Series connection of GTO thyristors for high-power static frequency converters

The introduction of gate turn-off (GTO) thyristors was an important milestone in the development of high-power static frequency converters. Used in conventional circuits, they allow converters with ratings of up to 30 MVA to be built. For higher powers, ABB has developed a technology for the series connection of GTO thyristors that offers considerably better availability and economy. The first high-power frequency converter with series-connected GTO thyristors is due to enter commercial operation with the German utility Stadtwerke Bremen.

Line-commutated thyristor-based frequency converters have been operating successfully for decades in a wide range of industrial and electric utility applications. A characteristic feature of their circuit design is the control method, which relies on the firing instant being delayed by a certain firing angle.

The amount of reactive power that the converter takes from the network increases approximately in proportion to the active power. Depending on the circumstances, it may be necessary to install expensive filters for reactive power compensation and to reduce the harmonics that can occur. In addition, the mode of operation of the thyristor-based converter does not allow it to be used independently of the power system, which defines the frequency and phase sequence.

Major disadvantages of the thyristor converter are therefore its continuous need for reactive power from the network and the fact that this does not allow it to be operated separately in 'island' mode. These drawbacks are the direct result of the lack of a means of interrupting the current at a required time. As a result, circuits for generating and controlling the turn-off current were developed to allow self-commutated operation of the thyristor converters. However, this increased the cost of the converter systems and introduced several operational disadvantages.

The complexity and cost of the earlier technology were reduced considerably by the introduction of gate turn-off thyristors. Converters based on these semiconductor devices are self-commutated, making them suitable for supplying power to isolated networks. The phase angle between the voltage and current can be set in all four quadrants as required, allowing the active and reactive powers to be adjusted independently of each other. By connecting modules featuring phase-displaced firing in series or increasing the pulse frequency it is also possible to generate an almost sinusoidal output voltage.

Due to their versatility as final control elements, converters based on GTO thyristors represent a major advance over conventional thyristor converters. However, GTO thyristors do not only have advantages. The technology, for example, is considerably more complex; another drawback is that the GTO thyristor-based converter makes high demands on the protective circuitry and gate control. The losses are also greater than with ordinary thyristors. For many applications, therefore, thyristor converters with reactive-power compensation equipment are still more economical than converters based on GTO thyristors.

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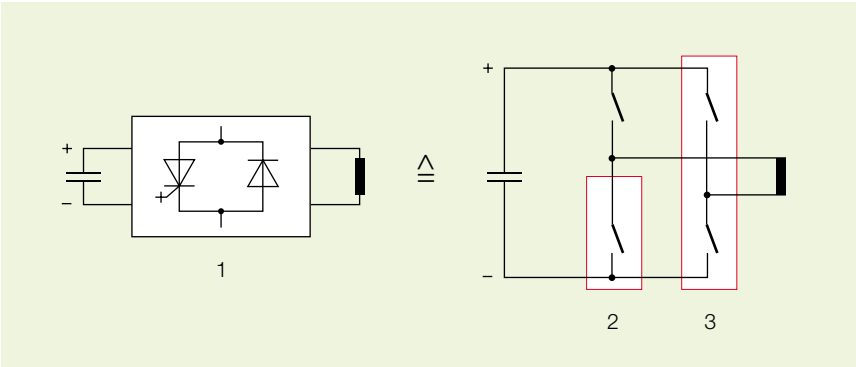
Voltage-source or current-source converters

Self-commutated converters can be built with current-source or voltage-source DC links. Only converters with voltage-source DC links will be referred to in the following, as they can be used universally and allow better utilization of the semiconductor devices.

Design and power rating of GTO thyristor converters

A frequency converter based on GTO thyristors is made up of phase modules, each with two branches. 1 shows them, in simplified form, as switches. Two or three phase modules, arranged in a bridge circuit, provide the basis for a

GTO thyristor converter for a single-phase and three-phase network, respectively. Thus, the converter output is designed for either forward, reverse or zero voltage (transformer winding, motor winding, etc). The GTO thyristors used most widely today allow a maximum transmission power of 5 MVA per bridge circuit.



Modules of a frequency converter **1**

1 *H-bridge for single-phase unit* 2 *Branch* 3 *Phase module*

A wide range of applications

In the past, GTO thyristor converters have been used mainly with variable-speed drives in industry and on board vehicles. The majority of these applications lie in the power range of a few 100 kW to several megawatts.

At 100 MW and above, power transmission ratings are, of course, in an entirely different class. System ties are a case in point. A demand exists already today for fast-response static compensators which are capable of efficient reactive power and voltage control and which will eliminate flicker.

Flexible AC transmission systems, or FACTS, are the subject of an assortment of development programmes worldwide. The projects focus on power electronics systems for the optimized control of energy flow in large interconnected power grids. The chief goals of the programmes are a reduction in losses, avoidance of unacceptable circulating currents, protection from single-line overloads as a result of power system failure, increased transmission stability, and load flow control as per contractural agreements. Work is concentrating on improving the controllable series and shunt compensation as well as unified power flow control (UPFC). High-power converters based on GTO thyristors are at the heart of all of these systems.

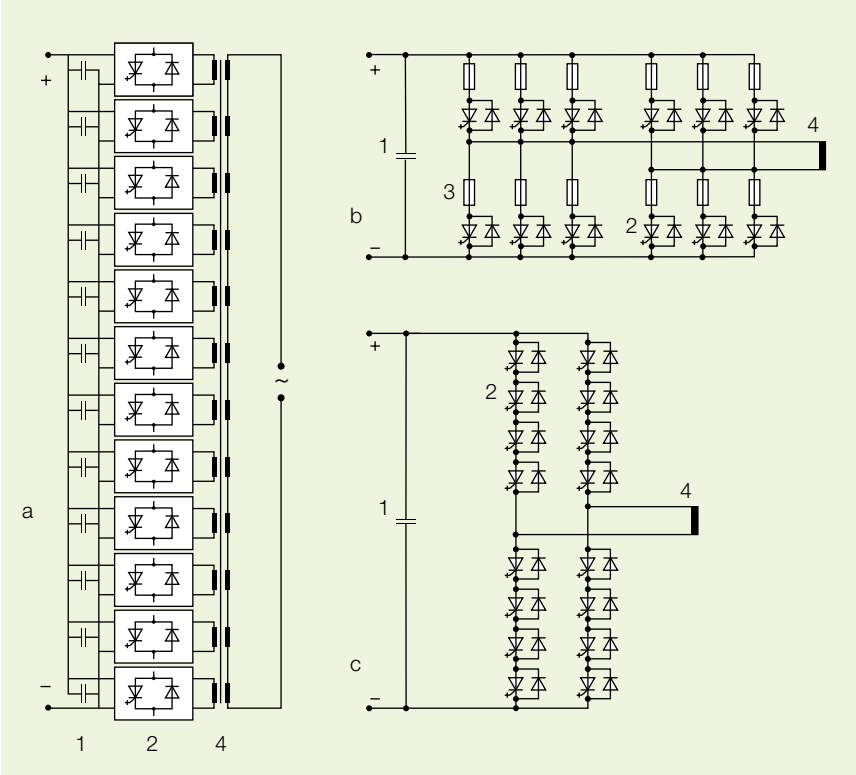
Circuits for high-power converters

GTO power semiconductor development is progressing only very slowly in terms of turn-off performance. There are both physical and economical reasons for this. Where higher power ratings are needed, one of the solutions is to divide the total power between several subsystems. Such installations are considerably more complex than one with a single high-power converter. What is more, they are more expensive to purchase and operate, exhibit lower efficiency and reduced full-power availability, and take up more space.

Circuit configurations for high-power converters **2**

a *Parallel/series-circuit in Giubiasco*
b *GTO thyristors connected in parallel*
c *GTO thyristors connected in series*

1 *DC link capacitors*
2 *GTO thyristor converter (H-bridge)*
3 *HV semiconductor fuses*
4 *Power system transformer*



Another possibility is to connect multiple GTO bridge circuits either in series or parallel. An example is the static frequency converter installed by ABB in the Giubiasco converter station of Swiss Federal Railways' traction power supply [1, 2]. It has a DC voltage link with 12 parallel H-bridges, the line sides of which are connected in series via a transformer 2a. In this way, a power rating of 25 MVA is achieved for each subsystem. The drawback of such a configuration is the high cost of the transformer on the line side. Fuse protection has to be provided by the GTO thyristors, which have to withstand the full DC link voltage, to limit the fault current in the event of a component failing (eg, due to a short circuit).

Parallel connection of GTO thyristors

When high powers are required, electrical equipment vendors try to circumvent the disadvantages of configurations with large numbers of GTO thyristor bridge circuits by connecting converter subsystems in parallel. GTO thyristors cannot be connected directly in parallel 2b, as this would lead to an unequal distribution of the current. For several projects in which the excitation equipment of rotating converters is being upgraded to make it state of the art, ABB has chosen in favour of converter subsystems with paralleling reactors.

Series connection of GTO thyristors

Series-connected thyristors are a proven HVDC transmission technology, and such configurations have been used successfully for decades. The series connection of GTO thyristors 2c also offers the greatest benefits in terms of first-time and operating costs. Although, in principle, the DC link voltage can be raised by increasing the number of GTO thyristors connected in series, special attention has to be paid to ensuring that the voltage is evenly distributed among the semiconductors. GTO thyristors have not been connected in series in the past because of the unequal delay times and the unbalanced voltage distribution during turn-off. 3 shows clearly what happens during turn-off when no special measures are taken. A number of important innovative steps were necessary before the required reliability and high efficiency could be ensured.

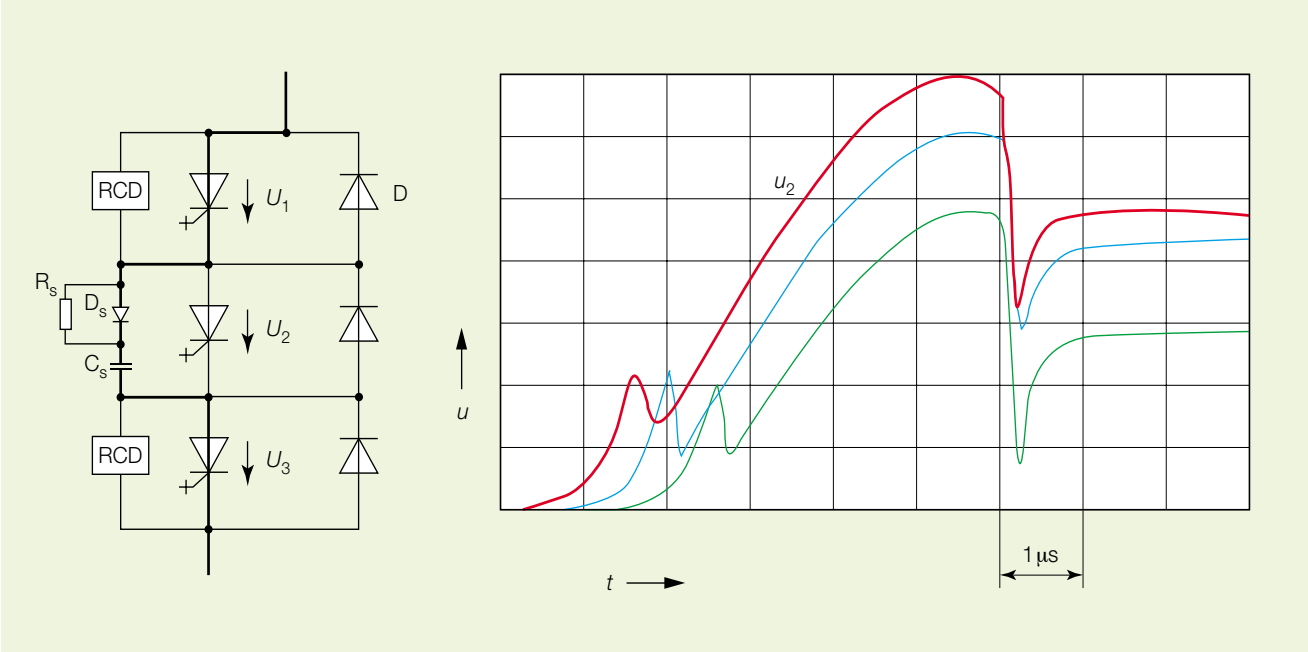
Simultaneous turn-off

During the turn-off process, the DC link voltage is divided among the GTO thyristors. To ensure that none of the semiconductor devices are loaded beyond their maximum voltage, the series-connected thyristors must all be turned off at exactly the same time. Various possibilities exist for this:

- *Component selection:* only semiconductor devices with highly similar char-

Turn-off procedure for three GTO thyristors connected in series, without measures taken to improve the voltage distribution. In the case of the first GTO thyristor to turn off, current flows in the snubber circuit and charges the capacitor with $i_c = C_s$ du/dt. This causes a transient overvoltage across the GTO thyristor. 3

U_1, U_2, U_3 Partial voltages RCD (R_s, C_s, D_s) *Snubber circuit* D *Diodes in antiparallel connection*

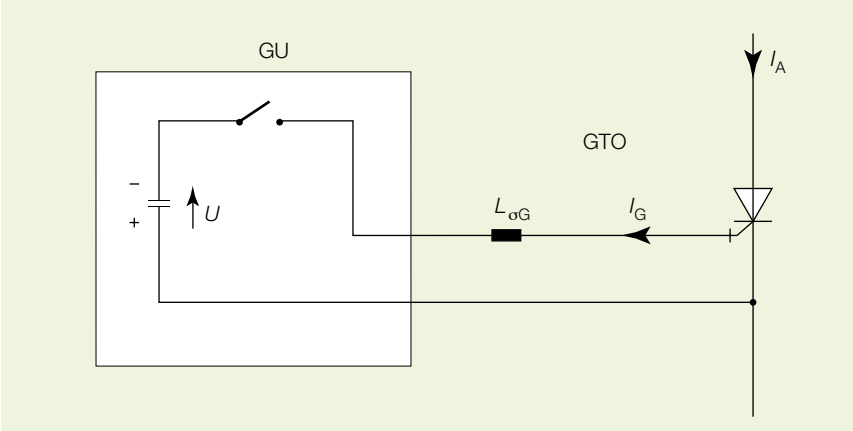


acteristics are connected together. However, this has a very adverse effect on the spare-parts inventory.

- *Adaptation of the gate units:* a result similar to that obtained through semiconductor device selection can be achieved by adapting the gate units.
- *Gate control:* simultaneous switching can also be achieved through gate control. The turn-off signal is given individually and at a defined time for each GTO thyristor such that voltage is applied to all the thyristors within less than 500 nanoseconds. Extensive laboratory tests carried out by ABB have demonstrated that this method functions with non-grouped GTO thyristors, and even with types from different vendors. However, the method requires complex electronics for each individual GTO thyristor and necessitates special commissioning of the converter.
- *Hard gate drive:* considerably simpler gate control is offered by the so-called hard gate drive, which was developed by ABB in collaboration with *Stadtwerke Bremen AG* and is highly suited to the switching principle of the GTO thyristor. The rate of rise and amplitude of the gate current I_G **4** is much higher with the hard gate drive (3000 A/µs) than with the conventional gate drive (30 A/µs).

A look inside the GTO thyristor shows why the hard gate drive offers advantages: semiconductor devices consist of several thousand individual GTO elements connected in parallel on a wafer. With the conventional gate drive, turn-off confines the current flow to a small number of GTO elements which are still conductive. The result is poor utilization of the substrate and a risk of hot spots. Tests show that with the hard gate drive turn-off is practically uniform over the whole substrate, and that considerably higher currents can be interrupted with the same devices. Better utilization of the substrate is therefore possible.

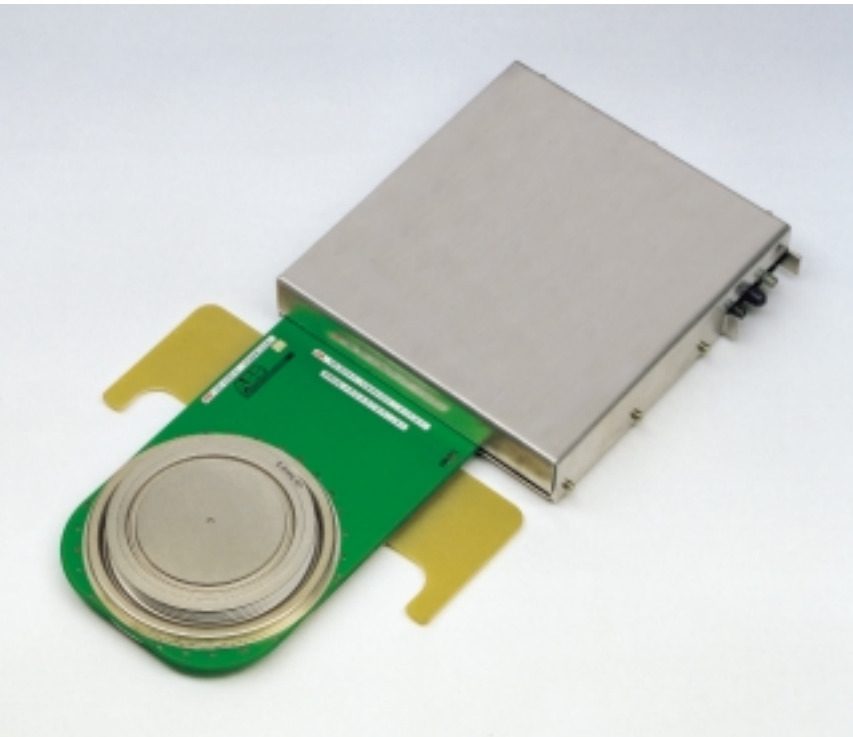
The hard gate drive reduces the response times of the GTO thyristors as well as their scatter to about a tenth of the value with conventional gate drives. When it is used, series connection of GTO thyristors is feasible without special selection of the semiconductor devices and without having to adapt or control the operation of the gate units. Since turn-off is uniform over the entire thyristor, the device is more rugged and critical values, such as the maximum rate of voltage rise du/dt, can be increased. It also allows the value of the capacitor in the snubber circuit to be reduced, thereby lowering the converter losses.



Equivalent diagram of the GTO thyristor gate unit circuit **4**

GU *Gate unit*
U *Supply voltage, gate unit*
I_A *GTO thyristor phase current*
I_G *Gate current*
$L_{\sigma G}$ *Leakage inductance in gate circuit*

GTO thyristor (foreground) with gate unit **5**



To achieve the required high rate of rise, the leakage inductance $L_{\sigma G}$ of the gate circuit must be kept very low, since

$$dI_G / dt = U / L_{\sigma G}$$

An increase in voltage U is also possible in principle, and has been investigated. However, due to the higher power loss and the amount of hardware that is necessary, problems arise with the reliability, so that this option cannot be justified.

Low-inductance gate unit

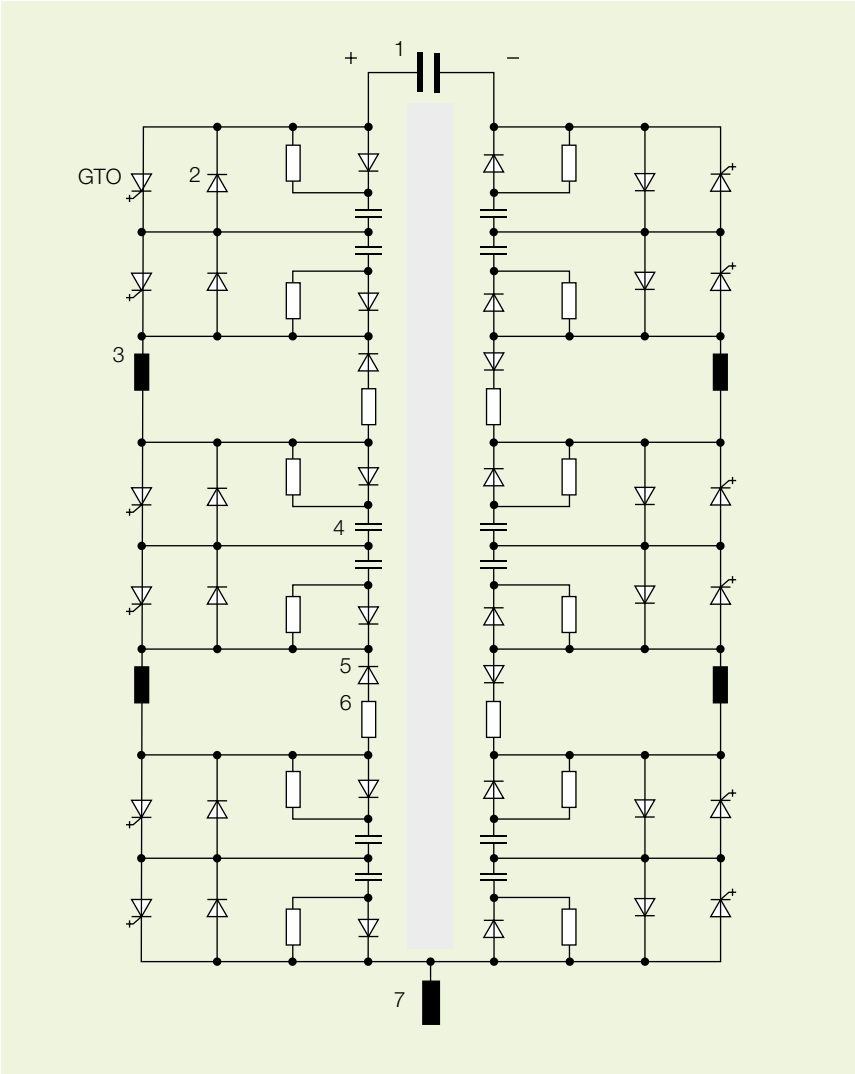
Low-inductance gate terminals for the GTO thyristors were given a high priority already during the design of the conventional gate units. As a result, these gate units already have internal buses. The unit is connected to the thyristor by special, high-strength coaxial wires of the shortest possible length (0.5 to 1 m).

A reduction in the gate circuit inductance by a factor of 100 obviously calls for a fundamentally new design. Not only the gate unit but also the GTO thyristor itself had to be redesigned, since a thyristor of conventional design will alone contribute an inductance equal to ten times the new value that is required.

By working closely together with a renowned manufacturer of semiconductor devices, it was possible to get the new configuration out of the design office and into the factory in just one year. The gate control unit and the GTO thyristor are now combined in a single assembly **5**, so that no connecting wire is needed. The gate current flows directly from the control transistors of the gate unit via the electronics circuitry to the GTO thyristor, which receives it via an annular terminal around its periphery. A rate of current rise of 3000 A/µs is thus achieved without having to adopt any special measures.

Circuit diagram of the phase module **6**

1 *Capacitor bank in DC link*
2 *Diode in antiparallel connection*
3 *Current limiting reactor*
4 *Snubber circuit*
5 *Freewheeling diode*
6 *Freewheeling thyristor*
7 *Transformer winding*



Redundant GTO thyristors

One way of ensuring maximum availability is to connect more GTO thyristors than are necessary in series. This makes sense, since it improves the installation in a number of ways:

- In the event of a GTO thyristor, a diode or a component in the snubber circuit failing, the installation will continue to run without interruption. This is because the device is designed to behave as a short circuit when it is defective. The failure is detected by a specially developed electronic circuit and signalled over fiber optic wires. The failed device can be replaced later, during routine maintenance.
- The addition of 'redundant' GTO thyristors reduces the voltage load for each individual device, including the snubber circuit. It is known that the lifetime of the individual devices depends strongly upon the voltage stress. When it is reduced by a third, for example through an increase in the number of semiconductor devices, the average lifetime of the GTO thyristors is increased by a factor of about 20.

- To avoid secondary faults, controlled turn-off of the entire installation takes place if failure of the redundant semiconductor devices incorporated in a branch should occur. This prevents through-conduction, ie, the unwanted tendency for a phase to become conductive and with it a discharge of energy from the capacitors in the DC link. The incorporation of redundant GTO thyristors allows the converter to be designed and built without fuses. Thus, in addition to the costs, losses and failures associated with high-voltage semiconductor fuses being eliminated, a very low-inductance design is made possible.

Low-inductance phase module

The phase module 6 is the basic element of the converter. Its function is to act as a changeover switch, alternately applying a positive and negative voltage to the load.

During commutation, the energy ($W = \frac{1}{2} L_{\sigma G} I_A^2$) stored in the leakage inductance has to be absorbed by the snubber circuit. To keep the losses low, the phase module is built with the lowest possible inductance, for example by choosing a U-shaped configuration with a small surface area (represented in 6 by the area, shaded grey).

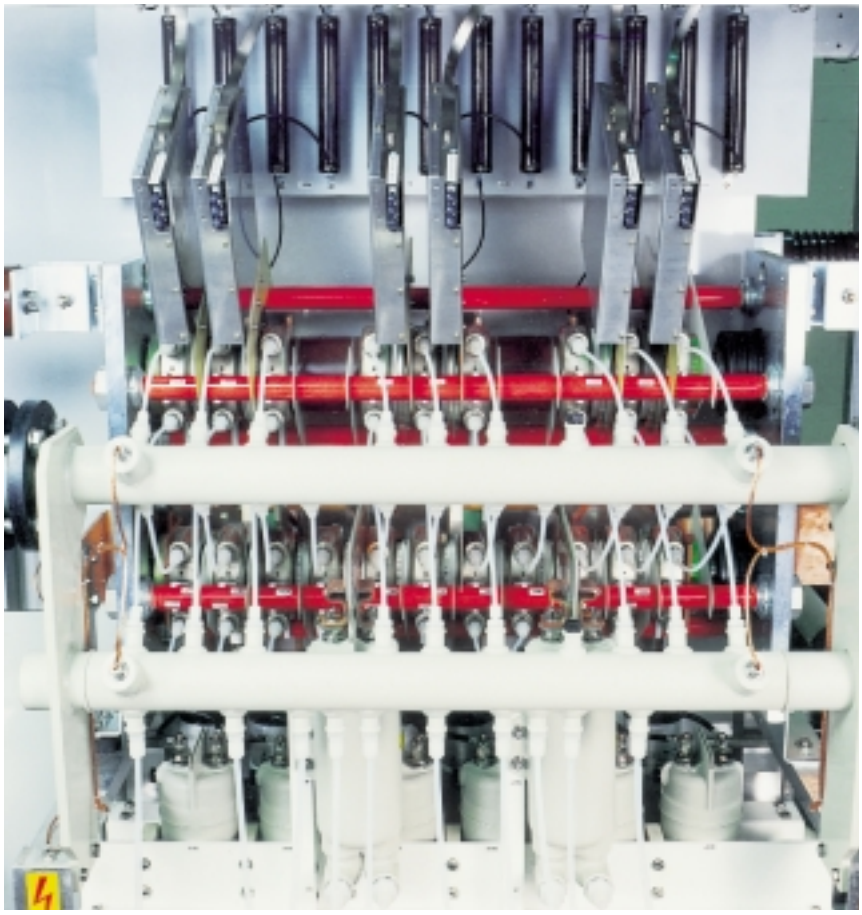
In the design considered, the phase module has two branches, each of which consists of two horizontally arranged semiconductor stacks, a gate unit and a snubber circuit 7. This arrangement allows quick and easy replacement of the semiconductor devices. One of the stacks contains the GTO thyristors, the other the diodes in antiparallel connection and the freewheeling diodes. The snubber circuit and the current limiting reactors are situated below the stacks, the gate units being mounted above them.

Special attention was paid to the modular design. This allows the same structure to be used with different DC link voltages in a variety of applications. 8 shows the modular layout, consisting of basic units with two GTO thyristors, diodes connected in antiparallel, and the snubber circuit.

Low-inductance phase module 7

1 *Gate units* 2 *Semiconductor stack* 3 *Snubber circuit*

Another priority during the design of the converter installation parts was ease of maintenance. The modules have been built to provide easy access to all the components and at the same time ensure maximum compactness for the phase



GTO thyristor stack with gate units above it 8

module and a high power output rating per GTO thyristor.

Comprehensive tests were carried out

The functional reliability of the series circuit and the innovations that contributed to it were verified by means of comprehensive computer calculations and simulations, plus tests under power conditions performed together with *Stadtwerke Bremen*. An initial project, involving a 16⅔-50 Hz frequency converter linking the 110-kV grid of *German Railways* and *Stadtwerke Bremen* and rated at 100 MVA, benefited from the experience gained in the Giubiasco converter station [1], especially in the conceptual area and in the layout design.

Following this, a complete H-bridge with two converter phases, each with six GTO thyristors connected in series, was systematically tested to confirm its performance under all operating conditions. For example, an endurance test was carried out for 100 hours with all the data increased (50 % higher rms value of the phase current, 50 % higher frequency, DC link voltage corresponding to the transient overvoltage in the installation, modules without redundancy); the test was concluded successfully, without a single failure occurring.

All possible fault conditions were not only simulated but also tested on components and modules in the high-power laboratory. These tests showed that even when all the protective functions fail, mechanical damage is caused to neither the components nor the modules.

The entire test programme was brought to a successful conclusion in December 1995.

Outlook

An increase in demand for self-commutated converters rated up to the very highest powers is evident worldwide. For such converters, ABB uses GTO thyristors in series connection. The problems involved in ensuring uniform voltage distribution during switching were solved with the help of the hard gate drive unit, which ABB developed. Combined with a low-inductance design for the phase modules, this guarantees high economy and reliability for converter installations.

In May, 1994, ABB was awarded a contract by *Stadtwerke Bremen* for the delivery of a static frequency link rated at 100 MVA. The installation could be built with one frequency converter unit with GTO thyristors connected in series as described above. The installation is currently being commissioned and will begin commercial operation in the autumn of this year.

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