— Switching or resistive loads (*e.g.* electric furnace)

High voltage vacuum contactors are designed to meet IEC - 470, DE 066, BS 775-2, AS 1864 etc.

Construction and function (Ref. Fig. 15.19)

The vacuum contactor consists of a low-voltage section, a high-voltage section and an integral rocker as a dynamic link between the solenoid operating mechanism and the vacuum interrupters.

The LV section contains the solenoid mechanism, auxiliary switch blocks, centrally arranged terminal blocks, mechanical closing latch, and a mechanical lock-out.

The main HV parts are the moulded plastic housing with the three vacuum interrupters and the power terminals. The contactors are fitted with **vacuum interrupters** for the required particular voltage (3.6/7.2/12 kV). When the contactor closes the operating stroke of the solenoid is transmitted by the integral rocker to the moving contact of the vacuum interrupter. The contact gap is closed by the atmospheric pressure and an additional spring. When the solenoid circuit is interrupted the two restoring springs establish the contact gap by acting on the integral rocker. The contactor has a life expectancy of upto 2×10^6 operation cycle.

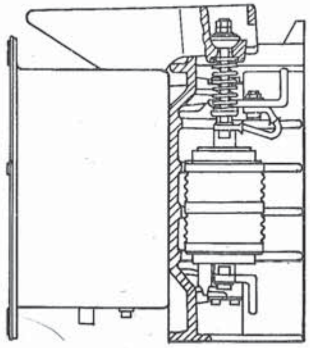


Fig. 15.19. Cross Section of Vacuum Contactor. Side View
Courtesy : Siemens, West Germany.

16

HVDC Circuit-Breaker and Metallic Return Transfer Breaker (MRTB)

Introduction to HVDC Systems — Why no need of HVDC Circuit Breaker in main power poles ? — Bipolar 2-Terminal HVDC System — Three Terminal Parallel Tapping — Multi-terminal (MTDC) — Back to Back HVDC Coupling Station (BBCS) — Metallic Return Transfer Breaker (MRTB) in Earth Return Path.

HVDC Arc Interruption by Artificial Current Zero-Energy Considerations in Breaking of Direct Current in HVDC Circuit Breakers — HVDC Circuit Breaker Principle — Commutation Principle — Control of dv/dt — Triggerred Vacuum Gap — HVDC Switching Devices in use — Metallic Return Transfer Breaker in 2TDC — Switching Arrangement in 3T Parallel tapping HVDC — Type of Breakers in Main DC Circuit : Type A, Type B1, Type B2 — Time considerations. HVDC Circuit Breaker for Parallel Tap-Conclusions.

16.1. INTRODUCTION TO HVDC SWITCHING SYSTEM

— HVDC Transmission Systems have become commercially successful in India and many other nations after around 1980. High Voltage Direct Current Transmission (HVDC) is an alternative to 3 Phase, 50 Hz, AC transmission in following applications :

— Bipolar Long Distance High Power Transmission from Super Thermal Power Plants/Super Hydro Plants to Mega-load centers. Typical Ratings of such HVDC Links ; single circuit 2 Pole ± 500 kV DC or ± 600 kV DC, 1500 MW, 2000 MW, 6000 MW, 750 km to 2000 km long, without any compensating substation in between. For example : Rihand Delhi HVDC Link : 820 km, ± 500 kV DC, 1500 MW. Chandrapur Padghe HVDC Link of same rating.

— System Interconnections (100 MW, 500 MW, 1000 MW, 2000 MW).

— Frequency conversion (50 Hz/60 Hz)

— Back to Back HVDC Coupling Station between two neighbouring AC Grids. National Grids with several such interconnections.

— Submarine Cable Transmission through oceans and lakes for feeding power to islands or for interconnection between two Grids separated by long ocean/channel.

— Multi-terminal interconnections between several AC Networks by Long High Power HVDC Transmission Bus.

Table 16.1. Particular Applications of HVDC Transmission Systems

Type	*Principal Criteria of Choice*
1. Long 2-Terminal Bipolar High Power HVDC Systems *e.g.* Rihand Delhi, India 1991 ; Chandrapur-Padghe (1997)	— Economy in capital cost, — Better power control, accurate, fast control of power flow (30 MW/min) through particular line, this is not possible with AC Line in a Network. — Lower transmission losses as no reactive power flow. — Energy Conservation — Higher Stability Limit

	Type	Principal Criteria of Choice
2.	Back-to-Back HVDC Coupling Stations between two independently controlled AC Networks *e.g.* Vindhachal Back-to-Back (WR/NR) 1989; Chandrapur Back-to-Back (WR/SR) 1998	— Technically Superior — Better Stability of AC Networks at both ends. — Excellent Interconnection which provides operational flexibility of power reversal, accurate fast power and frequency control, damping of power swings etc. — Large scale blackouts in Interconnected AC Networks are prevented.
3.	Long High Power Submarine Cable-Links (*e.g.* British Channel HVDC Link between France and UK, 1983)	— No continuous charging currents. Hence no upper limit of power and length of cable.
4.	Multi-Terminal HVDC interconnection System between three or more independently controlled AC Networks (*e.g.* New England-Hydro Quebek Canada-USA, 5-Terminal HVDC System)	— Accurate, Fast, control of power exchange between 3 or more AC Networks — No total Black-outs. — Higher Stability Limit — Lower losses — Energy Conservation

Modern Power Systems have a few HVDC interconnections and a few long 2TDC transmission links and a large 3 phase AC Network of transmission and distribution lines. These HVDC *Links transfer power in DC form from one AC network to another.* For rest of the generation, transmission and distribution, and utilisation, 3 Phase 50 Hz AC system shall continue. The 3-Phase AC system operates simply and automatically in synchronism. Design, expansion, operation etc. of AC Systems are simple, easy, of lower cost, AC Power Transformers and AC Switchgear can be used in several locations conveniently.*

More than 60 HVDC Transmission Systems have been installed in the world (1995) including 4 HVDC Systems in India. Several new schemes are under planning/execution. HVDC Technology has matured and has been accepted as an essential part of Modern Power Systems due to its several merits. HVDC is a solution to interconnected Power System Stability Problems.

The *protection and switchgear* requirements of HVDC Systems is quite different than that of 3 Phase AC Systems. Whereas in AC Transmission Systems the protective relays and AC Circuit Breakers are essential at every switching point and for every transmission line. HVDC Poles do not need any Circuit Breakers.

In HVDC Systems, Protection and Control functions are integrated with the Thyristor Convertor Control. There are no HVDC Circuit-Breakers. For normal operational control and for protection from abnormal currents and voltages etc. Thyristor control is employed. In the event of single-pole faults beyond the capability of the thyrister control ; the AC circuit breakers of the faulty pole are tripped after reducing power flow and the faulty pole is isolated. The healthy HVDC pole continues to be in service for such single pole faults.

All the present HVDC Systems are without HVDC Circuit Breaker in the DC Poles. Circuit Breakers are provided on AC Side of Converter Transformers. [Fig. 16.1 (*a*) to (*e*)].

The control of DC current, DC voltage and DC Power flow is achieved by Tap-changing of converter-transformers and simultaneous thyristor-control of converter valves take care of protective functions. Therefore, there is no need of any HVDC Circuit Breaker in Main DC Poles. Even if such breakers are provided, they will not be operated, as the Converter Controls and continuity of power flow would be adversely affected.

However, the HVDC Switching Devices in form of Metallic Return Transfer Breaker (MRTB) are necessary in the earth return path in present 2-Terminal HVDC Systems for interrupting earth return currents during change over from earth return to pole return (Metallic Return). DC Switching Arrangement are also used in HVDC parallel tapping for current reversal. These DC Switching

* The notion that HVDC will replace 3-phase AC is wrong. 3-Phase AC Network will continue for ever. HVDC is for a few particular applications listed above. HVDC Systems are between 2 or more AC Systems. HVDC has no independent stay.

Devices are rated for normal current breaking with low arc energy, (i.v.t.-joules). They are not true HVDC Circuit Breakers which would break HVDC Short-circuit currents or full load DC Currents at rated DC Voltage of poles. Such HVDC current interruption involves high energy arc switching (i.v.t-joules) which is difficult due to absence of natural current zeros.

Artificial Current Zero Arc Interruption Principle

Why is an HVDC Breaker different from an High Voltage AC Breaker ? Why is the low voltage DC Breaker different from an High Voltage DC Breaker* ?

AC breaker easily interrupts the arc at natural current zero in the AC wave. At current zero, the energy ($1/2\, Li^2$) to be interrupted is also zero. The contact gap has to cool and recover the dielectric strength to withstand natural TRV. With DC Breaker, the problem is more complex as the DC waveform does not have natural current zeros. Forced arc interruption would produce high transient recovery voltage and restrikes without arc interruption and ultimate destruction of the breaker contacts.

The artificial current zero principle must be employed in HVDC switching devices for interruption of DC arcs. The artificial current zeros are produced in the LC oscillatory circuit in the loop of circuit-breaker while opening the contacts. The arc is extinguished by the circuit breaker. A ZnO arrester in parallel limits the Transient Recovery Voltage and absorbs associated energy. The limit is imposed by the energy (i.v.t-joules) associated with the interruption. DC Current has *no natural current zeros* like in AC Current.

During circuit breaking, the current through the capacitor and parallel reactor produces oscillations and several artificial current zeros are obtained in the current. The breaker interrupts the arc during one of the current zeros. The subsystem for producing artificial current zeros requires large energy storage capacitor bank, trigger gap, ZnO arresters, reactors etc. The HVDC Breaker Pole has ZnO arresters in parallel with the main break for absorbing switching overvoltages. Artificial Current Zero Principle is employed in all the present medium voltage and high voltage DC switching devices. In these devices, the Arc is interrupted at artificially produced current zero and thus involves low arc energy dissipation. The Breaker Pole itself is airblast type or Minimum-oil type. The presently used DC switching devices are of lesser current rating and with medium DC Voltage. They are not true high power HVDC Breakers which would interrupt full rated DC Current/Short-circuit Current of HVDC Poles. During 1970s, research and development efforts were focussed on development of HVDC Circuit Breakers and HVDC Systems. These development have been technically successful but are not used in practice due to high cost and complexity of HVDC Breaker Systems.

The Original Objectives of HVDC Breaker Development

The development of HVDC Circuit Breakers was undertaken by CIGRE Working Group on HVDC Breaker during early 1970s. The converter control by thyristors was not yet fully developed then. HVDC Breaker development was with the following three *basic presumptions* :

Presumption 1. HVDC Circuit Breakers would be essential for protection during abnormal conditions and also for normal switching operations and lack of HVDC Circuit-Breaker Technology would be a bottle-neck in the use of HVDC Systems in Network. This presumption was based on the AC Breaker and Protection Principles and proved to be *wrong* for HVDC Systems by early 1980s. The HVDC Converters with thyristor control do not need of HVDC Circuit Breaker. The thyristor control itself regulates the DC current. Breakers on AC Side of Converter Transformers are enough. Fig. 16.1 (*a* to *e*) show the practical schematics.

* Refer Sec. 5.9 and Sec. 4.7.1 for Low Voltage DC Arc Interruption achieved by *high resistance arc interruption methods.* Arc is lengthened, cooled, split, to dissipate energy as heat. These methods are applicable only to Low Voltage DC Circuits Breakers. This method is not suitable for Medium DC Voltage (3.3 kV and above) switching devices due to high arc energy dissipation required. Artificial Current Zero Method is applicable.

Presumption 2. HVDC Circuit-Breakers would be essential in Multi-Terminal HVDC Systems. This presumption also proved to be *wrong* during late 1980s. The 5-Terminal New-England, Hydro Queback MTDC System with HVDC Converters has thyristor control of valves and no HVDC Circuit-Breakers. Fig. 16.1(*e*) shows a practical schematic.

Presumption 3. Development of High Power HVDC Circuit-Breaker may be technically impossible as flow of DC energy cannot be interrupted instantaneously. This presumption was also proved wrong by 1985 as *truly High Power High Voltage HVDC Circuit Breaker has been developed successfully by a group of companies under a CIGRE HVDC Breaker Development Project.*

Though HVDC Breakers could have been used after 1985, they have never been used in practical HVDC Systems due to following reasons.

— HVDC Circuit Breakers *are not necessary* as the control and protection functions are performed by thyristor control of converters. The short-circuit currents in HVDC System are controlled quickly and automatically by converter control and the switching is carried out by AC circuit breakers.

— If HVDC Breaker is used, each HVDC Circuit Breakers would need another Back-up Breaker. HVDC Poles would need two HVDC Breakers at each switching point (one for main and other for back-up) and in addition to the thyristor control for protection and automatic controls. *Such a system would be prohibitively costly and complex.*

— The breaking of full load DC currents (2 kA to 5 kA) at High Voltage (± 500 kV DC) and with large energy in inductance (0.5 LI^2), is a complex, costly process and unreliable. It requires a very costly and complex HVDC Switching System. Such a system is practically uneconomical. With such a HVDC Circuit Breaker the already costly HVDC Schemes would be *economically unacceptable as against alternative EHV AC Systems.*

The high cost and complexity of HVDC System with HVDC Circuit-breaker is not acceptable as against the alternative EHV AC System of proven simplicity and reliability.

HVDC Systems without any HVDC Circuit Breaker in Main Poles

Todays HVDC Systems [Fig. 16.1(*a*)-(*e*)] are without HVDC Circuit Breakers in main pole. AC Circuit Breakers are installed on AC side of converter transformers. *Current in DC Poles is controlled by thyristor valves quickly and accurately without need of DC Circuit-Breakers.* In the event of a fault on DC side or in converter transformers, the DC current is blocked quickly by several control actions from both the terminals and the AC Circuit breakers are the rectifier end and opened. Even if HVDC Circuit Breaker were present, the converter control and AC Circuit-breakers would be and essential for operational control and protection.

Metallic Return Transfer Breakers (MRTB) is installed in the neutral to earth return path in one terminal-substation. This MRTB DC breaker is rated for switching earth return currents at medium voltage DC.

16.2. SCHEMATIC OF A 2-TERMINAL, BIPOLAR LONG DISTANCE HVDC TRANSMISSION SYSTEM

Such Systems are used for Long Distance High Power Transmission due to economic line construction, reduced line losses, easy rapid and accurate power flow control through a particular high power transmission link (*e.g.* from Rihand (UP) to Delhi, ± 500 kV DC, 1500 MW, 820 km long Bipole Link, 1991).

The principle of operation of a typical 2-Terminal bipolar point-to-point HVDC System is explained by means of the schematic Fig. 19.1.(*a*) The two AC Networks are connected by an HVDC Link. The HVDC Link has two identical converter substations, one at each end. Each converter substation has the following :

— AC Circuit Breakers
— Converter Transformers
— Converter Valves
— AC Harmomic Filter Banks
— DC Harmonic Filter Banks
— DC Smoothing Reactors.

The HVDC Line has two pole conductors, Pole 1 and Pole 2. One pole is positive with reference to the earth and the other is negative. The neutral points of the 12-pulse-thyristor coverter bridge is earthed via the earth return transmission line and earth-electrodes. There is no HVDC Breaker in the system. The MRTB Metallic Return Transfer Breaker is provided between the neutral point of the rectifier and the earth.

One of the terminals acts in Rectifier mode and the other terminal in Inverter Mode.

The converter at sending end terminal (*e.g.* Rihand) is operated in Rectification Mode (AC → DC) by appropriate firing angle of thyristor-valves. The receiving end converter (*e.g.* Delhi) is operated in Inverter Mode (DC → AC) by appropriate firing angle of thyristor valves. The power is fed again into AC Grid at receiving end (Delhi). Thus the HVDC Link transfers power from one AC Network (1) to the other AC Network (2).

Smoothing Reactor in DC Poles reduces the current ripple from DC waveform. Smoothing Reactor has high inductance (*e.g.* 0.4 H) and carries DC Current. Therefore stored energy ($1/2\ LI^2$) is high and pole current interruption is difficult and not resorted to.

DC Filters eliminate DC Harmonics from DC waveform and thus minimise telephone interference in neighbouring areas. DC Filter Capacitors also provide reactive power compensation to AC System for regulating AC Bus Voltage and for converter operation. Earth return currents in bipolar operation are usually small (< 3%) of rated DC current). Earthing of converter neutral is by an earth electrode about 15 km away from the terminal. The earth electrode line is installed between the neutral and the Earth Electrode. The earth return current can be interrupted by a specially designed MRTB. Full details of HVDC System are described in Chapter 47. Chapter 16 covers details about the HVDC Circuit Breakers.

During normal operation as well as during abnormal operation the DC current, DC voltage and power flow are controlled by controlling phase angle of thyristor firing of Rectifiers and inverters and by tap-changer control simultaneously, continuously and automatically. Tap changer control is slower (10 seconds) and thyristor control is faster (few tens of milliseconds).

During a *temporary fault* on DC Line, the following *operating modes* are tried :

— In the faulty pole, Converter at Rectifier Terminal is put to inverter mode, and voltage is reduced. This results in "starvation" of line fault current and fault dies out within a few tens of milliseconds.

— Meanwhile the other healthy pole conducts more power without any interruption.

— After a few tens of milliseconds, the converter of the faulted pole is put back to rectifier mode and the service restoration is attempted. Voltage is increased and normal Bipolar Mode is restored.

— If the line fault is permanent or if converter/valve is faulty, the converter control reduces the voltage and power, then the AC Circuit Breakers of that pole are tripped for protection.

— If the fault in one of the station poles is permanent, the HVDC System is automatically transferred from the usual Bipolar mode to Monopolar Mode and the DC power flow is made continuous without interruption. This Monopolar Mode is either to begin with, of Monopolar with Earth Return (MPER). But for long duration Monopolar Operation, Monopolar with Metallic Return is preferred. This is explained below.

The monopolar operation can have two operating modes

1. Monopolar with Earth Return. Full pole current flows through one pole conductor and return earth. The earth electrodes get rapidly consumed during the Monopolar earth return mode. The earth currents cause damage to substation earthing systems and gas/water pipelines if allowed to flow for long time.

2. Monopolar with Metallic Return. Full pole current flows through one pole conductor and returns through other pole conductor (Metallic Return). The Monopolar Operation with Metallic Return can be made continuous as there are no problems of earth electrode consumption and problems of galvanic corrosion of metallic pipes and earthing mesh due to heavy ground current.

The transfer from Monopolar Earth Return Mode to Monopolar Metallic Return Mode (and *vice versa*) is accomplished by the MRTB.

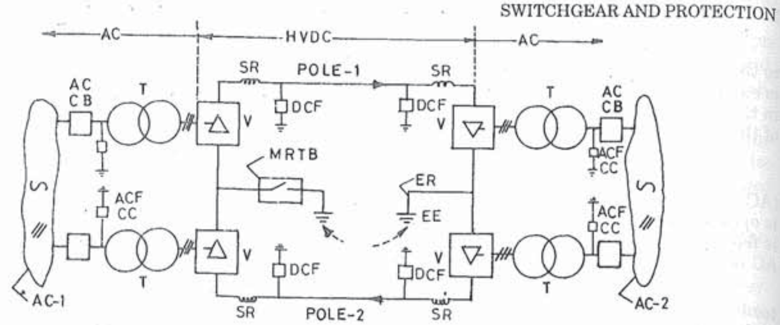


Fig. 16.1. (*a*) Schematic of a 2-Terminal Bipolar HVDC System indicating Circuit Breakers on AC Side.
(There are no HVDC Breakers in Main DC Poles)

AC-1	AC System 1	V	Thyristor-Converter Valves		
AC-2	AC System 2	MRTB	Metallic Return Transfer Breaker		
ACCB	AC Circuit Breakers	T	Converter-Transformer with OLTC		
SR	DC Smoothing Reactors	ER	Earth Return Line	EE	Earth Electrode

ACF-CC — AC Harmonic Filters and Compensating Capacitors
Pole 1 Path with say, positive DC Polarity with respect to earth
Pole 2 Path with negative DC Polarity with respect to earth
DCFDC Harmonic Filters

The MRTB is an HVDC Switching Device based on Artificial Current Zero. MRTBs are used in todays commercial HVDC Systems. But the HVDC Systems do not need/have any HVDC Breaker in the pole circuit.

Full details of HVDC System are described in Chapter 47. This chapter covers details about the HVDC Circuit Breakers.

16.3. BACK-TO-BACK HVDC SYSTEM

The interconnection between two independently controlled adjacent AC Networks is either by conventional AC Transmission Line (Interconnecting AC Line) or by an HVDC Back to Back Coupling Station (*e.g.* Vindhyachal Back-to-Back 1989) or an HVDC submarine Cable Link (England-France 1970s).

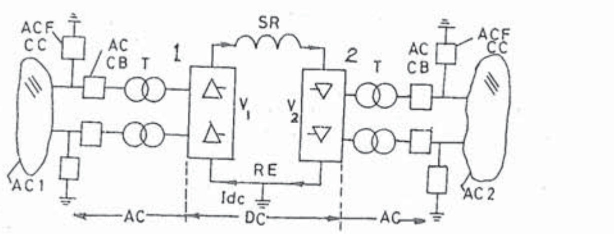
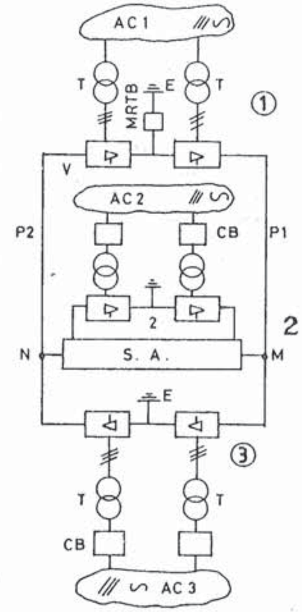


Fig. 16.1. (*b*) Back-to-Back Coupling System.
Interconnecting Substation between two adjucent AC Networks
(There are no HVDC Breakers in Main Poles)

AC-1 —	AC System 1	V —	Converter Valves
AC-2 —	AC System 2	RE —	Reference Earthing
ACCB —	AC Circuit Breakers	T —	Converter-Transformers with OLTC

ACF-CC — AC Harmonic Filters and Compensating Capacitors
SR — Smoothing Reactors
Pole 1 — Path with say, positive DC Polarity with respect to earth
Pole 2 — Path with negative DC Polarity with respect to earth
V_1, V_2 — Thyristor Converter bridge with several thyristors in series per arm



SA — Switching Arrangement [shown in Fig. 16.1 (*d*)]
M, N — Points of connection for SA
1, 3 — Terminal of 2-T HVDC System
2 — Additional Parallel Tapping at MN
P_1 — Pole-1, P_2 — Pole-2
MRTB — Metallic Return Transfer Breaker
CB — AC Circuit Breaker
V — Valve, T — Converter-Transformer

Fig. 16.1. (*c*) Additional Parallel Tapping with 2-Terminal HVDC System.

In India the neighbouring Regional Grids will be ultimately interconnected by small back-to-back HCDC Coupling stations rated about 500 MW each. Vindhyachal Back-to-Back (1989) couples Western Region with Northern Region. Chandrapur back-to-back (1998) couples Western Region with Southern. Three more HVDC Coupling Stations are in initial planning/execution stage (1998).

HVDC Coupling Stations enable rapid, accurate power exchange in either directions between the two AC Networks, improved stability of both AC Networks, better frequency control. Fig. 16.1(*b*) illustrates the essential parts in a Back to Back HVDC Coupling Station.

The principle of operation of a typical HVDC Coupling System is explained in Ch. 47.

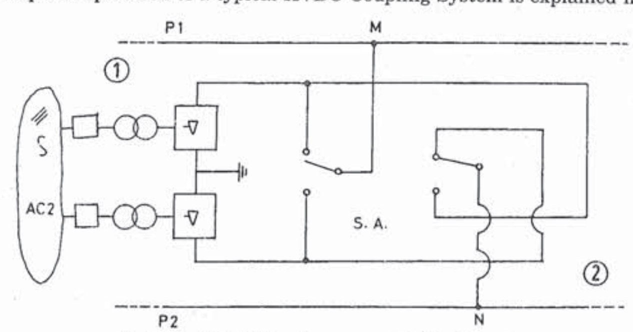
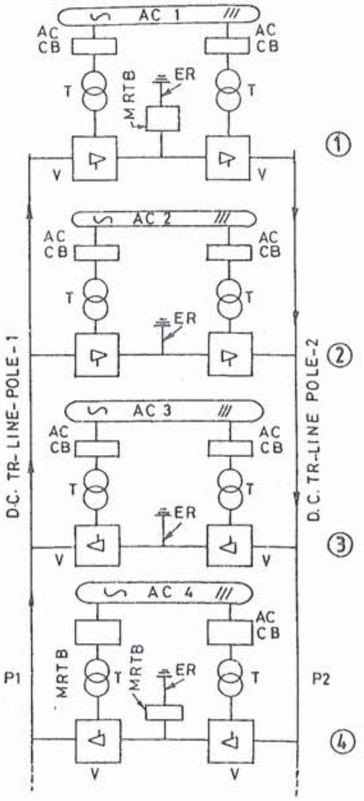


Fig. 16.1. (*d*) Switching Arrangement (SA) of Fig. 16.1 (*c*).
P_1 — Pole-1 P_2 — Pole-2

16.4. MULTI-TERMINAL HVDC SYSTEMS (MTDC)

An MTDC System interconnects three or more independently controlled AC Networks [Fig. 16.1 (*e*)-1, 2, 3, 4]. HVDC Systems are the solution to black-outs in Large Interconnected Power Systems.

The surplus AC Network (*e.g.* 1 and 2) can supply power into the HVDC Pole Lines *via* the converters operated in Rectifier Mode (AC $\rightarrow$ DC). The deficit AC Networks (*e.g.* 3 and 4) can draw power from the HVDC Pole Lines via the converters operated in Inverter Mode (DC $\rightarrow$ AC). The overall system stability is improved, the transmission losses are reduced, energy is conserved, large scale black outs in the total AC System are prevented. Such blackouts do occur in AC Networks interconnected by AC Transmission lines during cascade tripping of interconnecting lines. The first MTDC System in the world is the New England — Hydro Quebek 5 Terminal HVDC System (1996) in USA and Canada. The MTDC System does not need HVDC Circuit Breakers as each terminal has its Converter Controls for controlling DC voltage, power and current. The Circuit Breakers are provided on AC Side.



P_1 — HVDC Transmission line Bus Pole 1
P_2 — HVDC Transmission line Bus pole 2
V = Valves
ACCB = AC Circuit Breaker
ER = Earth Return Line
T = Converter Transformer
MRTB — Metallic Return Transfer Breaker

Fig. 16.1. (*e*) MTDC System with 4-Terminals.
(AC-1, AC-2, AC-3, AC-4 : AC Networks)

Metallick Return Transfer Breakers (MRTB) are provided in earth return circuits in Rectifier Terminals for the switching from Monopolar Earth Return Mode to Monopolar Metallic return Mode as described in Sec. 16.2.

16.5. SCHEMATIC OF DC SWITCHING SYSTEM AND WAVEFORM OF IDC WITH ARTIFICIAL CURRENT ZEROS

In Fig. 16.2 (*a*) the Main Break (MB) represents a Circuit-Breaker Pole which is capable of breaking the arc at artificial current zero. Single pole MOCB/Air-Blast CB have been used successfully. The DC Switching System has an additional LC-Circuit in parallel A. Triggered Vacuum Gap (TVG) is in this parallel path. The ZnO Arrester is in parallel for transient overvoltage absorption. Refer Fig. 16.2 (*b*). The DC current Idc starts rising from the instant of fault (t_1) on the DC side of the DC pole. The fault is sensed by the protection and control circuits. The tripping command is given to the MB and trigger command is given to the TVG.

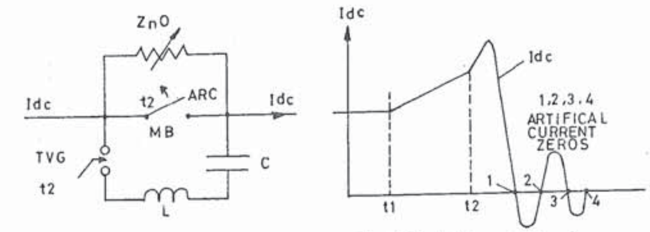


Fig. 16.2. (*a*) Schematic of DC CB   Fig. 16.2. (*b*) Current Waveform

Idc — DC current through the pole and circuit breaker MB
MB — Main Breaker with interrupter
TVG— Triggered Vacuum Gap
ZnO — Zink Oxide Arrester (Ref. Sec. 18.5B)
L, C — Inductor and Capacitor in parallel with MB
t_1 — Fault occurs on DC pole conductor, current Idc starting rising
t_2 — MB opens and arc is initiated in MB contacts, TVG sparks over
LC is brought into the circuit in parallel with MB
Time *t* is in milliseconds, (t_1) to (4) is about 100 ms.

As the Main Break opens (at t_1), the DC arc is initiated between the contacts. Idc flows through the arc in the MB. As the TVG sparks over, the parallel LC path comes into circuit and the Idc oscillates producing artificial current zeros (1, 2, 3, 4...). The MB interrupts the arc at one of these artificial current zeros. The transient recovery voltage (TRV) across the Main Break tries to produce a restrike between open contacts of MB. The ZnO Arrester limits the transient recovery voltage across the MB and parallel path. The ZnO Arrester absorbs the energy in the bypassed current associated with the TRV. The Idc is finally interrupted at one of the artificial current zeros.

16.6. CONCLUSION

From the experience of present HVDC Systems, the true HVDC Circuit Breaker is not necessary in HVDC Poles of 2TDC, MTDC, Back-to-Back HVDC Systems. All the control and protection functions are performed effectively by the converter controls without the need of HVDC Breakers in pole circuit. HVDC Circuit-Breakers/Switching Systems, though available are of no practical use as they are complex, costly and unreliable for practical use in the Main DC Poles. However Metallic Return Transfers Breakers. HVDC Switching Arrangement based on Artificial Current Zero Principle of arc quenching are used in present 2-TDC and 3-TDC Systems. The details about HVDC Switching Systems are covered in following sections.

16.7. ENERGY CONSIDERATION IN BREAKING DIRECT CURRENT IN HVDC CIRCUIT-BREAKERS

(Refer Secs. 3.2 and 4.5 for fundamentals of energy in L, C and difference between A.C. and D.C. arc interruption).

Forms of Current Zeros

In a.c. circuit-breaking, the current is interrupted at current zero of the alternating current wave [Fig. 16.3 (*a*)]. As the contacts separate, the arc is initiated. The arc has a tendency to disappear around current zero. The arc is quenched at current zero by removing the ionised medium from contact space by flow of quenching medium. The contact space filled with fresh dielectric medium has then to withstand the Transient Recovery Voltage. The arc provides a resilient transition between the current carrying state and the voltage withstanding state. The post zero conductivity of contact space assists in dampening the TRV.

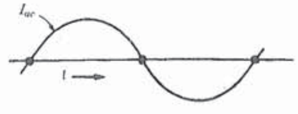


Fig. 16.3 (*a*). Current zeros in A.C. waveform.

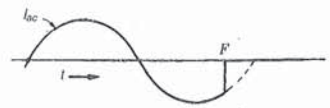


Fig. 16.3 (*b*). Forced current zero in AC wave (current chopped at instant F).

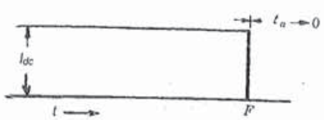


Fig. 16.3 (*c*). Abrupt forced current zero in D.C.

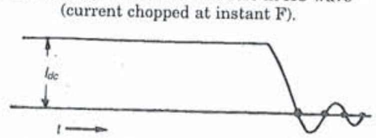


Fig. 16.3 (*d*). Artificial current zeros in DC by inserting LC parallel circuit across the circuit-breaker contact separation.

While breaking direct current, the natural current zero is not available. Hence the problem in D.C. circuit-breaker is to bring down the current from full value to zero, smoothly without chopping it abruptly. The abrupt current zero can be achieved by a high pressure blast on the arc zone. Such an abrupt forcing of current zero (current chopping) would result in excessive overvoltages [Fig. 16.4]. Hence, the switching system should bring down the direct current to zero artificially without chopping it [Fig. 16.3 (*d*)]. D.C. circuit-breaker should be capable of breaking all the values of currents from rated normal currents to highest short-circuit currents without excessive overvoltages.

This discussion can be visualised by comparing the flow of current with flow of water in a pipe-line (Fig. 16.4). If valve is suddenly closed, the flow of water is stopped and the pressure rises suddenly. The level of water in the surge tank thereby increases. Likewise, by interruption of current I by current chopping the energy in system inductance gets converted to capacitive charge, increasing voltage across system capacitance. If current is interrupted at zero value, the rise in voltage would be minimum.

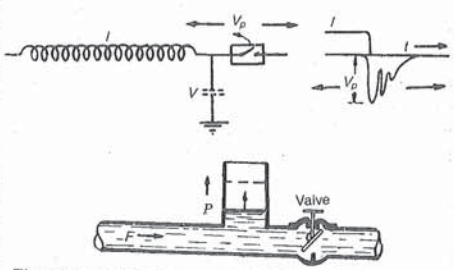


Fig. 16.4. Analogy between water flow and current flow.

Energy Equation

Refer Fig. 16.5 representing HVDC transmission system, let V_o = D.C. voltage at sending end, V_o is a function of i, t during transient switching condition.

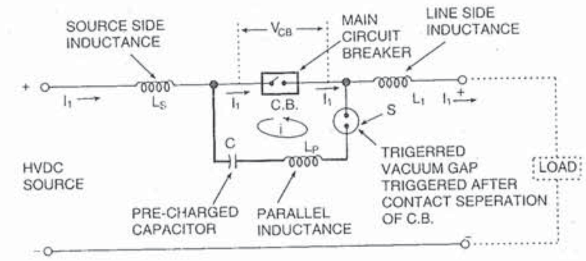


Fig. 16.5. Schematic of HVDC Switching System.

Before switching off, the steady direct current I flows through line induction L and resistance R and the d.c. circuit-breaker CB. The initial and final conditions are as follows :

$$t = 0, \quad i = I$$
$$t = ta \quad i = 0$$

Current decreases from initial value I to final value in time ta. The voltage equation can be written as–

$$L\frac{di}{dt} + iR + V_{CB} = V_0 \qquad ...(16.1)$$

where $L\dfrac{di}{dt}$ = Voltage drop across line inductor L ... Volts

iR = Voltage drop across resistance R ..., Volts

V_{CB} = Voltage across a circuit-breaker CB ..., Volts

V_0 = Sending end voltage, Volts

The energy (W) can be derived from simple relation given by

$$W = \int_0^{ta} iV \cdot dt \text{ ... joules}$$

Multiplying equation (16.1) by idt and integrating with respect to time,

$$\int_0^{ta} V_0 \, idt = \int_0^{ta} Li\, di + \int_0^{ta} i^2 R\, dt + \int_0^{ta} V_{CB} \cdot i\, dt \qquad ...(16.2)$$

rearranging the terms and simplifying

$$\int_0^{ta} V_{CB} \cdot idt = \frac{1}{2}LI^2 - \int_0^{ta} V_0 \cdot idt + \int_0^{ta} i^2 Rdt \qquad ...(16.3)$$

Total Switching Energy = Magnetic Energy in Inductance − Input Energy from Network + Total Joule Losses Converted into heat of arc

From equation (16.3) it can be seen that the switching duty is a question of energy. The total switching energy gets shared by the three component energies. The task of the switching system is to achieve the switching condition without abrupt change in magnetic energy.

As discussed in chapter 3, as per fundamentals, the current in inductance cannot be changed instantaneously (in zero time). Similarly the energy is capacitance cannot be changed instantaneously. If the current in inductance is forcibly chopped to zero in zero time, the energy in inductance has no way to dissipate except to get converted into energy in capacitance in form of charge, *i.e.* if $\frac{1}{2}LI^2$ in equation (16.3) is made zero instantaneously so as to interrupt the current, the component $\frac{1}{2}LI^2$ gets converted into $\frac{1}{2}CV^2$ the resulting overvoltage will stress the insulation and cause flashovers. To avoid this, the current I should vary with relatively low di/dt. In general, the value of time t_a varies between 10 to 30 milliseconds. The total switching energy can be increased quickly beyond the magnetic energy so as to quench the arc. The switching energy can be dissipated by charging capacitors (energy storage) or through resistors (energy dissipation).

Recently developed (1980's) Metal Oxide Resistors (ZnO) have superior voltage/current characteristic and energy absorption capability. Such resistors are used in HVDC switching-system.

In practical d.c. systems, the value of d.c. current is of the order of a few kilo amperes and the value of voltage across the circuit-breaker would be of the order of 10 to 200 kV. The switching power would be in the range of a few kilo-watts to a few megawatts depending upon the inductance of the line and smoothing reactors.

16.8. HVDC SWITCHING SYSTEM

In a.c. circuit-breakers, the arc is extinguished at natural current zero of the wave. Thus, the energy in system inductance at current zero is practically zero and current interruption is relatively easy.

In d.c. Switching system, a LC resonant circuit is introduced in parallel, just after contact separation of main circuit-breaker. Thereby oscillations are produced in the main current resulting in a few artificial current zeros. The main circuit-breaker catches one of the current zeros so as to quench the arc and break the direct current.

16.8.1. Commutation Principle of HVDC Circuit-breaker

The principle of a HVDC switching system is illustrated in Fig. 16.6.

The *Main Circuit-breaker* (CB) may be, MOCB or ABCB. The circuit-breaker should be capable of withstanding very high rate of rise of transient recovery voltage. It should also be able to dissipate the arc energy. It should be capable of opening consistently with precise opening time.

L_s and L_L represent the circuit inductance on either sides of the circuit-breaker.

C and L_p represent properly selected values of inductance and capacitance.

The capacitor C is pre-charged by a separate charging circuit (for obtaining current i in the loop).

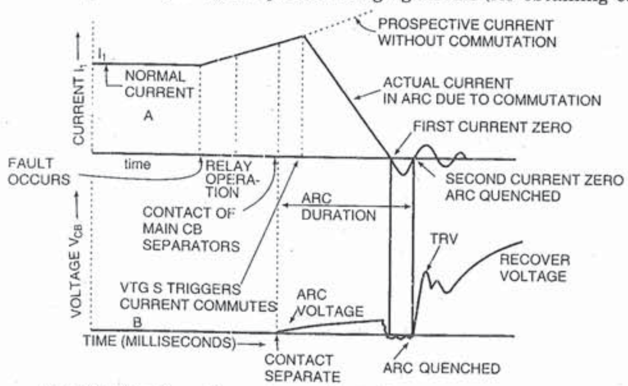


Fig. 16.6. Waveform of current zero achieved by commutation principle.

The parallel L_p-C circuit is switched immediately after opening of the contacts of Main Circuit-breaker CB. This switching is achieved by closing of a switch S or by triggering a vacuum gap or a thyristor in place of switch S.

When switch S is closed, the capacitor C discharges through the circuit-breaker causing current i opposite to current I_1. Current i is oscillatory, the frequency of oscillations depend upon value of L_p and C.

The oscillations of i are superimposed on the main current I_1, thereby producing several artificial current zeros in the main current I_1. These current-zeros are created during the arcing state in the main circuit-breaker (Fig. 16.6).

The current I_1 is interrupted by the main circuit-breaker at a suitable current zero (Fig. 16.6).

The rate of rise of TRV depend upon the dI_1/dt at current zero. The dI_1/dt is reduced by proper selection of C and L_p. The rate of TRV is also reduced by connecting ZnO arrester, and capacitors across the interrupters of the main circuit-breaker.

The final current zero in the main circuit-breaker (CB) does not stop the current. The current is now commuted to the parallel circuit. However, the capacitor C offers an open circuit to steady direct current and the direct current in the main path dies down on its own. The principle of HVDC circuit-breaker described above is called *Commutation Principle* as the current is commuted from main circuit to parallel path for achieving artificial zeros.

16.9. CONTROL OF dI/dt and dv/dt

Interruption of direct current is not simply a problem of creating artificial current zero. The circuit-breaker should be capable of withstanding the TRV. For comparison with A.C. circuit-breaker, the rate of change of current in an a.c. circuit-breaker for breaking 40kA is of the order of 20 A/μ sec. Whereas the rate of change of current in a d.c. circuit-breaker for interrupting 5000 A would be around 1000 A/μ sec.

To reduce dI/dt and dV/dt the following steps are taken in HVDC circuit-breaking system :

— Additional saturable reactor (L_{SAT}) is connected in series with the Main Circuit-breaker to reduce dI/dt prior to current zero.

— A combination R-C_1 is connected in parallel across the interrupter to reduce the dV/dt after zero.

— Resistance R is connected across load side through S. Each circuit-breaker has a limitation of withstanding the TRV stresses depending upon the properties of extinguishing medium and the flow pattern within the interrupter (Refer Ch. 4). Hence besides commutating circuit, there should be provision in the switching system to reduce dI/dt before final current zero and dV/dt. For reducing the severity of stresses on the circuit-breaker, switching stress factor F should be low. The interrupters which can withstand higher factor F are more suitable for HVDC main circuit-breaker.

$$F = \frac{dI}{dt} \times \frac{dV}{dt} \qquad \text{...(16.4)}$$

where F = Switching stress factor (watt/sec^2)

dI/dt = rate of change of current (A/sec)

dV/dt = rate of change TRV after final current zero, (V/sec).

Since the current in the inductance cannot change instantaneously, the saturable reactor reduces dI/dt, since the voltage across the capacitance cannot change instantaneously, the capacitance reduces the dV/dt.

16.10. TRIGGERED VACUUM GAPS (TVG)

Since the commutation process should be established immediately after contact separation, conventional make switches are not convenient for switch *S*. Triggered vacuum gaps are preferred. These are vacuum gaps with a third electrode (trigger). When a pulse is given to the trigger, the vacuum gap breaks down giving a conducting path (Fig. 16.7).

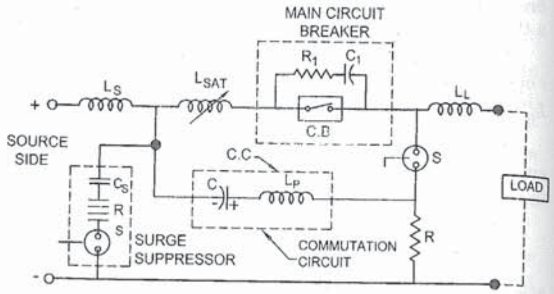


Fig. 16.7. Modification of basic circuit of dampen dI/dt and dV/dt.

16.11. SURGE SUPPRESSION

The current chopping by D.C. circuit-breaking (forced current zero prior to artificial current zero) can cause increase in voltage. To limit to such voltages, surge suppressor are necessary on both sides of the circuit-breaker. The *surge suppressor* is a combination of suitable non-linear resistor in series with capacitor and a vacuum gap. Now ZnO Arresters are used in addition to the surge suppressors.

16.12. COMPLETE CIRCUIT OF HVDC SWITCHING SYSTEM

Summarising, the complete HVDC circuit-breaking scheme comprises the following components (Fig. 16.7) :

— Main circuit-breaker (CB) with R_1 and C_1 in parallel with the interrupters for reducing dV/dt after final current zero.

— Saturable Reactor (L_{SAT}) in series with CB for reducing dI/dt before final current zero.

— Parallel series circuit containing triggered vacuum gap *S*, pre-charged capacitor *C* and reactor L_p for producing artificial current zero after contact separation in CB.

— Surge suppressor (SS) containing triggered vacuum gap in series with non-linear resistor, capacitor and parallel ZnO Arrester.

16.13. MAIN CIRCUIT-BREAKER FOR HVDC SWITCHING

The main circuit-breaker (CB in Fig. 16.7) has following functional requirements :

— It should be able to open and close the normal currents and fault currents in conjunction with the other components in the switching system.

— The short-circuit currents should be interrupted in minimum time.

— Overvoltages should be minimum.

— High switching stress withstand capability.

The main circuit-breaker is subjected to much more severe temperature stresses than conventional A.C. circuit-breakers because energy to be dissipated in the D.C. arc is much larger than A.C. arc (Refer Eq. 16.3). In A.C. circuit-breakers, the energy dissipated in the arc (Refer Ch. 4) is low as the arcing time is only of the order 10 to 20 milliseconds and during the period the current varies sinusoidally. Arc resistance is also not increased deliberately. Whereas in main DC circuit-breaker, part of the energy in inductance is dissipated in the arc.

DC circuit-breaker should be able to withstand high switching stress factor *F* (Refer Eq. 16.4). The following circuit-breakers have been successfully tried in HVDC experimental systems :

— Air-blast circuit-breaker. — Minimum oil circuit-breaker.

— Minimum oil circuit-breaker with pumping feature or with pressurised chamber (Refer Sec. 8.4).

Minimum-oil circuit-breakers can withstand high rate of the TRV and initial TRV. Hence they are suitable for HVDC. However, they have inherent disadvantage that the arcing time is dependent on current.

Vacuum circuit-breakers have basic advantage of very high rate of dielectric recovery. However, they have a limitation of lower voltage per interrupter. Hence they are not preferred for HVDC.CB.

SF_6 CB are sensitive to initial TRV (ITRV) during first microsecond after current zero. Hence they are not preferred for HVDC-CB.

16.14. SWITCHING DEVICES IN PRESENT BIPOLAR HVDC SUBSTATIONS

The change over from Bipolar mode to Monopolar mode necessitates both convertor control and switching arrangements on DC side. HVDC yards have following DC switching devices.

1. Medium voltage HVDC circuit breaker in neutral bus circuit to transfer earth return current to metallic return current. Such a circuit breaker has high normal current rating (1000 A to 2000 A) and medium DC voltage rating.

2. **HVDC Isolator Switches.** These are designed to open HVDC circuits after the current is brought to zero by convertor control.

3. **Earth switches.** For discharging dead circuits to earth for safety.

The DC voltage Ratings, Normal current Ratings, Breaking current rating and speed (time) of the above are quite different. But present systems do not have any HVDC circuit breaker in main pole to break full short-circuit in DC poles at rated DC voltage. Present schemes have following arrangements in the event of a fault on HVDC side.

If a fault occurs on HVDC pole side, the convertor control acts rapidly and the fault current is reduced rapidly by putting rectifier into invertor mode. The line is de-energized within about 120 ms.

After about 120 ms the re-energizing is attempted. If the fault is permanent, the complete faulty pole is removed from service by blocking the convertor bridges and tripping AC circuit-breakers feeding that pole.

This principle is followed in present 2 TDC and MTDC systems. Hence present 2 TDC and MTDC systems do not need HVDC circuit-breaker of high interrupting ability. Present HVDC systems use HVDC circuit breaker of low interrupting ability for transfer between earth return and metallic return.

As the DC fault current is rapidly and automatically controlled by convertor control, real need of HVDC circuit-breaker for interruption of HVDC fault currents is being questioned, debated and doubted. Even the recent MTDC systems are without HVDC CB for fault current interruption and depend on convertor control for operation and protection.

In case the pole is to be tripped, the tripping is from AC side by tripping AC circuit breakers on the AC network side of convertor transformers which feed the pole.

The bipolar HVDC system is divided into two poles for the purpose of protection and control. In the event of a permanent fault on one pole, almost half the rated bipolar power continues through the Monopolar operating Mode with either earth return or metallic return. The convertors of each pole are provided with on-line microprocessor based controls.

As the basic requirements of operation, control and protection are performed essentially by the convertor control system and tripping can be performed for the faulty pole from AC side by AC circuit-breakers associated with the faulty pole, *the lack of HVDC circuit-breakers has not posed any limitation to 2TDC systems or MTDC systems.*

16.15. TYPES OF HVDC CIRCUIT-BREAKERS

The types of circuit-breakers are identified with reference to

— switching time — current to be interrupted

— switching energy — voltage at which the current is interrupted

— voltage (TRV) after current interruption.

The current to be interrupted by HVDC circuit-breaker depends upon the (1) Switching time (2) Action of convertor control (3) Short-circuit ratio of HVDC system with respect to AC Networks.

Two extreme cases of HVDC circuit-breaker applications are

1. **Ideal high capability HVDC circuit-breaker** associated with ideal protection system which is so *fast* that the DC current is suppressed and interrupted immediately after occurrance of fault within shortest possible time (app. 15 ms) before the current has time to rise to full value (30 to 40 ms.)
2. Low capability HVDC circuit-breaker which is capable of interrupting lesser value of DC fault current at lesser voltage at the time when the DC fault current and DC voltage has been de-energized.

Practical HVDC Circuit-breakers (Proposed-1986)

The **Practical proposed HVDC circuit-breakers** (for which prototypes have been successfully tested) have a capability to interrupt DC currents at DC voltage; in between the two extreme cases that

— the breaker is not interrupting the current immediately on occurrence of fault.

— The breaker comes into action before the convertor control brings down the fault current and voltage to zero.

The proposed practical HVDC circuit-breaker have certain specified capability to interrupt HVDC currents at certain specified HVDC system voltage and Transient Recovery Voltage (TRV) such proposed practical HVDC circuit breakers are classified into two categories called A-type and B-type.

Type-A Breaker is fast and does not depend on converter control action.

Type-B Breaker is slow and depends upon convertor control to act before the current interruption is initiated. Type-B is further divided into Type **B1 and B2.** Type B-1 Breaker has full voltage capability and TRV capability. Type B-2 Breaker has limited capability with respect to system voltage and TRV withstand.

Table 16-1-B. Classification of Proposed Practical HVDC Circuit-breakers (1986)

Class of HVDC Breaker	*Operating time*	*Characteristics*
1. **Type 'A' HVDC Circuit-breaker**		
— High current and voltage capability and fast HVDC breaker. Breaker interrupts fault current before current peak. — Breaker does not depend on convertor control to reduce fault current.	— Less than 15 ms considerably shorter than usual AC breaker. — Breaker reduces fault current before the current reaches positive peak — Breaker quenches arc before the control of thyristor convertors bring down the DC current and voltage.	— Breaker capable of breaking peak DC fault current at rated voltage and rated TRV — Breaker requires very high energy absorption capability — The demand on convertor control is reduced.. — Breaker very complex and costly.
2. **Type 'B-1" HVDC Circuit-breaker**		
— Breaker with reduced current interruption capability and full voltage capability — Breaker operates after the current is brought down by convertor control — Breakers has full voltage capability and TRV capability	— 60 to 90 ms	— Breaker is simpler than type A breaker. — Breaker depends on convertor control to reduce fault current. — Breaker takes lesser time than Type B-2. — Compromise between complex control and complex breaker.
3. **Type 'B-2' HVDC Circuit-breaker**		
— Breaker with minimum voltage capability, TRV capability and current capability. — Breaker operates only after DC current and voltage are brought to low value by convertor control.	— 90 to 120 ms	— Breaker simpler and least costly. — Breaker least useful — Controls are costly and complex. — Time required for restoration of system after temporary line faults is very long (150 ms).

16.16. HVDC Circuit-breaker Capabilities and Characteristics

These include the following :

— Voltage capability

— Current interruption capability

— Switching time.

— TRV capability

— Energy absorption capability

Each of these characteristics has a significant influence on the performance of the circuit-breaker individually and simultaneously. These characteristics also influence the behaviours of the HVDC system at the time of the breaker action. Therefore the requirements of the characteristic of the optimum. Circuit-breaker are determined by the system operating strategy with respect to energizing and de-energizing sequence during and after a fault.

In DC circuit-breaker the current is artificially brought to zero since DC current has no natural current zero. The current suppression generates a voltage transient. The prospective peak value of voltage transient depends on the rate of suppression of current (dI/dt) and inductance L in the DC circuit.

Besides the current zeros, there is another major difference between AC and DC systems. *In HVDC system, current and voltage on DC side is routinely controlled by the convertor control.* The same controls can be used to assist the circuit-breaker in its interrupting process by reducing the DC voltage and DC current when the breaker operates. In the limit it is possible to open the DC circuit-breaker at zero current and zero voltage, after an elapsed time of the order 120 ms (Type B-2 Breaker).

The required voltage and current capability of HVDC circuit-breaker is therefore associated with the questions "whether the control is assisting the breaker or not?" and "to what degree are the controls assisting the breaker". *In other words "what is the sequence of time events with reference to occurrence of fault, action of controls to reduce fault current and pole voltage and operation of HVDC breaker ?".*

Therefore there are *opposite demands* on (1) complexity of controls and (2) complexity of HVDC breaker. The choice is made after making a *compromise* between them in economic and technical terms.

A closed HVDC circuit breaker is designed to carry maximum load current continuously and fault current for short-time. When a fault occurs on HVDC line or Tap-off, the DC current starts rising rather rapidly before the convertor control comes into action. The rate of rise of HVDC fault current (dI/dt) depends upon the value of prevailing system voltage and inductance (L) in the system. HVDC side has large inductance due to smoothing reactors and the series inductance of HVDC line. The convertor control acts and reduces the current to 5 per cent of rated current and reduced DC voltage to low value (LVDC). Therefore of opening of HVDC breaker is delayed, relatively low current interruption is required (5 to 15% of Normal Load Current).

Alternatively if the HVDC breaker operates fast enough (less than 15 ms) before the DC fault current reaches the prospective peak, the interruption rating can be modest. However for such a scheme, fast protective system (detecting time of only a few ms) and a fast circuit-breaker (less than 10 ms) must be used.

16.17. DEFINITIONS OF SWITCHING TIME FOR HVDC CIRCUIT-BREAKERS

Between the instant of occurrence of DC fault and final current interruption by HVDC circuit-breaker the switching time has following component times :

1. Time to sense the abnormal condition (fault) and to send trip signal to circuit-breaker. This is called relay time.
2. Time to open circuit-breaker contacts. This is called opening time of CB.
3. Time to commute the current out of the arc and subsequently to reduce the current to zero.

In some circumstances, time to restore the system on the healthy pole should be added to the above. If the circuit breaker has limited voltage capability, full power cannot be restored on healthy pole unless the isolators (disconnecting switches) open and isolate the breaker. In such a case, the following time must be added.

4. Time for opening disconnector switches. The healthy pole can be energized and full power can be restored after a total time given by addition 1 to 4 above.

16.18. SHORT-CIRCUIT RATIO (SCR) OF HVDC SYSTEM

Short-circuit ratio of HVDC system is defined as the ratio of fault MVA of the AC system at the connection point of HVDC system to the rated capacity of line.

$$SCR = \frac{\text{Fault MVA of AC system}}{\text{Rated MW Capacity of DC System}}$$

SCR indicates the strength of AC system at the point of connection of HVDC substation. (Ref. Sec. 20.14)

Effective Short-circuit Ratio (ESCR)

It is defined as the ratio which includes fault MVA including contribution of AC harmonic filters. ESCR is now more commonly used. The performance of HVDC link is associated with the strength of the connected AC systems. SCR and ESCR give a measure of the strength of connected AC system. The AC systems are called strong, weak etc. as follows :

AC system	*SCR*	*ESCR*
Weak system	< 3	< 2.5
Strong system	> 6	> 5

16.19. Conclusions

1. HVDC circuit-breakers are classified into four categories :

(*i*) Low voltage Metallic Transfer Breaker

(*ii*) Type A Breaker which does not depend on control actions

(*iii*) Type B1 Breaker which depends on control action but has high voltage capability.

(*iv*) Type B2 Breaker does depend on control action and has no high voltage capability.

2. HVDC Breakers are likely to be used for a switching off parallel taps.

3. Though the HVDC C.B. have been developed, their use in HVDC systems is not envisaged.

For Further Reading :

1. Book : "EHV AC and HVDC Transmission Engineering and Practice" Khanna Publisher, Delhi (2nd Ed. 1996).
2. Ch. 47, Fig. 47.19, 20, 21, and sec 20.14.

QUESTIONS

1. With the help of sketches, explain the principle of Artificial Current Zero Circuit adopted in DC circuit breaking.
2. Draw a schematic of a two-pole two terminal HVDC System indicating main components. Explain why HVDC Circuit Breakers are not necessary.
3. Explain the configurations of a multi-terminal HVDC System without a HVDC Circuit Breaker.
4. Explain the function of Metallic. Return Transfer Breaker in a typical Bipolar Two Terminal HVDC System.
5. Discuss why HVDC Circuit Breakers are not necessary in HVDC Transmission System.

17

Electrical Substations, Equipment and Bus-bar Layouts*

Introduction — Connections — Bus-bar arrangement — Single bus-bar systems — Duplicate bus — Ring bus — Sectionalizing — Generator connections — Classical system — Unit system — Direct generator switching — Multiple generator transformer units — Layout of switching yard — Bus-bar design — Summary.

17.1. INTRODUCTION

The electric power system can be divided into the following regions :

1. Generating stations 2. Transmission systems 3. Receiving stations
4. Distribution systems 5. Load points.

In all these regions need switchgear. Busbars are conducting bars to which a number of local feeders are connected. Bus-bar operate at constant voltage. Busbars are insulated from earth and from each other. Besides the bus-bars there are other equipment in the electrical schemes such as circuit-breakers, current transformers, potential transformers etc. These equipments can be installed according to various schemes depending upon requirements. The total plant consists of several equipment.

The Substations have following distinct circuits :

1. *Main Circuits.* Through which power flows from generators to transmission lines. The components *in series with the main circuit of power flow* include : Busbars, Power Transformers, Circuit Breakers, Isolators, Current Transformer CT, Line Trap Units, Series Capacitors, Series Reactors, Diode or Thyristor Rectifiers. The components *in shunt circuits connected phase to ground* include Shunt Capacitors, Shunt Reactors, Static VAR Sources, Harmonic Filters, Voltage Transformers, Surge Arresters.

1. *Bus-bar and conductor systems* are of following alternatives :

— Tubelar or Solid Aluminium or Copper Conductors supported on Porcelain or epoxy insulators.

— Isolated Phase Busducts

— Flexible ACSR stranded conductors.

— Single core or Multicore Power cables through trenches.

2. *Auxiliary Power Circuits* through which power flows to Substation Auxiliaries. The supply conductors are generally Power Cables.

3. *LV Control Circuits* Measurement, Protection, Control, Monitoring, Communication Circuits. SCADA and Computer/Microprocessors. The supply conductors are generally of Control Cables.

4. *Auxiliary Low Voltage AC and Low Voltage DC Supply Circuits.* The conductors are generally of power cables or solid busbars.

Main Circuit and Equipment are described in Sec. 17.2 to 17.28.

* Refer following books by Khanna Publishers for more details :
— Electrical Substation Engineering and Practice, S. Rao
— Power Transformers and Special Transformers, S. Rao,
— EHV AC and HVDC Transmission Engineering and Practice, S. Rao.