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THE APPLICATION OF LIGHT TRIGGERED THYRISTORS TO HVDC TRANSMISSION.

by

Peter Kuffel

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ABSTRACT

This study presents an assessment of the applicability of light triggered thyristors to HVDC transmission. It is based on information obtained through a detailed literature search and from manufacturers actively engaged in light triggered thyristor development. Light triggered thyristors with characteristics suitable for HVDC transmission applications are presently available. Their use could provide many advantages over the conventional electrically triggered thyristor in the area of valve design, complexity and reliability, as well as offering operational improvements, especially when the use of fully digital controls is considered. The main drawback of the light triggered thyristor is the reduced ability to provide overvoltage protection via individual external circuits. This results from the elimination of the electrical gate contact. This limitation has resulted in a concentrated effort by manufacturers to develop an overvoltage self-protection mechanism within the light triggered thyristor. Some success in self-protection has been attained through the use of curved junction gate structures. Light triggered thyristor test valves presently in operation have proven very satisfactory and have led to the development of high voltage prototype valves.

ACKNOWLEDGEMENTS

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1.1 HVDC Transmission

High Voltage Direct Current (HVDC) schemes have become a very important element of power transmission technology. The acceptance of HVDC in the past has been largely due to the reliability of the conversion equipment and the operational features provided by the controls. By far, the most important single piece of conversion equipment is the valve, and the most important control component, the valve firing controls.

The first valves used in HVDC schemes were mercury arc valves. These were large, complex valves which possessed inherent operational disadvantages and caused many possible HVDC users to adopt a "wait and see" attitude. This lack of widespread acceptance led to the development of semiconductor devices which could replace the ionic valves. These devices were first known as Silicon Controlled Rectifiers and later as thyristors.

The thyristor is a four layer device with three P-N junctions and a control terminal called the gate. Under normal forward voltage the thyristor will not conduct until an appropriate gate pulse is received. The first thyristors developed were the Electrically Triggered Thyristors (ETT), in which the gate pulse is in the form of an electrical current.

The application of ETTs to HVDC converter stations became widespread, and all commercial schemes built after the Eel River scheme in Canada in 1972 employ ETTs. The widespread acceptance of the ETT was the result of its improved characteristics over the mercury arc valve. However the use of ETTs in HVDC converter stations posed some problems which were a direct result of the required firing system and the particular application.

The valves within a HVDC converter station must be controllable. That is they must be made to conduct by an appropriate firing signal at a specified time. Because of the nature of a HVDC converter, the firing pulses sent to the valves must be isolated, and the firing circuits must be immune to the noise present in their environment. It is due to these restrictions on firing circuits that some form of optical valve firing system is used.

Therefore in order to employ an ETT valve, the electric gate firing pulse generated near ground potential must be converted to an optical signal which is transmitted to the valve potential via a light guide. There it is converted back to an electrical signal suitable for firing the ETT. Since the optical signal must be converted back to an electrical signal at the valve potential, some additional circuits are required. The most popular firing systems use a light guide to carry the firing signal to a thyristor level firing circuit provided for each ETT. The thyristor level firing circuit is basically composed of a light-electric converter, a pulse amplifier, and a power source capacitor. Most thyristor level firing circuits are so arranged that the power source capacitors are charged by the forward bias across the thyristor itself.

This complex firing system is the source of disadvantages associated with ETT valves. Firstly, the added thyristor level electronics result in a very complex valve structure, increasing its total number of parts and decreasing its overall reliability. Secondly, since many thyristors must be connected in series to make up a valve they must be made to conduct simultaneously. This is more difficult to achieve as the firing circuit becomes more complex which causes a greater spread of turn-on times. Thirdly, auxiliary power required for the light-electric conversion and pulse amplification at the thyristor level also increases valve complexity. If a scheme containing power supply capacitors as described is used, some operation restrictions result. These occur at start up, during bypass operation, and operation with reduced ac voltages. In all three situations the lack of the required forward voltage across the thyristors may result in the capacitors being insufficiently charged, which disables the firing system.

It was due to these shortcomings associated with ETT valves that the development of a directly Light Triggered Thyristor (LTT) applicable to HVDC valves was undertaken. The use of LTTs would enable the optical signal to be fed directly into the thyristor. This would eliminate the need for the thyristor level firing circuits associated with the ETT, resulting in a dramatic decrease in the number of valve parts and valve complexity causing increased reliability. It would also eliminate the operational restrictions associated with the thyristor level firing circuits.

1.2 Thesis Objective

The objective of this thesis is to determine the applicability of LTTs to HVDC converter stations.

1.3 Study Approach

The method used to perform this study was to conduct a detailed examination of available literature. This in turn led to direct contact with some manufacturers actively engaged in the development and testing of LTT valves. An assessment of the applicability of light triggered thyristors to HVDC transmission systems was made from the information located.

1.4 Scope of the Study

In order to fully assess the applicability of LTTs to HVDC transmission systems it is necessary to determine both the effects of LTT use on the HVDC conversion equipment and how the LTTs will interact with the controls. The author assumes that the reader has a basic knowledge of HVDC systems, including common HVDC terminology.

Chapter 2 introduces some general theoretical background into the two major areas of HVDC systems, namely the conversion equipment and controls. The basic concepts of conversion are discussed along with equations describing converter operation. Valve requirements are then presented along with a brief discussion of their past development. The HVDC control hierarchy is introduced, along with a discussion of the general modes of control and the bridge controls. Finally, the protection of HVDC systems is presented, with emphasis on thyristor protection requirements.

Chapter 3 contains a discussion of HVDC controls, in particular the valve firing controls. Voltage dependent schemes and equidistant firing schemes are described. The benefits and shortcomings of each type are discussed. Fully digital control schemes are then considered with emphasis on their configuration and operational characteristics. The inherent protection features associated with the controls are then presented.

Chapter 4 discusses thyristors in more detail. Classifications of thyristor properties are presented along with a discussion of each. Turn-on of a thyristor is described using the two transistor analogy and a general discussion of triggering methods is presented. The need for overvoltage protection of thyristors is determined along with a description of two philosophies for providing protection using external circuitry.

Chapter 5 presents an indepth comparison between ETTs and LTTs with regards to HVDC transmission applications. Consideration is given to differences in valve circuitry and configuration, firing systems, operation and performance, and overvoltage protection.

Chapter 6 is devoted to a discussion of the LTT. Different light triggering configurations are presented along with their associated advantages and disadvantages. Gate requirements for a LTT are discussed with regards to minimum light triggering power, dv/dt capability, and di/dt capability and a successful gate design is presented. Two general approaches for optical firing systems are discussed along with their components, configurations, advantages and disadvantages. The concept of built-in voltage breakover protection is discussed, and two gate structures providing overvoltage protection are presented. Test valves in operation and under design are described and performance data of a 125 kV - 1800 A LTT valve is presented.

Chapter 7 contains conclusions drawn from the study.

CHAPTER 2 GENERAL THEORETICAL BACKGROUND

2.1 Introduction

Over the past thirty years, HVDC has become a very important element of power transmission technology. The first commercial scheme was in Sweden and was rated at 100 kV and 200 A. It supplied 20 MW to the island of Gotland via a 96 km monopolar cable. Present day schemes such as Itaipu in Brazil, which will ultimately consist of two bipoles and be rated 600 kV, 2610 A supplying a total of 6300 MW, illustrate how HVDC transmission has developed. This chapter presents a brief overview of the requirements and development of HVDC technology.

An HVDC system basically consists of two parts. The first is the conversion equipment which forms the basis of the system. The second is the controls which are responsible for the proper application of the conversion equipment, supervision of the conversion process and protection of the equipment. Although these two component parts are separate entities, it is only through their appropriate combination that reliable HVDC transmission can be attained.

2.2 Conversion Equipment Requirements

Although the acceptable and reliable conversion of ac to dc and vice versa depends on the proper application and coordination of many pieces of equipment, the central and most important is the converter itself. The converter basically consists of a number of valves connected to a converter transformer. Various references [1] [2] have shown that the most suitable arrangement of valves is the bridge connection.

2.2.1 Rectifier Operation

For a more detailed explanation of rectifier operation the reader is referred to references 1 and 2.

A three phase rectifier bridge circuit is shown in Figure 2.1(a) and the corresponding ideal voltage and current waveforms are shown in Figures 2.1(b) and 2.1(c) respectively. Under ideal conditions (ie. no transformer winding reactance and no grid control) the dc output voltage is:

$$Vo = \frac{3}{\pi} \int_{-\pi/6}^{\pi/6} \sqrt{2}\, E \cos wt \, dwt$$

$$= \frac{3\sqrt{2}}{\pi} E \quad , \qquad \text{Eqn. 2.1}$$

where E = transformer secondary rms phase to phase voltage.

The rms value of the transformer secondary current is

$$I = \sqrt{\frac{1}{\pi} \int_{0}^{\pi} i^2 \, dwt}$$

$$= \sqrt{\tfrac{1}{\pi} \int_{-\pi/3}^{\pi/3} Id^2 \, dwt}$$

$$= \sqrt{\tfrac{2}{3}}\ Id \quad , \qquad \text{Eqn. 2.2}$$

The transformer rating is

$$\text{MVA rating} = \sqrt{3}\ E\ I$$

$$= \tfrac{\pi}{3}\ Vo\ Id \quad , \qquad \text{Eqn. 2.3}$$

Under ideal conditions, it is seen in Figure 2.1(c) that the current transfer from one valve to another takes place instantaneously. In reality, this is not possible because of the presence of transformer winding leakage reactance. Therefore the current transfer takes a finite amount of time to occur, and the resultant waveforms are illustrated in Figure 2.2.

In Figure 2.2 it is seen that the commutation voltage follows the mean of the two phases participating in the commutation. Therefore there is a drop in the output voltage, and the resultant voltage is given by

$$Vd = \frac{3\sqrt{2}}{\pi} \frac{E\ (1 + \text{Cos}\ \mu)}{2} \quad , \qquad \text{Eqn. 2.4}$$

where μ is the overlap or commutation angle.

As is seen from Equation 2.4, as μ approaches zero, the ideal voltage is obtained.

Under ideal conditions it was assumed that no gate control was available. However, some means of controlling the power flow through the converter is necessary. This can be accomplished by varying the direct voltage from its maximum value down to zero. If the transformer leakage reactance is ignored, then

$$Vd = \frac{3}{\pi} \int_{-\pi/6+\alpha}^{\pi/6+\alpha} \sqrt{2}\ E \text{ Cos } wt \ dwt$$

$$= \frac{3\sqrt{2}}{\pi} E \text{ Cos } \alpha$$

$$= Vo \text{ Cos } \alpha \ , \qquad \text{Eqn. 2.5}$$

where α is the delay angle.

The situation is illustrated in Figure 2.3. As is seen in Figure 2.3, the instant of commutation is delayed passed the natural commutation point a by some angle α, causing a net reduction in dc output voltage.

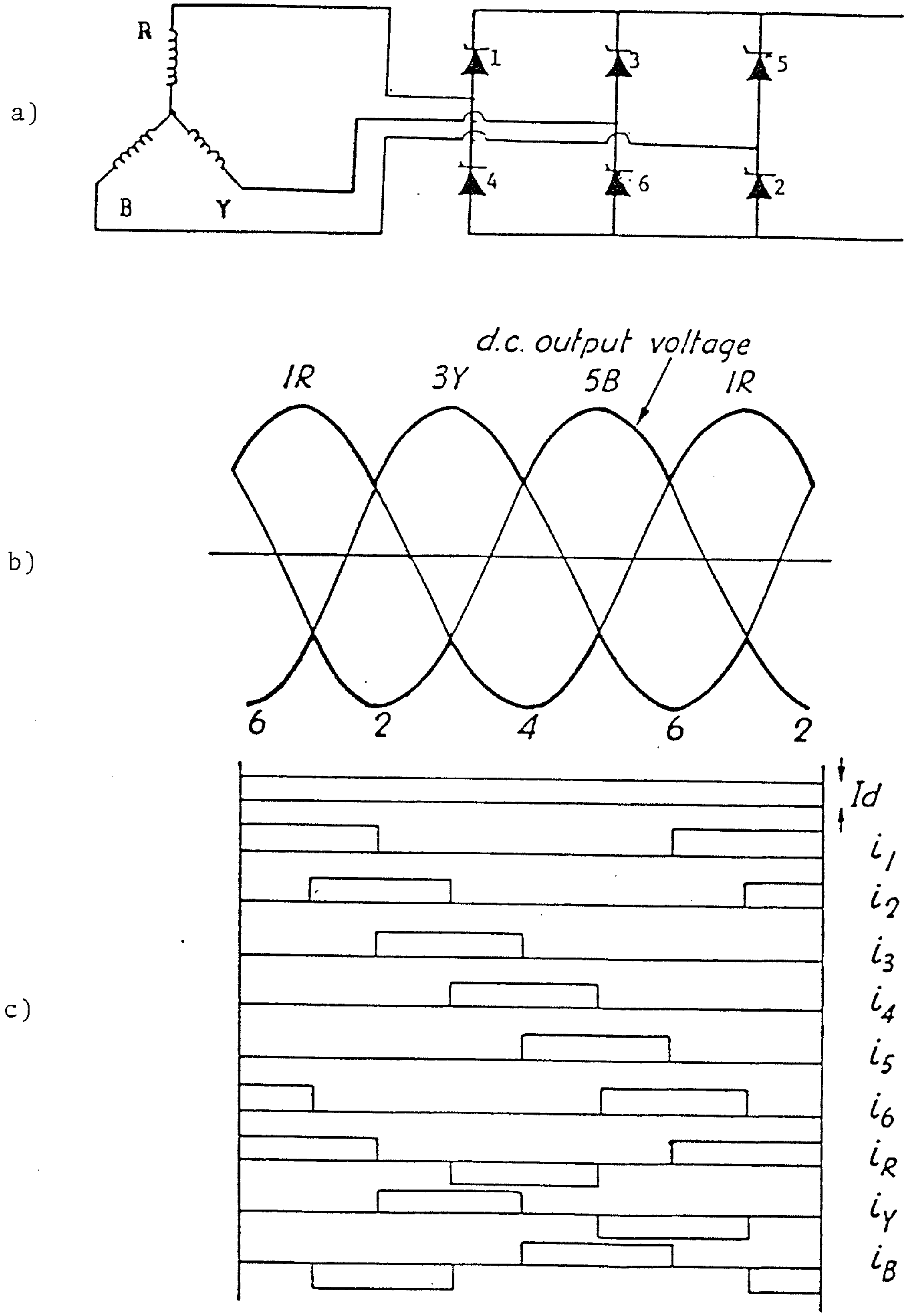


Fig. 2.1 a) Three Phase Bridge Rectifier Circuit, b) Ideal Voltage Waveform, c) Ideal Current Waveform Reference 1.

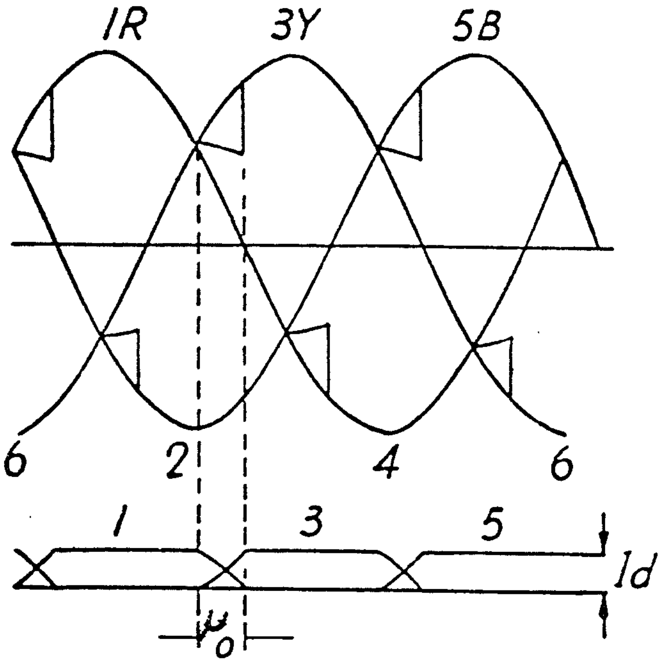


Fig. 2.2 Rectifier Voltage and Current Waveforms with Transformer Leakage Reactance Considered.
Reference 1.

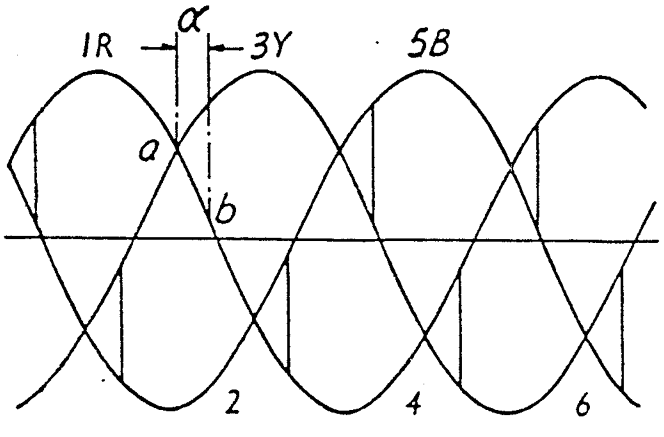


Fig. 2.3 Rectifier Voltage Waveforms with Gate Control.
Reference 1.

In reality both gate control and transformer leakage reactance must be considered and the resultant waveforms are shown in Figure 2.4. Evident in the waveform of Figure 2.4 are the separate effects of gate control and leakage reactance. The dc output voltage under these conditions is given by

$$Vd = \frac{Vo}{2}(\text{Cos}\ \alpha + \text{Cos}\ (\alpha + \mu))$$

$$= \frac{3}{\sqrt{2\pi}} E\ (\ \text{Cos}\ \alpha + \text{Cos}\ (\alpha + \mu))\ , \qquad \text{Eqn. 2.6}$$

where α = delay angle

μ = overlap angle

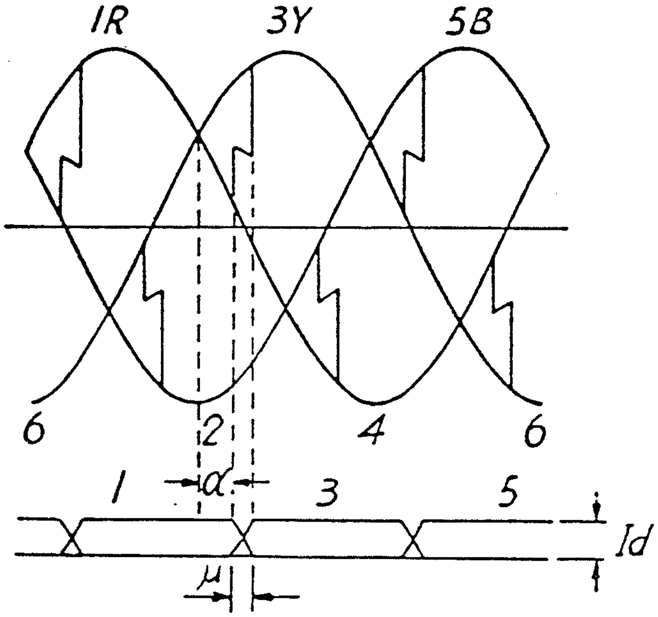


Fig. 2.4 Overall Rectifier Voltage and Current Waveforms.

Reference 1.

2.2.2. Inverter Operation

For a more detailed explanation of inverter operation see References 1 and 2.

As was seen for a bridge operating as a rectifier, gate control enabled the delay of commutation and control of the dc output voltage. If the commutation instant is delayed more than 60°, some negative voltage will result. Because of the presence of the large inductance in the circuit, the net dc output voltage becomes the sum of the positive and negative voltages. At $\alpha = 90^\circ$, the two voltages are equal, providing a net dc output voltage of zero. If the delay angle can be increased past 90°, and an external voltage used which forces the current to flow in opposition to the system voltage, power will be supplied to the ac system. That is, the rectifier has now become an inverter. At $\alpha = 180^\circ$, only negative voltage is present and the inverter is operating at its maximum voltage. Note that delaying commutation past 180° is not possible since at $\alpha = 180^\circ$ the anode voltage of the valve about to fire becomes less than the anode voltage of the outgoing valve and commutation can no longer take place. In fact some overlap angle μ must be allowed for before reaching 180° due to the non-instantaneous transfer of current. As well, an additional angle γ, must be left to allow for the outgoing valve to recondition itself.

The resultant voltage and current waveforms for a three phase bridge inverter circuit are shown in Figure 2.5. Inverter characteristics can be determined the same way the rectifier characteristics were. The final results are:

Let $\beta = 180 - \alpha$

μ = overlap angle

γ = deionization angle

$$Vo = \frac{3\sqrt{2}}{\pi}E \quad , \qquad \text{Eqn. 2.7}$$

$$Vd = \frac{Vo}{2}(\cos\beta + \cos\gamma)$$

$$= \frac{3}{\sqrt{2}\pi}E\ (\cos\beta + \cos\gamma) \quad , \qquad \text{Eqn. 2.8}$$

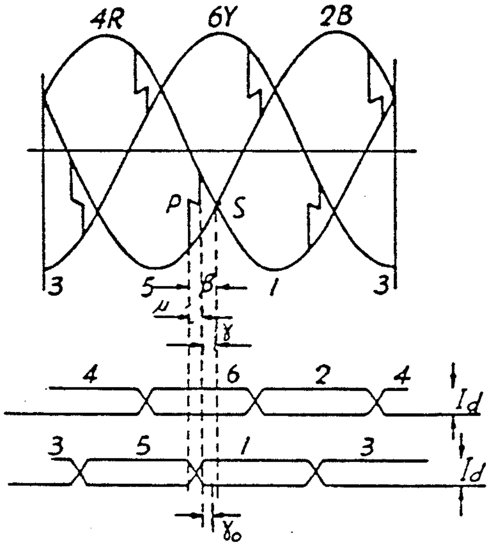


Fig. 2.5 Inverter Voltage and Current Waveforms.

Reference 1.

2.2.3 Converter Development

A converter basically consists of valves connected to a converter transformer in the bridge circuit arrangement. Although the converter transformer plays an integral role in the converter's operation it will not be considered. Instead the valves themselves will be discussed focusing on the various stages of development.

To appreciate the design and development of valves it is first necessary to define the function of the valve. The major functional constraints on a valve are [3]:

1) allow current to pass during the conduction period with a low voltage drop across the valve,
2) the valve should be able to withstand a high negative voltage during the inverse period,
3) the valve should be controlled by the gate, thus when the anode is positive the valve should not fire until a gating pulse is received,
4) the reconditioning time should be as short as possible for inverter operation.

The first generation of valves for HVDC converters were ionic valves. Their development dates back to the early 1900's, and all schemes prior to Eel River in 1972 employed mercury arc valves. However the use of mercury arc valves was not quickly accepted because of their inherent drawbacks. These include such things as:

1) The complexity of the valve, especially as the number of parallel anodes increases.
2) Strict constraints on temperature and pressure.
3) Valve faults such as arcback, firethrough, arc quenching, misfire and consequential arcback [1] [4].
4) Necessity for a bypass valve (ie. a seventh valve) used to relieve the normal service valve from current conduction during a fault since most valve faults are not self clearing [1].
5) Deterioration of characteristics with service time and the need for a major overhaul every five years of service.
6) Large and expensive valve hall building.

It was because of these disadvantages that a new approach was taken. In 1957 the General Electric Company invented the Silicon Controlled Rectifier [6], better known now as the thyristor.

A thyristor is a four layer semiconductor device with three P-N junctions and a control terminal called the gate. Under a forward voltage, two of the P-N junctions are forward biased and one is reverse biased, therefore conduction does not take place. There are a number of ways in which a thyristor can be turned on [6]. These include:

a) Application of a gate pulse.
b) High anode voltage can cause enough leakage current to flow to start the regenerative process.

c) High rate of rise of anode voltage (dv/dt). Since P-N junctions have a capacitance and i = C * (dv/dt), high dv/dt can cause enough leakage or transient gate current to turn on the device.

d) An increase in temperature results in an increase in leakage current which can lead to turn on.

e) Light can induce turn on.

Some of the more important thyristor characteristics include [6] [7]:

1) Gate drive requirements.
2) Rate of rise of anode current capability during turn on (di/dt).
3) Rate of rise of forward voltage capability (dv/dt).
4) Peak forward voltage the device can withstand without suffering damage.
5) Peak reverse voltage that the device can withstand without suffering damage.
6) The minimum forward current that causes the thyristor to maintain conduction, called the holding current.
7) The minimum forward current that causes the thyristor to begin conduction, called the latching current.

The first commercial HVDC scheme using thyristors was Eel River. Each valve consisted of five series connected modules containing a number of series stacks of groups of four parallel thyristors [8]. The thyristors were air insulated and air cooled [8]. Each bridge had a continuous rating of 2000 A, 40 kV and two of these were operated together to form a 12 pulse system, rated 160 MW, 80 kV.

The advantages that thyristor valves offer over mercury arc valves include:

1) No arc backs therefore less bracing is required in the converter transformer resulting in a lower transformer cost. In addition the elimination of arc backs reduces the number of service interruptions and simplifies the protection scheme.
2) No bypass valve is required.
3) If oil immersed valves are used then no valve hall is required.
4) No degassing facilities are needed.
5) Elimination of the clean room needed for mercury arc valve assembly and maintenance.
6) Overall lower maintenance cost since thyristors do not require a major overhaul after a certain period of operation.
7) Thyristors do not deteriorate in service.
8) No warm up time is required.
9) Overall substation space is reduced.
10) Use of 12 pulse system offers a cost savings and operational improvement.
11) Thyristors posses an inherent overload capability which aides overall system stability.
12) Ease of system buildup to any desired rating.

13) High reliability of thyristors.

14) Ease of replacement of failed units.

The main disadvantage of the thyristor valves was the complexity introduced by the need to connect them in series and parallel strings [4]. This requirement was the result of low voltage and current ratings of the individual thyristors and necessitated the use of very complex voltage grading and current sharing systems to ensure proper operation.

As the thyristor technology progressed, improvements in design and cooling resulted in higher voltage and current ratings. The most widely accepted configuration became the air insulated water cooled valve. Such valves were first used in the Nelson River Bipole II scheme.

At present, thyristors with individual ratings of 5 kV, 3000 A are readily available. As a result it is no longer necessary to connect thyristor strings in parallel, offering a great simplification of the valve construction and the control scheme.

As a result of the advantages of the thyristor over the mercury arc valve, the use of mercury arc valves was abandoned. In addition the thyristor has resulted in a greater acceptance of HVDC.

As was mentioned earlier, the two main basic components of an HVDC system are the conversion equipment and the controls. As has been already illustrated, conversion equipment has progressed through a wide range of development and improvement. This development has been equally matched by advances in control schemes.

2.3 Controls

HVDC controls can be generally classified into three groups: the Master Controller, the Pole Controller, and the Bridge Controller. The Master Controller occupies the highest level of the control hierarchy and its output effects the entire system. Its function is to accept an external power order from either a local operator or a remote load dispatch center, modify this order according to present system conditions such as ac system frequency, power angle, etc., and supply each HVDC station with the required inputs for its local controls. The Pole Controller occupies the next level in the hierarchy. Its functions include the control, monitoring and protection of each pole. Typically, each Pole Controller receives an input from the Master Controller specifying either a power or a current order. It also performs other functions such as setting current limits, subtracting the current margin for the inverter, etc. The Bridge Controller determines the required valve firing angle based on inputs received from the Pole Controller and generates firing pulses which cause the appropriate valves to conduct.

Effective control of the HVDC system is based on the reliable and economic supply of a required amount of power. The power Pd delivered by an HVDC system is dependent on the direct voltage Vd and direct current Id. For rectifier operation it can be shown that [1] [2]

$$Vd = \frac{Vdo}{\pi}(\text{Cos } \alpha + \text{Cos } (\alpha + \mu))$$

$$= Vdo \text{ Cos } \alpha - \frac{3wL}{\pi} Id \quad , \qquad \text{Eqn. 2.9}$$

$$Id = \frac{\sqrt{2}}{2wL} (\text{Cos } \alpha - \text{Cos } (\alpha + \mu)) \quad , \qquad \text{Eqn. 2.10}$$

where Vdo = ideal no load direct voltage
E = transformer secondary rms line to line voltage
Id = ideal direct current
α = delay angle
μ = commutation or overlap angle

For inverter operation it can also be shown that [1] [2]

$$Vd = \frac{Vdo}{\pi}(\text{Cos } \gamma + \beta)$$

$$= Vdo \text{ Cos } \gamma - \frac{3wL}{\pi} Id \quad , \qquad \text{Eqn. 2.11}$$

$$Id = \frac{\sqrt{2}}{2wL} E \ (\text{Cos } \gamma - \text{Cos } \beta) \quad , \qquad \text{Eqn. 2.12}$$

where Vdo, E, Id as for rectifier
γ = extinction or deionization angle
β = advance angle = $\gamma + \mu$
μ = commutation or overlap angle

From the preceding equations it is evident that manipulation of Vd and Id (hence Pd) is accomplished through changes in α and μ

for the rectifier and γ, μ, and β for the inverter. Therefore, effective control of the power on the HVDC system is critically dependent on the control of the above mentioned angles, hence the instant of valve firing.

2.3.1 Control Modes

Since each HVDC system is unique, depending on its own requirements, the control system used in each is also unique. Despite this vast difference in actual systems, there are in general only two modes of control [10].

Mode 1 - Rectifier operating in constant current control and inverter operating in constant extinction angle control.

Mode 2 - Inverter operating in constant current control and rectifier operating along the natural voltage characteristic.

In fact, all systems to date operate in Mode 1 although studies indicate that Mode 2 control offers some advantages [10]. Among these are:

- if unidirectional power flow is required then diode bridges can be used for the rectifier since it must only follow the natural voltage level characteristic.
- less reactive power drawn by rectifier.
- less chance of inverter commutation failure since

inverter constant current control tends to use increased γ.

- less rectifier harmonic instability will occur.
- reduced telecommunications are required since more control is at the inverter.

However, Mode 2 control has some inherent disadvantages which include:

- control and protection provided by diode rectifiers is inferior to that of thyristors.
- more reactive power is consumed by the inverter operating with larger γ.

Control Mode 1 has proven through experience very acceptable [10]. As stated before the rectifier operates under constant current (CC) control accomplishing this through affecting required changes in direct voltage based on ordered power and present conditions. The inverter meanwhile, operates under constant extinction angle (CEA) control ensuring safe commutation at the inverter. The complete steady state operating characteristic is shown in Figure 2.6.

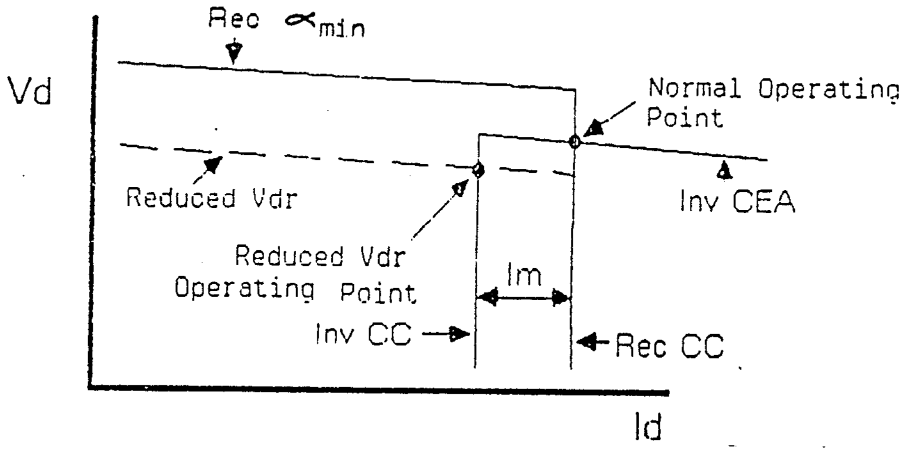


Fig. 2.6 Complete Steady State Operating Characteristic

As is seen in Figure 2.6, the normal operating point is at the intersection of the rectifier CC and inverter CEA characteristics. Changes in the operating point are effected by changing α in the rectifier to increase or decrease the current (shift horizontally) or adjusting tap changers on the inverter transformer causing a change in valve side ac voltage (shift vertically). Also evident in Figure 2.6, is a rectifier α_{min} voltage characteristic and an inverter CC characteristic. The rectifier α_{min} characteristic represents the maximum rectifier direct voltage possible with gate control. If additional changes in rectifier dc voltage are required, then transformer tap changers must be used. In practice, rectifier tap changers are always invoked to bring α into some range (about 10° to 20°) to allow for quick increase in rectifier direct voltage while maintaining acceptable reactive power consumption. The inverter CC characteristic is provided to insure the system does not run down when the rectifier direct voltage drops suddenly below the inverter direct voltage. Instead, it will operate at a reduced current equal to the rectifier current order minus the current margin.

Therefore, the required controls are as follows:

Rectifier

- normally operate under constant current control by varying α and hence the rectifier direct voltage.
- operate at maximum possible rectifier direct voltage if rectifier direct voltage suddenly decreases below inverter direct voltage.
- invoke tap changers to keep α in some predetermined range.

Inverter

- normally operate under constant extinction angle control to minimize reactive power consumption and minimize risk of commutation failure.
- operate at constant current control at a reduced current when rectifier direct voltage suddenly drops below inverter direct voltage.
- invoke tap changers to keep γ at predetermined value.

It is therefore obvious that a carefully designed control system is required in order to ensure the proper coordination and execution of rectifier and inverter operation.

2.3.2 Bridge Controls

As has been previously mentioned, HVDC controls are classified into three groups. Although the Master Controls and Pole Controls occupy higher positions in the control hierarchy than the Bridge Controls, it is the Bridge (or Valve Firing) Controls which have undergone the greatest change.

The function of the Master and Pole Controls is basically to determine the desired power transfer and monitor the system's performance. The valve firing controls, on the other hand are more complex and are the point of interfacing of the controls and conversion equipment, therefore emphasis will be placed on valve firing controls in this study.

An optimal valve firing control scheme would include among other things [10]:

- low amount of uncharacteristic harmonic generation by converters.
- lowest possible reactive power consumption therefore smaller α and γ.
- smooth transition between CEA and CC controls.
- low occurrence of inverter commutation failure, even with distorted ac voltages.
- correct rectifier and inverter operation during frequency variations.

All actual firing control schemes in operation today can be classified into two categories. The first to be developed were called individual phase control schemes or voltage dependent schemes since the generation of valve firing signals is derived directly from the ac system voltage. The second are classified as equidistant firing control schemes and are less dependent on the ac system voltage.

2.4 Protection

In HVDC, controls and protection are complimentary functions to one another. In fact, protection is carried out to a great extent by control action, and when this is integrated along with some protective devices very acceptable operation is achieved.

There are basically five types of faults in an HVDC scheme [1] [2]:

1) Faults on the ac side of the inverter station.
2) Faults within the inverter station.
3) Faults on the dc line.
4) Faults within the rectifier station.
5) Faults on the ac side of the rectifier station.

Of concern in this study are those faults which can cause damage to the valves and what steps are taken to protect the valves. Since the use of thyristors is universally accepted, the protection requirements of the thyristors should be known. The methods which are used provide protection are discussed.

The basic protection requirements of thyristors are [6] [7]:

1) Protection against overvoltage which can cause permanent damage is of the utmost importance.
2) Protection against overcurrent which can cause damage.
3) Protection against too high a dv/dt which can cause commutation failure.
4) Protection against too high a di/dt during turn on which can cause damage.

Protection can be implemented at various levels, that is at the pole level, bridge level, valve level and/or thyristor level. The most common form of overvoltage protection provided is the surge arrester. Surge arresters are usually located at various levels and their use is very well accepted. Protection against overcurrents originating outside the converter station is provided by the smoothing reactor which is also an accepted practice. Therefore the protection methods examined within this study will be those associated with controls and the various protection schemes within the thyristor valves themselves.

CHAPTER 3 HVDC CONTROLS

Since this thesis is a study of the application of LTTs to HVDC a brief discussion of controls and protection is appropriate. This chapter discusses control schemes used in the past, focusing on various valve firing control strategies, then considers the fully digital controls now available and finally examines some additional control functions.

3.1 Conventional Valve Firing Controls

As mentioned in the previous chapter, valve firing controls can be classified into two categories. These are the individual phase control (or voltage dependent) schemes and the equidistant firing control schemes. A brief discussion of both types is presented here, for a more detailed discussion the reader should consult Reference 10.

3.1.1 Voltage Dependent Schemes

Normal rectifier operation is under CC control. Therefore control is basically accomplished by comparing an ordered current value I_{do} with the measured dc line current I_d. A regulator compares the two and produces a signal representing their difference, which when amplified forms a dc control voltage. This control voltage is then used to determine the present α required to make the ordered and measured currents equal.

Normal operation of the inverter is along the CEA portion of the characteristic with the valves firing at some angle β in advance of the natural commutation point. Hence some form of prediction would seem to be appropriate.

Determination of the firing angle is based on the commutation equation [1]

$$-\sqrt{2}Ec \text{ Cos } wt - \sqrt{2}Ec \text{ Cos } \gamma_o + 2wLId = 0 \quad , \qquad \text{Eqn. 3.1}$$

which can be rewritten as

$$-\sqrt{2}Ec \text{ Sin } (wt_1 - \pi/2) + \sqrt{2}Ec \text{ Cos } \gamma_o - XcId = 0 \quad , \qquad \text{Eqn. 3.2}$$

Where Ec = rms value of commutation voltage
Id = average direct current
wt_1 = delay angle
$Xc = 2wL$
γ_o = minimum deionization angle

Various methods have been developed, however all are similar in that they attempt to fire the valves at a predetermined CEA based on prediction using the commutation equation.

Another possible method which eliminates the prediction discussed previously is the closed loop control system. Here the actual extinction angle is measured and compared to the preset value. The error between the two is then minimized by using a negative feedback approach.

Employing such a closed loop system requires careful selection of the loop gain. If the gain is too large, swings between large and small angles may occur when an asymmetry exists. If the gain is too small, inverter stability may be lost for rises in direct current.

As is evident voltage dependent schemes offer a simple and accurate method of firing pulse determination for steady state operation. However, asymmetries which exist in the alternating voltages used to determine the pulse spacing can cause the generation of uncharacteristic harmonics [10]. The effect of these harmonics becomes more pronounced for systems with low equivalent short circuit ratios.

To improve the performance of voltage dependent control schemes, filters are included between the ac system voltages and the control system. The purpose of the filters is to attenuate harmonics which may exist in the ac voltages before they reach the control system. Use of such filters has proven beneficial although they have the inherent disadvantage that the voltages applied to the valves differ from those that the controls are reacting to [10].

3.1.2 Equidistant Firing Control Schemes

Most equidistant firing control schemes employ a voltage controlled oscillator which generates a train of pulses at equal spacing ($60^\circ$for 6 pulse). Such schemes, since not directly dependent on ac voltages, are less likely to produce unequally spaced pulses. Therefore they are less susceptible to uncharacteristic harmonic generation.

The first such scheme was the Phase Locked Oscillator [13]. Many modifications have been added but the principle is still common. The system basically consists of a voltage oscillator and a ring counter. The oscillator generates a train of equally spaced pulses and the ring counter supplies the pulse to the appropriate valve.

A simplified diagram of an oscillator control scheme operating in CC control [14] is shown in Figure 3.1. Operation is as follows:

- control voltage Vc is determined by addition of a bias voltage to the error signal proportional to the difference between measured and ordered currents.
- Vc is then input to the oscillator which under normal conditions produces a train of pulses with a repetition frequency of 6 times the ac system frequency for 6 pulse operation or 12 times for 12 pulse operation.
- the oscillator output is passed to the ring counter which causes the appropriate valve to fire.

The oscillator basically contains an integrator, a level detector and a pulse generator. The output of the integrator and a control voltage V_3 are input to the level detector which sends a signal to the pulse generator when the two are equal. The pulse generator drives the ring counter and resets the integrator. Bias voltage V_1, control voltage V_3, and the integrator constant K are chosen to ensure the system settles to zero steady state error between measured and ordered current. It has been stated [14] that applying the feedback "raw" to the integrator (that is without smoothing or integral control amplifiers) is beneficial since it improves both response speed and stability.

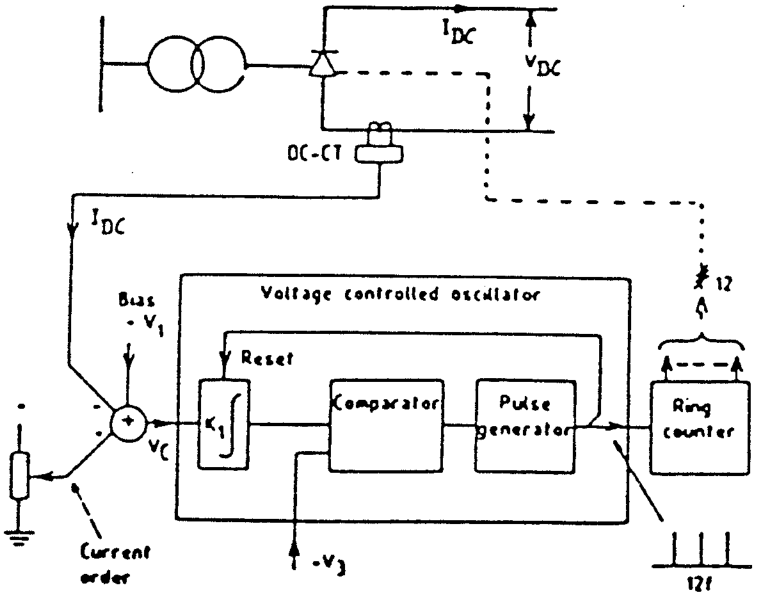


Fig. 3.1 Basic Principle of Phase Locked Oscillator with CC Control Loop.
Reference 10.

CEA control is imperative for an HVDC converter because it is the normal control mode for an inverter and it is used as a backstop for increased firing angles in a rectifier. It has been suggested [14] that the best form of CEA control is the closed loop method since any prediction causes a greater chance of commutation failure.

3.2 Digital Controls

According to a CIGRE report [16], about 44% of the forced outages of HVDC plants surveyed are due to failures in control and protection equipment. The conventional control equipment for HVDC has been composed mainly of analog circuits. However, it was established fairly early in HVDC development that digital control would offer many improvements [17]. There are two basic requirements on a control system [18], and these are:

1) An occurrence such as a component failure should not lead to a system shut down.
2) Any failure must be located within a short time.

In the early 1970's attempts were made to digitalize HVDC control equipment using mini-computers, and later using micro-computers. Many of the control schemes developed were composed of a simple conversion of analogue schemes to difference equations. This resulted in a sampled data control scheme with time delays and dead times which limited speed and accuracy [19].

Recent developments in digital controls are the result of advances in microprocessor technology. Figure 3.2 shows the hardware configuration of a digital HVDC control scheme presented in reference 18. It has the following features:

1) A microprocessor is used to determine gate firing angles from actual plant situations and desired conditions. The microprocessor is also the core of a multiplex system which can oversee itself.
2) Gate firing pulses can be transmitted continuously even if the ac bus voltage is zero resulting in a short restart time. This is due to the memory card and aides the stability of the network.
3) All signals are isolated electrically by using a pulse and optical interface unit.

With reference to Figure 3.2, the major components of the digital control scheme are:

1) Microprocessing Unit (D-HVDC) - The unit enables calculation of a gate firing angle within 1.6ms,providing stability and quick response to overcurrents. The hardware and software self check functions monitor the major functions of all components. Any detected failures are indicated by light emitting diodes.
2) Automatic Pulse Phase Shifter (APPS) - Outputs equidistant gate firing pulses even when the ac bus

voltage is lost by employing a memory circuit.

3) Optical Interface Unit - The control signals interfaced with the control system are isolated from each other in order to allow maintenance of the multiplex system while in operation. In addition, the optical interface checks the signal form and upon detection of a failure, it indicates this and outputs the preceding signal.

4) Multiplex System - A multiplex system is used to ensure that any component failure in the control equipment does not lead to a system down. To ensure stable and reliable operation a triplex system was adopted. The triplex system can operate even when two of the three systems fail.

With the completion of the Blackwater back-to-back scheme in the United States in January 1985, the first completely digital, redundant, fault tolerant control system came into operation [21]. Control is microprocessor based and the fault tolerant redundancy is achieved through the use of Programmable High Speed Controllers (PHSC). All control and protection programs are implemented in the PHSC [21].

The basic fault tolerant control and protection structure adopted for the Blackwater scheme [20] [21] is shown in Figure 3.3. The figure shows a two channel configuration where one channel is in operation and the other remains on 'hot standby'. The change over logic (COL) is used to decide which channel controls the process. This is accomplished through the use of hardware generated self test signals and additional signals from the safe area control (SAC). The SAC is completely independent of the controller and continuously monitors the current and voltage values, initiating changeover if abnormal values are detected. The channel in hot standby mode is updated using a fault isolating bidirectional data link between the channels.

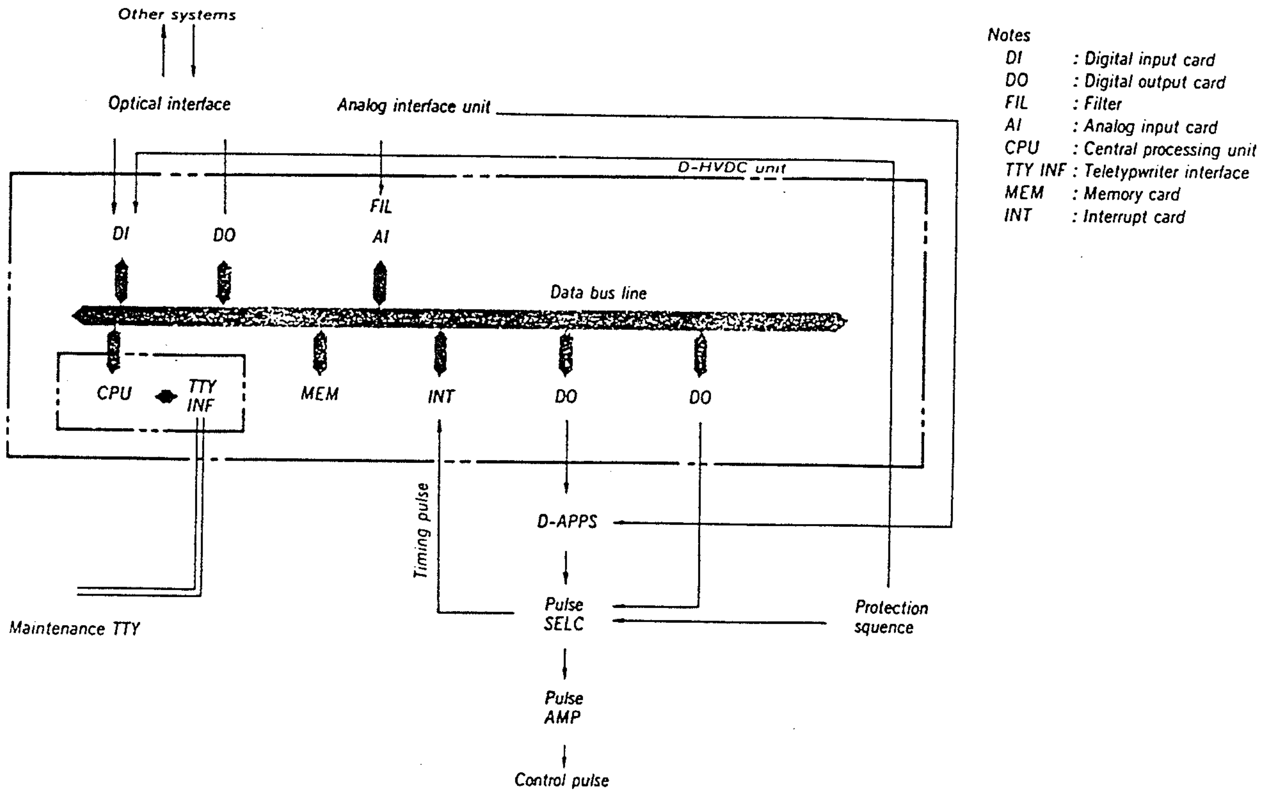


Fig. 3.2 Hardware Configuration of Digital HVDC Control Scheme.

Reference 18.

Benefits of digital control over conventional control are many since microprocessor based controls are more reliable than analog controls [20]. In addition reliability can still be increased further by using a multi-channel redundant system. Another advantage of digital controls is the precise and accurate control they provide and the ease with which the control scheme can be changed [19]. Due to the inclusion of a memory circuit, digital controls will continue the generation of firing pulses even when ac system voltage drops to zero. In general digital controls are more reliable, flexible and accurate than conventional controls.

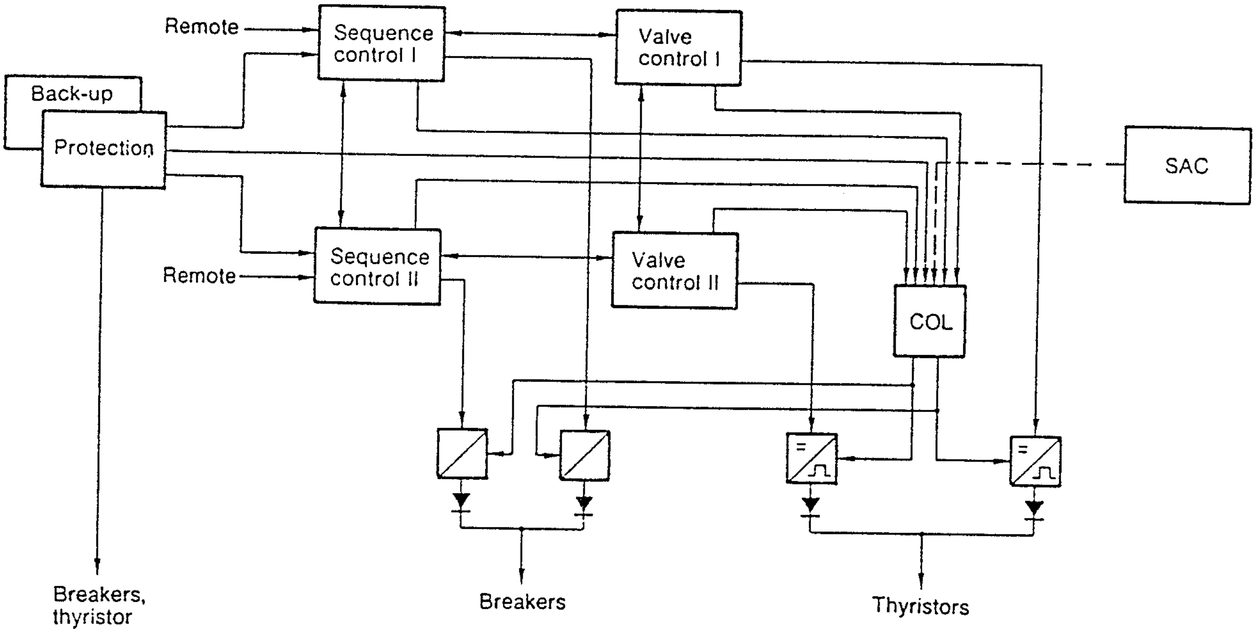


Fig. 3.3 Fault Tolerant Control and Protection Structure

Reference 20.

3.3 Protection by Control Functions

Protection in an HVDC scheme is provided by a combination of protective circuits and controls. The basic protection requirements of the thyristor have already been established, and this section examines the role controls play in providing this protection.

The very nature of HVDC controls, that is the constant current controller, is always striving to ensure that the actual dc line current is equal to the ordered current. For example, upon the occurrence of a dc line fault, the rectifier current will tend to increase, however the automatic action of the current controller will be to reduce this current back to its preset value. In addition, the line fault causes the inverter end current to decrease. This is counter acted by its current controller which takes over from the rectifier current controller. Therefore, control action can limit the fault currents to safe values. In order to clear the fault, the rectifier must be subjected to inverter operation, thereby discharging the stored energy in the dc system. This procedure is initiated once positive fault detection is made [10].

Therefore the basic role of controls in protecting the converters is to limit fault currents. The speed of control actions makes this a very attractive solution. The success of using controls to limit overcurrents in past schemes has proven that the lack of a suitable dc circuit breaker is not a drawback of HVDC when two terminal operation is considered [10].

CHAPTER 4 THYRISTORS

One of the design objectives of LTT development is that non optical characteristics be equivalent to or better than those of an equally rated ETT [23]. The main differences arise as a result of the optical firing system. This chapter provides a discussion of basic thyristor properties and compares differences in LTTs and ETTs which result from the adoption of direct optical triggering.

4.1 Introduction

Since their commercial introduction in the early 1970's, high power thyristors have undergone rapid development. The surface area of the silicon wafers used has increased by 20 times and voltage ratings commonly used have tripled. This has resulted in a doubling of switching power each three to four years, accompanied by a dramatic reduction in the number of thyristors required per MW of dc link power [26]. Figure 4.1 illustrates this trend.

As in many engineering situations, thyristor design is a trade-off process. Table 4-1 illustrates thyristor design parameters and the thyristor properties affected [26]. By assigning economic values to each of the thyristor parameters, the dc converter designer and the thyristor designer can work together to optimize each installation based on performance and cost.

Thyristor Design Parameter	Property Improved	Property Degraded
Increased Base Width	V_{DRM} V_{RRM}	V_{TM} Q_{RR} t_q t_d
Decreased Life-time	Q_{RR} t_q	V_{TM}
Increased Shorting Density	dv/dt	di/dt V_{TM}

Table 4-1 Thyristor Design Parameters and Properties Affected.
Reference 26.

where

V_{DRM} : Maximum repetitive off-state forward voltage

V_{RRM} : Maximum repetitive off-state reverse voltage

V_{TM} : Maximum forward conduction drop

Q_{RR} : Repetitive reverse stored charge

t_q : Circuit commutated turn off (forward recovery) time

t_d : Turn on delay time

di/dt : Permissible rate of rise of turn on current

dv/dt : Permissible rate of rise of voltage

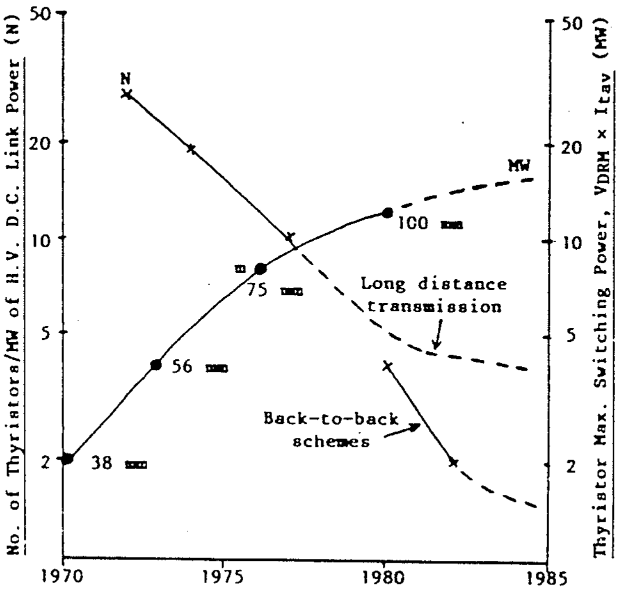


Fig. 4.1 Influence of Thyristor Switching Power Development on the Number of Thyristors/MW of HVDC Link Power.
Reference 26.

4.2 Classification of Thyristor Properties

The main thyristor properties which must be considered for HVDC application are illustrated in Figure 4.2 and can be grouped into the following classes [26]:

1) Those properties which result in a dynamic interaction between the thyristors and other power circuit components. Such interactions occur at gated turn-on and turn-off of the thyristors, and influence the ratings of the power circuit components.

2) Those properties upon which ungated turn-on is dependent. These set the limit for non-destructive thyristor operation and the required protective elements.

3) Those properties which determine the thyristor losses, (basically the forward conduction loss) and determine the rate of cooling required to control the thyristor junction temperature within a preset range.

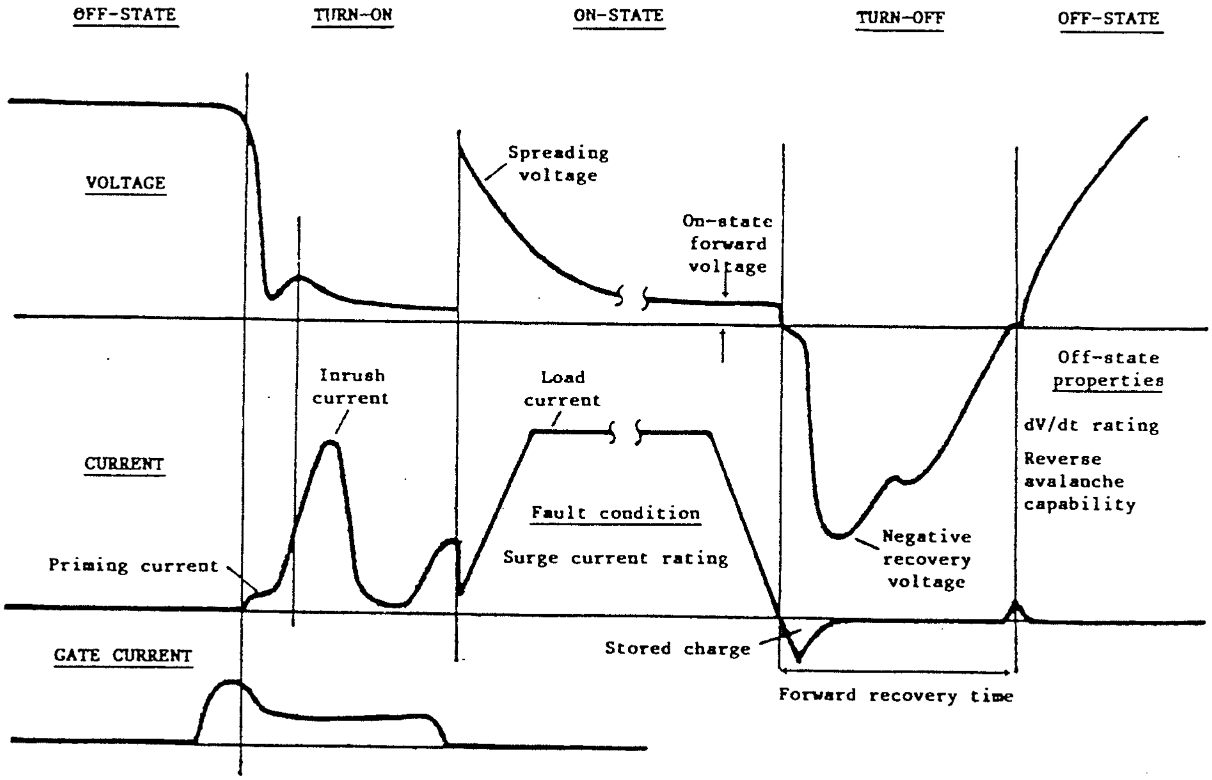


Fig. 4.2 Thyristor Properties Important in HVDC Reference 26.

Class 1

Generally the rate of rise of valve current during gated turn-on is relatively slow. However, stray capacitances always present within an HVDC valve and the capacitors contained in the RC snubbers must be discharged during turn-on [27]. The inrush current oscillation resulting from the discharge of these capacitances must be limited to within the thyristor's di/dt capability. This is best accomplished by the distribution of series linear and saturable reactors within the valve [26] [27] [28].

The principal quantities of concern at turn-off are the stored charge (Q_{RR}) and the forward recovery time (t_q) which result from residual current carriers from the forward conduction period. The stored charge depends on the commutating di/dt near current zero, temperature, magnitude of negative recovery voltage and the thyristor itself [26]. The forward recovery time is the time which must elapse between the stoppage of forward current flow and the reapplication of a forward voltage. Premature application of forward voltages can cause the thyristor to begin conducting again. The forward recovery time is dependent upon the same factors as the stored charge in addition to the forward dv/dt and thyristor level reactor impedance [26].

During turn-off, the thyristor does not block reverse voltage instantaneously, and the commutating voltage causes reverse current to flow [27]. When the thyristor blocks, the reverse current stops suddenly and can result in a high reverse voltage ($E = L*di/dt$) [6]. In order to reduce the di/dt, a capacitor is placed across the thyristor which can absorb the energy of the commutating inductance. However, a capacitor can not be used alone since the circuit would be seriously underdamped and results in a high voltage for the first oscillation. Therefore a resistor, which approximates the critical damping of the circuit is included [6]. The RC circuit mentioned above is better know as the snubber, and is connected across each individual thyristor.

Class 2

All types of ungated turn-on have the potential to damage the thyristor. This is because ungated turn-on can produce weak triggering of the thyristor. Weak triggering results in a very limited initial conduction channel and hence possible damage if the current following turn-on is high.

Ungated turn-on may result from insufficient recovery time, excessive dv/dt, and overvoltage. The conditions for the first two types of turn-on are similar in that a forward voltage is applied across the thyristor. Overvoltage turn-on occurs as a result of forward avalanche at normal operating temperature, or thermal runaway due to excessive leakage current at high temperature [26]. The process of voltage breakdown as well as various protection options for thyristors will be further discussed in later sections of this chapter.

Class 3

The dominant factor in calculating the energy dissipation within the thyristor is the forward conduction loss. This can be evaluated from the thyristor current waveform and a thermal and electrical model based on measured V-I-T characteristics [26].

As was mentioned at the start of this chapter the major differences between an LTT and ETT result from the triggering methods used. This includes differences within the thyristor, differences between firing circuits and effects of the triggering methods on overvoltage protection.

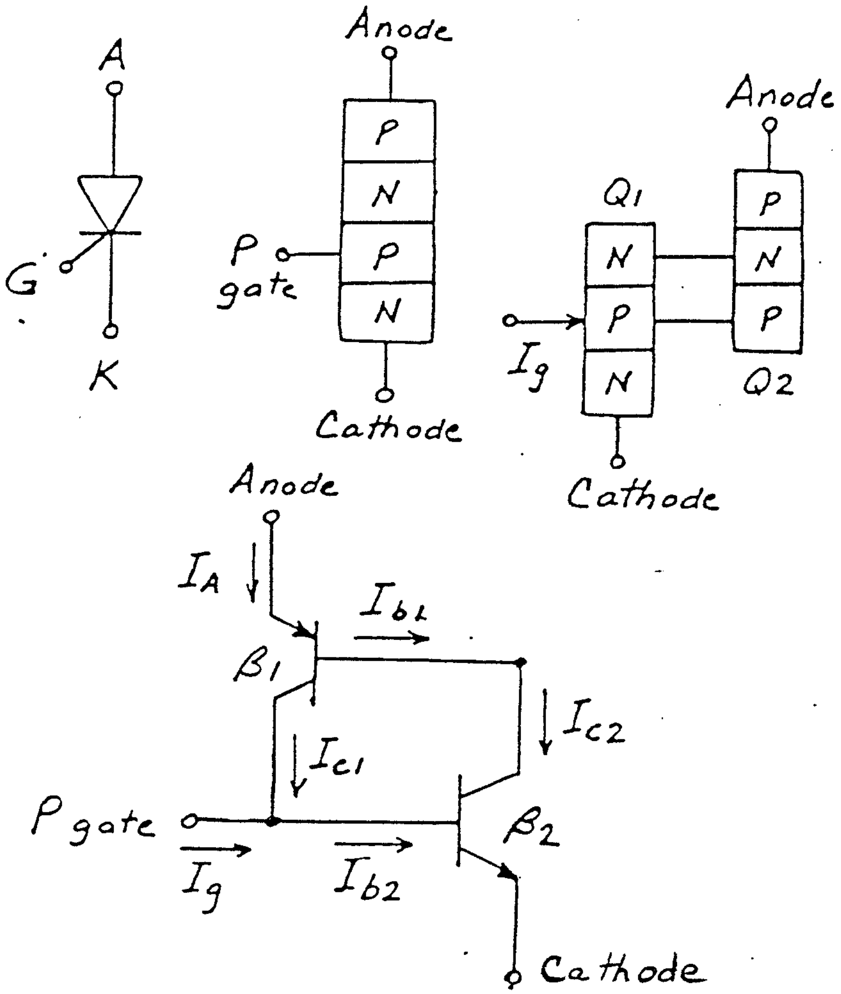


Fig. 4.3 Two Transistor Model of a Thyristor.
Reference 6.

4.3 Thyristor Turn On

As discussed in Chapter 2, the thyristor is a four layer device with three P-N junctions and a control terminal called the gate. A simple way to illustrate thyristor operation is to use the two transistor equivalent representation [6] shown in Figure 4.3.

In the circuit shown in Figure 4.3, the two transistors have common emitter current gains. Therefore

$$I_{C1} = \beta_1 I_{B1} \qquad \text{Eqn. 4.1}$$

$$I_{C2} = \beta_2 I_{B2} \qquad \text{Eqn. 4.2}$$

and since

$$I_{B1} = I_{C2} \qquad \text{Eqn. 4.3}$$

hence

$$I_{C1} = \beta_1 \beta_2 I_{B2} \qquad \text{Eqn. 4.4}$$

Also from Figure 4.3

$$I_{C1} + I_g = I_{B2} \qquad \text{Eqn. 4.5}$$

From equations 4.1 to 4.5 it is seen that as I_g increases so do

I_{c1} and I_{c2}. In addition for most silicon transistors β increases as emitter current increases for low values of emitter current. This is an important characteristic for thyristor operation. Accompanying the increase in I_g, there is a regenerative increase in I_{c1} and I_{c2} until both transistors saturate. As long as there is anode voltage available to cause base current in Q1 to flow, I_{c1} forms a positive feedback to saturate Q2. In turn, Q1 is saturated by I_{c2}. Under these conditions the thyristor is conducting, being limited only by forward voltage drops.

The thyristor will stop conduction if the current is reduced and I_g is not present. A reduction in current causes a reduction in β_1 and β_2 and hence a reduction in I_{c1} to the point where the regenerative process stops and the thyristor turns off.

In many ways an ETT and a LTT are structurally similar. Figure 4.4 (a) and (b) illustrate a partial radial cross section of an ETT and LTT respectively [22]. In both figures (a) and (b), current components 1 and 2 bias and charge the pilot stage emitter and components 3 and 4 bias and charge the main emitter junction. Components 1 and 3 are composed of a capacitive component which charges up the N^+ emitter - P base junction capacitance and a resistive component whose relative size depends on the P-N junction voltage. Components 1 to 4 are primarily hole currents. Components 5 and 6 are hole and electron currents respectively composed of photon generated electron hole pairs separated in the field of the reverse biased

N base - P base junction.

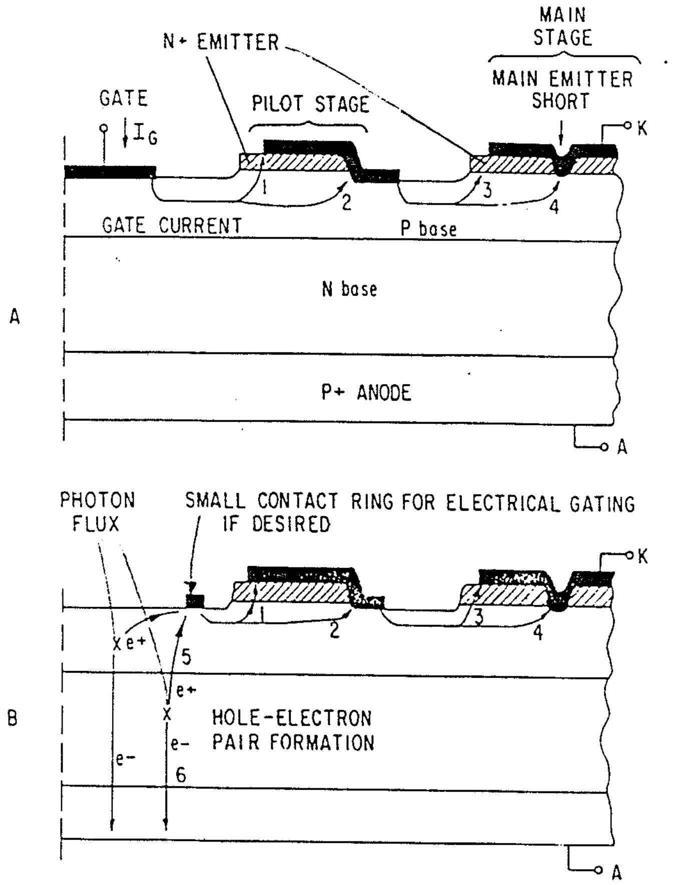


Fig. 4.4 Partial Cross Section of: a) ETT, b)LTT.
Reference 22.

In the ETT holes are caused to flow between the gate and cathode by an applied electrical signal and triggering is thus accomplished [22]. In the LTT, triggering is possible because of the production of electron hole pairs when light of certain wavelengths is absorbed in silicon [24], with the holes providing the gate current [22]. For efficient utilization of the photogenerated electron hole pairs, it is desired that they be generated in or near the depletion layer so that they are rapidly accelerated apart by the electric field in the depletion layer and do not have a chance to recombine. Electron hole pairs generated outside the depletion layer will not be efficient in triggering the thyristor since many will recombine [25].

The light energy available at the thyristor end of a practical optical firing system may be as low as several tenths of the electrical energy supplied to an ETT [29]. This very limited amount of light energy requires a very sensitive gate structure, capable of triggering the thyristor. However, a highly sensitive gate tends to be more affected by noise from the main circuit which results in a low dv/dt capability. The dv/dt capability can be increased by making the light sensitive area small, however this results in reduced di/dt capability [29].

4.4 Thyristor Triggering Methods

One problem of using thyristors in HVDC and other utility applications is that many thyristors must be strung in series and must therefore be turned on simultaneously. Therefore a major requirement of thyristor use in HVDC converters is that they must be triggered by a gate signal isolated from ground and the control circuitry must be capable of correct operation in the high noise environment [22].

It has long been established that there are basically two methods of firing ETTs to achieve signal isolation and noise immunity [4]. The first employs light guides to bring the firing signals to valve potential, and isolating transformers to transmit the signals to each thyristor. Auxiliary power is then only required at the valve platform and can be supplied through an auxiliary transformer.

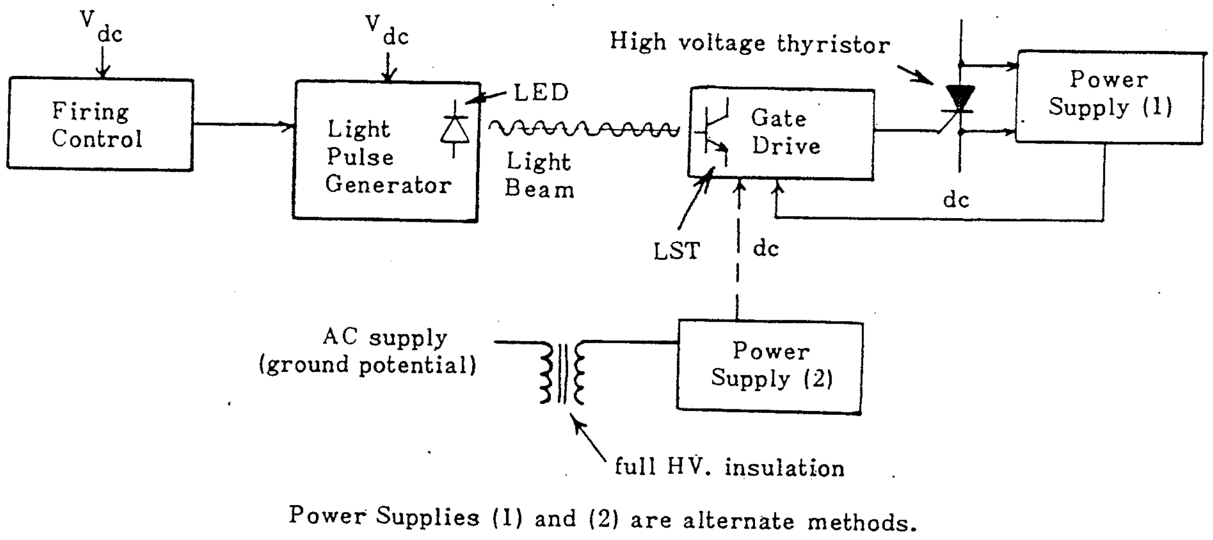


Fig. 4.5 Basic Components of ETT Firing System.
Reference 6.

The second method is to use light guides to transmit the firing signals right up to each of the thyristors. This approach requires the use of amplifying circuits at each thyristor and therefore auxiliary power at the thyristor level. This auxiliary power can be supplied either by cascaded transformers or from the voltage across the thyristor itself.

The basic components of such a firing system are shown in Figure 4.5

The first method of ETT triggering has the problem of noise immunity and gate current rise rate. The second method has the drawback of the large number of components needed for the light-electric conversion and amplification in the gate system [30]. The use of LTTs will allow the direct connection of the optical guide to the thyristor, therefore eliminating a large number of components at the thyristor level required for ETT use.

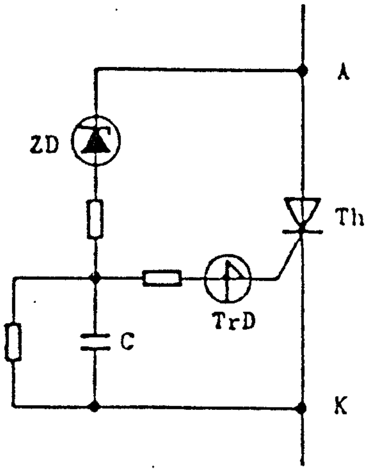


Fig. 4.6 Individual Overvoltage Protection Circuit. Reference 31.

4.5 Overvoltage Protection

Power semiconductor devices of all kinds are susceptible to destructive breakdown if the avalanche voltage is exceeded. The reason that avalanche turn-on is so destructive is that it is extremely rapid and involves a very narrow current path. With such high voltages and such small semiconductor volumes only a few millijoules of energy are needed to melt the silicon along the current path [22]. Therefore breakdown voltage levels are designed for the highest system voltage transients.

Voltage breakdown can be avoided by triggering the thyristor upon the detection of dangerous voltage levels. This can be done by a variety of external circuits, which can be basically grouped into two practical categories [31].

1) Individual Device Emergency Firing

This system basically consists of a voltage detection unit and a circuit to produce a firing signal when the measured voltage exceeds a preset value for each thyristor. Figure 4.6 illustrates the principle of such a scheme. When the forward voltage between the anode (A) and cathode (K) of the thyristor (Th) exceeds the breakdown voltage of the zener diode (ZD), the capacitor (C) is charged rapidly. As the voltage across the capacitor reaches the switching voltage of the trigger diode (TrD) the TrD impedance is sharply reduced. This allows the charging current to flow into the thyristor gate and acts as a firing pulse to turn the thyristor on. In such a method, the breakover voltage of the zener diode must be carefully selected in order to assure protection and avoid unwanted operation.

2) Central Emergency Firing Device

In this method, the voltage across all or some of the thyristors is monitored. This monitored voltage is sent to the valve base electronics where its logic decides whether the thyristor valve requires emergency firing. The basic requirements of one possible such a system [31] are shown in Figure 4.7.

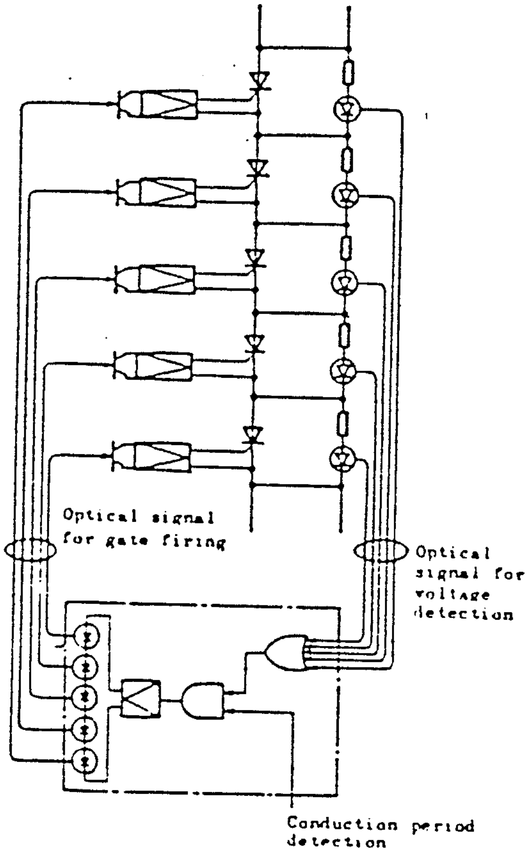


Fig. 4.7 Central Emergency Firing System.
Reference 31.

The above two methods have been proven effective at installations using ETTs. However the first method uses the overvoltage itself as the source of the electric gate current and hence can not be used for LTT valves since no terminal for electrical input is provided. Therefore the only possible method of external protection is the central firing of all thyristors. Another possible method of overvoltage protection is to provide a built-in nondestructive voltage breakdown mechanism within the thyristor itself. Advances in LTT overvoltage self protection will be discussed in forthcoming chapters.

This chapter has provided a more detailed discussion of thyristors and has also illustrated some basic differences between the ETT and LTT. Before proceeding with a discussion of LTT status with regards to HVDC applications, it is useful to determine whether the use of LTTs would indeed be beneficial to a HVDC transmission system. This can be accomplished by qualitatively comparing the effects of using ETTs and LTTs in HVDC transmission
systems.

CHAPTER 5 LTT VERSUS ETT

In order for the LTT to become commercially accepted, its use must offer some advantages over the use of the well proven ETT. These advantages must be either economic or provide improved reliability. In addition, the use of LTTs must not pose any additional drawbacks on acceptable HVDC operation. Therefore, a detailed discussion of all the advantages and disadvantages associated with LTT use as compared to ETT use is essential.

5.1 Thyristors

One goal of LTT design is to keep non optical characteristics the same as a comparable ETT [23]. Figure 5.1 shows an LTT and a correspondingly rated ETT developed by Mitsubishi for use in HVDC transmission systems [32]. Table 5.1 illustrates their major ratings and electrical characteristics.

As is evident from Figure 5.1 the only difference in physical appearance between the two is the gate connection. The ETT has wires extending out of the package to connect to the thyristor level firing electronics, while the LTT has an optical connector to which a light guide is connected. The main idea between the LTT and ETT being physically similar is that the proven cooling and insulation methods developed for the ETT can be applied to the LTT [24] [30].

From Table 5.1 it is seen that all major ratings and electrical characteristics of the LTT and ETT are identical except the di/dt. Again the idea behind keeping the two similar is that the technology proven in reactor design and grading circuits used for ETTs can be applied to LTTs [30].

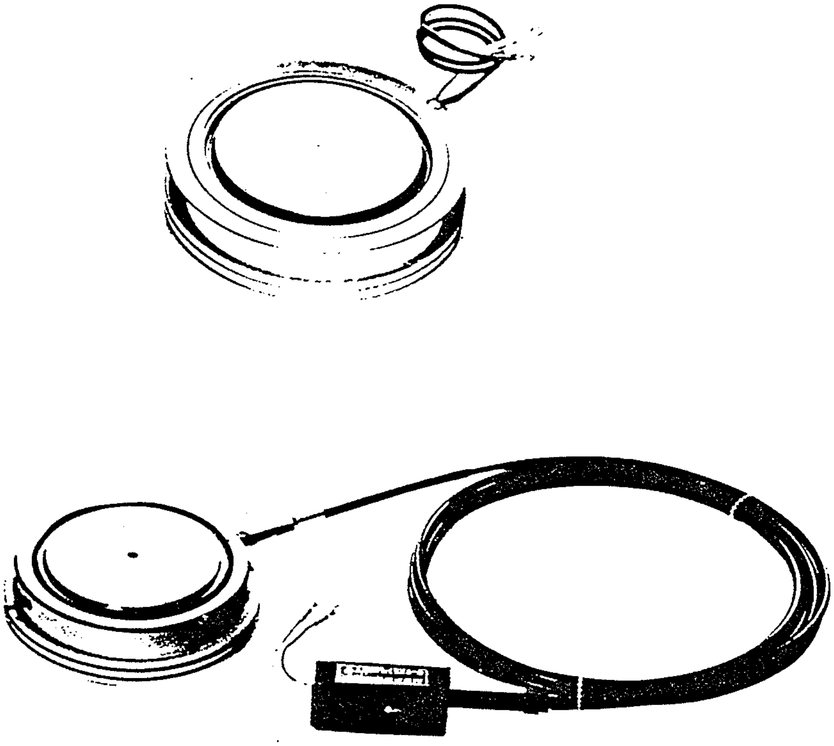


Fig. 5.1 Mitsubishi ETT (FT1500DU) and LTT (FT1500FU-120)
Reference 32.

Characteristics		ETT FT1500DU	LTT FT1500FU-120
V_{DRM}	(V)	6000	6000
V_{RRM}	(V)	6000	6000
V_{RSM}	(V)	6000	6000
$I_{T(AV)}$	(A)	1500	1500
I_{TSM}	(A)	30000	30000
di/dt	(A/us)	250	200
T_j	(C)	-40~125	-40~125
V_{TM}	(V)	3.0	3.0
t_q	(us)	400	400
dv/dt	(V/us)	2000	2000
R_{th}	(C/W)	0.010	0.010

Table 5-1 Ratings of Mitsubishi ETT and LTT in Figure 5.1 Reference 33.

where

V_{DRM} : Repetitive peak off-state voltage

V_{RRM} : Repetitive peak reverse voltage

V_{RSM} : Nonrepetitive peak reverse voltage

$I_{T(AV)}$: Average on-state current

I_{TSM} : Peak one cycle surge on-state current

di/dt : Critical on-state current rate of rise

T_j : Storage and operating temperatures

V_{TM} : Peak on-state voltage

t_q : Turn-off time

dv/dt : Critical off-state voltage rate of rise

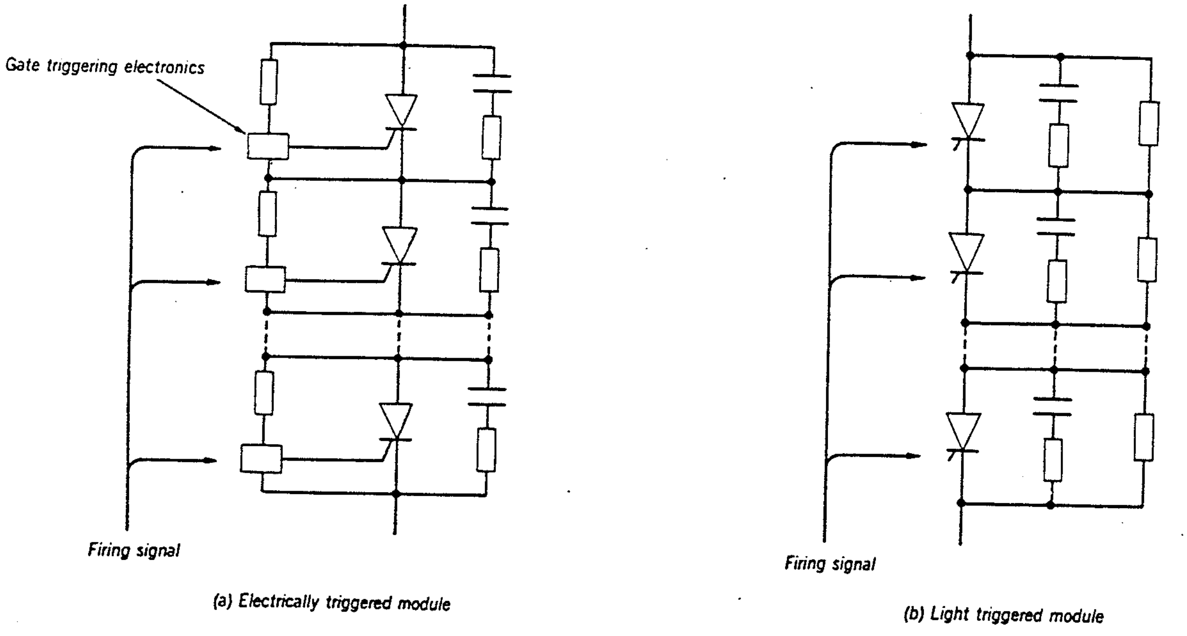
R_{th} : Thermal resistance

5.2 Valve Configuration

Past trends have shown that the most beneficial design of a valve is based on a modular approach using air insulated, water cooled thyristors. Each module contains a certain number of electrical components and all the auxiliary and cooling facilities for those components. This approach is used to enable quick and easy replacement of any failed modules. Each thyristor module contains a number of thyristors connected in series, any gate firing electronics that may be required, any monitoring electronics that may be required, and the appropriate cooling facilities. (Note that the valves for the China scheme presently under construction by Brown Boveri & Company have the ability to replace a single thyristor at a time. Therefore the effective module size has been reduced to a single thyristor. The discussion here is based on a multi-thyristor module valve design, however this can be equally applied to the valve design used for the China scheme.)

A simplified schematic illustrating the basic components required by both an ETT module and an LTT module [33] is shown in Figure 5.2 As is evident from Figure 5.2, the gate triggering electronics required in the ETT module are absent in the LTT module. Figure 5.3 illustrates in more detail the ETT valve and LTT valve configuration used by Toshiba [34].

By far the greatest impact of LTT use is the elimination of the thyristor level electronics, as illustrated in Figure 5.3. The elimination of the thyristor electronics provides a variety of advantages.

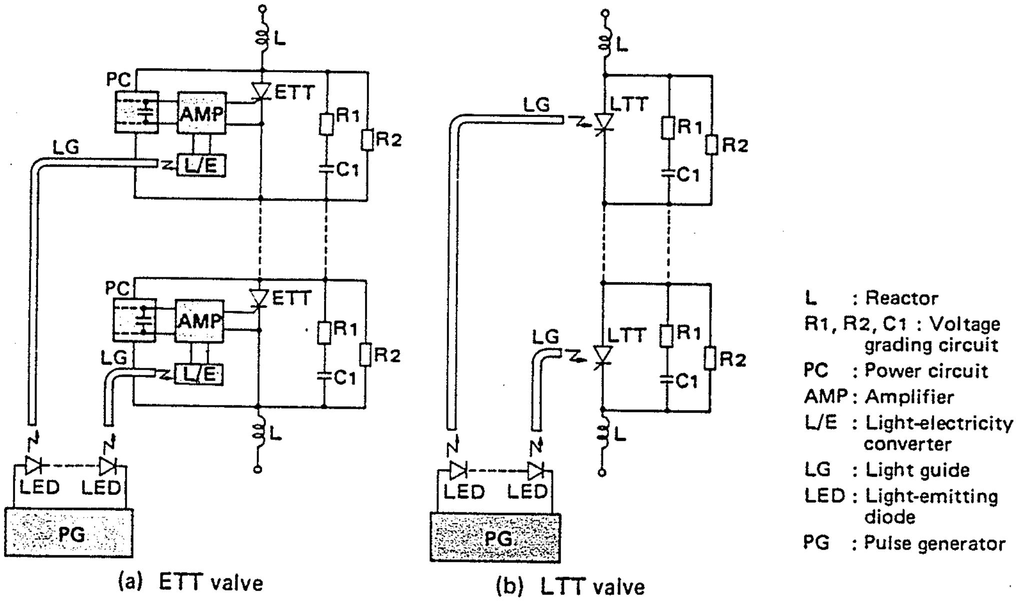


(a) Electrically triggered module

(b) Light triggered module

Fig. 5.2 Basic ETT and LTT Module Configuration.

Reference 33.



(a) ETT valve

(b) LTT valve

Fig. 5.3 Toshiba ETT and LTT Valve Configuration

Reference 34.

Reduced Number of Parts

Valves constructed with ETTs require a large number of thyristor level electronics which make up roughly 90% of the total number of parts in a valve [34]. Figure 5.4 shows a comparison of the number of parts required in a Toshiba ETT valve and LTT valve [34].

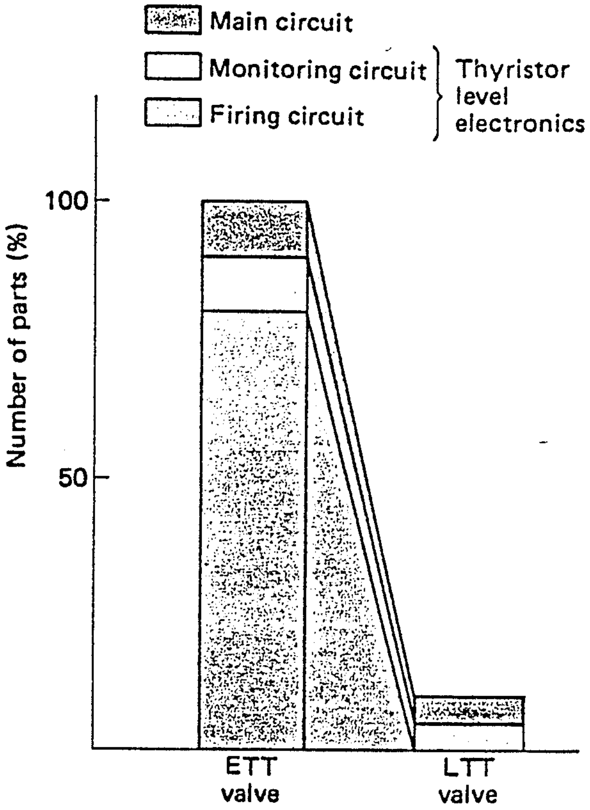


Fig. 5.4 Number of Parts in ETT and LTT Valve.
Reference 34.

Reliability

The reduction in the number of parts within a module results in a higher overall reliability. Figure 5.5 shows a reliability comparison between an LTT and ETT valve claimed by Toshiba [34]. From Figure 5.5 it is seen that the operating duration of the LTT valve is nearly double that of the ETT valve.

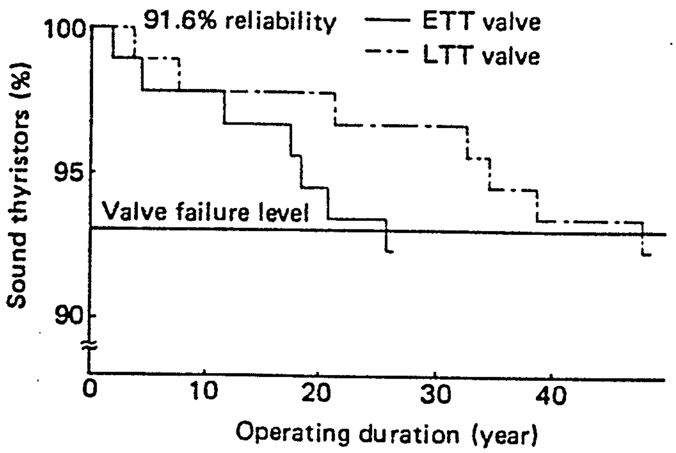


Fig. 5.5 Reliability Comparison for ETT and LTT Valve. Reference 34.

Maintenance

By eliminating thyristor level electronics overall valve maintenance is simplified. Since no complex thyristor level electronic circuits are present, maintenance of the LTT valve requires only the inspection of a small number of components at each thyristor level. Table 5.2 illustrates the differences in valve maintenance time Toshiba claims [34], and clearly shows the LTT valve as superior.

Item	LTT	ETT
Inspection Parts	Approx. 30%	100%
Maintenance time	Approx. 30%	100%
Maintenance Interval	Approx. 200%	100%
Maintenance Cost	Approx. 15%	100%

Table 5-2 Comparison of Valve Maintenance.
Reference 34.

Improved Dimensions

In a LTT valve, the space occupied by the thyristor level electronics in an ETT valve is no longer necessary. Therefore an overall reduction in valve size is possible [33]. The size of an LTT valve is only about 85% of the size of a corresponding ETT valve [34]. This valve size reduction results in a reduction in valve hall building size and overall substation space.

Table 5.3 illustrates the effect of use of Toshiba's LTT valve on valve size [35].

Improved Cost

The reduction in valve size results in an overall capital cost saving when LTT valves are used [34]. In addition, improved reliability and simplified maintenance result in an improved operating cost. Overall the use of a LTT valve offers cost savings as opposed to an ETT valve.

Item	ETT Valve	LTT Valve
Number of Parts	1	0.13
Module Size	1	0.83
Valve Size	1	0.85

Table 5-3 Comparison of Valve Size.
Reference 34.

5.3 Effects Due to Differences in Firing Circuits

The basic differences in firing circuits used by the LTT and ETT have been discussed in Chapter 4 and Figure 5.3 illustrated two such schemes in more detail. However, the effects of the firing circuits on overall reliability and operation have not been considered up to this point.

Reliability

A very attractive feature of the LTT valve is the ease with which the gate firing system can be multiplied [30]. This is a very important method of increasing overall valve reliability. By increasing the number of separate gate firing systems to each thyristor, the overall LTT valve redundancy can be reduced while maintaining the same availability level [30]. This approach is very economically advantageous.

Operation and Performance

The benefits associated with a direct light triggering system are that the gate signal can be considered as totally isolated and is also very immune to the noise present in the valve environment. This is because the gate firing system is basically comprised of optical signals and transmission facilities. This isolation and noise immunity results in less frequent misoperation of the thyristors.

The thyristor level electronics associated with the gate firing circuit in an ETT valve usually consist of a light-electricity converter, a pulse amplifier and power circuits [34]. As was mentioned in Chapter 4, there are two methods of obtaining the necessary auxiliary power, but the most common is to use the voltage across each thyristor. The power circuit which receives energy from the thyristor terminals, includes capacitors for energy storage to provide stable power to the pulse amplifier and light-electricity converter [34]. The following operational restrictions are present in such ETT valves [35]:

1) Prior to starting the valve, it must be placed in a floating voltage condition for a specified time in order to fully charge the power source capacitors. Therefore the ETT valve is unable to start as soon as the converter is connected to an ac system.
2) During bypass pair operation, the voltage across the bypass valve drops to nearly zero, therefore the capacitors can not be charged. Hence only a limited

number of gate pulses can be produced during bypass operation, limiting its duration.

3) In the event of an ac system fault, the ac system voltage is either reduced or reduced and distorted. This again may lead to the situation where the capacitors may be unable to be charged and operation must be discontinued.

In contrast, the LTT valve has no power supply capacitors to charge therefore it can begin operation immediately, and can operate for extended periods in bypass mode and with reduced ac system voltage. Therefore the LTT valve has greatly improved operational flexibility [35].

The improved operational flexibility can best be utilized with the coordinated implementation of LTT valves and digital controls. This is so because the digital controls are able to continually produce firing pulses, even when the ac system voltage drops to zero, as a result of their memory circuit. The LTT valves have no delay on start-up and no operation time limit with reduced ac voltage and thus can take full advantage of the operational benefit of digital controls. Therefore the two systems together offer quick restart after voltage collapse, and extended operation with reduced ac system voltage or bypass operation.

5.4 Overvoltage Protection

Thyristors are vulnerable to damage caused by overvoltage when avalanche breakdown occurs in the weakest region of the device. Methods of protecting ETTs and LTTs from overvoltage damage were discussed in Chapter 4.

For the ETT it was found that protection could be accomplished by either furnishing each thyristor with individual emergency gate firing circuits or by supplying a single emergency gate firing pulse to all thyristors within a valve upon the detection of dangerous voltage levels.

For the LTT it was found that it is not practical to provide a forced firing overvoltage protection circuit for each thyristor. This is because such an additional circuit would make the LTT valve a very complicated structure since the overvoltage energy across the thyristor must be converted into light before being applied to the thyristor gate [36]. Therefore a central protective firing scheme must be used.

Another option mentioned in Chapter 4 was that of built-in overvoltage protection within the thyristor. Some success in self-protected LTTs has been claimed [22] [36] [37] [38] and such a feature if it were to be realized would prove very beneficial. Further discussions about self-protected LTTs are contained in Chapter 6.

5.5 LTT or ETT?

When considering the use of LTTs as opposed to ETTs the following factors should be examined:

1) Similarities

- LTTs are designed to be physically and electrically similar to correspondingly rated ETTs. Therefore proven technologies used for ETT cooling, voltage grading, and reactor circuit design can be applied to LTTs.

2) Advantages of Using LTTs

- drastic reduction in the number of components contained in the valve resulting in increased reliability, simpler and more compact valve design, and simpler maintenance, all of which contribute to an overall cost savings.
- the ease of duplicating the optical firing systems which allows a decrease in thyristor redundancy while maintaining the same level of availability, which again results in a cost savings.
- high level of gate signal isolation and noise immunity of a direct light firing system which results in better valve performance.
- higher operational flexibility due to the elimination of power supply capacitors for pulse amplifiers at the thyristor level required in an ETT valve. Improved operation at start-up, during bypass operation, and with low ac system voltage results. This improved

operation flexibility is best utilized by digital controls which contain a gate firing pulse memory circuit.

- possible overvoltage self protecting LTTs in the near future.

3) Disadvantages of Using LTTs

- ETTs can be individually protected against damage due to overvoltage, whereas LTTs cannot. Therefore a very reliable central emergency firing control must be used with LTTs.
- lack of experience of the use of LTTs in commercial HVDC converters.

From the preceding, it is obvious that using LTTs in HVDC converter stations would prove beneficial. Now what must be examined is the current status of the LTT, to what stage it has developed, in what areas is research being carried out, what sort of actual performance tests have been conducted and the results of these tests. The following Chapter discusses these points in greater detail, providing an outlook for the future of LTT use in HVDC converter applications.

CHAPTER 6 THE LIGHT TRIGGERED THYRISTOR

Light triggered thyristors have been available for many years, however not in a form suitable for application in HVDC converter stations. Although not technically feasible at the time, the advantages of using LTTs in HVDC converters were realized and active development was undertaken.

The fundamental technological problem in employing optical triggering was to realize a gate structure with sufficiently high light sensitivity while not causing a degradation in conventional high power electrically triggered thyristor characteristics such as dv/dt and di/dt capabilities [23]. In order to overcome this problem and obtain successful optical triggering two avenues were taken. The first was to employ an auxiliary light triggered thyristor connected between the gate and anode of a conventional power thyristor. The second was to develop a suitable method of direct optical triggering within the main power thyristor itself.

6.1 The Separate Light Triggered Thyristor (SLTT)

Using this approach, the main power thyristor is triggered by an electrical pulse received from a SLTT which is optically fired. Figure 6.1 shows a SLTT and Figure 6.2 illustrates the connection of the SLTT and power thyristor [39] [40]. The small low cost package used for the SLTT is similar to ceramic packages used for integrated circuits, with light reaching the SLTT through a hermetically sealed window in the package [39].

The SLTT is connected in series with a limiting resistor between the anode and gate of the main power thyristor as shown in Figure 6.2. When a forward bias is present, the SLTT receives almost as much voltage as the main thyristor. Hence when the SLTT receives an optical gate pulse it conducts a current into the gate of the main thyristor. The magnitude of the current gating the main thyristor is dependent on the bias voltage and limiting resistor. Therefore when the bias is high and the turn on duty of the thyristor severe, the circuit delivers a strong gate pulse. In addition the duration of the gate pulse is not fixed. Once the main thyristor turns on, the bias across the gate circuit drops to a low enough level to stop the flow of gate current [39].

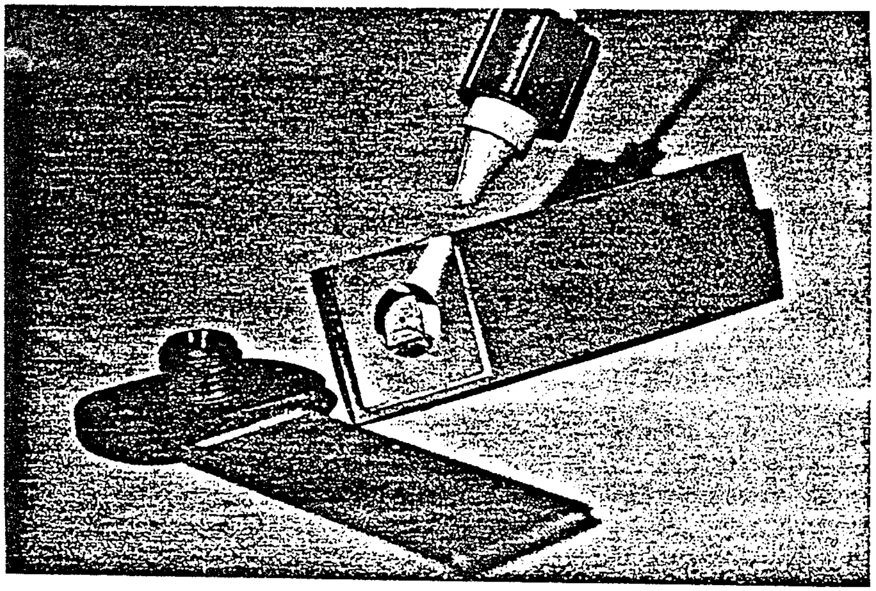


Fig. 6.1 Separate Light Triggered Thyristor (SLTT).
Reference 39.

Such a system has some very attractive features [40]. Firstly, no energy storage is required to fire the main thyristors. This results in lower losses, simpler valve construction and eliminates the operational restrictions resulting from the use of energy storage capacitors. In addition such an arrangement allows access to the electrical gate of the main thyristor, which enables the use of individual emergency firing circuits similar to those in conventional ETT valves. Also, since the SLTT is in a separate package, it can be separately cooled allowing better combination of gate sensitivity and dv/dt withstand capability which is temperature dependent.

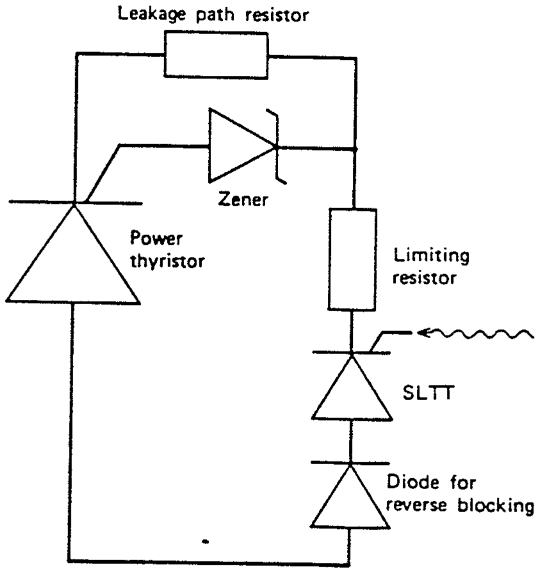


Fig. 6.2 Circuit Connection Using SLTT.
Reference 40.

A disadvantage of such a scheme is that it requires the use of additional components to ensure reliable operation [23]. In addition some other disadvantages arise as the result of the circuit configuration [40]. The first of these is that the specifications for the SLTT and main thyristor must be carefully coordinated, since the two are basically connected in parallel. In addition the turn-on delays associated with the circuit arrangement become critical. This is important since too long a delay may make triggering of the SLTT impossible. In addition, longer time delays diminish the ability to simultaneously turn on all the thyristors of a valve.

Although the SLTT scheme described above is achievable, it does not offer the HVDC user all the benefits possible of direct light triggering. For this reason, considerable effort has been spent by manufacturers on developing a direct light triggered thyristor which is capable of reliable operation in HVDC converters.

6.2 The Direct Light Triggered Thyristor (LTT)

In order to overcome the previously mentioned design problems of the LTT, some of the methods used by researchers included [23] [33]:

1) Development of new amplifying gate structures to balance the trade-off between high light sensitivity and high dv/dt and di/dt capabilities.
2) Factors influencing quantum efficiency were closely

examined.

3) New diffusion methods were employed to ensure uniform P-N junctions with long carrier lifetimes.

4) New package designs were developed to ensure efficient optical energy transmission.

5) Computer aided design was used to optimize device design.

The result of these efforts was the realization of an LTT with a basic cross section as shown in Figure 6.3.

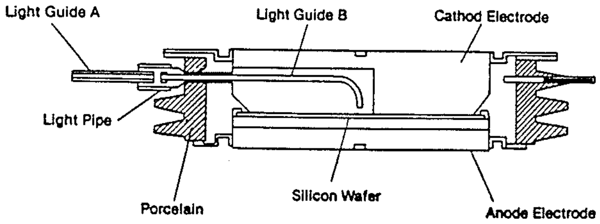


Fig. 6.3 Basic Cross Section of LTT.
Reference 42.

6.2.1 Gate Design

The three basic considerations when designing an LTT gate are the light sensitivity or the minimum light triggering power required, and its effects on dv/dt capability and di/dt capability. In order to meet all three requirements, a new gate structure was considered which was used as a first pilot thyristor for a multi-stage amplifying gate structure [29]. Figure 6.4 shows the three structures examined in reference 19. Figure 6.4(a) (Category A) shows a conventional light triggered thyristor where the P-base surface is irradiated by the light signal. Figure 6.4(b) (Category B) illustrates a structure which provides greater light sensitivity while still retaining high enough dv/dt capability for HVDC applications. Figure 6.4(c) (Category C) is a structure with increased di/dt capability over that of Category B while not negatively effecting its light sensitivity and dv/dt capability.

Minimum Light Triggering Power

When the light signal irradiates the light sensitive region of each structure, a photo-current flows through the P-base lateral resistance to an emitter shunt region of the main thyristor. This is indicated by the solid line in Figure 6.4(b). The resultant lateral voltage generated in the P-base region acts as a forward bias to the N-emitter. This forward bias voltage is given by

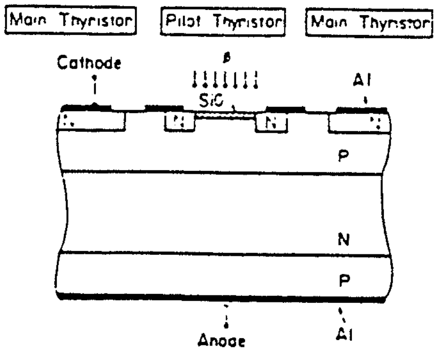
$$V_P = \rho_b \int_{X_1}^{R} J(x)\, dx \quad , \qquad \text{Eqn. 6.1}$$

where $J(x)$ = lateral current density

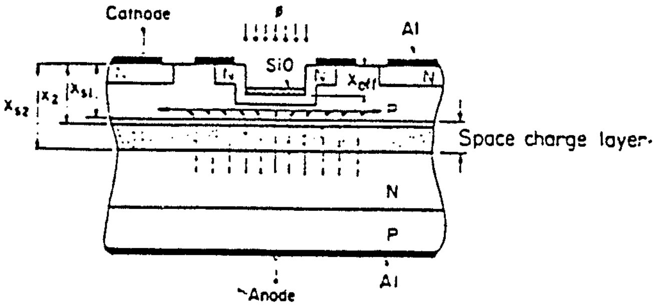
ρ_b = P-base resistivity

R = N-emitter outer radius, Figure 6.4

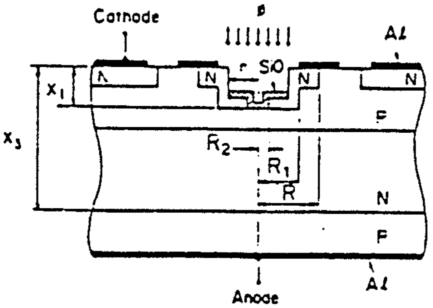
X_1 = N-emitter inner radius, Figure 6.4



(A) : Category—A



(B) : Category—B



(C): Category—C

Fig. 6.4 Three Possible LTT Gate Structures.
Reference 29.

It is assumed that successful light firing occurs when an abrupt increase in electron injection from the N-emitter takes place. This results when V_p is increased beyond some critical value. The minimum light triggering power based on the above assumption was calculated [29], and it was found that Categories B and C require approximately the same minimum light triggering power, while Category A requires more.

dv/dt Capability

A rapidly rising positive voltage across the thyristor results in the flow of a displacement current as shown by the dashed line in Figure 6.4(b). Since this current flows through the P-base lateral resistance, a procedure similar to that used in determining minimum light triggering power was used to determine dv/dt capability [29]. Figure 6.5 illustrates the relationship between dv/dt and minimum light triggering power for the three categories [29]. From Figure 6.5 it is evident that Categories B and C offer superior gate sensitivity over Category A for the same dv/dt capability.

di/dt Capability

There are two basic methods for improving di/dt capability. The first is to use a larger initial turn-on area, and the second is to control anode current crowding to the initial turn-on area [20].

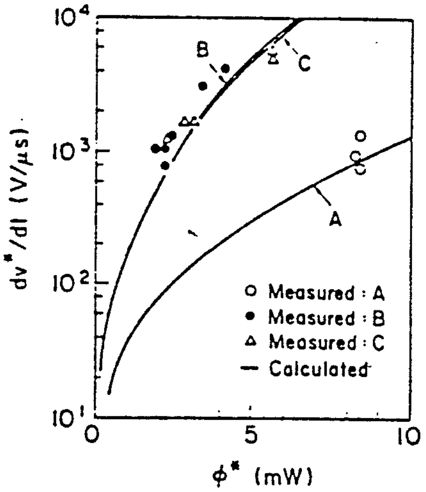


Fig. 6.5 dv/dt Versus Minimum Light Triggering Power.

Reference 29.

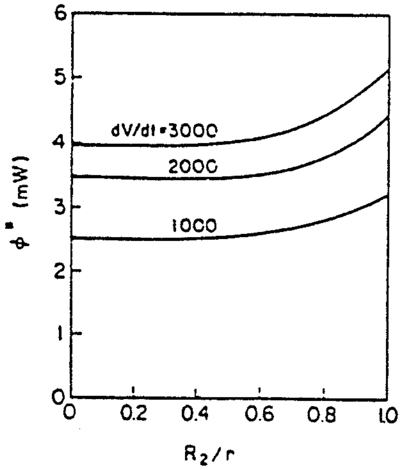


Fig. 6.6 Minimum Light Triggering Power Versus Irradiated P-base Radius.

Reference 29.

With regards to Category C, Figure 6.6 [29] shows the calculated minimum light triggering power versus the ratio of the irradiated P-base radius R_2, to the total irradiated area's radius r. By increasing R_2/r, di/dt capability can be increased. As is evident from Figure 6.6, R_2/r can be increased to about 0.5 before a substantial increase in minimum light triggering power is observed. This corresponds to an increase in di/dt capability of about 1.5 times over Category B which has $R_2/r=0$ [29].

The second method of increasing di/dt capability is to control anode current crowding to the initial turn-on area. One way of achieving this is to make the P-base lateral resistance large between the pilot thyristors and main thyristor, thereby limiting the anode current. However, increasing the lateral resistance has a negative effect on the turn-on characteristics of the main thyristor [29].

An alternate method of limiting anode current crowding is the use of a multi-amplifying gate structure [29]. As the number of pilot thyristors used increases, the anode current in the first pilot thyristor decreases proportionally, causing an increase in di/dt capability. The increase in di/dt capability for a 3 stage amplifying gate structure is increased two to three times over that of a single amplifying gate structure [29]. In actual LTTs all of these methods are combined to provide high di/dt capability.

With the use of such a gate structure, LTTs with characteristics applicable to HVDC converter stations were realized. Once acceptable LTT design had been achieved, it was necessary to devise the required firing circuits, protection systems and overall valve design needed to allow commercial implementation of LTTs in HVDC converters.

6.3 Optical Firing Systems

An HVDC thyristor valve composed of either ETTs or LTTs contains many thyristors connected in series. One major operational constraint, is that all of the series connected thyristors must turn on simultaneously. Therefore each thyristor must receive a firing pulse at the same time. This results in two possible options for a firing scheme. The first is a scheme which produces a single pulse from a central source which is distributed to all the thyristors in a valve. The second possibility is to provide each thyristor with its own source and cause all the sources to produce firing pulses at the same instant. Both types of schemes have been developed for firing LTT valves.

6.3.1 Central Source Optical Firing System

A central source optical firing system must be capable of generating a light pulse which when it is distributed and transmitted to each LTT is still strong enough to trigger all the LTTs. One such system developed [39] [40] is shown in Figure 6.7. It basically consists of redundant cesium arc lamps, a quartz mixer and an optical transmission system.

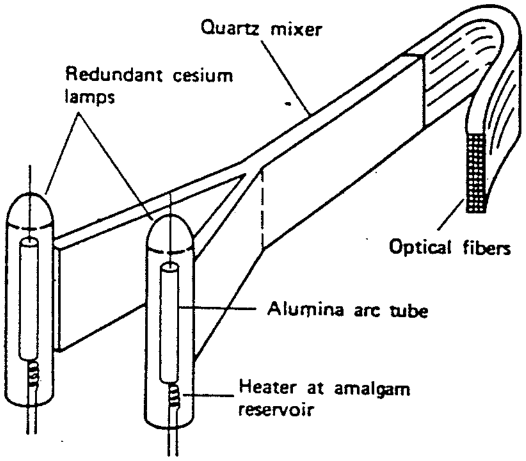


Fig. 6.7 Possible Central Firing System.
Reference 40.

Each lamp consists of a polycrystalline alumina arc tube containing cesium-mercury amalgam jacketed in a pyrex sleeve. The light is produced by a 420 A pulse of 1.5 μsec width and normally occurs at 8.65 msec intervals. A 300 mA dc current is continuously applied to maintain ionization within the tube during the off portion of the cycle. The time for the output light intensity to drop to half value is 15 μsec.

A single lamp is capable of supplying the required amount of light to all the thyristors, however two lamps and power supplies are used to increase the overall system reliability. The light output from both lamps is combined in the quartz mixer which also distributes the light pulse to optical fibers which carry the light firing signal to the thyristors. Each thyristor gate is fed from its own optical fiber.

The main advantage of such a system is that all the LTTs are fired from the same source so that the constraint of simultaneous turn-on is better satisfied. However this may also be considered a disadvantage since a problem with the lamp may result in the loss of firing pulses to the entire valve. Although the chances of this occurring are reduced by employing redundancy in the scheme a central source may still not be very attractive. Another drawback of such a system is the lack of experience with such equipment in an HVDC converter application. Such a system would still require much study and field testing.

6.3.2 Separate Source Firing System

The separate source firing system, in contrast to the central source firing system just described, contains a separate light source for each LTT. The most commonly used light source is the high power light emitting diode (LED). Each LTT is connected to its own LED by an optical fiber. The basic configuration of the light system is shown in Figure 6.8, where it is evident that the light power at the LTT inlet (P_{LT}) is given by

$$P_{LT} = P_{LED} * \eta_1 * \eta_2 * \eta_3 \qquad \text{Eqn. 6.2}$$

In Equation 6.2, P_{LED} is the light output of the LED. η_1 is the ratio of light transmitted through the light guide to the total light output of the LED and depends on LED directivity, light guide bundle diameter and the packing density. η_2 is the transmission efficiency of the light guide and depends on the light guide material and length. η_3 represents the ratio of light introduced to the thyristor gate to the light coming out of the light guide and depends on the light receiving area of the LTT and the light guide diameter [30].

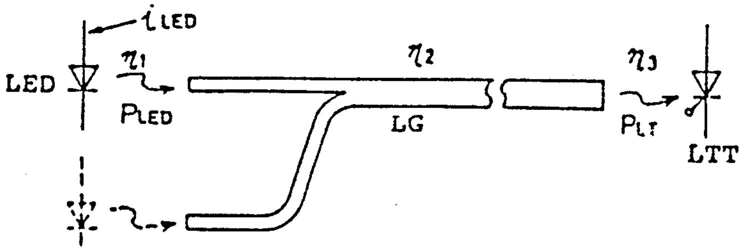


Fig. 6.8 Basic Separate Source Light Firing System. Reference 41.

It has already been established that a certain minimum amount of light power must reach the LTT for turn-on to occur. As the amount of light power reaching the LTT increases, its turn-on delay decreases. This relationship is shown in Figure 6.9 [41]. Therefore in order to better satisfy the constraint of simultaneously turning on all series connected thyristors additional gate power is desired to reduce the LTT turn-on time. A value of approximately 5 to 10 times the minimum required light power has been adopted [33]. The LED must be capable of supplying this increased amount of light energy plus enough to compensate for the losses in the optical transmission system. Figure 6.10 illustrates the LED light output versus the LED current of an LED specifically designed for use with LTTs [34]. In addition the output of the LED tends to decrease with service time as shown in Figure 6.11. Therefore in order for the LED to provide the desired output for an extended period of time, sufficient derating must be incorporated at the design stage.

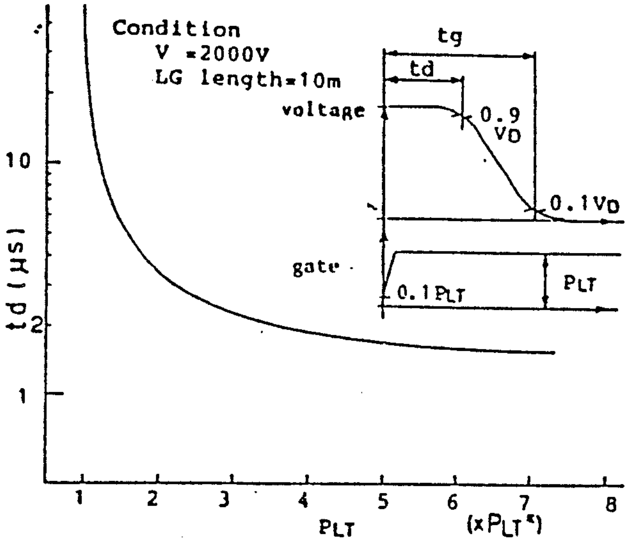


Fig. 6.9 LTT Turn-on Characteristics.

Reference 41.

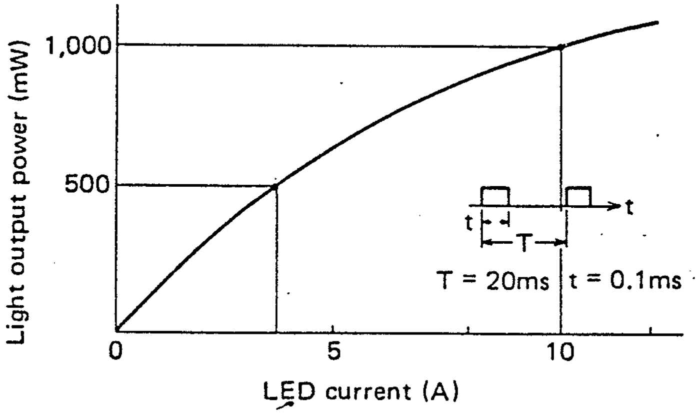


Fig. 6.10 LED Output Versus LED Driving Current. Reference 34.

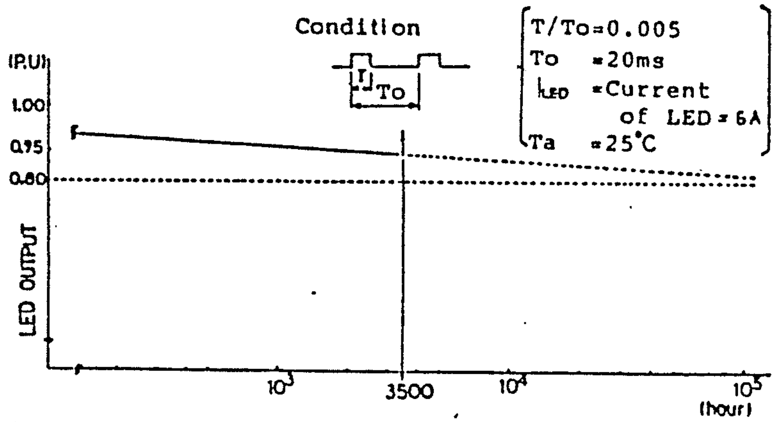


Fig. 6.11 Long Term LED Characteristics. Reference 41.

The light produced by the LED must be efficiently transmitted to the LTT. This is accomplished by employing light guides of plural optical fibers [34] as shown in Figure 6.12. Since the light guide connects the LTT at high potential to the LED on the ground, it must possess good dielectric strength. Therefore factors which must be considered in the choice of a suitable light guide are its optical transmission efficiency, its dielectric strength and its mechanical characteristics.

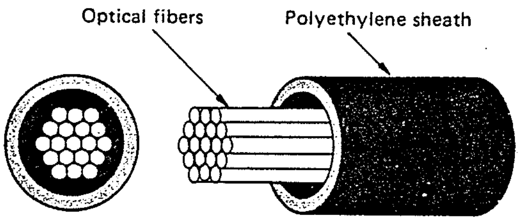
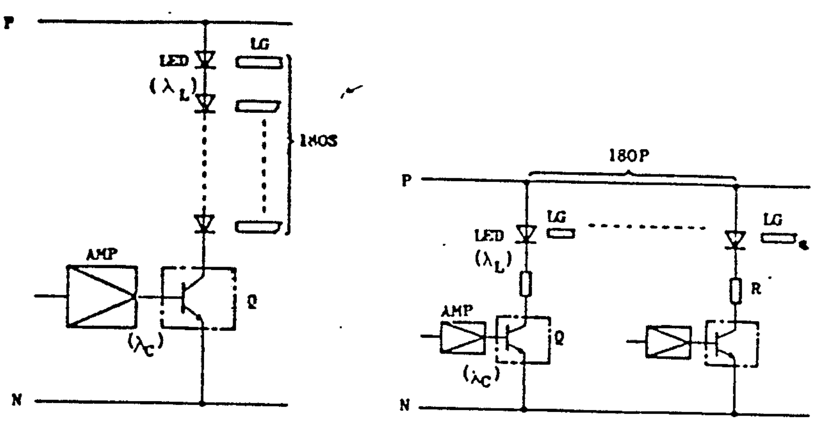


Fig. 6.12 Light Guide Composed of Plural Optical Fibers. Reference 34.

Due to the fact that each thyristor in a valve is gated by its own light source, two possible configurations for the valve's electric-light converter arise [30]. These are shown in Figure 6.13 for a valve consisting of 180 LTTs. Figure 6.13(a) shows the case where the 180 LEDs are connected in series and are controlled by a common switching element Q and its control circuit AMP. Figure 6.13(b) shows the case where the 180 parallel connected units are used. Each unit consists of an LED, a switching element Q, and the LED driving AMP.



a) Serial method b) Parallel method

Fig. 6.13 Possible Electric Light Conversion Circuits. Reference 30.

In order to determine the reliability of both systems it must be established under what conditions the entire valve may fail to operate. For the serial connected circuit valve failure may occur when either the AMP or Q is faulty, or when the number of faulty LEDs exceeds the number of redundant thyristors within the valve. In the parallel connected system, entire valve failure can occur when the number of faulty parallel units (composed of the LED, its Q and AMP) exceeds the number of redundant thyristors within the valve.

The reliability for both schemes was calculated [30] and is shown graphically in Figure 6.14. For the serial connection, the unreliability F_S approaches a certain value determined by λ_c as the number of redundant thyristors increases. For the parallel system, F_P can be improved by increasing the number of redundant thyristors. In addition the effect of overall system duplication was considered, as illustrated by $F_{S(double)}$ and $F_{P(double)}$ in Figure 6.14. It should be noted that LED life was not considered in this reliability assessment. It is felt that by periodic replacement of the LEDs it is possible to avoid system failures [30].

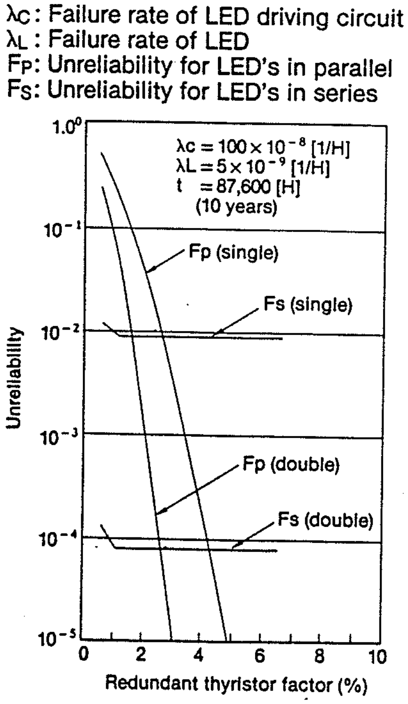


Fig. 6.14 Electric Light Converter Circuit Reliability. Reference 42.

6.4 Built-in Voltage Breakover Protection

It was previously determined that all power semiconductor devices can suffer damage as a result of overvoltages. There are basically two general methods of providing overvoltage protection to thyristors. The first method is to supply external protection circuits which detect the presence of an overvoltage and cause the thyristor to turn on by the application of an external gate pulse. The second method would be to provide built-in voltage breakover protection within each thyristor. The limitations of providing external protection to LTTs was discussed in Chapter 4, therefore it would seem that built-in overvoltage protection is very applicable to LTTs.

6.4.1 Process of Self-Protection

The goal of providing built-in voltage breakover protection is to safely turn on the thyristor before the avalanche voltage is reached. In principle the solution is quite simple. A region is selected where the breakdown is to occur by lowering its avalanche voltage. A limiting resistance is used to control the resultant current density in that region. This avalanche current is then used to gate the rest of the device safely. To realize safe overvoltage self-protection, three conditions must be satisfied [37].

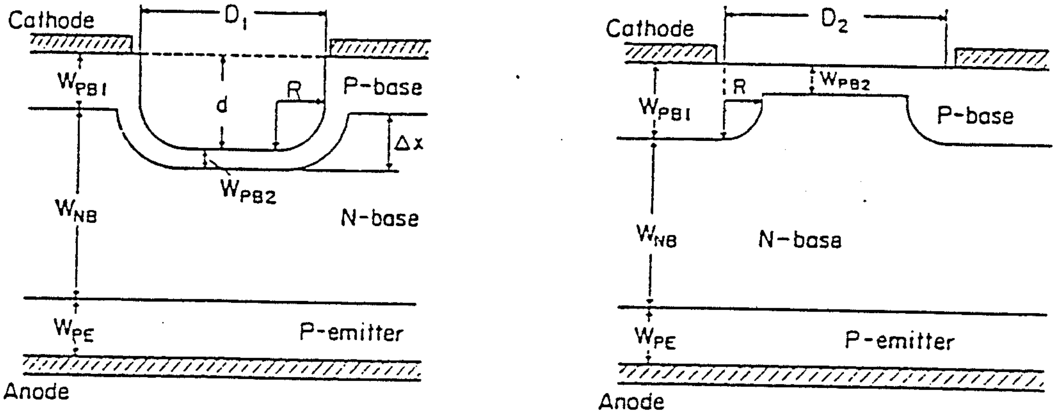
1) Fine breakover voltage control is needed.

2) Safe turn-on in the normal manner must be achieved with the limited avalanche current available.

3) The development of overvoltage self-protection should not degrade any of the other thyristor characteristics.

6.4.2 Design of Self-Protected LTT

Two gate structures with curved forward junctions as shown in Figure 6.15 were investigated [37]. Figure 6.15(a) shows the Category A device where the curved junction is fabricated by an etching technique. Figure 6.15(b) illustrates Category B, whose curved junction is fabricated by a selective diffusion technique. Emitter regions are neglected in Figure 6.15 for simplicity.



(A) Category A

(B) Category B

Fig. 6.15 Gate Structures with Curved Forward Junctions. Reference 37.

The main structural difference between conventional and self-protected LTTs considered in Figure 6.15, is the curved form of the forward blocking junction in the gate region. Upon the application of an overvoltage, avalanche breakdown will occur due to the curved junction, and the resultant avalanche current will act as the normal gate current to turn the thyristor on [25]. The breakdown voltage of the curved junction is affected by both N-base sheet resistivity and the curved junction geometry. Variation of the breakdown voltage with the N-base sheet resistivity requires N-base thickness control which affects other thyristor characteristics. Therefore the breakdown voltage control is achieved by the curved junction geometry.

The junction parameters shown in Figure 6.15(a) which influence the breakover voltage for the Category A structure are R, Δx, and D_1. The variation of the normalized breakdown voltage upon Δx and R was determined [37] and is shown in Figure 6.16. Note that normalized breakdown voltage is not temperature dependent therefore all comparisons are based on such a value. From Figure 6.16 it is evident that V_{BO}/V_0 decreases rapidly as Δx increases. Also the effect of R on V_{BO}/V_0 becomes less pronounced as Δx decreases. This second effect is caused by weakening of the electric field crowding around the curved junction. This weakening is caused by the plane P-base region, which is surrounded by an etched well area, and acts as a field plate, especially for small Δx. It was also determined [37] that D_1 does not influence the breakdown voltage. Therefore for

Category A the controlling junction geometrical parameters were found to be Δx and R [37].

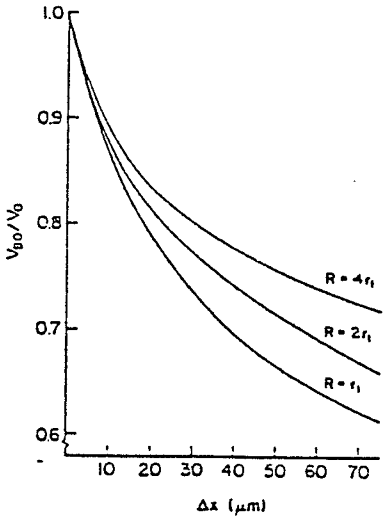


Fig. 6.16 Variation of Breakdown Voltage for Category A. Reference 37.

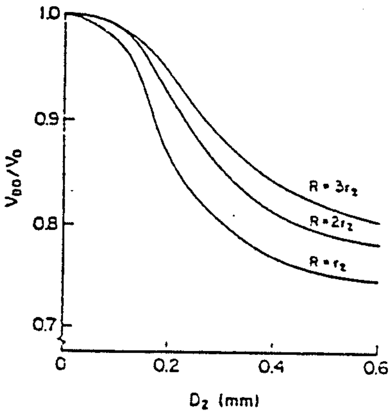


Fig. 6.17 Variation of Breakdown Voltage for Category b. Reference 37.

For the Category B gate structure shown in Figure 6.15(b),the geometrical parameters of concern are D_2, R and W_{PB}. Figure 6.17 illustrates the relationship between V_{BO}/V_0 and R and D_2. From Figure 6.17 it is seen that V_{BO}/V_0 decreases as D_2 increases. It is also evident that R has little effect for small values of D_2. This is again due to the electric field around the curved junction. The electric field concentration in the curved junction area of Category B is effected by the guard ring function of the P-base layer and the P^+ layer field plate function [37]. When the P^+ area diameter is small, the former effect dominates. As D_2 increases, the field plate function begins to effect the electric field concentration and breakover voltage dependency on R begins to develop. The breakover voltage relationship with D_2 and W_{PB} was also determined [37] and was found to be similar to Figure 6.17. Therefore it was determined that the controlling junction geometry parameter for Category B structure was D_2 [37].

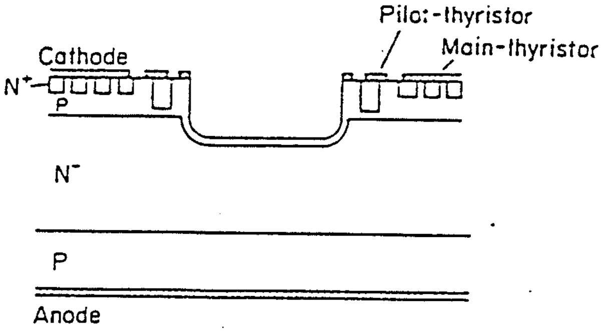


Fig. 6.18 Curved Junction and Amplifying Gate Structure. Reference 37.

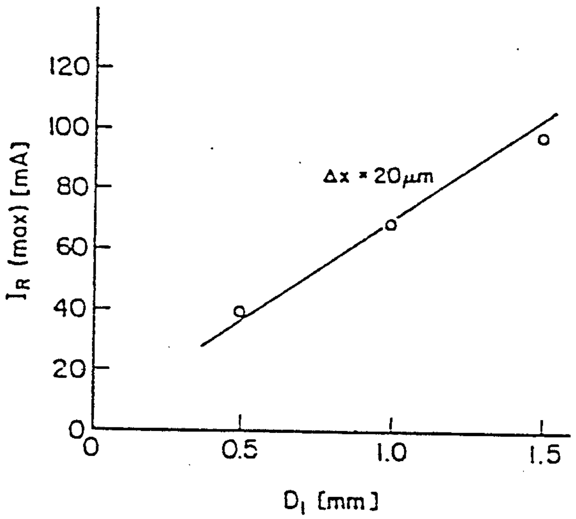


Fig. 6.19 Relation Between $I_{R(max)}$ and D_1.
Reference 37.

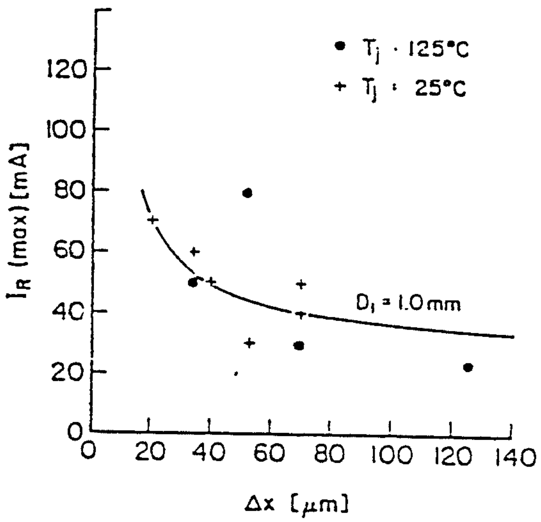


Fig. 6.20 Relation Between $I_{R(max)}$ and Δx.
Reference 37.

For safe voltage turn-on it is required to trigger the LTT in a normal manner with the limited avalanche current available. Therefore it is desired to produce as large an avalanche current as possible without risking possible device failure. Figure 6.18 shows a curved junction surrounded by a highly sensitive amplifying gate. The amplifying gate is similar to that used for the conventional LTT which was previously discussed [37]. Figure 6.19 and 6.20 show the relationship between the maximum available avalanche current, $I_{R(max)}$, and the junction geometry parameters D_1 and Δx respectively [37]. The increase in $I_{R(max)}$ with increase in D_1 seen in Figure 6.19 is due to reduced current crowding as the curved junction periphery increases. The reason for the rapid increase in $I_{R(max)}$ with decreasing Δx as seen in Figure 6.20 is not apparent [37].

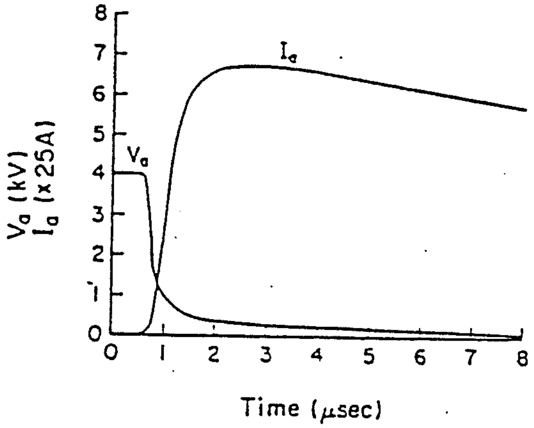


Fig. 6.21 Typical Overvoltage Turn-on Waveforms Obtained. Reference 37.

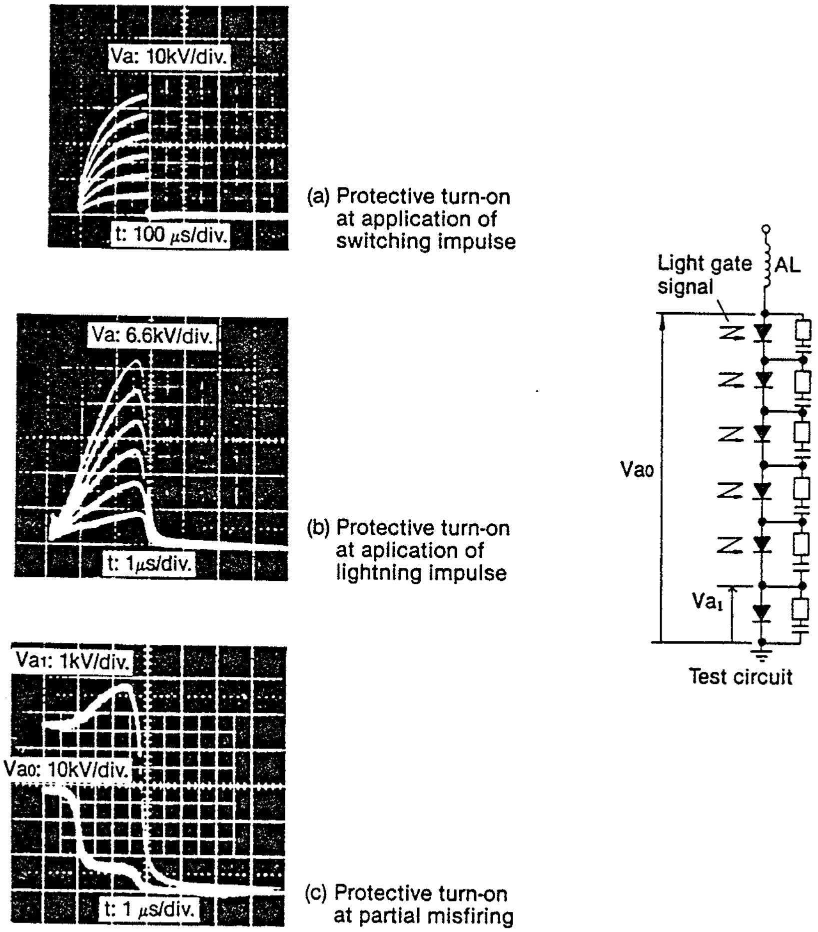
By combining the curved junction structure of Category A with an optimized amplifying gate structure a 4 kV test unit was developed [37]. The test unit provided more than 250 A/μs di/dt capability under 125°C and demonstrated successful overvoltage triggered turn-on. Typical overvoltage turn-on waveforms are shown in Figure 6.21 [37]. In addition other operating characteristics of the self-protected LTT did not suffer degradation [37].

6.4.3 Success of Self-Protection

By the application of designs similar to those mentioned in the previous section, some success in self-protected LTTs has been claimed. The Toshiba Corporation of Japan is actively developing self-protected LTTs at the 4, 6 and 8 kV level [36] [42]. Figure 6.22 shows the performance of a 6 kV self-protected LTT under development at Toshiba [42]. Successful design of a 5.2 kV self-protected LTT has also been achieved by Marconi Electronics Ltd. of the U.K. [25]. Partial success has also been claimed by the General Electric Company of the U.S.A. [22] [38].

6.5 Valve Development and Testing

As was mentioned in Chapter 5, past experience has shown the most favorable valve design is based on a modular approach, employing air insulated, water cooled thyristors. The development of LTT valves has been carried out by a number of manufacturers, however due to the availability of information only those valves designed by Toshiba Corporation of Japan will be considered. The realization of a LTT valve was the result of developments in many fundamental technologies as shown in Figure 6.23.



(a) Protective turn-on at application of switching impulse

(b) Protective turn-on at aplication of lightning impulse

(c) Protective turn-on at partial misfiring

Fig. 6.22 Performance of 6 kV Self-Protected LTT. Reference 42.

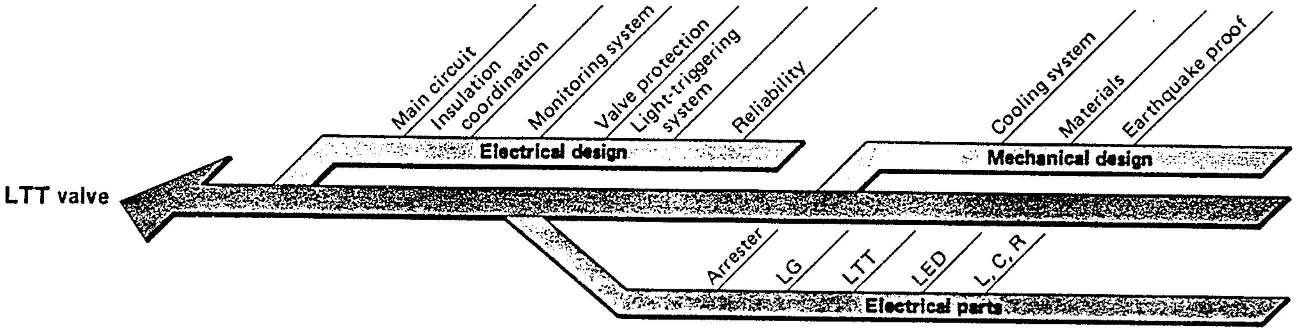


Fig. 6.23 Formation of LTT Valve.

Reference 34.

6.5.1 125 kV - 1800 A LTT Valve

In 1982 a LTT module developed by Toshiba was inserted into a 125 kV - 1200 A ETT valve at the Sakuma Frequency Converter Station (Electric Power Development Co., Ltd., Japan) [30]. Figure 6.24 is an illustration of the valve. The LTT module consisted of six series connected air insulated, water cooled thyristors rated 4 kV and 1500 A. Based on the success of field tests, a 125 kV - 1800 A water cooled LTT valve shown in Figure 6.25 was developed. This valve was subsequently installed in place of a mercury arc valve at the Sakuma Frequency Converter Station late in 1983, since then it has been operational [35]. Figure 6.26 illustrates the circuit diagram of the Sakuma Frequency Converter Station with the LTT valve in place.

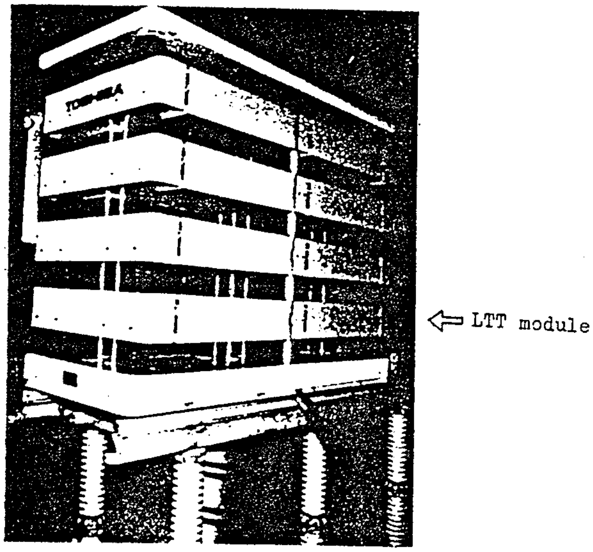


Fig. 6.24 ETT Valve with LTT Module.

Reference 30.

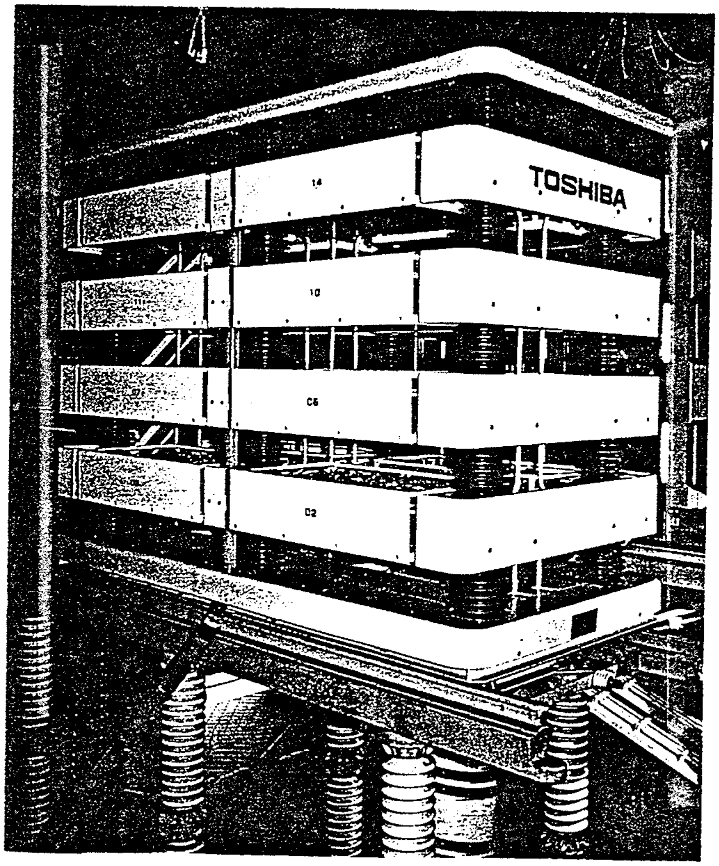


Fig. 6.25 125 kV - 1800 A LTT Valve (Toshiba).

Reference 34.

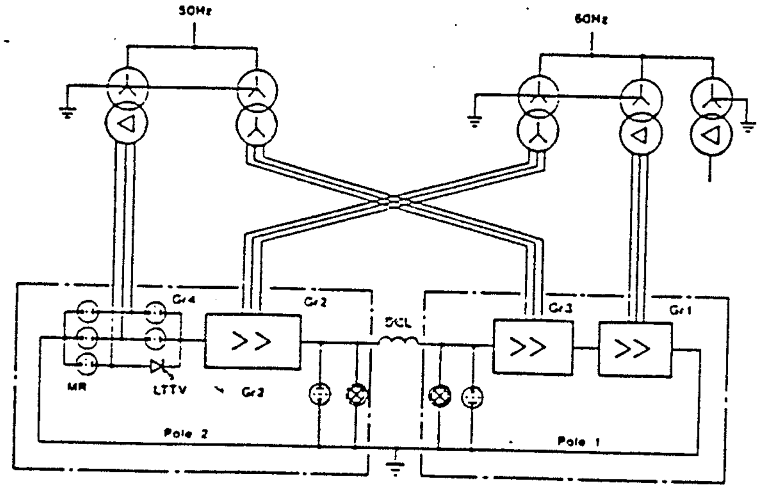


Fig. 6.26 Sakuma Station with LTT Valve.

Reference 35.

Basic Valve Specification

The basic valve design specifications are shown in Table 6.1.

Item	Value
Rated DC Voltage	125kV
Rated DC Current	1,800A
BIL	332kV (1.2 * 50us)
BSL	322kV (100 * 2500us)
Cooling	Water cooled
Insulation	Air insulated
Thyristor	4kV-1500A LTT 90S-1P
Gate Triggering	Direct light

Table 6.1 125 kV - 1800 A LTT Valve Specifications.

Reference 35.

Mechanical Design

The protective level of the gapless ZnO surge arrester applied to the valve is 288 kV [35]. A safety factor of 1.15 was allowed, resulting in a BIL and BSL of 332 kV [35]. Based on this BIL and BSL the valve must withstand, it was determined that 90 LTTs were required to be connected in series [35]. The maximum overcurrent possible in this installation was found to be 18 kA, which is well below the 22 kA maximum allowable surge current in the LTT [35]. Therefore no parallel strings of LTTs were required. The valve was divided into fifteen modules. Each module contains six series connected LTTs and associated circuits [35] as shown in Figure 6.27.

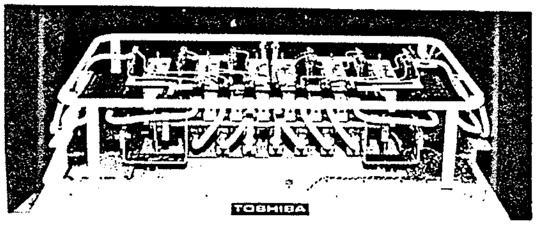


Fig. 6.27 LTT Module.
Reference 34.

Electrical Configuration

Each thyristor unit has an associated snubber circuit and dc grading circuit in order to assure even voltage distribution. Two anode reactors are connected to every six serially connected LTTs to supress the di/dt [35].

Optical Firing System

The minimum firing energy required by the LTTs used is 10 mW. It was desired that the light energy available at the LTT be at least five times this minimum value to prevent time differences in turn-on [35]. In order to supply the desired amount of light output, a high power LED shown in Figure 6.28 was developed. This was combined with an optical fiber light guide to form the firing system. The LEDs were connected serially and two redundant systems, as shown in Figure 6.29 were used to increase reliability [35].

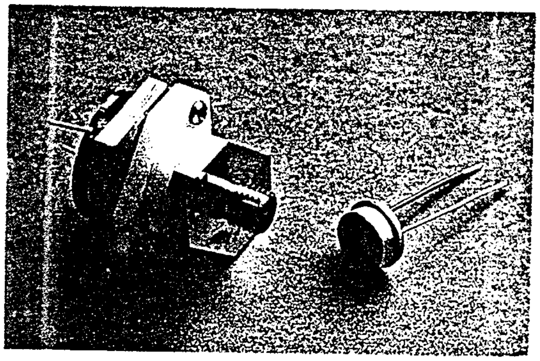
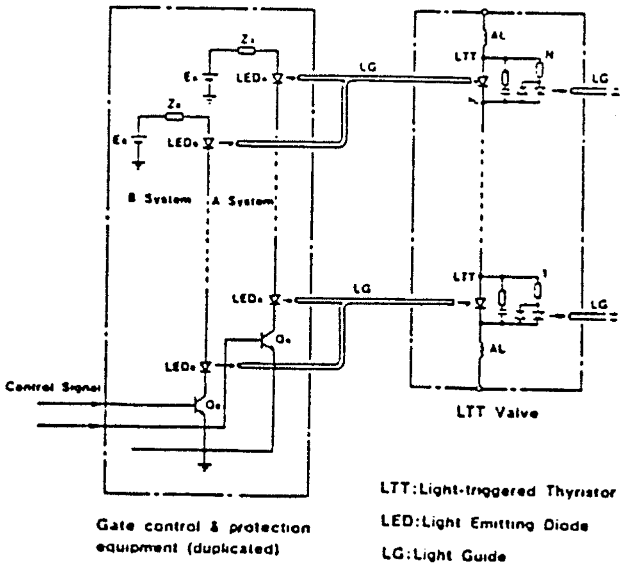


Fig. 6.28 High Power LED Developed by Toshiba. Reference 34.

Gate Control and Protection

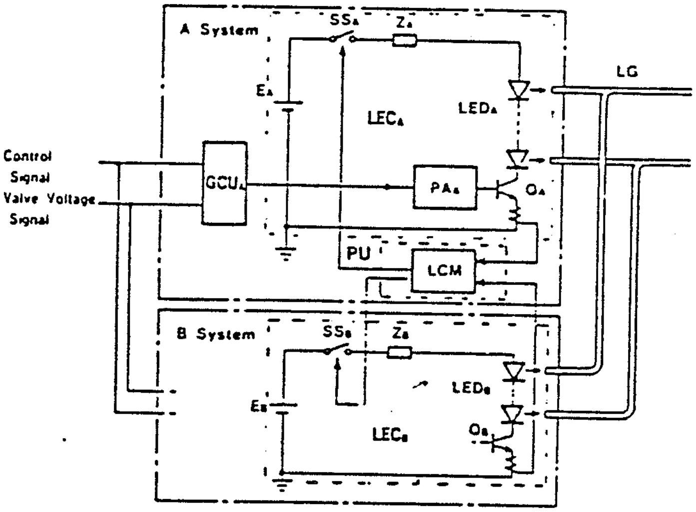
The gate control and protection equipment (GCP) must control and protect the LTT valve under all operational conditions. The basic circuit configuration is shown in Figure 6.30. The GCP consists mainly of a gate control unit (GCU) for controlling the gate signal, a light-electricity converter (LEC) for amplifying the signal from the GCU and carrying out the conversions to produce a light gate signal, a protection unit (PU) for protecting the valve and GCP, and a control power source unit (CPS) [35].



LTT:Light-triggered Thyristor
LED:Light Emitting Diode
LG:Light Guide

Fig. 6.29 Optical Firing System Used.
Reference 35.

The GCU generates a narrow width gate control signal based on signals from a central control panel and monitored LTT voltage. The signal originating from the central control panel has a width corresponding to the valve conducting period (ie. 120°). The GCU gate signal is sent to the LEC where it is pulse amplified to drive the LEDs. The LEDs produce the optical signal which is transmitted via fiber optics to each LTT.



SS :Semiconductor switch
GC :Gate control unit
PA :Pulse amplifier
LCM:LED current monitor

Fig. 6.30 Basic Configuration of GCP.
Reference 35.

Two separate firing systems are included to increase reliability as shown in Figure 6.30. If a problem develops in one, it is necessary to be able to determine which of the two systems is faulty. This is accomplished by checking the LED currents in each system using the LED current monitor (LCM) [35]. For example, if system A were to produce a continuous LED current, due to short circuiting of transistor Q_A, the LCM would detect the problem and open the semiconductor switch SS_A to cut off the light gate signal from system A. Meanwhile, system B can continue to output the required gate signals, to ensure proper operation.

The forward and reverse voltage across each thyristor is monitored by a circuit consisting of a dc grading circuit resistance and a series connected LED. The detected signal is sent via a separate optical transmission system to the monitoring circuit as shown in Figure 6.31. The monitoring circuit recognizes any thyristor failures and will issue an alarm and print out showing the location of the failed unit. Overvoltage protection is provided by a surge arrester across the entire valve. Overvoltages that may occur across part of the serially connected string are detected by the thyristor monitoring circuit and protection is provided by issuing a gate signal to all the thyristors [35].

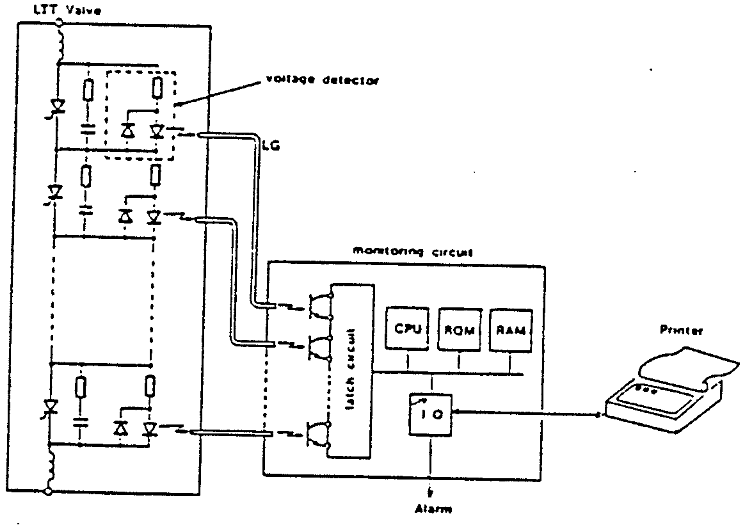


Fig. 6.31 Monitoring Circuit.

Reference 35.

Cooling

The LTT valve is cooled in a similar way as a conventional water cooled ETT valve [35]. Figure 6.32 shows the cooling system within each module. A leak detector is provided in each module. A water leakage signal is sent through a light guide to the thyristor monitoring system which decides whether any water leakage has occurred.

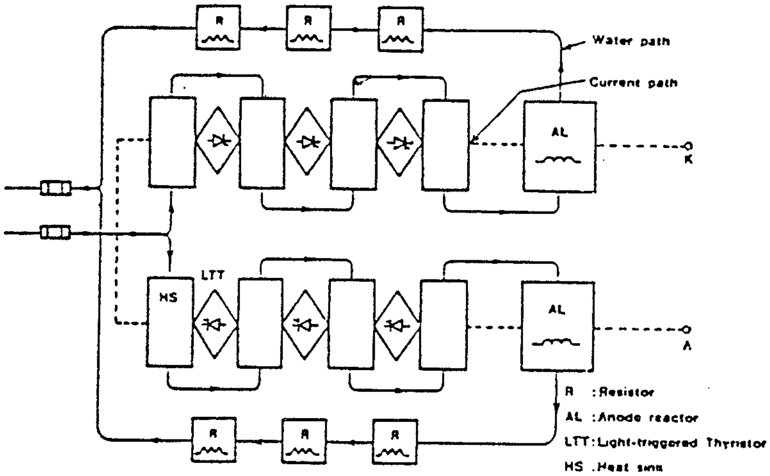


Fig. 6.32 Cooling System Within a Module.
Reference 35.

6.5.2 125 kV - 1800 A LTT Valve Performance

After rigorous factory testing [35], two complete LTT valves were installed at the Sakuma Station in place of mercury arc valves late in 1983, one on the 50 Hz side and one on the 60 Hz side. The operational experience of the LTT valves from December 16, 1983 to May 1984 [43] is shown below:

Operating Time

Operating time	1411.39 hrs.
Floating time	2529.44 hrs.
Total	3940.83 hrs

Energy Transmitted

From 50 Hz to 60 Hz system	70,181 MWh
From 60 Hz to 50 Hz system	145,673 MWh
Total	215,854 MWh

Energy Utilization 18.26%

Energy Availability 97.96%

Energy Unavailability

Scheduled outages (for mercury arc valve maintenance)	2.04%
Forced outages	0.00%

Forced Outages none

Number of SAB and CAB

Single Arc Back	7
Continuous Arc Back	none

Overall neither failure nor deterioration of the LTT valves were observed. No data indicating valve losses was available.

6.5.3 500 kV LTT Valve

Based on field test results of the previously described 125 kV - 1800 A LTT valve, a 500 kV prototype LTT valve has been developed [41]. Figure 6.33 is an illustration of the 500 kV LTT valve and Table 6.2 lists its basic specifications. After completion of its type test the performance and reliability of the 500 kV LTT valve have been verified as satisfactory [41].

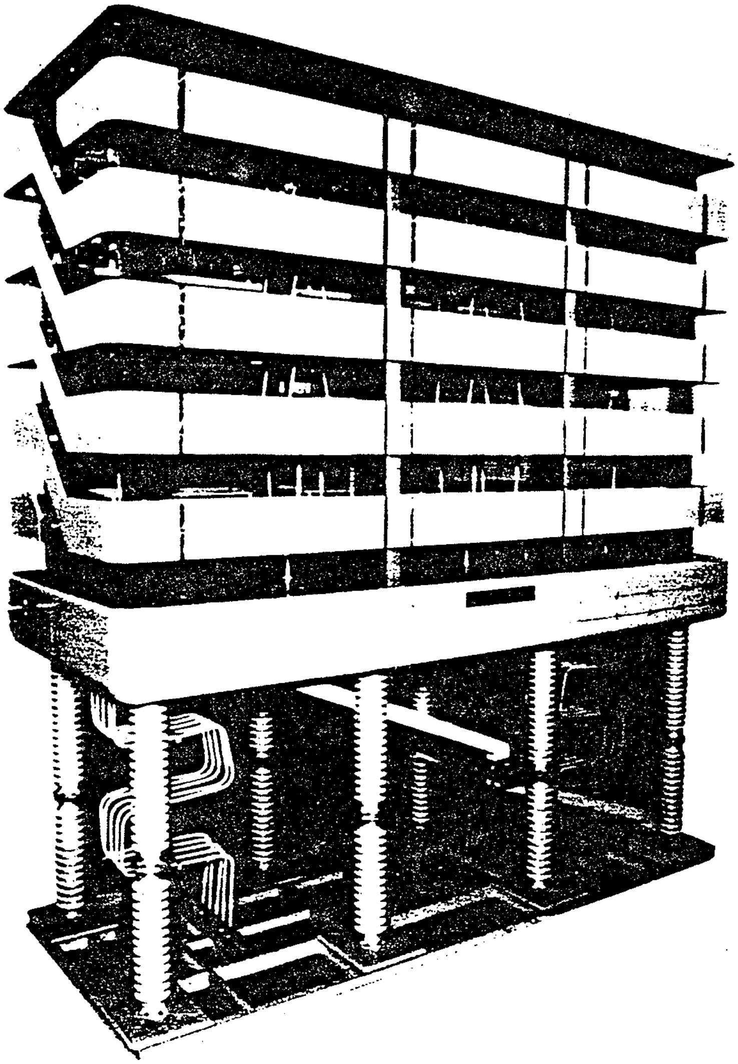


Fig 6.33 500 kV LTT Prototype Valve.

Reference 35.

Item	Value
DC System Voltage	500kV
Rated DC Voltage (between terminals)	250kV
Rated DC Voltage (Valve base)	250kV
Rated DC Current	1800A
AC Input Voltage	216kV
Power Frequency	50Hz
Impedance of Converter Transformer	20%
LIWL	662kV
SIWL	662kV
Cooling	Water cooled
Insulation	Air-insulated
Thyristor	4kV-1500A 75mm dia.
Number of Thyristors	180 s - 1 p

Table 6.2 500 kV LTT Valve Specifications.

Reference 35.

6.6 The Future of LTTs

Presently, LTTs with characteristics applicable to HVDC converter stations are available. Table 6.3 lists three such devices produced by Toshiba. Since an acceptable balance between gate sensitivity and dv/dt and di/dt has been attained, the focus of development has been the realization of built-in overvoltage protection. Although some success has been claimed, no such devices have been tested in the field.

Toshiba Type		**SL1500GX21**	**SL3000GX21**	**SL1200JX21**
Voltage Rating		4000	4000	6000
$I_{T(RMS)}$	(A)	2355	4710	1885
$I_{T(AV)}$	(A)	1500	3000	1200
I_{TSM}	(A)	30000	60000	24000
di/dt	(A/us)	250	300	100
T_j	(C)	-40~125	-40~125	-40~125
V_{TM}	(V)	2.3	2.5	2.7
P_{LT}	(mW)	10	10	10
t_d	(us)	5	5	5
t_q	(us)	400	400	400
dv/dt	(V/us)	1500	2000	1500
R_{th}	(C/W)	0.02	0.0075	0.02

Table 6.3 Characteristics of LTTs Suitable for HVDC Use. Reference 36.

Further testing in actual HVDC installations is required to fully assess the performance of LTT valves. One area in need of more study is the evaluation of valve losses. Valve losses are directly related to the adopted redundancy level within the valve. Therefore it is beneficial to reduce the number of series connected thyristors from an 'operating losses' point of view. However, reducing the number of series connected thyristors may result in an unacceptable valve reliability level. An optimization process is required to attain the most suitable valve redundancy level to ensure minimum operating losses and an acceptable reliability level.

CHAPTER 7 CONCLUSIONS

Based on the information avaialable detailing LTT development, completed research, and field testing it has been determined that the use of LTTs in a HVDC transmission system would result in the following advantages and disadvantages:

Advantages

- the number of valve parts are reduced, resulting in increased reliability, simpler and more compact valve design, and simpler maintenance which all contribute to cost savings
- the direct light triggering system can be easily duplicated, allowing a decrease in overall valve redundancy while maintaining the same availability level which is economically advantageous
- higher operational flexibility due to the elimination of the power supply capacitors required by the thyristor level firing circuits in a conventional ETT valve
- possible overvoltage self-protected LTTs in the near future

Disadvantages

- a central emergency firing system must be used to provide external overvoltage protection (ETT valve use allows individual external circuit protection)
- lack of experience with the use of LTTs in commercial HVDC transmission systems

Overall the possible advantages of using LTTs in HVDC transmission systems far outnumber the possible disadvantages.

Therefore based on the overall understanding of the subject light triggered thyristors should be used in HVDC transmission systems in the future due to their associated advantages as shown above. In addition the use of LTTs could occur in two situations. Firstly, in new HVDC schemes if LTTs are combined with fully digital controls a greater utilization of the capabilities of both would result. This is with regards to the memory circuit contained in the digital controls which allows continuous output of gate firing pulses even with no ac system voltage and the improved operational ability of the LTT valve. Secondly, LTT valves could be used as replacements for the aging mercury arc valves in present day schemes. The excellent performance of the LTT test valves at the Sakuma Frequency Converter Station has illustrated the compatibility of LTT and mercury arc valves. This would allow a gradual replacement of mercury arc valves while providing the HVDC system user some exposure to direct light triggering.

During the course of this study it was found that the literature available on the subject of light triggered thyristors was very limited. This is not surprising since the technology is still at a very young stage of development. The nonavailability of specific test data indicates the level of development of the field.

The information available often dealt with a particular aspect of LTT use in a HVDC transmission system such as gate design, overvoltage protection, test valve configuration, etc. This study has compiled the various available information into a single source. An assessment of LTT applicability to HVDC transmission was then conducted based on this information. By compiling this information and performing the assessment, the HVDC user has a single document available detailing present LTT status as well as LTT applicability to HVDC transmission.

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