Chapter 4

HVDC Controls

The historical background to the developments that took place in the evolution of HVDC controllers will be presented in this chapter. The basis and formulations of modern controllers will be discussed. Because these controllers have an important bearing upon the interconnected AC system, a section will be devoted to inter-actions between the controllers and the system with examples drawn from practical systems.

4.1 HISTORICAL BACKGROUND

To control the firing angle of a converter, it is necessary to synchronize the firing pulses emanating from the trigger unit to the ac line commutation voltage which has a frequency of (60 or) 50 Hz in steady state. In the early 1950s, when the first HVDC converter installations were implemented with mercury arc valves, the relative size of the terminals was small compared to the MVA capacity of the ac systems coupled to these converters. This essentially meant that the grid firing system [1], which was synchronized directly to the sinusoidal ac system waveform, could generate the firing pulses in a relatively stable manner. However, since the three-phase sinusoidal ac waveforms of the ac systems were used as the synchronizing elements, the firing pulses were individually generated for each of the valves of the converter.

In the early 1960s, problems of firing pulse synchronization [2,3,4] were observed due to the distortion of the ac waveform caused by harmonic instability. It was noted that the commutation voltage was neither constant in frequency nor amplitude during a perturbed state. However, it is only the frequency that is of primary concern for the synchronization of firing pulses. For strong ac systems, the system frequency is relatively distortion free to be acceptable for most converter type applications. But, as converter
connections to weak ac systems became required more often than not, it became necessary to devise a scheme for synchronization purposes which would be decoupled from the commutation voltage for durations when there were perturbations occurring on the ac system.

The most obvious method was to utilize an independent oscillator at (50 or) 60 Hz which could be synchronously locked to the ac commutation voltage. This oscillator would then provide the (phasor) reference relationship to the trigger unit during the perturbation periods, and would use the steady state periods for locking in step with the system frequency. The advantage of this independent oscillator was to provide an ideal (immunized and clean) sinusoid for synchronizing and timing purposes. Due to its timing stability, it offered the possibility of equi-distant firing pulses [5,7,13] which eliminated the generation of non-characteristic harmonics during steady-state operation. This was a prevalent and undesirable feature during the use of the earlier Individual Phase Control (IPC) system where the firing pulses were directly coupled to the commutation voltage, \( V_{\text{com}} \).

There were two possibilities for this independent oscillator:

- Use of a fixed frequency oscillator (also called the Pulse Phase Control Oscillator (PPCO)) operating at a fixed frequency of 60 Hz. However, since the system frequency actually drifts between say 55-65 Hz due to the generators used to produce electricity, it was necessary to employ a control loop to track the drifting firing angle. One manufacturer employed a Current Controlled Oscillator (CCO) for this technique.

- Use of a variable frequency oscillator (also called the Pulse Frequency Control oscillator) with a locking range of between say 55-65 Hz and the centre frequency of 60 Hz. This oscillator would then employ a control loop of some sort for tracking the drifting system frequency; the control loop would have its own gain and time constants for steady state accuracy and dynamic performance requirements [19]. Two manufacturers employed a Voltage Controlled Oscillator (VCO) for this approach.

During the mid 1960s, industry, therefore, switched to this type of synchronization unit based on an independent, frequency controlled oscillator controlled by either a voltage or a current source. Both versions relied on an independently controlled oscillator whose frequency was decoupled from the frequency variations of the ac system feeding the converter. This meant that the converter firing pulses could now be truly equi-distant in the steady state.
With time, however, the variant with PPC [8] has become virtually obsolete, and only the PFC [5,7] variant is presently being used by industry.

The equi-distant pulse firing control systems used in modern HVDC control systems are identical to those developed in the mid-1960s [5,7]; although improvements have occurred in their hardware implementation since then, such as the use of micro-processor based equipment etc., their fundamental philosophy has not changed much.

4.2 FUNCTIONS OF HVDC CONTROLS

In a typical two-terminal dc link connecting two ac systems (Figure 4-1), the primary functions of the dc controls are to:

- Control power flow between the terminals,
- Protect the equipment against the current/voltage stresses caused by faults, and
- Stabilize the attached ac systems against any operational mode of the dc link.

![Diagram of typical HVDC system linking two ac systems](image)

**Figure 4-1: Typical HVDC system linking two ac systems**

The two dc terminals each have their own local controllers. A centralized dispatch centre will communicate a power order to one of the terminals which will act as a Master Controller and has the responsibility to coordinate the control functions of the dc link. Besides the primary functions, it is desirable that the dc controls have the following features:
• **Limit the maximum dc current.**

Due to a limited thermal inertia of the thyristor valves to sustain over-currents, the maximum dc current is usually limited to less than 1.2 pu for a limited period of time.

• **Maintain a maximum dc voltage for transmission.**

This reduces the transmission losses, and permits optimization of the valve rating and insulation.

• **Minimize reactive power consumption.**

This implies that the converters must operate at a low firing angle. A typical converter will consume reactive power between 50-60% of its MW rating. This amount of reactive power supply can cost about 15% of the station cost, and consume about 10% of the power loss.

• **Other features.**

Such as the control of frequency in an isolated ac system or enhance power system stability.

In addition to the above desired features, the dc controls will have to cope with the steady-state and dynamic requirements of the dc link, as shown in Table 4-1.

### Table 4-1: Requirements of the dc link

<table>
<thead>
<tr>
<th>Steady State Requirements</th>
<th>Dynamic Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limit the generation of non-characteristic harmonics</td>
<td>Step changes in dc current or power flow</td>
</tr>
<tr>
<td>Maintain the accuracy of the controlled variable, i.e. dc current and/or constant extinction angle</td>
<td>Start-up and fault induced transients</td>
</tr>
<tr>
<td>Cope with the normal variations in the ac system impedances due to topology changes</td>
<td>Reversal of power flow</td>
</tr>
<tr>
<td></td>
<td>Variation in frequency of attached ac system</td>
</tr>
</tbody>
</table>
4.3 CONTROL BASICS FOR A TWO-TERMINAL DC LINK

A two terminal dc link is shown in Figure 4-2 with a rectifier and an inverter. The dc system is represented by an inductance $L$ and a line resistance $R$; the value of the inductance $L$ comprises the smoothing reactor(s), dc line inductance whereas the value of $R$ includes the resistances of the smoothing reactor(s) and the resistance of the dc line etc.

![Diagram of a two terminal dc link with a rectifier and an inverter]

Using Ohm’s law, the dc current $I_d$ in the dc link depicted in the figure is given as

$$ I_d = \frac{(V_{dr} - V_{di})}{R} \quad (4-1) $$

where $V_{dr}$ - dc voltage of the rectifier,

$V_{di}$ - dc voltage of the inverter, and

$R$ - is the dc line resistance.

The power flow transmission of the dc link is therefore given by

$$ P_d = V_d * I_d \quad (4-2) $$

From converter theory, in the case of a CSC the $V_d*I_d$ relationship for a rectifier is given by:
\[ V_{dr} = V_{dor} \cos \alpha - R_{cr} I_d \]  
(4-3)

From converter theory, in the case of a CSC the relationship for an inverter is given by either

\[ V_{di} = V_{dir} \cos \beta - R_{ir} I_d \]  
(4-4)
or, depending on choice of control variable

\[ V_{di} = V_{dir} \cos \gamma - R_{ir} I_d \]  
(4-5)

Using equations describing \( V_{dr} \) and \( V_{di} \) for the case of a CSC, the dc line current is given by either one of two options depending upon the choice of the control mode at the inverter:

\[ I_d = \frac{(V_{dor} \cos \alpha - V_{doi} \cos \beta)}{(R + R_{cr} + R_{ci})} \]  
(4-6)
or

\[ I_d = \frac{(V_{dor} \cos \alpha - V_{doi} \cos \gamma)}{(R + R_{cr} - R_{ci})} \]  
(4-7)

These equations provide the equivalent circuits for the dc link, as shown in Figure 4-3.

Changes in \( I_d \) can therefore occur by:

1. Varying \( \alpha \) at the rectifier. Due to electronic control, this is quite fast and will occur within one-half cycle (or about 8-10 milli-seconds).
2. Varying \( \beta \) or \( \gamma \) at the inverter. This is quite fast and will occur within milli-seconds.
3. Varying AC voltage at rectifier by means of the converter transformer tap changer. This is a slow process and usually takes the order of several hundreds of seconds.
4. Varying AC voltage at inverter by means of the transformer tap changer. This is a slow process and usually takes the order of several hundreds of seconds.
The choice of control strategy is selected to enable a fast and stable operation of the dc link whilst minimizing the generation of harmonics, reactive power consumption and power transmission losses.

The three characteristics represent straight lines on the $V_dI_d$ plane, as shown in Figure 4-4. Notice that eq. (4-4), i.e. the beta characteristic, has a positive slope while the eq. (4-5), i.e. the gamma characteristic, has a negative slope.
The choice of the control strategy [12] for a typical two-terminal dc link is made according to conditions in Table 4-2.

**Table 4-2: Choice of control strategy for two-terminal dc link**

<table>
<thead>
<tr>
<th>Condition #</th>
<th>Desirable features</th>
<th>Reason</th>
<th>Control implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Limit the maximum dc current, $I_d$</td>
<td>For the protection of valves</td>
<td>Use constant current control at the rectifier</td>
</tr>
<tr>
<td>2</td>
<td>Employ the maximum dc voltage, $V_d$</td>
<td>For reducing power transmission losses</td>
<td>Use constant voltage control at the inverter</td>
</tr>
<tr>
<td>3</td>
<td>Reduce the incidence of commutation failures</td>
<td>For stability purposes</td>
<td>Use minimum extinction angle control at inverter</td>
</tr>
<tr>
<td>4</td>
<td>Reduce reactive power consumption at the converters</td>
<td>For voltage regulation and economic reasons</td>
<td>Use minimum firing angles</td>
</tr>
</tbody>
</table>
Condition 1 implies the use of the rectifier in constant current control mode and Condition 3 implies the use of the inverter in constant extinction angle (CEA) control mode. Other control modes may be used to enhance the power transmission during contingency conditions depending upon applications.

4.4 CURRENT MARGIN CONTROL METHOD

The so called “Current Margin Method” of control for two terminal HVDC system is the most widely accepted method in use at present. The method relies on a defined zone of operation of the dc system, with clear functions for both terminals. It also incorporates protection features to protect the dc link [12].

4.4.1 Rectifier mode of operation

The rectifier mode of operation is defined by a number of characteristics as shown in the Figure 4-5.

1. Alpha-min characteristic at rectifier

From converter theory, it can be shown that

\[ V_d = V_{dor} \cdot \cos \alpha - R_{cr} \cdot I_d \]  \hspace{1cm} (4-8)

where \( R_{cr} = \frac{3}{\pi} \cdot \omega \cdot L_{cr} \)

Equation (4-8) describes a straight line AB when plotted as a \( V_d-I_d \) characteristic in steady state, as shown in Figure 4-5. The slope of this characteristic is the value \( -R_{cr} \) which is defined as the equivalent commutation resistance; a low value of \( R_{cr} \) would imply a strong ac system, and the characteristic would be almost horizontal. The intercept of this characteristic on the \( V_d \) axis is equal to the value \( V_{dor} \cos \alpha \) when the value of \( I_d = 0 \). The maximum limit of the voltage \( V_d \) will be defined by the value of \( \alpha = 0 \) degs., i.e. when the rectifier is a theoretical diode converter with firing angle equal to zero. In reality, a minimum value of about \( \alpha = 2.5 \) degs. is normally
required to ensure that the converter valves have a minimum positive voltage for turning on. This zone is bounded by the hatched area in Figure 4-5.

**Figure 4-5: Static $V_d-I_d$ characteristic**

2. **Constant $I_d$ characteristic:**

The converter valves have limited thermal inertia, and therefore cannot carry a large current over their rated value for any extended period of time. Typically, a maximum limit of $I_{max} = 1.2$ pu is specified as the upper limit for the current carrying capacity of the valves. The $I_d = \text{constant}$ current characteristic is a straight line BC, as shown in the figure. The zone of operation is also indicated.
3. **VDCL characteristic:**

The Voltage Dependent Current Limit (VDCL) is a limitation imposed by the ability of the ac system to sustain the dc power flow when the ac voltage at the rectifier bus is reduced due to some perturbation. Some variants of this characteristic utilize a horizontal portion, as defined by C’D, instead of a sloped portion (as defined by CD).

4. **$I_{\text{min}}$ characteristic:**

This limit is usually imposed to maintain enough dc current in the valves to avoid reaching discontinuous current operation with its consequential current chopping phenomena which could lead to dangerous transient dc voltages. Typical values of $I_{\text{min}}$ are between 0.2-0.3 pu.

4.4.2 **Inverter Mode of operation**

1. **Gamma-min characteristic:**

Equation (4-9) defines the $V_d$-$I_d$ characteristic at the inverter; although there are two possibilities, the minimum extinction angle (gamma) option is utilized generally. The line SR (Figure 4-5) defines this mode of operation and is referred to as the Constant Extinction Angle (CEA) control mode. The slope of this line is usually more pronounced than the corresponding one for the rectifier due to the relative strength of the inverter-end ac system.

$$V_d = V_{doi} \cdot \cos \gamma - R_{ci} \cdot I_d$$  \hspace{1cm} (4-9)

where

$$R_{ci} = \frac{3}{\pi} \cdot w \cdot L_{ci}$$

2. **Constant current characteristic:**

The line ST defines the Constant Current characteristic of operation at the inverter. In order to maintain a unique operating point of the dc link, defined by the cross-over point P of the characteristics of the rectifier and inverter, a current margin of $\Delta I_d = 0.1 \text{ pu}$ is normal for the current orders given to the rectifier ($I_{dor}$) and inverter ($I_{doi}$) i.e. $I_{dor} - I_{doi} = \Delta I_d$.

However, the current demanded by the inverter $I_{di}$ is usually less than the current demanded by the rectifier $I_{dr}$ by the current margin $\Delta I$ which is typi-
cally about 0.1 pu; its magnitude is selected to be large enough so that the rectifier and inverter constant current modes do not interact due to any current harmonics which may be superimposed on the dc current. This control strategy is termed the current margin method.

3. Alpha-min in inverter mode:

The line TU defines the alpha-min-in-inverter mode characteristic. This value is typically about 100-110 degrees, and is required to limit any excursions (even transiently) of the inverter into the rectifier mode of operation. Furthermore, the value of 100-110 degrees ensures a minimum dc voltage at the inverter during a fast start-up of the dc link with $I_d = 0$.

4. Current error region:

A modification to the inverter characteristic (line PS’ in Figure 4-5) is often made during the current margin period to avoid any instability due to multiple operating points occurring with a weak ac system at the inverter.

This modification is illustrated in Figures 4-6a and b. Note that the VDCL characteristic has been eliminated in these figures for reasons of simplicity.

![Figure 4-6: Static $V_d$-$I_d$ characteristic for a two-terminal link (a) unmodified and (b) modified](image)

The rectifier characteristic is composed of two control modes: alpha-min (line AB) and constant-current (line BC). The alpha-min mode of control at
the rectifier is imposed by the natural characteristics of the rectifier ac system and the ability of the valves to operate at an alpha angle equal to zero i.e. in the limit the rectifier acts a diode rectifier. However, since a minimum positive voltage is desired before firing of the valves to ensure conduction, an alpha-min limit of about 2-5 degrees is normally imposed.

The inverter characteristic is composed of two modes: gamma-min (line PQ) and constant-current (line QR). The operating point for the dc link is defined by the cross-over point X of the rectifier and inverter characteristics. In addition, a constant current characteristic is also used at the inverter. However, the current demanded by the inverter $I_{di}$ is usually less than the current demanded by the rectifier $I_{dr}$ by the current margin $\Delta I$ which is typically about 0.1 pu; its magnitude is selected to be large enough so that the rectifier and inverter constant current modes do not interact due to any current harmonics which may be superimposed on the dc current. This control strategy is termed the current margin method.

The advantage of this control strategy becomes evident if there is a voltage decrease at the rectifier ac bus forcing the line AB to move downwards. The operating point then moves to point Y and the inverter takes over current control. This way the current transmitted will be reduced to 0.9 pu of its previous value and voltage control will shift to the rectifier. However, the power transmission will be largely maintained near to 0.9 pu of its original value.

The control strategy usually employs the following other modifications to improve the behavior during system disturbances (Figure 4-7):
At the rectifier:

1. **Voltage Dependent Current Limit, VDCL**

This modification is made to limit the dc current as a function of either the dc voltage or, in some cases, the ac voltage. This modification assists the dc link to recover from faults. Variants of this type of VDCL do exist. In one variant, the modification is a simple fixed value instead of a sloped line.

2. **$I_d$-min limit**

This limitation (typically 0.2-0.3 pu) is to ensure a minimum dc current to avoid the possibility of dc current extinction caused by the valve current dropping below the hold-on current of the thyristors; an eventuality that could arise transiently due to harmonics superimposed on the low value of dc current. The resultant current chopping would cause high overvoltages to appear on the valves. The magnitude of $I_d$-min is affected by the size of the smoothing reactor employed.

At the inverter:

1. **Alpha-min limit at inverter**

   The inverter is usually not permitted to operate inadvertently in the rectifier region, i.e. a power reversal occurring due to, say, an inadvertent current margin sign change. To ensure this, an alpha-minimum-limit in inverter mode of about 100-110 degrees is imposed.

2. **Current error region**

   When the inverter operates into a weak ac system, the slope of the CEA control mode characteristic is quite steep and may cause multiple cross-over points with the rectifier characteristic. To avoid this possibility, the inverter CEA characteristic is usually modified into either a constant Beta characteristic or constant voltage characteristic within the current error region.

### 4.5 CURRENT CONTROL AT THE RECTIFIER

The current controller normally used at the rectifier is shown in Figure 4-8. A measurement of the dc current of the dc system is obtained and compared to a reference value $I_o$. The resultant current error $I_e$ is then fed to the PI
regulator with proportional and integral gains $K_p$ and $K_i$ respectively. The output of this regulator is a voltage signal known as the alpha order $\alpha_o$ which controls the frequency output of the VCO. Under conditions of $\alpha_o = 0$, the output frequency of the VCO is a constant at 360 Hz and is set by the input $U_{ref}$ which could be a voltage proportional to a measurement of the ac system frequency; this way any slow modulations of the system frequency could also be compensated for, if required. The sum of $\alpha_o$ and $U_{ref}$ is fed to the VCO which comprises of a resettable integrator and a comparator. The gain of the integrator is selected to be $720\pi$. The output of the comparator is a pulse train at 360 Hz, i.e. 6 times the fundamental frequency. The Ring Counter then derives individual firing pulses for the 6-pulse converter from the output pulse train of the comparator. It is noteworthy that the VCO presents an integral transfer function within the control loop.

![Figure 4-8: Current control at the rectifier end](image)

The frequency of the VCO is at 6 times the fundamental frequency of the ac system. Yet the VCO is totally independent of the frequency of the ac system, other than having the locking or centre-frequency set at 6 times the fundamental frequency. The VCO frequency is therefore free to drift within a frequency range of $f_o \pm \Delta f$, where $\Delta f$ is equal to $(f_{\text{max}} - f_{\text{min}})$. Typically
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The frequencies and represent the upper and lower frequency limits respectively of operation for the VCO.

The mechanism for controlling the frequency of the output of the VCO will now be explained. The negative feedback, current-error loop provides a method to synchronize the independent VCO output frequency with the ac system frequency. Any deviation of the current-error signal from zero will either speed up or slow down the VCO to maintain synchronism with the ac system frequency. For this reason, the term “phase locked oscillator” was coined by its inventor [5]. (In the case of an inverter, an alternative negative feedback loop utilizing constant extinction angle would provide a similar means to synchronize the VCO frequency with the ac system frequency).

4.6 INVERTER EXTINCTION ANGLE CONTROL

For the extinction angle control for the inverter, a technique similar to the current controller at the rectifier is employed. However, the approach is complicated due to the measurement of gamma. For the measurement of the gamma, a direct method would be to measure the valve voltage VV, and the gamma value would correspond to the period that the VV is negative. However, direct measurement of the VV is not always practically nor economically feasible, and alternative or indirect techniques to either measure or predict gamma are used. Furthermore, since there are 6 (or 12) valves in a converter, it is necessary to obtain the minimum value of the gamma of all the valves. Different approaches for the measurement or prediction of gamma have been reported in the literature [14,16,17,18].


One method uses the moment of the firing of the out-going valve and the detection of current zero in that valve to determine the value of the overlap angle μ (Figures 4-9 and 4-10). The ac commutation voltage zero cross-over point, with the voltage going positive, then provides the end of the gamma angle γ. Hence, the ignition angle β can be calculated from a knowledge of the period from the moment of firing of the out-going valve to the moment of the commutation voltage reversal, going positive i.e. \( \beta = \mu + \gamma \).
Figure 4-9: Measurement of gamma - approach 1

Figure 4-10: Measurement of gamma - approach 1

In this method, a prediction of the remaining commutation voltage-time area after commutation is made, and it is maintained to be larger than a specified minimum necessary for successful commutation. The prediction is approximate, but to increase its precision, a feedback loop is employed which measures the error and feeds it back. The choice of the voltage-time area is justified since commutation of a valve is a function of the remaining commutation voltage-time area rather than just the remaining time period alone.

The predictor continuously calculates (by a triangular approximation) the total remaining voltage-time area if firing would occur at that instant. Since the predictor is common to all the valves in one 6-pulse converter, it operates for a period of 60 degrees per valve. Figure 4-11 shows this function for one commutation voltage $U_{sr}$ for valve 3 of the converter bridge.

![Figure 4-11: Prediction of gamma - approach 2](image)

At instant $t_1$, valve 2 fires and a special selector circuit connects the voltage $U_{sr}$ to the predictor circuit. If firing were to occur at instant $t_2$, the remaining voltage-time area after finished commutation will be:
The term \( kI_d \) in the above equation makes an allowance for the fact that the overlap commutation voltage-time area is directly proportional to the dc current \( I_d \). The integral term in the equation can be approximated by a triangular area:

\[
A_m(t_2) = \frac{T/2}{(t - t_2)} \int (U_{sr} \cdot \sin wt) dt - (k \cdot I_d)
\]

(4-10)

where \( t^* \) is the predicted remaining time to the next zero crossing of the commutation voltage; it is calculated as the difference between the measured value of \( T/2 \) and the period \( t_n \), i.e. \( t^* = T/2 - t_n \). The period \( t_n \) started from the previous zero crossing of the voltage \( U_{sr} \) (as can be seen in Figure 4-11).

The voltage \( t_n \) is generated in a three phase device from which the actual phase is selected at each firing instant and connected to the predictor. This is illustrated in the Figure 4-12.
The prediction process follows the relationship

\[ A_{m \cdot pred}(t) = U_{k_n}(t) \cdot t^*(t) - kI_d \]  \hspace{1cm} (4-12)

The approximate method of prediction gives reasonably good values at low values of dc currents with a sinusoidal commutation voltage. However, with large values of dc current and overlap angle, or with harmonic distortion of the commutation voltage, the error becomes significant enough to merit correction through a feedback loop. To achieve this the value of the predicted gamma is stored in a holding circuit. The actual gamma is measured (one cycle later) and subtracted from the previously held value of gamma. The prediction error is defined as:
\[ \Delta A = A_m \text{ pred} - A_m \text{ real} \]  \hspace{1cm} (4-13)

where \( A_m \text{ real} \) is the actual margin. After filtering, \( \Delta A \) is used as a correction signal for the reference value one period (cycle) later. Thus the complete expression for the firing condition is defined as:

\[ (A_m \text{ pred})_k = A_m \text{ ref} + (\Delta A)_k - 1 \]  \hspace{1cm} (4-14)

where the index \( k \) indicates the instant \( k \) and the index \( (k-1) \) the corresponding point one period later.

The prediction process has an inherent individual phase character. If no further action were taken, each valve would fire on the minimum area margin condition. To counteract this, a special firing symmetrizer is used. When one valve has fired on the minimum margin condition, the following five valves are then fired equidistantly by means of the voltage controlled oscillator.

Once a measurement of the gamma angles from the six valves of the converter are obtained, the minimum value is selected. This value is then compared to the desired value of gamma and an error signal is generated and fed to a PI regulator. This gamma error signal is used in a similar manner to the current controller at the rectifier to generate the firing pulses for the converter.

### 4.7 Hierarchy of Controls

The terminal at one end of the DC transmission system is shown in the Figure 4-13. The terminal can be divided into sub-sections i.e. a Bipole which comprises of the positive and negative poles. Each pole can be further subdivided into the star valve group and the delta valve group depending on the transformer configuration used. Each valve group comprises a 6-pulse converter.
Figure 4-13: Hierarchy of controls
Details of the controllers at different hierarchical levels of the terminal are provided next.

### 4.7.1 Bipole Controller (Figure 4-14)

The bipolar controller usually receives a power order $P_o$ from the station operator. This is normally subjected to a controlled rate of increase/decrease in order to protect the system from sudden changes in desired power. A supplementary power modulation signal $\Delta P_o$ can also be inputted at this stage, if required. Maximum power $P_{\text{max}}$ and minimum power $P_{\text{min}}$ limits to the excursions of the power controller are imposed. Finally, the power order is divided by the DC voltage measured value to derive a current order $I_o$ which is sent to the two Pole Controllers. For this circuit, in case of start up routine when the dc voltage may be zero or low value, a bias circuit is required to counteract any problem due to a divide-by-zero function. The output of this controller is the $I_o$ limited value which is subjected to the protective Voltage Dependent Current Limit (VDCL).

![Figure 4-14: Bipole controller](image)

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4.7.2 Pole Controller (Figure 4-15)

The input to each of the Pole Controllers is the current order \( I_o \) from the Bipole Controller. The supplementary current input \( \Delta I_o \) can be added to this \( I_o \) to achieve any modulation of the order if desired. The current input is subjected to upper \( I_{max} \) and lower \( I_{min} \) limits for protective purposes. After limitation, the current order is compared to the measured value of dc current \( I_d \) to generate an error signal \( I_e \). Another signal which modifies the current order is the current margin \( \Delta I \) which is required only at the inverter end to bias off the current controller so that the gamma controller can take over. The current controller uses the PI regulator to provide dynamic properties to the control loop, and provides the alpha order \( \alpha_o \) at its output.

![Figure 4-15: Pole controller](image)

4.7.3 Valve Group (VG) Controller (Figure 4-16)

The alpha order signal from the pole controls is used to generate the firing pulses for the converter in the valve group controller. The VG controller has two separate secondary loops associated with it:
1. Tap Changer (TC) Controller

This is a relatively slow-acting loop (time constant of the order of several hundreds of milli-seconds) which maintains the tap position of the converter transformer. Its function is to maintain the firing angle alpha within a nominal range of about 15 degrees whenever it hits any limits by either raising or lowering the tap position. This will then minimize the reactive power consumption of the converter, and provide sufficient margin for dynamic operation of the converter.

2. The Commutation Failure (CF) Controller

This loop detects the possibility of a CF from measurements of the ac current, commutation voltage and the dc current. Rapid pre-programmed changes to the alpha order can be made as a function of the CF detector for assisting the recovery of the dc system from a CF.

![Figure 4-16: Valve group controller](image)

The measurements available for control and protection purposes comprise the 3-phase commutation ac voltages $V_{ac}$, the ac currents $I_{ac}$ on the primary and secondary sides of the converter transformer, and the dc current $I_d$ and dc voltage $V_d$. The other input/output variables from the various controls are depicted in the Figure 4-17.
4.8 ACTION BY CONTROLS AFTER A DISTURBANCE

Some of the actions that can be taken by the controls during a disturbance are indicated in the Table 4.3.
4.9 REFERENCES


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### Table 4-3: Control actions after disturbances

<table>
<thead>
<tr>
<th>Disturbance</th>
<th>Action</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase Distortion</td>
<td>$\beta_{\text{minimum}}$ limit increased temporarily from 150°-60° for 100 ms</td>
</tr>
<tr>
<td>Rectifier AC faults</td>
<td>$\alpha_{\text{minimum}}$ limit increased temporarily from 5° - 45°</td>
</tr>
<tr>
<td>Inverter AC faults</td>
<td>$\gamma$ Increased transientsly</td>
</tr>
<tr>
<td>- 1 Commutation Failure</td>
<td>$\gamma$ Increased in stages</td>
</tr>
<tr>
<td>- n Commutation Failures</td>
<td></td>
</tr>
<tr>
<td>Block/Deblock or Restart</td>
<td>$\alpha_{\text{minimum}}$ limit increased to 60° and released slowly</td>
</tr>
</tbody>
</table>


