PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

D.c. Transmission Systems

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VI. D.C. TRANSMISSION

D.c. transmission systems

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'D.c. transmission systems' covers the operational characteristics and equipment from the sending end a.c. system to the receiving end a.c. system, and includes the characteristics of those two a.c. systems as well as all the equipment in between.

Since d.c. transmission is the 'challenger' and a.c. transmission is the 'sitting tenant' it behoves d.c. to prove its worth using the well-developed a.c. technique as a yardstick with regard to technical excellence, performance, reliability and the all important cost.

Existing schemes are reviewed in terms of the system parameters which influenced the choice of d.c. and bulk long-distance transmission is used as an example. Control of a d.c. scheme is touched upon, followed by a discussion of some recent studies and operating experience.

1. D.c. schemes in operation or construction

A.c. as a means of generation, transmission and distribution has fulfilled the demands made upon it in the past and will continue to do so in the future by utilizing higher system voltages, larger generating units, faster operating circuit breakers and better overall control schemes. The question can therefore be posed why one should challenge such a well established technology, bearing in mind that the most fanatical adherent to d.c. will accept that a.c. reigns supreme for the purposes of power generation and distribution. On the other hand, confidence in the technical performance and economics of d.c. is such that today 14 schemes are in operation or under construction, and some eight further schemes are under active consideration in the world.

Table 1 lists the d.c. schemes in operation and under construction, and shows that the following applications can be established for d.c.:

(*a*) Submarine cables – six schemes

A.c. submarine cables, like all other cables, require large charging currents which considerably reduces the power transfer, such that for a given megawatt transmission many more a.c. cables are required than d.c. cables.

(*b*) Bulk long distance transmission – five schemes

The cost of d.c. overhead lines for the same megawatt transmission is about 70 % of that for a.c. lines, without allowing for the compensating equipment required in the latter case. When allowance is made for the cost of series compensation and shunt reactors, the cost of the d.c circuits is about 50 % of the cost of the a.c. circuits, neglecting substation costs in both cases.

(*c*) 50/60 Hz frequency changer – one scheme

The only alternative method to d.c. for interconnecting a.c. power systems of different frequencies is by rotating machines, which today are completely unacceptable.

(*d*) Asynchronous interconnexion – one scheme

In certain special cases instability precludes the interconnexion of large a.c. networks and a zero length d.c. asynchronous interconnexion is the only possibility.

(*e*) Power into cities – one scheme

Buried cables, as with submarine cables, require large charging currents necessitating compensation at intervals along the route. In addition more a.c. cables and much larger trenches are required compared with their d.c. equivalent.

Some of the schemes now being actively studied are shown in table 2 and all fall within the same categories referred to in (*a*) to (*e*) above.

It has been of considerable disappointment to those actively concerned in d.c. to find such a slow growth in demand over nearly 20 years, considering the enormous amount of a.c.transmission installed in that time. From the manufacturer's point of view, the investment in d.c. research and development is high and yet, surprisingly, there are manufacturers of heavy electrical equipment or groups of manufacturers, who are prepared to tender for converter stations of the largest size required today and who claim sufficient knowledge of the d.c. and a.c. system application technology. They are based in Canada, France, Germany, Japan, Sweden, U.S.A., U.S.S.R. and the United Kingdom.

2. Comparisons between a.c. and d.c. for bulk power transmission

Figure 1 shows a typical line diagram for a 9000 MW transmission system for a distance of 1000 km. Taking into account achievable ratings for converter station equipment and limitations on transformer transport weights the d.c. case could comprise three ± 600 kV circuits.

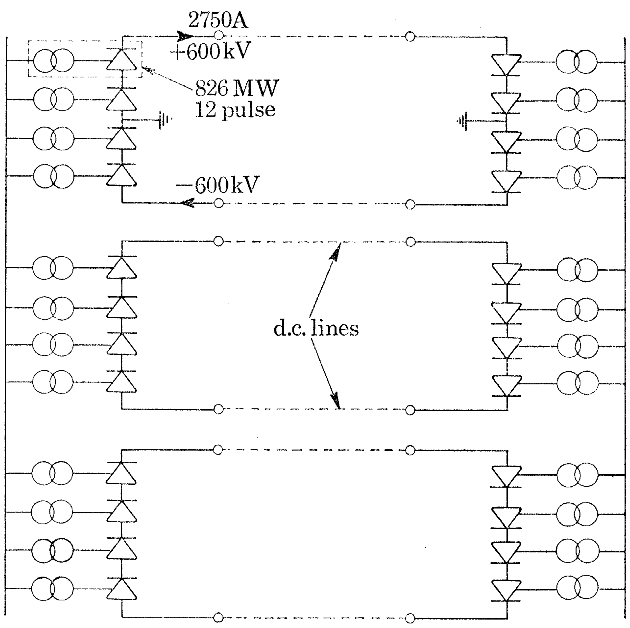

Figure 1. Basic d.c. circuit. Number of bi-polar d.c. circuits = 3; direct current = 2750 A; direct voltage = ± 600 kV; rating per 12-pulse converter group = 826 MW; transmission capacity = 9900 MW; transmission capacity (one converter out) = 9000 MW.

Earth return would be permitted for say one or two days to cover failure of the d.c. reactor and other equipment associated with one d.c. pole, and switching of one bi-pole into parallel operation with another bi-pole is included to meet the case of a permanent d.c. line fault, such as a tower failure.

Line diagrams are compared in figure 2 for d.c. with three bi-polar circuits and for a.c. with four 3-phase circuits at 800 kV, where the a.c. design follows the conventional practice for u.h.v., with series and shunt compensation and the lines switched in sections, and in this case three sections are considered adequate. These two line diagrams represent alternative methods for transmitting the required firm power and take into account as far as possible, similar rules for the determination of availability of equipment and security during and after various types of fault.

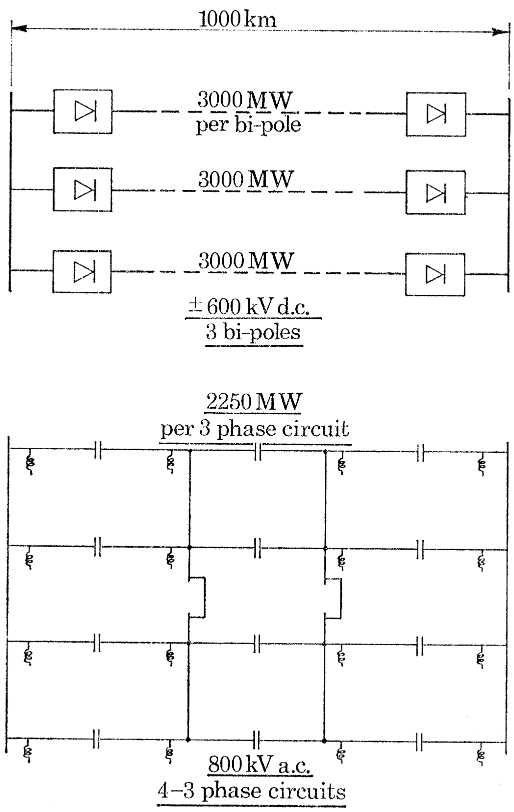

FIGURE 2. Line diagram for d.c. and a.c. alternatives.

D.c. has the advantage of very simple and cheaper towers and no line compensation equipment is required but, to offset this, has complication in the converter stations. A.c. has the advantage of ease of tapping power from the line at the intermediate switching stations and has simpler substations at each end. In the a.c. case transient and dynamic stability have to be taken into account in the normal way involving the sending a.c. system, the transmission system and the receiving a.c. system, and in the d.c. case stability of the sending and receiving systems must be carefully analysed during and after faults which interrupt the d.c., such as commutation failures and d.c. line faults.

The cost of a d.c. transmission scheme as indicated in figure 1, taking into account all equipment and civil works between the busbars at the sending and receiving a.c. systems, can be roughly divided into three main components: (*a*) the cost of the converter station equipment, excluding buildings, services and the a.c. switchyard – about 50 %; (*b*) the cost of the rest of the equipment, excluding d.c. lines – about 20 %; (*c*) the cost of the d.c. lines – about 30 %.

Banks (this volume, p. 233) gives a further breakdown of the costs referred to in (*a*) above.

As an indication why the equipment required in a converter station is expensive, the line diagram in figure 3 shows a 200 MW scheme installed some years ago to transmit power between the Italian mainland and Sardinia. Compared with an a.c. transmission scheme where the substations contain mainly switchgear and transformers, it is clear that a converter station requires, in addition, a.c. harmonic filters, more surge diverters, valve damping circuits, converter valve groups, bi-pass switches and isolators, d.c. reactors, d.c. filter circuits and in some cases earth return electrodes. The receiving station contains similar equipment, but often requires synchronous compensators where the short circuit level of the receiving system is relatively low, but this sometimes applies to a.c. transmission systems.

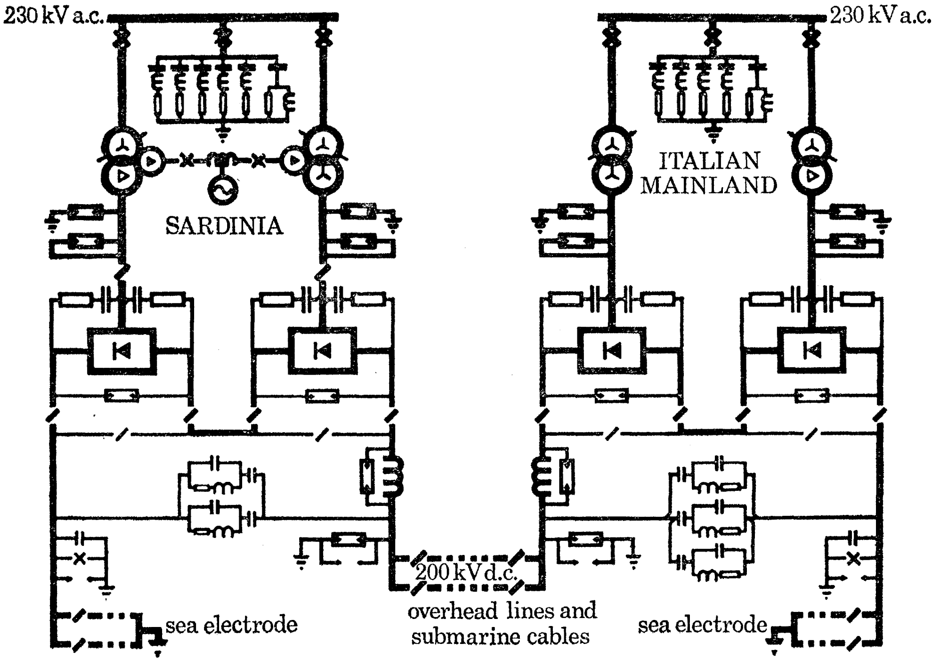

FIGURE 3. Sardinia–Italian mainland. 200 MW scheme. Published by kind permission of G.E.C. Switchgear Ltd.

3. Typical control system

D.c. transmission introduces a very fast control and protective function through the grids or gates of the valves. Figure 4 shows how the various controls are normally linked together to provide the best operating conditions. The load dispatching personnel at both ends agree on the required power transfer and this, divided by the operating d.c. voltage, gives the current reference I_0, which is fed to both the rectifier and inverter controls, but in the inverter case the current reference is reduced by the current margin I_m. At the rectifier any discrepancy between the current reference and the actual current operates to change the control angle α of the valves to bring the current back to the reference value. The α control has limits outside which the converter transformer tap changer corrects the a.c. input voltage to keep α within the prescribed limits. At the inverter end a safety angle γ is the operative quantity under normal conditions and the direct voltage is used to control the inverter transformer tap changers. By this arrangement the scheme operates with the inverter having an adequate safety angle, the maximum direct voltage possible on the line and minimum reactive power demand, and at the same time

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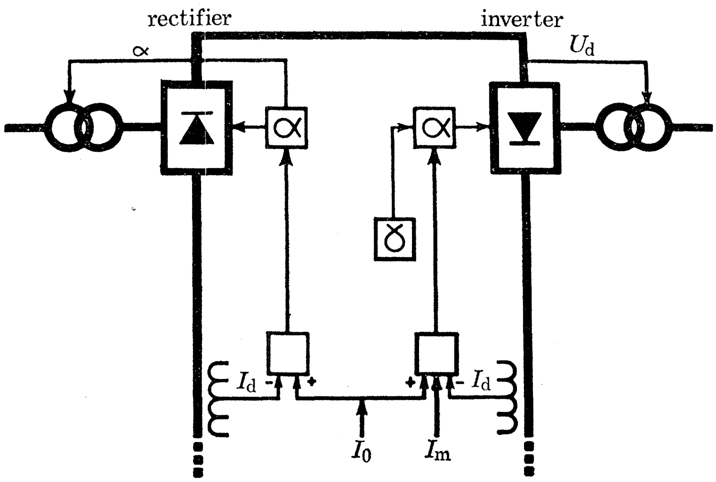

FIGURE 4. Simplified block diagram of control scheme. Published by kind permission of G.E.C. Switchgear Ltd.

the rectifier also demands the minimum reactive power from its own a.c. system and controls the direct current. Inherent in this system is automatic protection for d.c. line faults and maximum transmission efficiency, since the line is operated at its maximum possible direct voltage.

Serious faults at the receiving end a.c. busbars will cause the inverter back e.m.f. to fall to near zero, but the rectifier current control will hold the direct current nearly constant, and then through the protective sequences reduce it to zero. Consequently the power fed into the fault at the receiving system from the d.c. system is very small, this being one of the inherent advantages of using d.c. when the short-circuit levels of the receiving a.c. system have reached levels beyond the rating of the circuit breakers.

4. Some comparative studies between a.c. and d.c.

In considering the future demand for d.c. transmission it is instructive to examine the result of the studies carried out in relation to some of the schemes shown in tables 1 and 2, and those associated with bulk long-distance transmission have been selected. The U.S. Pacific Intertie (1330 km) comprises a double circuit 500 kV a.c. system (with heavy series compensation) operating in parallel with a ±400 kV d.c. circuit. The two schemes were designed at the same time and no direct comparison was made between a.c. and d.c., since the justification for using both forms of transmission arose from the inherent advantages of the two types of system in parallel. The transmission between Churchill Falls and Montreal (1400 km) was studied in detail at 735 kV a.c. with shunt compensation and no series compensation, and compared with ±500 kV d.c. The final conclusion was that d.c. was less expensive in capital cost and more expensive in annual cost, after allowance for losses. The decision to use ±500 kV d.c. for the comparison was sound since any higher voltage was beyond available experience at that time.

In the case of Nelson River (950 km) the comparison was between 500 kV a.c. and ±450 kV d.c. After making due allowance for the difficult terrain to be followed by the overhead line route, d.c. was found to be cheaper than a.c. It is interesting that when comparing Nelson River and Churchill Falls, the scheme with the shorter distance is the one which eventually utilized

Table 1. H.v.d.c. schemes in operation and construction

scheme	commissioning date	capacity MW	voltage kV	length overhead km	length land cable km	length sea cable km	remarks
Gotland							
Swedish – stage I	1954	20	100	—	—	98	sea crossing
Mainland – stage II	1970	add 10	150	—	—	98	d.c. voltage increased to 150 kV (by addition of thyristor group)
France–England	1961	160	± 100	—	—	55	sea crossing. Different frequency control
Volgograd–Dombass	1965	750	± 400	480	—	—	bulk long-distance transmission
New Zealand	1965	600	± 250	570	—	40	bulk long-distance transmission (part sea crossing)
Japan (Sakuma)	1965	300	2 + 125	—	—	—	interconnexion between 50 and 60 Hz
Sweden–Denmark (Konti Scan)	1965	250	250	85	—	86	interconnexion across sea
Sardinia–Italian Mainland	1966	200	200	290	—	115	interconnexion across sea
Vancouver Island							
stage I	1969	156	130	42	—	29	interconnexion across sea
stage II	1970	add 156	260	42	—	29	d.c. voltage increased by addition of 2nd valve group
U.S. Pacific Intertie	1970	1440	± 400	1330	—	—	bulk long-distance transmission
Kingsnorth (England)	1971	640	± 266	—	100	—	power into cities
Nelson River (Canada)							
Stage I	1971	810	450	950	—	—	bulk long distance transmission
North Kazakhstan–Moscow	1975	6000	± 750	2400	—	—	bulk long-distance transmission
Hydro–Quebec–New Brunswick	1972	320	± 80	—	—	—	asynchronous tie between two 60 Hz systems
Cabora Bassa (South Africa)							
stage I	1974	960	± 266	1360	—	—	bulk long-distance transmission
stage II	1977	add 480	± 400	1360	—	—	
stage III	1979	add 480	± 533	1360	—	—	

d.c., which is contrary to the views normally held by transmission engineers and illustrates the necessity to consider most schemes in detail before choosing the mode of transmission.

The transmission length required by Cabora Bassa project in Southern Africa (1360 km) was considered to be sufficiently far beyond the point where d.c. becomes cheaper than a.c. and since no tapping points were required *en route*, only very brief consideration was given to an a.c. alternative. Similarly the gigantic scheme now being built in the U.S.S.R., Kazakhstan to Moscow (2400 km) and rated at 6000 MW, seems clearly to be a case for d.c. and no a.c. studies have been reported.

The conclusions to be drawn from these examples is that for very long distances, say 1000 km or more, where no tapping points are required, d.c. seems the clear winner, but in all other cases detailed comparisons are necessary. At the present time comparative studies are proceeding in Brazil for a transmission over 850 km, and similarly in Quebec for a distance of 800 km.

TABLE 2. H.V.D.C. SCHEMES BEING ACTIVELY CONSIDERED

Inga–Shaba	long-distance bulk transmission
Finland–U.S.S.R.	asynchronous tie
Gotland no. 2	submarine cable
Norway–Denmark	submarine cable
Hokkaido (Japan)	submarine cable
Brazil	long-distance bulk transmission
James Bay (Canada)	long-distance bulk transmission
France–England no. 2	submarine cable

A further example is the 1600 km transmission between Inga and Shaba in Zaire where d.c. has been selected very early in the studies.

D.c. transmission has considerable advantage when considered in relation to the environment due to the smaller d.c. towers and ease of cabling. Conversion of existing a.c. overhead lines to d.c. is worth considering in special cases. A study carried out some time ago involving 275 kV circuits and some 400 kV circuits (then operating at 275 kV), on the basis that the 275 kV a.c. lines could operate at ± 200 kV d.c. and the 400 kV a.c. lines at ± 400 kV d.c., gave the facility to increase the firm power capability from 800 to 4000 MW. Obviously the cost of the converter equipment would be heavy, but it might be acceptable if, as in this case, no change at all was required to existing overhead lines.

5. OPERATING EXPERIENCE

There is today sufficient experience to indicate that all the major items of equipment associated with d.c. converter stations, lines and cables, can be made to acceptable practical standards for the highest rating required and at the highest voltages, but as more studies proceed it is clear that unless there is an appreciable change in converter station design and costs, or system planners arrive at some basis for costing the benefits of d.c., such as environmental gains, ease of power control and limitation of short circuit levels, d.c. is only likely to find acceptance in certain limited applications.

As the powers which are transmitted increase the question of reliability and availability becomes more important whatever the form of transmission. Study Committee 14 of C.I.G.R.E. carries out every 2 years a review of all operating d.c. schemes, the most recent being in 1972. Unlike any records on a.c. transmission, this report is all embracing in that it covers all equipment from the sending end a.c. system through the converter stations and d.c. lines or cables into the receiving a.c. system. The C.I.G.R.E. report in 1972 stated that: 'The average availability of the world's d.c. schemes was 82 %. A large part of the outage time was caused by faults in more or less conventional plant particularly in cables, overhead lines and transformers requiring long repair periods. Maintenance and testing accounted for the other major part of the non-availability. Most of the faults on the d.c. side of the converter stations were of a transitory nature and had little affect on the overall availability. It is significant that the average monthly availability for all schemes exceeded 99 % for approximately 1/3rd of the time.'

It would be most interesting if comparable figures were available for a.c. transmission. However, is this record very remarkable when compared with that of other equipment of advanced technology, such as large thermal turbo-generators and nuclear power stations?

6. Conclusions

1. If the cost and complexity of converter stations continues in the same pattern as it has in the past, and system planners continue to avoid attaching financial benefits to d.c., then d.c. transmission will continue to be used only in special cases.

2. Developments in a.c. transmission are making it more and more difficult for d.c. to compete in bulk power transmission, and d.c. will be confined to transmission over very great distances and in cases where no tapping points are required. The use of saturated iron static equipment with a.c. transmission is making the challenge of d.c. even more difficult.

3. The major area where d.c. should be given much more study is that of interconnexion between large power systems.

4. Converting existing a.c. lines to d.c., particularly where there are double circuit 3-phase a.c. lines should be considered in future system planning.

5. Existing schemes use converter bridges in series on the d.c. side. It is quite possible that some savings in converter station cost will arise by taking advantage of the capability of thyristor valves to be designed for voltages higher than the existing mercury arc valves and utilizing parallel connected converter bridges. By utilizing 12-pulse operation considerable savings in a.c. filters could be achieved.

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