Power Electronics in Electric Utilities: HVDC Power Transmission Systems

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Invited Paper

High Voltage Direct Current (HVDC) power transmission systems constitute an important application of power electronics technology. This paper reviews salient aspects of this growing industry. The paper summarizes the history of HVDC transmission and discusses the economic and technical reasons responsible for development of HVDC systems. The paper also describes terminal design and basic configurations of HVDC systems, as well as major equipments of HVDC transmission system. In this regard, the state-of-the-art technology in the equipments constructions are discussed. Finally, the paper reviews future developments in the HVDC transmission systems, including promising technologies, such as multiterminal configurations, Gate Turn-Off (GTO) devices, forced commutation converters, and new advances in control electronics.

I. Introduction

From the beginning of electric power history, dc transmission lines and cables have been less expensive than those for three-phase ac transmission. Alternating current, however, has been more advantageous than direct current for generation, low-voltage distribution, and electric power consumption. Therefore, to utilize the savings that dc transmission offers, generated ac power must be converted to dc at a converter station and transmitted over a dc line to another converter station, where it is converted back to ac. The lack of reliable high voltage power conversion equipment made application of dc systems impractical until the mid-1950s, when the development of the high voltage mercury arc valve resulted in a commercially competitive position for HVDC transmission.

Over the years, many attempts have been made to develop converters for HVDC transmission. The best known was developed by Thury in 1889. Thury's system was used in Europe from 1890 to 1937. It consisted of combinations of ac/dc generators and motors connected in series on the dc side and parallel on the ac side. Later on, converters based on mechanical switches were tested in England and Sweden in the 1920s and 1930s. In the United States, the General Electric Company built converters for dc transmission during the 1930s. These coverters used mercury arc valves with relatively low ratings, and were in operation from 1937 to 1945. The first commercial dc installation, which remains in operation today, was the Gotland transmission system in Sweden, commissioned in 1954.

Toward the end of the 1960s, solid-state semiconductor technology was introduced to HVDC converter systems. The first thyristor converters were commissioned around 1970 in the Gotland scheme as a commercial extension and in Sakuma, Japan, as an experimental back-to-back installation. In 1972, the world's first all solid-state HVDC system was commissioned at Eel River in New Brunswick, Canada, rated at 360 MW.

During the 1970s and 1980s, numerous HVDC transmission systems have been constructed throughout the world. Fig. 1 shows the installed, committed, and studied HVDC system capacity worldwide. The primary reasons for growing number of HVDC applications are economical and technical benefits as described below:

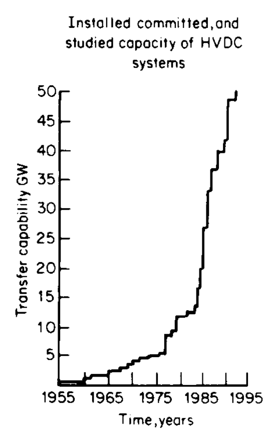

Fig. 1. The economic and technical advantages offered by HVDC have resulted in increased utility interest in HVDC transmission. Since 1983, 12 GW of HVDC systems have been installed and are operational, 20 GW are committed (orders placed and/or under construction), and 18 to 50 GW of HVDC systems are actively being studied.

Economical: HVDC systems are often more economical

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than the ac alternative. For the system with long overhead transmission lines, the lower cost of dc transmission lines offsets the higher costs of the converter terminals. There is no universally applicable breakeven distance, since the economical comparison between dc and ac alternatives depends largely on local conditions, such as required performance of the transmission system and properties of connecting ac systems. Studies show that under typical conditions it is advantageous to consider dc for overhead lines when the transmission distance is 500 km or more. In areas with high cost for right-of-way, HVDC transmission becomes advantageous even at a shorter distance.

For cables, the break-even distance is about 30 km. This is due to the fact that higher voltage ac cables require excessive capacitive charging currents. Underground cables can be compensated by intermediate costly shunt reactors. However, this solution is not practical for submarine cables. DC cables have no steady-state capacitive charging currents; thereby, do not require any shunt compensation.

Technical: HDVC systems offer significant technical benefits and performance characteristics that are not achievable with ac transmission systems. Those include asynchronous interconnections between two large ac systems, control of power flow, and power modulation control to enhance system operation. It should be noted that interconnection between two large power systems is often desirable because of economic reasons, such as sharing spinning reverses and taking advantage of less expensive energy sources. However, maintaining a stable weak ac connection between two large, independently controlled power systems is technically difficult and often impossible, whereas, an asynchronous HVDC tie is a practical approach. In addition, the asynchronous nature of a dc link allows interconnection of power systems with different nominal frequencies. In this regard, a potential application of HVDC systems is in pump storage stations, where the hydraulic systems may be run at variable speeds for maximum efficiency.

DC transmission links may be used to supply power to remote systems, such as islands. The power control feature of the link can then be used to advantage to control the island frequency.

II. Terminal Design and System Configuration

A. Terminal Design

The HVDC terminal is an integral part of the HVDC system. It provides the basic system function—conversion of ac to dc or vice versa. When a terminal converts ac to dc, it is referred to as a "rectifier" terminal; when it converts dc to ac, it is referred to as an "inverter" terminal. For simplicity, and since most terminals today are designed for both modes of operation, either terminal can be referred to as a "converter" terminal. The converter terminal is defined as an operative unit comprised of the following major components:

- converter (value) and its controls,
- converter transformers,
- reactors,
- filters,
- reactive power supplies,
- protective, monitoring, measuring, communications, and auxiliary equipments.

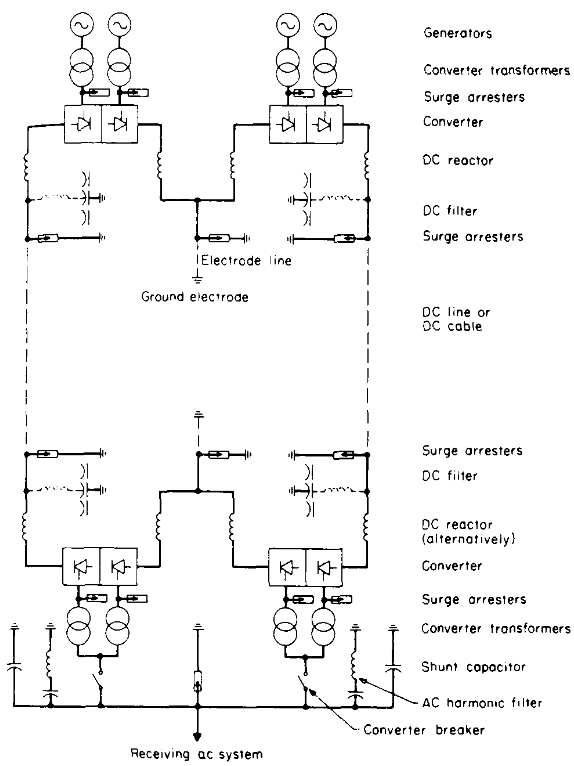

Fig. 2. A transmission arrangement with the sending end at point of generation, the receiving end connected to an ac system via a bipolar dc line, and ground return is used as a spare conductor.

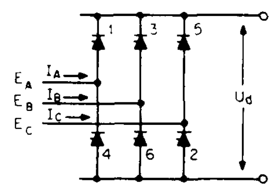

Fig. 3. The 6-pulse Graetz bridge is the basic building block for the ac/dc/ac conversion process.

Fig. 2 shows major elements of a bipolar dc transmission system. The 6-plus Graetz bridge (Fig. 3) is the basic building block for the ac/dc and dc/ac conversion process. Each 6-pulse bridge consists of six elements. Each element represents an optimized number of solid-state thyristors connected in series, and sometimes in parallel, to form a solid-state valve.

The dc output voltage of a 6-pulse bridge contains even voltage harmonics of order 6, 12, 18, $\cdots$, $6n$, while the valve side ac current contains odd current harmonics, 5, 7, 11, 13, $\cdots$, $6n \pm 1$. Unless these harmonic voltages are filtered, they will flow into the ac system and the dc line, and can cause voltage distortion and telephone interference.

A 12-pulse converter consists of two 6-pulse bridges in series. The two are identical except that the ac supply voltages of the two are shifted in phase by 30°. This is usually accomplished by supplying one bridge with a wye-wye transformer and the other with a wye-delta connection (Fig. 4). As a result of this 30° phase shift, certain harmonics are

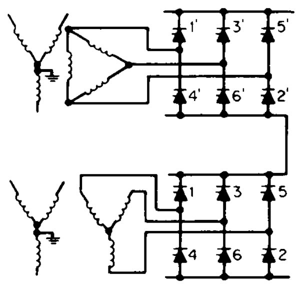

Fig. 4. The 12-pulse converter consists of two 6-pulse bridges in series.

canceled out, thus leaving even voltage hamonics on the dc side of the converter of order 12, 24, 36, · · · , 12*n*, and odd current harmonics on the ac side of the converter of order 11, 13, 23, 25, · · · , $12n \pm 1$. This reduction in filter requirements is a major reason why almost all modern solid-state HVDC systems operate as 12-pulse only.

B. System Configurations

In HVDC transmission, ground return can be used to advantage as a conductor if current flowing through ground is not objectionable. That is, each separately insulated transmission conductor, together with the ground-return path, would form a separate electric circuit. When ground current is objectionable, a dedicated metallic return is used instead. Utilizing this fundamental principle, the following basic transmission configurations can be considered.

Monopolar Arrangement: In this configuration, only one transmission pole is installed. Ground return is permanently used, as shown in Fig. 5. Monopolar transmission is

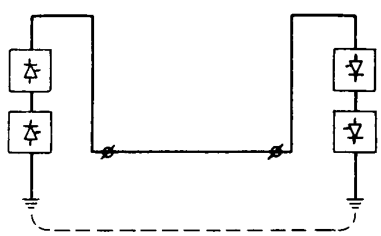

Fig. 5. Direct current monopolar transmission arrangements are used in systems of comparatively low power rating.

often used in systems of comparatively low power rating, primarily with cable transmission.

Bipolar Arrangement: It is mechanically not suitable to design an overhead-line tower for two insulated conductors, one suspended on each side of the center post. These can be arranged as plus and minus poles in bipolar transmission, as shown in Fig. 6. In bipolar transmission, ground return in not necessarily used, but is normally provided to increase the transmission availability in case of pole failure.

Homopolar Arrangement: A two-polar tower design can also be used in a homopolar transmission where both poles have the same polarity. Owing to reduced corona, the use of the homopolar arrangement can also be considered for very large overhead transmission systems where two bipolar circuits are used and the insulator chains of each tower

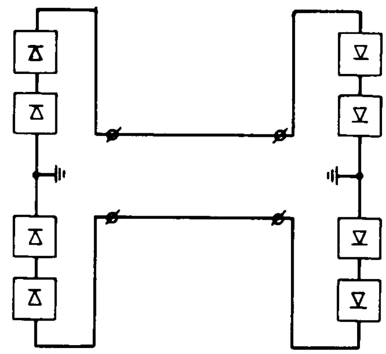

Fig. 6. Direct current bipolar transmission arrangements take advantage of the fact that towers are mechanically most studied for two insulated conductors.

are carrying two separate conductors with the same polarity (shown in Fig. 7).

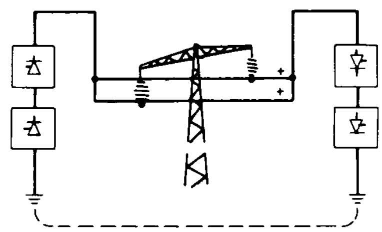

Fig. 7. Direct current monopolar transmission arrangements can be considered for very large overhead transmission systems where two bipolar circuits are used. The figure shows only one-half of a bipole.

III. Equipment Characteristics

HVDC systems are comprised of a variety of equipments, many of which are similar to those used in ac systems. The key equipments, particular to HVDC systems, are described in this section.

A. HVDC Valves (Converters)

The main requirements of an HVDC valve for power transmission are:

- low forward voltage drop during conduction,
- ability to withstand high negative and positive voltages without breaking down,
- controllable firing instant, and
- overcurrent capability to withstand internal and external faults.

Different types of equipment to fulfill these requirements have been used in commercial installations. Prior to 1970, mercury arc multigap technology was used in valve construction. In 1972, the first converter station composed entirely of thyristor valves went into operation. Since 1975, new converter stations have used only thyristor valves.

A thyristor is described by IEC and IEEE as: "reverse blocking triode thyristor," being a three-terminal (anode, cathode, gate) semiconductor device. It is functionally a unidirectional current flow switch. Over the years, thyristor voltage and current ratings have increased from approximately 200 V and 50 A in 1958 to the present ratings of about 6 kV and 3000 A.

The typical thyristor package consists of the silicon semiconductor wafer encapsulated in a disc-type porcelain package. The metal faces of the package are clamped under pressure to heat dissipators (either air or liquid cooled) as shown in Fig. 8. The metal faces are also the thyristor anode and cathode connections.

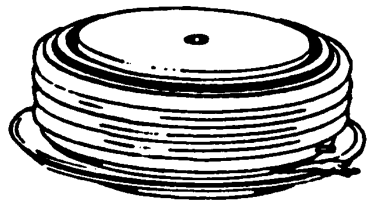

Fig. 8. Typical thyristor package for HVDC applications.

The major power loss in a thyristor occurs due to "spreading" phenomena. That is, when the thyristor first turns on, only a small portion of its junction area conducts. The area of conduction spreads with time until maximum conduction area is reached. The power loss occurs during the spreading period and is more pronounced in larger area thyristors. Also, a minor power loss occurs when the thyristor is not conducting. This minor power loss is due to leakage currents from the impressed voltage on the thyristor.

1) Thyristor Valve Circuits: Thyristor valves consist of series and parallel connection of thyristors and other valve circuit components. The number of series-connected thyristors varies from 20 to 150 thyristor levels, depending on the voltage ratings of the valve and thyristor. Parallel connection of thyristors is often used when the required valve rating exceeds the current capability of a single thyristor.

Valve circuits vary between valve manufacturers. All valve circuits contain saturable reactors connected in series with the thyristors. The reactor must control the initial rate of change of the thyristor current and minimize the effect of time variations between each thyristor turn-on. Valves also contain snubber circuits (series connection of resistors and capacitors) to control voltage distribution within the valve, and the valve voltage transient that occurs when the thyristors turn-off.

Valve protective circuits protect the thyristor levels from excessive applied voltages (auxiliary gating and voltage breakover circuits), while a status monitoring circuit in the valve indicates the thyristor levels that have become short-circuited during operation. Fiber-optic light guides may be used to provide a communication link between the valve and ground potential for status monitoring and valve gating (turn-on of the valve).

Thyristors and auxiliary circuits are usually arranged in modules, and are connected in series to make up a valve. Valve modules generally contain two to 12 series connected thyristor levels. The valve module has the same electrical properties as the complete valve, except at a reduced voltage rating. The valve module concept permits testing to a pro-rated stress encountered by the total valve in normal and abnormal operation. It is also easy to handle during installation and maintenance. Fig. 9 shows the valve module

Fig. 9. Comerford terminal valve module showing an eight thyristor series arrangement.

for the Comerford converter terminal comprising eight series thyristors.

The valve modules are connected in series in a valve structure to form a valve. The valve structure can contain as many as 12 valves, depending on the operating voltage. A common arrangement is a group of four valves in one valve structure with three valve structures forming a series connection of two Graetz bridge circuits as shown in Figs. 10 and 11. The advantage of such an arrangement is that the

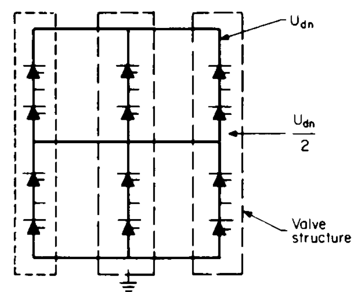

Fig. 10. A common arrangement of three valve structures, each containing four valves, to form a 12-pulse converter.

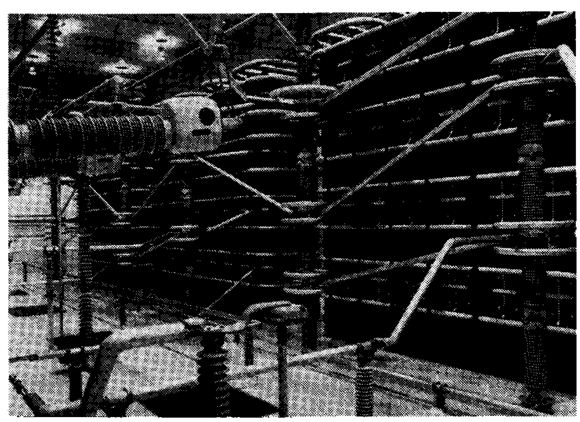

Fig. 11. One pole of the Comerford HVDC terminal. Pole rating: 345 MW, 450 kV.

valve operating at the highest dc voltage can be physically located the greatest distance from the ground plane, thus simplifying the electrical grading.

There are several combinations of valve insulation and cooling mediums as follows:

- air for both insulation and cooling,

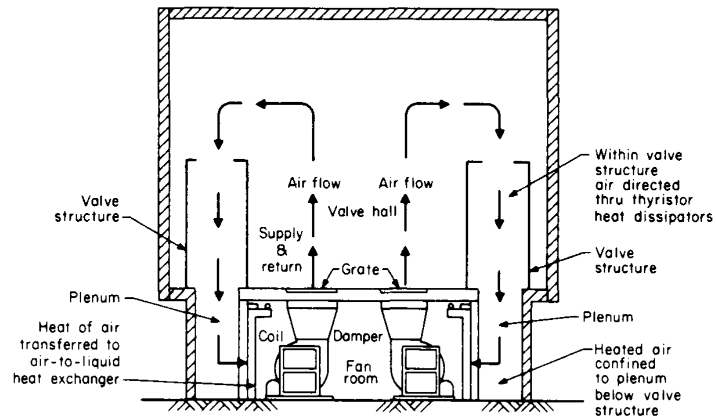

Fig. 12. The closed-loop cooling system, which simplifies control of contaminants in the loop, can be either air- or liquid-cooled.

- oil for both insulation and cooling,
- air for insulation and water, oil, Freon, etc., for cooling,
- SF_6 for insulation and oil, Freon, etc., for cooling.

Air insulation with air, water, or Freon cooling is the dominant design approach. Air insulation and cooling, however, is usually the simplest design. Other alternatives may offer a more compact valve design, although valve size is not a strong contributor to converter station size.

2) Valve Firing: Valve firing is the action of delivering a gating signal to the valve thyristors to initiate valve conduction. The typical approach is to provide a light pulse by a fiber-optic light guide to the valve. At the valve, a light-to-electrical interface provides the electrical signal to the gates of the individual thyristors. The firing system often includes redundant firing circuits for improved reliability. Complexity and energy requirements of the valve gating system can be reduced by the use of light-triggered thyristors.

3) Valve Cooling: The valve cooling system is an important part of the valve design, directly impacting the thyristor current capability. A closed-loop cooling system is often preferred, since it simplifies control of contaminants in the loop. The cooling medium can be either air or liquid. A typical arrangement for a closed loop air cooled valve is shown in Fig. 12. The air-to-liquid heat exchanger (coil) is part of the primary cooling system. The primary cooling system can reject its heat to the ambient air, a cooling tower, or a body of water, such as a lake or river. An ambient temperature or the converter power transfer changes during operation, the cooling flow rates can be controlled to obtain the lowest possible operating losses. The cooling system is generally designed to operate at the maximum ambient temperature.

B. Converter Control

The fundamental objectives of an HVDC control system are:

- to control a system quantity such as dc line current, transmitted power, or frequency of either of the two connected ac networks with sufficient accuracy and speed of response,
- to ensure stable converter operation in presence of small system disturbances, and
- to fulfill the above objectives at minimum reactive power consumption.

In addition to these items, the control system shall, if possible ensure correct operation at large disturbances, such as a fault, or at least minimize the consequences when the fault is cleared during normal operation.

In HVDC transmission, because of the rather small value of line resistance, the direct current will vary rapidly and drastically with small changes in the direct voltage difference between terminals. The widely accepted method for the control of the voltage difference is to change the ratio between direct voltage and alternating voltage by grid control, that is, change of the converter firing angle α. The firing angle α may be changed very rapidly by the grid control system.

To minimize the amount of reactive power consumed, it is usual to operate either the rectifier on minimum firing angle α, or the inverter on minimum margin of commutation γ. The latter operation mode is the normal one for the inverter where the value of γ is determined by the requirement for secure inverter operation without commutation failures even at reasonable disturbances in the ac system. A value between 15° and 18° is usually chosen for γ. A larger value would give a decreased risk for commutation failures, but simultaneously give increased stresses on the valves and increased reactive power consumption. The dc line voltage may then be adjusted by tap-changer control in the inverter. The current, and thus the transmitted power, may then be rapidly controlled by grid control in the rectifier, i.e., control of the rectifier direct voltage accomplished by means of firing angle control.

At steady-state operation, it is suitable to operate the rectifier with a firing angle of 15° to 18°. A smaller firing angle would give less demand for reactive power, but also would limit the ability to rapidly increase the rectifier voltage by decreasing the firing angle. As the direct voltage is established by the inverter, the suitable firing angle range for the rectifier may be obtained by tap-changer control in the rectifier.

1) Static Characterization of a Converter: Assume a converter with a basic constant-current control system with a current order I_{d1}. The converter is also provided with a constant γ control system, which prevents the margin of commutation angle from decreasing below the set value.

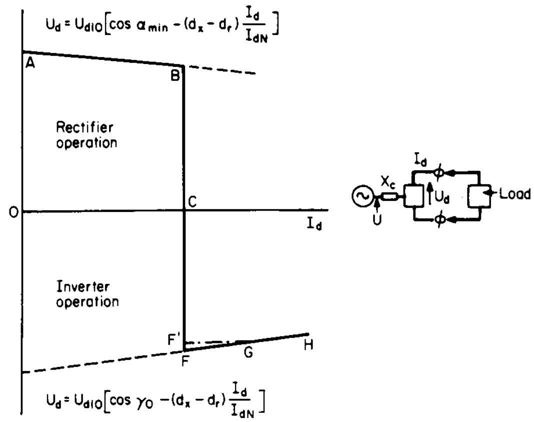

Fig. 13. Voltage current characteristics for a current-controlled converter are shown when the load is increased from zero.

Fig. 13 shows the characteristics for such a converter when the load is increased from zero. From point *A* to point *B*, the load could be assumed to be a resistance decreasing from infinity at point *A*. In this region, the load resistance is too high and the converter voltage too low for the converter to be able to deliver the ordered current. Therefore, the converter operates at the minimum limit value of the firing angle, which usually is set at 5°.

At point *B*, the resistance of the load has decreased to such a value that the desired current is achieved if the converter voltage has its maximum value. At a further decrease of resistance, the converter must increase its firing angle to keep the direct current at the value I_{d1}. This occurs in the region *B-F* where the converter operates in current-control mode.

At point *C*, the converter changes polarity and, if the overlap angle is neglected, has a firing angle equal to 90°. From this point, the converter operates as an inverter and the load must be active; for example, a direct voltage source in series with a resistor.

At point *F*, the firing angle α has increased to a value where the margin of commutation has reached its minimum value, γ_0, and the γ control system takes over. The point *F* represents the point at which the inverter has its maximum voltage.

From *F* through *G* the margin of commutation is kept constant. Thus, when the voltage of the load, and thus the direct current and the overlap angle *u* of the converter, is increased, the converter direct voltage is decreased. This gives the converter a characteristic in this region corresponding to a negative resistance.

From this discussion, the following modes of operation for a converter may be summarized:

- Rectifer operation against the minimum firing angle (from *A* to *B*). This occurs when the converter voltage is not high enough to generate the desired current.
- Constant current control (between *B* and *F*). There are no principle differences between rectifier and inverter operation.
- Control on constant margin of commutation (from *F* and further). This is the normal inverter mode of operation.

2) Control Coordination: Consider a two terminal HVDC transmission system. The terminal with index 1 is operating as rectifier and the one with index 2 as inverter.

The rectifier has the characteristic *A-B-C* of Fig. 13 and the inverter is principally represented by the characteristic *C-F-G*. The inverter is, however, given a current reference I_{r2} slightly less than the rectifier reference I_{r1}. The difference ΔI between the rectifier and the inverter current reference is called the current margin and is normally in the order of 10 to 15 percent of related current.

The coordination between the rectifier and inverter terminals with characteristics as defined above is illustrated by Figs. 14 and 15. The dc line voltage drop can either be

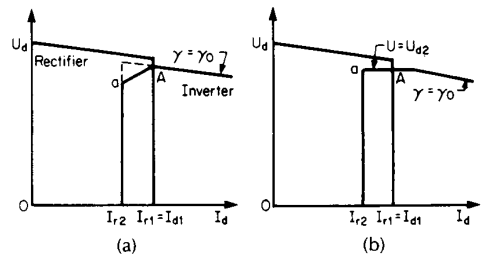

Fig. 14. Direct voltages are plotted against the direct current with higher maximum voltages on the rectifier side.

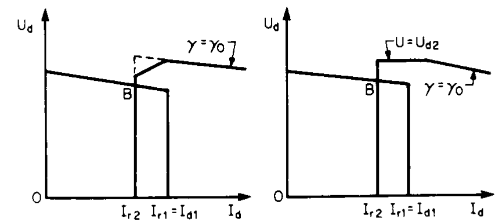

Fig. 15. Direct voltages are plotted against the direct current with higher maximum voltages on the inverter side.

neglected or included in any of the characteristics for the terminals.

In contrast to Fig. 13, where the line voltage has been defined as positive for rectifier operation, the inverter characteristic has been defined as positive for inverter operation in Figs. 14 and 15. The figures also indicate that the inverter characteristic has been slightly modified by cutting the sharp corner (*A* in Fig. 14(a)). This measure may be taken to avoid an undefined intersection between the rectifier and inverter characteristics if they coincide or nearly coincide at voltage deviations in either or both of the connected ac networks.

Fig. 14 depicts the usual operation mode with minimum firing angle in the rectifier giving a higher direct voltage than the minimum extinction angle in the inverter. The interconnection point *A* between the two characteristics defines a stable operation point. The direct voltage is determined by the inverter and the current by the rectifier. If the alternating voltage is decreased in the rectifier terminal or increased in the inverter terminal, the condition may change in such a way that the inverter takes over the current control as depicted in Fig. 15 operation point *B*. With more than one converter connected in series, such a transition will also occur when one rectifier is disconnected (blocked) or when another inverter is connected in series (deblocked).

The reason for introducing a margin between current orders in the rectifier and inverter becomes obvious from the two figures, as zero margin or a negative margin would not have given any stable operation point.

A change of power-flow direction for an HVDC transmission is usually performed by a polarity change of the line voltage. This is illustrated in Fig. 16 where the complete converter characteristics have been drawn for both stations. The initial operating point is A and the current margin is ΔI. If the latter is removed in station 2 (initially inverter) and the current order in station 1 is reduced by the amount ΔI, the broken line characteristics will be valid and the new operation point B is obtained. Thus, the dc line has changed polarity and the two converter stations have changed mode of operation.

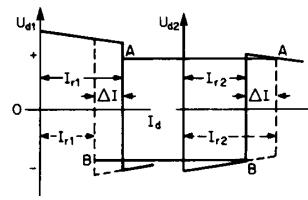

Fig. 16. A change in power-flow direction for an HVDC transmission is usually performed by a polarity change of the line voltage.

In practice, the reversal of power-flow direction also requires other operations, such as switching the minimum limit of α from about 100° for the inverter to about 5° for the rectifier and vice versa.

3) Closed-Loop Current Control: The rectifier normally is provided with a basic feedback current control system, simply illustrated by Fig. 17. The control amplifier is used to give suitable static gain and dynamic compensation for stabilization of the control loop. Control pulses are generated by the firing control system and transmitted to valve potential by the valve control system (assumed included in the valve bridge symbol in Fig. 17). Firing control system designs may differ considerably between manufacturers, but they belong mostly to one of two types: the individual phase control system and the equidistant firing control system.

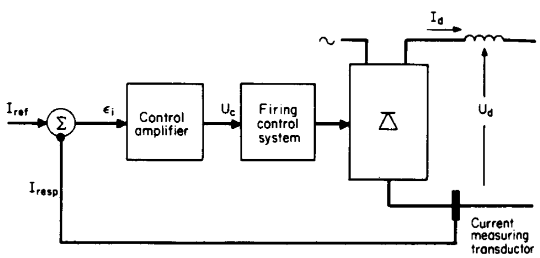

Fig. 17. Simplified block diagram for a constant-current control system.

In the individual phase control system, the valves connected to the same phase are controlled separately from other valves. Design of such a system involves comparison of the output voltage from the control amplifier and a monotonically increasing voltage which starts at the zero crossing of the commutation voltage corresponding to $\alpha = 0$. At equality between the two voltages a control pulse is generated to initiate the firing of the valve.

Individual phase control is the traditional control method for HVDC converters. It was used prior to the Pacific HVDC Intertie transmission, which began operation in the late 1960s. In later HVDC applications, however, the equidistant control principle has been primarily used.

The basic element of an equidistant firing control system is a voltage-controlled oscillator. Its frequency in steady-state is equal to the product of the pulse number of the converter and the fundamental frequency of the ac network. The output frequency is controlled by the input voltage U_c from the current control amplifier as shown in Fig. 18.

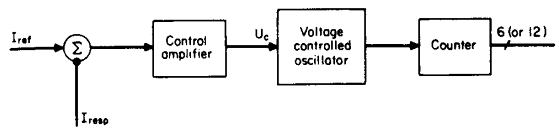

Fig. 18. A block diagram showing the generation of control pulses in an equidistant firing control system.

When transiently $I_{ref} > I_{resp}$, U_c is given a suitable value by the control amplifier to decrease the frequency of the oscillator. On the contrary, when $I_{ref} < I_{resp}$, U_c increases the same frequency. A decreasing frequency results in a steadily increasing firing angle α and decreasing voltage, whereas, an increasing frequency results in a steadily decreasing α and increasing voltage. In either case, the direct current is restored to its reference value.

The output signal from the controlled oscillator is a pulse train which contains all triggering pulses for a valve bridge. A separation must be done to obtain individual control pulses for each individual valve. This is performed be a digital counter of suitable design. The block diagram in Fig. 18 must also be completed with special control functions which prevents the oscillator from falling out of phase. Thus, control pulses must always be generated within a time interval defined by the limits α_{min} and γ_{min}.

Note that U_c in Fig. 18 is proportional to $d\alpha/dt$, as the oscillator is "frequency-controlled" by its input voltage. It is also possible to use a "phase-controlled" oscillator by which U_c corresponds directly to α.

4) Margin of Commutation Control: The control on minimum margin of commutation may, analogously to current control, be of the individual phase or equidistant firing type. Two further alternatives exist for both types, namely, a predictive system or a feedback control system.

A predictive system is a feedforward-type of control system which, based on instantaneous measurements of direct current and commutation voltage, calculates the correct time instant for firing. This type of system is, of course, inherently individual for each valve phase. However, if the most critical valve is chosen and allowed to establish the firing for all valves in an equidistant manner, an equidistant control system is obtained.

A typical feedback control system measures the actual γ, compares it to a reference value γ_r, and uses the difference $U_\gamma = \gamma_r - \gamma$ to control a voltage-controlled pulse oscillator,

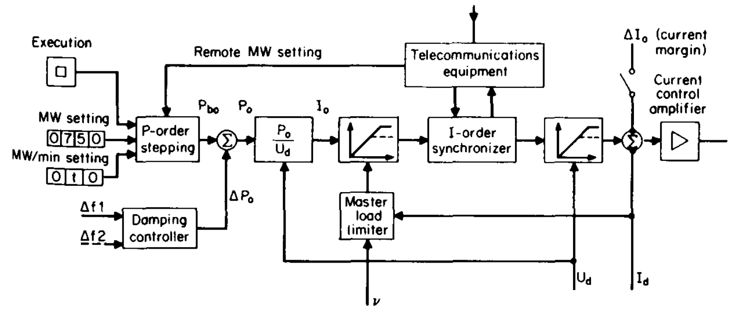

Fig. 19. The master controller in the lead station transmits the current order.

similar to that for the current control system. In this case, an equidistant firing control system is obtained. However, an individual phase control system using the feedback principle is also possible. Both predictive and feedback types have their advantages. The predictive system provides potentials for prevention of commutation failures during small disturbances, whereas the feedback system gives a better precision of control and may be simpler to implement, especially when combined with the voltage-controlled oscillator system for current control. The block diagram in Fig. 18 can be used to represent a feedback control system if I_{ref} and I_{resp} are respectively replaced by γ_{ref} and γ_{resp}, which represent the smallest measured γ for the valves within a bridge.

The firing control system may be designed for either 6- or 12-pulse operation with regard to both current control and margin of commutation control. A 12-pulse firing control system is here understood to mean an equipment common to both 6-pulse valve bridges within the 12-pulse converter and the voltage-controlled oscillator described earlier working with a frequency equal to 12 times the fundamental frequency of the ac network.

5) Master Control: In an HVDC system the line voltage is nearly constant, therefore, the direct current control is almost equivalent to power control. Occasionally, the line voltage changes due to a change in inverter ac voltage. It might then be desirable to control the current in such a way that the transmitted power is kept constant. The traditional way of doing this is to provide each terminal with a current-order calculator which supplies the reference to the current control system. This reference is calculated from the desired transmitted power by dividing it by the measured dc line voltage.

As identical current orders have to be supplied to both terminals, a telecommunications link must be used for system control. This may transmit either a current order or a power order. The common order is either set manually in any of the terminals or set from a control system of higher order, which may also consider the situation in the sending or receiving ac networks as described in the next paragraph.

Another type of master controller is shown in Figs. 19 and 20. In this case, all important signal conditioning of the orders is performed in common for both stations in a lead master controller which is placed in either of the two stations. Fig. 19 shows the block diagram of such a lead master controller, from which the current order is transmitted to the trail master controller, shown in Fig. 20, at the other station. The order transmission is performed in a synchronous manner by which changes in the order settings produce simultaneous changes in the effective current order at the two stations.

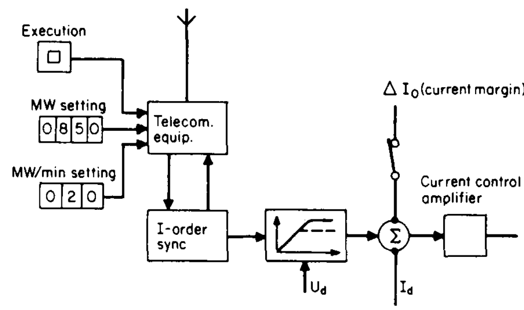

Fig. 20. The master controller in the trail station receives the current order.

Manual power-order setting and rate-of-change setting can be done at either of the two stations. Orders are transmitted by the telecommunications link to the station with the lead master controller if the settings are done in the station with the trail master control.

When the dc link is used for stabilization of an associated ac network, a power-order adjustment is generated by a power modulation controller and added to the normally set power order as shown in Fig. 19. In this case, it may be suitable to place the lead master control equipment in the station which is connected to the network to be stabilized to minimize the total telecommunications delay.

In the lead master controller, the power order and rate-of-change order are converted to a ramp by which the power on the dc transmission is changed when an execution button is pushed. A current order is calculated as the quotient between the power order and the dc line voltage, and the order is limited by a master load limiter (I_0 max controller) before it is transmitted to the other station.

The master load limiter performs an optimal limitation with regard to the current through the valves and, possibly, the cooling-medium temperature.

A voltage-dependent current-order limiter is present in both stations.

C. Converter Transformers

Converter transformers are the link between the ac and dc systems. They provide a natural barrier between ac and dc systems, preventing dc voltage and current from reaching the ac system. They also provide the necessary phase shifts required for 12-pulse valve operation through wye and delta secondary connections and maintain the valve voltage within a narrow band of ac system voltage variations through on-load tap changers. Through their closely matched impedances, a result of careful design and construction, they:

- reduce noncharacteristic harmonics,
- reduce ac phase imbalance, thus simplifying system regulation, and
- limit short-circuit currents to tolerable levels for the solid-state converter valve.

Converter transformers, therefore, have an important bearing on system performance and must be considered an integral part of any HVDC system.

A load tap changer (LTC) maintains rated dc voltage with variation in power transfer and ac system voltage. The tap range on the converter transformer network side winding may be as large as 30 percent of the winding turns.

Under normal conditions, losses in a converter transformer are composed of the same losses in an ac transformer plus losses due to harmonic currents produced during conversion.

Converter transformers have a unique set of dielectric design characteristics since the windings are subjected to direct voltage stress superimposed upon the customary ac voltage stress. The ac stress distributes as it would in a capacitive network, and the steady-state dc stress distributes as it would in a resistive network.

D. Smoothing Reactor

A smoothing reactor is placed in series with dc converters to smooth dc ripple current and reduce current transients during system contingencies (Fig. 2). It serves a secondary purpose of protecting the converter valves from voltage surges coming from the dc line. Special filtering circuits may be installed to reduce telephone interference from the dc line. These must be coordinated with the smoothing reactor to avoid a resonance problem.

E. Transductors

1) DC Current Transductor: For an HVDC power system, measurements of direct current are required as an input to the converter controller, and for metering and instrumentation.

The dc current transductor (DCCT) measures the direct current and provides a signal in the form of a direct voltage proportional to the direct current. The DCCT also provides isolation between the HVDC line, where the current is measured, and the control system ground.

A regular (uni-polarity) DCCT is comprised of a transductor unit and a sensor unit (Fig. 21). The transductor unit consists of two toroidal saturable cores, each with primary and secondary windings. In this case, the primary winding is merely the dc line conductor or cable passing through the windows of the toroidal cores. The secondary windings are connected in series and are excited by ac voltage. The sensor unit of each DCCT processes the secondary currents of the saturable cores and provides the output voltage. The DCCTs have a nominal rating of 1000-A dc and require a 120-V 60-Hz auxiliary voltage supply to give a dc output signal. The output voltage is 10-V dc across a 10-ohm resistor for rated primary dc current.

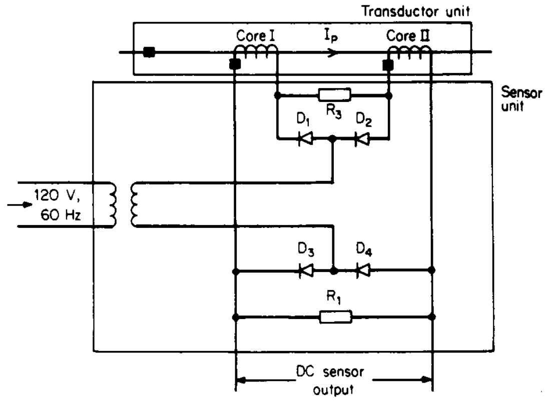

Fig. 21. A regular uni-polarity dc current transductor (DCCT) is comprised of a transductor unit and a sensor unit.

2) DC Potential Transductor: As previously indicated, measurements of dc line voltage are required as an input to the converter controller and for metering and instrumentation of an HVDC system.

The dc potential transductor (DCPT) measures dc line voltage with isolation between the power system and control system ground. The DCPT consists of the following main components:

- current limiting precision resistor,
- auxiliary unit,
- transductor cores, and
- distribution and sensor box.

The precision resistor, auxiliary unit, and transductor cores are located in the valve hall. The auxiliary unit is located at the base of one of the resistor columns.

Fig. 22 shows a schematic arrangement of the equipment forming the DCPT circuit for one pole. One DCPT is necessary for each pole.

AC control power is required to obtain dc output voltage, and is obtained from a first grade power source.

F. Arresters

Metal-oxide arrester elements, comprised primarily of zinc oxide, but containing a number of other metal oxides as well, have an extremely nonlinear voltage current characteristic. As illustrated in Fig. 23, a typical disk that conducts less than one milliampere of current at normal operating voltage exhibits a voltage only slightly more than twice normal operating voltage at a current of 10 000 A. Because of such a characteristic, it is possible to design both ac and dc arresters without series gaps. This is a simplification which is especially important for dc arresters because it is difficult to make a gap capable of clearing against dc voltage, particularly after the gap has been subjected to a high energy surge.

When the current is drawn at its maximum continuous operating voltage, a typical zinc-oxide disk has a negative temperature coefficient, as indicated by Fig. 23. That is, as the temperature increases, the leakage current and resulting watts loss increase, and this increase must be considered in the thermal design of the arrester. However, the temperature coefficient becomes very slightly positive at currents above a few amperes. This slight positive tem-

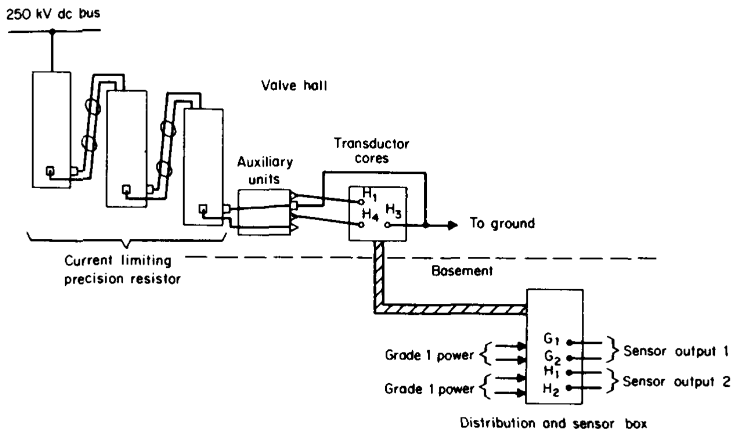

Fig. 22. The schematic for a dc potential transductor (DCPT) indicates locations for the main parts. One DCPT is necessary for each pole.

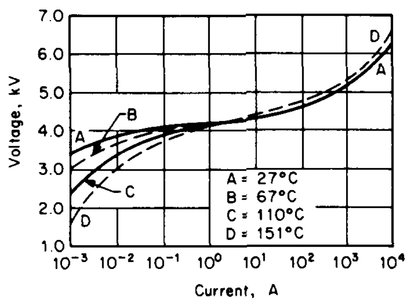

Fig. 23. These voltampere cures for a typical zinc-oxide disk show operating characteristics for a temperature range of 27 to 151°C.

perature coefficient at higher current, in contrast to the strong negative coefficient of silicon-carbide nonlinear elements, makes it possible to operate zinc-oxide elements in parallel to discharge high-energy surges.

IV. Multiterminal DC Systems

Successful applications of point-to-point dc links worldwide have shown power system planners that three-terminal dc (3TDC) and multi-terminal dc (MTDC) schemes will be the vehicles to fully utilize economic and technical advantages of HVDC technology in the future. In fact, MTDC systems are a reality now. The New England-Hydro-Quebec 5TDC is in the project design stage and the Sardinia-Corsica-Italy scheme is now in operation.

MTDC systems may be planned in advance or evolve from expansion of operating two-terminal dc (2TDC) links. In the latter case, advanced planning can often be advantageous in minimizing required modifications, thereby minimizing outage of the link during expansion.

There are two possible connection schemes for MTDC systems: a constant voltage parallel scheme and a constant current series scheme. In the parallel scheme, converters are connected in parallel and operate at a common voltage. Here, the dc network may be of either the radial (Fig. 24) or mesh type (Fig. 25). In the series scheme, converters are connected in series with a common direct current flowing through all terminals. The parallel connected scheme is discussed here, since it is widely accepted as the most practical configuration with the fewest operational problems.

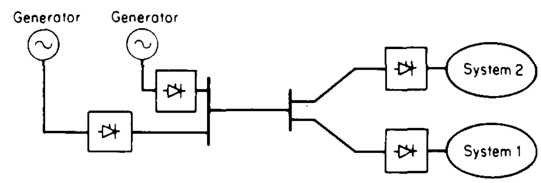

Fig. 24. A radial multiterminal dc network bulk power transmission.

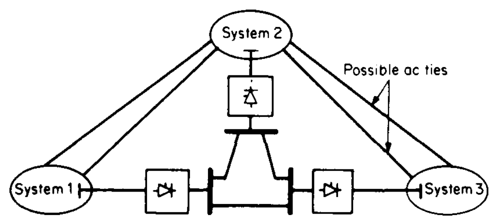

Fig. 25. A mesh dc network used as an ac network interconnection.

A. Potential Applications and Benefits

Potential applications for MTDC systems are similar to those for 2TDC systems and can be classified under three basic categories.

- Bulk power transmission—where low cost energy from several power plants is transmitted over a long distance to different ac systems (Fig. 24).
- AC network interconnection over a long or medium distance—where generation/load balancing and sharing of spinning reserves are of primary concern (Fig. 25).
- Reinforcement of an ac network—where limited ac expansion possibilities exist. Energy from a new power plant is fed to different locations of an ac system, usually metropolitan (Fig. 26).

MTDC systems offer both economical and technical advantages over several equivalent 2TDC systems. The primary economic advantages are as follows:

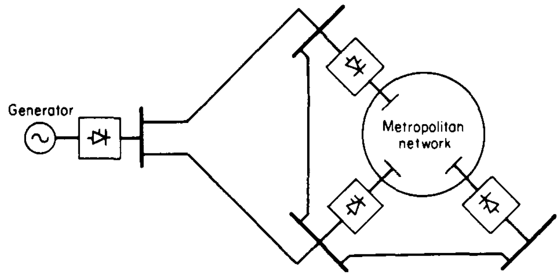

Fig. 26. A multiterminal dc system reinforces an urban network.

- The total installed converter rating in an MTDC system is usually less than that of several equivalent 2TDC systems.
- MTDC systems offer low cost transmission lines and/or cables.
- The inherent overload capability of MTDC transmission lines can increase the capacity of transmission corridors.

Technical advantages of MTDC systems include the following:

- MTDC systems provide greater flexibility in dispatching transmitted power. In mesh dc networks, the inherent overload capability of transmission lines allows for more flexible dc power transfer patterns.
- In a larger interconnected power system, MTDC systems can provide a powerful control action to damp out troublesome electromechanical oscillations.
- In conjunction with phase shifting transformers and generation shifting, MTDC systems may be used to enforce desired power flow patterns in a large interconnected power system.

B. Control of MTDC Systems

The fundamental control principle for MTDC systems is a natural generalization of that for existing 2TDC systems. That is, each converter is controlled according to a control characteristic virtually identical to those for 2TDC systems. As with 2TDC systems, there is a current margin requirement in MTDC systems: the sum of the rectifier current orders must exceed the sum of inverter current orders by a value known as current margin.

In normal operational mode for a given power transfer dispatch, a selected terminal establishes a normal direct voltage profile throughout the system. This voltage setting terminal (VST) operates on either constant voltage control or on constant angle control, exhibiting a nearly horizontal characteristic. Other terminals in the MTDC system operate on constant current, i.e., the vertical characteristic. Generally, the horizontal segment of the VST characteristic is at a relatively lower voltage than those of the current controlling terminals. Also, the current at the VST differs from its respective reference current by the current margin. If the VST is an inverter, the actual current is greater than the respective reference current by the current margin. If the VST is a rectifier, the actual current is less than the reference current.

These relationships are shown in Fig. 27 for a four-terminal dc system (4TDC). In Fig. 27(a), inverter terminal four is the VST, while the other converters are on current control. The current at terminal four is therefore more than the

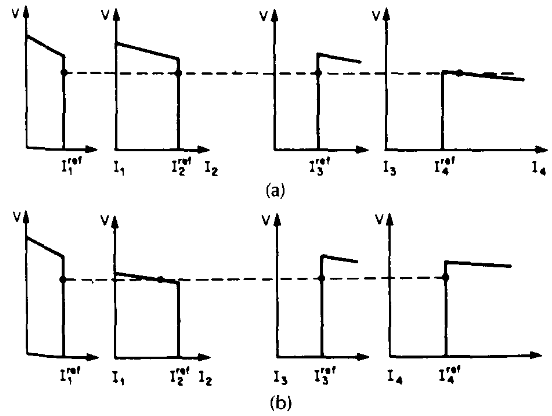

Fig. 27. Control characteristics for a 4TDC system. The voltage setting terminal (VST) is the inverter terminal 4 for (a) and the rectifier 2 for (b).

reference current, as previously described. In Fig. 27(b), it is assumed that the alternating voltage for rectifier terminal two has dropped and, therefore, terminal two becomes the voltage setting terminal. As a result, its operating current is decreased by the current margin. In this backup mode of operation, the previous VST (inverter terminal four) operates on constant current control.

Unlike 2TDC systems, the direct voltage polarity in MTDC systems may not be reversed unless it is desired to change power flow direction at every terminal in the system. Therefore, should any of the converters be changed from an inverter to a rectifier, or vice versa, its current must be reduced to zero, a polarity reversing switch must be operated there, and, finally, the converter current must be increased to the desired value. Coordination of current orders to ensure availability of sufficient current margin in the dc system is an essential requirement for such maneuverings.

C. Fault Clearing and Switching

In case of a fault in the dc transmission network, three methods are available for clearing the fault. The methods are based on the kind of switching device used to isolate the faulted line. The most versatile and flexible method is the use of dc breakers capable of interrupting the maximum fault current that the system can produce.

The breakers should be designed to react rapidly to a relay signal and interrupt the fault current in a matter of milliseconds. A rapid and accurate fault sensing or relay system is usually required as well. Fault sensing is local and structured similarly to one of the schemes presently used in the ac systems.

If the faulted line radially connects a converter to the remainder of the MTDC system, its disconnection would result in isolation of the converter from the system. Consequently, coordinating current orders of the remaining converters in the MTDC system is necessary, and should be done centrally, via high speed communication, to achieve the best performance. By using the breaker scheme, a fault in the dc transmission network may be cleared in approximately 10 ms.

Another method of clearing a fault is by using load break switches in conjunction with the converter controls. The switch is rated to interrupt direct currents as high as normal operating current—not the fault current. When a fault occurs on the dc transmission network and no other control action is implemented, the converter controls, by use of current regulators, reduce the fault current to less than normal values. The faulted line can then be isolated from the system by activating load break switches, in about 100 ms, and MTDC system operation may then be resumed. The requirements for balancing current orders in this case are similar to those for fault clearing by a dc breaker.

The third method forces all the converters to temporarily operate as inverters as soon as the fault is detected. The stored energy in the dc system is then delivered to the ac systems, resulting in de-energizing the entire MTDC system. When direct currents are driven to zero, the faulted line is disconnected by high-speed isolators. The MTDC system can then be restarted and resume operation. The requirements for current order balancing are similar to those discussed earlier. This protective measure may be implemented in 200–300 ms.

For MTDC systems that are energy ties, the third method of fault clearing is generally acceptable. The scheme, however, may not be desirable for an MTDC system with a relatively large number of converters and transmission lines. The scheme may even be unacceptable when the 200–300 ms period of MTDC shutdown may jeopardize rotor swing stability of generators in the vicinity of the dc terminals. Disconnecting the faulted line by load break switches or dc breakers is more appropriate for these situations. Generally, the appropriate method of fault clearing is application dependent and should be selected after sufficient system studies.

V. Future Trends

The thyristor devices are expected to continue the trend towards higher ratings, both in current and voltage ratings. Thyristor voltage ratings in the 8–10-kV range are within reach and should be available in the next two or three years time frame.

Gate turn-on thyristors (GTOs) are being actively evaluated for applications in static var and HVDC systems. Larger GTOs are expected to influence this trend.

Other advances in the thyristor area include development of integrated breakover protection within the device, improvements in heat transfer characteristics, and application of two-phase freon cooling.

VI. Bibliography and Acknowledgment

Some of the materials presented in this article, including figures, are excerpts of those already published by General Electric Company engineers in Chapter 15 of the *Standard Handbook for Electrical Engineers* (New York, NY: McGraw-Hill, 1987), where a bibliography of key publications on HVDC systems is given. In addition, a comprehensive annotated bibliography of HVDC systems has been compiled and published by Bonneville Power Administration for periods of 1932–1962, 1963–1965, 1966–1968, and 1969–1983. The latest set (1969–1983) was also sponsored by the IEEE Working Group on HVDC Bibliography and Records.

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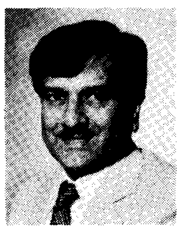
Dr. Nozari is a member of CIGRE and Senior Member of the IEEE Power Engineering Society.



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