

# High-voltage Thyristors for HVDC and Other Applications: Light-triggering Combined with Self-protection Functions

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High-power thyristors with direct light-triggering and integrated protection functions can be utilized advantageously for applications in which several thyristors are connected in series. This applies in particular to High-Voltage DC (HVDC) transmission, Static Var Compensation (SVC), converters for medium voltage drives, and also to certain pulse power applications. Recent progress in both device innovations and optimization of some application systems is reviewed in this article.

## 1. Introduction

Ever since the beginning of the thyristor era in HVDC applications in the 1960s, the blocking and current conducting capability of these power semiconductors has been improved. While in the early years about 84,000 devices rated at 0.9kA/1.65kV would have been necessary to build a 3,000 MW system, today the same amount of power can be transmitted using only 3,750 thyristors rated at 4kA/8kV. This remarkable reduction of the number of thyristors and their associated components has reduced costs for converters and increased their reliability.

In parallel to this development, at the beginning of the 1980s, direct-light-triggering of thyristors was introduced. However, implementation of the direct light-trigger function into the high-voltage thyristor, and its efficient utilization for HVDC applications, became possible only recently [1-3] when laser diodes became available and stable enough (with 30-year longevity) to be used in HVDC applications.

Further progress was achieved by the integration of functions for protection against overvoltage pulses, voltage pulses with too high  $dV/dt$ , and voltage pulses appearing during the forward recovery time.

Meanwhile it has been demonstrated that by using a new design of the Amplifying Gate (AG)

structure [4, 5], all three of these protection functions can be integrated successfully into the thyristor. The basic pre-condition for this development was the continuous improvement of the quality of the silicon starting material (lower contamination level and advanced homogeneity of the resistivity distribution). Furthermore, the development of a very clean process line was required.

In this article, we first recapitulate the chosen design concept for the integration of direct light-triggering and the protection functions. Then, we describe the details of an HVDC thyristor valve, and the advantages arising from the use of direct Light-Triggered Thyristors (LTTs) with integrated protection functions. Finally, we consider applications of direct LTTs in other high-voltage AC and DC applications.

## 2. Thyristor Details

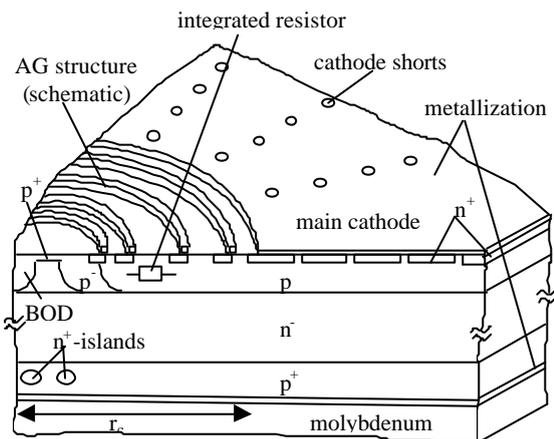
### *Direct Light-triggering & Overvoltage Protection*

The central area of the thyristor consists of a Break-Over Diode (BOD) and a four-stage AG structure (Fig. 1). The BOD is located inside the light-sensitive area. If the forward biased thyristor is illuminated by a short light pulse (typical duration = 10  $\mu$ s, light power = 40 mW,  $\lambda$  = 940 nm), the generated electron-hole pairs are immediately separated in the space charge region of the  $p-n$  junction formed by the central parts of the  $p$ -base and the  $n$ -base. The hole current generated in this way provides the trigger current for the AG structure.

If an overvoltage pulse in forward direction is applied to the thyristor, the BOD provides a trigger current to turn the thyristor on. This is achieved by the curved shape of the  $p-n$  junction which ensures that the electric field always has a maximum value at the BOD when a forward voltage is applied to the thyristor. Thus, when the device voltage exceeds a certain threshold,

avalanche generation starts in the BOD, providing a trigger current to turn on the thyristor safely by means of the AG structure.

The blocking voltage of the BOD can be adjusted by the curvature of the central p-n junction and the distance between the BOD and the p-ring below the optical gate. Details are described in Refs. [1] and [3]. However, an easy post-processing adjustment of the breakdown voltage can be done by irradiating a certain area around the BOD with helium ions or protons. To this end, the particle energy is chosen such that the penetration depth is larger than the depth of the p-n junction. While helium irradiation generates acceptor-like defects, proton irradiation followed by an annealing step at temperatures between 220°C and 300°C causes the appearance of hydrogen-related donors. In the first case, the breakdown voltage can be increased by several hundred volts; and in the second case, a well-defined decrease of the breakdown voltage is possible [6].



**Fig. 1: Central part of the thyristor (BOD & four-stage AG structure) and part of the main cathode area (from Ref. [4]).**

#### *dV/dt Protection*

Integration of a  $dV/dt$  protection function can be achieved by designing the AG structure and the main cathode area such, that the innermost AG has a higher  $dV/dt$  sensitivity than the other AGs and the main cathode area. This ensures that the thyristor is turned on safely by the AG structure when a voltage pulse with a  $dV/dt$  ramp exceeding the  $dV/dt$  capability of the innermost AG is applied to the thyristor. However, care has to be taken to fulfill the requirements concerning the light sensitivity and the  $dV/dt$  capability of the thyristor. Both features are mainly determined by

the doping concentration of the p-base and the depth, width, and radial position of the  $n^+$ -emitter, i.e. by the design of the innermost AG.

#### *Forward Recovery Protection*

Commutation of a thyristor leads to an extraction of the free charge carriers in the n-base and the p-base and the formation of an anode-side depletion layer in the n-base. Since the depletion layer extends only to a certain depth into the n-base, excess carriers remain in its quasi-neutral plasma region, recombining there at a certain rate. When large regions of the thyristor have completely recovered and an uncontrolled forward voltage pulse appears, the remaining small region with excess carriers in the main cathode area may turn on. This may result in current filamentation, self-heating and, finally, in local destruction of the thyristor.

To avoid this, the thyristor should also be turned on in a controlled way by the AG structure if such a failure occurs. An integration of a corresponding protection function into the AG structure is not so easy, because the AGs usually turn off earlier than the main cathode area does. Consequently, the carrier concentration in the AG region is typically lower compared with the main cathode area. However, an increase of the carrier concentration in the AG region can be achieved by modifying the carrier's lifetime distribution so that it is lower in the main cathode area ( $\tau > \tau_c$ ) than in the AG structure [4,5,7-9]. This can be realized with relatively little effort by using a masked electron irradiation instead of the homogeneous one that is usually applied to adjust the on-state voltage.

Re-triggering of the thyristor by means of the AG structure in the case of forward voltage pulses during the forward recovery phase can be further supported by phosphorus islands located inside the  $p^+$ -emitter of the inner AGs (Fig. 1). The resulting anode-side n-p-n structures operate as local transistors when a reverse voltage is applied to the device. Their carrier injection can be controlled by the doping concentration and the dimensions of the islands.

Thyristors designed in this way (i.e. provided with both non-homogeneous carrier lifetime distribution and local phosphorus islands) were subjected to extensive test measurements monitoring their response behavior on voltage pulses appearing during the forward recovery period. These test measurements demonstrated the effectiveness of the integrated forward recovery protection function [4, 5].

### 3. HVDC Thyristor Valve

#### Direct Light-triggering vs. Electrical-triggering

Because of the high-voltage environment of thyristors in HVDC applications rated up to 500 kV it is necessary to electrically separate the trigger unit at ground potential from the thyristor at high-voltage potential. The trigger command for the thyristor is transmitted as a light pulse via a fiber-optic cable, even if Electrically Triggered Thyristors (ETT) are used. Therefore, the possibility of triggering the thyristor directly with the help of a light pulse was considered early. That would make it possible to avoid converting the low-power light pulse into a high-power electrical gate pulse by a printed circuit board at thyristor potential when using an ETT (Fig. 3). Thus, using LTTs instead of ETTs significantly reduces the number of electronic parts necessary to trigger and to protect a thyristor, and thus increases the converter's reliability.

The amount of light needed to trigger an LTT is about 1,000 times higher than the amount of light needed to transmit the trigger command to the printed circuit board associated to an ETT. Although the principle of triggering a thyristor directly by light has been known for more than 30 years, LTT application in HVDC has been feasible only since sufficiently powerful and reliable light sources and optical components with low damping characteristics became commercially available.

A special challenge was the integration of protection functions into mass-produced thyristors. Once this was accomplished, the number of electronic components could be reduced to that necessary for monitoring, and no more firing pulses would be generated at the thyristor level. This significantly increases the electromagnetic immunity of the system.

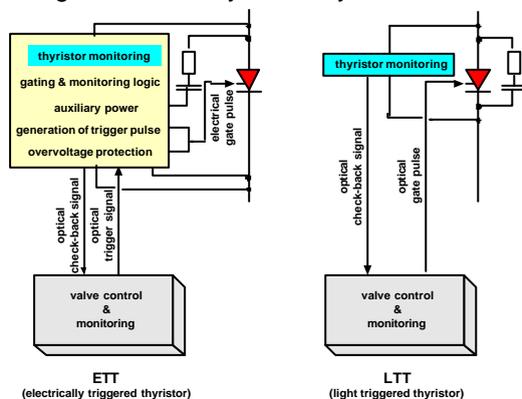


Fig. 3: Triggering and monitoring of thyristors, LTT versus ETT.

#### Status Quo of HVDC Valves with Light-triggered Thyristors

A demonstration valve with 44 units of 4"/8kV-LTTs with integrated overvoltage and  $dV/dt$  protection function has been in operation at the Celilo converter station of the Pacific Intertie / USA since Oct. 1997 [10]. The valve has performed flawlessly for 5 years; no component failed or caused a malfunction of the valve. Based on existing contracts, by the end of 2004 about 5,500 units of 4"/8kV-LTT and 3,800 units of 5"/8kV-LTT will be in commercial operation.

#### Optical Gating System

The major components of the gating system are:

- A commercially available laser diode (LD) as a light emitting device with a lifetime of more than 30 years of operation in a HVDC application.
- The optical link between the Valve Base Electronics (VBE) and the LTT. The link consists of light guides and an optical mixer, a so-called Multimode Star Coupler (MSC).

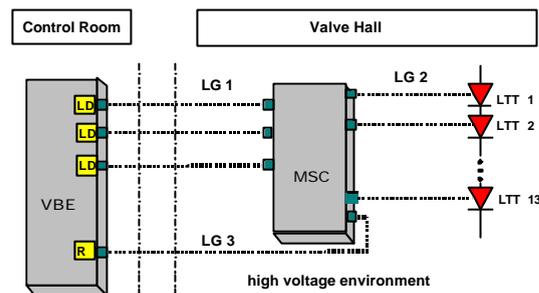


Fig. 4: Optical components for gating the LTT's of one valve section.

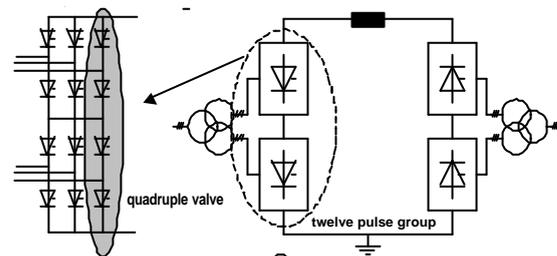


Fig. 5: Schematic diagram of a HVDC converter.

The fiber-optic cables, LG 1, connect the LD to the MSC as shown in Fig. 4. The light pulses from the three LDs are mixed and distributed equally between the thirteen outputs. Additional fiber-optic cables, LG 2, then carry the light pulse directly to the thyristor gates. The light from one

output of each MSC is routed back to the VBE (via LG 3) for monitoring purposes. One LD is redundant and the three diodes are installed on different PCB's, each of which can be changed without risk during operation.

### Mechanical Design of the Thyristor Valves

A 500-kV HVDC converter consists of twelve thyristor valves arranged in two serially-connected 3-phase-bridges forming a twelve-pulse group (Fig. 5). The mechanical design is based on an arrangement of three quadruple valve (Fig. 5) towers for a twelve pulse group. Each valve tower comprises four valves; each valve is made up of three thyristor modules. These twelve modules are arranged in a twin tower suspended from the valve hall ceiling. The high-voltage end is at the bottom and includes separate corona shields (Fig. 6).

Each valve typically includes 78 serially-connected thyristors with a peak blocking voltage of 8 kV. The snubber circuits (Fig. 7) are made from a single capacitor and resistor. The capacitor is filled with SF<sub>6</sub> rather than oil, to minimize the fire hazard. The resistor is of the "wire-in-water" type for maximum heat dissipation. A separate grading capacitor is used to linearize the voltage distribution along the valve for steep-fronted surges. It is also filled with SF<sub>6</sub>. The thyristors are monitored using a printed circuit board (TVM) associated with each LTT.



Fig. 6: Quadruple valve tower (photograph taken in the high-voltage test field of the University of Karlsruhe / Germany).

All plastic materials for tubing and insulation have flame-retardant self-extinguishing characteristics in accordance with UL 94-V0.

All heat-dissipating components (thyristors, snubber resistors and valve reactors) are cooled

with de-ionized water in a strictly parallel cooling circuit, a design which has proven its resistance to corrosion in nearly 20 years of service.

Mechanically, the serially-connected thyristor levels of one valve are grouped into six sections of typically 13 levels each. The thyristors and their heatsinks are mounted in a pressure-contact stack with the snubber circuits, water distribution pipes, and TVM boards arranged on either side. The valve reactor, typically consisting of three serially-connected sub-units and the grading capacitor, is located at the end of the stack. All active components of two valve sections rest on a surrounding aluminum frame which serves as a mechanical support and corona shield, and constitutes a modular unit.

The arrangement of the thyristors and heat sinks in the stack and their associated equipment is a straightforward image of the electric circuit diagram. Uniform voltage grading and ease of testing are advantages of this design.

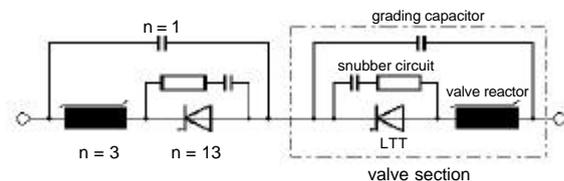


Fig. 7: Schematic diagram of a thyristor modular unit (=2 valve sections).

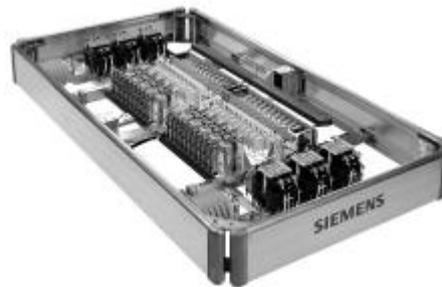


Fig. 8: Typical HVDC thyristor module with LTT technology.

## 4. High-voltage AC and DC Applications

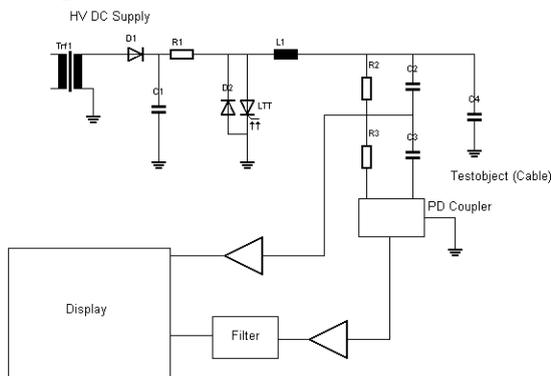
The possibility of easy series connection favors the application of direct LTTs not only for HVDC transmission lines, but also for various other applications. The whole spectrum of eupec high-voltage thyristors — all with integrated BOD and dV/dt protection function and with blocking voltages between 5.2 and 8 kV and pellet diameters from 2 up to 5 inch — can be used in the following examples.

### Medium-voltage Drives

Medium-voltage (MV) drives are getting more and more important, because of their cost effective performance. Existing MV drive products range between 2.3 and 7.2 kV, tending to higher voltages of up to 15 kV.

The main drives are mostly built with IGBT modules in inverters with two or more levels. For high-end voltage and power systems, Press Pack IGBT's and even LTTs (frequencies 50 - 110 Hz) may be of interest because direct series connection with redundancy of more than two semiconductors can be accomplished in one-level inverters.

In soft starters, which work with full sine waves, commutated thyristors can be used. In the upper voltage region where series connection of semiconductors is necessary, the use of smaller LTTs (eupec T553N) is a big advantage.



**Fig. 9: Schematic for a cable test system**

### Mobile High-voltage Cable Test Systems

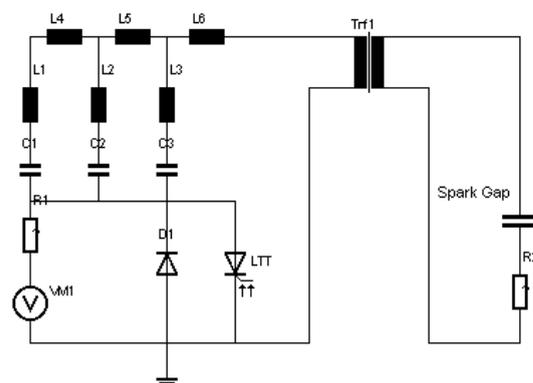
High-voltage network maintenance is necessary to ensure supply reliability. Measurement and location of partial discharges is internationally accepted as an indication of insulation system integrity. Such test systems are built like a resonant circuit (Fig. 9). When the LTTs are triggered they form together with the test object and an air-cored inductor a series resonant circuit. The inductance of the air core is selected such that the resonant frequency is similar to the power frequency of the service voltage. High-voltage cable insulation usually has a relatively low dissipation factor. Combined with the low loss factor of the air-cored inductor, this provides a high-Q resonant circuit. The specially developed measurement circuit detects all partial discharge pulses that occur during the oscillating wave. The partial discharge pulses are localized by the traveling wave method.

Because it is easy to connect LTTs in series, the devices will be used in a mobile high-voltage cable test system for 250 kV.

### Pulse-power Applications

Because of the high  $di/dt$ -capability, LTTs can be used in many pulse-power applications such as preservation of liquid food, fast magnetic forming, crow bars and high-power lasers. For such pulse-power applications the energy is normally stored in capacitors that are discharged in one or several pulses with high  $di/dt$  and peak current.

Preservation of liquid food is achieved by high-voltage arc discharges. The energy is stored in several capacitors. By triggering serially-connected LTTs, the voltage pulse is transformed to a higher level to trigger the spark gap (Fig. 10). There are three main mechanisms that cause microbial inactivation during arc discharge treatment: Shock waves, UV-radiation, and the formation of radicals. The advantages of this method are its cost effectiveness and that the taste of the food is not modified by pasteurization. This kind of applications normally works with a frequency of several ten Hz.



**Fig. 10: Schematic for preservation of liquid food**

Fast magnetic forming is becoming more and more important, especially for the automotive industry. For fast magnetic forming applications, normally a capacitor is charged to several kV, then the LTT is triggered by a laser pulse. The capacitor is discharged into a special air coil. A crow-bar diode protects the capacitor against negative charging. The object that is supposed to be deformed is placed in a special air coil. In this way, for example, two pipes can be fixed together without using any kind of rubber seal. LTTs are tested in this application with charging voltage of up to 5 kV, a load  $di/dt$  of 5 kA/ $\mu$ s and a maximum load current of 35 kA.

LTTs are used in *crow bar applications* to protect expensive and sensitive components such as klystrons or high-power capacitor banks. The LTTs are switched directly in parallel to the part that should be protected (Fig. 11). In case of overvoltage or high  $dV/dt$  in the system, the internal protection function triggers the LTTs and the current commutates to the thyristors. In case of any other failures or irregular functions, the LTTs are triggered by the laser pulse and the expensive parts are protected. LTTs are tested in this application with a charging voltage of 65 kV and a  $di/dt$  of about 5 kA/ $\mu$ s.

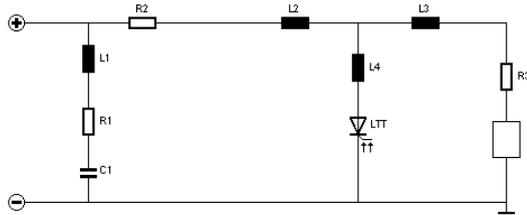


Fig. 11: Simplified schematic for a crow bar circuit

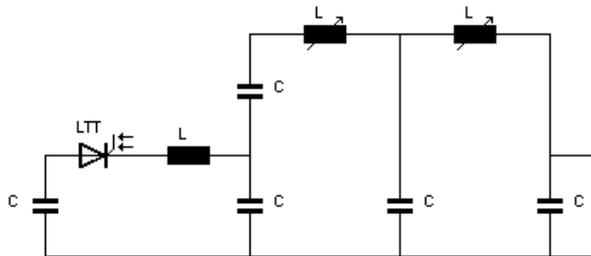


Fig. 12: Simplified schematic for laser application

*High-power lasers* are used in lithography processes to produce processors and TFT-displays. First, a capacitor bank is charged to several kilovolts (Fig. 12). Then, the LTTs are triggered and the current flows through a coil to produce a well-defined current pulse. This current pulse is compressed by two or more pulse-compression circuits. After this compression, the current pulse triggers the laser. These laser applications normally work at a frequency of several 100 Hz. LTTs are tested in this application with a charging voltage of 16 kV, a load  $di/dt$  of 2 kA/ $\mu$ s, a maximum load current of 2 kA, and a frequency of 300 Hz.

*Ignitrons* are used in several existing applications. These devices will be replaced because of the pollution that can be caused by the mercury in them. LTTs are a good solution for most of these replacements.

## Summary

In conclusion, we point out that light-triggered thyristors combined with self-protection functions

can be employed with great advantage to improve the reliability of such systems as HVDC transmission lines and other high-voltage AC and DC applications.

## Acknowledgments

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