CHAPTER 2

HIGH VOLTAGE DIRECT CURRENT

High-voltage direct-current (HVDC) transmission has advantages over AC transmission in special situations such as underwater cables longer than about 30 km, asynchronous link between two AC systems, transmission of large amount of power over the long distances.

2.1 Basic HVDC System Configurations

HVDC transmission system can be configured in many ways taking into account cost, flexibility and operational requirements. There are four basic configurations in the order of increasing complexity [2, 12].

a. Back-to-back interconnection

This is the simplest configuration in which the two converters are on the same site. That is no transmission line. It normally uses for low voltage (50 KV to 159 KV) to connect the asynchronous tie between two interconnected AC systems.

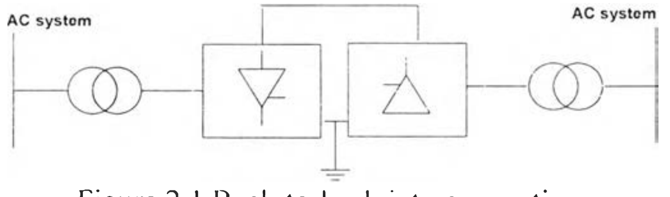

Figure 2.1 Back-to-back interconnection.

b. The monopolar link

In this configuration, the two converter stations are joined by a single conductor line, and the earth (or sea) is used as the return conductor, requiring two electrodes capable of carrying the full rated current.

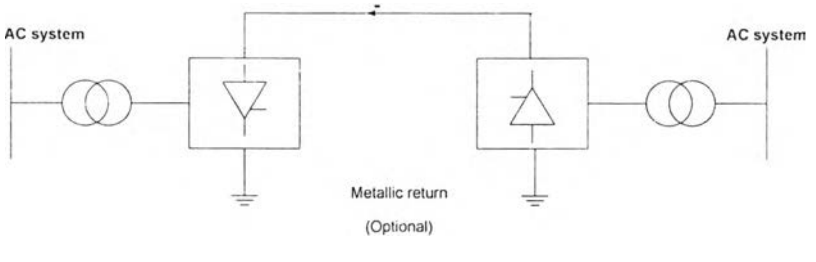

Figure 2.2 The monopolar link.

c. The bipolar link

This configuration consists of two monopolar system combined, one with positive and the other with negative polarity, with respect to ground. If one pole is isolated due to a fault on its conductor, the other pole can operate with ground and thus carry half the rated load or more by using the overload capabilities of its converters and line.

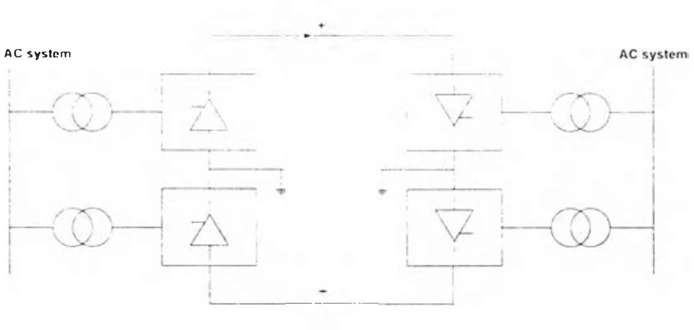

Figure 2.3 The bipolar link.

d. The multi-terminal link

In this configuration the DC system is to be connected to more than two nodes on the AC network.

2.2 HVDC Components

The main components associated with HVDC system are shown in Fig. 2.4 using a bipolar link as an example [2].

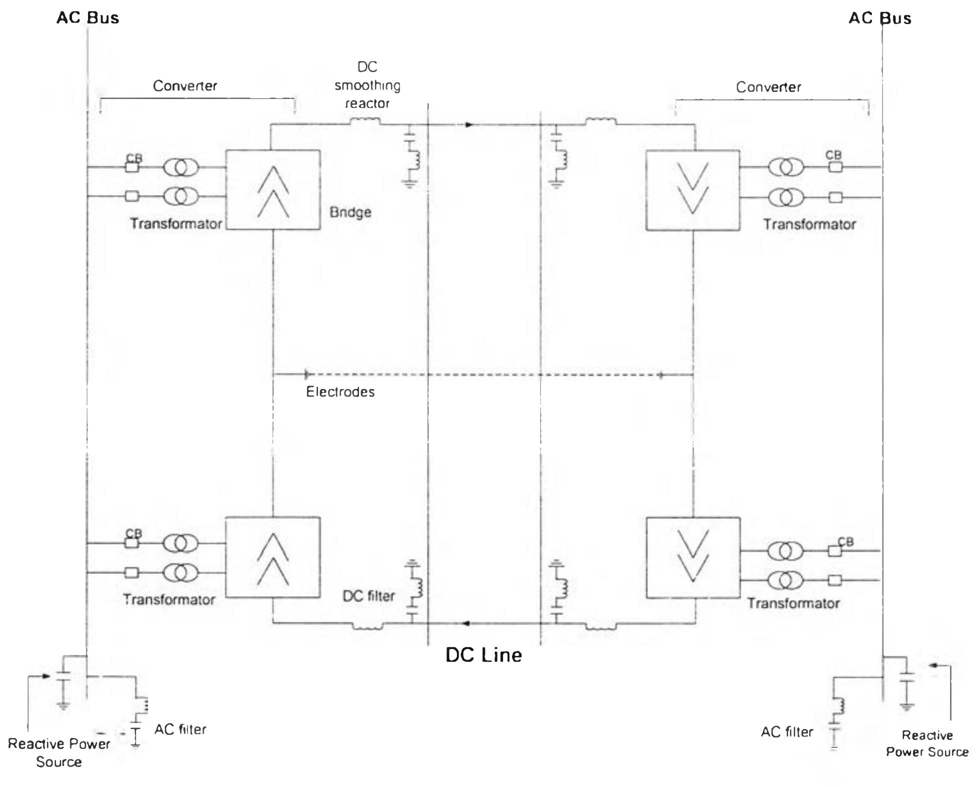

Figure 2.4 A schematic diagram of a bipolar HVDC system.

The followings are brief descriptions of each component shown in Fig. 2.4:

1. Converter
   This equipment performs AC-DC conversion (rectifier) or DC-AC conversion (inverter). It consists of valve bridges and transformer with tap changers. The valve bridges consist of valves connected in 6-pulse or 12-pulse arrangement.
2. DC smoothing reactors
   These are large reactors having inductance as high as 1.0 H connected in series with each pole of each converter station. They are used for curtailing harmonic voltage and current in the DC line to prevent commutation failure in the inverters, and to prevent current from being discontinuous at light load.
3. AC and DC filters
   Operations of the converters generate harmonic voltages and currents on both the AC and DC sides. So these filters are used to reduce such harmonics.
4. Reactive power sources
   DC converters inherently absorb reactive power. Under steady state conditions, reactive power consumed by converters is about 50% of active power being transferred. Under transient conditions, the consumption of reactive power can be even much higher. Thus reactive power sources are provided near converters.
5. Electrodes
   Most DC links use earth as a neutral conductor for at least brief periods of time.
6. DC lines
   It can be overhead lines or cable.
7. AC circuit breaker
   This equipment is used for clearing faults within the transformer, and for isolating the DC link for servicing if needed.

2.3 The AC-DC Converter Model

An individual AC-DC model representing the operation and control of each pole is given in Fig. 2.5. One of the basic modules of HVDC converter widely used, which is the three phase, full wave bridge circuit known as a Graetz Bridge [2]. This circuit has been universally used for HVDC converters as it provides better utilization of the transformer and lower voltage across the valve when not conducting. This circuit is also referred as a 6-pulse bridge circuit.

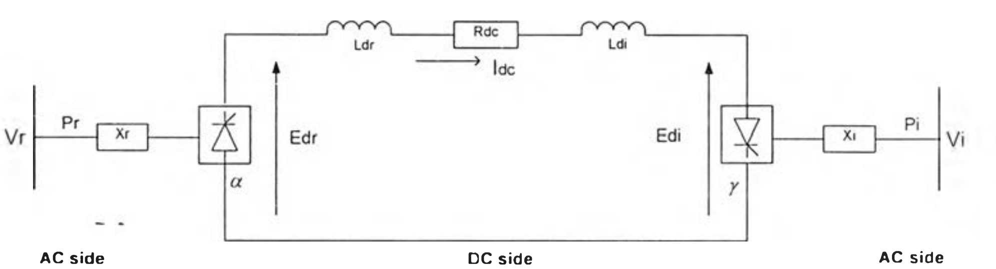

Figure 2.5 An individual AC-DC connection model.

In Fig. 2.5, each variable is defined as follows :

V_r is the AC terminal voltage at rectifier HVDC bus

V_i is the AC terminal voltage at inverter HVDC bus
E_{dr} is the DC voltage at the rectifier side
E_{di} is the DC voltage at the inverter side
X_r is the rectifier commutation reactance
X_i is the inverter commutation reactance
α is the firing/ignition angle of the rectifier circuit
γ is the extinction angle of the inverter circuit
I_{dc} is the direct current in HVDC line
L_{dr} is the smoothing reactor at the rectifier side
L_{di} is the smoothing reactor at the rectifier side
R_{dc} is the resistance in the HVDC link
P_r is real power flowing into the rectifier
P_i is real power flowing into the inverter

Hence, the steady state equations describing the quantities of the DC link can be written as follows :

$$E_{dr} = \frac{3\sqrt{2}}{\pi} V_r \cos(\alpha) - \frac{3}{\pi} X_r I_{dc} \tag{2.1}$$

$$E_{di} = \frac{3\sqrt{2}}{\pi} V_i \cos(\gamma) - \frac{3}{\pi} X_i I_{dc} \tag{2.2}$$

$$I_{dc} = \frac{\left(\frac{3\sqrt{2}}{\pi} V_r \cos(\alpha) - \frac{3\sqrt{2}}{\pi} V_i \cos(\gamma) \right)}{R_{dc} + \frac{3}{\pi}(X_r - X_i)} \tag{2.3}$$

From the above eq. (2.1), we see that the effect of ignition angle (α) is to reduce the average direct voltage at the rectifier by the factor of $\cos(\alpha)$.

Due to the inductance X_r of the AC source, the phase current cannot change instantly. In fact, it requires some finite time defined as the commutation or overlap time. This effect is represented by the DC voltage drop across $R_{cr} = \frac{3}{\pi} X_r$, so that the overlap angle (μ) does not explicitly appear in the equivalent circuit.

For describing of rectifier operation, we refer to the following angles :
α : ignition delay angle
μ : overlap
δ : extinction delay angle ($\alpha + \mu$)

The inverter operation can also be described in terms of α and δ defined above. However, the more common practice is to use an ignition advance angle (β) and an extinction advance angle (γ), of which they are related to the angles α and δ as follows :

β : ignition advance angle $\pi - \alpha$
γ : extinction advance angle $\pi - \delta$
μ : overlap angle $\delta - \alpha = \beta - \gamma$

The rectifier normally operates at a value of α within the range of 15^0 to 20^0. Typically, the value of γ is 15^0 for 50 Hz systems and 18^0 for 60 Hz systems.

2.4 Relationship between AC and DC Quantities

With losses in AC-DC conversion being neglected, the power on AC side is equal to that on DC side [2].

From [2], it can be shown that $I_{L1} = I_{L10} = \dfrac{\sqrt{6}}{\pi} I_{dc}$ (2.4)

where I_{L1} is the RMS fundamental frequency current on the AC side

The above relationship is exact if $\mu = 0^0$. It means that the RMS fundamental frequency current (I_{L1}) when $\mu = 0^0$ (I_{L10}) is exactly the same as in eq. (2.4). With $\mu = 60^0$ the error is 4.3%, and with $\mu < 30^0$ which is of normal operation, the error is less than 1.1%. From eq. (2.4) the converter has essentially fixed current ratio of $\dfrac{I_{dc}}{I_{L1}}$. The variation due to load is only within a few percent.

From Fig. 2.5 above, we can write the real and reactive power equation at the rectifier as :

$$P_r = E_{dr} I_{dc} \tag{2.5}$$

$$Q_r = P_r \tan(\cos^{-1}\phi_r) \tag{2. 6}$$

$$\text{where } \cos(\phi_r) = \frac{E_{dr}}{E_{dr0}} \tag{2.7}$$

The same equation can be written at the inverter side :

$$P_i = E_{di} I_{dc} \tag{2.8}$$

$$Q_i = P_i \tan(\cos^{-1}\phi_i) \tag{2.9}$$

$$\text{where } \cos(\phi_i) = \frac{E_{di}}{E_{di0}} \tag{2.10}$$

2.5 Modeling of HVDC Link

We will use the model depicted in Fig. 2.5 to present a monopolar link of HVDC. The smoothing reactors at the two ends are designated as L_{dr} and L_{di}.

The DC transmission link is presented by the equivalent RL circuit yielding a first order response for the DC current and its dynamics. Based on Fig. 2.5, we can write the following equations :

$$L_{dc}\frac{dI_{dc}}{dt} + R_{dc} I_{dc} = E_{dr} - E_{di} \tag{2.11}$$

$$\dot{I}_{dc} = \frac{\frac{3\sqrt{2}}{\pi}(V_r\cos\alpha - V_i\cos\gamma) - \left(\frac{3}{\pi}(X_r - X_i) + R_{dc}\right)I_{dc}}{\tau_{dc}R_{dc}} \tag{2.12}$$

where

$\tau_{dc} = \dfrac{L_{dc}}{R_{dc}}$ is the time constant of HVDC link

$L_{dc} = L_{dr} + L_{di}$ is the total inductor in the HVDC link

2.6 HVDC Control Model

Under normal operation, the HVDC control strategy consists mainly of constant current (CC) control at rectifier side and constant-extinction angle (CEA) control at inverter side [2, 9]. The CC control is to maintain DC current at its reference value determined from I_{dcr} and an auxiliary input Δu. The output of the current controller is a controlled voltage that goes to the firing angle of the rectifier. On the other hand, the CEA maintains adequate commutation margin.

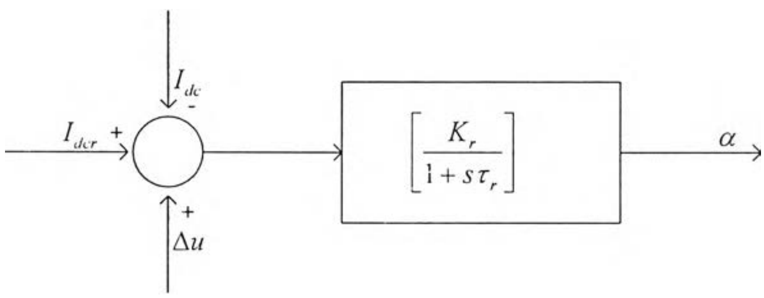

Figure 2.6 Constant current (CC) control at rectifier.

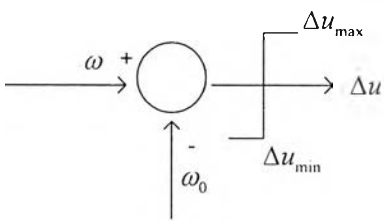

Figure 2.7 Auxiliary input from AC system for rectifier current controller.

Fig. 2.6 shows constant current (CC) control at rectifier side. This controller is adopted from reference [5, 9]. Input Δu of the converter is normally obtained from the AC system quantities. For example, it can be generator speed deviation signal $\Delta\omega$. The purpose of the auxiliary signal is to stabilize the AC system by modulating the current in the DC link. This gives significant damping when network is subject to severe disturbances.

From figures 2.6 and 2.7, we get the differential equation of the rectifier current controller. The dynamic equation for the converter firing angle control is given by :

$$\dot{\alpha} = \frac{K_r(I_{dcr} - I_{dc} + \Delta u) - \alpha}{\tau_r} \tag{2.13}$$

$$\Delta u = \omega - \omega_0 \tag{2.14}$$

where

K_r is a rectifier gain

τ_r is a rectifier time constant

Similarly, the inverter extinction angle control can be described as follows :

$$\dot{\gamma} = \frac{K_i(0.9I_{dcr} - I_{dc}) - \gamma}{\tau_i} \tag{2.15}$$

where

K_i is an inverter gain

τ_i is an inverter time constant

2.7 HVDC Installed in Thailand

Thailand and Malaysia have long enjoyed cooperation, particularly in the energy sector, which has significantly contributed to the security and development of both nations [1]. The HVDC transmission system establishes an interconnection between the Northern part of Malaysia (Gurun) and the Southern part of Thailand (Khlong Ngae, Songkla) as shown in Fig. 2.8.

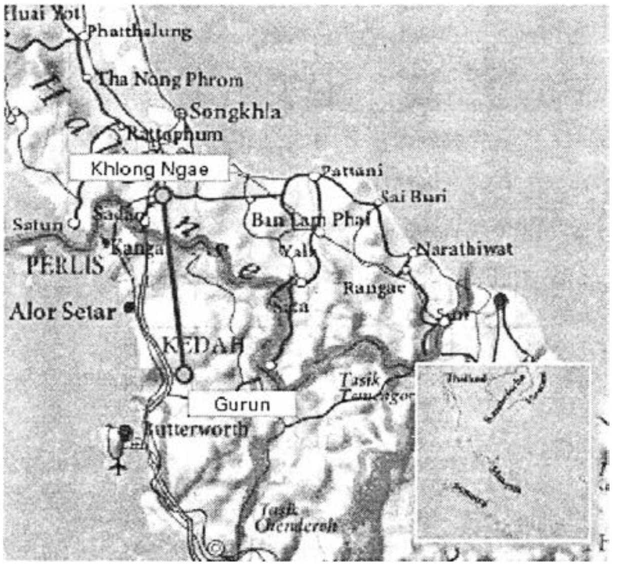

Figure 2.8 HVDC link between Thailand and Malaysia.

There is a wide variation surplus and deficit conditions of generation in the two regions. In the Southern AC network of Thailand the power transmission is southwards from the resources in the central area and is restricted by the long AC lines [13]. In 2002, maximum power demand in the southern of Thailand amounted to 1,356.20 MW. According to the recent load forecast, the demand is projected to increase to 3,547 MW by the year 2016, or an average annual growth of 7% over the next 15 year period. Although EGAT plans to upgrade to central to southern tie line with the addition of 500

KV transmission system. no power generating facilities will be put into the system after the oil-fired Krabi power plant. Thus HVDC interconnection system is expected to improve reliability of the power system of southern Thailand [1].

Both synchronously operated network of TNB (Tenaga National Bhd.) and EGAT (Electricity Generating Authority of Thailand) are interconnected with a 110 km overhead line. The HVDC link is rated at 300 MW (300 KV, 1000 A) and is presently configured as a monopole between the two converter stations. This link has capability to be extended to a 600 MW bipolar HVDC system in the future. The complete transmission line suitable for the bipolar interconnection has already been installed at the initial phase. The HVDC scheme has been in commercial operation since September 2001.

This interconnection system provides various benefits such as economic exchange of power between the two different networks, enhancing system reliability, reduction of reserve capacity of both countries power system by sharing spinning reserve, sharing of HVDC system operational and maintenance experiences, closer cooperation between Thailand and Malaysia [1]. In addition, this interconnection has been included in the ASEAN Interconnection Master Plan Study as a part of the ASEAN Power Grid. The success of the Thailand-Malaysia interconnection will greatly help accelerate the integration of the ASEAN power networks which will significantly enhance the region's sustainability and security of energy supply for benefit of all countries in the region.