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HVDC Power Transmission Systems

Technology and System Interactions

K R Padiyar

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1. DC Power Transmission Technology

1.1 INTRODUCTION

The industrial growth of a nation requires increased consumption of energy, particularly electrical energy. This has led to increase in the generation and transmission facilities to meet the increasing demand. In U.S.A., till the early seventies, the demand doubled every ten years. In developing countries, like India, the demand doubles every seven years which requires considerable investment in electric power sector.

The imperative of supplying energy at reasonable costs coupled with the depleting reserves of non-renewable energy sources has led to the establishment of remote generating stations - predominantly fossil-fuel fired thermal stations at pit head. Environmental considerations also sometimes dictate the siting of power stations at remote locations. Large hydro stations are invariably at distances of hundreds of kilometres from load centres. The need to economize on costly investments in generation reserves, sharing of benefits in utilising variability in generation mixes and load patterns have given rise to interconnection of neighbouring systems and development of large power grids.

Remote generation and system interconnections lead to a search for efficient power transmission at increasing power levels. The increase in voltage levels is not always feasible. The problems of AC transmission particularly in long distance transmission, has led to the development of DC transmission. However, as generation and utilisation of power remain at alternating current, the DC transmission requires conversion at two ends, from AC to DC at the sending end and back to AC at the receiving end. This conversion is done at converter stations - rectifier station at the sending end and inverter station at the receiving end. The converters are static—using high power thyristors connected in series to give the required voltage ratings. The physical process of conversion is such that the same station can switch from rectifier to inverter by simple control action, thus facilitating power reversal.

The HVDC transmission made a modest beginning in 1954 when a 100 kV, 20 MW DC link was established between Swedish mainland and the island of Gotland. Until 1970, the converter stations utilised mercury arc valves for rectification. The successful use of thyristors for power control in industrial devices encouraged its adoption in HVDC converters by development of high power semiconductor devices. The largest device rating is now in the range of 5 kV, 3000A. The highest transmission voltage reached is ±600 kV.

The relative merits of AC and DC transmission are reviewed in the next section.

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1.2 COMPARISON OF AC AND DC TRANSMISSION

The relative merits of the two modes of transmission (AC and DC) which need to be considered by a system planner are based on the following factors :

1) Economics of transmission
2) Technical performance
3) Reliability.

A major feature of power systems is the continuous expansion necessitated by increasing power demand. This implies that the establishment of a particular line must be considered as a part of an overall long term system planning.

1.2.1 Economics of Power Transmission

The cost of a transmission line includes the investment and operational costs. The investment includes costs of Right of Way (RoW), transmission towers, conductors, insulators and terminal equipment. The operational costs include mainly the cost of losses.

The characteristics of insulators vary with the type of voltage applied. For simplicity, if it is assumed that the insulator characteristics are similar for AC and DC and depend on the peak level of voltage applied with respect to ground, then it can be shown that for lines designed with the same insulation level, a DC line can carry as much power with two conductors (with positive and negative polarities with respect to ground) as an AC line with 3 conductors of the same size. This implies that for a given power level, DC line requires less RoW, simpler and cheaper towers and reduced conductor and insulator costs. The power losses are also reduced with DC as there are only two conductors (about 67% of that for AC with same current carrying capacity of conductors). The absence of skin effect with DC is also beneficial in reducing power losses marginally. The dielectric losses in case of power cables is also very less for DC transmission.

The Corona effects tend to be less significant on DC conductors than for AC and this also leads to the choice of economic size of conductors with DC transmission. The other factors that influence the line costs are the costs of compensation and terminal equipment. DC lines do not require compensation but the terminal equipment costs are increased due to the presence of converters and filters.

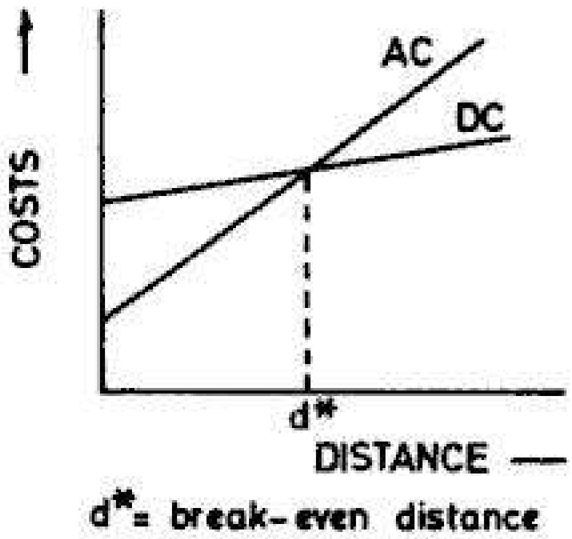

Fig. 1.1 Variation of costs with line length.

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Figure 1.1 shows the variation of costs of transmission with distance for AC and DC transmission. AC tends to be more economical than DC for distances less than 'break even' distance and costlier for longer distances. The break even distances can vary from 500 to 800 km in overhead lines depending on the per unit line costs.

1.2.2. Technical Performance

The DC transmission has some positive features which are lacking in AC transmission. These are mainly due to the fast controllability of power in DC lines through converter control. The following are the advantages :

1. Full control over power transmitted
2. The ability to enhance transient and dynamic stability in associated AC networks.
3. Fast control to limit fault currents in DC lines. This makes it feasible to avoid DC breakers in two terminal DC links.

In addition, the DC transmission overcomes some of the problems of AC transmission. These are described below:

Stability limits

The power transfer in AC lines is dependent on the angle difference between the voltage phasors at the two ends. For a given power level, this angle increases with distance. The maximum power transfer is limited by the considerations of steady state and transient stability. The power carrying capability of an AC line as a function of distance is shown in Fig. 1.2. The same figure also shows the power carrying capability of DC lines which is unaffected by the distance of transmission.

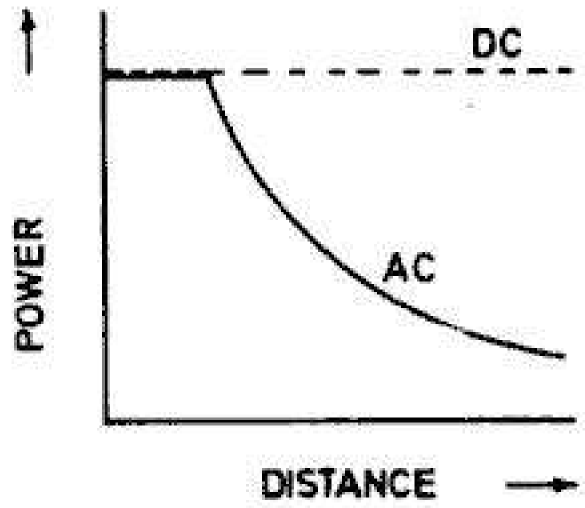

Fig. 1.2 Power transfer capability vs. distance.

Voltage control

The voltage control in AC lines is complicated by the line charging and inductive voltage drops. The voltage profile in a AC line is relatively flat only for a fixed level of power transfer corresponding to surge impedance loading (SIL). The voltage profile varies with the line loading. For constant voltage at the line terminals, the midpoint voltage is re-

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duced for line loadings higher than SIL and increased for loadings less than SIL. This is shown in Fig. 1.3.

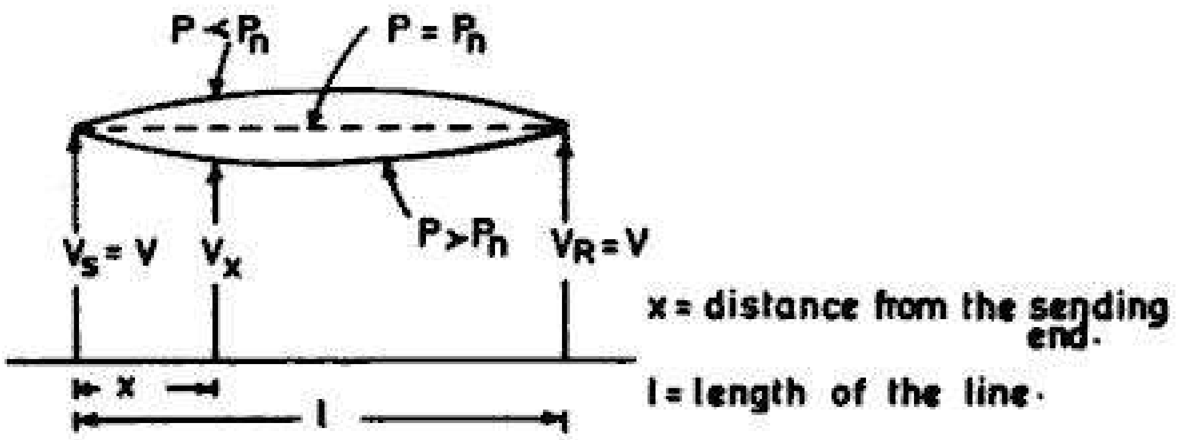

Fig. 1.3 Variation of voltage along the line.

The maintenance of constant voltages at the two ends requires reactive power control from inductive to capacitive as the line loading is increased. The reactive power requirements increase with the increase in line lengths.

Although DC converter stations require reactive power related to the line loadings, the line itself does not require reactive power.

The steady-state charging currents in AC lines pose serious problems in cables. This puts the breakeven distance for cable transmission around 40 km.

Line Compensation

For reasons mentioned earlier, AC lines require shunt and series compensation in long distance transmission, mainly to overcome the problems of line charging and stability limitations. Series capacitors and shunt inductors are used for this purpose. The increase in power transfer and voltage control is also possible through the use of Static Var Systems (SVS).

In AC cable transmission, it is necessary to provide shunt compensation at regular intervals. This is a serious problem in underwater cables.

Problems of AC interconnection

When two power systems are connected through AC ties (synchronous interconnection), the automatic generation control of both systems have to be coordinated using tie-line power and frequency signals. Even with coordinated control of interconnected systems, the operation of AC ties can be problematic due to (i) the presence of large power oscillations which can lead to frequent tripping (ii) increase in fault level (iii) transmission of disturbances from one system to the other.

The controllability of power flow in DC lines eliminates all the above problems. In addition, for asynchronous DC ties, there is no need of coordinated control.

It is obvious that two systems which have different nominal frequencies cannot be interconnected directly with AC ties and require the use of DC links.

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Ground impedance

In AC transmission, the existence of ground (zero sequence) current cannot be permitted in steady-state due to high magnitudes of ground impedance which will not only affect efficient power transfer, but also result in telephone interference. The ground impedance is negligible for DC currents and a DC link can operate using one conductor with ground return (Monopolar operation). The ground return is objectionable only when buried metallic structures (such as pipes) are present and are subject to corrosion with DC current flow.

It is to be noted that even while operating in the monopolar mode, the AC network feeding the DC converter station operates with balanced voltages and currents. Hence, single pole operation of DC transmission systems is possible for extended periods, while in AC transmission, single phase operation (or any unbalanced operation) is not feasible for more than a second.

Disadvantages of DC transmission

The scope of application of DC transmission is limited by the following factors :

1. The difficulty of breaking DC currents which results in high cost of DC breakers
2. Inability to use transformers to change voltage levels
3. High cost of conversion equipment
4. Generation of harmonics which require AC and DC filters, adding to the cost of converter stations
5. Complexity of control

Over the years, there have been significant advances in DC technology, which have tried to overcome the disadvantages listed above except for (2). These are :

1. Development of DC breakers
2. Modular construction of thyristor valves
3. Increase in the ratings of thyristor cells that make up a valve
4. Twelve pulse operation of converters
5. Use of metal oxide, gapless arrestors
6. Application of digital electronics and fiber optics in control of converters

Some of the above advances have resulted in improving the reliability and reduction of conversion costs in DC systems. It can be said without exaggeration that complexity of control does not pose a problem and can actually be used to provide reliable and fast control of power transmission not only under normal conditions but also under abnormal conditions such as line and converter faults. This has removed the need for DC current interruption in two terminal links. Even for multi-terminal operation, the requirements of current ratings of DC breakers are modest due to effective converter control.

1.2.3 Reliability

The reliability of DC transmission systems is quite good and comparable to that of AC systems. An exhaustive record of existing HVDC links in the world is available from which the reliability statistics can be computed. It must be remembered that the performance of thyristor valves is much more reliable than mercury arc valves and further developments in devices, control and protection is likely to improve the reliability level. For example, the development of direct light triggered thyristors (LTT)

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is expected to improve reliability because of elimination of high voltage pulse transformers and auxiliary supplies for turning on the devices.

There are two measures of overall system reliability-energy availability and transient reliability

Energy availability

This is defined as

$$\text{Energy availability} = 100\left(1 - \frac{\text{equivalent outage time}}{\text{total time}}\right)\ \%$$

where equivalent outage time is the product of the actual outage time and the fraction of system capacity lost due to outage.

Transient reliability

This is a factor specifying the performance of HVDC systems during recordable faults on the associated AC systems

$$\text{Transient reliability} = \frac{100 \times \text{No. of times HVDC systems performed as designed}}{\text{No. of recordable AC faults}}$$

Recordable AC system faults are those faults which cause one or more AC bus phase voltages to drop below 90% of the voltage prior to the fault. It is assumed that the short circuit level after the fault is not below the minimum specified for satisfactory converter operation.

Both energy availability and transient reliability of existing DC systems with thyristor valves is 95% or more.

The average failure rate of thyristors in a valve is less than 0.6% per operating year. It is common practice to provide redundant thyristors in the series string composing a HVDC valve, so that failed thyristors can be replaced during scheduled maintenance (once or twice a year). The maintenance of thyristor valves is also much simpler than the earlier mercury arc valves.

Table 1.1 HVDC Outage Statistics

Equipment	MTTF(years)	MTTR(hours)
Thyristor group	13.7	6.1
Converter transformer	16.1	1700.0
Smoothing reactor	76.8	1700.0
DC filter	19.7	7.9
AC filter	12.6	9.3
Master control	25.0	6.9
Pole control	9.0	8.6
Pole of transmission line	1.25/100 km	1.5
DC line switch	147.2	7.8

MTTF = Mean time to failure

MTTR = Mean time to repair

Some of the HVDC outage statistics is given in Table 1.1. In comparing the reliability of various alternatives, it must be kept in mind that bipolar DC line can be as reliable as a double circuit AC line with the same power capability. This is because of the fact that

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failure of one pole does not affect the operation of the other pole (with ground return). If the DC line conductor has adequate overload rating and if the converters on the failed pole can be paralleled with the converters on the healthy pole, the prefault power level can be maintained even with permanent outage of one pole.

1.3 APPLICATION OF DC TRANSMISSION

The detailed comparison of AC and DC transmission in terms of economics and technical performance, leads to the following areas of application for DC transmission:

1. Long distance bulk power transmission
2. Underground or underwater cables
3. Asynchronous interconnection of AC systems operating at different frequencies or where independent control of systems is desired
4. Control and stabilization of power flows in AC ties in an integrated power system.

The first two applications are dictated primarily by the economic advantages of DC transmission, where the concept of breakeven distance is important. To be realistic, one must also assign a monetary value for the technical advantages of DC (or penalty costs for the drawbacks of AC). The problem of evaluation of the economic benefits is further complicated by the various alternatives that may be considered in solving problems of AC transmission - phase shifters, static var systems, series capacitors, single pole switching etc.

The technical superiority of DC transmission dictates its use for asynchronous interconnections, even when the transmission distances are negligible. Actually there are many 'back to back' DC links in existence where the rectification and inversion are carried out in the same converter station with no DC lines. The advantage of such DC links lies in the reduction of the overall conversion costs and improving the reliability of DC system.

The alternative to DC ties may require strengthening of existing AC network near the boundary of the two systems. This cost can be prohibitive if the capacity of the tie required is moderate compared to the size of the systems interconnected.

In large interconnected systems, power flow in AC ties (particularly under disturbance conditions) can be uncontrolled and lead to overloads and stability problems thus endangering system security. Strategically placed DC lines can overcome this problem due to the controllability of power. The planning of DC transmission in such applications requires detailed study to evaluate the benefits.

Presently the number of DC lines in a power grid is very small compared to the number of AC lines. This indicates that DC transmission is justified only for specific applications. Although advances in technology and introduction of multi-terminal DC (MTDC) systems are expected to increase the scope of application of DC transmission, it is not anticipated that AC grid will be replaced by DC power grid in future. There are two major reasons for this. Firstly, the control and protection of MTDC systems is very complex and the inability of voltage transformation in DC networks imposes economic penalties. Secondly, the advances in DC technology have resulted in the improvement of the performance of AC transmission, through introduction of static var systems, static phase shifters, etc.

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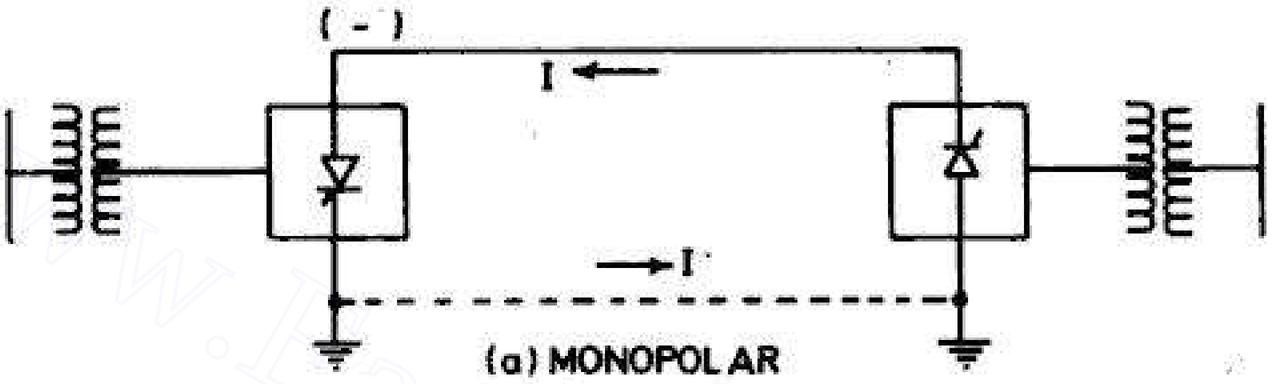
The rate of growth of DC transmission was slow in the beginning. In over 16 years, only 6000 MW of DC systems were installed using mercury arc valves. The introduction of thyristor valves overcame some of the problems of system operation mainly due to the arc backs in mercury arc valves. Since then, the rate of growth of DC transmission capacity has reached an average of 2500 MW/year.

The details of the HVDC transmission schemes in existence or under construction are given in Table 1.2.

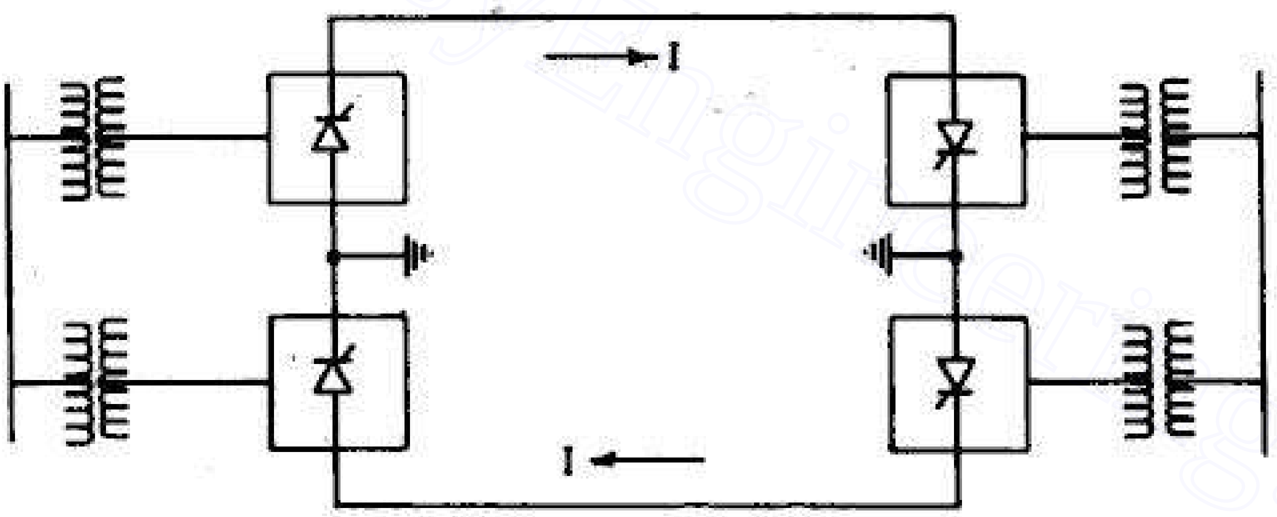
1.4 DESCRIPTION OF DC TRANSMISSION SYSTEM

1.4.1 Types of DC Links

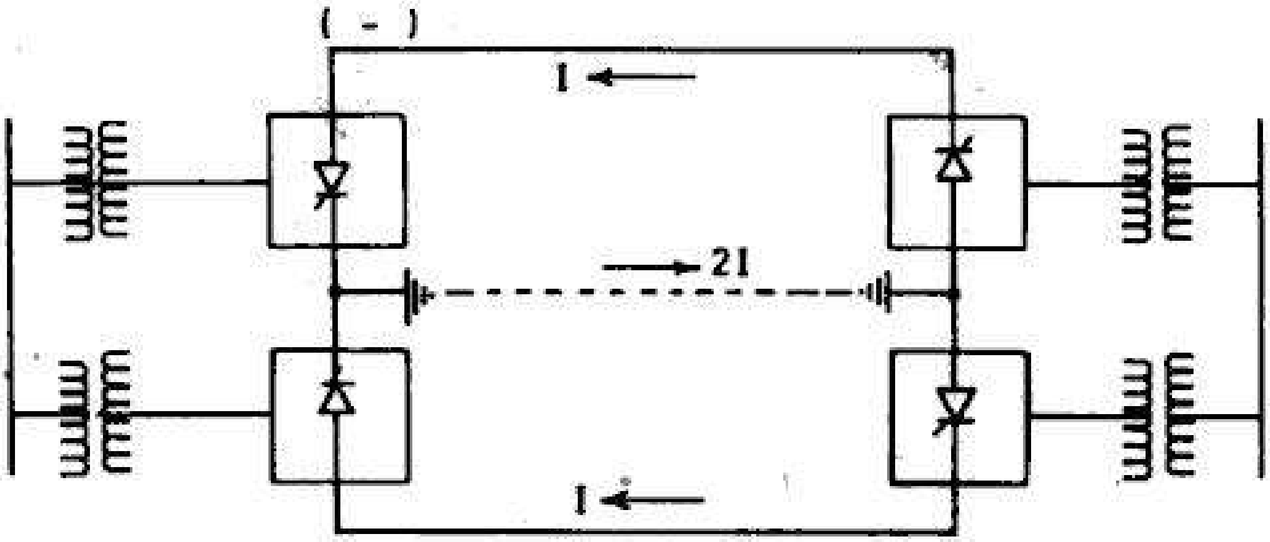
The DC links are classified into three types which are defined below :



(a) MONOPOLAR



(b) BIPOLAR



(c) HOMOPOLAR

Fig. 1.4 DC link configurations.

1. Monopolar link [see Fig. 1.4 (a)] has one conductor usually of negative polarity and uses ground or sea return. Sometimes metallic return is also used.

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Table 1.2 HVDC systems in service or under construction throughout the world

Sl. No.	HVDC - system	Transmission distance KM			Rated Voltage kV x No. of circuits	Nominal capacity MW	Max. continuous capacity MW	Commissioning date	Comments
		Overhead line	Cable	Total					
A.	**Mercury-arc Valve Systems**								
1.	Gotland-Swedish Mainland	0	96	96	150	30	30	1954/70	
2.	Cross Channel 1 (GB-F)	0	65	65	±100	160	160	1961	
3.	Volgograd-Donbass (SU)	470	0	470	±400	720	720	1962-65	
4.	Konti-Skan (DK-S)	95	85	180	250	250	275	1965	
5.	Sakuma (J)	—	—	—	125x2	300	300	1965	
6.	New Zealand (NZ)	570	39	609	±250	600	600	1965	
7.	Sardinia-Italian Mainland	292	121	413	200	200	200	1967	
8.	Vancouver Pole I (CDN)	total 41	total 33	74	±260	312	312	1968/69	
9.	Pacific Intertie (US)	1362	0	1362	±400	1600	1600	1970	
10.	Nelson River Bipole I (CDN)	890	0	890	±450	1620	1669	1973-77	
11.	Kingsnorth (GB)	0	82	82	±266	640	640	1974	
B.	**Thyristor Valve Systems**								
12.	Eel River (CDN)	—	—	—	80x2	320	350	1972	Asynchronous Tie
13.	Skagerrak (DK-N)	113	127	240	±250	500	510	1976/77	
14.	David A. Hamil (USA)	—	—	—	50	100	110	1977	Asynchronous Tie
15.	Cabora Bassa - Apollo (MOC-ZA)	1414	0	1414	±533	1920.	1920	1977/79	
16.	Vancouver Pole 2 (CDN)	total 41	total 33	74	−280	370	476	1977/79	
17.	Square Butte (US)	749	0	749	±250	500	550	1977	
18.	Shin-Shinano (J)	—	—	—	125x2	300	300	1977	50/60 Hz Tie

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Sl. No.	HVDC - system	Transmission distance KM			Rated Voltage kV x No. of circuits	Nominal capacity MW	Max. continuous capacity MW	Commissioning date	Comments
		Overhead line	Cable	Total					
19.	Nelson River Bipole 2 (CDN)	930	0	930	±250	900	1000	1978	
20.	Cu (Underwood Minneapolis)(US)	710	0	910	±400	1000	1100	1979	
21.	Hokkaido-Honshu (J)	124	44	158	250	300	300	1979/80	
22.	Acaray (PY-BR)	—	—	—	26	50	—	1981	50/60 Hz Tie
23.	EPRI Compact Station (USA)	—	0.6	0.6	100/400	100	—	1981	
24.	Vyborg (USSR-Finland)	—	—	—	±85 x 3	170	—	1982	Asynchronous Tie
25.	Inga Shaba (ZAIRE)	1700	0	1700	±500	560	—	1982	
26.	Durnrohr (A)	—	—	—	±145	550	633	1983	Asynchronous Tie
27.	Gotland 2 Swedish Mainland	7	91	98	150	130	165	1983	
28.	Eddy Co. (USA)	—	—	—	82	200		1983	Asynchronous Tie
29.	Itaipu (BR)	783/806	0	783/806	±300	1575		1984	
30.	Chateauguary (CDN)	—	—	—	140	1000		1984	Asynchronous Tie
31.	Itaipu (BR)	783/806	0	783/806	±600 x 2	6300		1985-87	
32.	Oklaunion (US)	—	—	—	82	200		1984	Asynchronous Tie
33.	Pacific Intertie (US)	—	—	—	±500	400		1985	
34.	Wien Sud-Ost (A)	—	—	—	145	550		1987	Asynchronous Tie
35.	Corsica Tap (F)	—	—	—	200	50		1986	
36.	Greece-Bulgaria	—	—	—	NA	300			Asynchronous Tie
37.	Madawaska (CDN)	—	—	—	144	350		1985	Asynchronous Tie
38.	Miles City (US)	—	—	—	82	200		1985	Asynchronous Tie
39.	Walker Co. (US)	256	0	256	±400	500-1500		1985	Asynchronous Tie
40.	Cross Channel 2 (GB-F)	0	72	72	±270 x 2	2000		1985/86	

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Sl. No.	HVDC - system	Transmission distance KM			Rated Voltage kV x No. of circuits	Nominal capacity MW	Max. continuous capacity MW	Commissioning date	Comments
		Overhead line	Cable	Total					
41.	Kanti-Skan 2 (DKS)	95	85	160	250	270		1988/89	
42.	Ekibastus-Centre (USSR)	2400	0	2400	±250	6000		1985-88	
43.	Store Baelt (DK)	35	30	55	280	350		1989-90	
44.	Skagerrak 2 (DK-N)	113	127	240	300	320		1988-89	
45.	Intermountain (US)	794	0	794	±500	1600		1987	
46.	Liberty Mead (US)	400	0	400	±364/±500	1600/2200		1989-90	
47.	Nelson River Bipole 3	930	0	930	±500	2000		1992/97	
48.	Chicoasen (MEX)	720	0	720	±500	900/1800		1985/90	
49.	Yukatan-Mexico City								
50.	Quebec-New England	175/375		175/375	±450	690/2070		1986/92	
51.	Des Cantons-Camerford	175		175	±450	690		1986	
52.	Sidney (US)	—	—	—		200		1986	Asynchronous Tie
53.	Blackwater (US)	—	—	—	56	200		1985	Asynchronous Tie
54.	Highgate (US)	—	—	—	56	200		1985	Asynchronous Tie
55.	SACOI - 2 (Italy)				200	300		1989	
56.	Pacific Intertie II (US)				±500	1100			
57.	Gezhouba-Nan Qiao (China)	1080	—	1080	±500	1200		1987-91	
58.	Rihand-Delhi (India)	1000	—	1000	±500	1000		1987	
59.	Uruguaiana (BR-Argentina)					50		1986/87	Asynchronous Tie
60.	Camerford-Sandy Pond	200				1400		1990	
61.	Vindhyachal (India)	—	—	—	70	250 x 2		1988	Asynchronous Tie
62.	Gotland 3 - Swedish Mainland	—	98	98	150	130	165	1987	
63.	South Finland East Sweden	35	185	220	350	420		1989/90	

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2. Bipolar link [see Fig. 1.4 (b)] has two conductors, one positive and the other negative. Each may be a double conductor in EHV lines. Each terminal has two sets of converters of identical ratings, in series on the DC side. The junction between the two sets of converters is grounded at one or both ends. Normally, both poles operate at equal currents and hence there is zero ground current flowing under these conditions.
3. Homopolar Link [see Fig. 1.4 (c)] has two or more conductors all having the same polarity (usually negative) and always operated with ground or metallic return.

Because of the desirability of operating a DC link without ground return, bipolar links are most commonly used. Homopolar link has the advantage of reduced insulation costs, but the disadvantages of earth return outweigh the advantages. Incidentally, the corona effects in a DC line are substantially less with negative polarity of the conductor as compared to the positive polarity.

The monopolar operation is used in the first stage of the development of a bipolar line, as the investments on converters can be deferred until the growth of load which requires bipolar operation at double the capacity of a monopolar link.

1.4.2 Converter Station

The major components of a HVDC transmission system are converter stations where

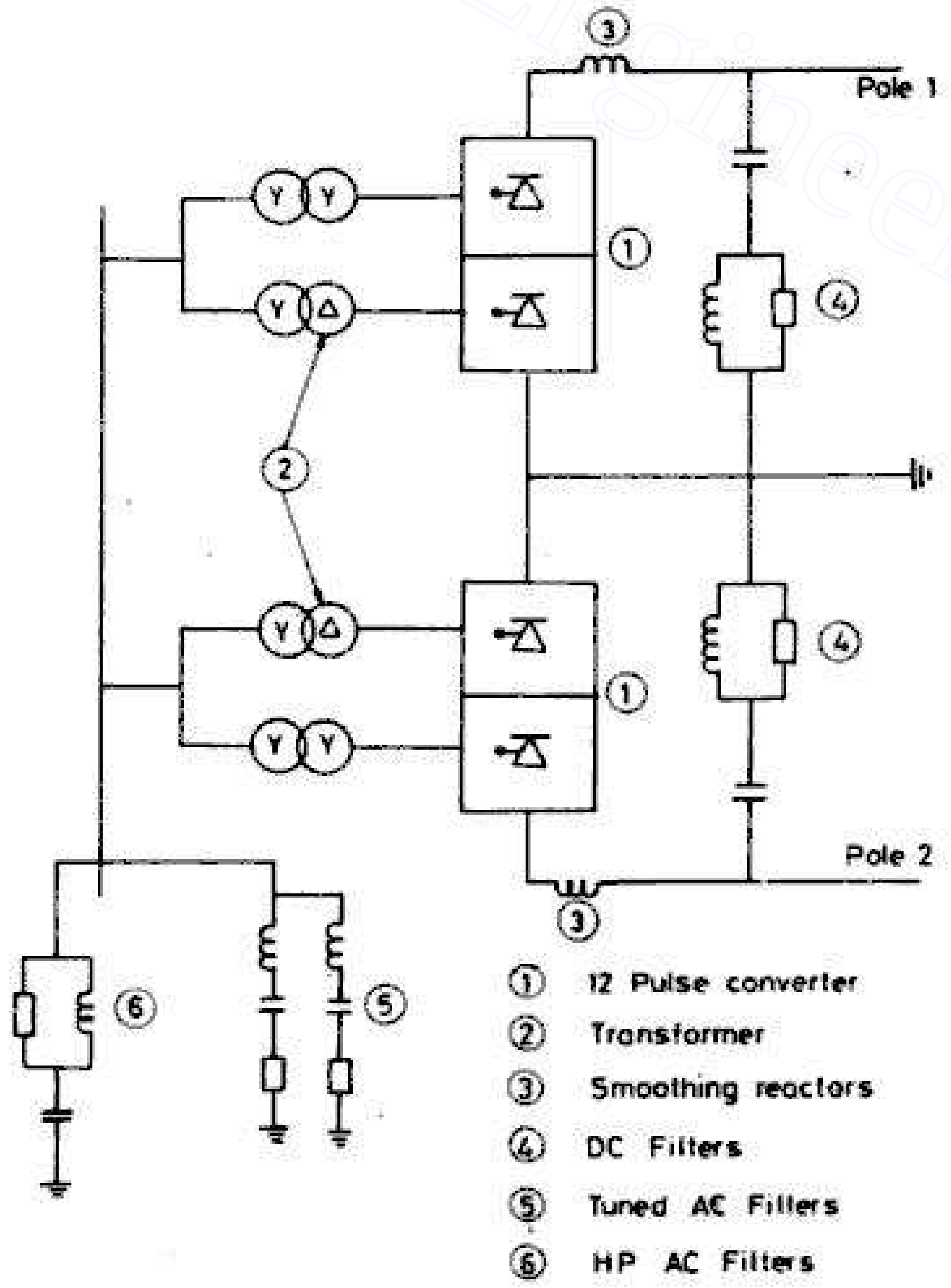

Fig. 1.5 Schematic diagram of a typical HVDC converter station.

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conversions from AC to DC (Rectifier station) and from DC to AC (Inverter station) are performed. A point to point transmission requires two converter stations. The role of rectifier and inverter stations can be reversed (resulting in power reversals) by suitable converter control.

A typical converter station with two 12 pulse converter units per pole, is shown in Fig. 1.5. The various components of a converter station are discussed below.

Converter unit

This usually consists of two three phase converter bridges connected in series to form a 12 pulse converter unit as shown in Fig. 1.6. The total number of valves in such a unit are twelve. The valves can be packaged as single valve, double valve or quadrivalve arrangements. Each valve is used to switch in a segment of an AC voltage waveform. The converter is fed by converter transformers connected in star/star and star/delta arrangements.

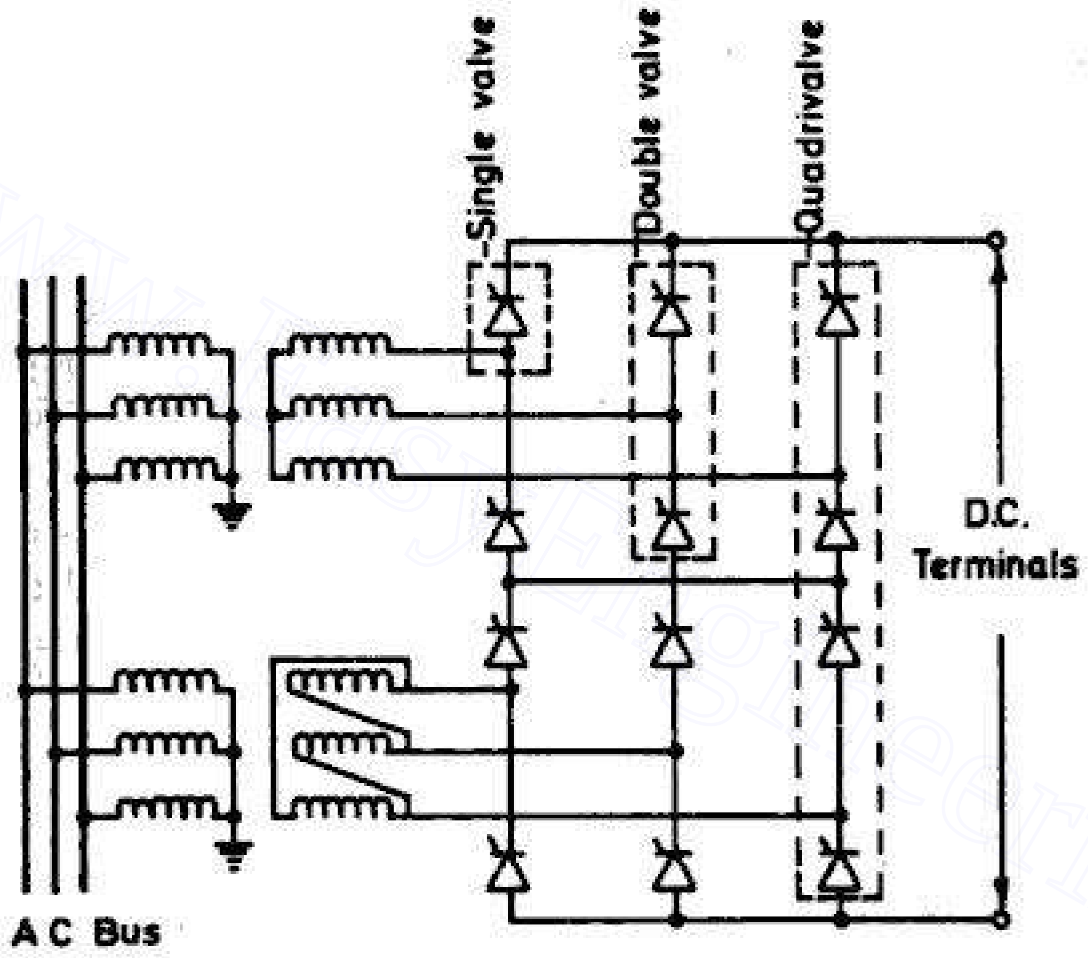

Fig. 1.6 A Twelve pulse converter unit

The valves are cooled by air, oil, water or freon. Liquid cooling using deionized water is more efficient and results in the reduction of station losses. The ratings of a valve group are limited more by the permissible short circuit currents than steady state load requirements. The design of valves is based on the modular concept where each module contains a limited number of series connected thyristor levels.

Valve firing signals are generated in the converter control at ground potential and are transmitted to each thyristor in the valve through a fiber optic light guide system. The light signal received at the thyristor level is converted to an electrical signal using gate drive amplifiers with pulse transformers.

The valves are protected using snubber circuits, protective firing and gapless surge arresters. Some of the details of the control and protection of thyristor valves are given in chapter 2.

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Converter Transformer

The converter transoformer can have different configurations - (i) three phase, two winding, (ii) single phase, three winding, (iii) single phase, two winding. The valve side windings are connected in star and delta with neutral point ungrounded. On the AC side, the transformers are connected in parallel with neutral grounded. The leakage reactance of the transformer is chosen to limit the short circuit currents through any valve.

The converter transformers are designed to withstand DC voltage stresses and increased eddy current losses due to harmonic currents. One problem that can arise is due to the DC magnetization of the core due to unsymmetric firing of valves.

In back to back links, which are designed for low DC voltage levels, an extended delta configuration can result in identical transformers being used in twelve pulse converter units. This results in the reduction of the spare capacity required. However, the performance of extended delta transformers in practice is still to be tested.

Filters

There are three types of filters used :

1. AC filters : These are passive circuits used to provide low impedance, shunt paths for AC harmonic currents. Both tuned and damped filter arrangements are used.
2. DC filters : These are similar to AC filters and are used for the filtering of DC harmonics.
3. High frequency (RF/PLC) filters: These are connected between the converter transformer and the station AC bus to suppress any high frequency currents. Sometimes such filters are provided on high-voltage DC bus connected between the DC filter and DC line and also on the neutral side.

Reactive power source

Converter stations require reactive power supply that is dependent on the active power loading (about 50 to 60% of the active power). Fortunately, part of this reactive power requirement is provided by AC filters. In addition, shunt (switched) capacitors, synchronous condensors and static var systems are used depending on the speed of control desired.

Smoothing reactor

A sufficiently large series reactor is used on DC side to smooth DC current and also for protection. The reactor is designed as a linear reactor and is connected on the line side, neutral side or at intermediate location.

DC switchgear

This is usually a modified AC equipment used to interrupt small DC currents (employed as disconnecting switches). DC breakers or metallic return transfer breakers (MRTB) are used, if required for interruption of rated load currents.

In addition to the equipment described above, AC switchgear and associated equipment for protection and measurement are also part of the converter station.

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1.5 PLANNING FOR HVDC TRANSMISSION

The system planner must consider DC alternative in transmission expansion. The factors to be considered are (i) cost, (ii) technical performance, and (iii) reliability.

Generally, the last two factors are considered as constraints to be met and the minimum cost option is selected among various alternatives that meet the specifications on technical performance and reliability.

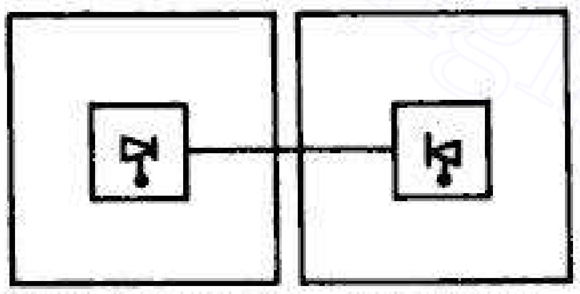
For submarine, cable transmission and interconnecting two systems of different nominal frequencies, the choice of DC is obvious. In other cases, the choice is to be based on detailed techno-economic comparison.

The considerations in the planning for DC depends on the application. Two applications can be considered as representative.

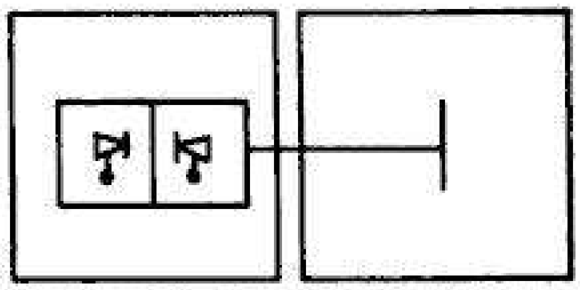
These are:

1. Long distance bulk power transmission
2. Interconnection between two adjacent systems

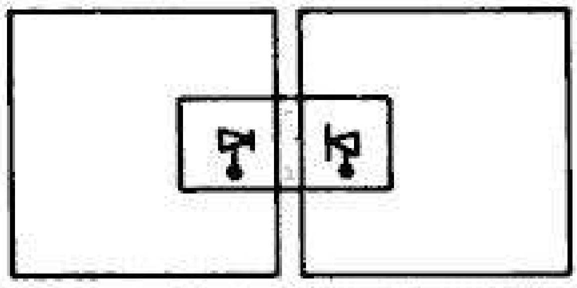
In the first application, the DC and AC alternatives for the same level of system security and reliability are likely to have the same power carrying capability. Thus the cost comparisons would form the basis for the selection of the DC (or AC) alternative, if the requirements regarding technical performance are not critical.



(a) TWO TERMINAL DC LINK



(b) BACK TO BACK DC LINK ALONG WITH AC FEEDER



(c) BACK TO BACK DC LINK AT BORDER

Fig. 1.7 Different configurations for asynchronous interconnection.

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In the second application, AC interconnection poses several problems in certain cases. For the same level of system security (and reliability), the required capacity of AC interconnection will be much more than that for DC (even ignoring the beneficial aspects of DC power modulation). Thus the choice for DC interconnection will be based on the following considerations.

1. Small fluctuations in the voltage and frequency do not affect the power flow which can be set at any desired value.
2. The system security can be enhanced by fast control of DC power.

Having settled on the DC link for interconnection, there are three possible configurations for interconnection. These are:

1. A two terminal transmission where each terminal is located at a suitable place somewhere within the network and connected by a DC overhead line or cable.
2. A back to back HVDC station (also called HVDC coupling station) located somewhere within one of the network and an AC line from the other network to the common station.
3. A back to back station located close to the border between the two systems. This is a special case of the above.

These are illustrated in fig. 1.7.

In the choice between the first and second configuration, it is to be noted that converter costs are less for the common coupling station and the AC line costs are greater than the DC line costs. If the distances involved are less than 200 km, the second configuration is to be preferred. If the short circuit ratio (SCR) is acceptable, then the third alternative will be the most economic.

The specifications and design of DC system require an understanding of the various interactions between the DC and AC systems. The interruption (or reduction) of power in a DC link can occur due to (i) DC line faults (ii) AC system faults.

The speed of recovery from transient DC lines faults is of concern in maintaining the integrity of the overall system. The power flow and stability studies are used in this context. The recovery of DC link from AC system faults is more complex. The depression of AC voltage at the inverter bus can lead to commutation failure and loss of DC power. The DC power is ramped up on the clearing of the fault. Too fast an increase in DC power output can lead to the reduction of AC voltage and failure of commutation (due to corresponding increase in the var demand). An optimum rate of increase in DC power can be determined from stability study. This is influenced by control strategy and system characteristics.

The following aspects also require a detailed study of the system interactions.

1. Var requirements of converter stations
2. Dynamic overvoltages
3. Harmonic generation and design of filters
4. Damping of low frequency and subsynchronous torsional oscillations
5. Carrier frequency interference caused by spiky currents in valves (at the beginning of conduction) due to the discharge of stray capacitances and snubber circuits.

The converter control plays a major role in these interactions and the control strategy should be such as to improve the overall system performance. Digital simulation and HVDC simulators are used for planning and design studies.

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Choice of voltage level

For long distance bulk power transmission, the voltage level is chosen to minimize the total costs for a given power level (P). The total costs include investment (C_1) and cost of losses (C_2). The investment costs per unit length are modelled as

$$C_1 = A_0 + A_1\, nV + A_2\, nq \tag{1.1}$$

where

V is the voltage level with respect to ground

n is the number of conductors

q is the total cross-section of each conductor

A_0, A_1 and A_2 are constants.

The cost of losses per unit length is given by

$$C_2 = [n(P/nV)^2\, \rho TLp]/q \tag{1.2}$$

where

ρ = conductor resistivity

T = total operation time in a year

L = loss load factor

p = cost per unit energy

C_2 can be simplified as

$$C_2 = (A_3\, (P/V)^2\rho]/nq \tag{1.3}$$

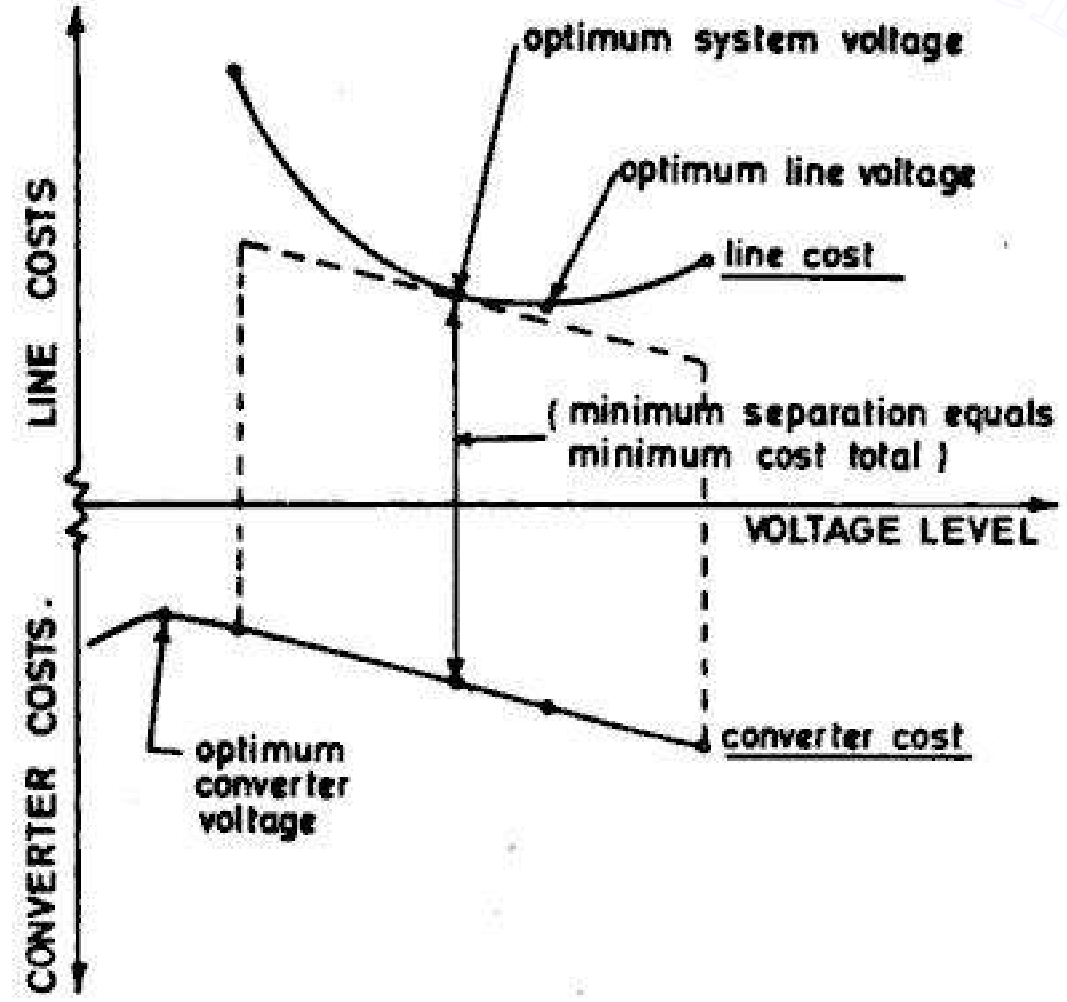

Fig. 1.8 Selection of Optimum System Voltage for A Fixed Power Transfer.

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instead of the conventional FZ (float zone) method. Research is also underway in reducing this packaging cost of a device.

Converter Control

The development of micro-computer based converter control equipment has now made it possible to design systems with completely redundant converter control with automatic transfer between systems in the case of a malfunction. Not only is the forced outage rate of control equipment reduced but it is also possible to perform scheduled preventive maintenance on the stand-by system when the converter is in operation. The use of a mini-simulator will make it feasible to check vital control and protection functions.

The micro-computer based control also has the flexibility to try adaptive control algorithms or even the use of expert systems for fault diagnosis and protection.

DC breakers

With the development and testing of prototype DC breakers, it will be possible to go in for tapping an existing DC link or the development of new MTDC systems. Parallel, rather than series operation of converters is likely as it allows certain flexibility in the planned growth of a system. The DC breaker ratings are not likely to exceed the full load ratings as the control intervention is expected to limit the fault current.

The control and protection of MTDC systems is not a straightforward extension of that used in the two-terminal DC systems. The possibility of decentralized control necessitated by communication failure, the coordination of control and protection are some of the issues currently being studied.

Conversion of existing AC lines

The constraints on RoW are forcing some utilities to look into the option of converting existing AC circuits to DC in order to increase the power transfer limit. There could be some operational problems due to electromagnetic induction from AC circuits operating in the same RoW.

An experimental project of converting a single circuit of a double circuit 220 KV line is currently under commissioning stage in India.

Operation with weak AC systems

The strength of AC systems connected to the terminals of a DC link is measured in terms of short circuit ratio (SCR) which is defined as

$$\text{SCR} = \frac{\text{Short circuit level at the converter bus}}{\text{Rated DC power}}$$

If SCR is less than 3, the AC system is said to be weak. The conventional constant extinction angle control may not be satisfactory with weak AC system. The recovery of inverters following the clearing of fault in the connected AC system can also be problematic.

Constant reactive current control or AC voltage control have been suggested to overcome some of the problems of weak AC systems. The use of fast reactive power

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where α_1 and α_2 are the common-base current gains and I_{CB01} and I_{CB02} are the common-base leakage currents of T_1 and T_2 respectively. From (2.1) to (2.3), we have

$$I_A = \frac{\alpha_2 I_G + I_{CB\,01} + I_{CB\,02}}{1 - (\alpha_1 + \alpha_2)} \tag{2.4}$$

A silicon transistor has the property that α is very low at low emitter current and rises rapidly as the emitter current builds up. When the device is off, $I_G = 0$, and I_A will be the leakage current. If it is possible to raise the emitter currents of T_1 and T_2, such that $(\alpha_1 + \alpha_2)$ approaches unity, then the device triggers into saturation. There are several means of achieving this :

1. Injection of gate curent (normal turn-on)
2. By increasing the forward voltage above a limit, V_{bo} called break-over voltage. In this case, the minority-carrier leakage current at middle junction increases due to avalanche effect.
3. By increasing the anode voltage at a rate such that the depletion layer capacitance at the middle junction will create a displacement current (*dv/dt* turn-on).
4. At a high enough junction temperature, the leakage current increases and causes a turn-on.
5. Direct irradiation of light on silicon creates electron-hole pairs, which under the influence of electric field result in a current to trigger the thyristor.

Triggering the device into saturation is called turn-on.Controlled turn-on without damaging the device is only feasible through gated turn-on. The device remains in a conducting state until the current is maintained by the circuit action, above the holding current. During this period, the gate has no control on the conduction. The turn-off process which results in the deivce regaining its blocking state is achieved either by : (i) line commutation or (ii) forced commutation.

In both cases, the circuit voltage source is reversed which in turn will drive the current to zero. After a time lapse of t_q, the turn-off time, the voltage can be reversed again, when the device regains its blocking state.

2.2.3 Device Characteristics

The device can be in one of the three following states :

(i) Forward biased and blocking
(ii) Forward biased and conducting
(iii) Reverse biased and blocking.

The transition from the first to the second state is called turn-on, while the transition from the second to the third state is called turn-off. The characteristics of the device refer to the parameters of the device both in steady-state and transient conditions (during the transition of state).

Steady state characteristics

Off-State : The volt-ampere characteristics of the device are shown in Fig. 2.3. During the off-state (both forward and reverse blocking), only a small magnitude of leakage

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thyristors are used to limit *di/dt*, particularly arising from the discharge of current due to stray capacitances and snubber circuits.

There are three phases of turn-on shown in Fig. 2.6. The delay time is associated with the establishment of regenerative action in response to the gate current. Its duration depends upon the level of the gate drive. Regeneration is well established during the rise time. The current continues to increase during the spread-time. The losses during the spread time can result in increase of 10-20% of that predicted for normal conduction using on-state voltage of the thyristor. The spreading phase may last over hundred micro-seconds.

Ungated turn-on can occur due to overvoltage, *dv/dt* or incomplete forward recovery. This is to be avoided because of the damage it can cause to the device. Protective turn-on by applying a gate pulse whenever the possibility of ungated turn-on is detected, is usually adopted.

Turn-off : All the three junctions are forward biased during on-state and the base regions contain excess minority and majority charge. This charge must either be swept out by an electric field or decay through regenerative processes within the silicon.

When the circuit voltage is reversed, the current falls to zero at a certain rate. Once the current reaches zero, the flow reverses, since the minority carrier concentration at the junctions can support this current by diffusion without build-up of depletion layer. The peak value of this reverse current is reached when the excess hole concentration at the anode junction has fallen to zero. At this time, the voltage across the thyristor reverses with the development of the depletion layer and the current decays in a near exponential manner as a result of charge recombination within the *n*-base region. The decay of current is dependent on the mean life-time of carriers in the *n*-base region. The turn-off process is shown in Fig. 2.7.

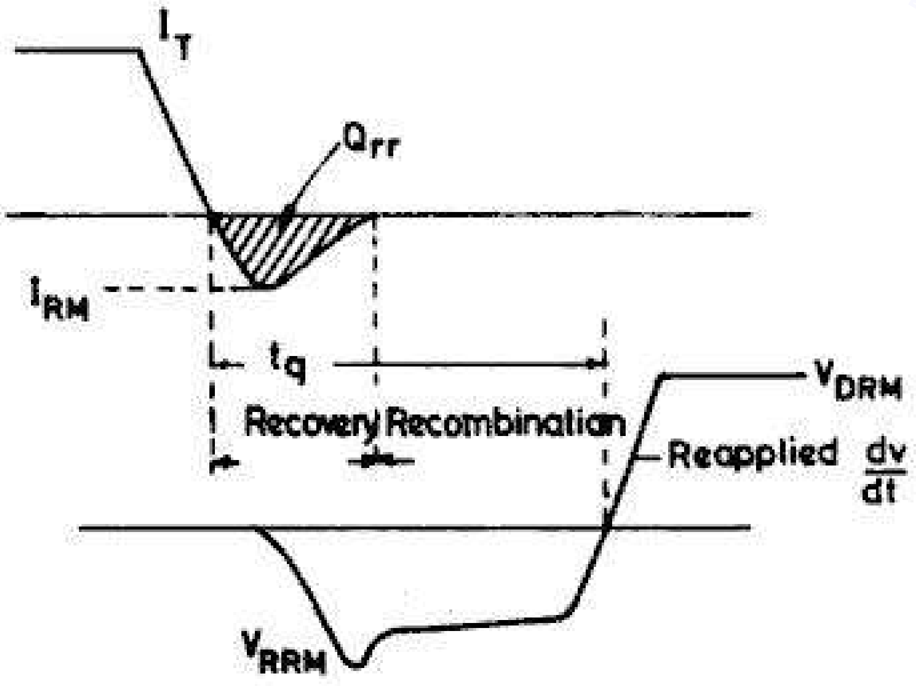

Fig. 2.7 Turn-off characteristics

Immediately after current zero, a thyristor is unable to support forward voltage. Gradually, the thyristor acquires some forward blocking capability but its ability to withstand forward *dv/dt* is severely limited. Off-state *dv/dt* capability is attained only after a millisecond or so has elapsed from current zero. This characteristic is circuit and

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Thus each thyristor level is independent, sharing only a duplicated light source at the ground potential.

The valve control unit also includes many monitoring and protective functions. The return pulse system coupled with short pulse firing scheme is used in present day valve control units. A separate light guide is used to send a return pulse whenever the voltage across a thyristor is sufficient and the power supply unit is charged. If at that time, firing pulses are demanded from the valve control, the light signals are sent to all the thyristor control units simultaneously.

During normal operation, only one set of light pulses are generated in a cycle for each valve. However, during operation at low direct currents, many light pulses are generated due to discontinuous current.

2.3.3. Valve Design Considerations

The design of the valve must consider the voltage and current stresses that occur during normal and abnormal conditions. The overvoltages across a valve may be generated internally during switching action or the result of external causes such as short circuits on AC and DC systems. The fundamental frequency dynamic overvoltage is crucial in determining the voltage ratings and this arises when the load is thrown off due to blocking of converters. The magnitude of the dynamic overvoltage is dependent on the AC system strength.

The overcurrents in a valve arise from short circuits across a valve or a converter bridge. The surge current rating of a valve is limited both by transformer leakage and system impedances. The transformer leakage impedances have been reduced to 0.12 pu with higher rated devices.

The overload rating of a valve is a function of the size of the device as well as ambient temperature and the cooling system. For example, it is possible to increase the direct current by 20% for a decrease in ambient temperature by 8°C, with water cooling.

The losses in a valve include (i) the losses during on-state and switching losses, (ii) damper and grading circuit losses and (iii) losses due to auxiliary power required for cooling. The resistances of the damper and grading circuits are also watercooled. Their losses are functions of converter delay and overlap angles.

The calculation of internally generated overvoltages and the design of valve components such as damper circuits is facilitated by digital computer programmes which can

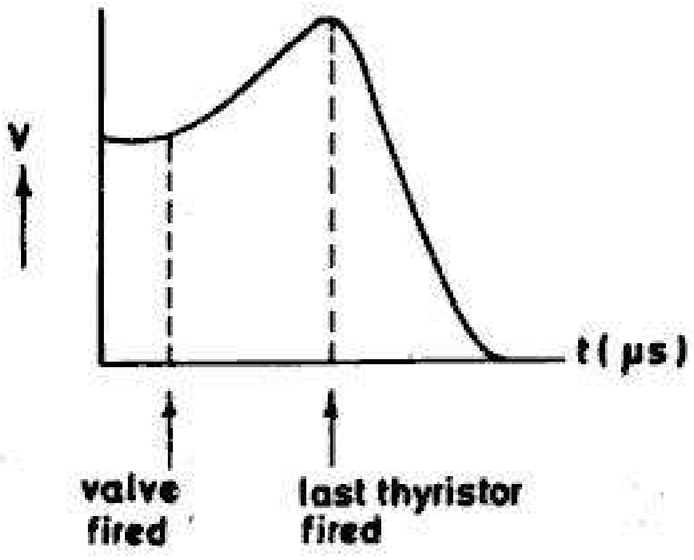

Fig. 2.12 Voltage on last firing thyristor.

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The typical current waveform in the damper circuit is shown in Fig. 2.17. This shows that the current is appreciable only around the voltage jumps which are 8 in number in a cycle.

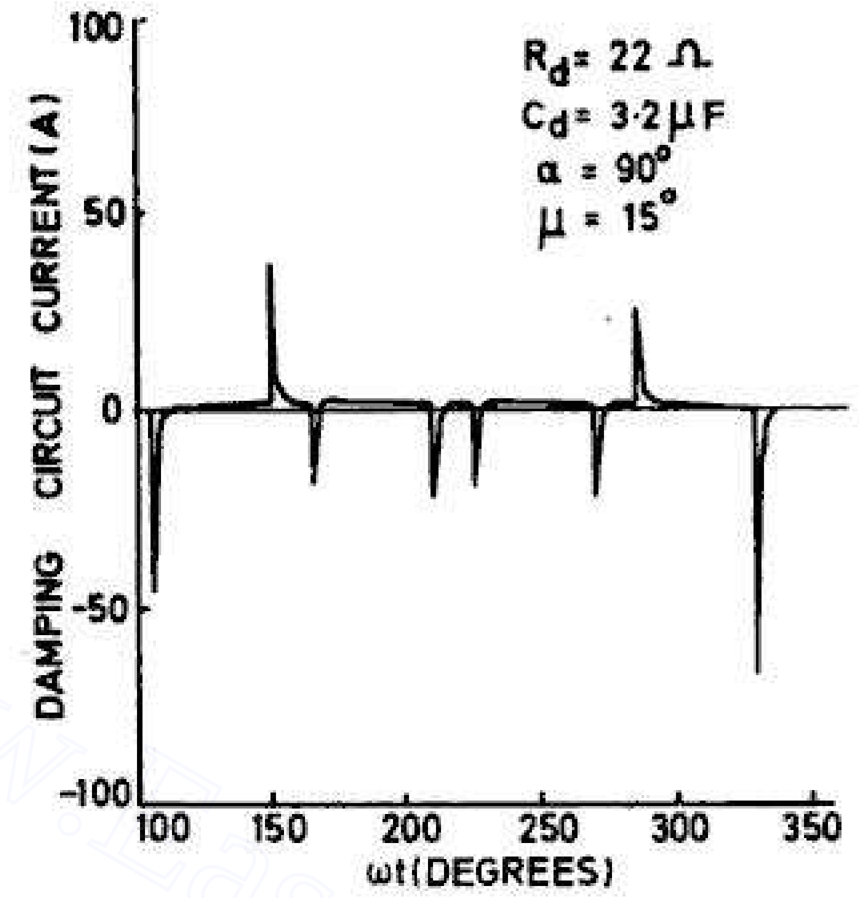

Fig. 2.17 Computed damping circuit current waveform

2.3.5 Valve Protection

Overvoltage Protection

A HVDC valve must be designed to withstand (a) internal and (b) external overvoltages. The causes for the internal voltages have been mentioned in the previous section. The external sources of overvoltage across a valve can be due to (i) lightning and switching surges, (ii) dynamic overvoltages caused by load rejection, (iii) low order harmonic resonance in the AC system, and (iv) injection of AC voltage on the DC line due to converter faults.

Zinc oxide, gapless DC surge arresters across a valve can protect the valve against transient overvoltages. The overvoltage in the forward direction can be controlled by protective firing of the thyristors in a valve. This is achieved by utilizing the voltage sensitive switching action of a high voltage break-over diode across each thyristor. The protective firing thus is independent for each thyristor level. If there is some malfunction in the main firing system, the protective firing circuit is designed to work as a back-up, working continuously until the next maintenance period.

The overvoltages in the forward direction can also arise from partial recovery of a valve following turn-off process, (in inverters). In bypass pair mode operation, uneven distribution of voltage in a series connected string can arise due to dispersion in the holding current (I_H) of the thyristors. In such cases, forward *dv/dt* protection is also required by sensing the *dv/dt* measured across a level and turning on the device if the threshold is exceeded. The threshold *dv/dt* level can be made a function of the junction temperature.

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The criteria for the success of a type test are the following :

1. Not more than 1% of thyristors have failed
2. No failure of electronic or other components
3. There are no disruptive discharges across dielectric material, cooling tubes or light guides.

2.5 RECENT TRENDS

The recent developments are expected to improve reliability and reduce the cost of HVDC valves. These are mainly :

1. Development in high power semiconductor devices - these include direct light triggered thyristors (LTT) and metal- oxide semiconductor controlled thyristors (MCT)
2. Better cooling techniques such as forced vaporization (two phase flow) as a means of reducing thermal resistance between the heat sink and the ambient.
3. Suspension of quadrivalve assembly from ceiling to withstand seismic forces.

Light Triggered Thyristor [3, 4, 8, 18]

Both in USA and Japan, high power, high voltage LTT have been developed and tested. LTT has the following advantage over electrically triggered thyristors (ETT).

1. Infinite gate isolation
2. Total noise immunity for the control circuit
3. Faster turn-on time
4. Elimination of high voltage pulse transformers and auxiliary power supplies.

The light sources used are either gallium arsenide light emitting diodes (LED) or laser diodes.

One of the problems of LTT is the reduced *di/dt* rating. This problem can be solved by (i) a separate gate LTT to fire an ETT or (ii) controlled LTT turn-on. The electrical equivalent of the latter is shown in Fig. 2.18.

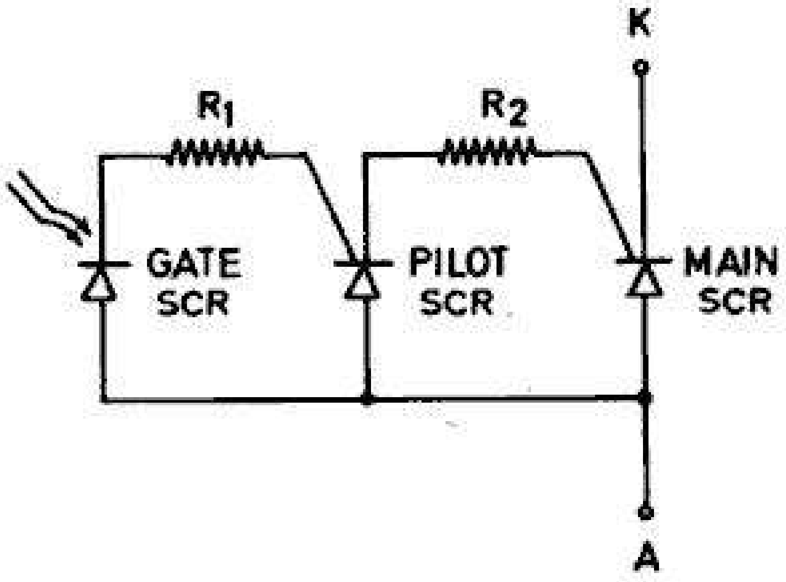

Fig. 2.18 Light triggered thyristor

Although the power supply circuits (at the thyristor level) in LTT are eliminated, the overvoltage protection circuits are still required. To improve the system reliability, it would be advantageous to eliminate these also. With this objective, a novel LTT with

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voltages onto the DC circuit. One possible configuration for a 'p' pulse converter is shown in Fig. 3.2. A valve can be treated as a (controllable) switch which can be turned on at any instant, provided the voltage across it is positive. A diode is an uncontrolled switch which will turn on immediately after the voltage becomes positive whereas the thyristor switching can be delayed by an angle α (alpha). The voltage sources are actually obtained from the transformer secondary windings. The opening of the switch (both for diode and thyristor) occurs at the current zero (neglecting the turn-off time).

The output voltage V_d of the converter consists of a DC component and a ripple whose frequency is determined by the pulse number.

3.2 CHOICE OF CONVERTER CONFIGURATION

The configuration for a given pulse number is selected in such a way that both the valve and transformer (feeding the converter) utilization are maximized.

The configuration shown in Fig. 3.2 is not the best. In general, a converter configuration can be defined by the basic commutation group and the number of such groups connected in series and parallel (see Fig. 3.3). If there are 'q' valves in a basic commutation group and r of these are connected in parallel and s of them connected in series, then

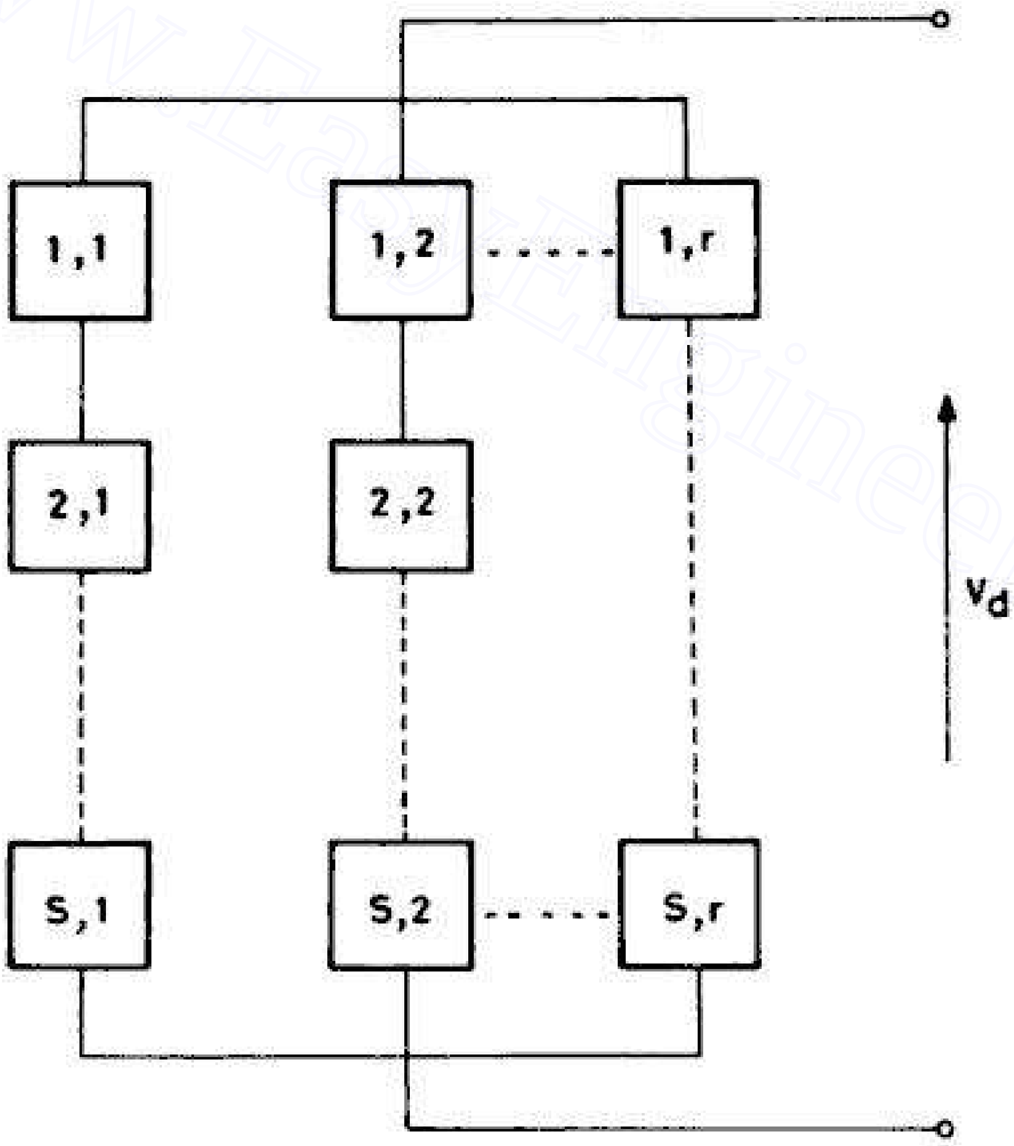

Fig. 3.3 Converter made up of series and parallel connection of commutation groups

$$p = q\ r\ s \tag{3.1}$$

(Note: A commutation group is defined as the group of valves in which only one (neglecting overlap) conducts at a time).

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$$\text{Average dc voltage} = V_d = \frac{3}{\pi}\int_{\alpha}^{\alpha+60°} \sqrt{2}\,E_{LL}\,\sin(\omega t + 60°)\,d\,\omega t$$

$$= \frac{3}{\pi}\sqrt{2}\,E_{LL}\,[\cos(\alpha + 60°) - \cos(\alpha + 120°)]$$

$$V_d = \frac{3\sqrt{2}}{\pi}\,E_{LL}\cos\alpha = 1.35\,E_{LL}\cos\alpha$$

$$= V_{do}\cos\alpha \tag{3.8}$$

Equation (3.8) indicates that for different values of α, V_d is variable. The range of α is 180° (from 0° to 180°) and correspondingly V_d can vary from V_{do} to $-V_{do}$. Thus the same converter can act as a rectifier or inverter depending upon whether the dc voltage is positive or negative. It is to be noted that this is based on the assumption of continuous conduction of current by any valve over the 120° interval.

DC Voltage Waveform

The dc voltage waveform contains a ripple whose fundamental frequency is six times the supply frequency. This can be analysed in Fourier series and contains harmonics of the order

$$h = n\,p$$

where p is the pulse number and n is an integer.
The rms value of the h^{th} order harmonic in dc voltage is given by

$$V_h = V_{do}\,\frac{\sqrt{2}}{h^2 - 1}\left[1 + \left(h^2 - 1\right)\sin^2\alpha\right]^{1/2} \tag{3.9}$$

The waveform of the direct voltage for different values of α are shown in Fig. 3.5. The waveforms of the valve voltage are also shown in the same figure. The figure shows

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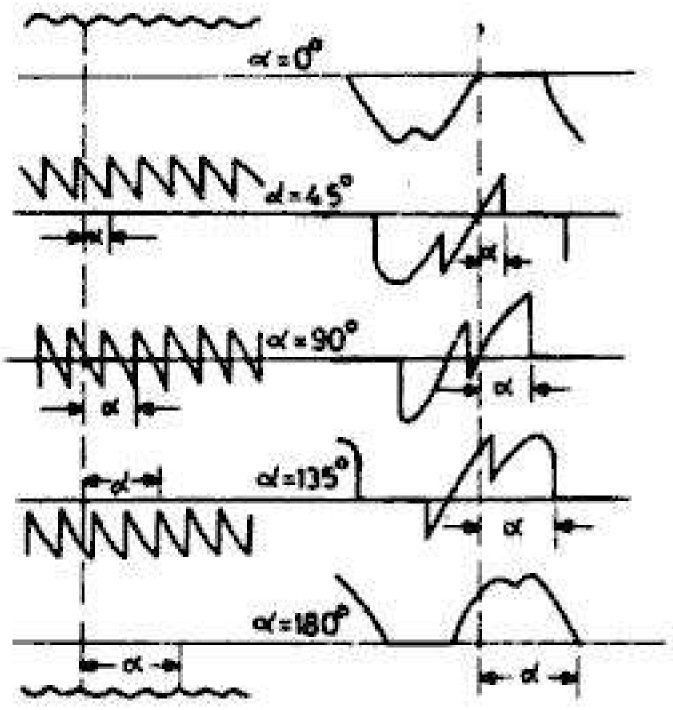

Fig. 3.5 DC and valve voltage waveforms

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Note that the solution given in (3.20) is obtained from the initial condition

$$i_3\,(\omega t = \alpha) = 0 \tag{3.22}$$

At $\omega t = \alpha + u$, $i_3 = I_d$. This gives

$$I_d = I_s\,[\cos\alpha - \cos(\alpha + u)] \tag{3.23}$$

The waveforms of direct voltage and the valve currents during commutation for a rectifier and an inverter are shown in Fig. 3.9(a) and 3.9(b) respectively. It is to be noted that during commutation, the instantaneous dc voltage is $\frac{-3}{2}e_c$ instead of $(e_b - e_c)$.

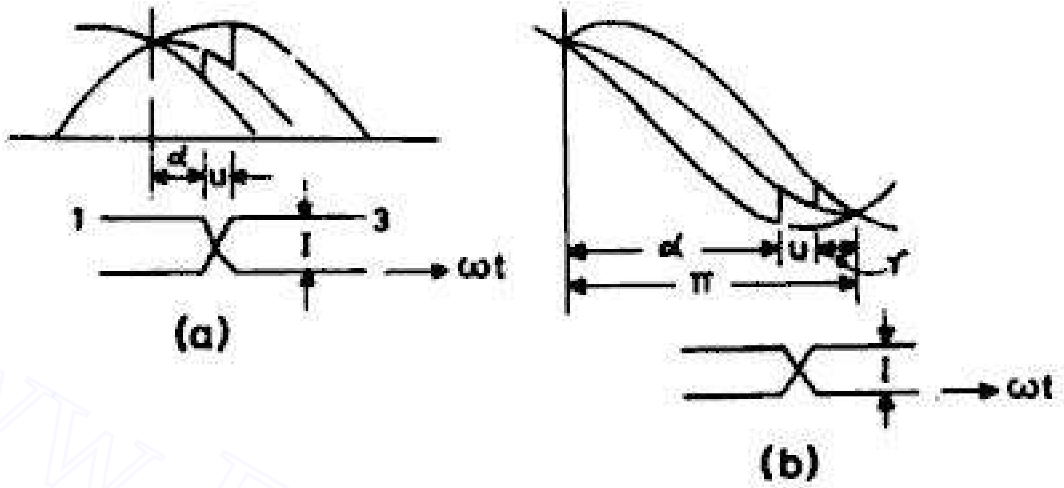

Fig. 3.9 Voltage and current waveform during firing of a valve (a) rectifier (b) inverter

Average Direct Voltage

The average direct voltage can be obtained as

$$V_d = \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+u} \frac{-3}{2} e_c \, d(\omega t) + \int_{\alpha+u}^{\alpha+60^\circ} (e_b - e_c)\, d(\omega t)\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60} e_{bc}\, d(\omega t) - \int_{\alpha}^{\alpha+u} \frac{2e_b + e_c}{2}\, d(\omega t)\right]$$

$$= \frac{3}{\pi}\left[\int_{\alpha}^{\alpha+60^\circ} e_{bc}\, d(\omega t) - \int_{\alpha}^{\alpha+u} \frac{(e_b - e_a)}{2}\, d(\omega t)\right]$$

$$= V_{do}\cos\alpha - \frac{3}{2\pi}\int_{\alpha}^{\alpha+u} \sqrt{2}\,E_{LL}\sin\omega t\, d(\omega t)$$

$$= V_{do}\cos\alpha - \frac{3}{2\pi}\sqrt{2}\,E_{LL}\,[\cos\alpha - \cos(\alpha + u)] \tag{3.24}$$

Since $\frac{3}{\pi}\sqrt{2}\,E_{LL} = V_{do}$, we get

$$V_d = \frac{V_{do}}{2}\,[\cos\alpha + \cos(\alpha + u)] \tag{3.25}$$

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The harmonics in the direct voltage are also altered due to overlap. It can be shown that

$$\frac{V_h}{V_{do}} = \left\{ \frac{1}{2} \left[F^2 + G^2 - 2FG \cos(2\alpha + u) \right] \right\}^{1/2} \tag{3.39}$$

where

$$F = \frac{\cos (h+1)\frac{u}{2}}{(h+1)}, \quad G = \frac{\cos (h-1)\frac{u}{2}}{h-1} \tag{3.40}$$

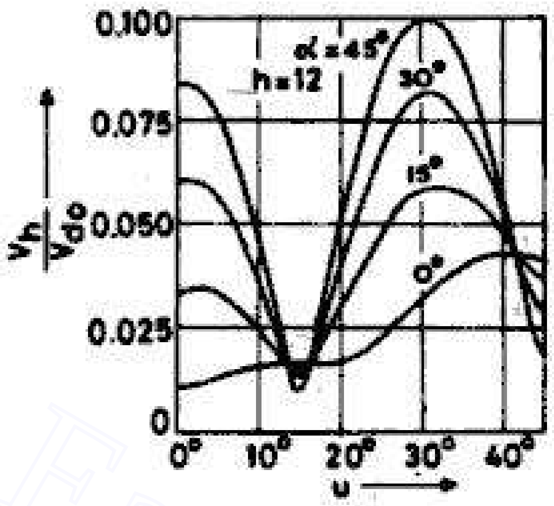

Fig. 3.14 Variation of DC voltage harmonics with overlap

Figure 3.14 shows $\left(\frac{V_{12}}{V_{do}}\right)$ for different values of u and α.

(ii) Three and Four valve conduction mode

Although two and three valve conduction mode is the normal mode of operation, during DC line faults or a dip in the AC voltage, it is likely that the overlap angle u would be larger and may exceed 60°.

When the overlap angle exceeds 60°, the minimum number of valves conducting are three and there are intervals when four valves are conducting. This is because when a commutation process is started, the previous commutation process is not yet completed. For example, when valve 3 is fired, the valves 1, 6, and 2 are still conducting. The equivalent circuit for this condition is shown in Fig. 3.15.

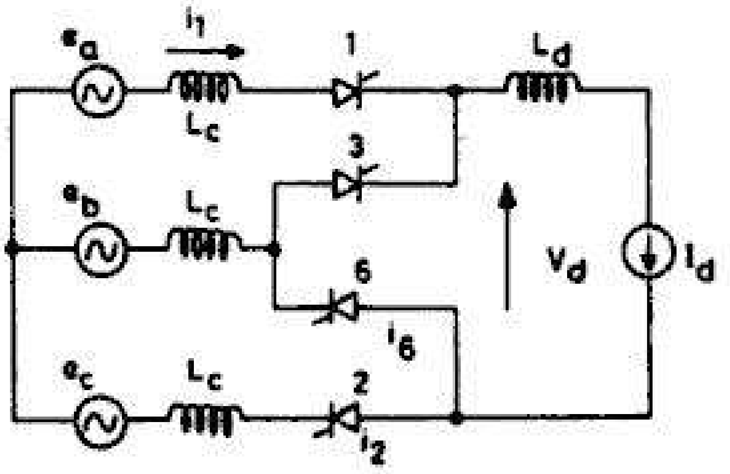

Fig. 3.15 Equivalent circuit for four valve conduction

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For mode (2) $u = 60°$. For u = constant, the characteristics are elliptical and the equation is given by

$$\left(\frac{\bar{V}_d}{\cos\frac{u}{2}}\right)^2 + \left(\frac{\bar{I}_d}{\sin\frac{u}{2}}\right)^2 = 1 \tag{3.53}$$

where $\bar{V}_d = \dfrac{V_d}{V_{do}}, \bar{I}_d = \dfrac{I_d}{2I_s}$

Equation (3.53) follows from the following relations

$$\bar{V}_d = \frac{1}{2}\left[\cos\alpha + \cos(\alpha + u)\right] = \cos\left(\alpha + \frac{u}{2}\right)\cos\frac{u}{2} \tag{3.54}$$

$$\bar{I}_d = \frac{1}{2}\left[\cos\alpha - \cos(\alpha + u)\right] = \sin\left(\alpha + \frac{u}{2}\right)\sin\frac{u}{2} \tag{3.55}$$

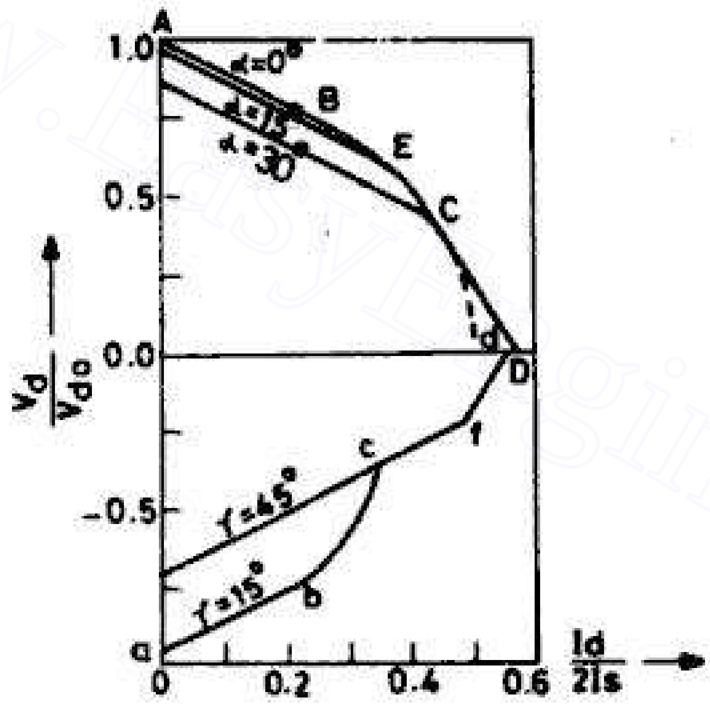

Fig. 3.19 Converter $V_d - I_d$ characteristics

The boundary for the rectifier operation is shown in Fig. 3.19. The coordinates of points A, B, C, D and E on the boundary are given in Table 3.2. The point E corresponds to the maximum power output of the converter.

Table 3.2 Boundary of Rectifier Characteristics

Point	α	u	$\bar{I}_d$	$\bar{V}_d$
A	0	0	0	1.0
B	0	60°	0.25	0.75
C	30°	60°	$\frac{\sqrt{3}}{4}$	$\frac{\sqrt{3}}{4}$
D	30°	120°	$\frac{1}{\sqrt{3}}$	0
E	15°	60°	$\frac{1}{2\sqrt{2}}$	$\frac{\sqrt{3}}{2\sqrt{2}}$

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Effect of Source Reactance on converter without AC filters

When the source reactance is not zero and no AC filters are provided (see Fig. 3.22), the operation of either bridge is affected by the commutation process taking place in the other bridge. In this case, the operation of the twelve pulse converter is quite complex and there could be two additional modes (i) 5 valve conduction and (ii) 6-7-8-7 valve conduction. Also there could be a new mode of 5-6-7-6 valve conduction (instead of 6 valve conduction), depending on the value of a coupling factor K defined by

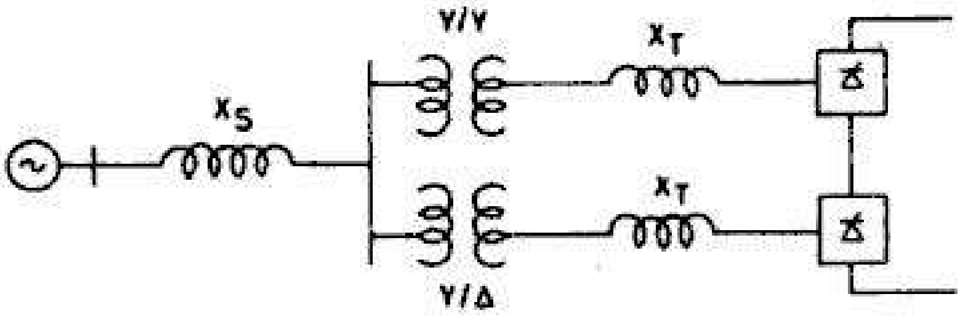
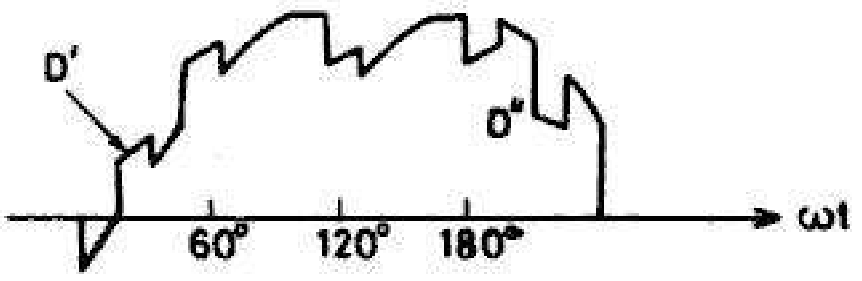


Fig. 3.22 A 12 Pulse converter unit with source reactance included

$$K = \frac{X_s}{X_s + X_T} \tag{3.62}$$

The different modes of operation as a rectifier are summarized in Table 3.3. The inverter operation has only 4 major modes with 3 sub modes corresponding to the first 3 modes. The various modes for the inverter operation are summarized in Table 3.4. The effect of the common source inductance for the two bridges results in additional dents in the valve voltage waveforms, caused by the commutation in the adjacent bridge. A typical valve voltage waveform is shown in Fig. 3.23 D" and D' are the two additional dents caused by the common source reactance.



$\alpha = 150°$, $u = 15°$, $\delta = 15°$

Fig. 3.23 Valve Voltage 4-5 Valve Conduction Mode of Inversion

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where $C = [0 : 1]$

From considerations of symmetry, we have

$$x_1(0) = [S_n]\, x_2(T_1) \tag{3.70}$$

where S_n is a constant matrix.

After some manipulations, we get

$$x_1(0) = Q^{-1} g \tag{3.71}$$

where

$$Q = \left[I_{n+1} - S_n e^{A_2(T_1 - t_1)} K e^{A_1 t_1} \right]$$

$$g = [S_n] \left\{ \left[xs_2(T_1) + e^{A_2(T_1 - t_1)} \right] \left[-xs_2(t_1) + kxs_1(t_1) - ke^{A_1 t_1} xs_1(0) \right] \right\}$$

and t_1 is determined from the nonlinear equation

$$[C] \left\{ xs_1(t_1) + e^{A_1 t_1} \left[Q^{-1} g - xs_1(0) \right] \right\} = 0 \tag{3.72}$$

Once t_1 is calculated, the initial condition $x_1(0)$ and the steady-state solution using equations (3.66 and 3.67) can be obtained. This is best achieved through a digital computer program in which the state transition matrix e^{At} and the forced response $xs(t)$ are evaluated.

Analysis for a six pulse convertor with Filters

The method outlined earlier is illustrated with the analysis of a six pulse convert system shown in Fig. 3.24. At the converter bus, four single tuned and a high pass filter

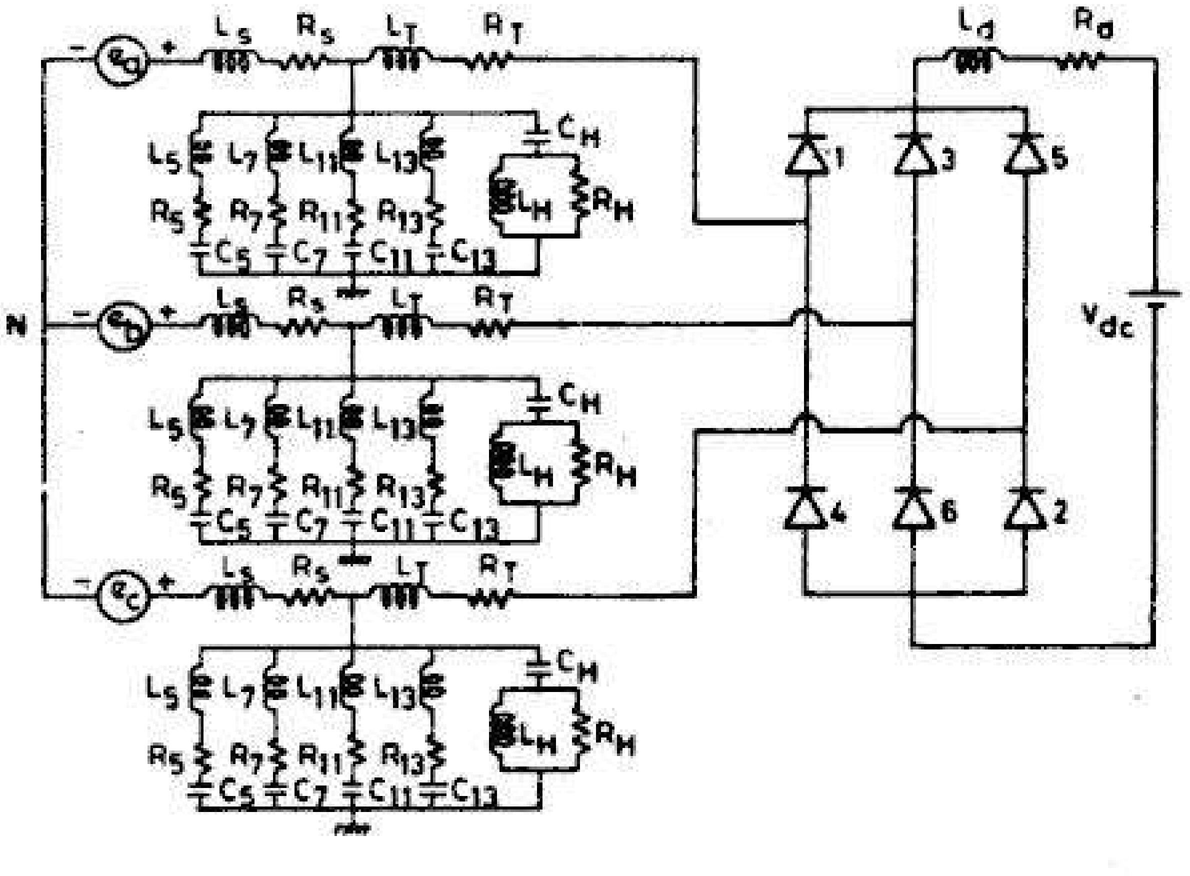

Fig. 3.24 Six Pulse converter including AC filters

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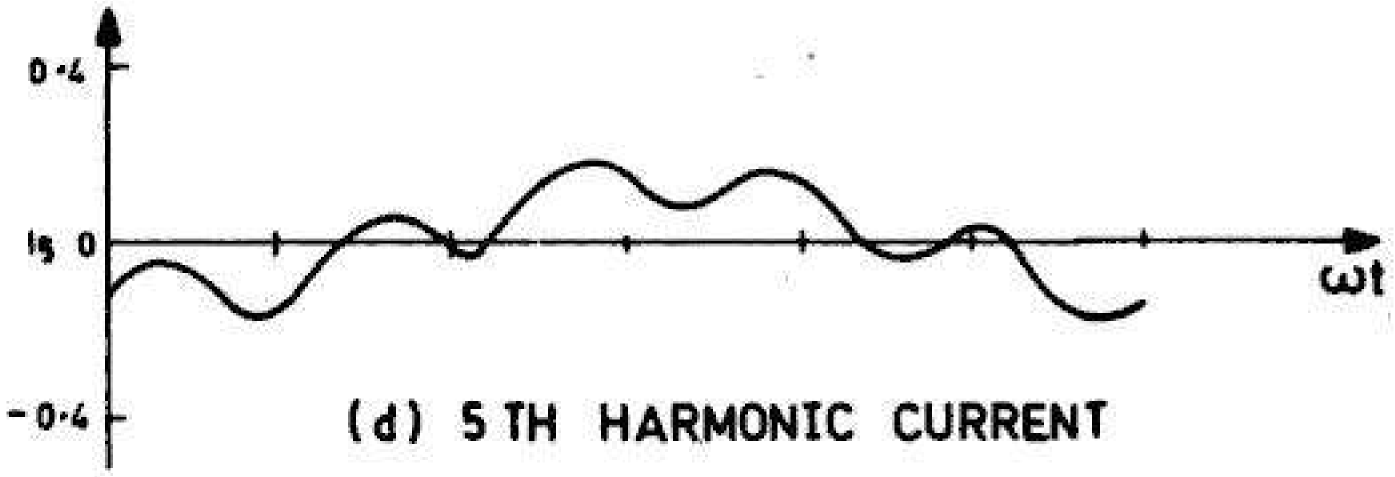
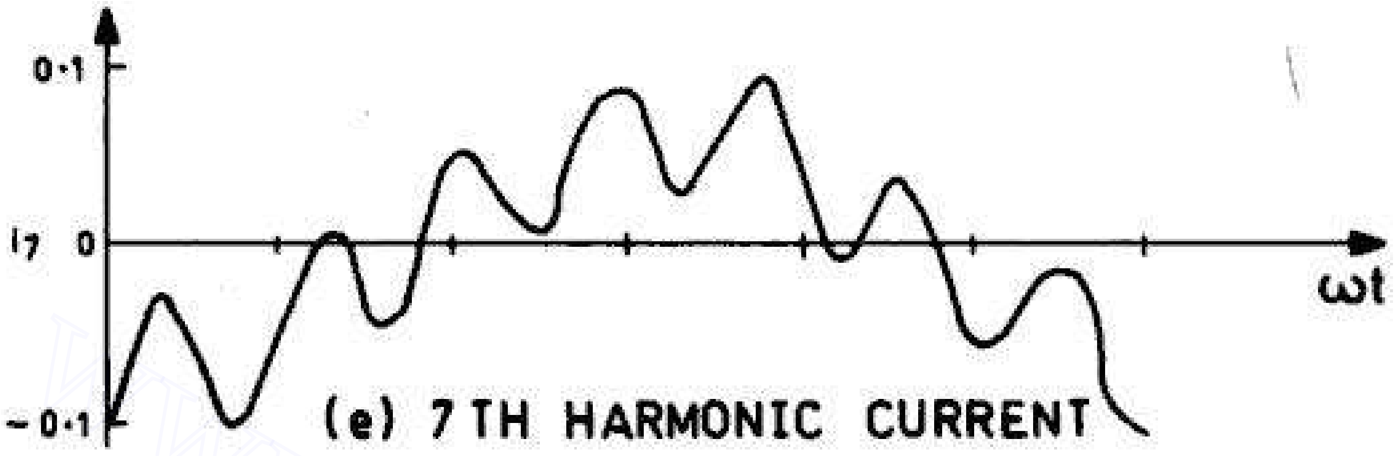
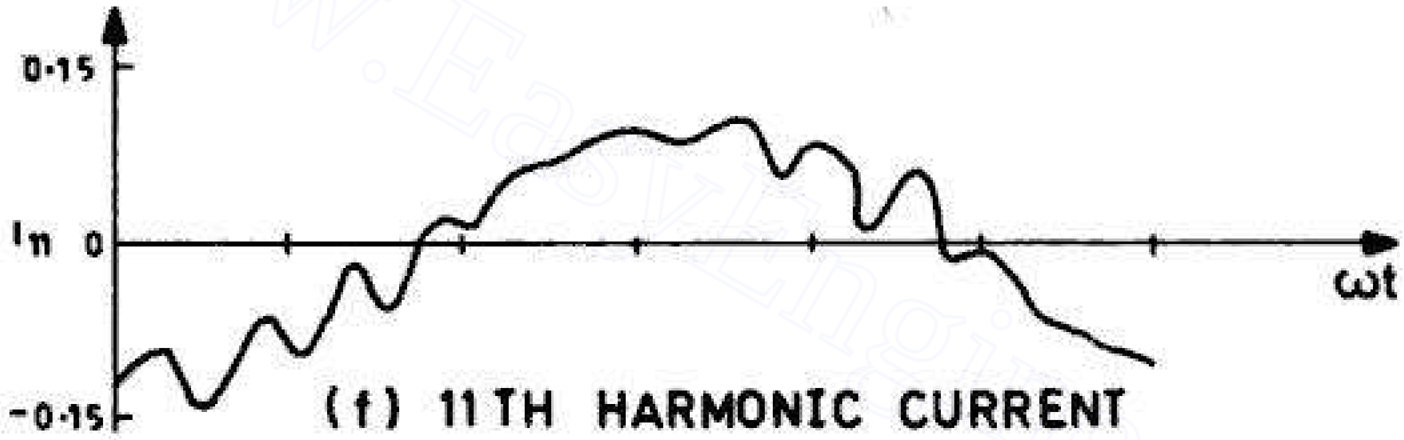


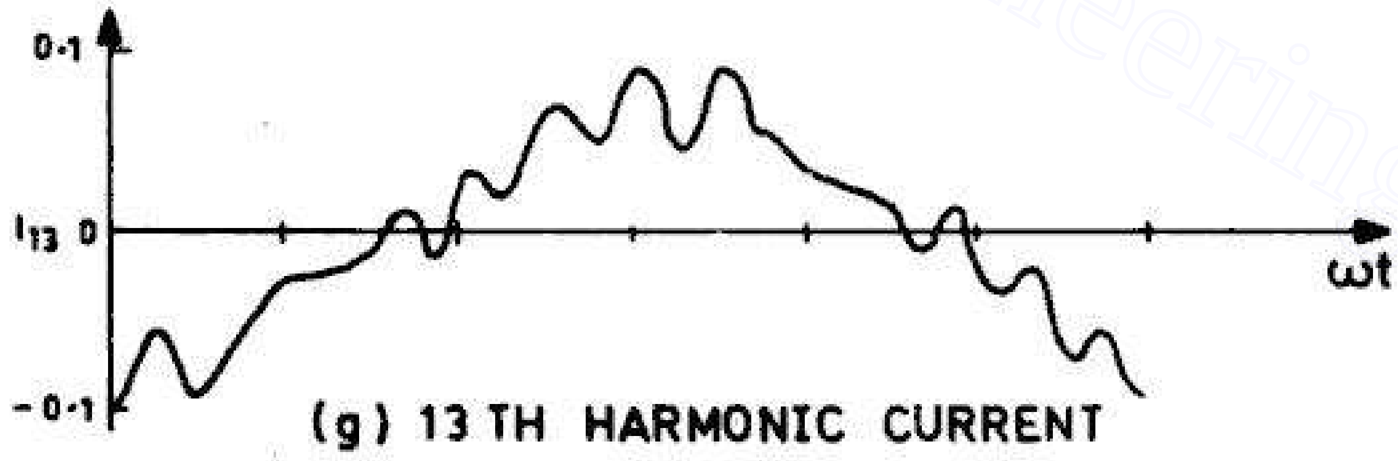
(d) 5TH HARMONIC CURRENT



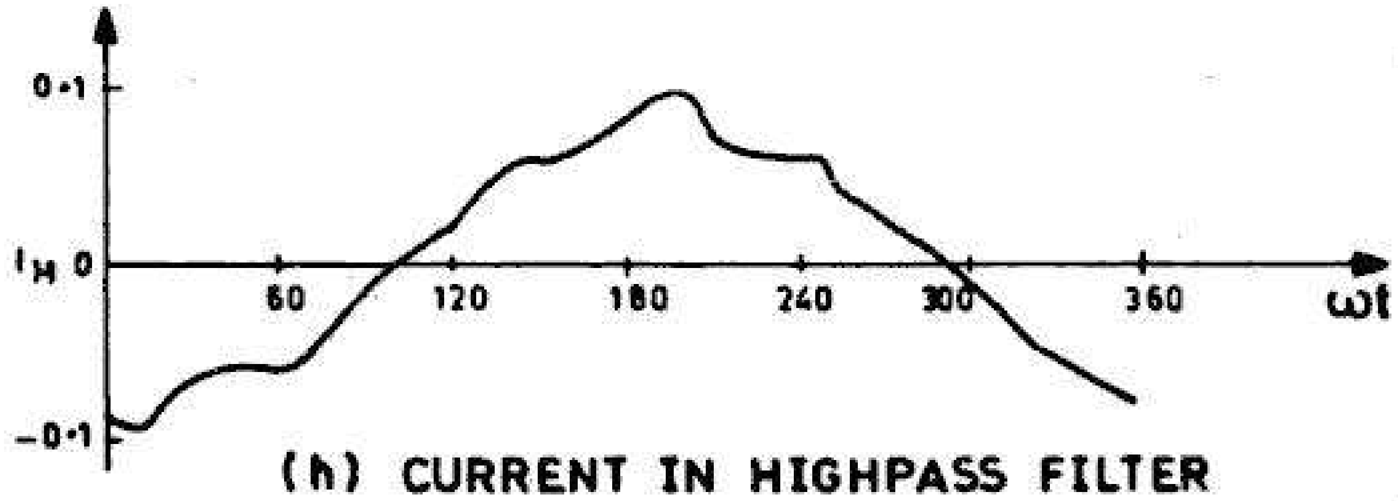
(e) 7TH HARMONIC CURRENT



(f) 11TH HARMONIC CURRENT



(g) 13TH HARMONIC CURRENT



(h) CURRENT IN HIGHPASS FILTER

Fig. 3.26 Steady-state current waveforms

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$$\alpha = 15°, \quad f = \frac{\omega}{2\pi} = 60 \text{ Hz}$$

The waveforms of AC and DC voltages across the capacitors in the filter arms are shown in Fig. 3.27.

The waveform of DC current and consequently the valve winding current is also dependent on the source impedance. This is brought out by varying the source impedance. For the 3 different values of the source impedances, the current in the valve winding is shown in Fig. 3.28. The detailed analysis of converter is complex and requires knowledge of the AC and DC system parameters. Also, the solution is obtained numerically which varies with the system parameters. Except in situations where an accurate calculation of harmonics is required, it is adequate to use the results of the simplified analysis.

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transition from CEA to CC takes place whenever the link current starts falling. To avoid the clash of two current controllers, the current reference at the inverter is kept below that at the rectifier by an amount called the 'current margin'. This is typically about 10% of the rated current.

The power reversal in the link can take place by the reversal of the DC voltage. This is done easily by increasing the delay angle at the station initially operating as the rectifier, while reducing the delay angle at the station initially operating as the inverter. Thus, it is necessary to provide both CEA and CC controllers at both terminals.

The on-load tap changer control at the inverter is used mainly to maintain a constant DC voltage (when the inverter is in CEA control). The tap changer control at the rectifier is designed to maintain the delay angle within certain limits (say 10° to 20°) in order to maintain certain voltage margin for the purposes of current control. A voltage margin of 3% is generally considered to be adequate to meet any sudden demand for the increase in the link current.

The feedback control of power in a DC link is not desirable for the following reasons:

1. At low DC voltages, the current required is excessive to maintain the required level of power. This can be counter productive because of the excessive requirements on the reactive power, which depresses the voltage further.
2. The constant power characteristic contributes to negative damping and degrades dynamic stability.

4.3 CONVERTER CONTROL CHARACTERISTICS

4.3.1 Basic Characteristics

The basic principles of the control of DC link have been stated in the previous section. The control characteristics of both stations are illustrated in Fig. 4.2 which shows the DC voltage at the station II versus DC current. Each station characteristic has three parts as given below:

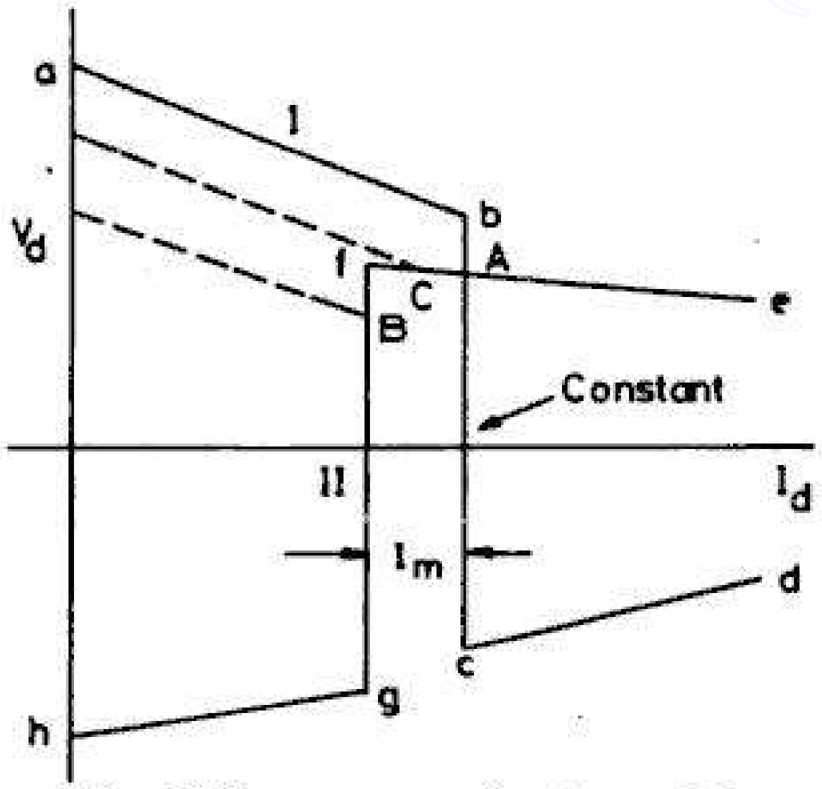

Fig. 4.2 Converter controller characteristic

Station I	Station II	Type
ab	*hg*	minimum α
bc	*gf*	constant current
cd	*fe*	minimum γ

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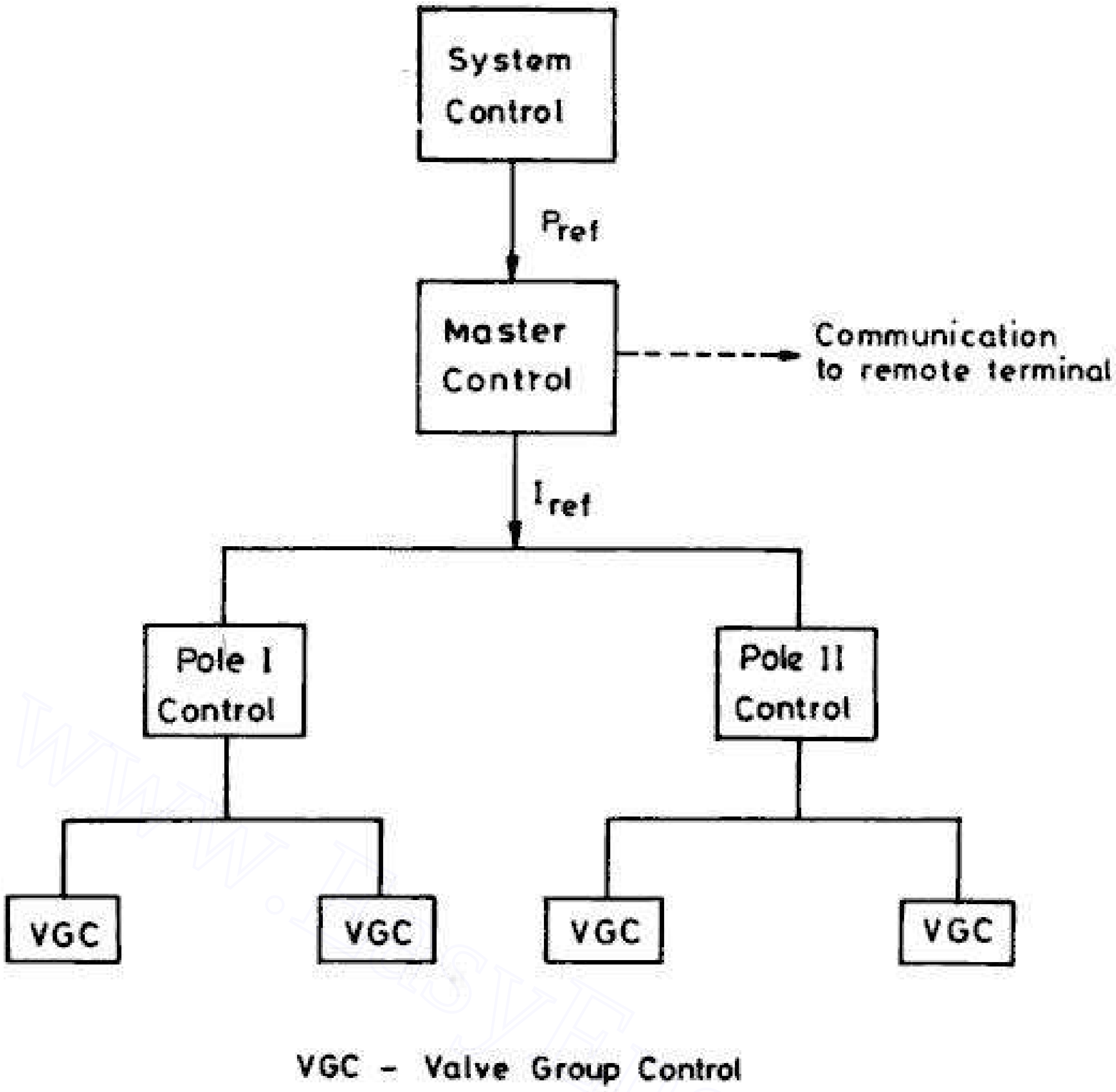

Fig. 4.7 Hierarchical Control Structure for a DC link

The pole control also incorporates pole protection, DC line protection and optional converter paralleling and deparalleling sequences. The master controller which oversees the complete bipole includes the functions of frequency control, power modulation, AC voltage and reactive power control and torsional frequency damping control. It also

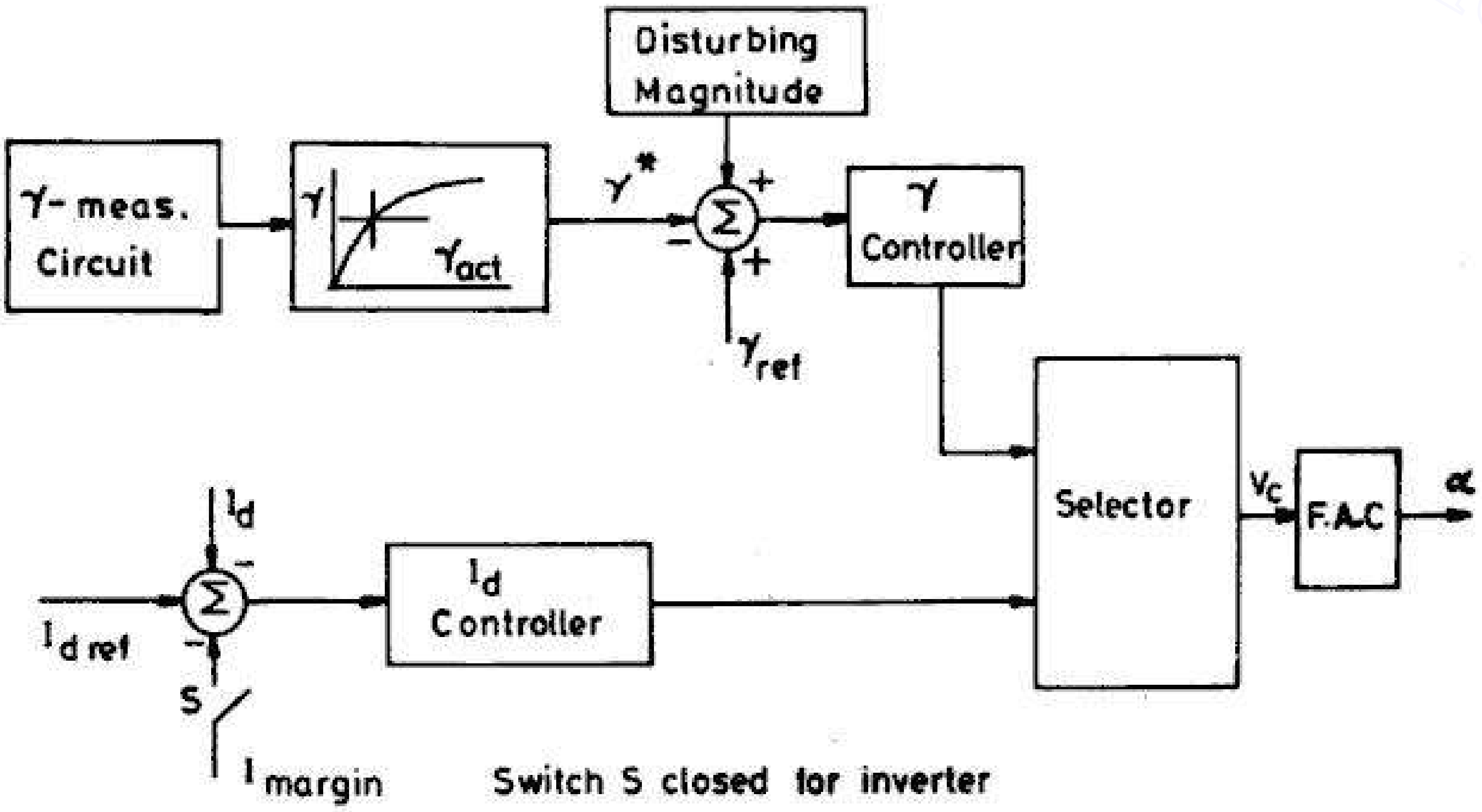

Fig. 4.8 Block diagram of pole and converter controllers

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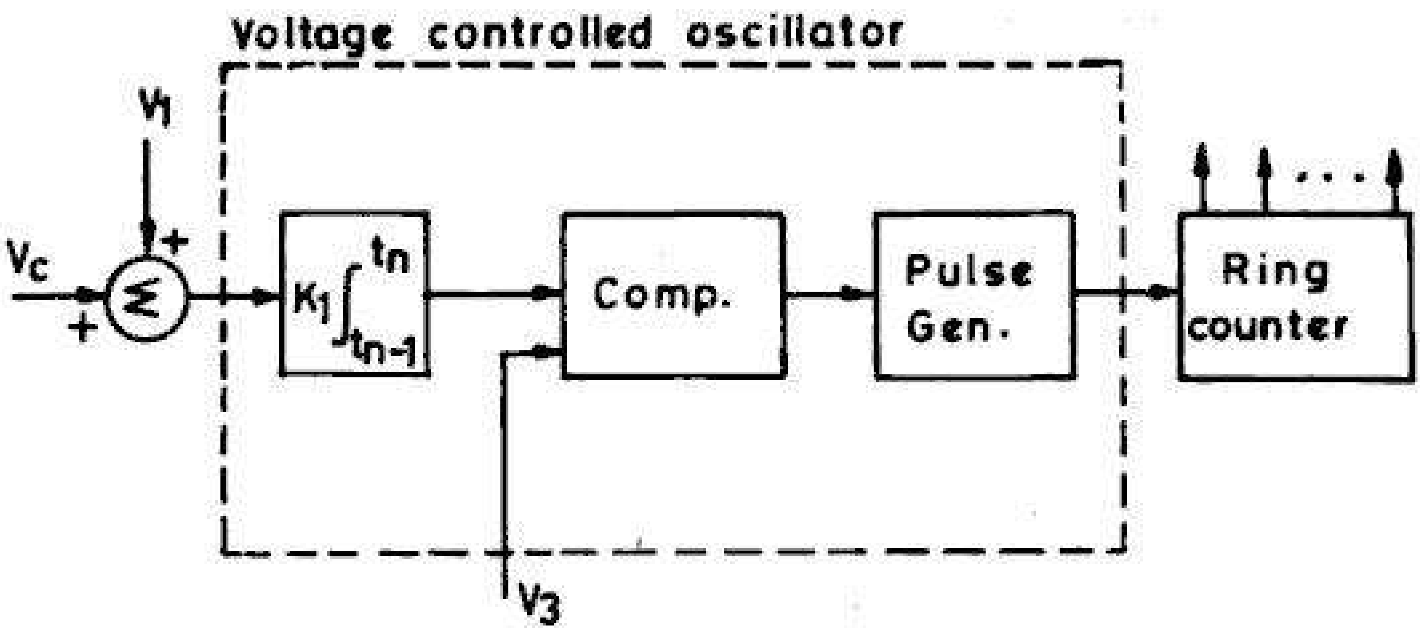

Fig. 4.11 Block diagram of PFC system

The output pulses of the generator drive the ring counter and also reset the integrator. The instant (t_n) of the firing pulse is determined from the following equations:

$$\int_{t_{n-1}}^{t_n} K_1 (V_c + V_1)\, dt = V_3 \tag{4.10}$$

where V_1 is a bias (constant) voltage and V_3 is proportional to the system period. In steady-state, $V_c = 0$, and from Eq (4.10) we get

$$K_1 V_1 (t_n - t_{n-1}) = V_3 \tag{4.11}$$

Since

$$t_n - t_{n-1} = 1/pf_0 \tag{4.12}$$

in steady-state, the gain K_1 of the integrator is chosen as

$$K_1 = pf_0 V_3 / V_1 \tag{4.13}$$

The circuit shown in Fig. 4.11 does not incorporate frequency correction (when the system frequency deviates from f_o). The frequency correction according to Ainsworth is obtained by deriving V_3 as shown in Fig. 4.12. From Fig. 4.12, we have

$$V_3 = V_2 / (1 + ST_1)\,, \quad V_2 = K_1 V_1 (t_{n-1} - t_{n-2})$$

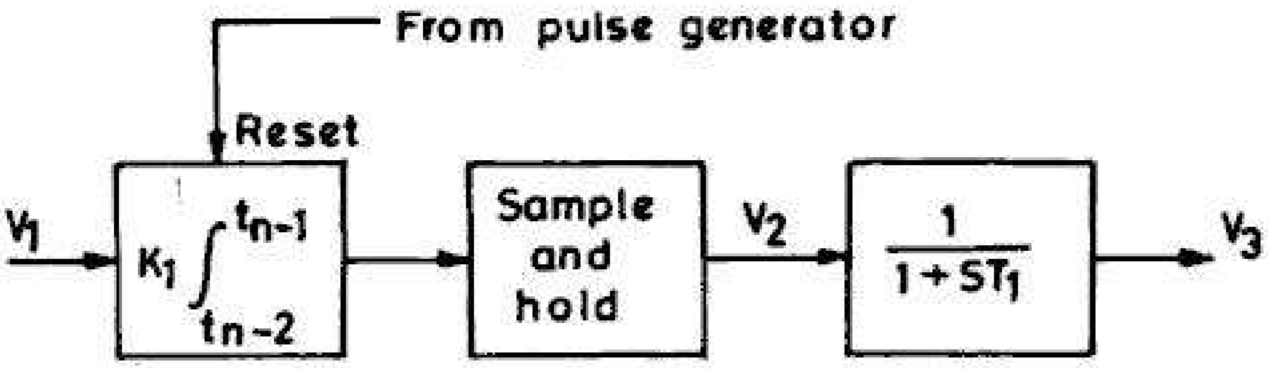

Fig. 4.12 Frequency correction for PFC

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The bypassing of the bridge can be done with the help of a separate bypass valve or by activating a bypass pair in the bridge (two valves in the same arm of the bridge). The bypass valve was used with mercury arc valves where the possibility of arc backs makes it impractical to use bypass pairs. With thyristor valves, the use of bypass pair is the practice as it saves the cost of an extra valve.

The process of deenergization of a bridge is explained with reference to Fig. 4.15. The valves 2 and 3 are assumed to be conducting initially when the blocking command is given. With the selection of bypass pair 1 and 4, the commutation from valve 2 to 4 is in the usual manner, but the commutation from valve 3 to valve 5 is prevented. In the case of a predetermined choice of the bypass path, the time lapse between the blocking command and the current transfer to bypass path can vary from 60° to 180° for a rectifier bridge. This time can be reduced (from 60° to 120°) if the bypass pair is chosen such that the valve with the lower valve number carrying current at the instant of blocking is included in the bypass pair. In the inverter, there is no time lag involved in the activation of the bypass pair. The voltage waveforms for the rectifier and the inverter are shown in Fig. 4.16(a) and (b) respectively. The overlap is neglected here.

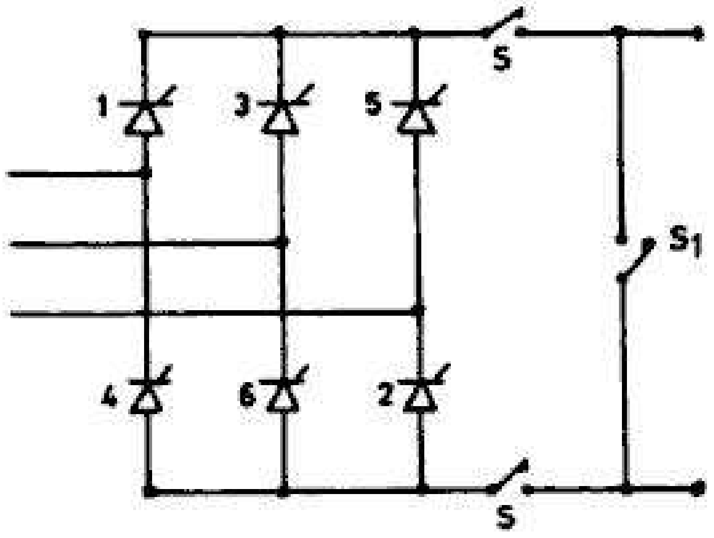

Fig. 4.15 A converter bridge with isolators

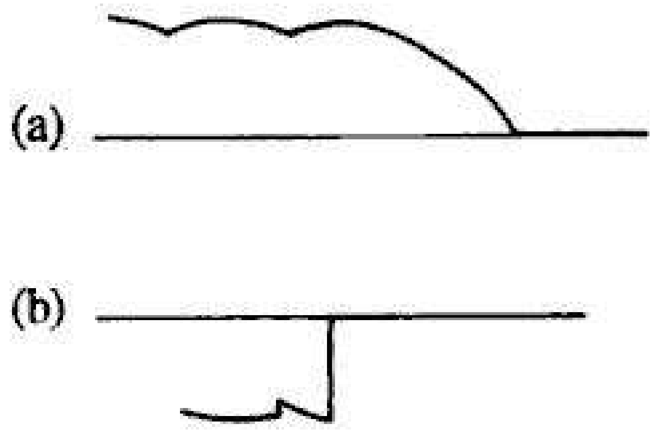

Fig. 4.16 Voltage waveforms during de-energisation for rectifier and inverter

The current from the bypass pair is shunted to a mechanical switch S_1. With the aid of the isolators S, the bridge can now be isolated. The isolator pair S and switch S_1 are interlocked such that one or both are always closed.

The energization of a blocked bridge is done in two stages. The current is first diverted from S_1 to the bypass pair. For this to happen, S_1 must generate the required arc voltage and to minimize this voltage, the circuit inductance must be small. In case the bypass pair

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large that the link cannot be expected to influence the frequency of either, it is prudent to incorporate an element of frequency control which in the event of a partial break-up of a system, will prevent overspeed or underspeed.

4.9.2. Stabilization of AC Ties

When a DC tie is connected to a system with weak AC ties to neighbouring systems, DC link power can be varied quickly and automatically to balance the load flows and maintain stability if one of the AC tie trips.

A DC tie used in parallel with an AC tie can be employed to damp the low frequency interarea oscillations in the AC tie. The control signal used can be the rate of change of AC tie line power (or current) or the phase angle difference across the AC tie. The DC tie can also provide frequency control for one end if the AC tie becomes disconnected and can thus permit resynchronization of the AC tie.

4.9.3. Emergency Control

In an AC tie line, the power flow is determined by conditions in the systems which it interconnects. If one of the systems suffers a disturbance there are only two options; to allow the disturbance to affect the other system also, possibly resulting in a catastrophe for both or to trip the tie in which case the system in difficulty may lose one of the main infeeds on which it is dependent even before the disturbance.

A HVDC link on the other hand, even with simplest controls, buffers one system from disturbances on the other. Power flow can continue at worst unchanged but the option is available to vary power flow to assist the system in trouble to the extent to which the healthy system can allow without putting itself in difficulty, subject only to the rating of the link. In general, with suitable control, a disturbance originating in either system can be shared in a predetermined manner and the oscillations occurring in the two systems can be damped simultaneously. Substantial damping can be achieved with a very small amount of DC power modulation. However, if a large degree of modulation is required with the DC line already operating close to its full capacity, it is found that significant results can be achieved simply by reduction of DC power at the appropriate instants.

4.9.4 Reactive Power Control

The reactive power control is important, particularly in weak AC systems in reducing the dynamic overvoltages. Also in inverters, the fast reactive power control can help in allowing the injection of increased power at times of need to improve the stability of the receiving end AC system.

4.9.5 Subsynchronous Damping Control

A radial HVDC link connected to a thermal generating station can contribute to the negative damping of the torsional oscillations at subsynchronous frequency due to the interactions with the current controller. This problem usually surfaces when there are no parallel AC links. The power modulation controller mentioned earlier which is designed to damp low frequency rotor oscillations can aggravate the problem. However, a suitably designed subsynchronous damping controller (SSDC) with control signal derived from the rotor velocity can help to damp torsional frequency oscillations.

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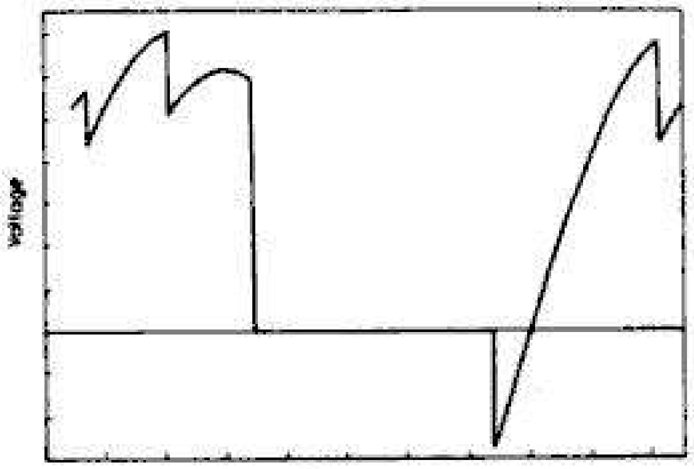
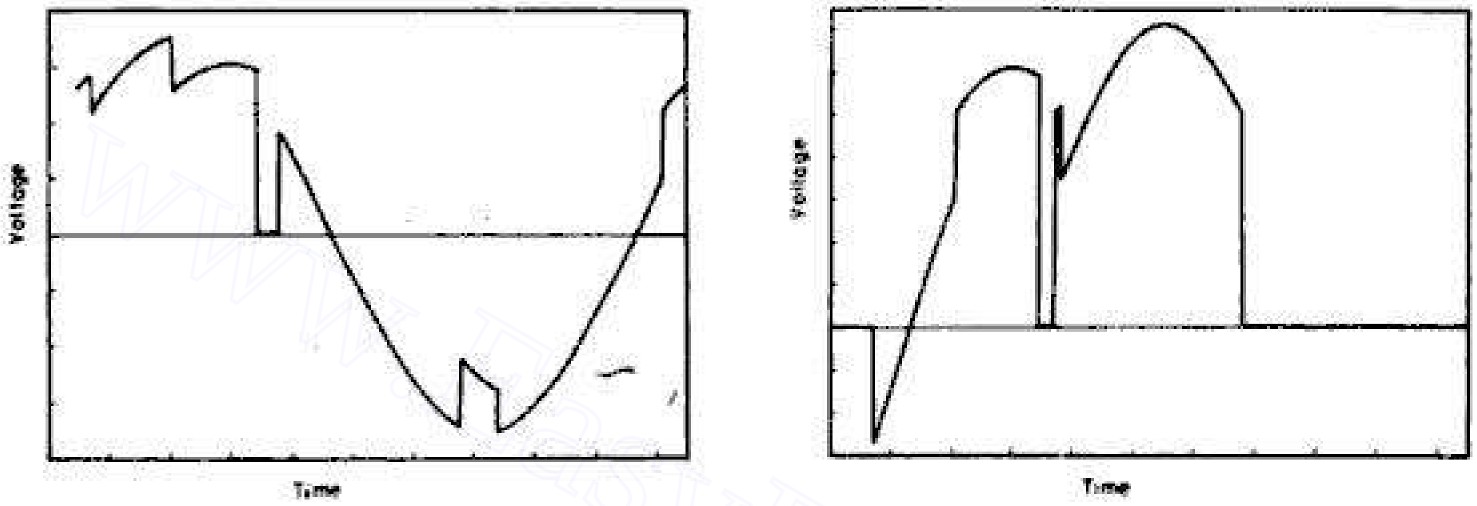


(d) Voltage across valve 4



(e) Voltage across valve 5

(f) Voltage across valve 6

Figure 5.1 Voltage waveforms for a single commutation failure

The failure of two successive commutations in the same cycle, is called 'double commutation failure'. If the commutation failure occurs when valve 4 is fired also, the valves 1 and 2 are left in the conducting state until the instant in the next cycle when valve

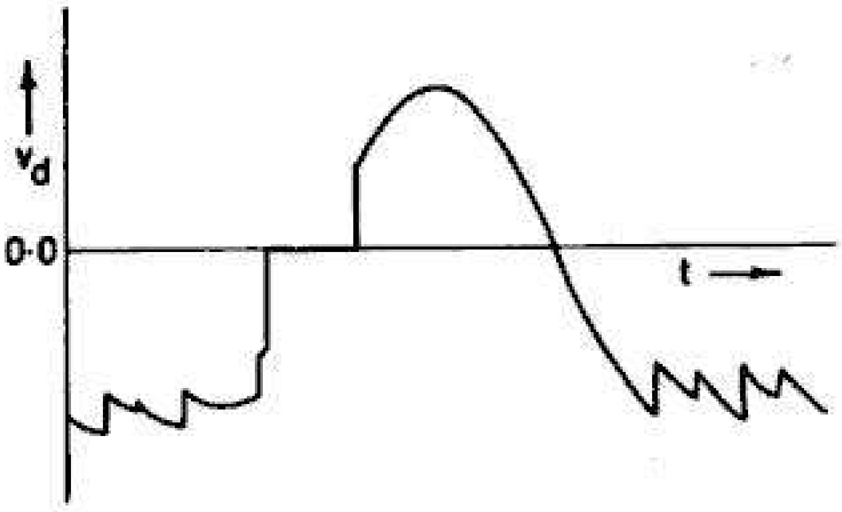


Fig. 5.2 Bridge voltage waveforms for a double commutation failure

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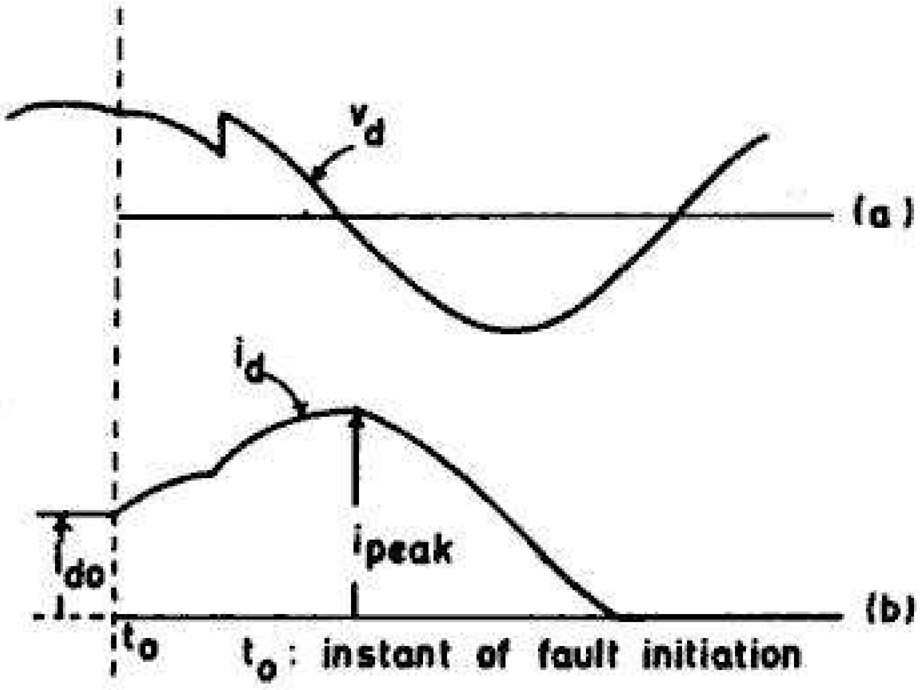

Fig. 5.4 Bridge voltage and current waveform during short circuit

The peak currents are of the order of 10 to 12 times the rated current and the thyristor valves must have surge current ratings above this value. The fault clearing is performed by blocking the pulses when the fault current goes to zero, the valve assumes blocking state provided the voltage across it is not high. If the valve is unable to block the forward voltage, additional loops of overcurrents result and this can be avoided only by tripping the AC breaker.

The detection of bridge or valve short circuit is also performed by comparing the AC and DC currents. In this case, the DC current goes to zero while AC current tends to increase.

5.3 PROTECTION AGAINST OVERCURRENTS

The overcurrent protection in converters is based on principles similar to those used in AC systems. The factors that must be considered in designing a protection system are i) selectivity ii) sensitivity iii) reliability and iv) back up.

The main feature of converter protection is that it is possible to clear faults by fast controller action (in less than 20 msec) by blocking gate pulses or current regulation and control. The selectivity is also enhanced by high impedances of the smoothing reactor and the converter transformer. Further, the converters are divided into independent valve groups such that the protection system must be able to switch off only the affected valve group (or bridge).

Consider a converter station with a 12 pulse converter per pole (2 valve groups per pole). The protection system used for a pole is shown in Fig. 5.5. This does not show protection against DC line faults, undervoltage or transformer protection.

The basic protection against converter faults (considered in the previous section) is provided by valve group differential protection, which compares the rectified current on the valve side of converter transformer to the DC current measured on the line side of the smoothing reactor. The differential protection is employed because of its selectivity and fast detection. The overcurrent protection circuit is used as back-up. The level of overcurrent required to trip must be set higher than that of the valve group differential protection to avoid tripping with faults outside the station (that can be cleared by the control action).

The pole differential protection is used to detect ground faults which may not be otherwise detected, such as faults at the neutral bus.

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It is seen that the temperature coefficient of the material is slightly negative at low currents, but becomes positive at currents above a few amperes. This makes it possible to operate the zinc oxide elements in parallel to discharge high energy surges. The long term stability of the material is satisfactory although it is influenced considerably by disc composition and processing.

The properties of the material are such that it is possible to design arresters to control dynamic overvoltages in addition to switching surges. This results in economic insulation coordination. However, proper design of the arrester based on the evaluation of the energy losses is essential. The ultimate limit on the energy dissipation capability of a disc is imposed by the cracking of the disc under thermal shock. A single column arrester is capable of absorbing around 7 kJ per kV of the maximum continuous operating voltage (MCOV).

In many DC applications, the energy capability of a single column of discs is inadequate and multiple columns are used. A parallel column arrester is made up by selecting discs such that the voltage for each column is the same at a predetermined current. The maximum difference in the currents of parallel columns can be made less than 0.5%.

5.6 PROTECTION AGAINST OVERVOLTAGES

5.6.1 General

The basic principles of overvoltages protection is the same in DC systems as in AC systems. These are given below:

1. The overvoltage stresses in equipment with non self-restoring insulation must be limited at all times by providing surge arresters. The protection level of the arresters must be lower than the breakdown voltage of the insulation.
2. Self restoring insulation such as air may be allowed to breakdown where there is no danger to the safety of the personnel.
3. The operation of surge arresters or flashover of air insulation must not be frequent. Frequent discharges of arresters may damage them.
   This implies that the protective level of arresters must be higher than the maximum operating voltage in the system.
4. There must be proper coordination of the insulation and overvoltage protection in different parts of the system, taking into account the characteristics of the insulation, the nature of overvoltages, etc.

The overvoltages generated on the AC side should, as far as possible, be limited by arresters on the AC side. The overvoltages generated on the DC side must be limited by DC line, DC bus and neutral bus arresters. The critical components such as valves are directly protected by arresters connected close to the components.

5.6.2 Overvoltage Protection in a Converter Station

The typical arrangement of surge arresters in a converter station (for a pole) is shown in fig. 5.7. For a system with two 12-pulse converters per pole, there are about 40 arresters per pole. The arresters are selected with adequate energy dissipation capabilities which vary with the location of the arresters. For example, the valve arrester

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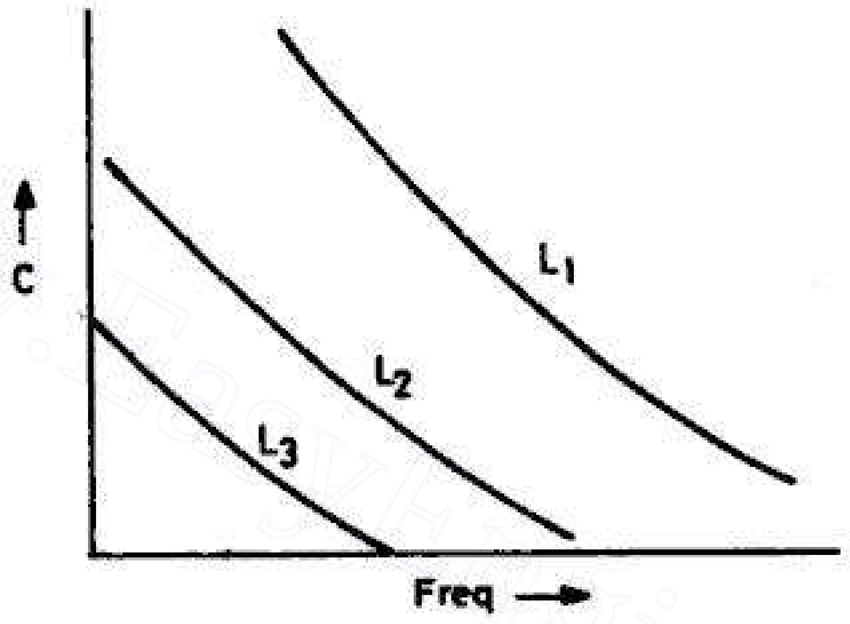
It is to be noted that in back to back HVDC systems, the last three functions are not relevant. For systems with DC transmission lines, the inductors of value from 0.27H to 1.5H have been used. For back to back HVDC systems, the value ranges from 12 mH to 200 mH.

The sizing of the reactor is done not only from the considerations mentioned above, but also from the point of view of minimizing the effect of low order harmonic resonances in the AC/DC system. It is necessary to avoid series resonance of the DC system at fundamental frequency and also at the second harmonic. The effect of the inductor value on the resonant frequency (corresponding to the first peak of the admittance as seen by the converter) as a function of the DC filter capacitance is shown in Fig. 6.1. This shows that the resonant frequency is reduced by increasing the inductance.



C - filter capacitance

L - smoothing reactor inductance

Fig. 6.1 Series resonant frequency as a function of smoothing inductor and filter capacitance

The inductance value must remain practically constant with variations in the direct current. This requires aircore construction. The smoothing reactor helps to limit the fault current in the DC line as mentioned above. This is feasible only if the reactor does not get saturated by the fault current. By the way, it is to be noted that saturable reactors used for the limitation of *di/dt* in thyristor valves, cannot replace the smoothing reactor as smoothing reactors unaffected by saturation reduce commutation failures.

The location of the smoothing reactor can be either at the high voltage terminal or at the ground terminal as shown in Figs. 6.2 (a) and (b) respectively. In the latter case, it is also necessary to have a small reactor of the order of 5 to 10 mH on the line side, to protect the converter station from the consequences of lightning strokes to the line. The advantage of having the reactor at the ground side is that it allows the converter ground faults to be cleared by converter control (of increasing the delay angle to its maximum limit to control the current). The insulation level of the reactor also is reduced for this location of the reactor.

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The other quantities are as defined earlier. ln refers to the natural logarithm.

The power loss predicted by Eq. (6.7) gives correctly the mean fair-weather corona loss levels. With rain, the DC losses may increase by a factor of 10 to 1 while AC losses may increase by 50 to 1. However, the average ratio of rain weather loss to fairweather loss varies from 2 to 4, with higher ratios applicable to operation at lower gradients.

The bipolar corona loss per pole is higher than the monopolar corona loss by a factor of 1.5 to 2.5. However, for a given voltage, the positive and negative polarity losses are approximately equal. DC corona losses usually increase with wind velocity in the range of 0 to 10 m/sec.

Radio Interference (RI)

The most predominant corona effect that may determine the conductor design is the radio interference. This is measured at a frequency of 1 MHz and for a receiver bandwidth of 9 kHz, at a horizontal distance of 30 meters from the outermost conductor.

The RI is mainly due to the positive conductor. This is because of the fact that the corona discharges from the negative conductor are in the form of Trichel pulses which are uniformly distributed over the conductor surface. Positive corona discharges are of three types—Hermstein glow, plume discharge and steamers. Plumes and steamers are randomly distributed and the more persistent discharges are usually associated with high stress points due to surface imperfections. These are mainly responsible for the RI.

The expression for RI (in decibels above the field strength of 1 μV per meter) is empirically obtained as

$$\mathrm{RI} = 25 + 10 \log n + 20 \log r + 1.5\,(g - g_0) \tag{6.10}$$

This is due to the positive conductor. The RI due to the negative conductor is about 20 db lower and is not of consequence.

Interestingly, DC-RI levels are decreased by rain and wet snow which completely wet the conductor. This phenomenon is opposite to that in AC conductors.

DC-RI levels are increased by wind, with maximum increase during the wind flow from negative to positive conductor.

The bipolar lateral RI profile is symmetric about the positive pole and attenuates inversely as the square of the distance from the conductor initially (upto 50 meters) and inversely as the distance thereafter.

The television interference (TVI) with DC lines is mainly due to the ion currents and is of little consequence at distances greater than 25 meters from the right of way.

Audible Noise (AN)

The corona discharges from the conductor produce compressions and rarefactions that are propagated through the medium as acoustical energy. The portion of the acoustical energy spectrum that lies within the sonic range is perceived as audible noise (AN).

The sound level is expressed in decibels and is defined as

$$dB = 20 \log (P/P_R) \tag{6.11}$$

where P is the measured sound-pressure level and P_R is the reference pressure level. The standard level for P_R is 20μ Pascal which is the average threshold of audio perception at 1 kHz. Test line studies [3] indicate that ± 600 kV DC lines would produce an audible noise of 45 to 55 dB measured at 30 meters from the ROW centreline. This is not considered to be serious. In general, the annoyance produced by the audible noise varies linearly with the conductor surface voltage gradient.

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healthy pole of magnitudes exceeding 2.0 p.u. [9, 10] (although typically they are 1.7 p.u.). The maximum overvoltage occurs at midpoint in a pole when the fault is also at the midpoint of the other pole. For off-centre faults, the maximum overvoltage occurs at a location which is a mirror image of the fault location (with respect to the midpoint). For example, if a fault occurs at a point of one third distance from the sending end, the overvoltage occurs at a point of one third distance from the receiving end.

There are two modes of travelling waves on a bipolar DC line. One is termed as the pole to pole mode (analogous to positive sequence) while the other is termed as the pole to ground mode (analogous to zero sequence). If the prefault voltage is V at a given location, it can be shown that immediately after the fault, the voltage at the other pole rises by an amount ΔV, given by

$$\Delta V = [(Z_0 - Z_1) / (Z_0 + Z_1)]\, V \tag{6.15}$$

where Z_1 and Z_0 are the surge impedances of the first and the second mode respectively. Generally $Z_o > Z_1$. For typical values of Z_o and Z_1, $\Delta V \simeq 0.3V$.

The travelling waves originating at the fault location travel in both directions and are reflected by the terminals. The kind of termination at the converter station—inductive, capacitive or resistive has a bearing on the voltage waveform at the converter and in the line.

The typical voltage waveforms at the midpoint and the terminal are shown in Fig. 6.7 for (i) inductive, (ii) capacitive and (iii) resistive terminations. The parameter of the DC filter also affects the nature of the terminal voltage waveform. The following conclusions can be drawn from a digital computer study [10] of the transient overvoltages.

1. With capacitive termination to the wavefront, overvoltage in the unfaulted pole is caused by pole to pole mode. The attenuation and distortion of this mode is slight.
2. The surge capacitor, while helping in reducing the overvoltage at the terminal, does this at the expense of the DC line. It is desirable to use a surge arrester to protect the terminal against overvoltages.
3. The resistive termination to the wavefront with $R = Z_1$ is the best and can be achieved by putting $R = Z_1$ in the high pass DC filter and not having a surge capacitor.
4. With inductive termination to the wavefront, overvoltages are caused by the pole to ground mode for which the attenuation is substantial. But the overvoltage at the terminal is high.
5. It is desirable to provide extra insulation around the middle portion of the DC line to take care of the highest overvoltages that may occur in that zone.
6. With capacitive termination, the lowest limit on the *dv/dt* setting of the line fault protection is determined by the maximum fault resistance above which the fault will not be detected.

It is also necessary to provide a time delay in the operation of the protection (using *dv/dt*) to prevent the tripping of the healthy pole. Typically, a time delay of about 3 milliseconds may be adequate.

The tests carried out on Pacific intertie [11] and subsequent simulation using digitial computer have shown that the modelling of frequency dependent characteristics of the line for both modes is essential for accurate prediction of the overvoltages [12].

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It is obvious that reduction of I_d has a significant effect on the breaker costs as W_b is decreased which results in the reduced requirements of the energy capability of a breaker.

The current I_d is brought down to the rated value by the normal action of current control in converters. Although this requires certain amount of time (say 30 to 50 msec), the time required for interruption reduces. The alternate strategy is to interrupt the fault current fast but this will increase the interruption time T_i apart from increasing the cost of the breaker.

The counter voltage produced by the arc that is struck when the breaker contacts separate, is not sufficient in HVDC breakers. This requires an auxiliary circuit in which a capacitor is inserted to develop the required counter voltage. However, a capacitor is unable to dissipate the energy and the current in the capacitor has to be commutated to nonlinear resistors which then dissipate the energy without undue increase in the voltage across them.

The general arrangement of a HVDC circuit breaker is shown in Fig. 6.9. The current in the breaker (when closed) is normally carried through CB with moving metallic contacts. This may be vacuum, oil, airblast or SF_6 device. After a trip signal is given to the breaker, the breaker contacts open to draw an arc. This is initiated at time t_1 (see Fig. 6.10 which shows the current and voltage waveforms). At a short time later at t_2, the commutation circuit is inserted through the insertion device S_c. The commutating impedance is primarily made up of a series L-C circuit which is tuned to a certain frequency. The capacitor may or may not be precharged. The insertion devices S_c may be a triggered vacuum gap or spark gap or in the so called 'passive' commutation circuit, just a solid connection (no switching required). The main purpose of inserting a commutating impedance is to create current zero in CB and transfer the current to Z_c with sufficient contact separation in CB to regain its dielectric strength. This current transfer is completed by time t_3. The DC circuit current i_d, flowing through the capacitor in Z_c rapidly builds up to a high voltage V_b across the breaker. When the voltage reaches V_b at time t_4, the energy absorber R_d is inserted through the device S_d. The nonlinearity of the resistance R_d acts as a switch which closes when its clipping voltage is reached. The direct current now decays to zero by discharging its energy to R_d after the interval of T_i (at time t_5). The breaker operation is completed by t_5 if the three parallel paths CB, Z_c and R_d have adequate voltage withstand capability. Otherwise, fast acting isolators that operate at zero current level may be used to prevent overstressing of the breaker until the

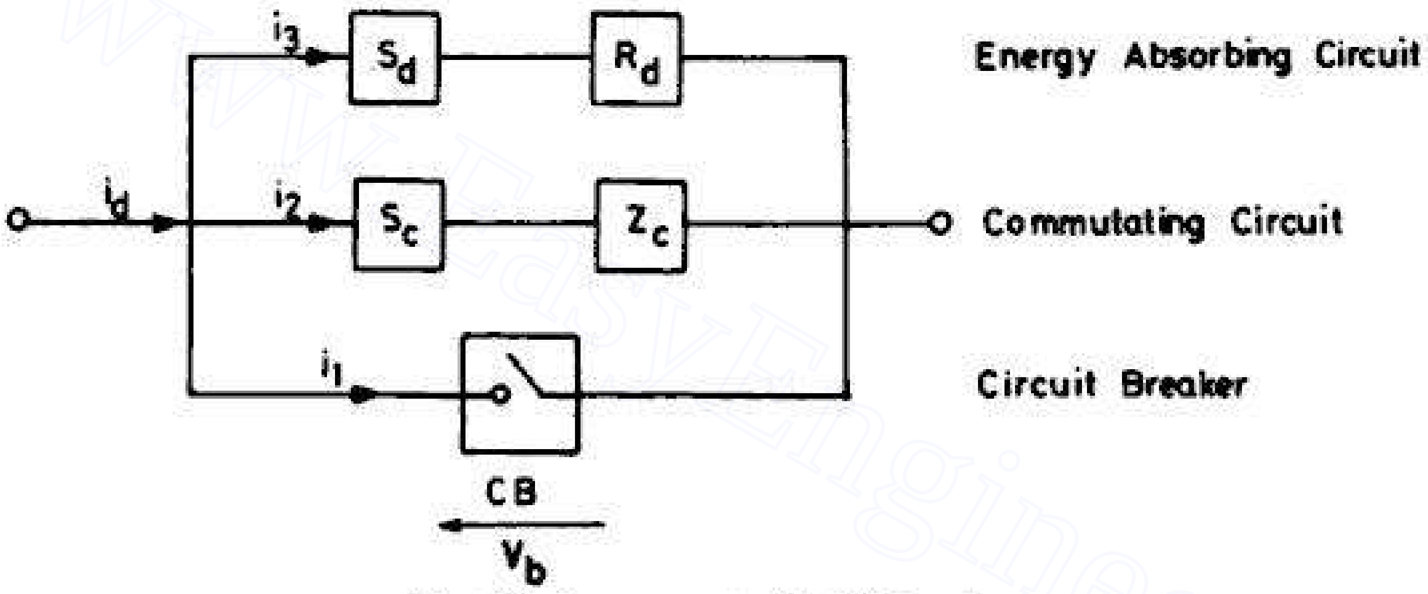

Fig. 6.9 Arrangement of a DC breaker

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valve stresses and additional losses in valve grading/damping circuits. Both options are costly and third alternative is to derate the DC link during the metallic return operation

3. Reduced reliability due to the fact that two conductors are exposed as compared to one conductor with ground return
4. Increased requirements for the protection of the ungrounded neutral.

The last factor arises from the consideration of the transient overvoltage to which the ungrounded neutral is subjected to, when valve groups are blocked/deblocked, or line faults, commutation failure takes place. According to a study carried out on Pacific Intertie system [19], it is preferable to ground the inverter terminal as the worst condition for overvoltage is the blocking of an inverter group if it is floating.

Capacitors in shunt with spark gaps were used initially for protection against transient overvoltages. But the disadvantage is the large value of capacitance required and increased telephone interference due to harmonic currents flowing through the capacitor. The present day solution to the problem is the use of zinc oxide arresters in place of the capacitors [20].

6.7.1 Ground Electrodes

The grounding of the neutral points of a bipolar DC line is not done near the converter stations to prevent the interference effects of ground currents in converter transformers, etc. Also, the electrodes must be placed in soil of low resistivity and of sufficient depth. The ground electrodes are usually located at distances around 20 km and upto 55 km, if necessary. The line connecting the neutral to the ground electrode site is called the 'electrode line' and is usually made of two sections in parallel to facilitate detection of faults in electrode lines (by differential protection). Although steady-state voltages on electrode lines is small (less than 5 kV), the transient voltages can exceed 300 kV for line faults. The voltage is maximum at the midpoint of the electrode line and is highest when it is on the same tower as the DC line. Providing a separate right of way for the electrode line reduces these overvoltages considerably.

The design of ground electrodes are based on the requirements of (i) low resistance, (ii) adequate current carrying capacity, (iii) low maintenance cost, (iv) accessibility and (v) safety.

The form of the electrode can be of several types— (i) ring, (ii) straight, (iii) six pointed star, or (iv) branched star. The electrodes can be located in the land or sea shore (if nearby).

The electrodes can be designed for either continuous operation or intermittent operation (during monopolar operation of a bipolar line with ground return).

The factor that is often responsible for the failure of DC ground electrode is electroosmosis which causes the migration of moisture in the direction of current. The electrode tends to dry because of this and also by heating effect. To retain moisture, a land electrode may be irrigated by pumping water to it.

6.8 EFFECTS OF PROXIMITY OF AC AND DC TRANSMISSION LINES

For reasons of economy and constraints on the right of way, it is possible that AC and DC lines may be situated in the same right of way. Also, it is possible to have them on

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where n_b is the number of bridges connected in series.

Base AC voltage (on the valve side) $(V_b) = V_n$

Base AC power = Base DC power = $(\sqrt{18}/\pi)\, V_n I_{db}\; n_b$

The average DC voltage across a converter bridge is given by

$$\bar{V}_d = \bar{V}\cos\alpha - \bar{R}_c \bar{I}_d \tag{7.1}$$

where

$\bar{V}_d = V_d/V_{db}, \bar{I}_d = I_d/I_{db}, \bar{V} = V/V_b$

$\bar{R}_c = \bar{X}_c/2$

$\bar{X}_c$ = p.u. leakage reactance of the transformer on its own base.

The power factor is given by

$$\cos\phi = (\bar{V}_d/V_{do}) = (\bar{V}_d/\bar{V}) = \cos\alpha - (\bar{R}_c \bar{I}_d/\bar{V}) \tag{7.2}$$

The power and reactive power in per unit are given by the following equations

$$\bar{P}_d = \bar{V}\,\bar{I}_d \cos\phi \tag{7.3}$$

$$\bar{Q}_d = \bar{V}\,\bar{I}_d \sin\phi \tag{7.4}$$

Equation (7.1) is also valid for the inverter if α is replaced by γ.

For typical values of $\alpha = 15°, \bar{X}_c = 0.2, \bar{V} = 1.0$ the variation of Q_d versus P_d is shown in Fig. 7.1.

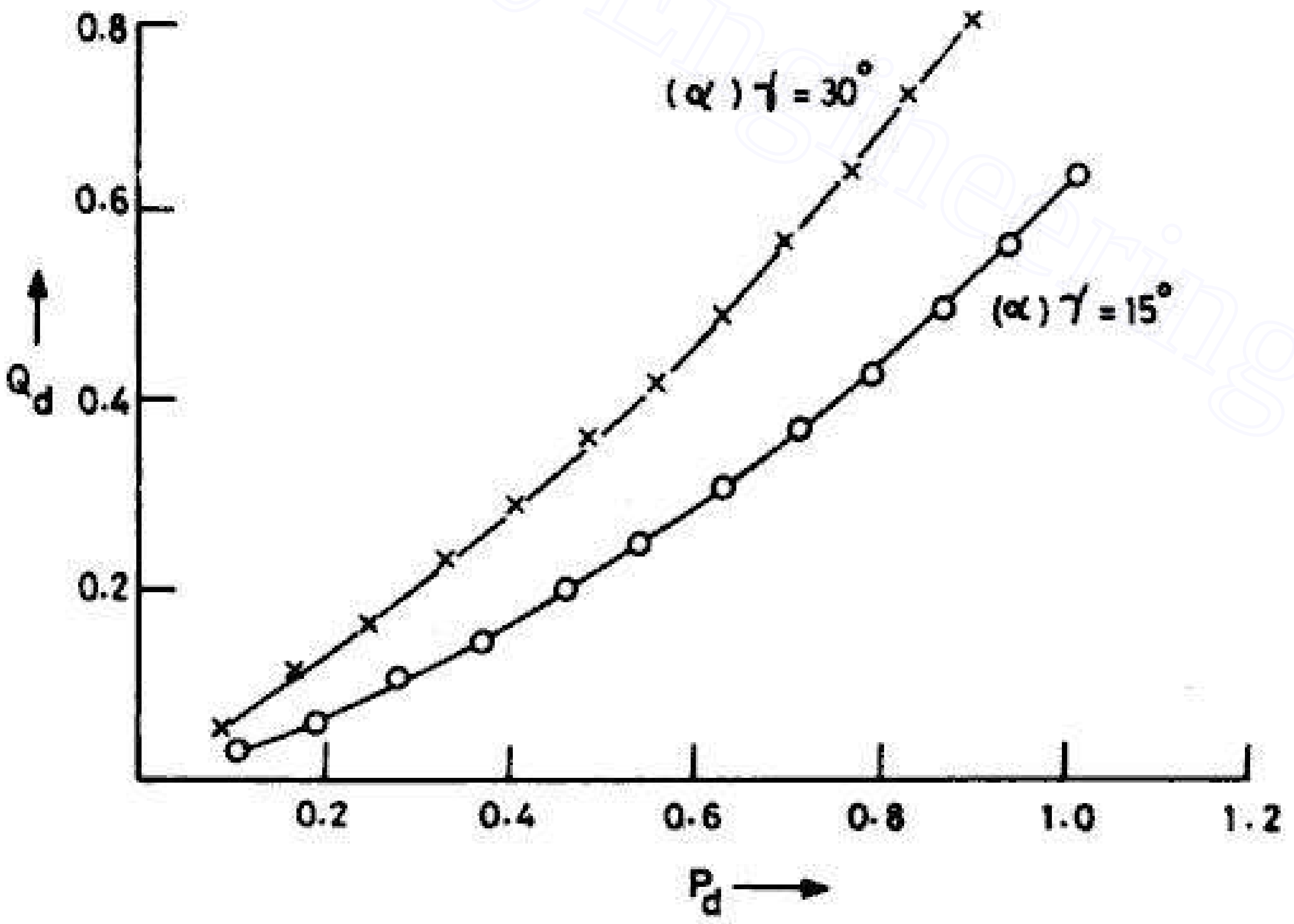

Fig. 7.1 Variation of Q_d with P_d

It is to be noted that the rated DC power is less than 1 p.u. as the rated voltage is less than the DC base voltage. Actually, the two are related by

$$V_{dn}/V_{don} = \bar{V}_{dn} = \cos\phi_n \tag{7.5}$$

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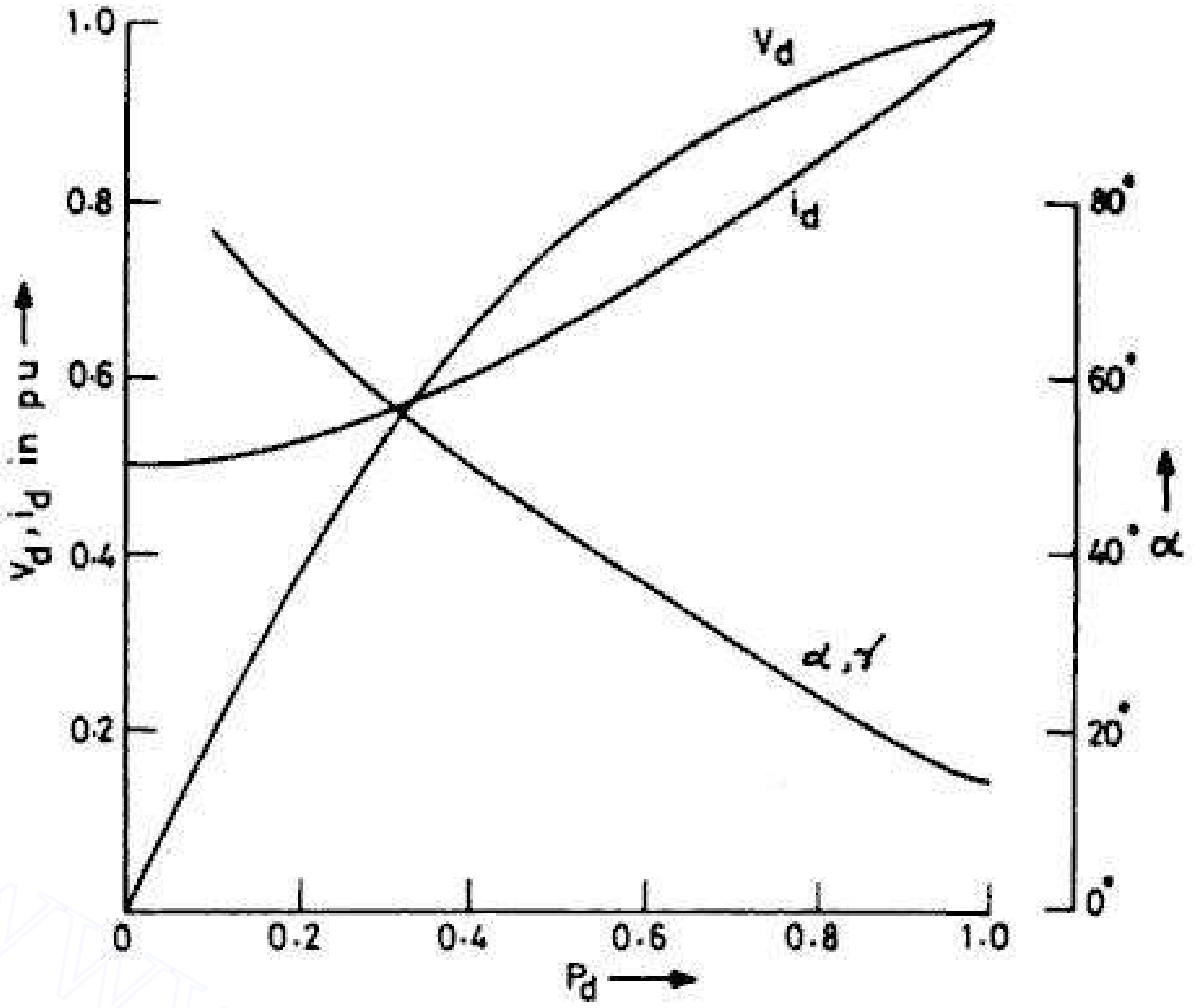

Fig. 7.6 Variation of i_d, v_d and α with P_d for constant reactive power

The variations of i_d, v_d and α with variation in P_d are shown in Figs. 7.6 and 7.7 for cases (i) and (ii) respectively. These are drawn for $V = 1.0$ and $\phi_n = 30°$. These are also applicable equally for the inverter operation except that *a* is replaced by γ. The increase in α or γ above the minimum implies additional losses in the snubber circuits.

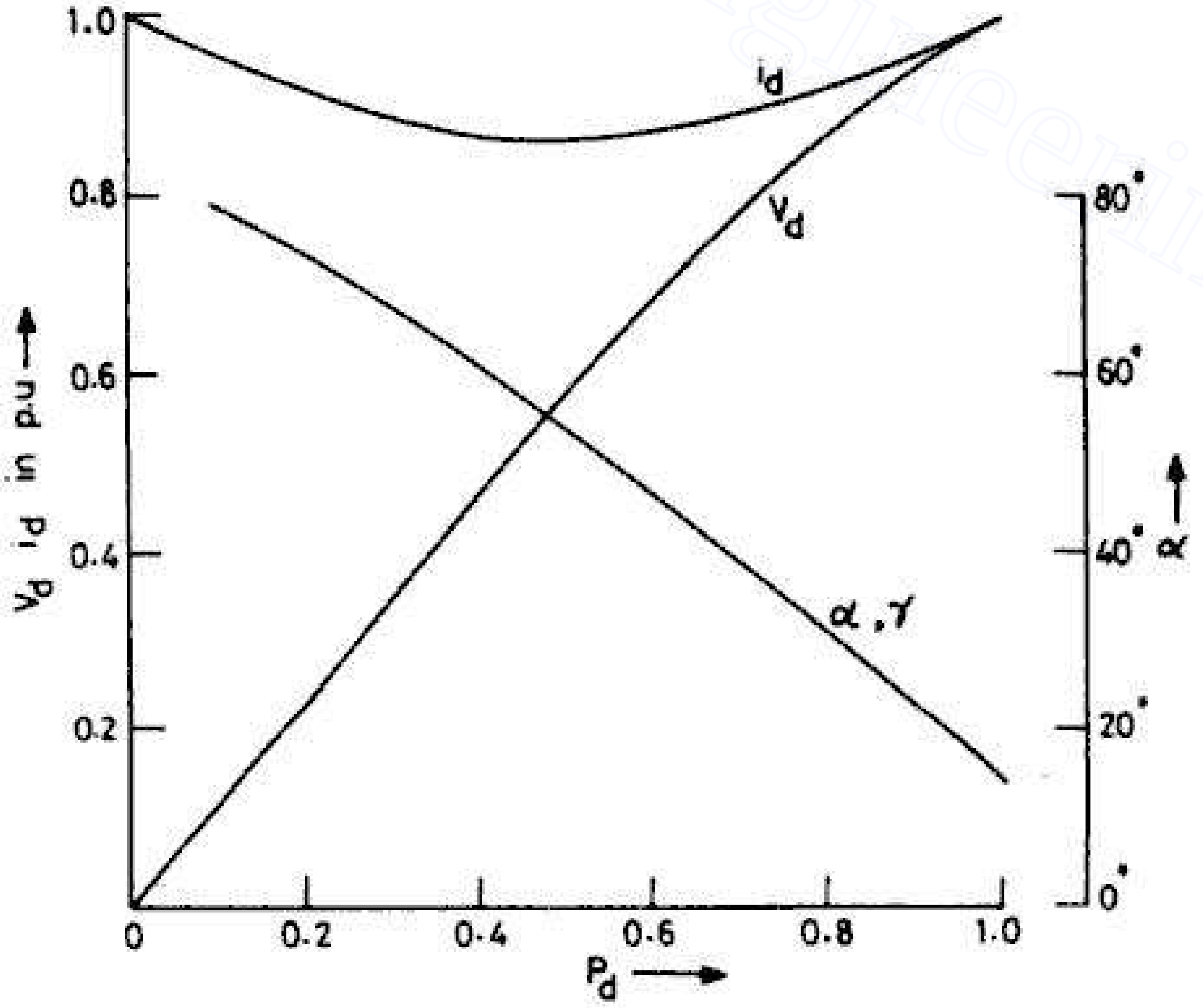

Fig. 7.7. Variation of i_d, v_d and α with P_d for constant leading power factor

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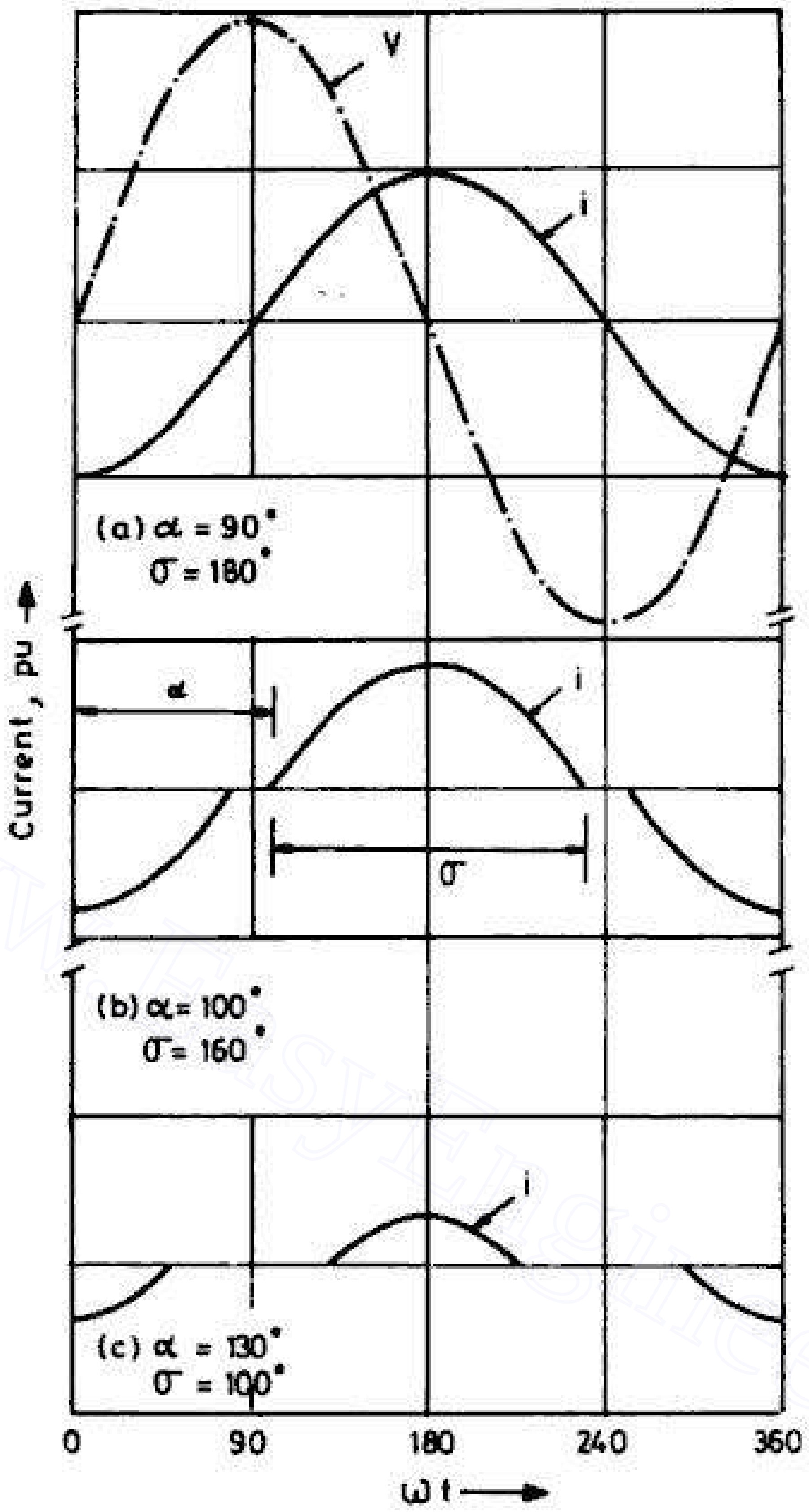

Fig. 7.11 Current control in TCR

The fundamental component of the inductor current is given by

$$I_1 = \frac{\sigma - \sin \sigma}{\pi X_L} . V \tag{7.15}$$

where V is the rms voltage across the TCR, X_L is the fundamental frequency reactance and σ is the conduction angle related to α by the following equation.

$$\sigma = 2(\pi - \alpha) \tag{7.16}$$

Equation (7.15) can be written as

$$I_1 = B(\sigma) V \tag{7.17}$$

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Calculation of AC Harmonics

Consider 12 pulse converter unit shown in Fig. 8.1. From Fourier analysis, it can be shown neglecting overlap, that the current in the primary side of star-star connected transformer (assuming turns ratio of 1:1) is given by

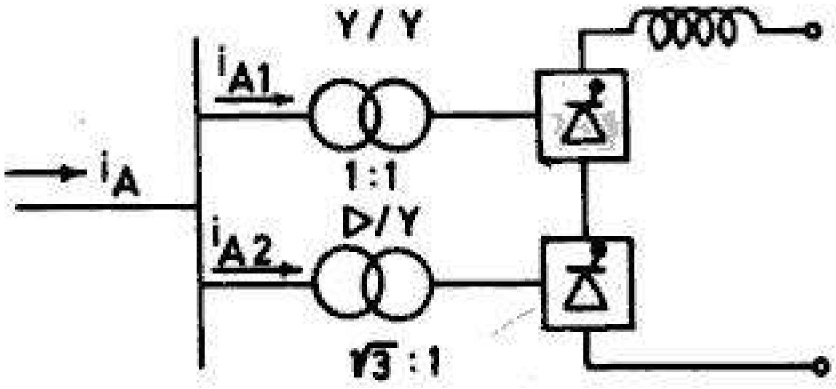

Fig. 8.1 Schematic Diagram of a 12 Pulse Converter Unit

$$i_{A1} = (2\sqrt{3}/\pi)\, I_d\, [\cos\omega t - (1/5)\cos 5\omega t + (1/7)\cos 7\omega t - (1/11)\cos 11\omega t + (1/13)\cos 13\omega t - \ldots] \tag{8.3}$$

Similarly, it can be shown that i_{A2} is given by

$$i_{A2} = (2\sqrt{3}/\pi)\, I_d\, [\cos\omega t + (1/5)\cos 5\omega t - (1/7)\cos 7\omega t - (1/11)\cos 11\omega t + (1/13)\cos 13\omega t - \ldots] \tag{8.4}$$

It is assumed that delta-star connected transformer has turns ratio of √3 : 1.

The current i_A is given by

$$i_A = i_{A1} + i_{A2} = (4\sqrt{3}/\pi)\, I_d\, [\cos\omega t - (1/11)\cos 11\omega t + (1/13)\cos 13\omega t - (1/23)\cos 23\omega t + (1/25)\cos 25\omega t - \ldots] \tag{8.5}$$

From the above expression, it can be observed that

$$I_{10} = (2\sqrt{6}/\pi)\, I_d \tag{8.6}$$

$$I_{h0} = (I_{10}/h) \tag{8.7}$$

where I_{10} and I_{h0} are rms values of the fundamental component and harmonic of order '*h*'. The second subscript "0" indicates that the overlap angle *u* is assumed to be zero.

When overlap angle is non-zero, the expression for I_h is given by

$$i_h = \frac{I_{h0}\,[A^2 + B^2 - 2AB\cos(2\alpha + u)]^{1/2}}{\cos\alpha - \cos\delta} \tag{8.8}$$

where, $A = \dfrac{\sin\,(h+1)\,u/2}{h+1}$, $B = \dfrac{\sin\,(h-1)\,u/2}{h-1}$

$\delta = \alpha + u.$

The above expression is valid for $u \le 60°$. For higher values of the overlap angle, the expression given by eq. (8.8) can still be used if α, *u* and δ are replaced by α', u' and δ' where

$$\alpha' = \alpha - 30°,\; u' = u + 60°,\; \delta' = \delta + 30° \tag{8.9}$$

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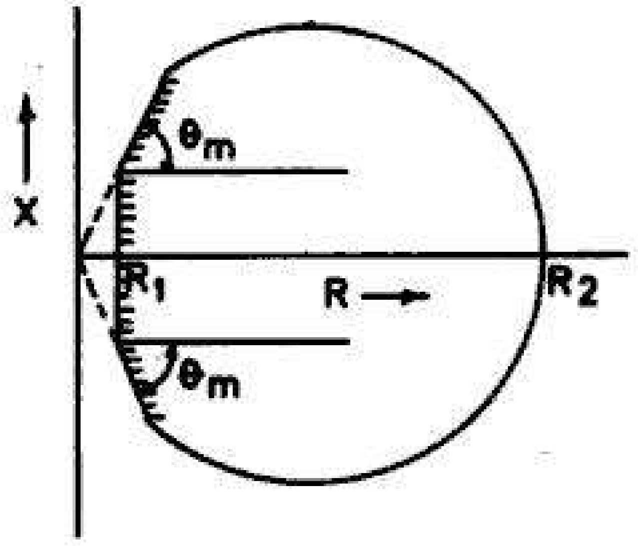

Fig. 8.6 Network impedance characteristic : Case (b)

Although assumption (a) is rather simplistic, it allows a simple choice of Q. The locus of filter admittance with variation in Q (and for a fixed value of $\delta = \delta_m$) is shown in Fig. 8.7. This also shows the optimum angle of filter admittance for which the maximum value of V_h that can occur is minimized. From the figure, it can be shown that

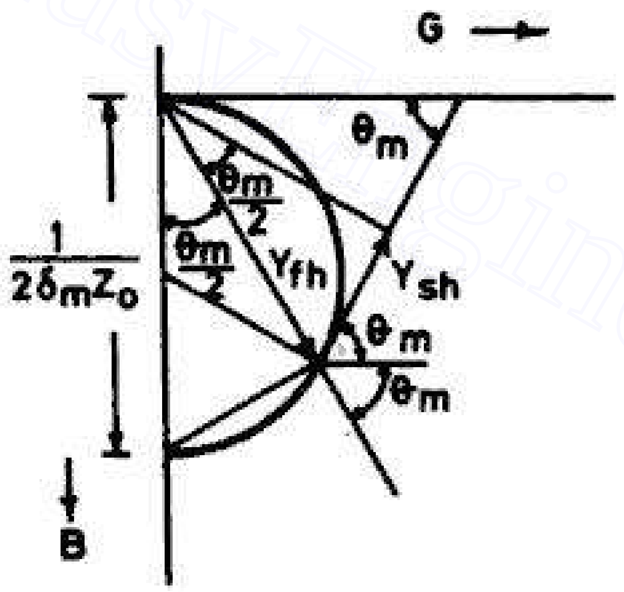

Fig. 8.7 Loci of filter and network admittance

$$Q_{opt} = \frac{\cot \theta_m/2}{2\delta_m} = \frac{1 + \cos\theta_m}{2\,\delta_m\,\sin\,\theta_m} \tag{8.31}$$

The corresponding harmonic voltage V_h is

$$V_h = \frac{I_h}{|Y_{fh} + Y_{sh}|} = \frac{4\,\delta_m\,Z_0 I_h}{1 + \cos\,\theta_m} \tag{8.32}$$

Minimum Cost Tuned Filters

The costs of the reactor and the capacitor which make up the tuned filter are dependent on their respective ratings. The rating of the capacitor is given by

$$S_c = \left(V_{c1}^2 + V_{ch}^2\right)\omega_1 C \tag{8.33}$$

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ensuring the same level of flexibility in energy exchange, three two terminal DC links will be required in addition to a link connecting the two receiving systems, which could be AC or DC (see Fig. 9.2). This would result in extra costs for the converter stations, lines and additional power losses in increased number of conversions.

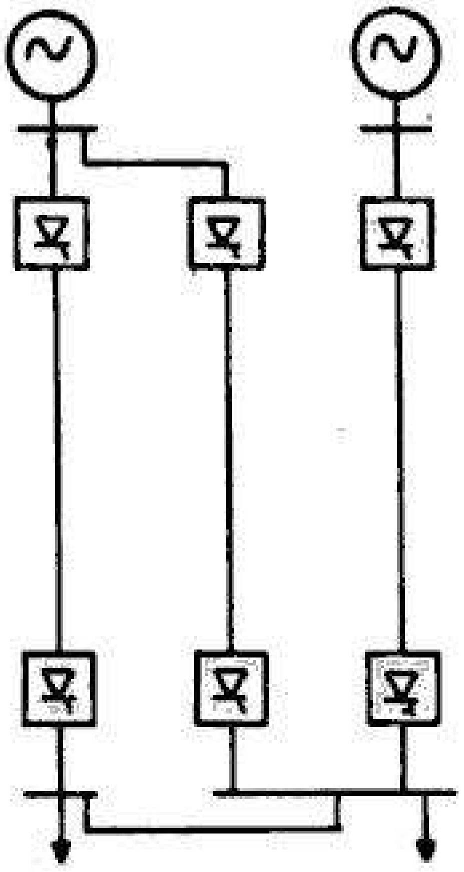

Fig. 9.2 Bulk power transmission using two terminal links

The elimination of AC collector system at the remote hydro generating stations can result in better efficiency in the operation of hydraulic turbines which are free to run at a speed independent of the system frequency.

2) Asynchronous interconnection between adjacent power systems. The advantages of asynchronous interconnection have already been described in Chapter 1. When more than two systems are involved, a MTDC system for interconnection is more flexible and economical than employing several two terminal DC links.
3) Reinforcing of an AC network which is heavily loaded. Consider an urban power system which is fed by a distant power station. It would be advantageous to arrange the power injection at more than one point so that the underlying AC network is not overloaded. This is easily achieved using a MTDC system with one rectifier station and several inverter stations (see Fig. 9.3).

9.3 TYPES OF MTDC SYSTEMS

There are two possible types of MTDC systems

(i) Series
(ii) Parallel.

The parallel MTDC systems can be further subdivided into the following two categories:

(a) Radial
(b) Mesh

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where I_{margin} is a positive quantity.

The converter with the lowest voltage ceiling always acts as a voltage setting terminal. The changes in the voltage setting terminal due to disturbances in the AC system are called mode shifts. Uncontrolled mode shifts can be minimized by selecting a terminal with highest short circuit ratio as the voltage setting terminal. Due to the negative resistance characteristics of the constant extinction angle control, it would be advisable to choose a rectifier terminal. The magnitude of the current margin is critical as converters of lower ratings can be overloaded when operating at angle limit.

The central controller that regulates the current orders at all the converter stations is termed as Current Reference Balancer (CRB) and is shown in the analog version in Fig. 9.7. Here, the current orders calculated from local power controllers are adjusted in order to satisfy Eq. (9.2). The limits on the current orders are taken into account in balancing current references. The actual implementation of CRB can be performed by using microprocessors.

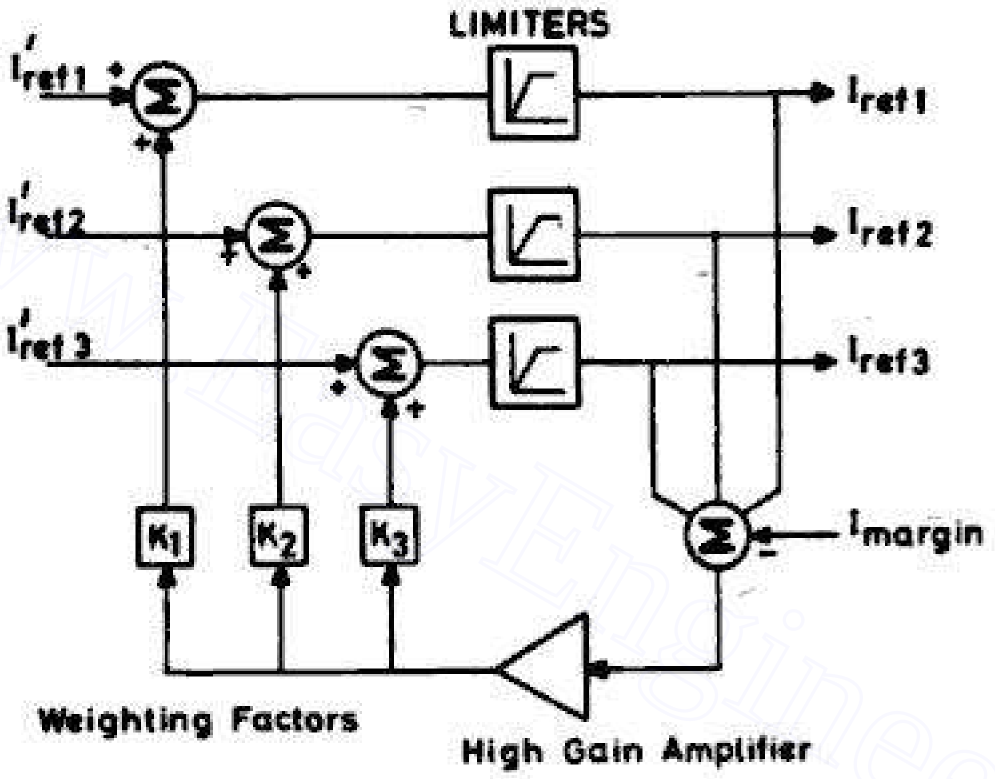

Fig. 9.7 Current reference balancer (Source : Reference 4)

Satisfactory operation of MTDC systems requires a reliable central CRB that operates at all times. This requires reliable two way communication between a central station and each converter station. If there is loss of a station and this information is not communicated, the system operation is adversely affected. In case of loss of a rectifier station, the power transfer is interrupted by voltage collapse. In case of loss of an inverter station, other stations will be overloaded.

In the current margin method, the change in the voltage setting terminal requires the operation of tap changing in converter transformer to modify the voltage margin. This can be slow and results in less flexible control to deal with mode shifts. An improvement has been suggested by using a modified control scheme termed as voltage margin control method. In this method, all converter stations are provided with automatic voltage regulators (AVR) along with automatic current regulators (ACR). In the voltage setting terminal, AVR reference voltage is set to the rated voltage and in other stations, AVR reference voltage is set higher by an amount ΔE.

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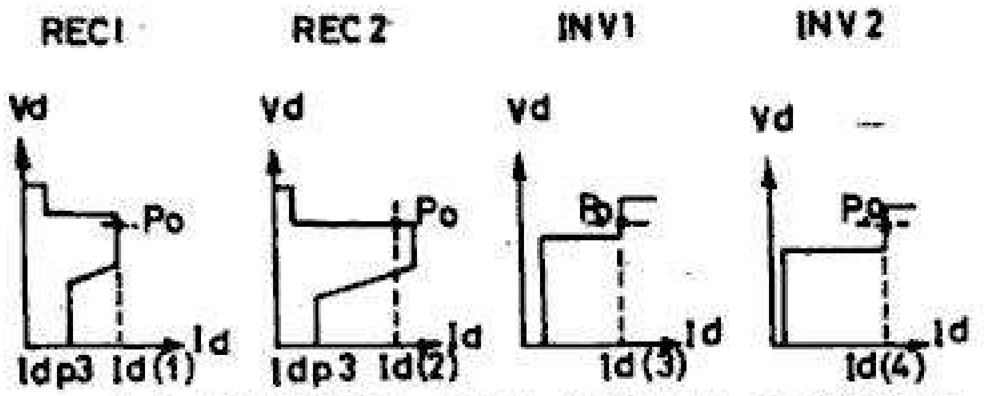
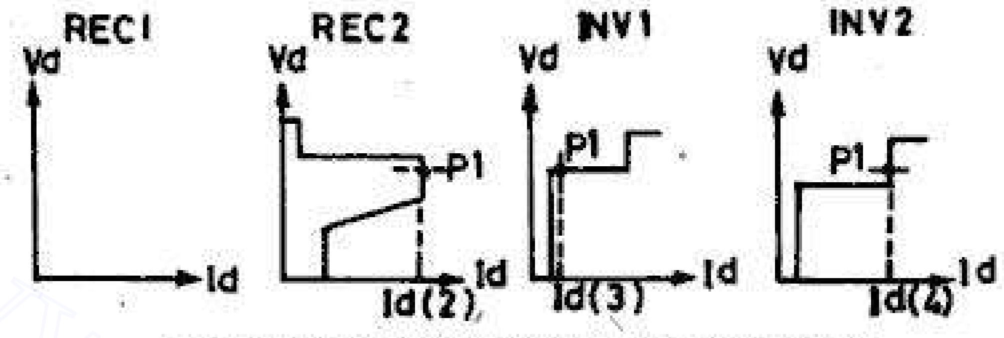
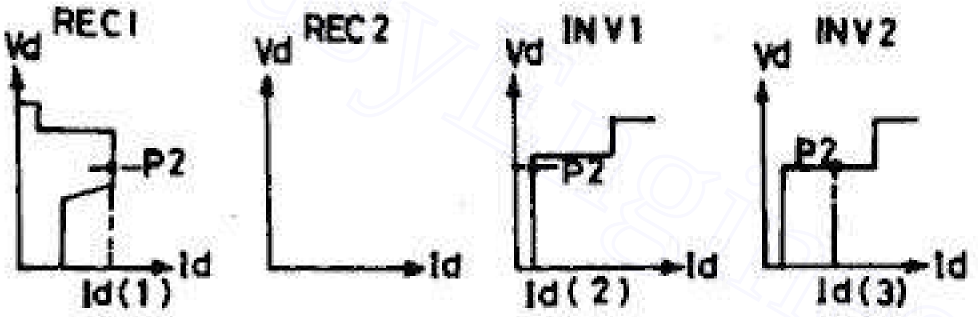


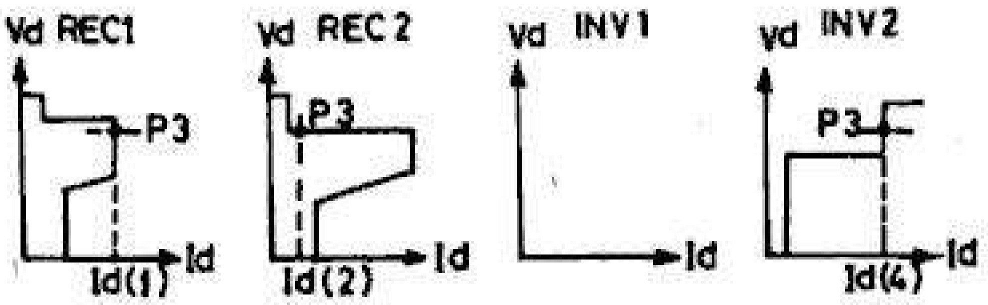
(a) OPERATING POINT WITH ALL TERMINALS



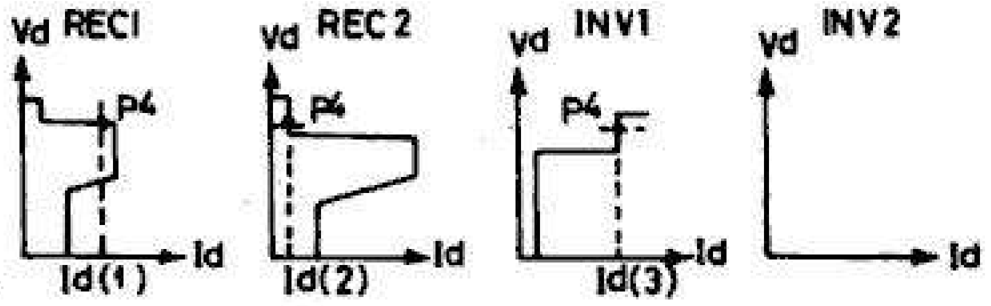
(b) OPERATING POINT WITHOUT REC1



(c) OPERATING POINT WITHOUT REC2



(d) OPERATING POINT WITHOUT INV1



(e) OPERATING POINT WITHOUT INV2

Fig. 9.13 Operating point in case of a loss of a terminal (b) Operating point without REC 1 (c) Operating point without REC 2 (d) Operating point without INV 1 (e) Operating point without INV 2.

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this procedure is not valid for the discrete model as the time interval is reduced to half of the value for a six pulse bridge. Hence the discrete model has to be derived separately for the 12 pulse converter. Two cases are considered (i) with four and five valve conduction mode (overlap angle <30°) and (ii) with five and six valve conduction mode ($30° < u < 60°$).

Four and Five Valve Conduction Mode

The normal operation of a 12 pulse converter with 4/5 valve conduction mode is shown in Fig. 10.4. e'_a, e'_b and e'_c are the converter transformer secondary voltages for bridge 2. 1', 2' indicate the valve number in bridge 2. It is assumed that the voltage e'_a lags e_a by 30° so that the valves are fired in the sequence 1,1' 2, 2', 3, 3', etc.

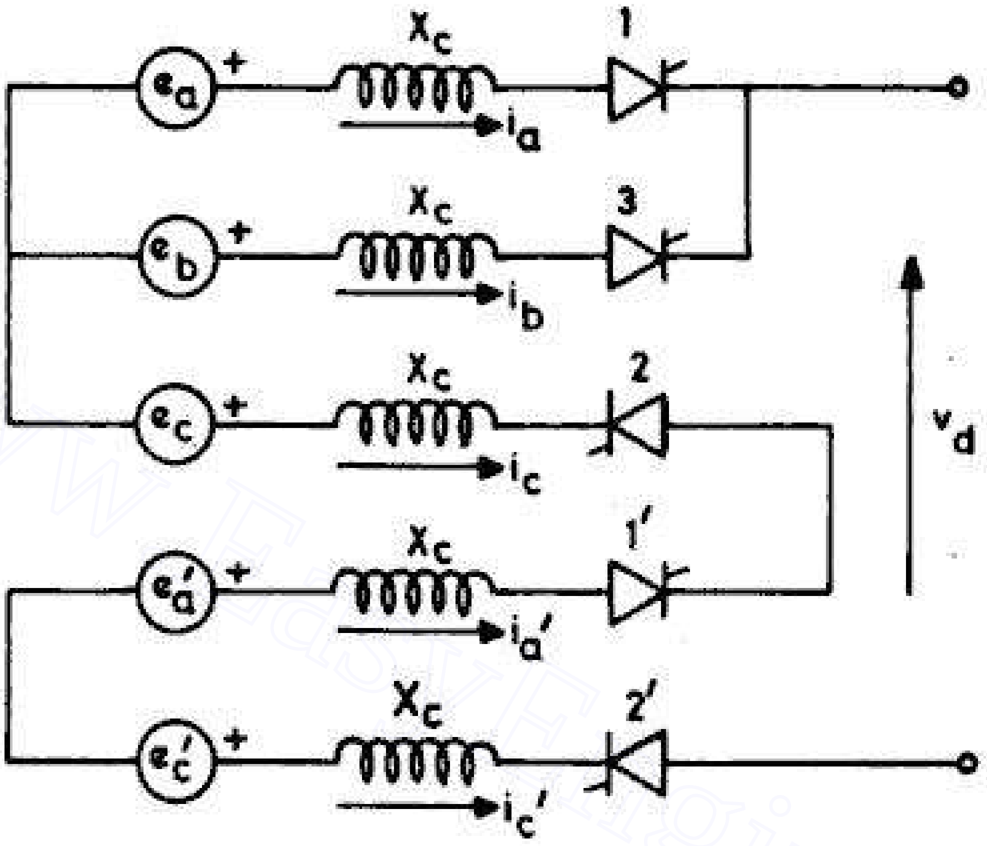

Fig. 10.4 A circuit showing 5 valve conduction

Consider that at the instant t_k the valve 3 is fired. Prior to t_k, four valves (1,1', 2, 2') are conducting. Before the instant of firing of next valve (3') t_{k+1}, the valve 1 would have stopped conducting.

The instantaneous DC voltage is

$$v_d = (e_b - (X_c/\omega_0)(di_b/dt)) - (e_c - (X_c/\omega_0)(di_c/dt))$$
$$+ (e'_a - (X_c/\omega_0)(di_a/dt)) - (e'_c - (X_c/\omega_0)(di'_c/dt)) \tag{10.13}$$

The average DC voltage is

$$V_d = (1/\Delta t_k) \cdot \int_{t_k}^{t_{k+1}} v_d(\tau)\, d\tau \tag{10.14}$$

where $\Delta t_k = t_{K+1} - t_k = H = \pi/6\,\omega_0$ (10.15)

Substituting Eq. (10.8) and the expression

$$e'_a - e'_c = \sqrt{2}\, E_s \cos\,[\omega_0(t - t_k) + \alpha_k] \tag{10.16}$$

in (10.13) and integrating we get,

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14.2.3 Core Saturation Instability [2]

This was observed on the Kingsnorth and Nelson River HVDC schemes. In the former, a 12th harmonic component in the magnetizing current of the converter transformer was magnified due to the instability and this also resulted in a circulating current between the 11th and 13th harmonic filters. The total filter current rose to values exceeding the filter rating and caused the protection to shut down the DC link. The build-up of instability was slow and took upto 5 minutes.

The major causes for this type of harmonic instability are due to (i) the DC system having series resonance at or near the fundamental frequency, (ii) low short circuit ratio at the converter bus. If there is a second harmonic voltage at the converter bus, this causes fundamental frequency voltage on the DC side. Due to series resonance in the DC line, there will be relatively large fundamental frequency components in the current through the converters. This, in turn, results in DC components in the currents flowing in valve windings of the converter transformers causing magnetic saturation of the cores. This will reinforce the original second harmonic component of the voltage present at the converter bus.

The main feature of this instability is the presence of DC components in the magnetizing current of the converter transformers causing saturation. The harmonics generated due to the core saturation contain a large spectrum of even harmonics and if the system impedance has a large value at one of these frequencies (due to parallel resonance), the harmonic distortion in the bus voltage is aggravated. In the case of Kingsnorth scheme, the parallel resonance occurred at the 12th harmonic due to the presence of 11th and 13th harmonic (tuned) filters. In Nelson River scheme, the resonance occurred at the fourth harmonic.

It is to be noted that the core saturation instability can occur even with EPC scheme. This type of instability cannot be predicted unless the finite nature of the DC system impedance and its variation with frequency is taken into consideration. In the earlier analysis [1], the DC current was assumed to be constant.

The possible solutions to this instability are as follows :

1. Selecting smoothing reactor values to avoid the resonance in the DC system at or near the fundamental frequency.
2. Modification of the controller by adding an additional dc flux control loop [3]. The control signal is derived from the measured DC magnetizing current or the second harmonic component. This is used to modulate the control signal that is normally generated from the converter controllers. The modulating signal is limited to a low amplitude so that its effect on the normal operation is negligible.

The DC component in the converter transformers may also be caused by the induction of fundamental frequency currents in the DC line caused by adjacent AC circuit on the same right of way [4].

14.2.4 A Generalized Analysis of Harmonic Instability

It is shown by Yacamini et al [5] that there can be problems of harmonic instability independent of the firing control scheme and transformer saturation. The problem of magnification of a harmonic of particular frequency (f_a) can arise if the AC system (including the filters) has a parallel resonance at that frequency and the DC system

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HVDC Power Transmission Systems
Technology and System Interactions

HVDC transmission technology is fast advancing and its applications are rapidly expanding. This book presents the various aspects of HVDC technology in sufficient depth to a beginner. In addition, it also includes the analysis and simulation of AC-DC system interactions which are of importance in the planning, design and operation of HVDC systems. The book gives up-to-date information and integrates material that has been scattered in several journals.

The book is divided into two parts. The first part has 9 chapters and covers the techniques and components of HVDC systems in detail. The emphasis is on the unique components of HVDC systems, such as thyristor valves, converters, control, protection and harmonic filters. One chapter each is devoted to each of these items. Reactive power control and multiterminal DC system operation are also included as two separate chapters. Static Var Systems used for reactive power control in converter stations are also discussed.

The second part of the book deals with the modelling, analysis and simulation of AC/DC systems. Seven chapters are included in this part which cover component models, power flow, transient stability, dynamic stability and power modulation, harmonic and torsional interactions, simulation of converters and HVDC systems. The coverage is fairly detailed and includes some new information not published before.

The book should be of interest to graduate students, researchers and engineers from utilities/industries who are involved with HVDC power transmission.

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