ROLE OF ECONOMY AND EFFICIENCY OF RECTIFIERS AND INVERTORS IN HIGH VOLTAGE DIRECT CURRENT TRANSMISSION

A dissertation submitted in partial fulfilment
of the requirements for the degree
of
MASTER OF ENGINEERING
in
POWER SYSTEM ENGINEERING

By
VIMAL PRAKASH

DEPARTMENT OF ELECTRICAL ENGINEERING
UNIVERSITY OF ROORKEE
ROORKEE
July, 1965

CERTIFICATE FROM GUIDE

Certified that the dissertation entitled 'Role of Economy and Efficiency of Rectifiers and Inverters in High Voltage Direct Current Transmission' which is being submitted by Shri Vimal Prakash in partial fulfilment for the award of the Degree of Master of Engineering in Power System Engineering of University of Roorkee is a record of student's own work carried out by him under my supervision and guidance. The matter embodied in this dissertation has not been submitted for the award of any other Degree or Diploma.

This is further to certify that he has worked for a period of six months from January to July 1965, for preparing dissertation for Master of Engineering Degree at the University.

O. P. Kulshreshtha
31/7

July - 1965.
ROORKEE (U.P.)

(O.P. Kulshreshtha)
Reader,
Elect. Engg. Dept.,
University of Roorkee(UP)

-0-

ACKNOWLEDGEMENTS

The author expresses his sincere gratitude and thanks in connection with this work, to Dr. O.P. Kulshreshtha, Reader, Elect. Engg. Dept., University of Roorkee, for his guidance and valuable suggestions at every stage of the preparation of this dissertation.

The encouraging and inspiring counsel of Dr. T.S.M. Rao formerly, Associate Professor in Elect. Engg. Dept., University of Roorkee, is gratefully acknowledged by the author.

The author is also indebted to Prof. C.S. Ghosh Head of Elect. Engg. Dept., University of Roorkee, for various facilities offered in the department in connection with this work.

Enough sincere thanks can never be acknowledged by the author to Shri R.N. Agrawal, lecturer Elect. Engg. Dept., University of Roorkee, for his constant help and personal interest from time to time.

July - 1965.　　　　　　　　　　　(VIMAL PRAKASH)

ROORKEE (U.P.)

SYNOPSIS

The h.v.d.c. power transmissi n is undoubtedly economical and efficient as compared to h.v.a.c. power transmission for transmitting large amount of powers over long distances. Comparative calculations regarding the advantages of h.v.d.c. power transmission as against a.c. have been carried out on various lines.

Various converting devices available have been discussed and it has been established that upto the present stage the grid-controlled mercury-arc-converters are the most satisfactory converting devices for converting large amount of powers at high voltages, because it can work both as a rectifier or as an invertor satisfactorily.

The economical and efficient range of d.c. power transmission depends upon the cost and efficiency of converting devices along with the amount of power to be transmitted and the length of the transmission route.

The cost and efficiency of the converting equipments largely effect the limiting distance for adopting h.v.d.c. power transmission. Detailed calculations as regards the effect of economy in cost and efficiency of the converting equipments on the limiting distance for adopting h.v.d.c. have been carried out.

-0-

CONTENTS

CHAPTERS PAGE

CHAPTER - 1

INTRODUCTION

The history(1,2) of Electrical-Power begins with direct current. The first electrical power source, the Galvanic-Battery, delivered d.c. and the first lighting systems were fed either from batteries or from d.c. - generators, or both in combination. In 1880, Thury(3) found in 'Edison-Laboratories of Distribution' by putting loads in parallel across constant voltage mains - a method that is now universal. This system was however working on 110 v.d.c. only, both at the generator and load end. Soon, however, a.c. superseded d.c. in generation, transmission, and utilization of electricity.

Why did a.c. gain such a predominant position? The answer is - economical generation of power, easy voltage transformation, simple and reliable motors, general flexibility of the system and so on.

The development of a.c. power system began in U.S. in 1885 when William Stanley, an early associate of Westinghouse, tested first transformer and Westinghouse himself brought the American-Patents covering the a.c. transmission system.

The early transmission lines and motors were single-phase. Soon the advantages of poly-phase systems were realised and there was a switch over from single-phase to poly-phase systems. Thereafter, the transmission of electrical energy by a.c. (especially three-phase) gradually replaced d.c. systems.

An a.c. generator is a simpler device than a d.c. generator, hence economical also. With a higher voltage of transmission, there are lesser losses in the line, and a smaller cross-section of the conductor is needed. So, one of the main reasons for the early acceptance of a.c. transmission was the

'Transformer' which makes possible the transmission of electrical energy at a voltage higher than the voltage of generation or utilisation. Now it is a universal practice from economy and efficiency point of view, to transmit electrical power at extra-high-voltage from the point of generation to the point of utilisation on long distances.

In recent years a rival(4) to a.c. long distance transmission of energy has come forward - 'The High-voltage Direct current Power Transmission'. Direct current offers, as will be shown, distinct advantages for certain transmission condition. For this reason comprehensive development work is being carried out for a number of years in various countries e.g. in Switzerland, Sweden, New-Zealand, and Germany, as well as in Soviet Union, in order to make h.v.d.c. power transmission a reality.

Upto the begining of the last decade no adequate methods of obtaining bulk d.c. power at high voltage either from low voltage a.c. or d.c. were available. Conversion of d.c. to a.c. was also a problem. The only method of utilising h.v.d.c. was the Thury method. In this method, the current is kept constant and the voltage of transmission is varied according to the power required. The Thury-system between Moutiers and Lyons, 128-miles apart, has a constant line current of 75 amps. and a maximum voltage of 125 k.v. But the main disadvantage of the Thury system is the fact that the line losses are constant at all loads.

It is an indisputable fact, that the generation of power as a.c. one is better from efficiency and economy point of view. Thus in the light of d.c. we can consider the question of transmission of power. The power is to be generated at the centre of source of energy (fuel or water head) as a.c. and after converting it to d.c., it may be transmitted to the centre of utilisation and can be used as a.c., after converting it back to a.c.; provided the power and the length of transmission route is beyond a certain economical limit. Alternatively, two existing a.c. power systems may be connected by d.c. power link and the power may be interchanged as and when needed in either direction.

The figure - 1 below illustrates schematically the arrangement of an h.v.d.c. power transmission.

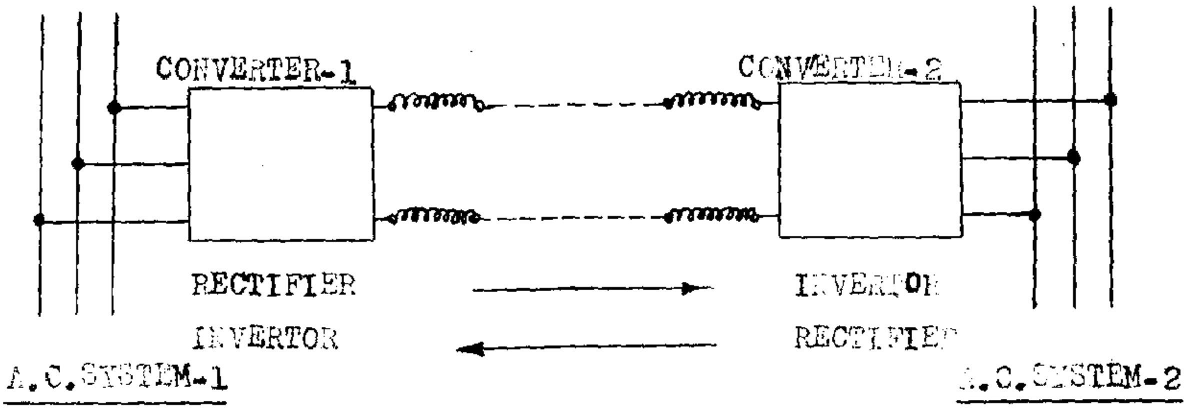


Fig.1- PRINCIPLE OF ARRANGEMENT OF AN h.v.d.c. POWER TRANSMISSION

The static power converters with a d.c. power link operate in tandem to connect the two independent a.c. systems. The d.c. link may consist of an overhead transmission line, or a land or submarine cable, or a series combination of overhead line and cable.

One of the power converters operates as a rectifier and the other as an inverter, depending upon the direction of flow of current required. The function of the inductors in the d.c. circuit is to smooth the d.c. and also to limit the rate of rise of d.c. if a short-circuit condition occurs in the d.c. link.

So we see converting devices - the rectifiers and inverters, play an important role in h.v.d.c. power transmission. As we are using the rectifiers and inverters in a h.v.d.c. power transmission system, the efficiency and economy of the system will depend mainly on the economy and efficiency of the converting devices.

Upto early thirties, the converting devices were not efficient enough and were also incapable of converting large amount of power. These devices were also much costly. But now various rectifiers of the mercury-vapour type are available which can handle large amount of power at high-voltages. Power can be transformed from a.c. to d.c. and from d.c. to a.c. with a very high efficiency and at reasonable cost. The first practical appearance of the controlled mercury-arc-converter was in late thirties and a practical solution to the converting problem became apparent in latter fourties.

Comparative calculations regarding the advantages of d.c. transmission as against a.c. have been carried out on various lines, and have been formulated(5) into the conclusion that the economical range of d.c. power transmission depends on the amount of power to be transmitted, the number of intermediate sub-stations, and the operating conditions of the system. Apart from these, one of the main item in the cost of d.c. power transmission is the cost of converting devices. The cost of converting equipment contributes a good percentage of capital to the total cost of d.c. power transmission. So the economical limit of d.c. power transmission will go on reducing with the reduced cost of converting devices. So to get the maximum economical advantage economical converting devices; or in other words the cost of converting devices will have to be reduced to the minimum possible limit. As the converting devices become more economical the h.v.d.c. power transmission can be applied to smaller route length of transmission.

Apart from the cost, the efficiency of the converting devices also plays an important role in h.v.d.c. power transmission. The limiting efficiency range of d.c. power transmission will vary with the efficiency of the converting devices. So the converting devices must be as efficient as possible, so that h.v.d.c. may be used on smaller lengths of transmission route.

-0-

CHAPTER - 2

ECONOMICS OF HIGH VOLTAGE DIRECT CURRENT POWER TRANSMISSION

For past several years the idea of using direct current instead of alternating current has repeatedly come under consideration for the purpose of transmitting large amount of powers over long distances, or more specifically for transmission over submarine or underground cables. The realisation of such plans had been prevented until 1950 on account of immature development of the high voltage converting equipments.

Substaintial developments had taken place in the last decade both in the d.c. and a.c. fields. The first 100-Km. commercial h.v.d.c. power transmission between two a.c. systems has been developed and placed in regular operation in Sweden, with a capacity of 40 M.W. at 100 k.v. direct current. A trial d.c. system had also been installed in the Soviet Union. Its operation has given very promising results.

At the first instant as we think of the transmission of power by direct current, it seems to be uneconomical due to additional cost required for converting equipments at either end. If the distance of transmission is long enough, however, the extra cost of the converters will not only be compensated by the reduced cost of the transmission lines (cables) carrying d.c. power, but it will render it more economical.

Requirement of Conducting Material:-

The cost of conductor is one of the most important items in a transmission system. The table 2.1(6) - below shows the ratio of the conducting material in a system compared with that in the corresponding d.c., 2-wire (mid-point earthed) system.

If we consider overhead lines or single core cables which alone are generally used with extra-high-voltage.

so that the maximum voltage to earth is the criterian the ratio of the conducting material required in the d.c. 2-wire system with earthed mid-point and the 3-ø, 3-wire system is

$$\frac{1}{2/\cos^2\phi} = 0.5\cos^2\phi$$

(cos ø is the power factor in a.c. system.)

S. No.	SYSTEMS	Same Max. Voltage to Earth
1.	D.C.; 2-wire (Mid-point earthed)	1
2.	D.C.; 2 wire	4.0
3.	D.C.; 3-wire(Neutral=$\frac{1}{2}$ Outer)	1.25
4.	D.C.; 3-wire (Neutral=Outer)	1.5
5.	1-ø; 2-wire	$8/\cos^2\phi$
6.	1-ø; 2-wire (Midpoint=earthed)	$2/\cos^2\phi$
7.	1-ø; 3-wire (Neutral=$\frac{1}{2}$ Outer)	$2.5/\cos^2\phi$
8.	2-ø; 4-wire	$2/\cos^2\phi$
9.	2-ø; 3-wire	$5.84/\cos^2\phi$
10.	3-ø; 3-wire	$2/\cos^2\phi$
11.	3-ø; 4-wire (Neutral=Outer)	$2.67/\cos^2\phi$

Table 2.1 - Ratio of conducting material required in different systems compared with 2-wire; D.C.(mid-point earthed) system, for same transmitted power, efficiency, and max. voltage to earth.

Thus if the p.f. is 0.85, the d.c. power system will require only 36 % of the conducting material required for a.c. .

From the above discussion, we may conclude that the cost of a d.c. transmission line is much less than that of a.c. transmission line. But at the same time the cost of terminal stations increases considerably in the case of d.c. system of transmission. There is a certain maximum distance upto which a.c. is economical but beyond that distance the d.c. system becomes economical.

Transmission of Power through Overhead lines:-

In Fig. 2.1[7], the curves of total cost are plotted against transmission distance for comparative a.c. and d.c. overhead power lines, at a fixed power level of 1500 M.W.

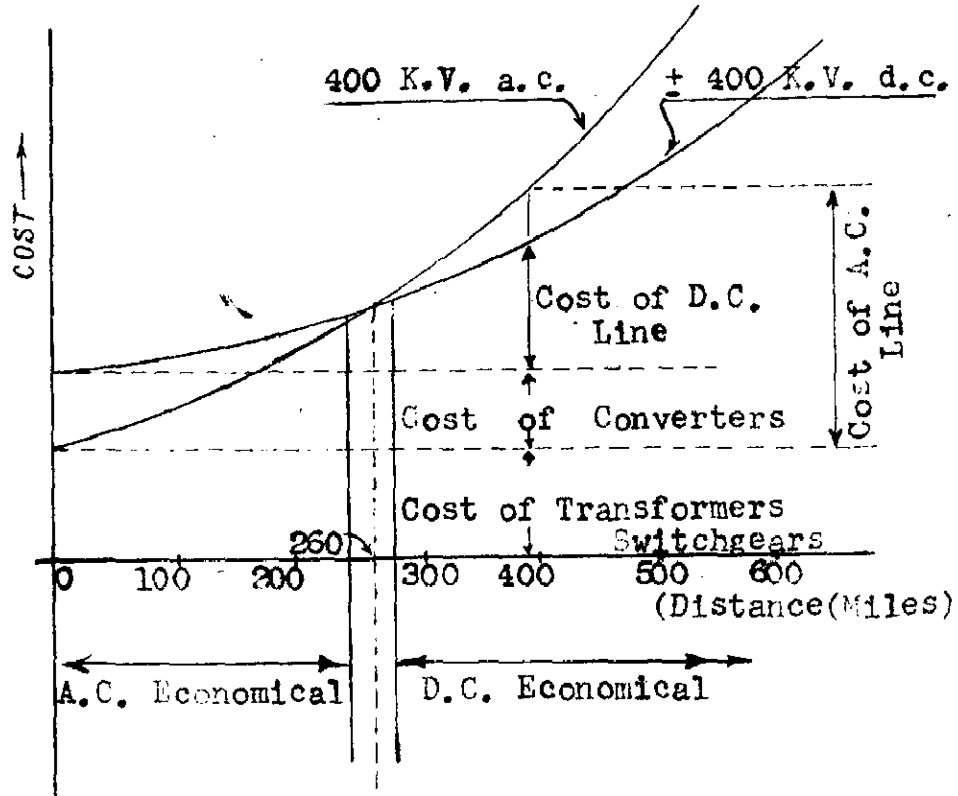


Fig. 2.1- A cost comparison of a.c. and d.c. over head power lines, transmitting a power of 1500 M.W.

In general the specific values of cost of different a.c. and d.c. power schemes cannot be compared as the price index applied to each factor in a study of this kind fluctuates through a wide range from time to time and country to country.

Only a comparative cost study can be made out. In above figure - 2.1 the cost of transformers and switchgears etc. for both the schemes are assumed to be the same, only the cost of converters at the terminal stations is added to d.c. system; that is why the curve for a.c. starts at a lower point on the cost axis than the curve for d.c. power line. For a short distance the cost of transmission line in the case of a.c. is greater than that for direct current. At about a distance of 240-280 miles it is difficult to say which power scheme will be more economical; but above this distance d.c. scheme becomes increasingly advantageous.

Estimated cost comparison for a.c. and d.c. overhead power schemes-

A number of projects were estimated in Sweden for both a.c. and d.c. power systems of overhead transmission. The result of few are tabulated below in table 2.2.

[illegible] →	[illegible]				[illegible]			
→	[illegible]		[illegible]		[illegible]		[illegible]	
→	[illegible]		[illegible]		[illegible]		[illegible]	
→			[illegible]		[illegible]		[illegible]	
	Millions Rs.	Rs./k.w.	Millions Rs.	Rs./k.w.	Millions Rs.	Rs./k.w.	Millions Rs.	Rs./k.w.
[illegible]	137.2	92.0	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	131.8	[illegible]	131.8
	-	-	-	-	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	225.4	150.0	133.3	178.5	279.2	186.1	147.6	197.2

[illegible] - [illegible] cost comparison of a.c. and d.c. system of transmission
([illegible] capital costs for 700- [illegible] ([illegible]-miles) overhead transmission.)

From the previous table 2.2 it is clear, that for the overhead transmission the d.c. power transmission is much more economical provided the distance (as shown in the table) of transmission is large enough, and of course the power and voltage of transmission is also large. The ratio of costs for a.c. and d.c., 440-miles long overhead line delivering 1800 M.W. at 400-k.v. from the table $= \frac{\text{Rs. 279.2}}{\text{Rs. 225.4}} = 1.24$; which can be verified from the figure 2.2, which is developed from Fig. 2.1, for a fixed power level of 1800 M.W.

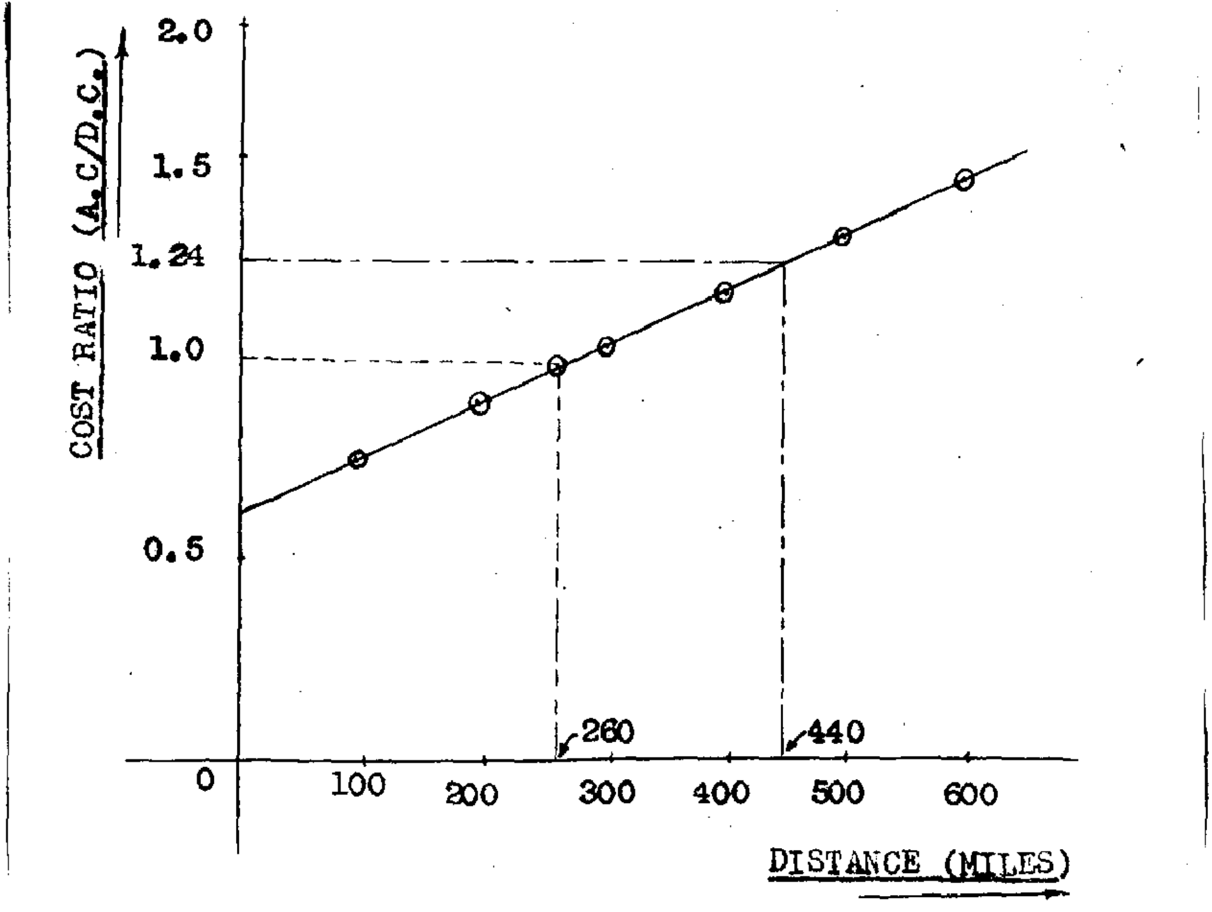


Fig.- 2.2 - COST RATIO A.C./D.C. V/S DISTANCE

Russians have also made a comparative study(8) of overhead d.c. and a.c. power lines from economy point of view. Calculations made for various overhead transmission systems indicate that the relationship between the optimal voltages is

[illegible] where V is the voltage of

one line pole to ground in the d.c. scheme, and U~ is the r.m.s. value of line to line voltage in the a.c. scheme. The total conductor cross-section selected in each scheme on the basis of economical current density is 1.5 to 2.5 times smaller for d.c. than for alternating current. When these relationships are observed, the d.c. line is always less expensive.

A cost comparison of two schemes was made for a.c. and d.c. overhead power line as tabulated below in table 2.3.

BASIC PARAMETERS	TRANSMISSION SYSTEM A		TRANSMISSION SYSTEM B	
	D.C.	A.C.	D.C.	A.C.
1. Length of line Km.	1000		2800	
2. Capacity M.W.	1000		6000	
3. Annual Energy transmitted Billion K.W. Hr.	7		42	
4. Voltage K.V.	± 500	500	± 600	600
5. No. of Circuits	1	1	1	1
6. Cost of transmitting 1 K.W.Hr				
(a) Kopeks	0.80	1.05	0.72	1.22
(b) Paisa Indian	3.92	5.15	3.53	5.98

Table 2.3 Economic comparison of D.C. and A.C. over head transmission systems.

From the comparison of the two schemes it follows that the use of alternating current for transmission system A is more expensive approximately by 25 % , while for transmission system B, this figure rises to 98.5 % .

Transmission of Power through Cables:-

If the transmission is done through cables, d.c. system of power transmission becomes economical even for a very small distance. A balance of cost may be obtained for a distance as short as twenty-miles, as shown in Fig. 2.3.(7) A comparative cost study can be made from the figure for two type of schemes. Moreover, in the case of transmission through cables, above thirty miles a.c. transmission becomes technically prohibitive for large amount of power at high voltages. This is due to the high level of the reactive charging current required at industrial frequency of a.c. system.

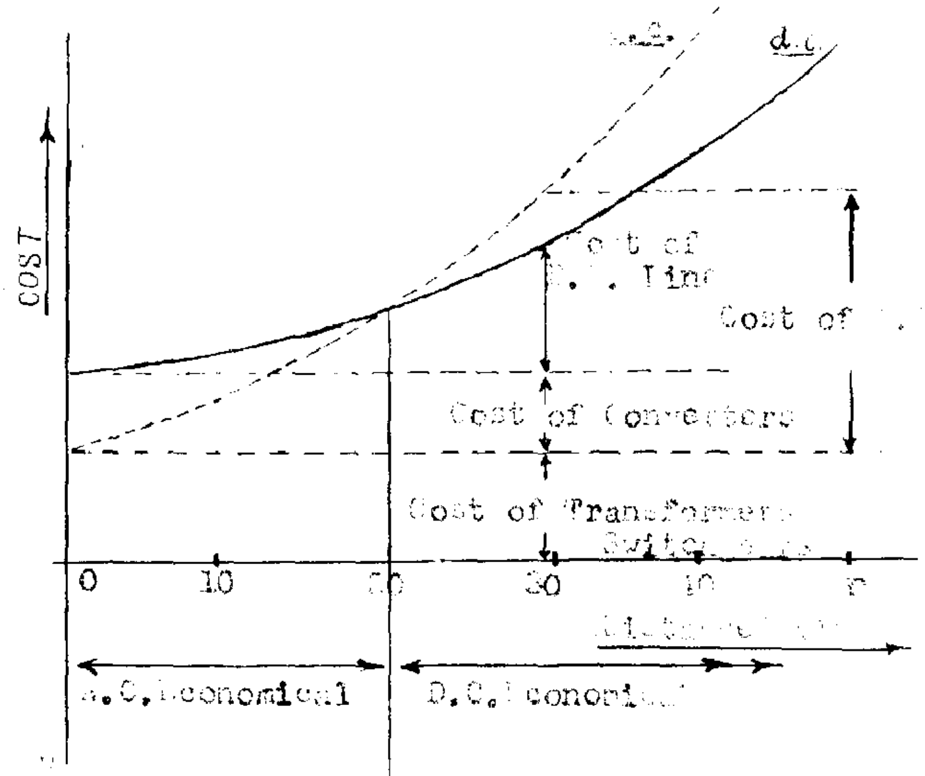


Fig. 2.3- A cost comparison of a.c. and d.c. transmission systems through cables.

The transmission of power as direct current, through cables is economical as compared to alternating current The cost of number of estimated projects in Sweden are tabulated in table 2.4.(15) (as shown on the next page.)

TYPE →	D.C.						A.C.							
CASE →	D_3		D_4		D_5		A_3		A_4(130)		A_4(220)		A_5	
CAPACITY (M.W.)	2X375		1X200		1X100		2X375		200		200		100	
VOLTAGE (K.V.)	2X300		1X200		1X200		220		130		220		130	
	million Rs.	Rs/K.W.	million Rs.	Rs./K.W.	million Rs.	Rs/K.W.	million Rs.	Rs./K.W.	million Rs.	Rs/K.W.	million Rs.	Rs/K.W.	million Rs.	Rs/K.W.
Both Terminal Stations	71·2	94·8	25·0	125	16·3	163	22·5	29·9	3·4	17·0	8·65	43·3	2·85	28·5
Reactors	—	—	—	—	—	—	2·76	3·68	0·74	3·68	1·66	8·28	0·83	8·28
Cable including 2 % Administration.	21·0	28·0	6·73	33·6	4·05	40·5	111·2	149	41·4	207	49·2	246	41·4	414
Transport laying jointing etc.	0·37	0·47	0·18	0·92	0·18	1·84	1·93	2·58	0·83	4·6	0·92	4·6	0·83	9·2
TOTAL	92·57	123·26	31·91	159·52	20·53	205·3	138·39	185·16	46·37	232·28	60·43	302·18	45·91	459·9

Table 2.4- A cost comparison for 60-Km. Submarine Cable Transmission a.c. and d.c. systems.

Now if we compre, project D_4 with project A4(220) when both are having a transmission length of 60 Km., and the power to be transmitted is 200 M.W., we conclude, the cost of terminal stations in the case of D_4 is 2.9 times as to that of A4(220), while the cable cost is only 13.6 % and hence in this way, the net total cost in the case of d.c. comes to 53 % (approx.) as that of a.c. system of transmission.

Taking into consideration the economy with d.c. power transmission also, 'Joint Technical Committee of British and French Engineers'(9) finally recommended in 1957, a submarine d.c. power cable link between English and French power grids through Cross-Channel. Both the possibilities of connecting the two power grids i.e. submarine a.c. power cable link and submarine d.c. power cable link will be about 20 % cheaper. The details of the cost estimation are shown below in Table 2.5.

ITEM	COST	
	A.C.	D.C.
1. Capital cost of terminal equipment and line	21.5 %	49.3 %
2. Capital cost of cables and installation(route length 25-miles - short route)	53.5 %	20.5 %
3. Capital cost of providing frequency control in Great Britain. (already provided in France)	9.3 %	-
4. Contingencies and Engineering costs	15.7 %	10.9 %
TOTAL	100 %	80.7 %

Table 2.5 - A cost comparison for submarine a.c. and d.c. power cable link between England and France.

As shown in table, the capital cost estimated with d.c. power link was only 80.7 % that required with a.c. power link. The total estimated capital cost of scheme was £0.5(18) Million (= Rs. 66.7 Millions). Thus a large saving was there with this d.c. power proposal.

-0-

CHAPTER 2

OTHER ADVANTAGES OF HIGH-VOLTAGE DIRECT CURRENT POWER TRANSMISSION

High voltage d.c. power transmission is not only economical as compared to an a.c. power transmission system, but there are few other advantages also. These advantages give a good incentive for adopting h.v.d.c. transmission, provided the power and distance of transmission are quite large. These advantages have been discussed below:

1. Efficiency of Transmission System:-

At the first glance, it seems that the d.c. power transmission system will be inefficient due to extra losses in the converting equipments at both ends. But if we make a comparative study of a h.v.d.c. and the corresponding h.v.a.c. power transmission system, we will find that the efficiency of transmission in case of a d.c. power transmission system is much beyond satisfaction.

All the losses in the conductor, in the sheath of the cable, in the dielectric or due to corona are rather greater with a.c. power transmission than with direct current. The losses, with normal power frequency a.c. are approximately 15 % greater than with d.c. Just as in the cost comparison, there is a limit of distance of transmission beyond which the losses in the d.c. power transmission turn up to be less as compared to those in a.c. power transmission. In the diagram below,(10) for a power level of 750 M.W. and annual energy transmission of 4-milliard (10^9) K.W. Hr., the total energy losses expressed in million K.W.Hr. per annum are compared at different distances of transmission. The station losses for all distances in both the cases are remaining constant. The line losses in the case of a.c.

power transmission at all distances. The line losses in the case of a.c. power transmission are increasing more rapidly with increase in distance.

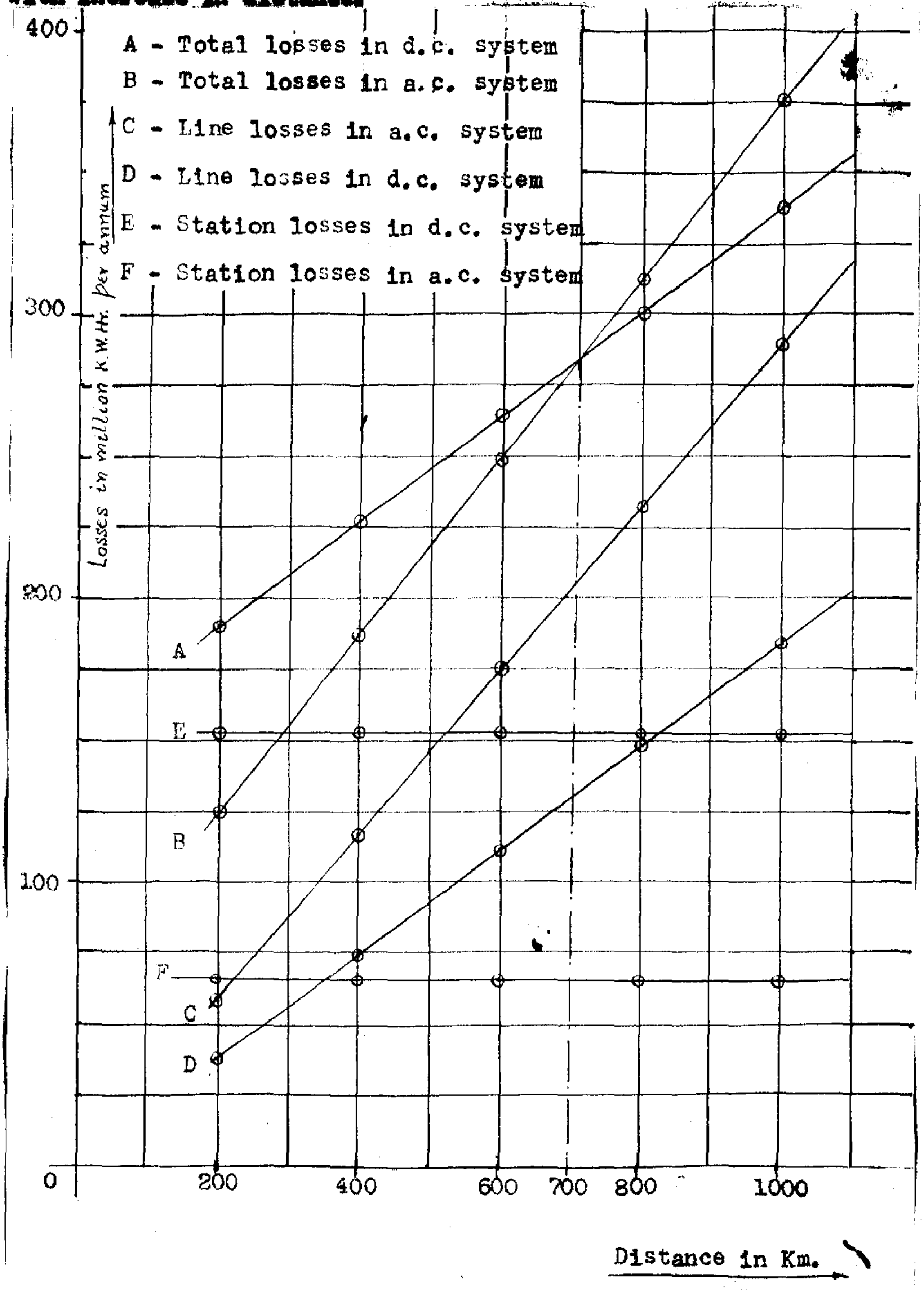


Fig. 3.1 - Graph showing losses in Million K.W. Hr. per annum

In this way with the curves of total losses in a.c. and d.c. power transmission, we get a limiting distance of 700-Km. for a fixed power level of 750 M.W.; beyond which d.c. system of power transmission is increasingly efficient.

The efficiency of the system is also effected by the power level of transmission. Greater is the amount of power to be transmitted, better is the efficiency of the d.c. system. As shown in the table below, the no-load losses in the case of d.c. converting stations are higher as compared to an a.c. terminal station. At higher loads the percentage of total losses in the case of d.c. power transmission are quite low.

Capacity	Transmission												
		Case	Station	Line	Station	Line	Total	Case	Station	Line	Station	Line	Total
[illegible]	O.H. Line	(700 K.V)	[illegible]		[illegible]	[illegible]	[illegible]	(400 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		(600 K.V)	[illegible]		[illegible]	[illegible]	0.61	(400 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]	Submarine Cable	(600 K.V)	[illegible]		[illegible]	[illegible]	[illegible]	(220 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]		(200 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(220 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
								(130 K.V.)	[illegible]	[illegible]	[illegible]	[illegible]	
[illegible]		(200 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	(130 K.V)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

The total losses for same power level in the case of large loads, is less in the case of d.c. power transmission as compared to those in case of a.c. power transmission. That is why, the efficiency at large loads is also better in the case of d.c. power transmission.

The Russians have also tried and compared the efficiency of d.c. and a.c. power transmissions. As in Russia the distance of transmission and the amount of power to be transmitted are quite large, they have compared the efficiency of long lines having high power levels. A comparative study of the efficiency of different a.c. and d.c. power transmission systems can be made from the following table - 3.2.

BASIC PARAMETERS	TRANSMISSION SYSTEM A.		TRANSMISSION SYSTEM B.	
	d.c.	a.c.	d.c.	a.c.
1. Length of the line(Km.)	1000		2200	
2. Capacity (M.W.)	1000		6000	
3. Voltage(K.V.)	±500	500	±600	600
4. Percentage losses -				
a) Line	2.74	5.33	8.84	12.15
b) Substation	2.70	1.44	3.20	2.19
c) Compensative device	-	0.58	-	1.40
TOTAL	5.44	7.35	12.04	15.74

Table 3.2 - Comparison of losses in D.C. and A.C. Transmission systems.

The above table shows that for system A, the line losses in the case of d.c. power transmission are only 50 % (approx.) of those in a.c. power system; but the terminal station losses are as high as 200 % . But the total losses in d.c. power transmission comes out to be 74 % of the losses in a.c. transmission, for a fixed power level of 1000 M.W., to be transmitted over a distance of 1000-Km.,

Similarly, in the case of system B, the line losses and the terminal-stations losses in the case of d.c. power transmission, are respectively 72.5 % and 146 % of those in a.c. power transmission. Hence the total losses in the case of d.c. power transmission are only 74 % of those in a.c. power transmission for a fixed power level of 6,000 M.W. to be transmitted over a distance of 2,200-Km.

From the tables-3.1 and 3.2 we can compare the loss estimations of two countries (Sweden and Russia). In table-3.1 the total losses in d.c. power transmission are 75.6 % of those in a.c. power transmission for a power level of 1800 M.W. over a distance of 700-Km. and voltages as ± 400 k.v.d.c. and 400 k.v.a.c. At the same time from table 3.2, the total losses in d.c. power transmission are 74 % of those in a.c. power transmission for a power level of 1000 M.W. over a distance of 1000-Km. and having voltages as ± 500 k.v.d.c. and 500 k.v.a.c. . Thus we find that for the two lines of somewhat similar specifications tested in two different countries, the order of the losses is approximately same; and hence the efficiency in case of d.c. power transmission is definitely better, provided the distance and amount of power to be transmitted is quite large.

2. Charging - Current :-

In long lines of high voltages the charging current, due to the line capacitance may have a considerable effect on regulation. Its tendency is to cause the voltage to rise from the sending end to the receiving end.

This charging current in the case of long distance transmission is considerably high. For having an idea of this charging current, take the example(11) of a 140-miles long, 132 k.v., 3 ø, 60 c/s , transmission line delivering 40 M.W. at 0.85 p.f. logging, with a line loss not exceeding 10 % of power delivered.

triangle 12' on a side. For this transmission line, the total charging current is approx. 60 A, as compared to a load current of $\frac{40 \times 10^3}{\sqrt{3} \times 132 \times 0.85} = 206$ A.

It is a very high current and is to be compensated in a.c. transmission line, while in the case of d.c. power line during normal operation, no power is required for charging the line.

3. Stability Consideration(12) :-

Apart from economical considerations, the main and foremost advantage with d.c. transmission is the stability of the system. By using d.c. for the transmission of electrical power, it is possible to over come the stability problems inherent in transmission by a.c. beyond certain limiting transmission distance.

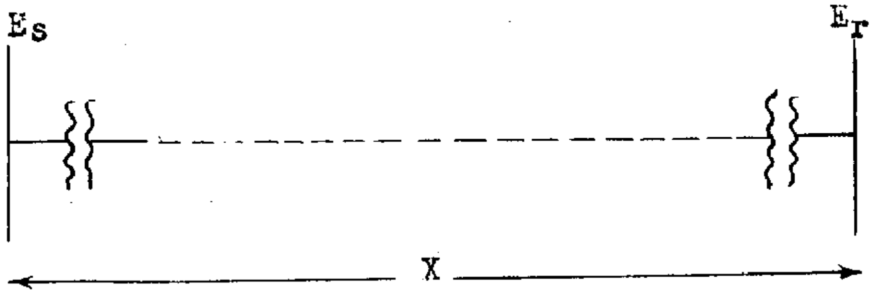


Fig. 3.2 - A.C. Power Transmission System.

In the case of a.c. power transmission, the stability problem is mainly due to the inductance of the transmission line. The inductance does not affect the transmission of power by direct current. The power 'P' which can be transmitted by an a.c. power line is given by $P = \frac{E_s . E_r}{X} \sin \delta$.

where δ is the phase angle between two voltages E_s and E_r, and X is the reactance of the system into consideration.

Now the maximum power 'P_M' which can be transmitted over the transmission line is given by

$$P_M = \frac{E_s \cdot E_r}{X}$$

(shown also in the diagram below)

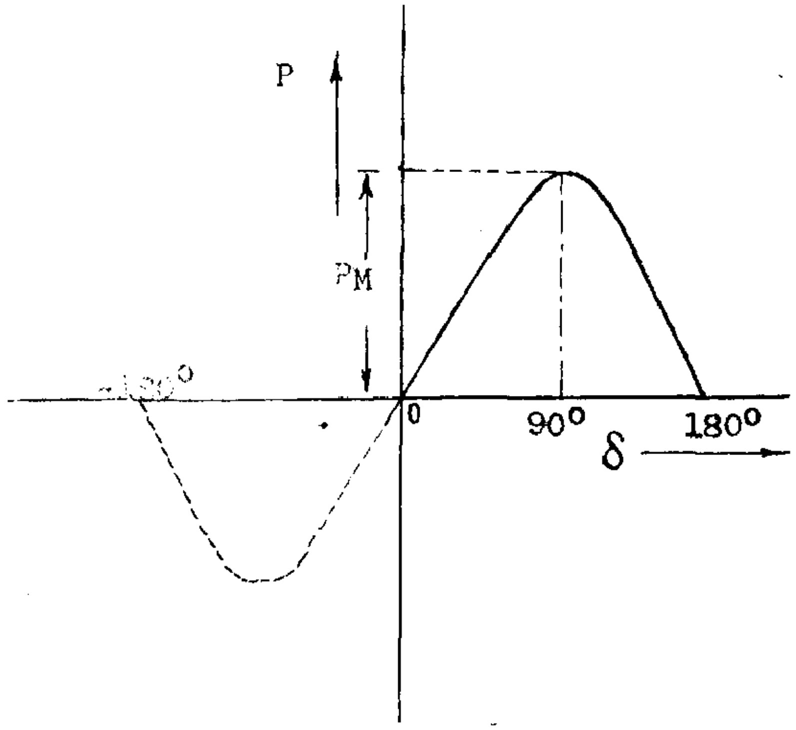


Fig. 3.3 - POWER STABILITY CURVE

If we want to transmit more power than P_M, while keeping E_s and E_r constant, we have to reduce the value of X - the reactance of the system. (of course neglecting resistance of the system).

There are number of ways adopted to increase the stability of the system. These are mainly to reduce the value of system reactance. Few of them are enumerated below;

a. Use of Series Capacitances.

b. Use of the Quadrature -Boosters.

c. Use of the frequency-charger. (transmit the power on some low frequency).

But still after using such costly and complicated us. These devices help us only partially. We have also to use very quick auto-reclosing circuit breakers on a.c. power systems for better stability, which are quite costly.

While if we consider the d.c. system of power transmission from stability point of view, the system is perfectly stable and any desired power can be transmitted over any length. There is no question of stability with d.c. power transmission.

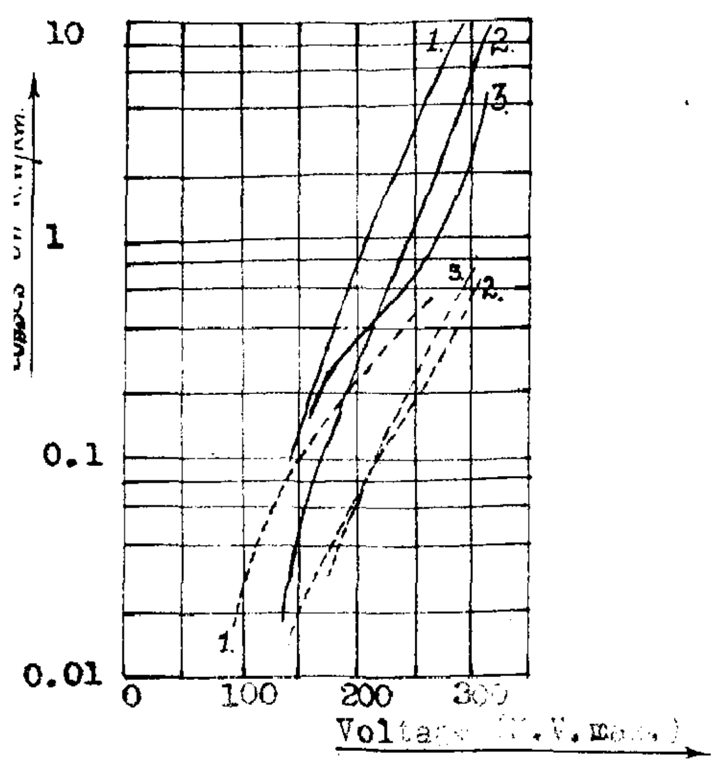
4. Corona Losses:-(2)

There is no direct mathematical relation to compare the corona losses in a.c. and d.c. high voltage power transmission lines. Only the experimental values may be compared and we get a comparative idea of these losses. Experiments have been carried out in Sweden, France and Russia on corona losses on d.c. and a.c. high voltage lines, under similar atmospheric and conductor surface conditions.

In Sweden the experiments were carried on a line 480-meters long with space for three conductors. The conductors were of steel-cored-aluminum with diameters of 27.7 and 33.9-m.m., The measurements were taken with a voltage applied between one on conductor and earth, and with the other two earthed.

From Fig. 3.4, it can be seen that the corona starts at approximately the same voltage for both direct and alternating (peak) voltages. The losses with a.c. increase much more rapidly than with direct current.

French investigations were carried out on two parallel conductors of 16 m.m. diameter (147 m.m^2 cross-section), 100-meters long and with 4- meters spacing.



- - - D.C. : —— A.C.

1. Heavy snow storm
2. Clear Sky (+ 2°C)
3. Clear Sky (- 10°C)

Fig. 3.4 - a.c. and d.c. corona losses, shown as a function of the peak voltage to earth.

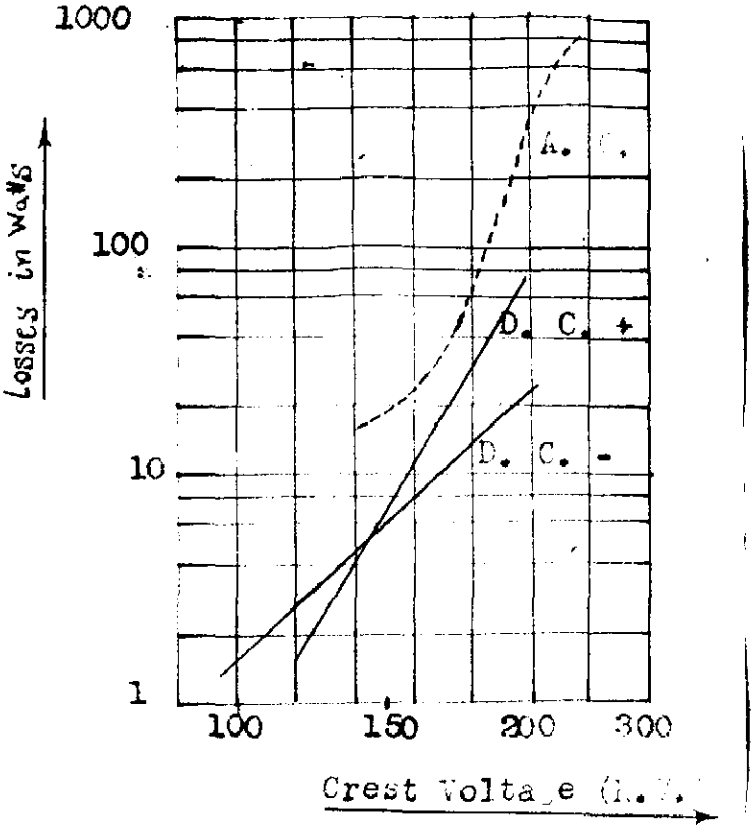


Fig. 3.5 - a.c. and d.c. corona losses in two conductors, one is energised and other earthed.

Fig. 3.5 shows, a.c. and d.c. losses under similar conditions. Out of two conductors, one being earthed and the other energised with direct voltage equal to a.c. peak voltage. It can be seen that losses with a.c. increase very rapidly as the voltage is increased and are considerably higher than in either the case of positive or negative polarity with d.c. (7).

Russians also carried out tests on a.c. and d.c. power lines in similar condition of weather. It was concluded, the average yearly corona losses for d.c. lines, contrary to the case of a.c. lines, is basically determined by the corona losses during clear weather. This is explained by the fact that during the worst weather (which for corona implies heavy rain, sleet and wet snow), the corona losses on d.c. lines rises by no more then ten times, whilst for a.c. lines they may increase by 100 times.

So in general, following are the overall conclusions of these experimental results.

1. The corona losses on power lines, as voltage increase, starts at approximately the same voltage for both direct and alternating(peak)voltage.
2. The losses with a.c. increase much more rapidly than with d.c., with the rise of voltage.
3. The corona losses in the case of a.c. power lines are considerably higher as compared to the losses in d.c. power lines.
4. In stormy weather, the corona losses on a.c. power lines increase by a greater percentage than the increase in losses on d.c. power line in stormy weather.

5. Insulation Level(2):-

We compare a d.c. power line of voltage $\pm \frac{V_d}{2}$ to a three-phase, a.c. line having the phase voltage as E_p. Both the lines are having the same size of conductor, same percentage losses and the same power is to be transmitted.

So losses on a.c. line $= 3 I_L^2 R$

losses on d.c. line $= 2 I_d^2 R$

Equating these losses we get, $I_d = \sqrt{\frac{3}{2}}\, I_L$ ----(1)

Now, power in the a.c. system $= 3 E_p I_L = \sqrt{3} E_L I_L$

(assuming $\cos \phi = 1$)

power in d.c. system, $= I_d V_d$

So equating powers we get, $3\,E_p I_L = I_d V_d$ ------(2)

from (1) and (2) we get $V_d = 3\sqrt{\frac{2}{3}}\,E_p$

It gives that for transmitting the same power, the voltage relation between the systems must be as $V_d = \sqrt{6}\,E_p$.

Now assuming, that the direct voltage $\frac{V_d'}{2}$ (say) is equal to the peak value of the alternating voltage to cause the break down of an insulator, and assuming identical internal and atmospheric conditions, we get

$$\frac{V'_d}{2} = \sqrt{2}\,E_p$$

$$\text{So}\quad \frac{V_d/2}{V'_d/2} = \frac{\sqrt{6}}{2\sqrt{2}} = 87\,\%\ ;\ \frac{V_d}{2} = 87\,\%\ \frac{V'_d}{2}$$

Now we see, the insulation level of line is $\frac{V'_d}{2}$, but we are needing only a level of $\frac{V_d}{2}$, which is 87 % of $V'_d/2$. So, the d.c. power line will not only have two conductors instead of three (of same size) as for the a.c. power line, but in addition the insulation level required will only be 87 % of that of a.c. power line.

A considerable saving will be there. For example the insulation of a 400 k.v.a.c. overhead line is sufficient for a d.c. line of a voltage rating of not less than 800 K.V. Moreover, the insulation level of the main sub-station equipment is the same for 400 k.v.a.c. as for 800 k.v.a.c. The considerably higher voltage for which d.c. power transmission plant can be designed at present warrants a higher transmission capacity for circuit, and correspondingly better economy.

6. Reliability of the System :-

From the reliability point of view, if the two pole d.c. power transmission is disturbed by an insulator or conductor failure or a fault at the terminal station, the transmission can go on operating on the other half; thus carrying at least half the rated capacity. On the other hand, on a single-circuit a.c. power transmission line, such faults generally cause a complete interruption of the power flow. So from the reliability point of view the two-pole d.c. transmission is superior to the single-circuit a.c. transmission of the same rating. The two-pole d.c. power transmission, thus, is more similar to a double-circuit a.c. line having in all six phase conductors, which is of course more expensive than the single d.c. power line.

Even if, an existing three-phase double circuit line is replaced by a d.c. power line, there will be three d.c. circuits compared with two a.c. power circuits, reliability tends to increase. If the earth is to be used as a temporary return circuit, there will be six d.c. circuits and their reliability of service is increased still more. The temporary loss of one conductor results in nearly 17 % loss of power capacity.

◆

CHAPTER - 4

PRESENT SCHEMES OF HIGH VOLTAGE DIRECT CURRENT POWER TRANSMISSION

Most of the present h.v.d.c. power transmission schemes under operation, installation or consideration are just for exchange of power as and when required between two existing a.c. power grids. Some times the distance of transmission is quite long. The longer the system, the more favourable will be a case for h.v.d.c. power transmission; of course if the power to be transmitted is large enough. If the water head or Nuclear-power is used for generating large power, the bulk of power have to be transmitted over long distances. High voltage d.c. power transmission can help us for such a transmission also. The possibilities of h.v.d.c. power transmission for this purposes are particularly attractive at present in Sweden and U.S.S.R.

Apart from the question of long distance transmission, there are two further incentives for the use of direct current. These are the interconnection of power systems having different frequencies, of which a good example is the Japan-power-link. The link connects two systems having frequencies as 50 c/s and 60 c/s for a power excahange of 300 M.W. at 250 K.V. direct current. Secondly, when power is to be transmitted in dense industrial city, as in U.K. and relatively less area is available for errection of towers; d.c. power transmission can help us in supplying the rapidly increasing loads through cables.

There are number of h.v.d.c. power transmission schemes under operation, commission, and consideration. The outlines of few of them are given below.

1. Gotland Power Link(35,40)

The world's first commercial d.c.h.v. power transmission in the Gotland link (Sweden) is operating since 1954. It was an efficiency and economy of the system. Connecting the Swedish mainland to Gotland through a 100-Km. submarine cable; the link can transmit 20 M.W. at 100 K.V. from the main land to Gotland, which have no water power source and thermal power generation is quite costly.

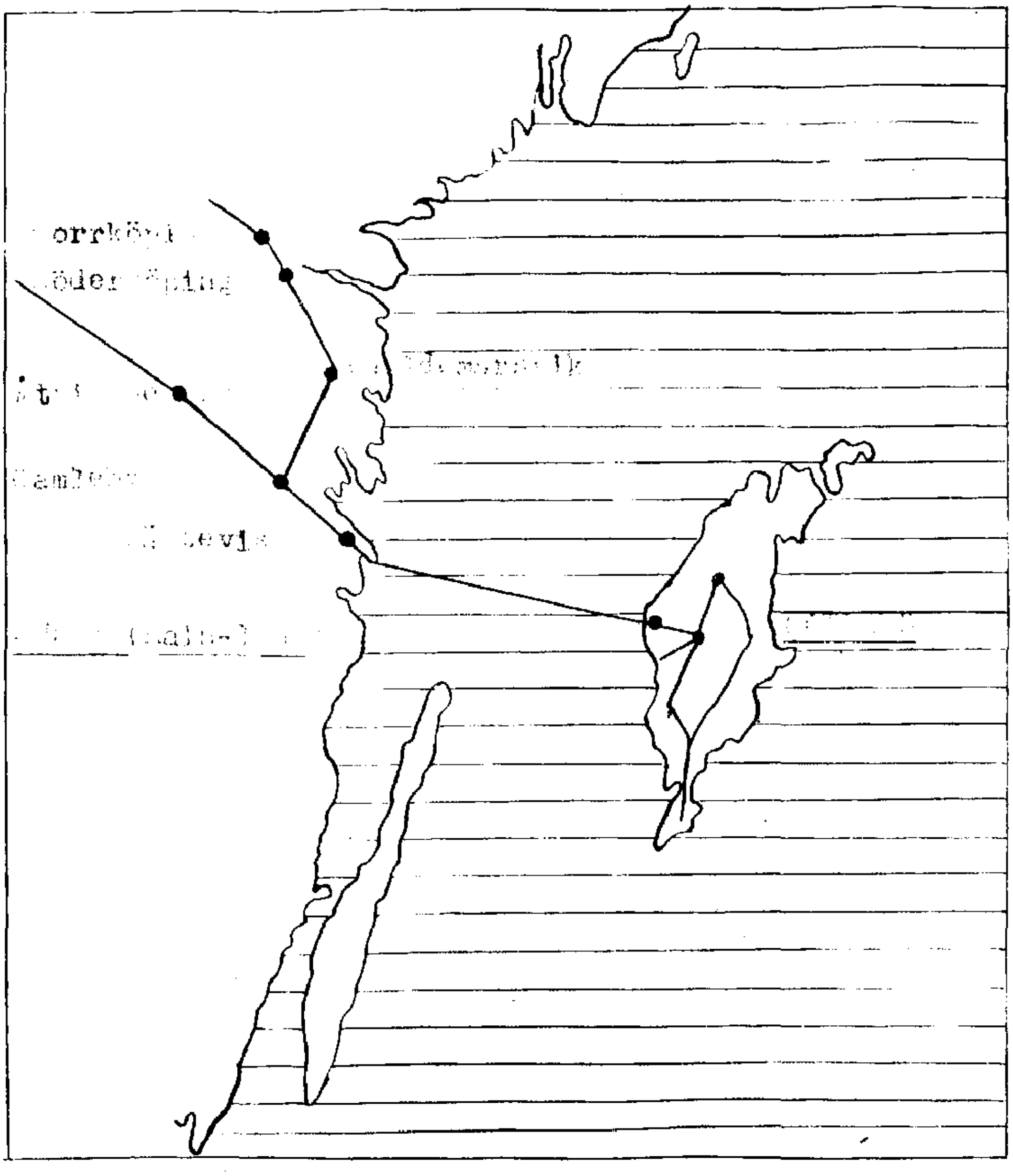


Fig. 1 - The h.v. d.c. transmission connects the 130 k.v. a.c. system on the Swedish mainland and the 30 k.v. system on Gotland.

An official investigation had shown that, when the post war prices of fuel. transport of power from the mainland would be economically justified if realised by h.v.d.c. The investigation also showed, on the other hand, that with this length of cable a.c. was out of question. The scheme has proved to be eminently satisfactory. In the second phase of construction, the rectifier installation was doubled in size and a further cable was laid, so that a power of 40 M.W. at a d.c. voltage of ± 100 K.V. will be transmitted; the neutral point of the system being earthed through the sea.

2. English Channel Scheme(9,17,18,19,20):-

There was a proposal to link British and French power grids so that the power may be exchanged in either direction in order to obtain a better flexibility in two systems. This power link was proposed just to reduce the need for new stand-by generating plant, because it is now possible to take the advantage of the fact that the peak loads in two countries occur at different times of the day.

Originally, the suggestion was made to lay four single core cables on the sea bed. Three of the cables would carry 150 M.W. of a.c. power at 132 K.V. and the fourth would act as a spare in the event of damage to any one of the other three.

Soon it was realised, the operation of an a.c. connection for a 150 M.W. power exchange would not be a simple problem. In this case British system would had to make a relatively expensive change over to automatic frequency control. The cable would have to be about 26-miles and it was found that the charging power for a 3- ϕ circuit of 100 M.V.A. would be 41 M.V.A.. So it would give rise to considerable operating problems.

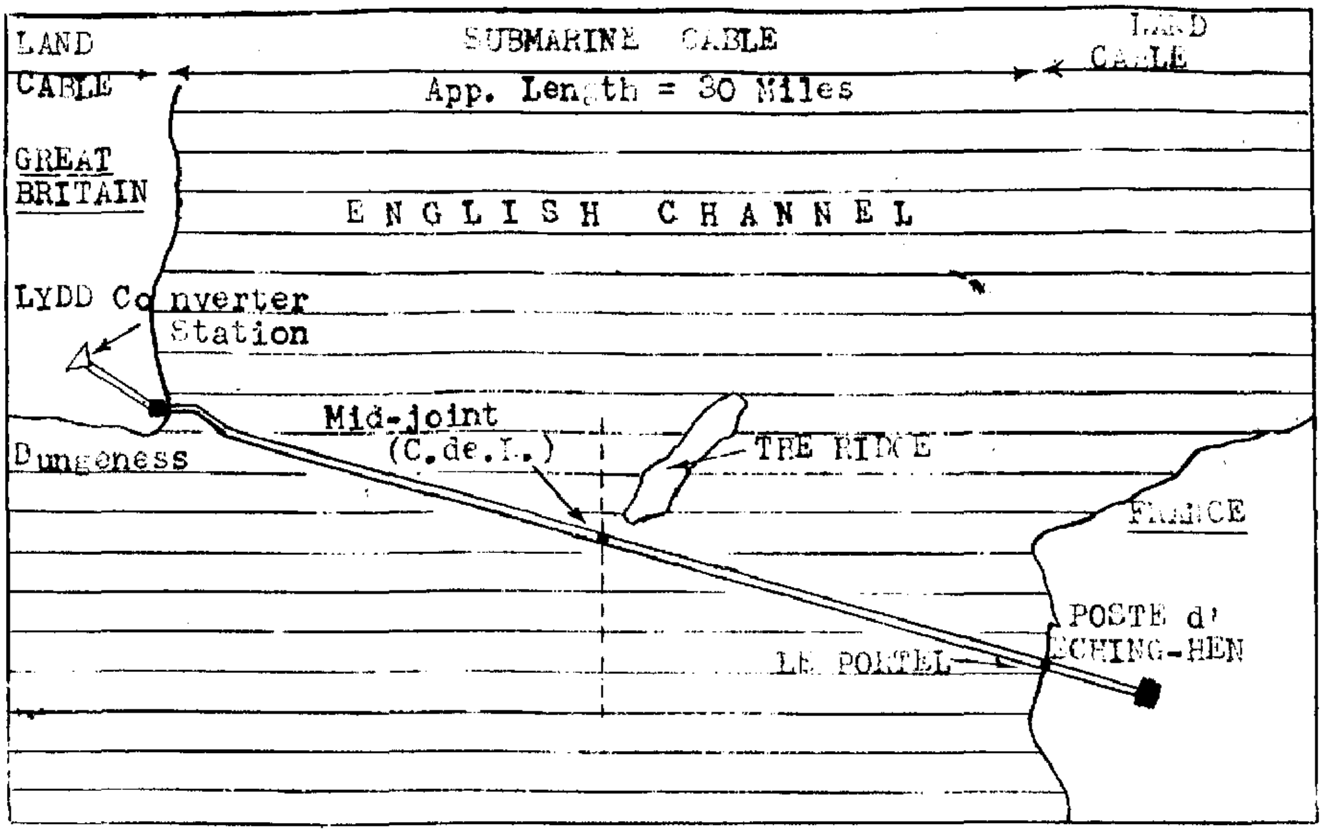


Fig. 4.2 - D.C. Submarine power cable thourhg Cross-channel between England and France.

The Gotland link was an incentive for thinking about d.c.h.v. transmission; and finally, the project committee recommended a submarine cable link about 60-Km. long in all, at ±100 k.v.d.c. between poles, carrying a load of 800 A, to give a power exchange capacity of 160 M.W.. The scheme which was officially inaugurated in Dec. 1961, is an economical and efficient one. There was an overall capital saving,(12) over the a.c. power scheme, of £0.5-millions(= Rs. 6.67 millions). The saving in cable cost of £1.6-millions(= Rs.21.3 millions) being practically offset by £1.1-millions(= Rs.14.7 millions) cost of the converting equipments. The estimated cost of the scheme was about £5 million (= Rs. 667-millions).

The losses in this scheme of d.c. power transmission are only one-third of the losses on a.c. system. This is not a negligible figure as the difference between a.c. and d.c. losses is about 150 K.W. per kilometer at full load or say 9 M.W. for 60-Km. cable route.

3. D.C. Power Scheme for New-Zealand [21,39] :-

A power link between the North and South Islands of New-Zealand is to be completed this year (1965). In the end of 1964 the system peak load in the North-Island has been 1,063.9 M.W. and in the South-Island 490.5 M.W. The division of this load between the two Islands is approx. 70 % in the North and 30 % in the South Island.

The hydro-electric potential of the South-Island is much greater than that of North, and can be developed more economically. In particular, the Benmore hydro-station in the South Island was scheduled for development, to provide an output of 600 M.W., and it is this station that is to be linked to the North-Island via the d.c. power scheme.

Among the d.c. schemes now either at work or under construction, any where in the world, the New-Zealand link is unique because of the amount of overhead line transmission involved. There will be a 500 K.V. (± 250 K.V.) overhead line from Benmore to Cook-Strait, and a cable crossing from there to Haywords in the North-Island. This d.c. power link will have a capacity of 1,200 A or 600 M.W. having the distances as, overhead line - Benmore to Cook-Strait (South Island) 335-miles; Submarine cable - across Cook-Strait 25-miles; overhead line - Cook-Strait (North Island) to Haywords 25-miles, and in this way the total length is as 385-miles.

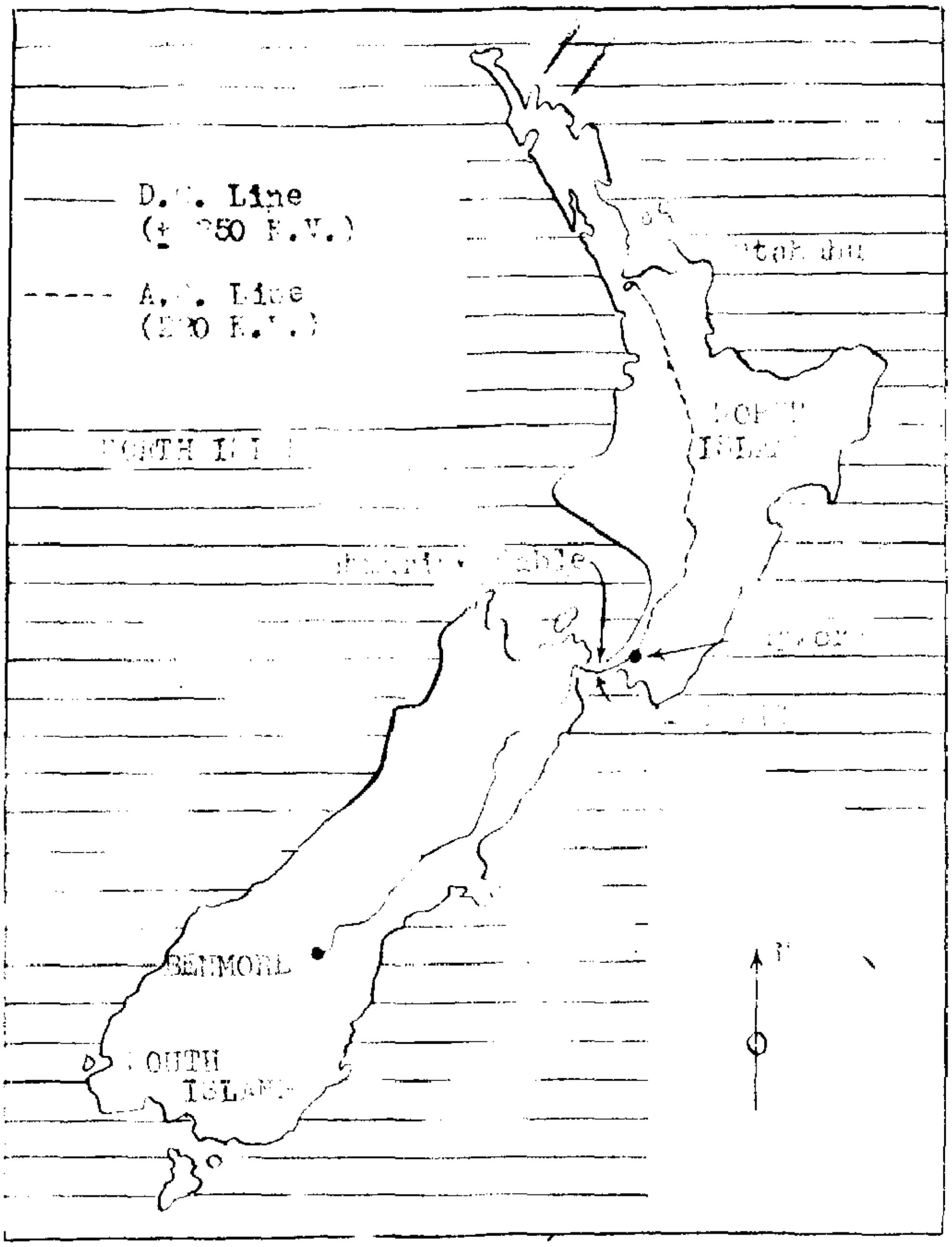


Fig. 4.3 - D.C. Power Scheme for New Zealand

The estimated cost of three cables scheme (one as spare) is worth about 18.8 million (= Rs. 250 million) against 28.3 million (= Rs. 377.5 million) for the a.c. equivalent. The cables are of gas filled type, using nitrogen at 450 lbs/sq. in. This pressure is 80 lbs/sq. in. higher than the greatest external water pressure. The 25-miles length will be made continuous without joints.

The converting equipment has the value of the order of 80-million Sweden crs. (= Rs. 73.6 millions). On South Island theconverters will be connected to the generator-voltage of 16 K.V.; 50 c/s, where as on North-Island they will be connected to the grid voltage of 110 K.V. 50 c/s. The most important part of the converting equipment consists of the mercury - arc electronic valves. Each converting station will have 28 such valves, divided into four groups.

It will be, noted, the power transfer of the inter-connection will not be reversible. Power will only be transmitted from South-Island which is rich in Hydro-electric power to be population centre - North-Island. This is in contradiction to the English-channel and Gotland projects.

4. Sakuma-Power Link (Japan)[46] :-

On the main Island of Hanshu there are at present two large, independent power grids, one operating with a frequency of 60 c/s and the other with 50 c/s. It has been decided to link these two grids together at Sakuma, and for this purpose ASEA (Sweden) will be supplying h.v.d.c. equipments. This equipment will permit the exchange of 300 M.W. in either direction at a voltage of 250 K.V.

The Sakma Project has been brought to fruition by the electric power development company. The converting stations is located near by Sakuma Hydro power station, which has an output capacity of 350 M.W. of either 50 c/s or 60 c/s and is well known as one of the largest hydropower station in Japan. The converting stations can perform frequency conversion at its rated output of 300 M.W. and can interconnect the Tokyo area (50 c/s) the Osaka area (60 c/s) and the Nagoya area (60 c/s) by means of the existing 275 K.V.a.c. transmission line. The work is going on very

6. The Konti-Skan Scheme (Sweden-Danmark)(2.3) :-

A project to transmit power between Scandinavia and West Germany was discussed and learnt that such a transmission had many advantages. Surplus hydropower could be sent to Germany during wet season of the year and in the other direction steam power from Germany could be sent to Scandinavia when there was hydro-power shortage. There was another advantage, the way in which the West Germany and Scandinavian system had evolved was different one from the other, and in one case the export of meagawatt might be advantageous while in the other case benefit could be obtained from exchanging mega-watt hours. There was also the possibility of diversity of peak demand giving other advantages, as in the case of cross-channel scheme.

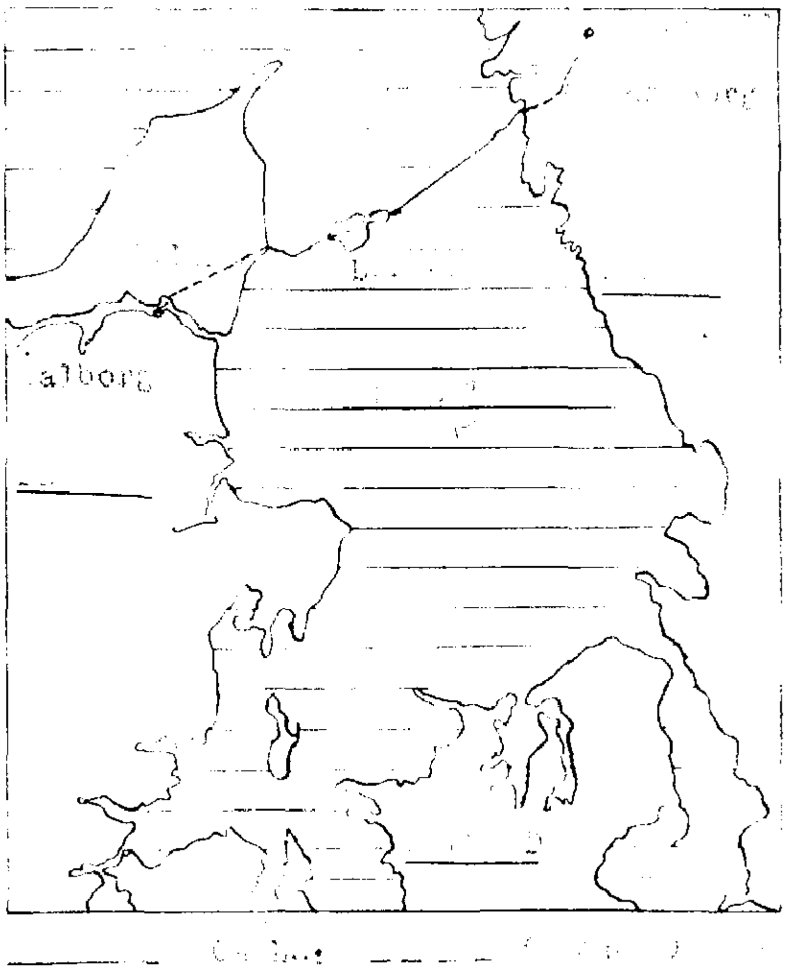


Fig. .4 - D.C. Power transmission route Konti- Skan link.

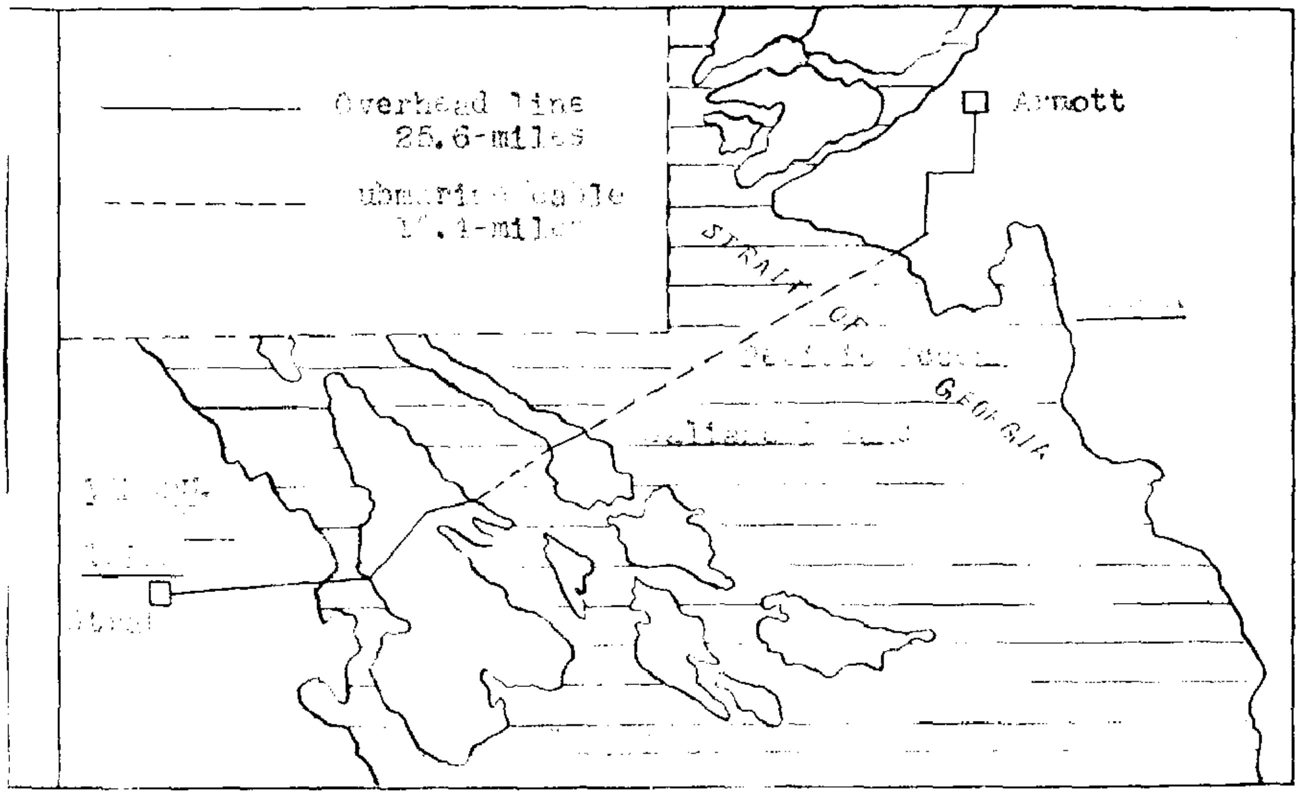
The link connecting the Swedish 400 K.V. network at Gothenburg with the 150 K.V. network at Ålborg will be commissioned this year - 1965. The latter network is inter-connected with the German network by a 220 K.V. double circuit line. The d.c. link will have a length of about 170-Km., including 75-Km. of cable; crossing the Kattegat, and 90-Km. of overhead lines. During the first stage, single pole transmission is to be employed, the sea being used as a return. The rated power of the link is 250 M.W., and the rated voltage 250 K.V. to earth. The link will be used for the exchange of power between Sweden and Denmark, and between Sweden and Germany via Denmark. During the first six years of operation, the link will transmit 250 M.W. peak power from Sweden to Germany for six hours every day. The total cost of the project is estimated near about 100-million Swedish crs.(about 19-million U.S. Dollers). In the ultimate stage the link may be extended to a double-pole transmission, for instance for 500 M.W. at ± 250 K.V.

7. Vancouver Island Link (Canada)(41) :-

A h.v.d.c. power link, the first on North American continent, to link the Island of Vancouver, off the pacific coast of Canada, with the mainland is proposed. It is all the more interesting because there exist already submarine cables across the Seventeen - miles Strait of Georgia, but these operate at 138 K.V.a.c. Thus it would obviously have been possible to extend the power transmission capacity of British Columbia Hydro Power Authority by a.c. means, but significantly d.c. was found to be technically and economically advantageous.

The firm of ASEA is responsible for practically all the h.v.d.c. power transmission developments outside the U.S.S.R., have again secured the contract, worth about 14-million Canadian dollers (= Rs. 66.6 millions), and the work will be carried out in three stages.

The first stage will allow a power transmission of 78 M.W. with 130 K.V. transmission voltage. The second stage will increase the capacity to 156 M.W., the transmission voltage being raised to 260 K.V. and the third and the final stage will provide a transmission capacity of 312 M.W. with 260 K.V. transmission voltage between poles.



The return path for the current will be through earth and sea. Normally, power will be transmitted only from the mainland to Vancouver Island, but it is stated that if power transmission in the reverse direction will be needed it could easily be arranged. The combined length of the transmission scheme is to be 43-miles, with 25.5 miles of overhead line and 17.5 miles of submarine cable. It is expected that the first stage of this new project will be in operation in Sept. 1967, and the second a year later.

8. Moscow-Kashira Link(U.S.S.R.)(14) :-

In 1950 a h.v.d.c. underground line had been brought into operation between Moscow and Kashira, 65 miles southwards. It was intended partly for experiments and partly for actual service, the power being inverted into the a.c. 110 K.V. network at Moscow. The transmitted power was 30 M.W. using single-anode converter valves of the Russian type VR-1, each rated 80 amps. at 120 K.V. The underground line was two single-core aluminium-conduct cables, paper-insulated and lead-sheathed, with an oil-resin impregnating, each cable being at 100 K.V. to earth. Later they were operated for more than 7,000 hrs, in all, with one cable at 200 K.V. and the other pole earthed.

9. Volgagrad-(Stalingrad) Donbass Link (U.S.S.R.)(37,42) : -

This link comprises a double-circuit d.c. transmission link 470 Km. in length, and two converting sub-stations, the Stalingrad substation, forming an integral part of hydro-electric station, and the sub-station in the Donbass. The power which can be transmitted in 750 M.W.

According to the project, the output of eight generators of the Stalingrad Hydro-electric stations will be transmitted to the Donbass. However, part of the output of these generators can also be made available at the 220 K.V. bus-bars of the hydro-electric stations.

When the energy is transmitted in the reverse direction the generators supply the K.V.Ar. requirements of Stalingrad substation(then operating as an invertor sub-station) and may, when required supply power to the 220 K.V. bus bars.

Out of 470 Km. length of transmission, 3.3 Km. is the length of ± 400 K.V.d.c. cable. The valves used are of the type VR-9, each rated 900 A at 130 K.V. In power and distance the scheme is, of course much greater than any existing scheme.

The summerised outlines of the main h.v.d.c. power transmission projects in commission, under construction can be seen from the following table:-(42)

Year	Country and Location	Voltage between poles k.v.	Length of route in Miles			Power Transmitted M.W.	Generation or Conversion System.
			Cable	O.H.	Total		
	a) Projects in Commission:-						
1950	U.S.S.R. (Moscow-Kashira)	200			72	30	-
1954	Sweden(Mainland-Gotland)	[illegible]	61		61	[illegible]	2-anode, MAV^s (Earth return)
1961	England France (Cross-Channel Link)	[illegible]	3[illegible]		3[illegible]	[illegible]	[illegible]-anode MAV^s
1963	U.S.S.R. ([illegible])				[illegible]	[illegible]	Single [illegible]
- - - - - - - - - -							
	b) Projects under Construction:-						
[illegible]	[illegible] (South Island-North Island)	[illegible]00	25	[illegible]	[illegible]	600	[illegible]
1965	Konti-Skan Scheme (Sweden-Denmark [illegible] Island of [illegible])	250	16	86	102	250	4-anode MAV^s single cable (Earth return)
[illegible]	Sardinia-Italy (via Corsica)	200	[illegible].5	135	258'5	200	4-anode MAV^s Single pole (earth return)
1965	Japan (Sakuma Frequency changer)	250				300	Multi-anode MAV^s conversion from 50 c/s to 60 c/s and vice versa
1967^a 1969^b	Canada-Vancouver Mainland of Canada-Vancouver Island	130^a 260^b	17.5	25.5	43	78^a 155^b 312^c	Multi anode MAV^s single pole earth return.

a - Ist stage b - Second stage c - Third stage

MAV^s - Mercury-arc valves

Table 4.1 - D.C. Power Transmission Projects in Commission and under construction.

Few Schemes under Active Consideration and Discussion (41) :-

There are number of h.v.d.c. power transmission schemes under active consideration and discussion listed (41) as below:-

1. Canada - U.S.A. (Hamilton Falls - Bastom and New-York via New-foundland) ---- 1000 K.V.; 4500 M.W., 1665 miles long.
2. U.S.A. Pacific North-West Pacific South west Intertie -- 800 K.V., 1,380 M.W., 840 - miles.
3. America -- East-west Zone Interties - 1,000 K.V.; 3,900 M.W.; 1000 - miles.
4. England - Kingsnorth into London - - 500 K.V.; 500 M.W., 55 - miles.
5. U.S.S.R. Krasnoyask, Eastern Siberia to the Ural Industrial area -- 750 K.V.; 12,000 M.W.; 1,553 - miles.
6. Iceland - Scotland Scheme -- 580 - miles.
7. Australia : Tasmania - Victoria -- 300 miles.
8. Australia : Tidal, Power in the north - west of western Australia - - 2,000 miles; 300,000 M.W.
9. Italy - Jugoslavia - - 300 K.V.; 450 M.W., 200 - miles.
10. Chile - Argentine - - 900 miles.
11. Japan ; Mainland and Islands.
12. Canada : Remote Northern Hydro sources into Ontario.

-o-

CHAPTER-5

VARIOUS CONVERTING DEVICES

The merits of d.c. have, however, never been doubted, and the interest in d.c. power lines has always been great. The main reason why h.v.d.c. transmission fell out of favour was that it was found impossible to combine h.v.d.c. transmission with a.c. generation and consumption owing to the lack of suitable conversion equipments.

It was May 1939, when first of all, a demonstration of grid-controlled steel tank mercury-arc conversion was given in Europe by Brown Boveri and Co. Ltd. The occasion was the fifth Swiss National Exhibition, at Zurich. At the Wettingen power station near Baden, 19-miles from Zurich, three-phase power at 6 K.V. was rectified to 50 K.V.d.c. Thence a d.c. current of 10 A, representing 500 K.W. was transmitted by a single overhead conductor, using earth return. The single conductor was actually the normal earth conductor of an existing three-phase overhead line. At the outskirts of Zurich the d.c. power was taken by an under ground cable, but the final run into the exhibition was given by single overhead conductor. Within the exhibition the power received as h.v.d.c. was inverted to its original three-phase 6 K.V. from and fed into the a.c. distribution system of the Zurich Electricity Works. This grid controlled mercury-arc-valve proved to be the only suitable converting device which practically solved the problem of conversion of large amount of power from a.c. to d.c. and vice versa; and the dream of h.v.d.c. power transmission in connecting two existing a.c. power systems seems to be an actuality.

In general the possible converting devices to get d.c. from a.c. or vice versa are as follows:-

1. Motor-Generator
2. Motor - Converter
3. Rotary-Converter
4. Mercury-Arc-Valves.
5. Semi-Conductor Devices.

In all rotating type of converting devices, the electrical energy is first of all converted to the mechanical one and then that mechanical energy is again converted to electrical form, and in this way a conversion from a.c. to d.c. takes place. Thereby giving greater losses in the device and a power efficiency as compare to a static device. High voltage d.c. cannot be obtained with the help of rotating converting devices. The maximum optimum value of voltage which can be obtained is 1500 V ; which is maximum value, can reliably and safely be applied to one commutator of rotating converters. For obtaining higher voltages, two or more machines must be connected in series, which greatly reduces the efficiency, increases the initial cost of the installation and introduces further operation difficulties.

Even if we are getting the rotating converting devices of some-what higher voltage ratings by their improved design and using better materials for insulation, and also sacrifising some efficiency and economy, there are number of other major disadvantages (16,22,36) with these rotating type of converting devices as mentioned below.

1. **Reliability** :-

Motor-generator consists of two entirely separate machines direct coupled and mounted on a common bed-plate. There are two running machines to consider, both subjected to risk of breakdown. The motor-converter and rotary-converter as being also rotating machines are less reliable as compared to a mercury-arc-valve —— a static device.

2. Efficiency :-

It is well-known, that the efficiency of a rotary-converter is higher than either that of a motor-generator or motor-converter. This is natural as the losses of two rotating machines will be higher than those of one rotating machine.

In a rotating machine, the losses are always greater as compared to a static machine. That is why, the efficiency of mercury-arc-converters are always higher as compared to all rotating type of converting devices. The normal value of efficiency in the case of low power of the order of one, two, five M.W. mercury-arc-rectifiers is about 96 % but with the units of very high ratings, the efficiency is of the order of 98.0 % - 98.5 %.

3. Overload Capacity :-

The rotary-converter has higher overload capacity than either the motor-generator or motor-converter. The rotary-converter can normally take 25 % overload for two hours. It can also work satisfactorily on voilently fluctuating loads provided in designing a properly constructed damper winding and good commutation conditions are obtained. While the mercury-arc-valve can take a overload as high as 180 %.

4. Synchronizing :-

All the rotating type of converting devices require proper synchronizing before they can be connected to a system. The fact that synchronizing is not necessary with the mercury-arc-valves is quite important. A considerable time is saved and much skilled-operaters are not needed.

5. Simple Operation and Minimum Attention :-

rotating converting devices, and its operation is much simple. There are no brushes, commutators, or sliprings to take care of. There is no dust spreading over the equipment. The ventilation of the equipment and building is also simplified as compared with rotating devices. No periodical lubrication and cleaning is needed.

6. Noiseless Operation and No Vibration :-

The absence of vibrations and noise in the mercury-arc-valves equipment makes it possible to install it in locations where rotating converting devices would not be used.

7. Sensitivity to Short-Circuit :-

Experiences have shown, that the mercury-arc-valves are not sensitive to short-circuit. Repeated reclosing on a short-circuit does not affect the mercury-arc valve. Under the same treatment a rotating converting device of the same capacity would be likely to flash over regardless of the protective devices.

Even if we tolerate all these disadvantages with these rotating type of converting devices, it is not possible to obtain high voltage d.c. of the order of 100/500 K.V. etc. with the help of these. Thus, the rotating type of converting devices are out of question with h.v.d.c. power transmission systems.

The Mercury-Arc-Valves (31,38) :-

The demonstration of a mercury-arc-device, as a fascinating source of light, on 7th Sept., 1860, by J.Th. Way in London, started a far reaching practical utilisation of the mercur arc. The discovery of the unidirectional property of a mercury po electrode was made by M.M.Jamin in 1882, but the recognition and exploitation of this important property as a significant engineeri feature was left to P.Cooper Hewitt, who had interested himself in the commercial application of mercury-arc-lamps, demonstrating th in 1901 on the occasion of the opening of the new building of the

Cooper Hewitt was searching for a method to operate his mercury-arc-lamps with a.c. In this effort he discovered that a device with two graphite electrodes and a mercury-pool electrode, when fed with alternating current, produced the flow of d.c. in a part of circuit and with great acumen he realised the technical significance of this discovery and started to develop and to manufacture mercury-arc-valves.

It was also Cooper Hewitt who recognised that ignition delay by charging the phase of the voltage applied to the ignition band around the glass vessel near the mercury pool could be used to control the mean value of the rectified voltage; but it was only after I. Lagmuir introduced the control grid in 1914 that the contro of the mercury-arc-valve became a practical proposition.

Glass was the material used for the envelopes of mercury-arc-valves constructed by Cooper Hewitt and the other manufacturers who at that time became interested in this new field. The first to succeed in making a partical steel-tank mercury-arc-valve was B.Schäfer, around 1911. His valve had multiple anode construction was a necessity in the design of the ignitor-controlled valve, the Ignitron.

Glass valves and Ignitrons were manufactured as sealed-off devices, that means that after final evacuation during the manufacturing process each valve was sealed off and no provision was made to pump it when in operation.

For a longtime, however, a high-vacuum pumping outfit was required as an ancillary requisite for steel tank valves, certain imperfections in the construction of such a valve making it necessary that it was pumped from time to time when in operation. In the course of time the difficulties in achieving vacuum tight seals were overcome and pumpless steel tank valves were developed and have come into general use.

Upto late thirties, all mercury-arc rectifiers were of multi-anode type with 6, 12, and 18 anode per tank. The trend has been to increase the number of anodes per tank to obtain a higher current rating per rectifier. This trend was changed by the introduction of the single-anode type Ignitron, followed several years later by the Excitron. Single-anode tanks or tubes, each containing one main anode and a cathod, are assembled in groups of six and twelve to make up a unit.

The single-anode type rectifier has largely superseded the multianode type in the U.S. for the following reasons.

1. Lower-arc drop and consequently higher efficiency.
2. Simpler maintenances, because individual tanks or tubes can be removed and replaced without affecting the others of the group.
3. Fewer sizes are needed, because higher ratings can be obtained by increasing the number of tubes per group.

<u>Connecting the Valves in Group</u>(26,32,34) :-

Mercury-arc-grid converters seem to provide the best solution so far 3-∅ a.c. conversion. They are made for voltages upto 60 K.V. and current 300 A. To obtain higher voltages, several converters can be connected in series, in which case the distribution of voltage between them should be regulated by parallel connection of condensers. However, since series connections of valves requires at least double the number of valves, and there is consequently double the voltage-drop in the arc, the method has been considered applicable only at very high d.c. power transmission line voltage.

With d.c., the switching problem is far more difficult and service-connection provides means of getting around the difficulties. It is of course possible to block the passage of current through a valve group by means of control grids. However, in the case of certain internal faults in the valves, this method is not reliable. On the other hand, it is always possible to take a converter unit connected in series with other converter units out of service merely by means of grid control. This can be done without disturbing the operation of the other units. For this purpose each valve group is equipped with a by-pass valve terminals of the blocked converter, thus leading the current part   the latter.

Thus, in the case of high-power-transmission, for natural reasons, there will be a number of series connected converters in each terminal station. It is convenient to have an even number of these and to connect the alternate rectifier transformer in D and Y. This increases the pulse number of the whole station from six to twelve and reduces the ripple and harmonies correspondingly. Plans have been drawn up from d.c. transmission systems with voltages of upto 400-800 K.V. between the outer pole and earth. However, study of a number of practical plans of the above type shows that the power has to be divided up over so many converters that the voltage per converter will seldom exceed the 125-150 K.V. mentioned above. On the other hand, the current strength can always be controlled by selecting an adequate number of anodes connected in parallel in each valve.

The Modern High-voltage Valve (24,27,30) :-

The ionic valves, more specifically, mercury-arc-valves, for high direct voltage, are, in principle, similar to those of ordinary mercury-arc-rectifiers for medium voltages. They thus consist of an evacuated tank in the bottom of which is a cavity, forming the mercury-pool cathod. In the same evacuated space there are one or more anodes, led in through vacuum-tight [illegible]

Composite with the cathod are associated devices for ignition and excitation. These maintain a cathod spot on the mercury-surface, which is a source of ample electrons emission and thus of the mercury-arc between anode and cathode. Since the arc is conducting only for current passing from the anode to the cathode, the ionic valve will have a unidirectional action.

A control grid in the arc-path serves, when given a negative potential to prevent the formation of an arc also when the anode is positive relative to the cathod. By reversing the potential of the grid to a positive valve, the phase of each cycle at which conduction through the valve begins can be controlled at will.

The high-voltage valve has its anode A, mounted inside a porcelain tube P, which is attached to the top of the valve tank. The Gatland valves have two such anode structures working in parallel. The ignitor I and excitation anode E are also led in through to the top of the valve tank.

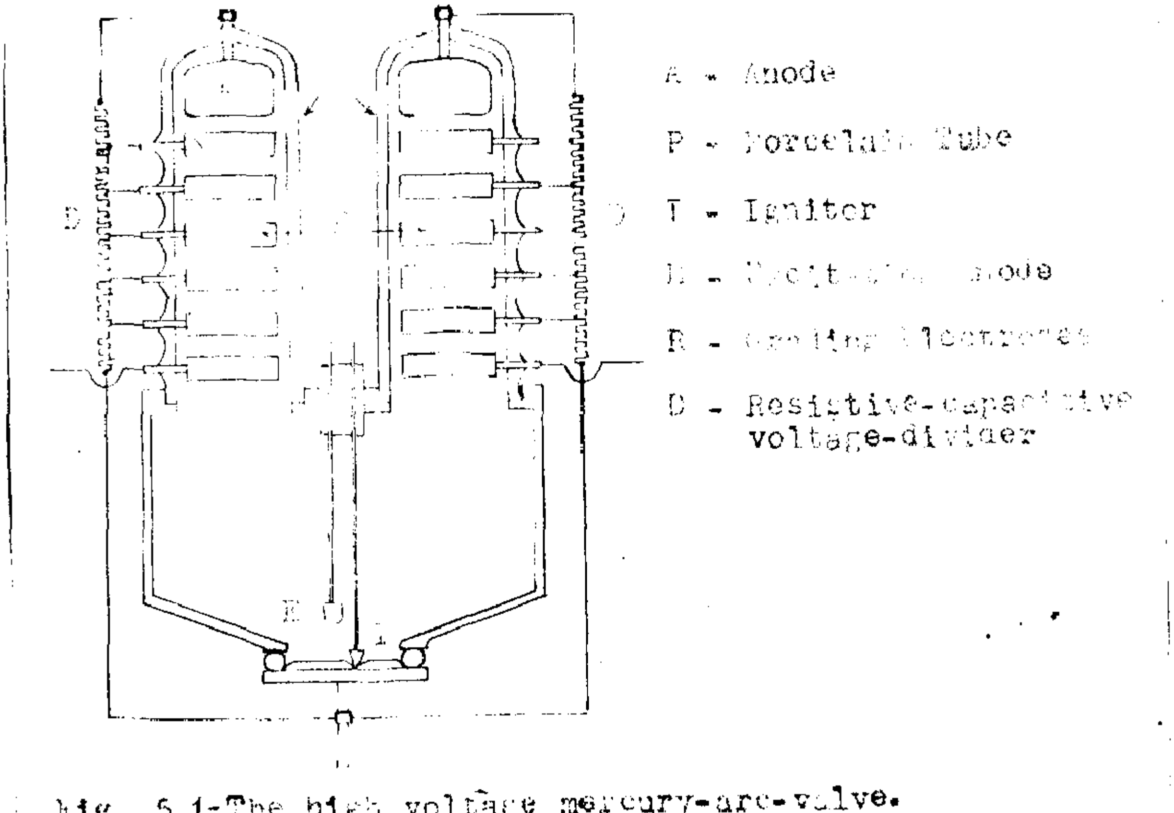


Fig. 5.1-The high voltage mercury-arc-valve.

The grading electrodes R, interposed between the anode head and the cathode vessel, are a characteristic feature of the h.v. valves. Their connectors are led in through the wall of the porcelain tube P and outside this they are connected to a resistive-capacitive voltage divider D. The grading electrodes serve to help the valve to with-stand the high reverse voltage, which is impressed on it during a certain part of the a.c. cycle, and also to with-stand the high positive voltage impressed on it during another part of the cycle, when the control grid is acting to prevent the valve from picking up current.

The All-Union Electrotechnical Institute has developed a 130 K.V. max. 900 A valve, for the transmission line Stalingrad-Donbass. This development was proceeded by through researches which proved the possibility of designing a large h.v. valve of the single-anode type.

The designs adopted for valve developments were accompanied by theoritical and experimental researches. In the course of these studies different types of valves have been developed, some of which deserve mentioning namely a 120 K.V., 150 A valve, a 130 K.V., 300 A valve, a 130 K.V, 750 A valve and a 130 K.V. 900,A valve, all single anode type.

Valves can today be offered for use in converters at a maximum operational direct voltage of 150 K.V. The current rating is dependent upon the number of parallel anodes, the normal converter rating to day being approx. 300 A for each anode in the valve. The arc voltage drop is 40-45 V.

In spite of the feasibility of series connection of complete converters there seems to be further economical justification for still higher voltages than 150 K.V. per converte Therefore, valve development is ebeing pursued towards higher voltages. An evaluation of the electrophysical picture seems to indicate that the same principles of valve design would permit an extension of the voltage range to 200-220 K.V.

The results of continued experiments at Trollhättan (Sweden) which are being carried out with the object of attaining still higher outputs, show that the designs for 125 K.V. are now a practical proposition and that a further extrapolation to at-least 150 K.V. is with in reach, using the same design principles. It is also confidently expected that the current valve per anode can be increased. However, in the end, the number of parallel anodes per valve will probably be determined on the basis of the economic optimum valve.

The Gotland scheme operates at 100 K.V.d.c. with two bridge connected converters in series. The valves of increased dimensions could be designed to increase this voltage to 150 K.V. A d.c. transmission at 300 K.V. with four bridge converters in series is thus well with in reach, furthermore, a voltage of 300 K.V. is adequate for the majority of d.c. transmission schemes so far proposed.

Valve Arrangements of Different Schemes :-

Now following are the outlines of the valve-arrangement of different schemes.

a) Gotland - Power Link :-

No account of the terminal converting stations associated with a h.v.d.c. transformer scheme can be made without extensive reference to the practice adopted in the Gotland Scheme. Swedish are so far ahead of the rest of the world in the operation of a successful plant is likely to form the basis for future endeavour for sometime to come.

The bridge connection of six valves for the three-phase full wave rectification appears to be universally favoured for h.v. rectification and inversion. This connection enables simple three-phase transformers to be employed. At each end of the Gotland line there are two such bridge circuits in series and a seventh valve, known as by-pass valve is added to each bridge. The by-pass valve in any group is only brought into operation in the even of a back fire in an associated rectifier or a persistant commutation failure in the associated invertor. The d.c. rating of each converter is 80 K.V., 200 A. With the type of valve designed by ASEA, the configuration of the cathod tank has little effect on the high-voltage behaviour of the valve the anode assembly being the vital part. Each of the Gotland valves has two such anodes in parallel that is to say the rating of each anode assembly is 100 A at 80 K.V. These figures refer to the current and voltage on the d.c. terminals of a compect six-phase group.

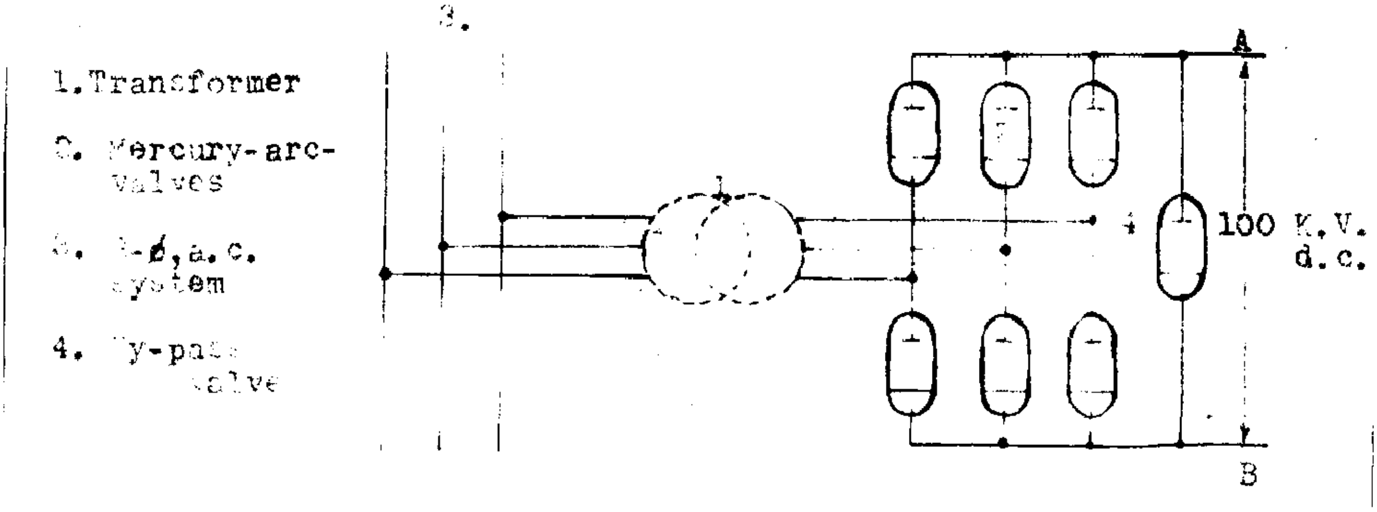


Fig. 5.2.- Converters in six pulse two-way connection. A and B are d.c. terminals.

2. English-Channel Link[18] :-

There are six valves in each bridge, with a by-pass-valve in addition. The two Graetz bridges are joined in series with the mid-point of the d.c. reactor which couples them together being earthed. Earthing will not normally be carried out at both ends of the link, to avoid a residual current passing through the sea, or the main current in case of fault.

Each valve, which stands about 10' high and is about 6' wide and 10' deep, has four anodes mounted on the steel tank containing the mercury pool cathod. The weight of each valve is about 5 tons. The current ratings of each anode is 200A, and thus each valve is capable of carrying 800 A.

The porcelain anode cylinders contain a number of grids spaced out over the distance from the anode at the top of the tank at the bottom. All but the bottom grid are intended for the purpose of distributing the potential over the length of the anode cylinder. These grids are connected externally to a potential grading network. The valves are mounted on insulators since the tank is alive at 100 K.V. to earth.

The valves for the English-Channel Project have the current and voltage ratings per anode which are twice those of Gotland-link valves. Since, in addition each valve has twice the number of anodes, that is to say, four, the power converter, 100 K.V; 800 A is eight times that of Gotland-link converters. The terminal stations contain two sets of mercury arc valves, each comprising six main valves and one by-pass valve. The rating of each set is 100 K.V.; 800 A,80 M.W. on the d.c. side the two valve groups are connected in series forming a 200 K.V.; 800A, 160 M.W. system.

3. New-Zealand Inter-Island h.v.d.c. Link(33):-

Mercury are valves are arranged in four 3-ø bridge circuits, in series on the d.c. side, and supplied on the a.c. side-through delta or star transformer secondries to give 12-pulses rectifiers. Each group is rated at 125 K.V. and 1200 A. The centre point of the d.c. circuit is earthed at each station and one pole (two groups) can be operated independently, in case of emergency, using the earth as a return path. A by-pass valve is provided in each group which allows current to continue in the event of a momentary valve fault within the group.

4. **Stalingrad- Donbass Link** :-

Each terminal station contains eight identical valve bridge-circuits (each designed for 100 K.V.), carrying out the conversion of a.c. into d.c. and vice versa. On the d.c. side all the valves may be connected in series. The voltage between poles is then 800 K.V. On the a.c. side pairs of adjacent bridge are connected to one transformer group consisting of three angle-phase transformers. The other transformer winding are connected to the 220 K.V. bus-bars to the hydro-generators of the Stalingrad hydro-electric station or to synchronous condensors or static capacitor banks (in the Donbass sub-station).

Semi-Conductor Devices (28,29,35) :-

In view of the remarkable properties displaced by modern semi-conducter type valves including adoptability to grid control, the question arises as to wheather they will supersede mercury-arc-valves for h.v.d.c. power transmission.

Semi-conductor power rectifiering devices can give a quite high converted power. But the main difficulty is with the voltage. They cannot give a high voltage, but may deliver very high currents. By proper circuit design, germanium power rectifier equipment may be produced to deliver upto 250,000 A, or more at voltage upto 300 V.d.c. The germanium rectifiers offer

high efficiency for the order

of 98- 98.5 %) and lighter weight among others. But at the same time they cannot be operated in series to get high voltage due to variation in their characteristics, from unit to unit. Even though by connecting the units of similar characteristics in series we may go upto a voltage of 3 K.V. but not higher than this. The use of this voltage is made in railway-traction. The voltages of the order of 100-200 K.V. is still beyond practicability. That is why upto the present time, the use of semi-conductor converting devices are out of question for h.v.d.c. power transmission.

The working value of voltage depends on Geometrical consideration of the width of the regions between adjacent junctions and the properties of the four semi-conductor regions. In order to obtain high reverse voltage it is always necessary to commence production with an extremely pure silicon crystal. The higher the purity the better will be the possibile voltage rating.

So after starting with a crystal of the highest purity the voltage rating will be influenced by the processes, many of which are secret, through which the device passes when being manufactured, extreme purity of atmosphere during manufacture is essential.

It is clear that the semi-conductor-converting devices have been developed upto the point of replacing the thyraton, but the development has still a long way to go before the new devices can replace the mercury-arc-rectifier.

It is difficult to envisage that the semi-conductor conversion devices will ever reach the stage of replacing the highly developed and extremely robust (as far as high voltages and large power are concerned) mercury-arc-valves. However, development in the field of solid state physics are occuring at such a rate that features tending to limit application at present time may be things of the past in a decade or two. For heavy power and high voltage duty as required in h.v.d.c. power transmission, the mercury-arc-valves still hold a place of pride. Mercury-arc-converters, that is rectifiers and invertors with mercury-arc-valves, have gained a position within this field which is likely to remain unchallenged for a long time.

-o-

CHAPTER - 6

ROLE OF RECTIFIERS AND INVERTORS

The main equipments needed with h.v.d.c. power transmission are the converting devices. It contributes a good percentage of the capital cost and the losses towards the total cost and the efficiency of a system. Upto present time, the only suitable converting device for getting h.v.d.c. from h.v.a.c. or vice versa is the mercury-arc-converter . It plays an important role in h.v.d.c. power transmission.

The converter-valves are the actual mercury-arc devices which are utilised in the three phase converter bridge which is the heart of the converting station. Almost all the manufacturing firms dealing with h.v.d.c. power transmission, are supplying the mercury-arc-valves as a part of equipment for complete converting stations. The firms do not market individual valves. That is why it is not possible to give generalised prices for the converting equipments. Roughly we can say, that the costs of the electrical equipments for a terminal converter station can vary from £ 5 per K.W. installed to £ 9 per K.W. installed dependent on so many factors.

According to English Electric Co., the cost of complete converter terminal stations is dependent on a variety of factors. Some of the major factors which determine converter station's price are:-

1. Station power rating.
2. A.C. harmonic filter requirements.
3. Number of series and/or parallel valve groups.
4. Type of power flow control.
5. Situation of station (e.g. in cities or in open country).

6. Short circuit ratings of A.C. system.
7. Nature of D.C. lines (overhead, or cable etc.)

Apart from these, there are number of other factors influencing the cost of the terminal stations. The price also varies from time to time and country to country. It is also fair to say that the price is also influenced to some extent by the following factors.

1. As station power rating increases, the price per K.W. decreases (within limit).
2. Stations in heavily populated areas tend to be more expensive than rural stations.
3. A weak A.C. -- system will necissitate more expensive converter station equipment.

Effect of Economy in Converters :-

Normally, the cost of the converting device, exclusive of all additional auxillaries lies between 20 to 30 or 35 % of the total cost of the terminal station. On the basis of the estimations of projects in Sweden the total cost of terminal stations can be roughly divided as follows(15):-

1. Conventional Apparatus	5 %
2. Transformers	30 %
3. Valves	30 %
4. Synchronous Condensers	20 %
5. Erection	15 %
Total	100 %

Japanies are quite pessimistic in estimating the project costs. In their estimations, the cost of the mercury-arc-converters without any auxillaries is as low as 12 %

to 20 % of the total cost of the terminal stations.

Now for studying the role of economy in converting devices take the estimated cost data(10) of 750 M.W. power link which corresponds to the design power capacity of the 800 K.V.d.c. power transmission line from Stalingrad hydro electric station to Donbass. The length of the transmission line has been varied between 200 to 1,000 Km. The 400 K.V.a.c. overhead line has been considered as constructed on free-standing portal towers, erected on foundations of prefabricated reinforced concrete blocks.

The d.c. sub-stations are equipped with converters, mounted indoor. Each connection of the converter equipment comprises eight bridge-circuits with two valves in series in each of the arms of every bridge. The parameters(10) of the valves are as follows:-

1. Max. magnitude of the valve current - 900A
2. Average value of the valve current - 300A
3. Amplitude of the anode voltage - 130 K.V.

Length of line in Km.	[illegible]							
	[illegible]			A.C.				
	[illegible]	Both terminal stations	[illegible]	Line	Both terminal stations	Series capaci-citor	Re-actors	Total
200	[illegible]	[illegible]	[illegible]	[illegible]	110.8	-	-	172.8
400	82.0	[illegible]	[illegible]	128.0	110.8	-	-	238.8
600	133.0	[illegible]	[illegible]	186.0	110.8	-	4.0	300.8
800	164.0	[illegible]	[illegible]	248.0	110.8	16.0	6.0	380.8
1000	205.0	[illegible]	[illegible]	310.0	110.8	30.0	8.0	458.8

Table 6.1(11) - Costs in million of roubles for transmitting 750 M.W. on overhead lines over various distances.

The details of the estimation of cost for different a.c. and d.c. power lines are shown in table - 6.1, on previous page.

The total cost curves for a.c. and d.c. power transmission systems against the distance in kilometers are shown in Fig. - 6.1 on the next page. The total costs of two systems are equal, when the line length is approx. 760-Km.

As shown in the table - 6.1 the terminal stations cost remains somewhat constant. The cost of line varies with distance. Initially, the total cost of a.c. power system is low as compared to the cost of d.c. power system of same transmission length. But beyond a length of 760-Km., the d.c. system of transmission becomes increasingly economical.

Here the estimated cost of both d.c. terminal stations is 208.3 million Roubles - a constant value. Now as the cost of converters varies from 20 % to 30 % , exclusive of all auxillaries, we assume the cost of converters as 25 % of the total cost of stations. So the net cost of the converters of both terminal stations exclusive of all auxillaries is 51.6 million Roubles. It is assumed to be the present cost of converters in the terminal stations.

Now suppose we improve upon converters from economy point of view, and let the improved converters have a cost as 90 % of their present cost, the total cost of d.c. power transmission system will reduce, and therefore the limiting distance for a.c. and d.c. transmission systems will also reduce from 760-Km. to 730-Km. as can be seen from Fig.-6.1.

So in this way from Fig.-6.1 the limiting distances for various improved converters from economy point of view can be obtained The limiting distances against the converters costs as 90 % , 80 % - - - - etc. of their present cost are shown in Fig.-6.2 on

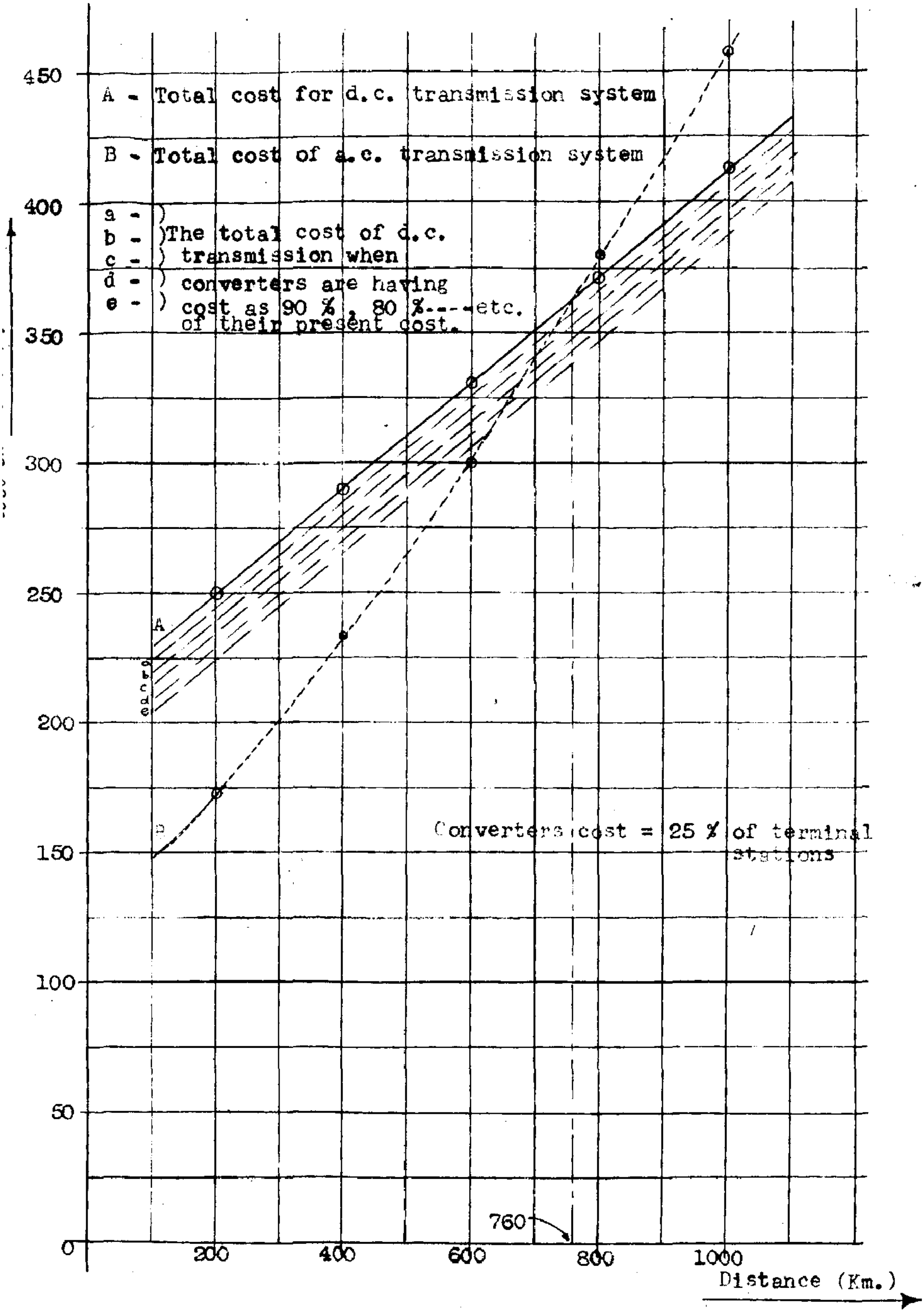
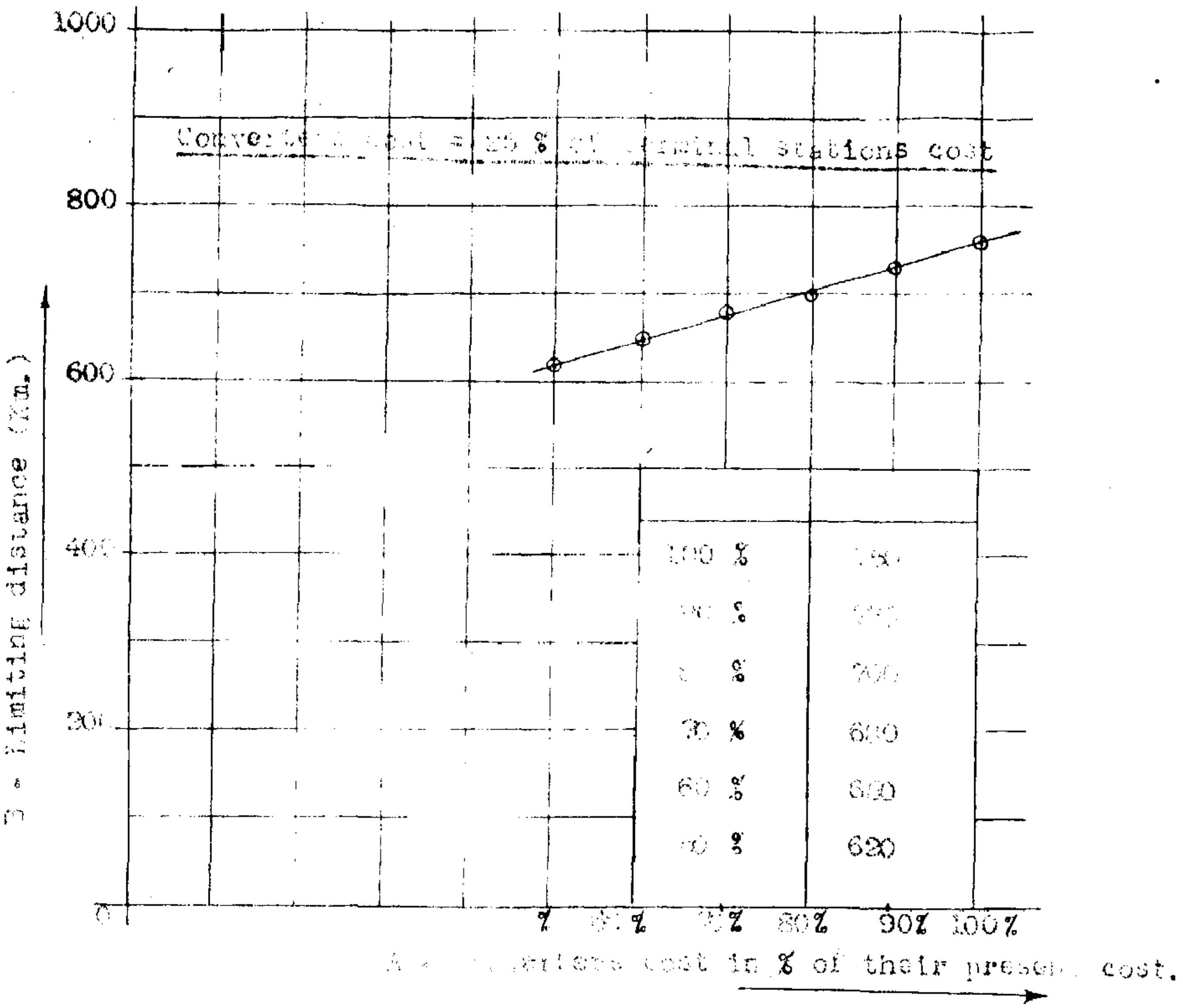


Fig. 6.1 - Total cost of d.c. and a.c. power transmission systems against the transmission distance in kilometers.



100 %	760
90 %	730
80 %	700
70 %	680
60 %	650
50 %	620

[illegible] - Limiting distance of d.c. transmission, against the percentage of present converters cost.

So it is concluded, that with the present cost of the converter, the limiting distance for adopting d.c. power transmission is 760-Km. beyond which d.c. power transmission is increasingly economical. However if there is a improvement upon the converters from economy point of view, and somehow we obtain economical converters having cost as low as 50 % of their present cost, the limiting distance for adopting d.c. power transmission reduces from 760-Km. to 620-Km. It can also be seen that the limiting distance varies linearly with the reduction in cost of the converters.

In the above discussion, the consideration of auxiliaries to be supplied with converters was not taken at all. In a similar type of derivation, now take a somewhat optimistic side and take the cost of converter along-with their auxiliaries such as harmonic filters, d.c. smoothing reactors etc. as 50 % of the total terminal stations cost as detailed below.

1. Cost of the converters	30 %
2. Cost of transformer-extra-auxiliaries	10 %
3. Cost of the other auxiliaries	5 %
4. Cost of the extra erection charges	5 %
Total	50 %

So, with 50 % cost of converting equipment, the cost of converting equipment for both d.c. terminal stations comes out as 104.15 million Roubles. Now as previously, again consider the reduction in cost of converting equipment along with auxiliaries and obtain different limiting distances beyond which d.c. power transmission will be increasingly economical, as shown in Fig.-6.3 on the next page.

Now, as shown in Fig. - 6.4, on page 64, it is concluded that if there is an improvement upon the converting equipment along with their extra auxiliaries from economy point of view, and somehow the cost is as low as 50 % of the present cost; the limiting distance for adopting d.c. power transmission reduces from a distance of 760-Km. to a distance as low as 460-Km.

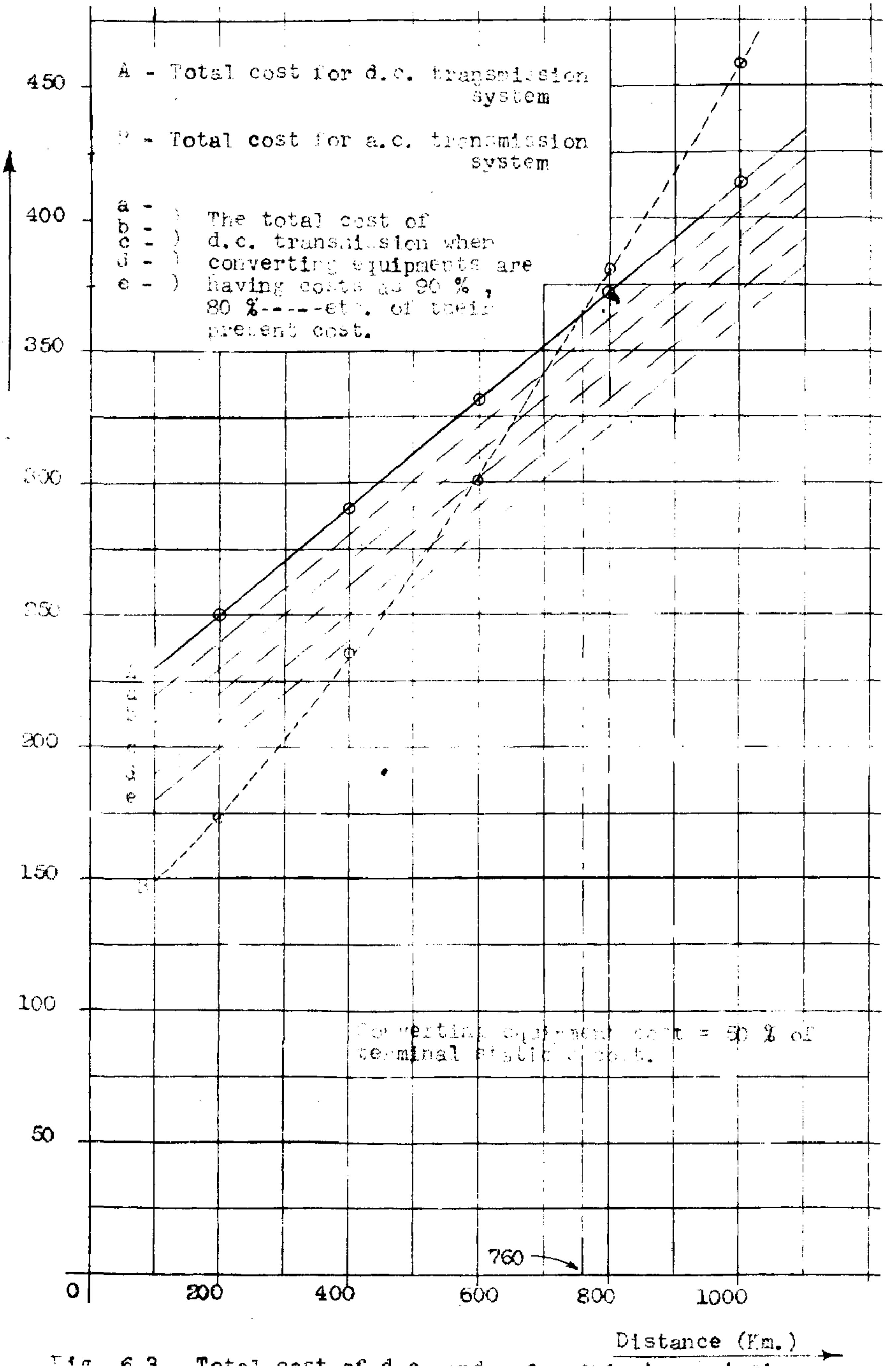


Fig. 6.3 Total cost of d.c.

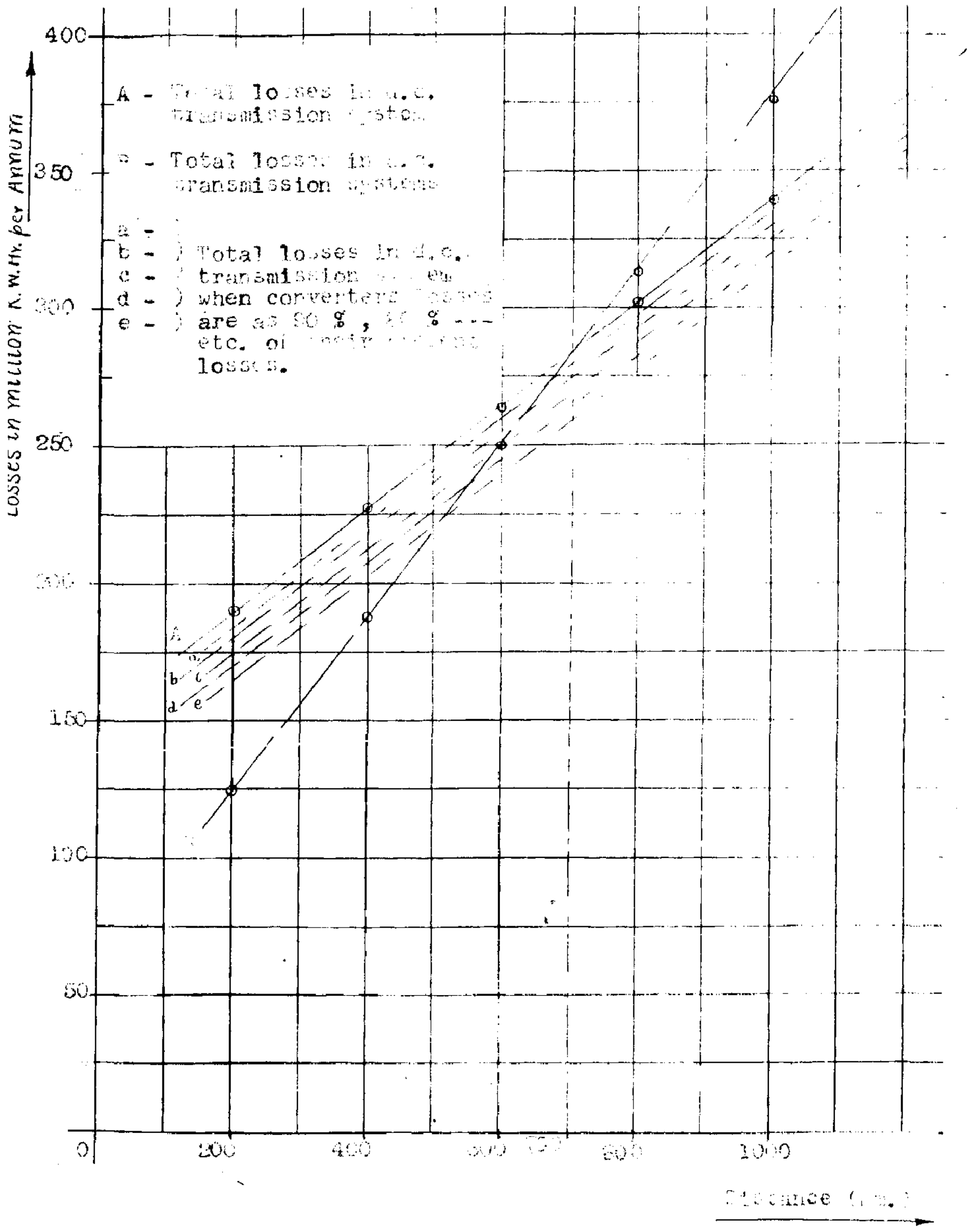
the efficiency of the order of 95 % to 97 %.

Length of line Km.	D.C.				A.C.					
	Line		Terminal stations	Total	Line		Terminal stations	Series capacitor	Reactors	Total
	Conductor	Corona			Conductor	Corona				
200	32.7	[illegible]	152.6	190.0	55.0	3.[illegible]	[illegible]	-	-	123.9
400	65.4	[illegible]	152.6	227.0	110.0	6.4	65.7	-	-	182.1
600	98.1	13.[illegible]	152.6	26[illegible].0	164.0	9.[illegible]	65.[illegible]	-	-	248.4
[illegible]	130.8	[illegible]	152.6	301.[illegible]	219.0	12.9	65.7	7.6	[illegible]	312.1
1000	163.[illegible]	[illegible]	152.[illegible]	338.0	274.0	[illegible]	65.[illegible]	[illegible]	[illegible]	375.0

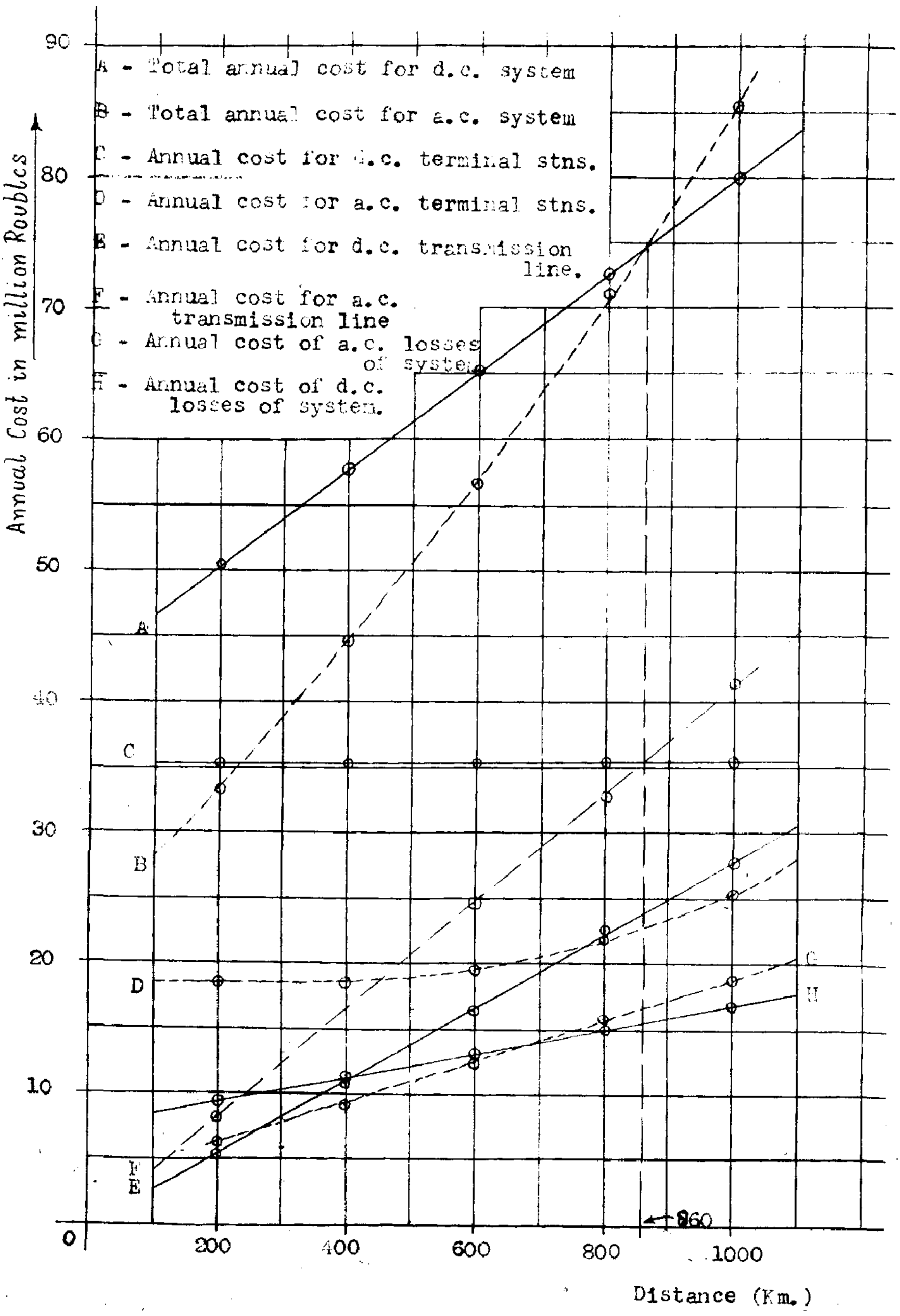
Table 6.2 - Losses in million K.W.Hr. per annum for 780 M.W. power level

The energy losses expressed in million K.W.Hr. per annum for a fixed power level of 780 M.W. for different transmission distances are shown in table - 6.2. The terminal stations losses are remaining constant but the line losses are increasing linearly with the increase of transmission distances. While comparing the total a.c. and d.c. power transmission losses, the annual losses become equivalent for line length of approx. 700-Km. as shown in Fig.-6.5 on the next page.

Now as there is no specific data regarding the converter losses, just assume the losses in the converters as one-third of the total losses in the terminal stations. As the total losses in both the d.c. terminal stations are as 152.6 million K.W.Hr. per annum, take the annual losses in the converters as 50.7 million K.W.Hr.



ig. 6.5 - Total losses in a.c. and d.c. power transmission systems in



6. 7 - Curves of annual cost for transmitting 4- milliard K.W.hr. over different distances.

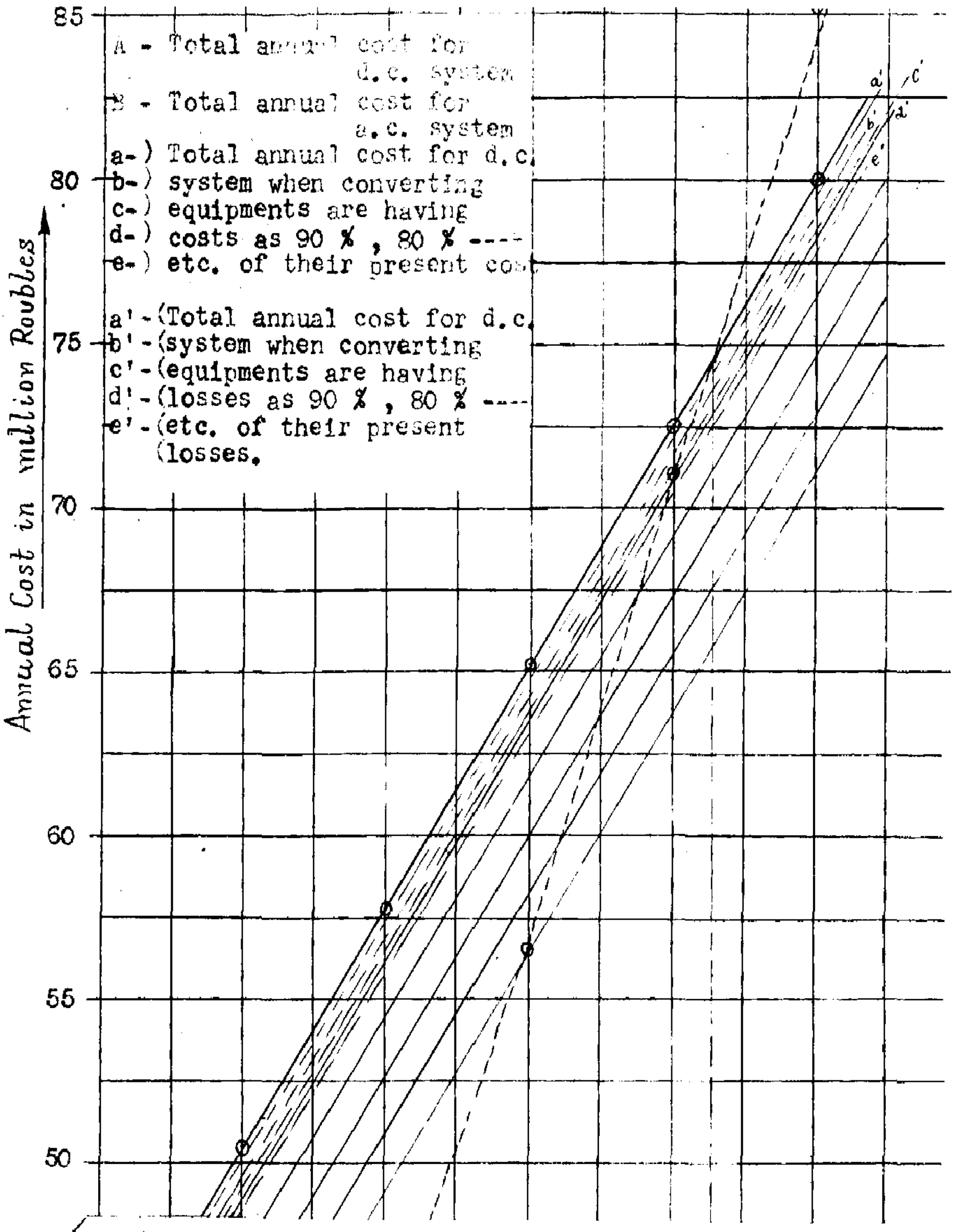
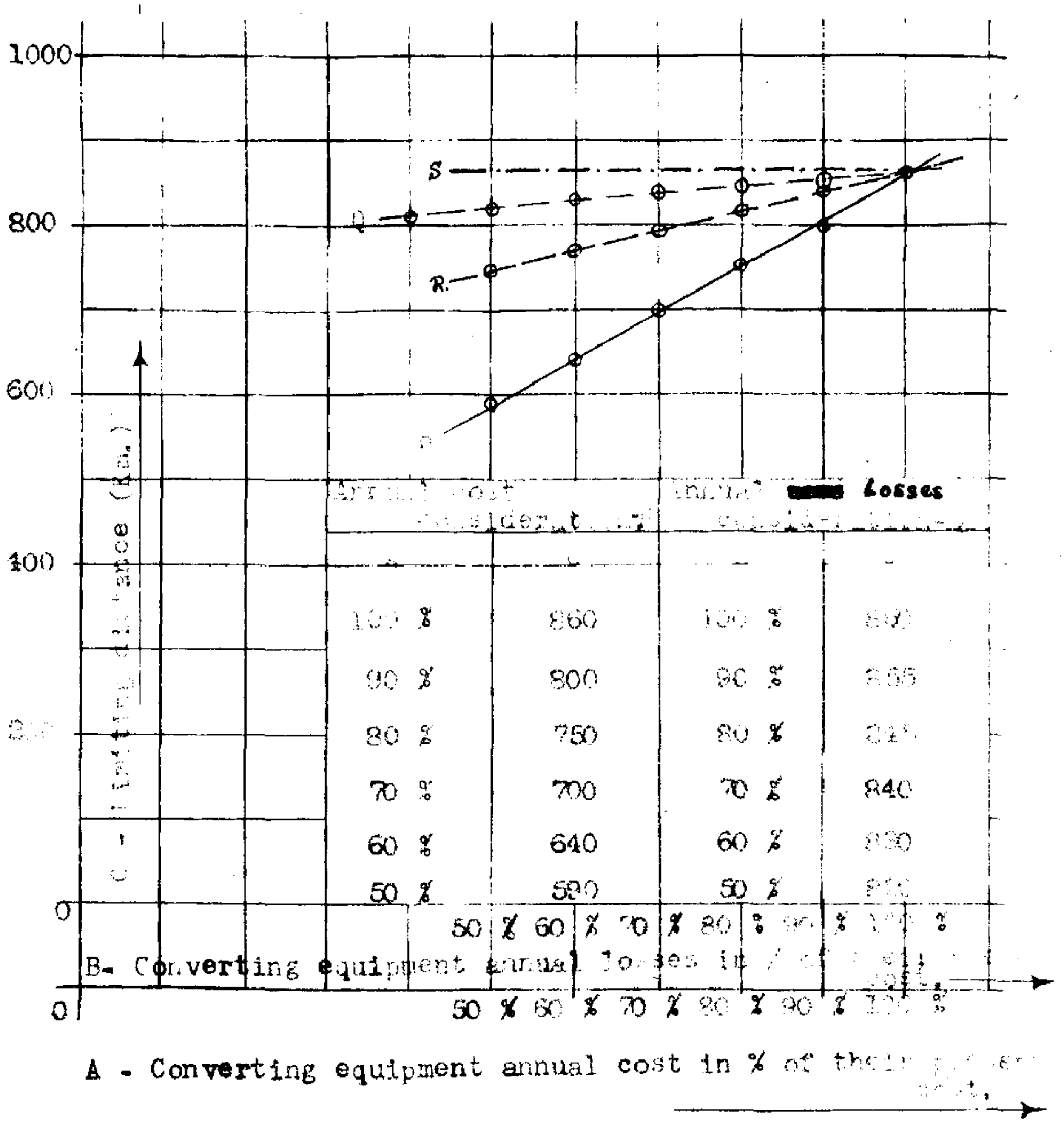

85
80
75
70
65
60
55
50
Annual Cost in million Roubles
A - Total annual cost for d.c. system
B - Total annual cost for a.c. system
a-) Total annual cost for d.c.
b-) system when converting
c-) equipments are having
d-) costs as 90 % , 80 % ----
e-) etc. of their present cost
a'-(Total annual cost for d.c.
b'-(system when converting
c'-(equipments are having
d'-(losses as 90 % , 80 % ----
e'-(etc. of their present
(losses.
a'
c'
b'
d'
e'

Fig. 6.8 - To
dis



Annual cost considered		Annual Losses considered	
100 %	860	100 %	[illegible]
90 %	800	90 %	855
80 %	750	80 %	[illegible]
70 %	700	70 %	840
60 %	640	60 %	830
50 %	590	50 %	[illegible]

Fig. 6.9 - Limiting distances of transmission against percentage of present annual cost and percentage of present annual losses.

The limiting distances beyond which d.c. power transmission is advantageous as the losses in the converting equipment reduces to 90 % , 80 % - - - - etc. of present losses can be obtained from Fig. 6.8 as shown by a dotted line in Fig. 6.9 above.

As shown in table 6.2, the difference in annual losses between d.c. and a.c. terminal stations is as 87 million K.W. Hr. approximately. This difference in losses is mainly due to the converting equipments along with their auxilaries. At the energy rate of 5-kopkes per K.W. Hr., these annual losses are having the cost value as 4.35 million Roubles. This is the annual cost of the energy going as a loss in the converting equipments, presently.

Now if there is an improvement upon the converting equipment, from efficiency point of view, and say the losses in the converting equipment are as only 90 % of the present losses, the total annual cost of d.c. energy transmission will reduce, that is why the limiting distance beyond which the d.c. power transmission is advantageous, reduces from 86-Km. to 83-Km. The limiting distance beyond which the d.c. power transmission is advantageous as the losses in the converting equipments reduces to 90 % , 80 % , 70 % , 60 % and 50 % of the present losses can be obtained from Fig.-6.8 as 830, 810, 790, 760 and 740 Kms. respectively, as shown by the dotted line 'R' in Fig.-6.9.

A datum is shown by a chain line, which indicate the limiting distance for adopting d.c. power transmission system at present stage of converting equipments. With the help of curves R and P a study of limiting distance can be made from the point of view of economy and efficiency, simultaneously. For instance if somehow there is a reduction in present cost of converting equipments to 70 % and at the same time the losses are also reduces to 70 % of present value, the limiting distance for adopting d.c. power transmission will reduce from 860-Km. to 630-Km. This distance can easily be obtained with the help of the datum line S.

CHAPTER - 7

CONCLUSION

High voltage d.c. power transmission is characterised by lower line cost and higher terminal stations cost, than for a.c. system. Beyond a certain limiting distance, it is advantageous to adopt h.v.d.c. power transmission which are 410-Km. (approx. 260 - miles) and 760-Km. (approx. 470 - miles) for overhead lines having power levels as 1600 M.W. and 750 M.W. respectively. This limiting distance in the case of submarine - cable transmission comes as 32-Km.(20-miles), for a capacity of 780 M.W. The other advantages with d.c. power transmission reveal, no charging current needed, the system is stable, a lower insulation level is needed, and the system is much reliable.

The outlines of number of h.v.d.c. power schemes are given in Chapter - 4. Study of the various converting devices shows that the mercury-arc-converters are the only suitable converting devices upto the present stage, for converting large amount of powers at high voltages. The semi-conductor converting devices have not been much developed for converting large amount of powers at high voltages. It is thus premature to forecast the future of semi-conductor devices for using with h.v.d.c. power transmission. It is libely that for some-time to come, the mercury-arc-valves will remain unchallenged in the field of h.v.d.c. power transmission.

The efficiency and the economy in the cost of converting equipments play a major role while determining the limiting distance for adopting h.v.d.c. as against h.v.a.c. power transmission. The specific results for adopting h.v.d.c. power transmission can not be obtained in general. There are so many factors which influences the limiting distance for adopting h. .

The limiting distance is also studied on the basis of annual cost of energy transmission. This limiting distance is 860-Km. for equal costs in the case of a.c. and d.c. This reduces to 880-Km. and 820-Km. When there is a reduction in the cost of the converting equipment by 80 % and the losses are reduced by 80 % of their present losses respectively.

A study of limiting distance is made from the point of view of economy and efficiency simultaneously of the cost and the losses in the converting equipments both reduce to 70 % of the present value, the limiting distance reduces from 860-Km. to 630-Km.

-o-

REFERENCES.

1. Editorial
''The History of D.C. Transmission Part I''
(Direct Current - - Dec. 1961, pp. 260)

2. Adamson Colin and Hingorani N.G.
''High Voltage Direct-Current Power Transmission''
(Book).

3. Stevenson
''The Growth of Electrical Power System''
(Power System Analysis - - pp. 2 - Book).

4. Schultze
''Possible Applications and Operating Characteristics of Power Transmission by H.V.D.C. in Comparision with A.C.''
(Direct Current - - Sept. 1956, pp. 52).

5. World Power Conference
''High Voltage D.C. Power Transmission''
(Direct Current - - Dec. 1958, pp. 88)

6. Starr A.T.
''Generation, Transmission and Utilization of Electrical Power''
(Book)

7. Grant J.C.
''High Voltage D.C. Power Transmission a Co mentary on Current Thoughts''
(Direct Current - - March 1955, pp. 94)

8. Editorial
''The Russian view of H.V.D.C. - Presented in America
(Direct Current - - March 1959, pp.94.)

9. Lane F.J.
''The Cross-Channel Cable''
(Direct Current - - 1956-57, pp.39).

10. CIGRE - Report
''The Proceeding of D.C. Study Committee of CIGRE Leningrad 1957''
(Direct Current - 1957, pp. 179).

11. Dawes, Chester L.
''A Course in Electrical Engineering Vol. II - A.C.''
(Book)

12. Kimbark
''Power System Stability Part I''

24. Marti O.K. and H. Winograd
''Mercury-Arc-Power Rectifiers - Their Application and Characteristics''

(Trans. A.I.E.E. - 1927, Vol. 46, pp. 437).

25. Melgunov N.M.
''H.V.D.C. Transmission in Soviet Union''

(Direct Current - - Sept. '57, pp. 172).

26. Editorial
''Technical Problems in D.C. Transmission''

(Direct Current - - June 1957, pp. 143).

27. Bertele H. Von and Tucker R.
''The Design of High Voltage, High Power Mercury-Arc Converters''

(Proceeding I.E.E. - - 1952 Vol. 99 II pp.555).

28. Editorial
''Silicon Diodes and Mercury-Arc-Convertors - British views on their Advantages and Disadvantages''

(Direct Current - - April '62, pp. 104).

29. Robinson T.P.
''Silicon Power Rectifier Equipments for Electro-Chemical Duty''

(Direct Current - - Sept. '62, pp. 138).

30. Bertele H.Von
'' The Continental Development of Single -Anode Mercury-Arc-Rectifier Valves of High Power''

(Proceeding I.E.E. -- 1950, Vol. 97 II, pp.663).

31. Feinberg R.
'' The Mercury-Arc-Valve and H.V.D.C. Power Transmission''

(Direct Current - - June 1961, pp. 65.).

32. Fleishman L.S.
''Prospects for the Use of Series Connected Valves at Low Voltage''

(Direct Current - - March 1960, pp. 226.).

33. Lamm Uno
'' Mercury-Arc Valves for High Voltage D.C. Transmission''

(Proceedings I.E.E. - - Oct. 1964, Vol. III, No. 10, pp. 1747).

34. Freris L.L.
''The Silicon Controlled Rectifier''
(Direct Current - - Sept. 1961, pp. 163).

35. Editorial
'' Application Data for the Germanium Power Rectifier''
(Direct Current - - March 1957, pp. 113).

36. Read J.C.
''Rectifiers and Rectifier Applications —- A Review of Progress''
(Proceedings I.E.E.-April 1963, Vol. 110, No. 4, pp. 714).

37. Butaev F.I. and Others
''Design Features of the Stalingrad -Donbass 800 K.V.D.C. Line ''
(Direct Current - - Sept. 1958, pp. 59).

38. Direct Current Publications
''The History of H.V.D.C. Power Transmission''
(Book)

39. Editorial
''New - Zealand Inter-lands H.V.D.C. Link''
(Energy International - - Sept. 1964, Vol. I, No. 7, pp. 8).

40. Editorial
''ASEA Tests at 250 K.V.D.C. 1000 A''
(Elect. - World - - August 1963, pp. 54).

41. Editorial
''The H.V.D.C. - year''
(Direct Current - - Feb. 1966, - pp.1)

42. Pinevov V.P. and others
''The D.C. Transmission from Stalingrad Hydro-Electric Station to Donbass''.
(Direct Current - - March 1957, pp. 106).

-o-