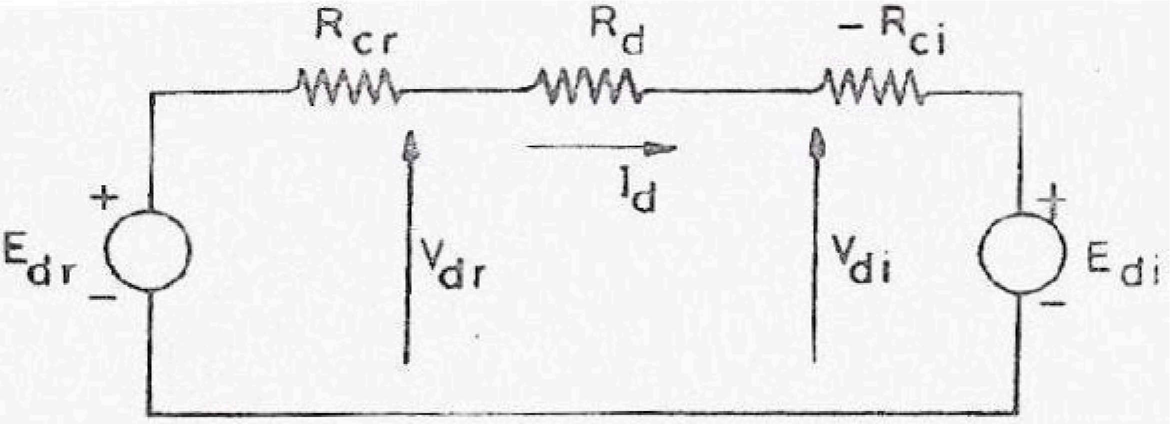
UNIT-II
Converter and HVDC System Control

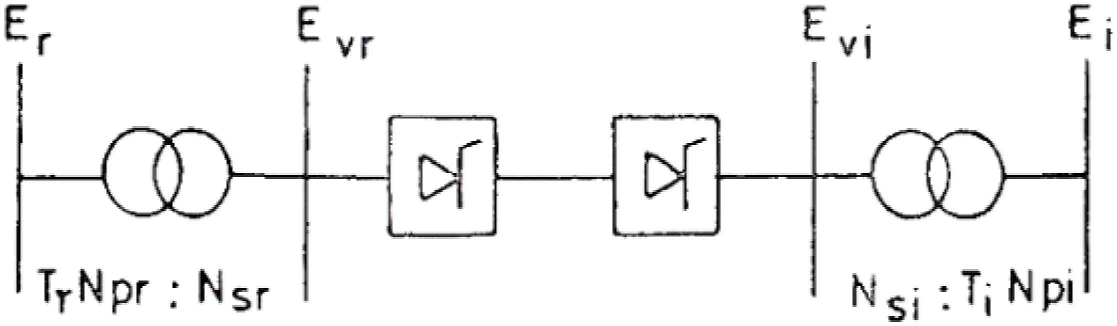
The major advantage of a HVDC link is rapid controllability of transmitted power through the control of firing angles of the converters. Modern converter controls are not only fast, but also very reliable and they are used for protection against line and converter faults.

Principles of DC Link Control

The control of power in a DC link can be achieved through the control of current or voltage. From minimization of loss considerations, we need to maintain constant voltage in the link and adjust the current to meet the required power.



Consider the steady state equivalent circuit of a two terminal DC link. This is based on the assumption that all the series connected bridges in both poles of a converter station are identical and have the same delay angles. Also the number of series connected bridges (n_b) in both stations (rectifier and inverter) are the same.



The voltage sources E_{dr} and E_{di} are defined by

$$E_{dr} = (3\sqrt{2}/\pi)\, n_b\, E_{vr} \cos\alpha_r \quad \text{---- (1)}$$

$$E_{di} = (3\sqrt{2}/\pi)\, n_b\, E_{vi} \cos\gamma_i \quad \text{---- (2)}$$

where E_{vr} and E_{vi} are the line to line voltages in the valve side windings of the rectifier and inverter transformer respectively. From the above figure these voltages can be obtained by

$$E_{vr} = \frac{N_{sr}E_r}{N_{pr}T_r} \quad , \qquad\qquad E_{vi} = \frac{N_{si}E_i}{N_{pi}T_i} \quad \text{---- (3)}$$

where E_r and E_i are the AC (line to line) voltages of the converter buses on the rectifier and inverter side. T_r and T_i are the OFF-nominal tap ratios on the rectifier and inverter side.

Combining equations (1), (2) and (3),

$$E_{dr} = (A_r\, E_r\, /T_r)\, \cos\alpha_r \quad \text{---- (4)}$$

$$E_{di} = (A_i\, E_i\, /T_i)\, \cos\gamma_i \quad \text{---- (5)}$$

where A_r and A_i are constants.

The steady-state current I_d in the DC link is obtained as

$$I_d = \frac{(E_{dr} - E_{di})}{R_{cr} + R_d - R_{ci}}$$

Substituting equations (4) and (5) in the above equation, we get

$$I_d = \frac{(A_r E_r / T_r)\cos\alpha_r - (A_i E_i / T_i)\cos\gamma_i}{R_{cr} + R_d - R_{ci}}$$

The control variables in the above equation are T_r , T_i and α_r , β_i . However, for maintaining safe commutation margin, it is convenient to consider γ_i as control variable instead of β_i .

As the denominator in the final equation is small, even small changes in the voltage magnitude E_r or E_i can result in large changes in the DC current, the control variables are held constant. As the voltage changes can be sudden, it is obvious that manual control of converter angles is not feasible. Hence, direct and fast control of current by varying α_r or γ_r in response to a feedback signal is essential.

While there is a need to maintain a minimum extinction angle of the inverter to avoid commutation failure, it is economical to operate the inverter at Constant Extinction Angle (CEA) which is slightly above the absolute minimum required for the commutation margin. This results in reduced costs of the inverter stations, reduced converter losses and reactive power consumption. However, the main drawback of CEA control is the negative resistance characteristics of the converter which makes it difficult to operate stably when the AC system is weak (low short-circuit ratios). Constant DC Voltage (CDCV) control or Constant AC Voltage (CACV) control are the alternatives that could be used at the inverter.

Under normal conditions, the rectifier operates at Constant Current (CC) control and the inverter at the CEA control.

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

The feedback control of power in a DC link is not desirable because

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

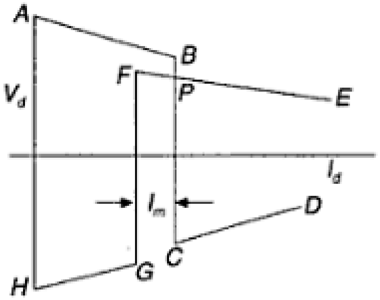
Converter Control Characteristics

Basic Characteristics:

The intersection of the two characteristics (point A) determines the mode of operation- Station I operating as rectifier with constant current control and station II operating at constant (minimum) extinction angle.

There can be three modes of operation of the link (for the same direction of power flow) depending on the ceiling voltage of the rectifier which determines the point of intersection of the two characteristics which are defined below

1) CC at rectifier and CEA at inverter (operating point A) which is the normal mode of operation.
2) With slight dip in the AC voltage, the point of intersection drifts to C which implies minimum α at rectifier and minimum γ at the inverter.
3) With lower AC voltage at the rectifier, the mode of operation shifts to point B which implies CC at the inverter with minimum α at the rectifier.

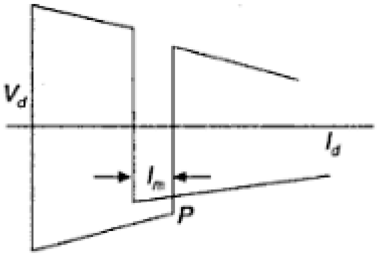


Controllers characteristics.

Types of Station Control Characteristics

Station-I	Station-II	Controller type
AB	*HG*	Minimum α
BC	*GF*	Constant current
CD	*EF*	CEA (minimum γ)

The characteristic AB has generally more negative slope than characteristic FE because the slope of AB is due to the combined resistance of (R_d + R_{cr}) while is the slope of FE is due to R_{ci} .



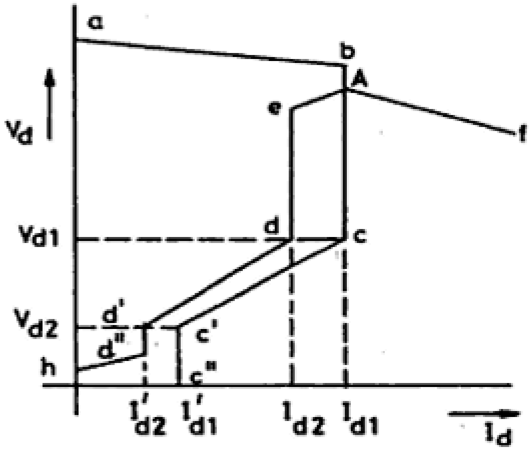
Power reversal controllers characteristics

The above figure shows the control characteristics for negative current margin I_m (or where the current reference of station II is larger than that of station I). The operating point shifts now to D which implies power reversal with station I (now acting as inverter) operating with minimum CEA control while station II operating with CC control.

This shows the importance of maintaining the correct sign of the current margin to avoid inadvertent power reversal. The maintenance of proper current margin requires adequate telecommunication channel for rapid transmission of the current or power order.

Voltage Dependent Current Limit:

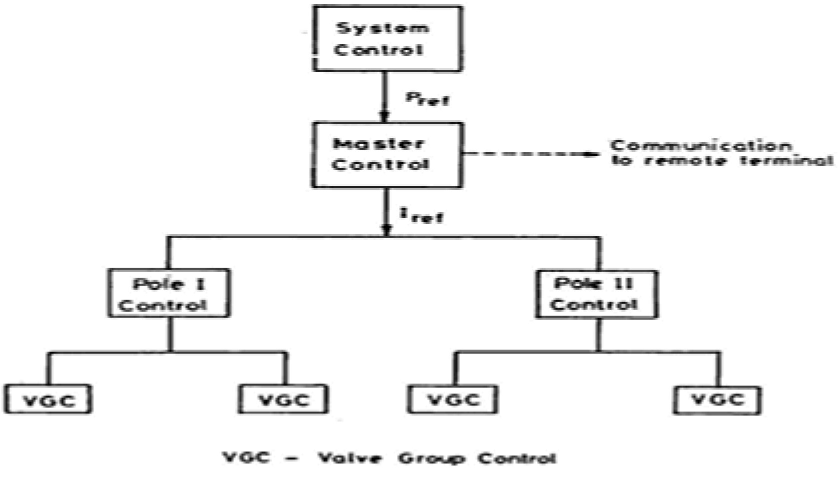
The low voltage in the DC link is mainly due to the faults in the AC system on the rectifier or inverter side. The low AC voltage due to faults on the inverter side can result in persistent commutation failure because of the increase of the overlap angle. In such cases, it is necessary to reduce the DC current in the link until the conditions that led to the reduced DC voltage are relieved. Also the reduction of current relieves those valves in the inverter which are overstressed due to continuous current flow in them.



If the low voltage is due to faults on the rectifier side AC system, the inverter has to operate at very low power factor causing excessive consumption of reactive power which is also undesirable. Thus, it becomes useful to modify the control characteristics to include voltage dependent current limits. The figure above shown shows current error characteristics to stabilize the mode when operating with DC current between I_{d1} and I_{d2} . The characteristic $cc^{|}$ and $c^{|}c^{||}$ show the limitation of current due to the reduction in voltage.

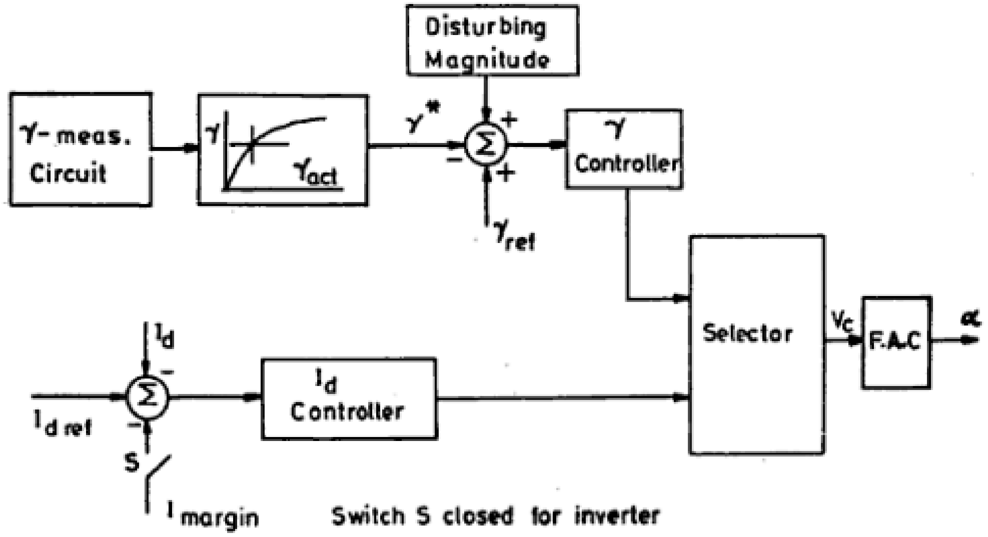
System Control Hierarchy

The control function required for the HVDC link is performed using the hierarchical control structure.



The master controller for a bipole is located at one of the terminals and is provided with the power order (P_{ref}) from the system controller (from energy control centre). It also has other information such as AC voltage at the converter bus, DC voltage etc. The master controller transmits the current order (I_{ref}) to the pole control units which in turn provide a firing angle order to the individual valve groups (converters). The valve group or converter control also oversees valve monitoring and firing logic through the optical interface. It also includes bypass pair selection logic, commutation failure protection, tap changer control, converter start/stop sequences, margin switching and valve protection circuits.

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



The current or extinction angle controller generates a control signal V_c which is related to the firing angle required. The firing angle controller generates gate pulses in response to the control signal V_c . The selector picks the smaller of the α determined by the current and CEA controllers.

Firing Angle Control

The operation of CC and CEA controllers is closely linked with the method of generation of gate pulses for the valves in a converter. The requirements for the firing pulse generation of HVDC valves are

1. The firing instant for all the valves are determined at ground potential and the firing signals sent to individual thyristors by light signals through fibre-optic cables. The required gate power is made available at the potential of individual thyristor.
2. While a single pulse is adequate to turn-on a thyristor, the gate pulse generated must send a pulse whenever required, if the particular valve is to be kept in a conducting state.

The two basic firing schemes are

1. Individual Phase Control (IPC)
2. Equidistant Pulse Control (EPC)

Individual Phase Control (IPC)

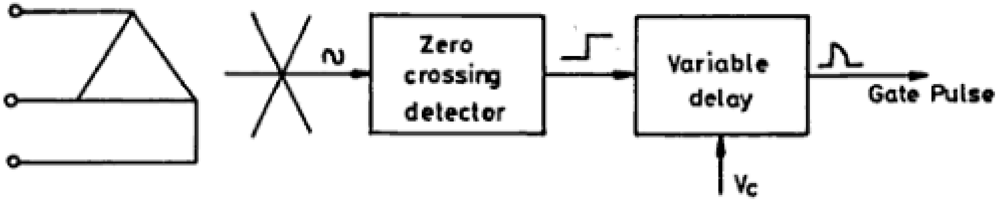
This was used in the early HVDC projects. The main feature of this scheme is that the firing pulse generation for each phase (or valve) is independent of each other and the firing pulses are rigidly synchronized with commutation voltages.

There are two ways in which this can be achieved

1. Constant α Control
2. Inverse Cosine Control

Constant α Control

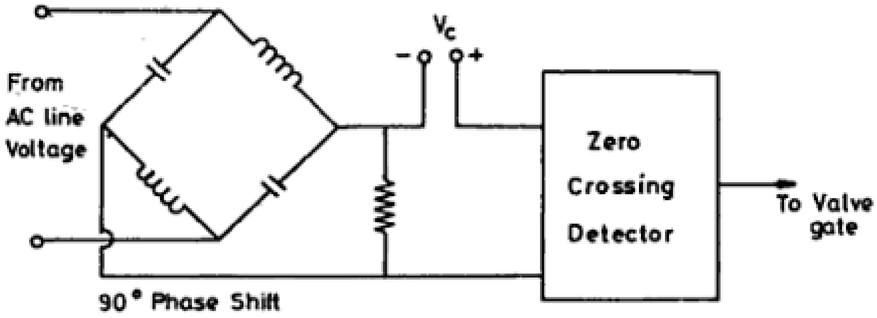
Six timing (commutation) voltages are derived from the converter AC bus via voltage transformers and the six gate pulses are generated at nominally identical delay times subsequent to the respective voltage zero crossings. The instant of zero crossing of a particular commutation voltage corresponds to $\alpha = 0^\circ$ for that valve.



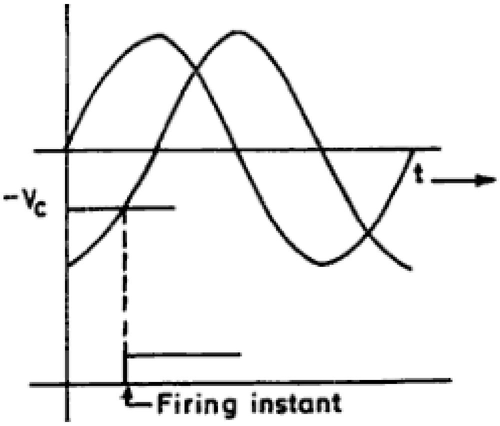
The delays are produced by independent delay circuits and controlled by a common control voltage V derived from the current controllers.

Inverse Cosine Control

The six timing voltages (obtained as in constant α control) are each phase shifted by 90° and added separately to a common control voltage V.



The zero crossing of the sum of the two voltages initiates the firing pulse for the particular valve is considered. The delay angle α is nominally proportional to the inverse cosine of the control voltage. It also depends on the AC system voltage amplitude and shape.



The main advantage of this scheme is that the average DC voltage across the bridge varies linearly with the control voltage V_c .

Drawbacks of IPC Scheme

The major drawback of IPC scheme is the aggravation of the harmonic stability problem that was encountered particularly in systems with low short circuit ratios (less than 4). The harmonic instability, unlike instability in control systems, is a problem that is characterized by magnification of noncharacteristic harmonics in steady-state.

This is mainly due to the fact that any distortion in the system voltage leads to perturbations in the zero crossings which affect the instants of firing pulses in IPC scheme. This implies that even when the fundamental frequency voltage components are balanced, the firing pulses are not equidistant in steady-state. This in turn leads to the generation of noncharacteristic harmonics (harmonics of order $h \neq np \pm 1$) in the AC current which can amplify the harmonic content of the AC voltage at the converter bus. The problem of harmonic instability can be overcome by the following measures

1. Through the provision of synchronous condensers or additional filters for filtering out noncharacteristic harmonics.
2. Use of filters in control circuit to filter out noncharacteristic harmonics in the commutation voltages.
3. The use of firing angle control independent of the zero crossings of the AC voltages. This is the most attractive solution and leads to the Equidistant Pulse Firing scheme.

Equidistant Pulse Control (EPC)

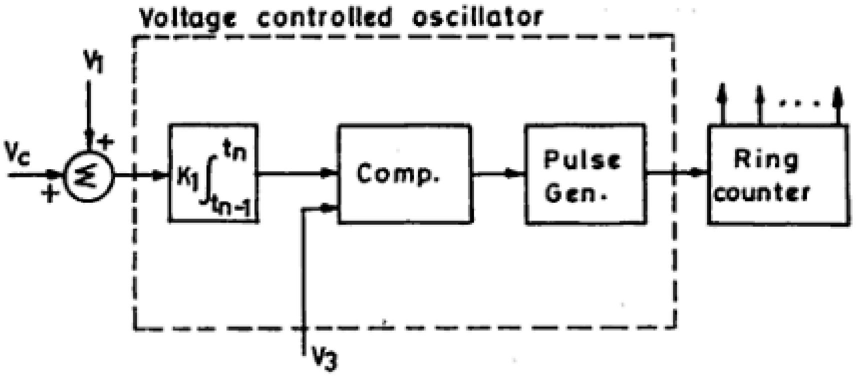
The firing pulses are generated in steady-state at equal intervals of 1/pf , through a ring counter. This control scheme uses a phase locked oscillator to generate the firing pulses. Thre are three variations of the EPC scheme

1. Pulse Frequency Control (PFC)
2. Pulse Period Control
3. Pulse Phase Control (PPC)

Pulse Frequency Control (PFC)

A Voltage Controlled Oscillator (VCO) is used, the frequency of which is determined by the control voltage V_c which is related to the error in the quantity (current, extinction angle or DC voltage) being regulated. The frequency in steady-state operation is equal to pf_o where f_o is the nominal frequency of the AC system. PFC system has an integral characteristic and has to be used along with a feedback control system for stabilization.

The Voltage Controlled Oscillator (VCO) consists of an integrator, comparator and a pulse generator.



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

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

where V_1 is a bias (constant) voltage and V_3 is proportional to the system period.

In steady-state, $V_c = 0$, and from the above equation, we get

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

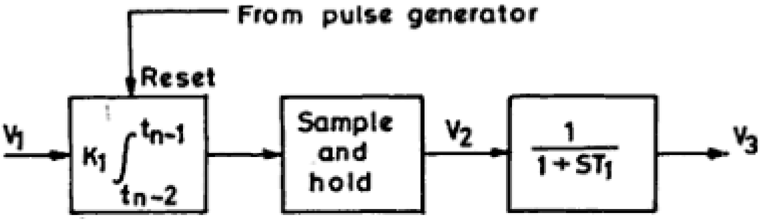
Since, $t_n - t_{n-1} = 1/pf_o$

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

$$K_1 = pf_o V_3 / V_1$$

The circuit does not incorporate frequency correction (when the system frequency deviates from f_o). The frequency correction is obtained by deriving V_3 as

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



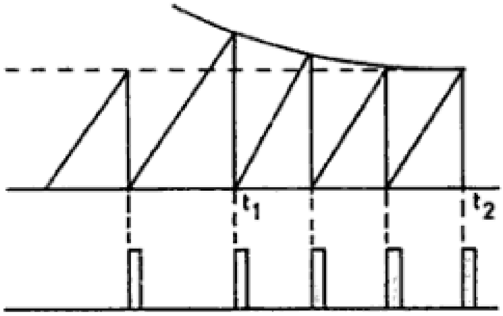
Pulse Period Control

It is similar to PFC except for the way in which the control voltage V_c is handled. The structure of the controller is the same, however, V_c is now summed with V_3 instead of V_1. Thus, the instant t_n of the pulse generation is

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_3 + V_c$$

$$K_1 V_1 (t_n - t_{n-1}) = V_3 + V_c$$

With $V_c = 0$, the interval between consecutive pulses, in steady-state, is exactly equal to $1/pf_o$.



The frequency correction in this scheme is obtained by either updating V_1 in response to the system frequency variation or including another integrator in the CC or CEA controller.

Pulse Phase Control (PPC)

An analog circuit is configured to generate firing pulses according to the following equation

$$\int_{t_{n-1}}^{t_n} K_1 V_1 dt = V_{cn} - V_{c(n-1)} + V_3$$

where V_{cn} and $V_{c(n-1)}$ are the control voltages at the instants t_n and t_{n-1} respectively.

For proportional current control, the steady-state can be reached when the error of V_c is constant.

The major advantages claimed for PPC over PFC are (i) easy inclusion of α limits by limiting V_c as in IPC and (ii) linearization of control characteristic by including an inverse cosine function block after the current controller. Limits can also be incorporated into PFC or pulse period control system.

Drawbacks of EPC Scheme

EPC Scheme has replaced IPC Scheme in modern HVDC projects; it has certain limitations which are

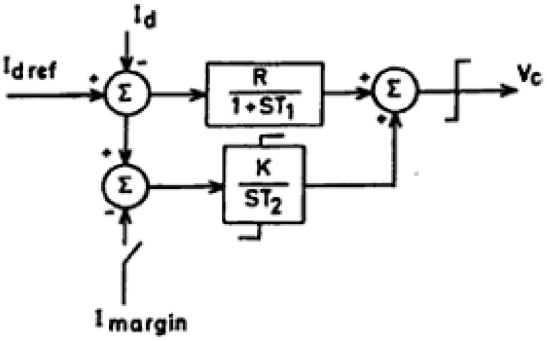
1. Under balanced voltage conditions, EPC results in less DC voltage compared to IPC. Unbalance in the voltage results from single phase to ground fault in the AC system

which may persist for over 10 cycles due to stuck breakers. Under such conditions, it is desirable to maximize DC power transfer in the link which calls for IPC.

2. EPC Scheme also results in higher negative damping contribution to torsional oscillations when HVDC is the major transmission link from a thermal station.

Current and Extinction Angle Control

The current controller is invariably of feedback type which is of PI type.



The extinction angle controller can be of predictive type or feedback type with IPC control. The predictive controller is considered to be less prone to commutation failure and was used in early schemes. The feedback control with PFC type of Equidistant Pulse Control overcomes the problems associated with IPC.

The extinction angle, as opposed to current, is a discrete variable and it was felt the feedback control of gamma is slower than the predictive type. The firing pulse generation is based on the following equation

$$0 = \int_{-\pi+\delta_{n-1}}^{\omega t_n} e_{cj}\, d(\omega t) + 2X_c I_d$$

where e_{cj} is the commutation voltage across valve j and t_n is the instant of its firing.

In general, the prediction of firing angle is based on the equation

$$B_j = \gamma_{ref} + \mu_j$$

where μ_j is the overlap angle of valve j, which is to be predicted based on the current knowledge of the commutation voltage and DC current.

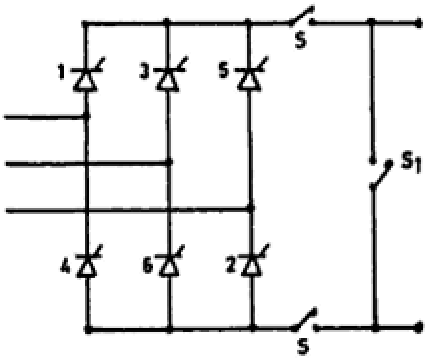
Under large disturbances such as a sudden dip in the AC voltage, signals derived from the derivative of voltage or DC current aid the advancing of delay angle for fast recovery from commutation failures.

Starting and Stopping of DC Link

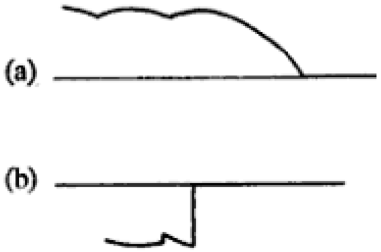
Energization and Deenergization of a Bridge:

Consider N series connected bridges at a converter station. If one of the bridges is to be taken out of service, there is need to not only block, but bypass the bridge. This is because of the fact that just blocking the pulses does not extinguish the current in the pair of valves that are left conducting at the time of blocking. The continued conduction of this pair injects AC voltage into the link which can give rise to current and voltage oscillations due to lightly damped oscillatory circuit in the link formed by smoothing reactor and the line capacitance. The transformer feeding the bridge is also subjected to DC magnetization when DC current continues to flow through the secondary windings.

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



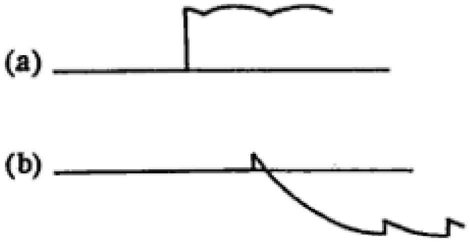
With the selection of bypass pair 1 and 4, the commutation from valve 2 to4 is there, but the commutation from valve 3 to valve 5 is prevented. In the case of a predetermined choice of the bypass path, the time lapse between the blocking command and the current transfer to bypass path can vary from 60^0 and 180^0 for a rectifier bridge. In the inverter, there is no time lag involved in the activation of the bypass pair. The voltage waveforms for the rectifier and inverter during de-energisation are shown below where the overlap is neglected.



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

The energisation of a blocked bridge is done in two stages. The current is first diverted from S_1 to the bypass pair. For this to happen S_1 must generate the required arc voltage and to minimize this voltage, the circuit inductance must be small. In case the bypass pair fails to take over the current, S_1 must close automatically if the current in that does not become zero after a predetermined time interval. AC breakers with sufficient arc voltage, but with reduced breaking capacity are used as switch S_1 .

In the second stage of energisation, the current is diverted from the bypass pair. For the rectifier, this can take place instantaneously neglecting overlap. The voltage waveforms for this case are shown below.



Start-Up of DC Link:

There are two different start-up procedures depending upon whether the converter firing controller provides a short gate pulse or long gate pulse. The long gate pulse lasts nearly 120^0 , the average conduction period of a valve.

Start-up with long pulse firing:

1. Deblock inverter at about $\gamma = 90^0$
2. Deblock rectifier at $\alpha = 85^0$ to establish low direct current
3. Ramp up voltage by inverter control and the current by rectifier control.

Start-up with short pulse firing:

1. Open bypass switch at one terminal
2. Deblock that terminal and load to minimum current in the rectifier mode
3. Open bypass switch at the second terminal and commutate current to the bypass pair
4. Start the second terminal also in the rectifier mode
5. The inverter terminal is put into the inversion mode
6. Ramp up voltage and current.

The voltage is raised before raising the current. This permits the insulation of the line to be checked before raising the power. The ramping of power avoids stresses on the generator shaft. The switching surges in the line are also reduced.

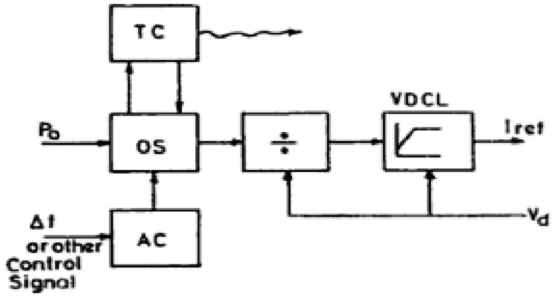
The required power ramping rate depends on the strength of the AC system. Weaker systems require fast restoration of DC power for maintaining transient stability.

Power Control

The current order is obtained as the quantity derived from the power order by dividing it by the direct voltage. The limits on the current order are modified by the voltage dependent current order limiter (VDCOL). The objective of VDCOL is to prevent individual thyristors from carrying full current for long periods during commutation failures.

By providing both converter stations with dividing circuits and transmitting the power order from the leading station in which the power order is set to the trailing station, the fastest response to the DC line voltage changes is obtained without undue communication requirement.

The figure below shows the basic power controller used.



TC-Telecommunication equipment
OS-Order Setting unit

VDCL-Voltage dependent current limiter

When the DC line resistance is large and varies considerably e.g., when the overhead line is very long and exposed to large temperature variations, the DC line voltage drop cannot be compensated individually in the two stations. This problem can be solved by using a current order calculated in one substation only and transmitting its output to the other substation.

Reactive Power Control in HVDC Systems

Introduction

Reactive power control is one of the most important aspects of High Voltage Direct Current (HVDC) transmission systems. Although power is transmitted in DC form through the transmission line, the converter stations operate with AC systems and consume a significant amount of reactive power. If adequate reactive power support is not provided, AC bus voltages may decrease, leading to poor system performance and instability.

Typically, HVDC converter stations require reactive power equal to about **50–60% of the active power transmitted**. Therefore, proper reactive power compensation is essential for efficient and reliable operation of HVDC systems.

Reactive Power Requirements in Steady State

Why Reactive Power is Required

Converter stations use thyristor valves for AC/DC conversion. During the conversion process, the current waveform lags behind the voltage waveform, resulting in reactive power consumption.

The reactive power requirement depends upon:

- Converter firing angle (α)
- Extinction angle (γ)
- DC power transmitted
- AC system voltage
- Converter transformer reactance

Reactive Power Consumption

The reactive power consumed by a converter is approximately given by:

$$Q = P \tan \phi$$

Sources of Reactive Power

The reactive power required by HVDC converters can be supplied by:

AC Filters

AC filters are installed to eliminate harmonics generated by converters. These filters also provide capacitive reactive power to the AC system.

Advantages:

- Harmonic reduction
- Reactive power support
- Improved power factor

Shunt Capacitor Banks

Capacitor banks are connected to AC buses to generate reactive power.

Advantages:

- Simple construction
- Low cost
- Easy operation

Static VAR Compensators (SVC)

A Static VAR Compensator (SVC) is a fast-acting reactive power compensation device widely used in HVDC converter stations.

Construction

An SVC consists of:

- Thyristor Controlled Reactors (TCR)
- Thyristor Switched Capacitors (TSC)
- Harmonic Filters
- Control System

Working Principle

- When system voltage decreases, the SVC supplies capacitive reactive power.
- When system voltage increases, the SVC absorbs excess reactive power.
- The thyristor control system continuously adjusts reactive power output.

Reactive Power Control During Transients

Introduction

A transient condition occurs whenever there is a sudden disturbance in the power system, such as:

- Faults on AC lines
- Sudden load changes
- Converter blocking
- Switching operations
- Generator outages

During such disturbances, converter reactive power demand changes rapidly, causing voltage fluctuations.

Problems During Transients

- Sudden voltage drop
- Voltage oscillations
- Increased converter commutation failures
- Power transfer reduction
- System instability

Methods of Reactive Power Control During Transients

Static VAR Compensators (SVC)

SVCs provide rapid reactive power support within a few cycles after a disturbance.

Functions:

- Maintain AC voltage
- Reduce voltage oscillations
- Improve transient stability

Synchronous Condensers

A synchronous condenser is an unloaded synchronous machine operating solely to generate or absorb reactive power.