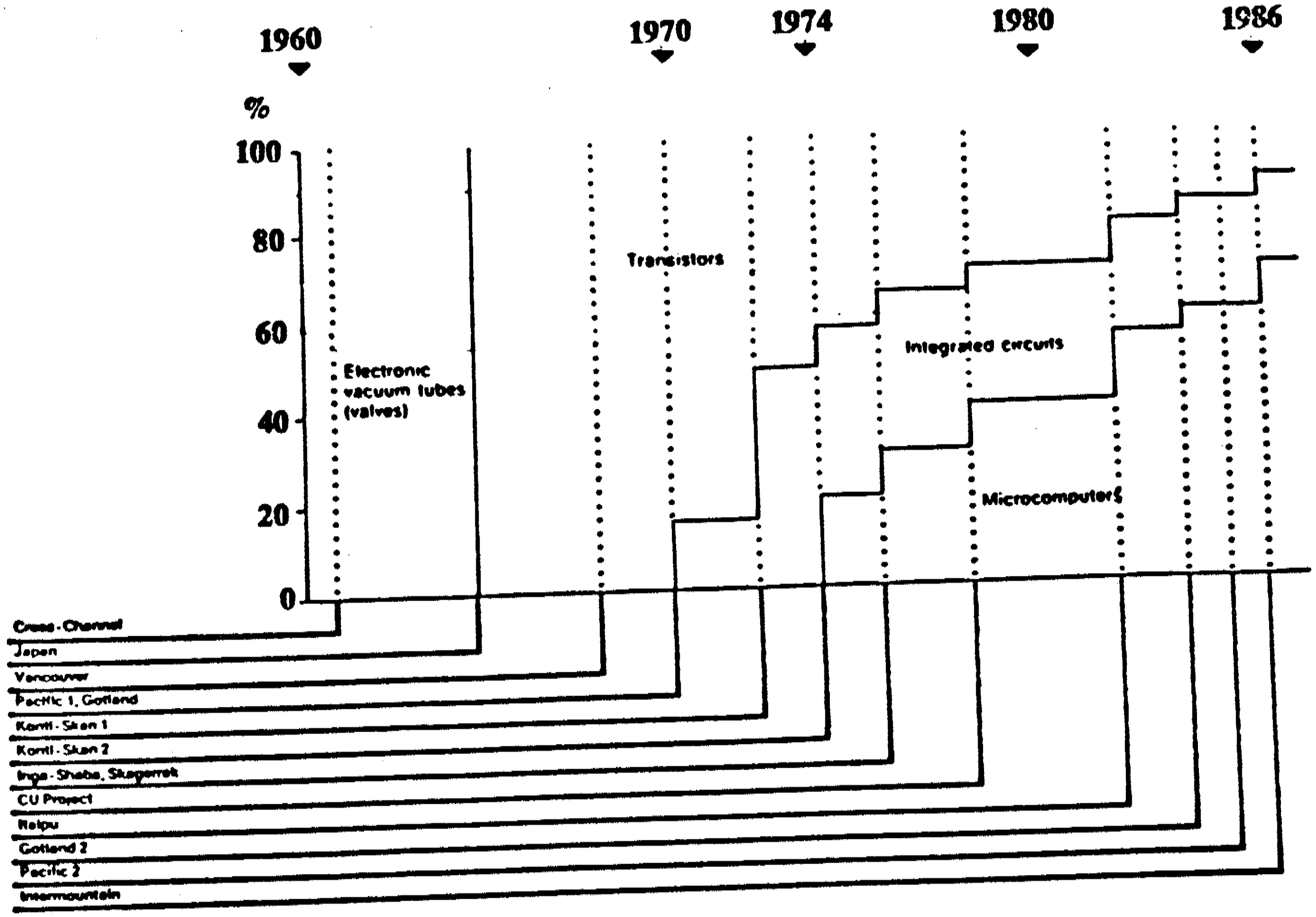


Fig. 5.2 Development of Microcomputer Application in HVDC Controls

The use of programmable systems in the controls has led to increase in reliability through self checking functions and through the introduction of redundancies for critical subsystems. Development of micro-computer based converter control equipment has led to redundant converter control systems with automatic transfer between the systems in case of a control equipment malfunction. This leads to increase in reliability and availability of the converter station. Such type of control is being employed in the Intermountain Project and is expected to become a standard feature in future HVDC projects [26].

Besides reducing the forced outage rate , the control redundancy will permit scheduled preventive maintenance on the stand-by system while the converter is in full operation.

5.8 Overload Capability

One of the drawbacks of the early HVDC transmission using thyristor valves was the limiting inherent overload capacity. This was due to the fact that relatively small thyristors were fully utilized when operated at rated condition.

This is not the case today as thyristors with higher power handling capacity have been developed and employed in recent HVDC schemes [26]. This inherent short time overload capability can be utilized for damping system oscillations and stabilizing parallel lines. The overload capability becomes of significance under load rejection conditions. In case one pole is lost , the other pole immediately and smoothly assumes the rejected load and thereby reduces the stresses on generator- turbine shafts. This is a very important but difficult-to-evaluate performance benefit.

The 1600 MW Intermountain Project converters have been designed for an instantaneous increase from rated load to 200 % load , which is then brought down 150 % with a constant ramp in a couple of minutes, after which the 150 % level may be maintained continuously [18] as shown in Fig. 5.3.

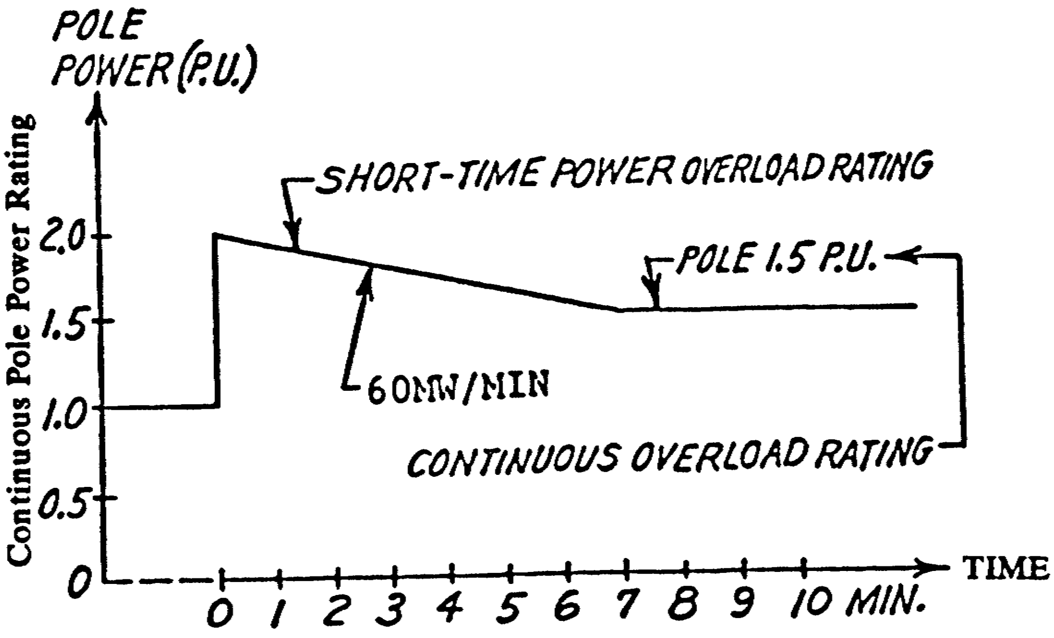


Fig. 5.3 Pole Overload Power Capacity

5.9 Reliability & Availability

According to the CIGRE Statistics [18], five representative HVDC transmission projects built during the 70's showed an average availability due to forced outages of 99.3 % and an average annual outage rate of 20 outages / per pole during the 1977-1981 period. The above figures exclude outages due to overhead lines or cables.

The new projects specify an even higher availability of 99.5% for transmitting 100 % of rated power and forced outages less than 5 [26].

The modular construction of valves and control system contributes to increasing availability. This ensures minimum cost for spares and negligible repair times, as only single modules have to be exchanged.

5.10 Stepped Development

HVDC offers an advantage in stepped or phased development as determined by load growth. This delays the need for capital funds. The converter capacity can be added in steps as required. An example of this feature is the Nelson River Scheme .

In some situations the system requires stepped development and the ultimate system capacity is known. With ac option the capital deferment may not be possible as ac equipment with ultimate full rating are required to be installed in the initial stage.

Chapter VI

Costing of Transmission Schemes.

The costing of high voltage transmission schemes is done on the basis of annual cost or cost per kw/h basis [2] as given by Eqn. 6.1 described in Appendix A5.

$$T = \frac{I\,.\,COST}{8760\,.\,LF\,.\,PR} + \frac{DP\,.\,LE\,.\,CEL}{LF\,.\,PR} \tag{6.1}$$

A common accounting procedure is adopted to capitalize the following factors :

1. Cost of lines and terminals and switchgear equipments including annual charges.
2. Cost of energy losses.
3. Cost of plant to supply the losses, i.e. capacity loss.

The variation in the line and equipment costs influence the total cost of transmission. It should be realized that local conditions prevailing in different countries viz., geography, economy, prices of equipment, technical practice etc. may considerably influence the absolute and comparative costs of ac and dc transmission.

6.1 Costing of EHV/UHV Transmission.

The economic study of high voltage transmission is made on an annual cost basis. The cost consists of the following :

a) Terminal substation cost - which includes the installed cost of transformers and breakers.

b) Transmission line cost.

c) Reactive compensation - The annual cost of receiving end reactive compensation, as well as series and shunt line compensation where required.

d) Losses - The cost of losses consists of the following :

   i) The energy losses cost which consists of line losses, corona losses and equipment joule losses.

   ii) Capacity loss - It is the cost of additional installed capacity required to compensate the energy losses.

6.2 Cost of DC Transmission Scheme.

The dc transmission cost consists of the following :

a) Converter terminal station cost - it is the installed cost of rectifier and inverter terminals, converter transformers, filters, earthing electrodes and smoothing reactors.

b) Installed cost of breakers.

c) Installed cost of dc line.

d) Cost of reactive compensation to provide voltage support at the inverter terminal.

The annual cost for dc transmission at a given voltage, in dollars per kw received will vary with circuit loading. As the circuit loading is increased, the annual cost of the line will decrease while annual cost of losses will increase. The annual cost of the terminal equipments will remain constant, being increased only slightly as the circuit loading increases and the resulting transmission efficiency decreases, since the investment costs for the terminal equipments are taken on a dollar per kw basis.

6.2.1 Converter Station Cost.

The converter ratings will be different at each end of the line, due to losses in the line, and this fact is taken into account when calculating the annual cost of the terminal stations. The station investment costs are taken as a total dollars per kw of rating cost for the installed terminal equipments.

The turnkey cost for dc terminal station [14] is shown in Fig. 6.1

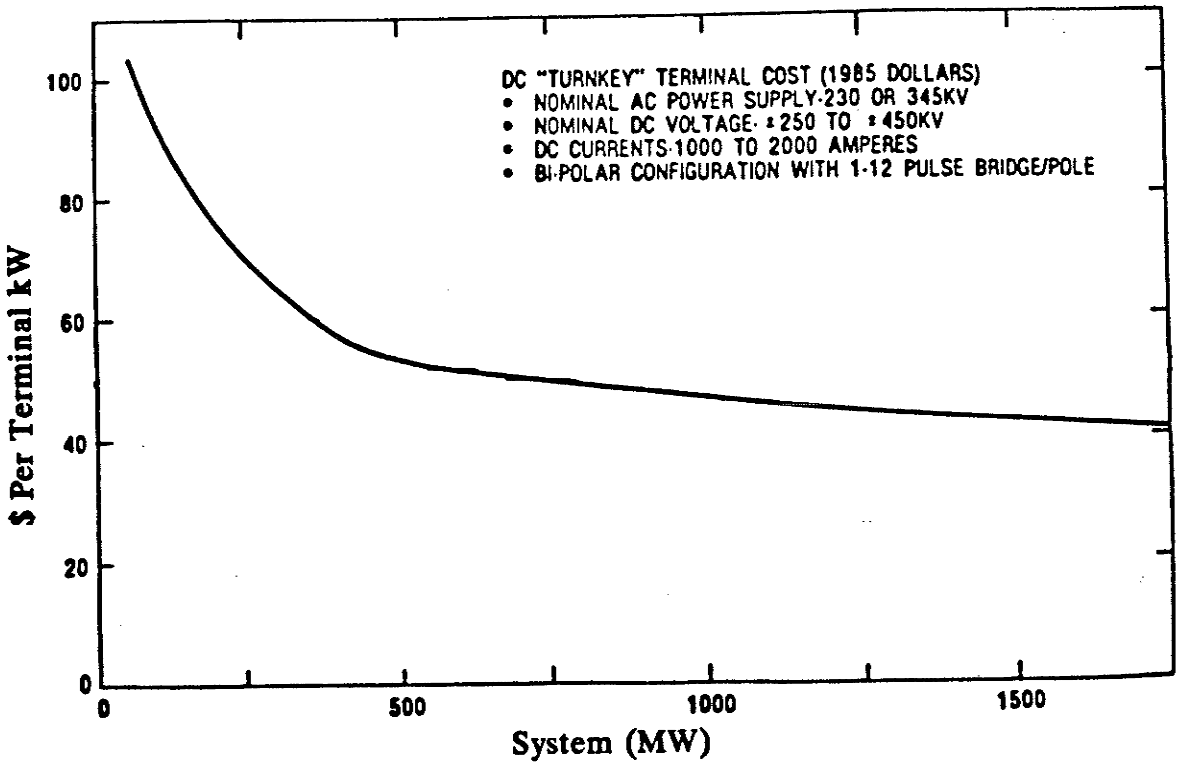


Fig. 6.1 Bipolar HVDC Terminal Station Cost

The dc station costs represent the entire terminal investment for installed transformers, converter, filters, switchgear, and earthing electrodes.

Table 6.1 shows the cost of different elements that make up a terminal.

Table 6.1 Cost Breakdown, US $ / Per Terminal / Per kW

DC System = ±600 KV, 2500 MW AC System = 345 KV		
ITEM	**$/KW (1977$)**	**%**
Transformers	5.7	23.7
Reactors	1.28	5.3
Valves	7.75	32.0
Auxiliaries	2.0	8.3
Filters	2.0	8.3
Buildings	1.0	4.2
Total Equipment	19.8	81.8
Installation	3.2	13.2
Project Design & Management	1.2	5.0
Total Terminal	24.2	100.0

Converter Losses = 1.44% (1977), For both terminals
= 1.17% (1990)

Source -- Progress report LA-7116-Pr,
DC Superconducting power transmission
line project at Los Alamos Scientific
Laboratory, January 1978

6.2.2 Converter Station Losses

The converter station losses are assumed to be 0.7% of the station rating [18]. Converter station losses comprise of transformers, valves, filters, smoothing reactors and auxiliary power losses. In Fig. 6.2, the itemized losses are given as a function of relative converter load.

For a fully compensated station the efficiency can, to a large extent, be influenced by the design of the equipment, such as converter transformers, and is therby a function of the loss evaluation.

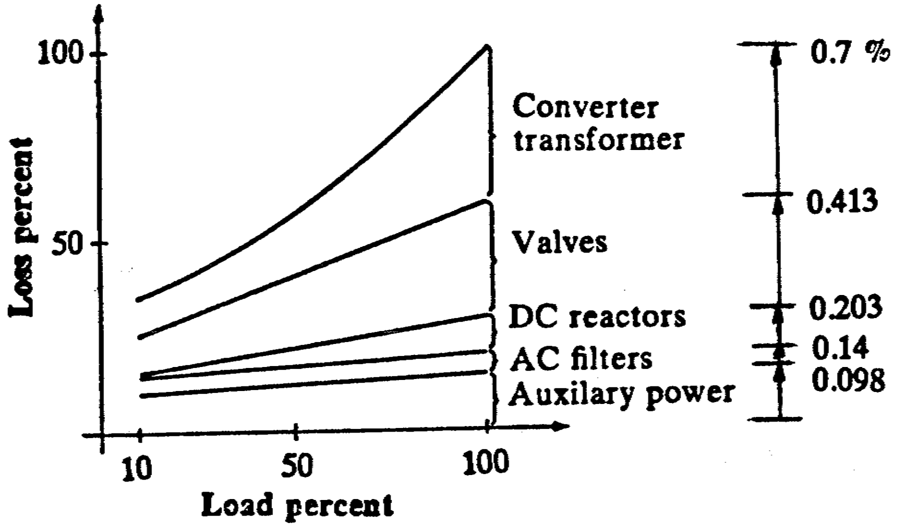


Fig. 6.2 Itemized Converter Station Losses as a Function of Load

Chapter VII

Economic Evaluation

The basis for an economic evaluation of the merits of a possible application of HVDC transmission should be based on the following aspects.

1. Economic aspects
2. Technical aspects
3 Reliability aspects

These aspects should be evaluated and all the intangible benefits should also be evaluated if possible and included in the evaluation.

There are many potential areas of application of HVDC which are discussed below such as long distance transmission, asynchronous interconnection of two ac systems, submarine cable connection, underground cable connection to metropolitan areas. In other areas HVDC should be considered as complementary to ac and dc should be considered as a possible alternative. The overall ac/dc integrated approach usually results in the best solution leading toward the achievement of the optimum system design.

7.1 Opportunities for the Application of HVDC Transmission

There are two basic general conditions under which HVDC should be considered :

1. When dc transmission only should be used
2. When dc transmission should be considered as an alternative to ac based on the overall detailed evaluation of all tangible and intangible aspects.

7.1.1 HVDC Transmission Only Should Be Used.

There are many situations under which HVDC transmission is the better alternative or the only solution on the basis of economic, reliability and technical considerations.

7.1.1.1 Interconnection Between AC Systems.

In such an interconnection advantage is taken of the asynchronous nature of dc. Interconnection by back-to-back HVDC converters is the only way to connect ac systems with different frequencies. Examples of such schemes are Sakuma and Shin-Shinano in Japan.

7.1.1.2 Submarine Cable Connection

The Cross-Channel link and the Konti-Scan link are examples of this connection application. In both these cases there is the natural barrier of the sea but one of the main advantages of dc in this application is the independence of the power transfer between the systems regardless of frequency differences and conditions within the systems.

If the length of cable is such that intermediate var compensating station is not required, then detailed economic, technical and reliability comparison has to be performed to determine the proper choice.

For an ac cable system the reactive power characteristic is a limiting design factor. From a certain length of cable the capacitive charging current limits the possible transmission current. Therefore, compensation by shunt reactors has to be provided every few kilometers. For underwater cables the scope for compensation is limited. On the other hand, the high capacitance of the cable has no negative effects in the case of dc. Therefore, no shunt compensation is needed at intermediate points along the line.

7.1.1.3 Interconnection Between Very Large AC Systems.

Interconnection by ac tie line between two large ac systems may cause extremely large power surges on the tie line. Such surges may cause follow-up surges of a cascading nature in the neighboring interconnected system. Also ac tie line results in excessively high short circuit contribution. On the other hand the above problems would not be present if dc tie tie line is used. This is due to the asynchronous nature of the dc link. This feature together with fast controllability enhances the stability of the ac system.

7.1.2 HVDC as An Alternative.

There are a number of situations where dc transmission should also be considered as an alternative to ehv and uhv-ac transmission. This will require a detailed comparison for arriving at a proper choice. In many instances the necessary data is not always available or it might be inaccurate and subjective. Thus one will have to exercise proper engineering judgement.

7.1.2.1 Remote Generation Resources.

There are two situations when remote generation might be present :

1. Hydraulic power sites such as in Manitoba, British Columbia and Quebec.
2. Mine mouth coal fired thermal generation such as Intermountain Power Project (IPP) and VEPCO schemes.

In these cases the transmission could be either ac or dc or both. The main factors in deciding which should be used are usually the capital cost and losses.

It is assumed in both cases that moderate power levels of about 500 MW and a distance of about 500 km are considered.

For typical distances and power ratings of long-distance transmission systems, the inherent characteristics of a dc system tend to result in the following system design :

a) One bipolar line is nearly always sufficient to meet security requirements.

b) The line and specifically the station capacity can be adapted very closely to the graduation of the steady-state transmission capacity required.

The inherent ac characteristics tend to result in a system design of the following nature for long distance transmission :

i) At least two lines in parallel from the beginning to meet security requirements.

ii) Loading at approximately 50% of the surge-impedance load resulting in very low loading during the initial stages.

iii) Fixed shunt reactors with a compensation factor of about 50% to compensate the line capacitance and to reduce power-frequency overvoltages.

iv) Substations are required to keep reductions in impedance during and following faults within reasonable limits.

v) In many cases series capacitors or controlled shunt reactors have to be installed in intermediate stations along the line.

When comparing the suitability of the two systems for specific transmission requirements the following general points have to be considered.

1. AC lines are more expensive than dc lines for the same power transfer capacity.
2. DC systems are more expensive as regards to terminal stations, hence only above a certain transmission distance the total cost of dc transmission link becomes less than that for an ac link.
3. To improve utilization of long ac lines, extensive compensating equipment is required.
4. The transfer capacity of an ac transmission system is governed by stability limits.

Thus, from a transmission point of view, dc is often more economical if long distances, e.g. more than about 500 km, are combined with moderate transmitted power. Furthermore, a dc system provides numerous operational advantages over long-distance ac transmission.

7.1.2.2 Interconnection Between Remote AC Systems.

Long ac-tie lines between ac systems are subject to the same pros and cons as mentioned above. The power flow will be bidirectional.

7.1.2.3 Power Infeed into Metropolitan Areas.

With the growth of city and urban areas the need of additional power infeed increases. The only way that an additional supply of electricity could be optimally provided is by :

a) DC underground cables.
b) Converting existing ac lines to dc lines.
c) Replacing existing circuits with new ehv/uhv ac lines or HVDC lines.

HVDC transmission can offer fundamental advantages for an underground system with respect to :

i) Improved and flexible load flow
ii) Limiting short circuit level
iii) Improvement in stability
iv) VAR control of a cable network

At present there are quite a few schemes of this nature under consideration over the past few years viz., Chicago, Philedelphia and NewYork etc. [14].

7.1.2.4 Very Costly Right-Of- Way.

In countries where availability of right-of-way is restricted or ROW are very costly necessitating either :

i) The building of new lines of higher capacity.
ii) Uprating of existing lines.

Since dc lines require less space for the same transmission capacity, existing ac lines can be replaced by dc lines of considerably high capacity. Moreover, single or multicircuit ac lines could be converted to dc lines to increase the original capacity.

7.1.2.5 Splitting of Large Network.

When the short circuit capacity of an existing network grows to an intolerably high capacity then such a system can very easily be segregated by means of HVDC link either by back-to-back or point-to-point HVDC transmission lines. The short circuit contribution by HVDC links is not higher than its rating.

7.2 Performance Benefits

There are many performance benefits of HVDC transmission which are often neglected in comparison of ac and dc transmission alternatives. These benefits range from the tangible to the difficult to evaluate advantages. The system planners should be aware of these benefits which can enhance power system performance with the application of HVDC system.

The unique differences between ac and dc, if used properly can give an improved system performance by realizing the complementary role with increased integration of HVDC into existing power systems.

7.2.1 Reactive Power Management

On long EHV lines and cables the production and absorption of vars is a serious problem. Ideally, loads close to surge impedance loading are carried on ac lines and the net reactive power is zero or very small. However, this ideal situation is rarely met.

DC transmission lines do not require reactive power, but converter terminals absorb vars from the ac system. This var requirement is proportional to the transmitted dc power and independent of line length.

Although both ac and dc transmission systems require reactive power, it is worth noting that EHV-AC lines require more reactive power above the length of 250 miles.

In ac cables the vars produced by charging the shunt capacitance greatly exceeds that consumed by the series inductance. In 20-25 miles of ac cable the charging current equals the rated current and even if supplied from both ends, severly limits the load carrying capacity. Shunt reactors offer a technical solution but impose an economic penalty. DC cables do not encounter this problem and therefore become increasingly attractive to transmit power beyond 20 miles.

In metropolitan areas with extensive cable networks, converter stations can be designed to absorb the excessive reactive power during light ac load condition.

With the use of static var compensation rapid voltage control can be achieved at converter locations and voltage stability can be greatly enhanced.

7.2.2 Reduced Voltage Operation.

In case of dc if line insulation is partially damaged as a result of a lightning stroke or other incident, the pole with damaged insulation can be returned to service with reduced voltage, thereby maintaining service continuity.

Reduced voltage operation can be achieved in steps by turning off discrete 12 pulse converter groups in a series connected system or it can be done by continuously lowering the dc voltage by firing angle control.

On ac systems such voltage reduction is not possible and therefore if insulation is damaged, the entire ac circuit must be removed from service.

The same unique characteristic can be successfully used in areas where insulator contamination requires reduced voltage operation.

7.2.3 Regional Interconnection.

Interconnection of systems is well known to be advantageous because it will contribute to continuity of service and will assure most economical power production.

During normal operating periods, generation is shared. Interchanges between different utilities are scheduled to take advantage of load diversity or available lower cost capacity, permitting lower overall operating costs and possible deferment of capital investment for new installations. During emergencies, spinning reserve capacity is shared, contributing to continuity of service.

Interconnection of two large systems is sometimes not feasible by conventional ac transmission techniques. AC-ties tend to open frequently because of overloads resulting during disturbances on either side.

HVDC is not susceptible to small disturbances and related phase shifts and therefore the tie remains intact.

HVDC links are able to recover quickly from large disturbances. DC links if properly designed will not propagate transients from one system into the other.

An example of this is the Stegall back-to-back tie which is the first regional interconnection between eastern and the western U.S. systems. Similar interconnection was completed at Eel River, Canada between the Hydro Quebec and New Brunswick systems in 1972.

Regional interconnections take advantage of seasonal and often daily time diversity of load occurrences which can be evaluated on an individual basis. An example of this type of installation is the Pacific Intertie with its peak power delivery to the southwest during the high run-off period of April to June and during some high water years may continue much of the year.

7.2.4 Controlled Power Interchange.

The Inherent characteristics of HVDC transmission system are such that power transfer across the link is controllable and independent of ac voltage angles. HVDC ties can deliver a predetermined constant amount of power in either direction which allows efficient reserve utilization and delivery of peak power independent of load variation.

HVDC interconnection between adjacent systems permits scheduled power interchange without restrictions on the frequency of either system or on the power angle relationship between the systems.

Without HVDC an ac tie may require massive modification to both ac networks. An example is the Stegall back-to-back dc tie referred to earlier. Estimates indicate that a stable ac tie could have reached 3000 MW size making the tie economically unattractive.

The flexibility of control systems associated with HVDC transmission systems presents a large number of possible solutions to power interchange control. The controls can suitably respond to various ac system conditions, and modulate the transfer of dc power in such a way that it will enhance the dynamic stability with a substantial increase in power transfer on coordinated ac and dc transmission systems [20-23].

7.3 Evaluation of Tangible Performance Benefits.

There are some tangible benefits which can be readily evaluated in terms of dollar value and some of them have been evaluated in the past.

7.3.1 Improve AC System Stability.

A rapidly growing application of hvdc is the coordinated control of parallel ac/dc systems, which makes it possible to increase the power transfer capabilities of parallel ac lines [20-23]. Since ac lines are normally designed with relatively high thermal capability compared to stability limits the increase of stability limits is a performance benefit which deserves serious cost evaluation.

In Pacific Intertie HVDC Scheme modulation of ±40 MW has been used to damp steady state oscillations in the parallel ac lines which resulted in the increase of ac transmission capability by a total of 400 MW [21]. The cost evaluation for this performance benefit was made at the time by using U.S. $120/kw. So this benefit is worth $48 million which was almost the cost of providing the dc transmission system terminal equipment.

7.3.2 Right-of-Way Requirement.

It has been customary to compare a bipolar HVDC transmission line to a double-circuit ac line. Using the actual right-of-way width of 120 ft (36 m) for the Square Butte HVDC Scheme and comparing it to the right-of-way of 250 ft (76 m) for an ac double-circuit line, the right-of-way acreage requirements show more than 50% saving in favor of the dc line as shown in Table 2.2.

The evaluated cost benefit for a 500 mile (800 km) long line assuming a land cost of $500/acre is approximately $4 million (US dollars)

7.3.3 Short Circuit Capacity.

Power can be brought in through HVDC transmission without increasing the short circuit capacity at the point of connection. Whereas ac lines increase the short circuit capacity which may exceed the interrupting capability of existing circuit breakers. Therefore, the benefit by HVDC transmission to heavy load centers without a costly breaker replacement program can be evaluated only on an individual basis.

7.3.4 Variable Speed Hydro.

Investigations have been made to explore the possibility of variable speed operation of hydro units [14].

Variable speed operation results in a substantial improvement in system performance. The speed of the hydraulic turbine could be adjusted freely to satisfy the load demand at the maximum possible hydraulic efficiency and also at a higher firm capacity. This improvement in efficiency could be 3-10% over conventional mode of operation [14].

7.4 Intangible Performance Benefits.

There are some benefits which are difficult to evaluate in terms of monetary value. Some of these items will have great significance in future decision making for improved power system performance.

7.4.1 Overload Benefits.

DC transmission systems have inherent short time overload capabilities which can be utilized for damping oscillations and stabilizing parallel ac lines.

A dc system reacts very rapidly to partial load rejection. In case one pole is lost, the other healthy pole can immediately and smoothly assume the rejected load and thereby reduce the stresses on generator-turbine shafts.

This is a very important, but difficult to evaluate performance benefit.

7.4.2 Lightning Performance.

One difficult to evaluate performance benefit is the dc transmission line lightning performance.

Since two dc conductors versus 6 conductors for an equivalent system are exposed to the atmosphere elements, reliability of the transmission system is favorably influenced by reduced exposure to lightning strokes. Furthermore in a bipolar link only one pole is usually struck by lightning and service continuity is maintained through monopolar operation with higher than 50% capacity depending on overall capability.

7.4.3 Environmental Impact.

Increased emphasis on environmental impact of transmission facilities creates incentives for dc transmission because fewer, less noticeable components are necessary. The fewer number of dc conductors and smaller towers are environmentally significant. Equally significant is the approximate 50% reduction in right-of-way area requirement.

Solid-state conversion equipment in dc terminal design have drastically reduced substation land area requirement as shown in the Table 7.1 . Area requirement for the Celilo Terminal was used as per unit.

Table 7.1 HVDC Terminal Land Use Comparison

Hvdc Scheme	**Area m^2**	**Area p.u.**	**m^2/kW**
Pacific Intertie Celilo Terminal, 1440 MW	325x264	1.0	0.75
Air insulated 2000 MW	320x140	0.51	0.24
Compact air insulated 2000MW	122x44	0.062	0.029
Compact gas insulated 2000 MW	91x15	0.016	0.0075

A 2 to 1 reduction can be seen from mercury-arc terminal to an air insulated solid-state terminal, while a 16 to 1 reduction is evident to a compact gas insulated installation. The real reduction in cost benefit can be evaluated only on an individual basis.

7.5 Limitations of HVDC Transmission.

There are some limitations of HVDC transmission due to its nature of operation. The converter thyristors are controlled switches and generate harmonics. The converters consume reactive power for its operation. Tapping and corrosion of subsurface pipes are the other areas of concern.

7.5.1 Tapping

Tapping of 10-15% is not a problem anymore as shown by recent investigations [47]. But the higher cost of converter is a definite economic disadvantage particularly for lower power level tapping.

7.5.2 Switching

For a long time, the lack of HVDC circuit breaker has been one of the unresolved issues affecting extensive application of HVDC transmission. Doubts about the technical feasibility and availability restrained utility system planners from planning HVDC systems that could derive significant benefit from the use of HVDC breakers. At present, HVDC transmission systems are two-terminal systems. Multiterminal systems are expected as the number of systems grow. HVDC breakers are needed for multi-terminal systems in :

1. Sectional isolation such that the remaining lines continue to transmit without interruption.
2. Isolation of a faulted line with minimal system disturbance.
3. Clearing converter terminal faults.

A recent paper reports on the development of two different dc breakers prototypes and full scale field tests of these breakers on the ±400 kV, 1360 km long Pacific DC Intertie [46].

One of the breakers was an air-blast design supplied by Brown Boveri Corporation (BBC), and the other was a SF6 puffer design supplied by Westinghouse Electric Corporation. Breakers were tested at 400 kV. The BBC breaker was tested for currents upto 2000 A and the Westinghouse breaker was tested for currents upto 1200 A. Field tests were made for line switching,load breaking, and fault clearing. Tests were conducted with the dc intertie operating as a two-terminal and as a three-terminal HVDC system. All of the tests were successful.

Thus availability of dc breaker is not a limitation any more. Breakers similar to the prototypes can be used on major transmission systems being planned today. The modular design of these prototypes should allow adaptation of these breakers to any voltage class.

7.5.3 Subsurface Metallic Corrosion.

Improperly designed earth return results in possible adverse effects that could arise due to the presence of earth return currents :

1. Interference with communication facilities.
2. Corrosion of subsurface metallic pipes and structures of other utilities like gas etc., if in proximity to the electrodes.
3. The saturation of neutral grounded transformers, and interference to the fast acting sensitive electronic relay may result if electrodes are located close to the terminals.

7.5.4 Reactive Power Supply.

The operation of converter terminals requires supply of reactive power. At either end, rectifier and inverter, the supply of vars is into the terminal stations as shown in Fig. 7.1 .

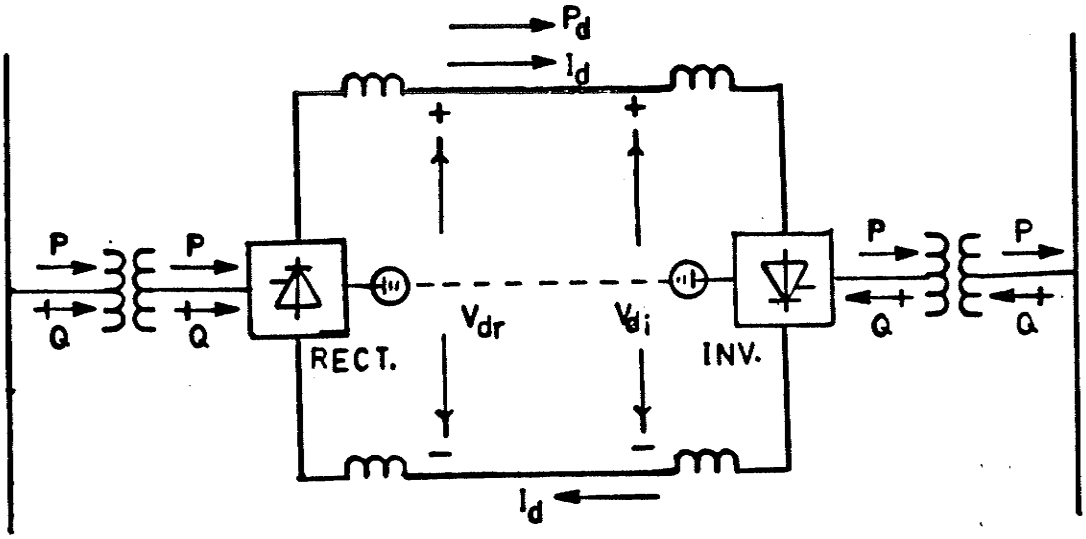


Fig. 7.1 Supply of Reactive Power into Converter Terminals

Under normal conditions converter require reactive power which is 50% of transmitted active power. While under transient conditions it is almost 75% of the real power rating. Also inverter operation requires an active ac source.

7.6 Developments in HVDC Converter Station Design.

The general concepts of the converter station design that was developed during the 70's are still used [18]. However there are certain changes in the requirements for the projects of the 80's that impact on the design.

Losses are much important today than what they were 5-10 years ago. Also a much greater emphasis is today placed on the reliability and availability of the converter stations with acceptable limits on unavailability and forced outage rates far below those which were used for the projects of the 70's.

A third group of requirements concerns the control systems, where much more sophistication is being required in many of the projects of the 80's. This includes :

1. More extensive use of active and reactive power modulation.
2. Reduction of voltage changes at reactive bank switching by firing angle control.
3. Reactive power flow management.

7.6.1 Thyristor Valves

The power handling capacity of thyristors has increased dramatically [18] as shown in Fig.7.2.

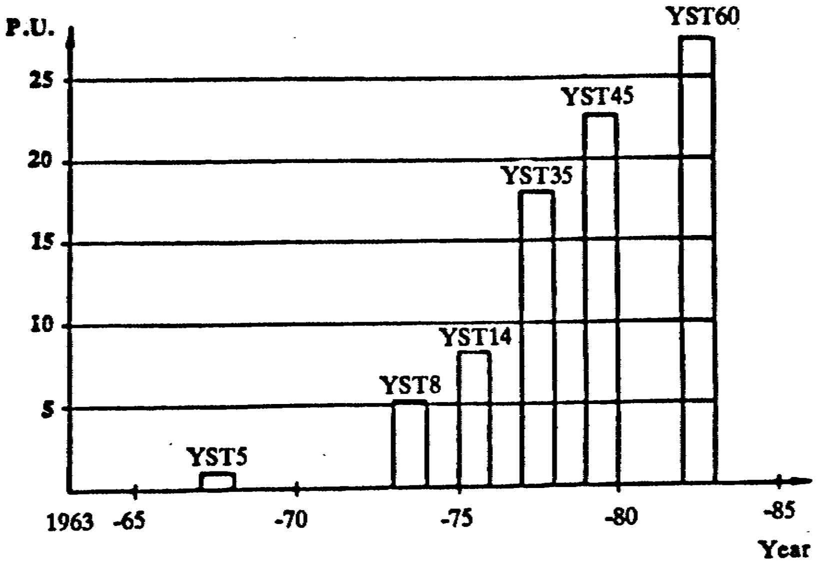


Fig. 7.2 Development of Relative Power Handling Capability of HVDC Thyristor

For the projects of the 70's typical wafer sizes were 8 and 14 cm. square. Today wafers of 100 mm diameter are available and the current capability of each thyristor is so high that a rated current of about 4 kA can easily be handled without parallel connection of thyristors.

Modern HVDC thyristors have blocking voltage capacity above 5.0 kV. As an example of development of the valves, the 1600 MW, ±500 kV, 1600 A Intermountain Power Project, will have only half the number of thyristors as the valves for Inga-Shaba Project (±500 kV, 730 A) [18]. This achievement is not only due to the improved voltage capability of thyristors but also to the introduction of voltage protective firing and the lower insulation levels made possible by improvement in surge arrestor design.

7.6.2 Control Equipment

The development of control equipment has resulted in increased use of microcomputer based programmable systems which leads to added flexibility in the design.

The use of programmable systems in the controls has made it possible to improve the reliability through self checking functions and through the introduction of redundancies for critical subsystems. Due to the development of micro-computer based converter control equipment, it has now become possible to design systems with completely redundant converter controls with automatic transfer between the systems in case of a control equipment malfunction. Such a facility will be installed in the IPP project and it is expected to become standard feature in future HVDC projects.

7.6.3 Converter Station Losses

When thyristor valve converter station were first introduced in the 70's, losses increased in comparison to the mercury arc valve stations built during 60's. This was a result of the higher valve losses and the higher auxiliary power demand for valve cooling.

Water cooled valves with large thyristors and a higher loss evaluation has now brought the losses down to levels far below [18] those of the mercury arc valve stations as shown in Fig. 7.3. The cost of losses is today an important consideration in valve design.

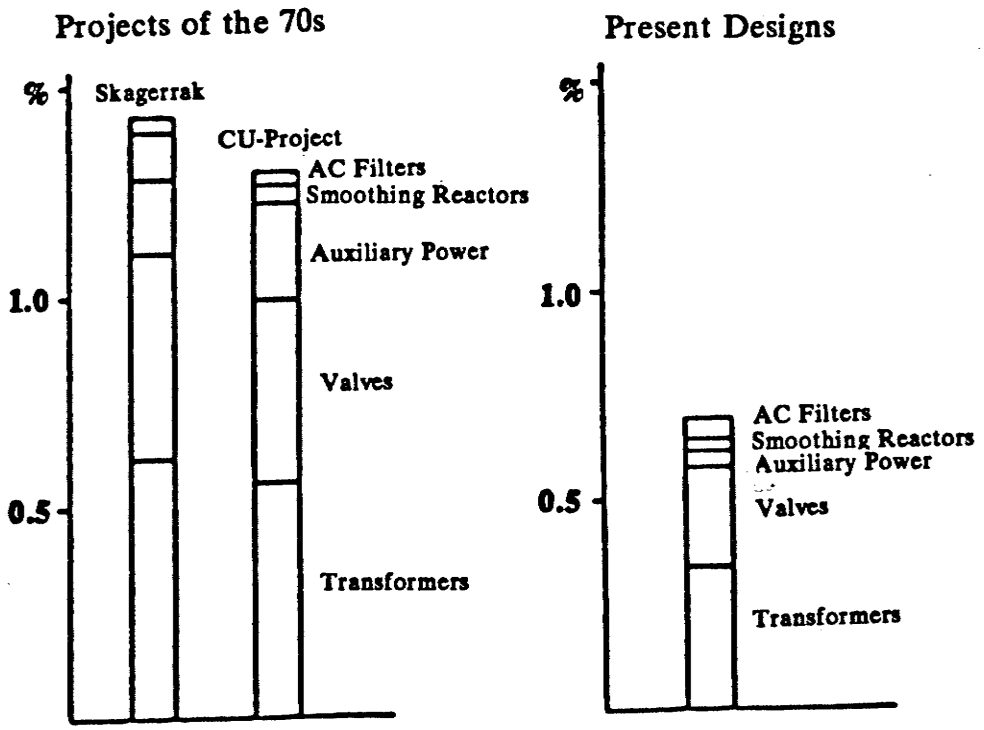


Fig. 7.3 Development of Converter Station Losses

7.6.4 Overload Capability.

One of the drawbacks of the early HVDC transmission using thyristor valves was the limited inherent overload capacity. This was due to the fact that the relatively small thyristors were fully utilized when operated at rated conditions. This is not the case today as thyristors capable of handling currents more than 3000 Amps. may be used in projects with a rated current of less than 2000 Amps. For example, Gotland 2 Scheme which has a rated current of 910 A will have 35 cm sq. thyristors and the IPP project with 1600 A will have 45 cm sq. thyristors. As a comparison Skagerrak Scheme with 1000 A has 8 cm sq thyristors and CU Scheme with 1250 A has 14 cm sq thyristors.

7.7 Economic Evaluation

The basis for an evaluation of the merits of HVDC transmission are the economic, technical, reliability and operational aspects.

As described before HVDC has many advantages and in some situations it is the most advantageous solution either because it is most economical or the only solution because of technical and operational reasons. There are a number of specific transmission applications when HVDC should be considered as an alternative to ac transmission. Technical and operational features should be evaluated in addition to economic aspects. HVDC can offer advantageous solutions for

a) Long distance transmission
b) Cable transmission
c) System interconnection
d) Uprating existing lines

Some of the inherent characteristics and virtues of HVDC transmission are :

i) Underwater or underground cables transmission.

ii) Overhead lines - Very simple, smaller and easier to construct towers having reduced visual impact.

iii) Uprating of existing transmission facilities by conversion to dc or replacing with dc.

iv) Because of asynchronous nature of dc there is no concern for stability of the lines as is in case of ac

v) Controllability of dc link enables :

  a) Fast and flexible load flow control.

  b) Fast power reversal.

  c) Stabilization of ac system.

  d) Various possibilities of power program can be instituted, especially with ac/dc parallel operation.

vi) Staging of facilities - Converter stations as well as lines can be built in stages to suit load growth.

vii) Overload capability - results in service continuity at more than 50% load in an emergency if one pole is out.

viii) Converter development - has lead to use of higher power thyristor, decrease in converter terminal losses, and reduced cost of converter terminal.

7.8 Project Evaluation.

The approach that is being used for economic comparison on project evaluation by some planners is too simplistic. The determination for break-even distance by itself is inadequate because it is based on known and easily priced elements i.e. tangibles while ignoring intangible elements. For any possible application of HVDC the best possible "Break-Even" distance should be determined and then all the intangibles should be included in the evaluation.

Table 7.2 [53] shows the generic cost elements which should be considered for evaluation of alternatives. For any application of HVDC the applicable cost elements should be considered to arrive at proper choice.

Table 7.2 Generic Cost Comparison Elements

System Cost Elements for Given Power(MW) Transmitted & Line Length

AC	DC
1. Right of way	Right of way
2. Load density/Acre ROW	Load density/Acre ROW
3. Transmission voltage	Transmission voltage
4. Line -	line -
conductors	conductors
towers	towers
5. Sub-or switching station	HVDC converter station
a) Breakers and Disconnects	a) Breakers & Disconnects
b) Transformers	b) Transformers
c) Reactive Power	c) Filters & var supply
-Shunt capacitor & reactors	
- Series capacitor	
- static var system	
	Valve assembly & S.R.
	Ground Electrode and metallic return
	Transfer breaker.
d) Protection	d) Protection
Control	Control
Station civil works	station civil works
6. Losses	Losses
a) Line	a) Line
b) Corona	b) Corona
c) Station	c) Station
7. Communication	Communication
8. Operating characteristics	Operating Characteristics
9. System reinforcement	System reinforcement
10. Environmental impact	Environmental Impact
a) RI	a) RI
b) AN	b) AN
c) Visual	c) Visual
11.Consequences & recovery from	Consequences & Recovery from
a) short duration line fault	a) short duration line fault
b) Long duration line fault	b) Long duration line fault
12. Stability Enhancement	Stability Enhancement
a) Dynamic	a) Dynamic
b) Transient	b) Transient
13. Fault magnitude & breaker interrupting duty	Fault magnitude & breaker interrupting duty
14. Energy availability	Energy Availability
15. Recovery from system breakup	Recovery from system breakup
16. Ease of tapping	Ease of tapping
17.	Conversion of ac line to dc

Chapter VIII

Example.

This example illustrates the economic evaluation of transmitting 2200 MW power over a distance of 1000 km by the following three different alternatives.

a) 735 kV AC

b) 2 x 500 kV AC

c) ±550 kV DC

The above three schemes are indicated in Figs. 8.1, 8.2 and 8.3 respectively

8.1 Assumptions.

The economic study was made on annual cost basis with the following assumptions :

i) No tapping or interconnection along the line.

ii) Line losses less than 5% .

iii) Most direct route over flat terrain.

iv) Use of 1 1/3 breaker switching for ac and dc transmission.

v) Total shunt compensation 65% of the total line charging MVAR. 25% of the shunt compensation was located at the sending end and the 50% was distributed along the line. The synchronous condenser at the receiving end supplies the balance necessary vars and was rated 35% of the total MW.

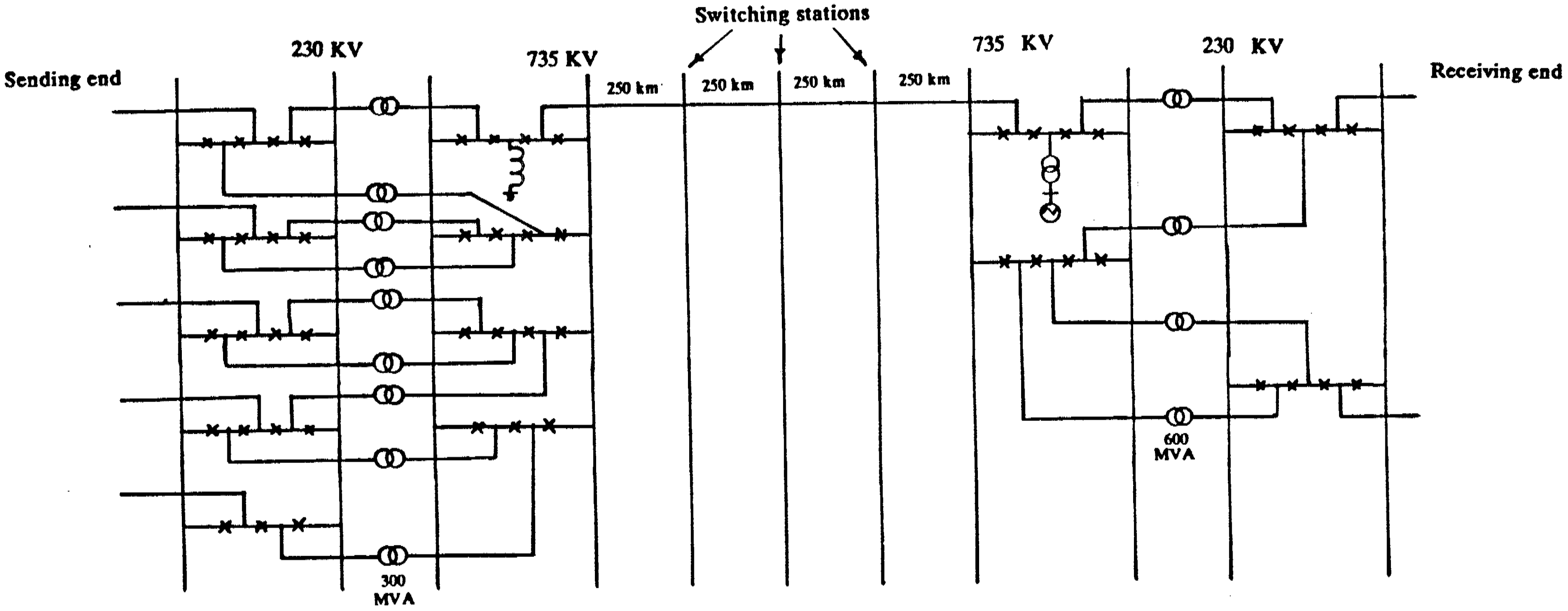


Fig. 8.1 Single Line Diagram of 735 kV AC Scheme

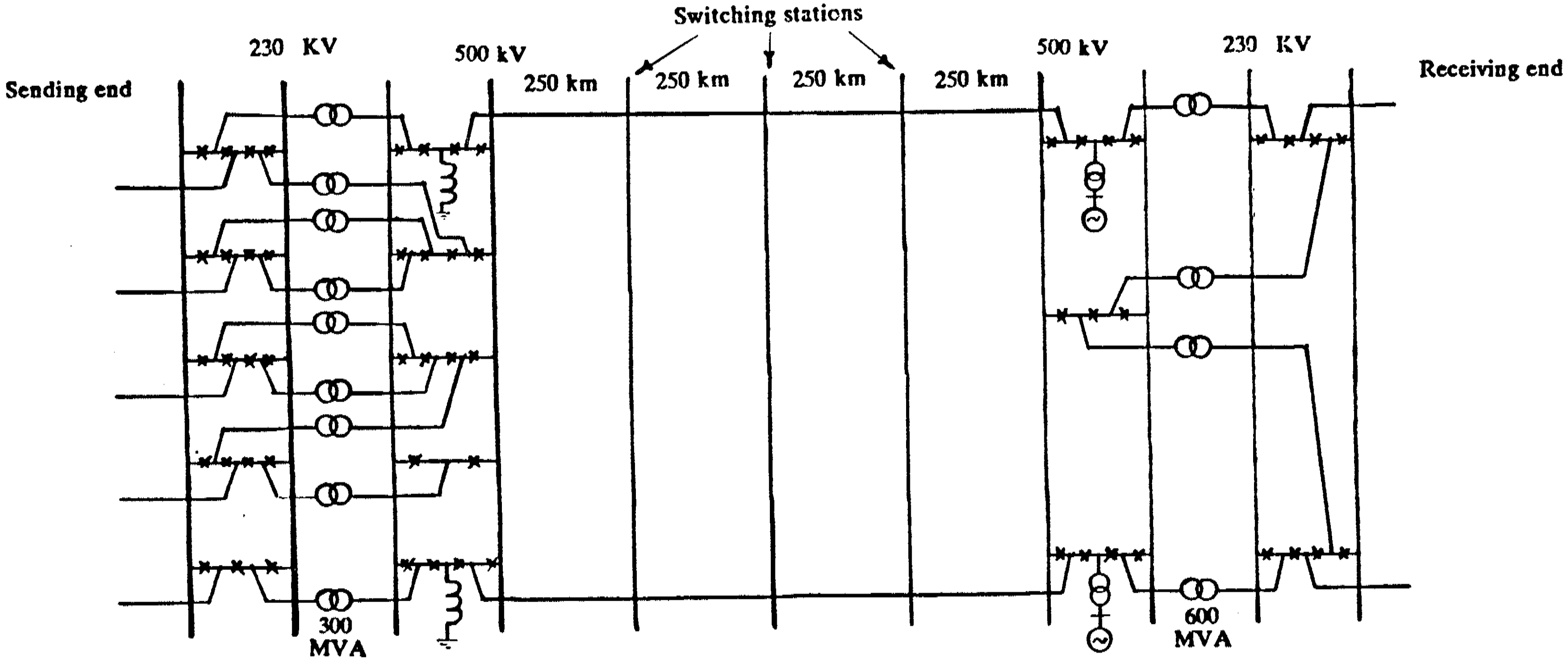


Fig. 8.2 Single Line Diagram of 2x500 kV AC Scheme

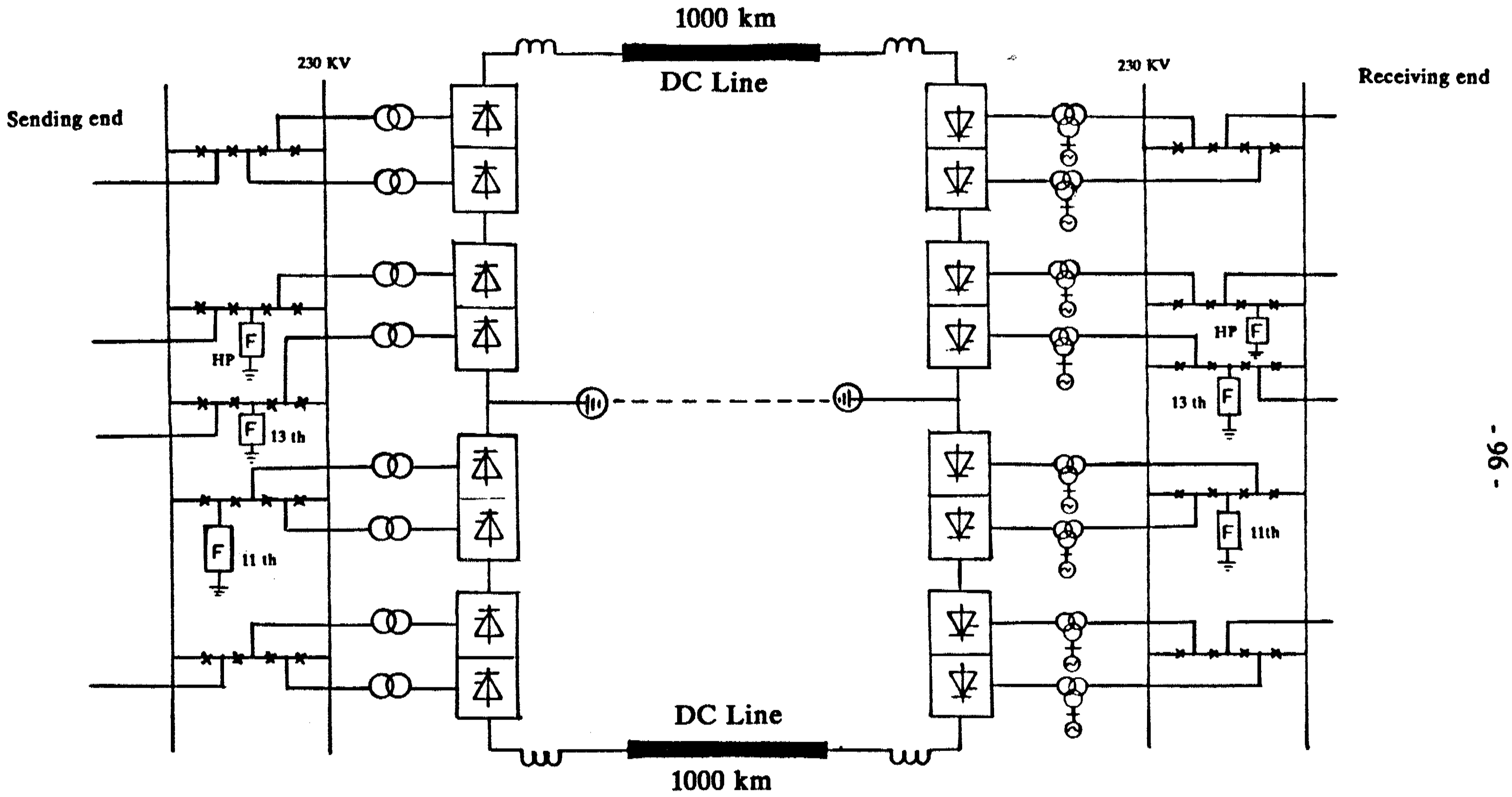


Fig. 8.3 Bipolar ±550 kV DC Scheme

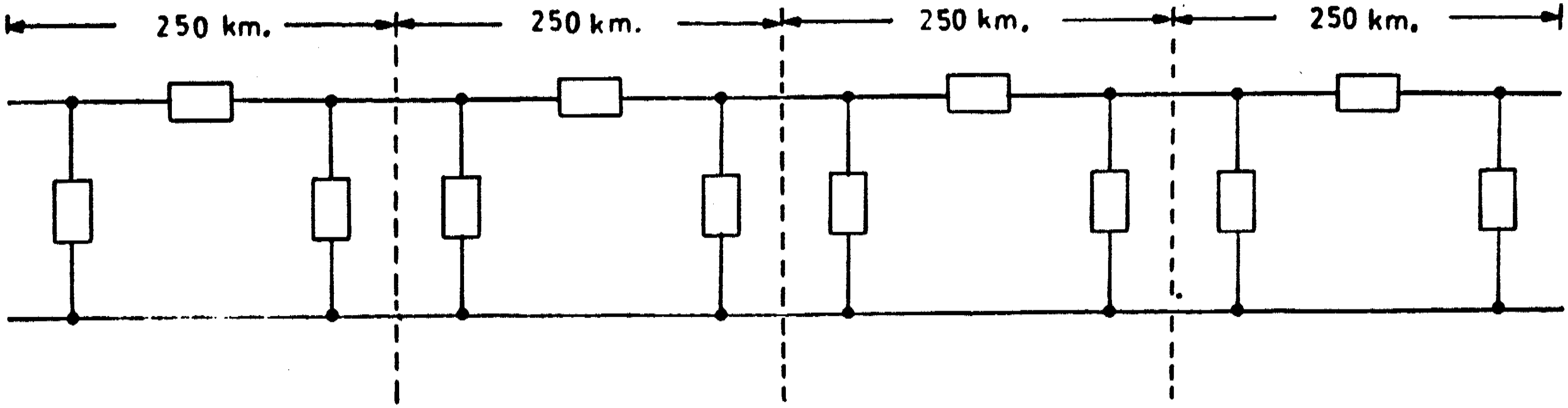


Fig. 8.4 Cascading Equivalent Π of Each Line

vi) The ac lines were sectionalized into four equal sections of 250 km each as shown in Fig. 8.4.

vii) The series capacitors banks were located in the switching stations. Fig. 8.5 shows the equivalent representation of the ac lines.

viii) The A,B,C and D line constants for a line section and the cascaded sections were calculatd as given in appendix.

ix) The values used for loss factor and load factors were 0.65 and 0.545 respectively.

x) Annual charges at 12%.

The following conductors were used for the three schemes.

a) 735 kv ac scheme -- For this scheme Chukkar ACSR 84/19 , 1780 MCM, 1.602 inch dia., 4 conductor bundle with conductor spacing of 18 inch and phase spacing of 50 feet with flat tower configuration was selected.

b) 2 x 500 kV AC Scheme -- Parrot ACSR 54/19 1510 MCM, 1.505 inch dia., 4 conductor bundle, with 18 inch conductor spacing and flat tower configuration with 40 feet phase spacing was chosen.

c) ± 550 kV DC Scheme -- Thrasher ACSR 76/19, 2312 MCM, 1.8802 inch dia., 2 conductor bundle, with 18 inch spacing and 44 feet pole spacing was selected.

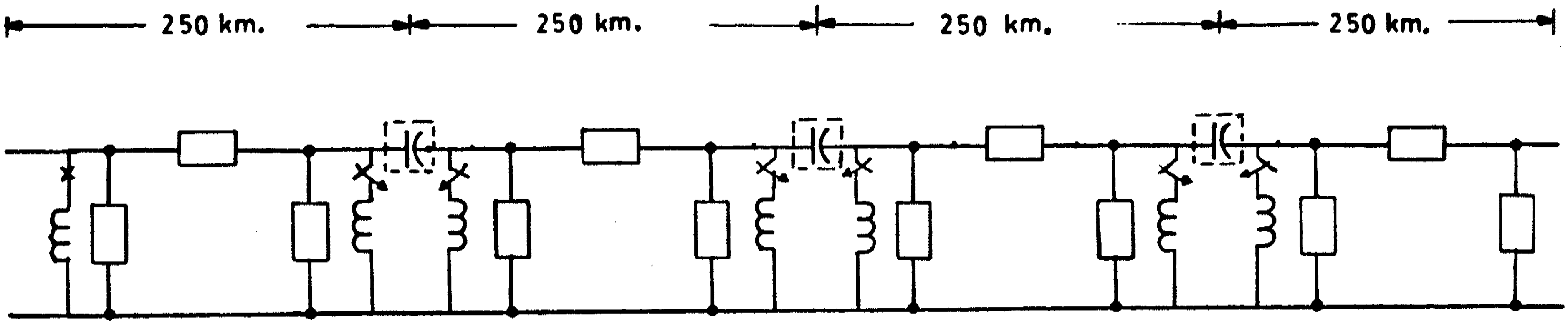


Fig. 8.5 Equivalent Representation of AC Line
(Capacitor Banks in Switching Station)

d) Cost Data -- The cost data for the equipments required for the three schemes is given in Appendix A6.

8.2 Cost of Schemes

The cost of the schemes includes all the equipments from the sending end 230 kV bus to the receiving end 230 kV bus. The 230 kV circuit breakers required for the sending end collector system feeders and the receiving end ac system feeders are excluded in the cost. The initial capital cost and cost of energy transmission are shown in Table 8.1 and Table 8.2 respectively.

Table 8.1 Cost of Schemes (C$, Millions)

2x500 kV AC	735 kV AC	±550 kV DC
969	851	816

Table 8.2 Cost of Energy Transmission (cents/kWh)

2x500 kV AC	735 kV AC	±550 kV DC
9.6	8.4	7.9

For transmission by HVDC the capital cost and cost of energy transmission are the minimum as can be seen from the above tables.

8.3 Losses

The line, corona, equipment and the total losses are shown in Table 8.3.

Table 8.3 Comparison of Losses (MW)

Losses	2x500 kV AC	735 kV AC	±550 kV DC
Line	111	98	97.8
Corona	2.2	3.3	2.0
Equipment	55.0	48	35.4
Total	168.2	149.3	135.2

The HVDC transmission scheme has the minimum overall losses. Moreover dc corona losses are lower than ac losses.

8.4 Technical Comparison.

The HVDC scheme does not require any line compensation. Whereas ac schemes are sectionalized for easier line energization, location of series and shunt compensation, and improving reliability of the system. The use of series compensation in ac schemes has a potential for subsynchronous resonance.

8.5 Reliability Comparison.

The reliability of bipolar hvdc scheme is considered to be equivalent to that of a double ac line. Thus 2x500 kV AC line and the dc line meet the reliability requirements.

8.5.1 HVDC Scheme

In case of dc one bipolar line is sufficient to meet security requirements. Even if one pole fails the other healthy pole is able to transmit at least 50% of the rated power. Due to the overload capability of the modern thyristors the power transmitted under this fault condition could be more than 50%. If one 12 pulse bridge in a pole fails, the continuity of supply is maintained at half the pole rating.

8.5.2 735 kV AC Scheme

The reliability of this scheme is poor because single line to ground faults are quite common and in such an event the continuity of supply is interrupted.

8.5.3 2x500 kV AC Scheme

The reliability of supply is improved because two lines are used. The series capacitors are located in the intermediate switching stations as shown in the Fig. 8.5 and continuity of supply is maintained even when a series capacitor and/or a line section is out of service.

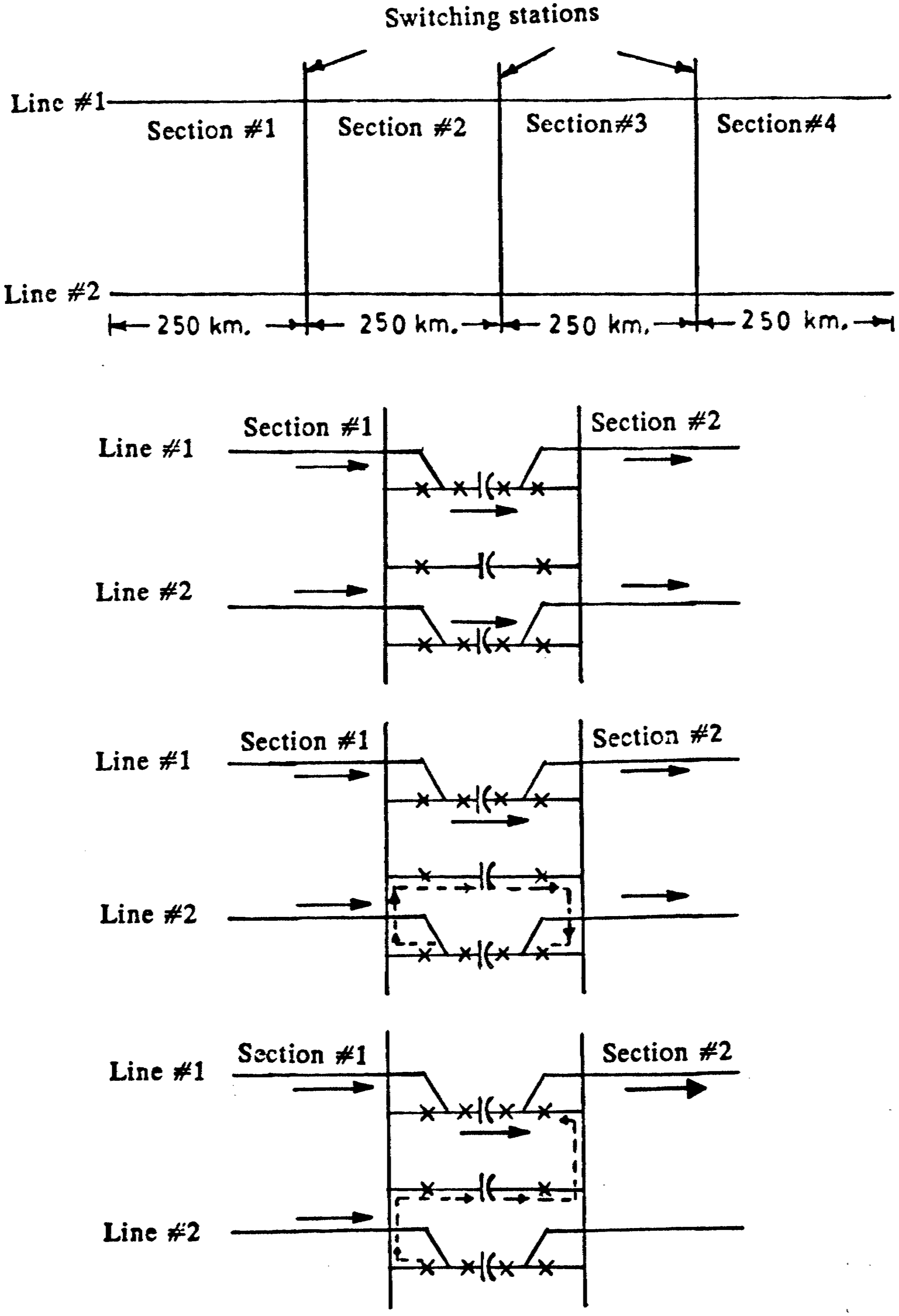


Fig. 8.6 Location of Capacitor Banks in Switching Stations

(a) Single line diagram

(b) Normal operation

(c) Capacitor bank of Line #2 out of service

(d) Section #2 of line #2 switched out

8.6 Environmental Considerations

The smaller towers for dc have less visual impact as compared to ac. This is an intangible benefit which can not be determined in terms of dollar value.

The HVDC scheme requires less right-of-way as shown in Table 8.4

Table 8.4 Right-of-Way Requirement.

Type of Transmission	**R-O-W (m)**
735 kV AC	85
2x500 kV AC	123
±550kV DC	72

8.7 Conclusions

The following conclusions are drawn from the above evaluation.

i The HVDC transmission scheme requires the minimum initial investment.

ii The cost of energy transmission by HVDC is the minimum.

iii Right of way required by HVDC is the least and the dc towers have less visual impact compared to other alternatives.

iv The absence of inductive and capacitivee effects under steady state on dc line results in simple line design. Whereas for ac alternatives the line is sectionalized for easier energization and stability reasons and needs series and shunt compensation.

Chapter IX

CONCLUSIONS

On the basis of economic evaluation undertaken the following conclusions are drawn :

I The transmission by HVDC is economical for long distance transmission

II There are a number of specific transmission applications when HVDC should be considered as an alternative to an ac transmission. In addition to economic aspect the technical, reliability and operational aspects should be properly evaluated. The intangible benefits should be considered and evaluated, if possible, in monetary terms. And the economic evaluation by this approach may lead to the conclusion that transmission by HVDC is the most economic solution even for short distances.

III Transmission by HVDC can offer advantageous solutions for :

- Long distance transmission.
- Cable transmission.
- System interconnection.
- Uprating existing ac lines

IV The modulation of dc system power flows permits greater dynamically stable loadings on parallel ac lines or on contiguous ac systems and provides rapid assistance between systems.

V It is advantageous to use back-to-back or long distance dc link to connect separate ac systems without the need to match voltage, insulation or frequency criteria.

VI The asynchronous back-to-back dc connection permits inter-regional load flow control.

VII The successful development of HVDC circuit breakers and its application would lead to improvement in performance of existing HVDC schemes.

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Appendix A1

Calculation of AC Corona Loss.

Petersons's empirical formula is used in order to calculate fair weather ac corona loss. The following Eqn. A1.1 gives the corona loss.

$$P_C = \frac{33.7\,(10^{-6})\,f\,E^2\,F}{\left(\log_{10}\frac{S}{r}\right)^2} \text{ kW per mile of conductor.} \qquad \text{(A1.1)}$$

Where,

f = frequency

r = conductor radius in inches.

S = equivalent phase spacing in inches.

F = corona loss function.

E = operating voltage, rms kv to neutral.

Appendix A2

Calculation of DC Corona Loss.

The following "Anneberg equation" is used for calculation of corona loss current in dc bipolar systems.

$$I_C = K_C\,(K+1)\,n\,r\,2^{0.25\,(g_{max} - g_o)}\,10^{-3}\ \text{Amp/km} \qquad \text{(A2.1)}$$

And corona loss is given by :

$$P_C = V\,I_C\ \ \text{kW/circuit-km} \qquad \text{(A2.2)}$$

Where,

n = number of subconductors.
r = radius of each subconductor in cm.
g_{max}= Conductor maximum surface gradient (kV/cm)
g_o= 22 δ kV/cm
δ = 3.92, air density factor
$K = \frac{2}{\pi} \arctan \frac{2H}{S}$ (=0.8)
H = medium height of conductor above ground.
S = Pole spacing.
K_C = conductor surface coefficient. (=0.2)
V = Pole voltage.

Appendix A3

Calculation of Auxiliary Line Constants.

The auxiliary line constants are given as follows :

$$A = \text{Cosh} \sqrt{Zl.Yl} \qquad (A3.1)$$

$$B = Zl. \frac{\text{Sinh} \sqrt{Zl.Yl}}{\sqrt{Zl.Yl}} \qquad (A3.2)$$

$$C = Yl. \frac{\text{Sinh} \sqrt{Zl.Yl}}{\sqrt{Zl.Yl}} \qquad (A3.3)$$

$$D = A \qquad (A3.4)$$

The ABCD constants can also be calculated from the following alternative expressions.

$$A = 1 + \frac{U}{2} + \frac{U^2}{24} + \frac{U^3}{720} + \frac{U^4}{40320} \qquad (A3.5)$$

$$B = Zl. \left[1 + \frac{U}{6} + \frac{U^2}{120} + \frac{U^3}{5040} + \frac{U^4}{36280} \right] \qquad (A3.6)$$

$$C = Yl. \left[1 + \frac{U}{6} + \frac{U^2}{120} + \frac{U^3}{5040} + \frac{U^4}{36280} \right] \qquad (A3.7)$$

$$D = A \qquad (A3.8)$$

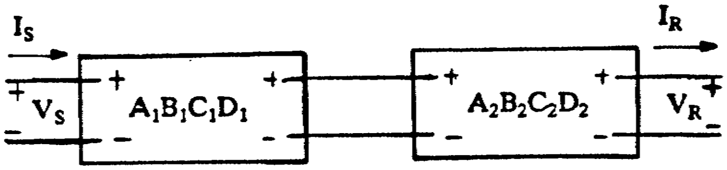
$$U = Zl.Yl \qquad (A3.9)$$

In the above expressions, Zl and YL are the total series impedance and shunt admittance respectively of the line section.

Appendix A4

Cascading of Line Sections.

The line sections are cascaded as shown in the following figure.



The equivalent ABCD line constants arer given by the following equations.

$$A = A_1 A_2 + B_1 C_2 \tag{A4.1}$$

$$B = A_1 B_2 + B_1 D_2 \tag{A4.2}$$

$$C = A_2 C_1 + C_2 D_1 \tag{A4.3}$$

$$D = B_2 C_1 + D_1 D_2 \tag{A4.4}$$

Appendix A5

Calculation of Cost

The cost of energy transmission per kilowatt-hour is calculated from Eqn. A5.1.

$$T = \frac{I \,.\, COST}{8760 \,.\, LF \,.\, PR} + \frac{DP \,.\, LE \,.\, CEL}{LF \,.\, PR} \qquad (A5.1)$$

where,

T = Cost of energy transmission in $/kWh

I = Annual charges in p.u (interest & depreciation)

DP = Total power loss in the system (capacity loss)

LE = Loss of energy factor

CEL = Cost of energy loss ($/kWh)

LF = Annual load factor

PR = Power at receiving end

COST = Total capital cost consisting of :

1) Cost of line
2) Cost of the plant to supply losses.
3) Cost of series capacitors (for ac schemes)

4) Cost of shunt reactors (for ac schemes)
5) Cost of circuit breakers.
6) Cost of synchronous condenser
8) Cost of line terminations.
9) In case of dc turnkey cost of converter terminals which includes converter transformers, valves, filters, smoothing reactors, earthing electrodes, auxiliaries and buildings.

Appendix A6

Table A6.1 COST DATA (Canadian Dollars)

S.No.	ITEM	500kV SCHEME	735kV SCHEME	± 550 HVDC BIPOLAR
1	230 kV Circuit breaker position	$\$0.5\text{x}10^{6}$	$\$0.5\text{x}10^{6}$	
	500 kV Circuit breaker position	$\$1.1\text{x}10^{6}$	$\$1.1\text{x}10^{6}$	
	735 kV Circuit breaker position		$\$1.6\text{x}10^{6}$	
2	Tr. Line (c$/mile)	300,000	450,000	250,000
3	Transformer (3ϕ,600MVA)	$5.35/kVA	$7.25/kVA	
4	Transformer (3ϕ,300MVA)	$8.0/kVA	$11.0/kVA	
5	Shunt Reactor (in line)	$15.3/kVA	$20.65/kVA	
6	Shunt Reactor (in station)	$10.1/kVA	$14.3/kVA	
7	Line Terminations	$412,300/line	$556,600/line	
8	Series Compensator	$22.35/kVA	$30.15/kVA	
9	Static Compensator	$33.5/kVA	$44.8/kVA	
10	Synchronous Condenser	$55.0/kVA	$71.8/kVA	$55.0/kVA
11	Syn. cond. transformer	$5.6/kVA	$6.0/kVA	
12	Converter Terminal	-	-	C$80/kW
13	Capacity Loss Cost	$2000/kW Inst.	$2000/kW Inst.	$2000/kW Inst.
14	Energy Loss Cost	$0.02/kWh	$0.02/kWh	$0.02/kWh
15	Transformer Losses	0.8%	0.8%	
16	Shunt Losses	0.4%	0.4%	
17	Series Compensator Losses	0.25%	0.25%	
18	Syn.Condenser Losses	0.5%	0.5%	
19	Converter Terminal Losses	-	-	0.7% of MW
20	Annual Charges	12%	12%	12%
21	Load Factor	0.8	0.8	0.8
22	Loss Factor	0.67	0.67	0.67