THYRISTOR PHASE CONTROL

The thyristor is a family of four-layer power semiconductor devices that exhibit switching characteristics as exemplified by controlled rectifiers, which are the main subject of this section. Besides the semiconductor controlled rectifier (SCR), the thyristor family includes a number of other power control switching devices, including the gate turn-off switch (GTO) and the Triac (bidirectional ac switch) (1–3). Figures 1(a) and 1(b) show the basic pnpn-structure common to all thyristors as well as the graphical symbol of the reverse blocking thyristor or SCR, which will be discussed here. The names of the terminals are anode, cathode, and gate; the inner *p* layer and *n* layer are called *p* base and *n* base, respectively. The anode-cathode voltage V_{AK} is also referred to as thyristor voltage V_T; it is positive if the thyristor is operated in the forward direction. Figure 1(c) shows the ideal and the practical doping profile. Diffusion, alloying, and neutron doping are often used production methods for such devices.

HISTORY OF DEVELOPMENT

The principle of a four-layer device (*pnpn*) for switching of currents was invented and described at Bell Telephone Labs (4). The first devices according to this principle were developed and built at the end of the 1950s by General Electric in the United States (5). These devices appeared on the market under the name silicon-controlled rectifiers (SCRs) and replaced in a short time applied thyratrons and mercury arc rectifiers. The name *thyristor,* introduced shortly thereafter, is an artificial nomination like the name *transistor*.

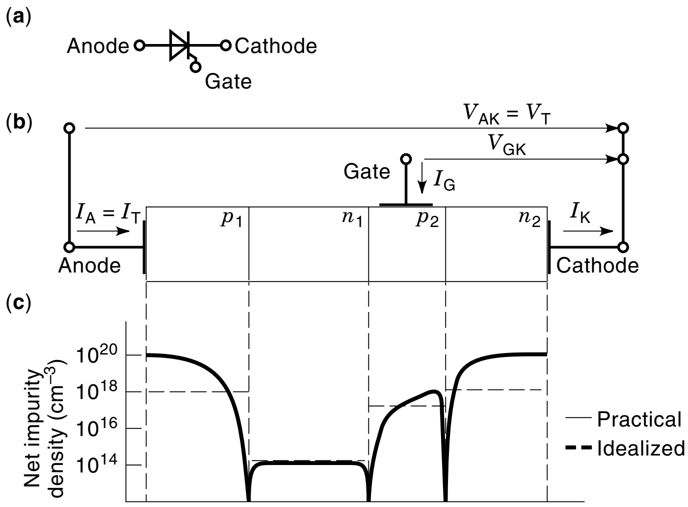

Figure 1. Thyristor. (a) Graphical symbol, (b) *pnpn* structure, (c) net impurity density representation.

PHASE CONTROL

The turn on of a controlled rectifier can be determined by the triggering of the gate. The delay of the turn on is expressed in delay or phase angle. Load current, load voltage, and power can thus be influenced by phase control. This is possible as well in ac circuits as in rectifier circuits. Later, in Fig. 12, an example of phase control is given for a three-phase rectifier.

TYPES OF THYRISTORS

Phase control thyristors are applied in alternating current (ac) single- and three-phase systems with 50 and 60 Hz. They are also called *N* thyristors. Normally these are cathode side-triggered thyristor triodes. Beside these thyristors, a series of other thyristor types has been developed (e.g., thyristor diodes, which are triggered by passing over the forward breakover voltage or the critical rate of rise of forward blocking voltage). Another type are thyristor tetrodes with gate contacts on both base zones. They can be triggered either on the cathode or anode side. Other species include bidirectional thyristors (TRIACs), thyristors for medium frequency (F thyristors or inverter thyristors), and light-triggered thyristors.

I-V CHARACTERISTICS

Figure 2(a) shows the current-voltage characteristics of a thyristor. In the reverse direction, the thyristor conducts a current that rises along with the reverse voltage but keeps negligibly small as long as the reverse breakdown voltage V_{BR} is not exceeded. If the voltage surmounts this point, the current may rise strongly if no external resistance is present. The thyristor behaves very similar to a diode in reverse direction. In the forward direction, the thyristor exhibits two stable states. If the forward voltage rises in the off state, the current increases also but stays insignificantly small as long as the forward breakover voltage V_{BF} is not reached. Some thyristors may block voltages up to several kilovolts. In this state, the thyristor behaves similar to a diode that is operated in the reverse direction. If the forward voltage rises beyond V_{BF}, the device switches to its on state and the current increases exponentially with the voltage, limited only by the circuit impedance. Some thyristors may conduct currents up to 4 kA at a minimal voltage drop of typically 1.5 V to 2.5 V. In this state, the device behaves similar to a diode that is operated in the forward direction. Figure 2(b) shows the corresponding *I-V* characteristics. A thyristor that is operated in the forward blocking region can be switched to the on state by applying a positive gate current pulse, by exceeding the forward breakover voltage, or by a very fast rise of the anode-cathode voltage. The first method is usually applied. To revert to the off state, the thyristor current has to fall below the holding current I_H [see Fig. 2(a)].

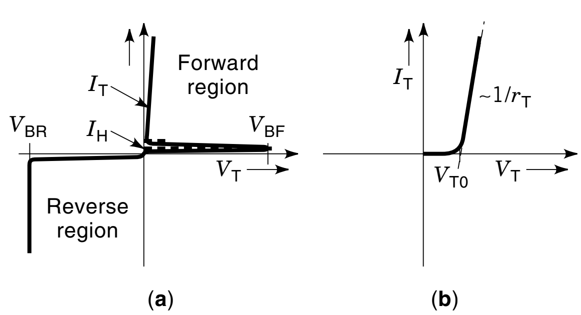

Figure 2. Forward and reverse *I-V* characteristics.

PHYSICAL MODE OF OPERATION

The useful features of thyristors are based on the interactions between the different *pn* junctions. The physical mode of operation is now discussed in more detail. To simplify matters, the doping profile shall be idealized, as shown in Fig. 1(b). The cross section of the thyristor shall be large enough to allow a one-dimensional study. Outside the depletion layers, the following principles shall be valid:

$$\begin{aligned}
n_n \approx N_D \text{ in } n \text{ layers}, N_D &= \text{net donator concentration} \\
n_n &= \text{electron concentration in} \\
& \; n \text{ layers} \\
p_p \approx N_A \text{ in } p \text{ layers}, N_A &= \text{net acceptor concentration} \\
p_p &= \text{hole concentration in } p \text{ layers} \\
n \cdot p &= n_i^2 \text{ in all regions except the} \\
& \; \text{depletion regions} \\
n_i &= \text{intrinsic carrier concentration}
\end{aligned}$$

Figure 3(a) shows the carrier concentrations in the thyristor under open-circuit conditions.

In this section, the forward blocking state shall be analyzed. If a positive voltage V_T is applied to the anode, *pn* junction J_2 will be reverse biased and absorb most of V_T. As a result, the depletion layer of J_2 will expand. The bulk of this region will stretch into the lower doped *n* base, the other part into the higher doped *p* base. Electrons and holes in the depletion layer are separated due to the electric field. Electrons move to the electrically neutral part of the *n* base. To maintain the balance of charge in the *n* base, J_1 is slightly forward biased, thus allowing holes to reach from the anode via J_1 to the *n* base. There the holes can neutralize the intruding electrons. Similar processes happen on the opposite side of J_2.

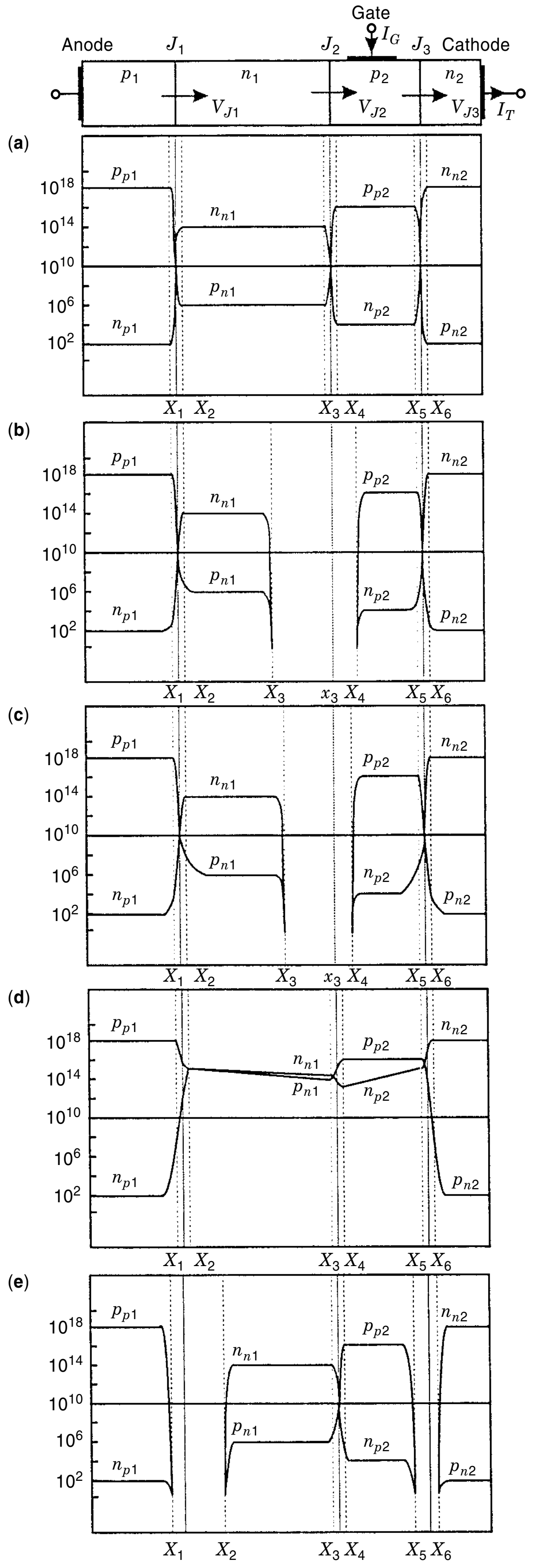

Figure 3. Carrier concentrations profiles: (a) Quiescent state, (b) forward blocking, (c) gate triggering, (d) forward conduction, (e) reverse blocking.

Electrons reaching from the cathode via J_3 into the neutral part of the p base compensate for holes that leave the depletion layer of J_2 due to the electric field. By this J_3 is slightly forward biased. The thermal generation in the depletion layer of J_2 permanently supplies the two bases with electrons and holes. The carrier gradients at the left and right border of the space-charge region also cause a small current. The gradient of the hole inclination at X_3 allows these carriers to diffuse in the space-charge region, where they are swept away to the p base. The number of holes injected into the depletion layer is very small because their equilibrium concentration as minority carriers is also very small. The majority-carrier concentration is much higher, but the electrons cannot diffuse into the space-charge region because the electric field pushes them back. In the same manner, electrons diffuse into the depletion layer at X_4 while the holes are pushed back. These two mechanisms, the thermal generation and the diffusion, establish a small current I_{T0}. The off state is stable. The I-V characteristics of the thyristor are mainly controlled by the reverse-biased junction J_2; therefore, it looks like the I-V curve of a diode that is operated in reverse direction. Figure 3(b) shows the carrier concentrations in this state.

This section explains how a positive gate current pulse I_G initiates the transition to the on state. This current I_G further biases the pn junction J_3 and raises the electron concentration on the right border of the p base at X_5. As the electron concentration on the right border of the space charge layer at X_4 adheres to its low level, a gradient of electrons is formed. Thus electrons diffuse to the space-charge region and are swept by the electric field to the n base, where they cause an imbalance of charge. This further biases J_1 in order to enable holes to reach from the anode via J_1 to the n base and increases I_T. The incoming holes not only neutralize the electrons coming from the cathode, but also form a gradient form J_1 to the depletion layer. Consequently, the holes diffuse to the space-charge region and are swept by the electric field into the p base, where they evoke an imbalance of charge. The surplus of holes biases the pn junction J_3 even further and increases the current via J_3 along with the current I_T. Thereby, electrons from the cathode reach the p base and neutralize the surplus of holes. The current via J_3, originally induced by the gate current I_G, has amplified itself after a short delay time. The courses can be summarized as follows: First the gate current I_G drives pn junction J_3, the resulting electron current drives J_1 and finally the hole current injected at J_1 drives J_3 again. The hole current from the anode acts in the same way as the gate current I_G did before: It raises the electron concentration on the right border of the p base and initiates a new feedback mechanism that again amplifies this current along with I_T. If the yield of current that can be measured after the delay time is less than the original current, the thyristor current I_T rises to a finite value. If the yield is equal to the original value, I_T rises infinitely and linearly by time; if the yield surmounts the original current, I_T rises infinitely and exponentially by time. The yield depends on the carrier concentrations that are linked with the thyristor current. This means that the yield rises along with the current I_T. If the gate current climbs over a certain value, the current increment that emerges from the feedback mechanism turns high enough so that the thyristor current starts to escalate exponentially by time. By this, the device is triggered. I_G is not necessary anymore because J_1 and J_3 drive each other mutually. The mechanism that raises the thyristor current is also explained in the next section from a different point of view, which is called the two-transistor analog.

Figure 3(c) shows the profile of the carrier concentration during the rise of current. The hole concentration at X_2 and the electron concentration at X_5 rise along with the current, injecting more and more holes and electrons in the depletion layer. In practical circuits, the thyristor current cannot rise infinitely because it causes an increasing voltage drop over the external resistance as well as over the bulk resistance. This decreases the voltage drop across the thyristor. The voltages over the junctions J_1 and J_3 cannot decrease; contrarily, they have to increase because the current I_T escalates. Therefore, the voltage of J_2 falls and the current increment descends also. If the thyristor voltage V_T falls below $V_{J1} + V_{J3}$, J_2 becomes forward biased and starts to inject holes into the n base as well as electrons into the p base. The forward voltage of J_2 (i.e., $-V_{J2}$) rises along with the hole concentration at X_3 and the electron concentration at X_4. This proceeds until the current increment that emerges from the feedback mechanism reaches zero. The thyristor voltage now reaches its minimum and the thyristor current its maximum. The device is completely switched on. Figure 3(d) shows the corresponding carrier concentration. There are so many carriers in the two bases that the device behaves like a pin diode. The bulk resistance is very low. For simulation purposes, the thyristor can be regarded as a resistor in series with a voltage source that represents the summed voltages $V_{J1} + V_{J2} + V_{J3}$.

Two further possibilities to trigger the thyristor shall be discussed at this point. The switch-on process may also be initiated by exceeding the breakover voltage. Two factors may be responsible for this event. The first one is an avalanche multiplication that happens if the electric field strength in the space-charge region surmounts a certain value. The carriers traveling through this layer are multiplied and become so numerous that they can drive J_1 and J_3 to initiate the feedback mechanism. The second possibility is the punch-through effect. The space-charge region propagates more into the lower doped n_1 zone and less into the higher doped p_2 zone. If V_T rises and the left border of the depletion zone at X_3 approaches the right border of the p_1 zone at X_2, the gradient of the holes becomes steeper and the diffusion of the holes increases. If the thyristor voltage grows enough and no avalanche multiplication occurs, then the diffusing holes sufficiently drive J_3 to trigger the thyristor. Furthermore, there is a third possibility to switch on the thyristor even if V_T remains far below the breakover voltage and no gate current is applied. This effect, which is called the dv/dt effect, is usually undesirable and can be avoided by external wiring. A rapidly rising anode-cathode voltage increases the space-charge region, thus causing a displacement current. This current moves the electrons that still can be found in the new space-charge area to the n base, where they bias J_1 in the forward direction. In the same manner, the removed holes drive J_3. If the voltage rise dv/dt comes very rapidly, the displacement current becomes so powerful that it triggers the device.

Phase control thyristors are not able to interrupt the current once they are triggered. This has to be achieved by external means that reduce the thyristor current below the holding current I_H. If this succeeds, the profile of carrier concentrations reverts to a profile similar to that of the initial profile, which is shown in Fig. 3(a). The thyristor returns to its off state. After that, a positive voltage may be applied again. A voltage that is applied too early immediately turns on the device. This is possible because the carrier concentrations in the p and n bases are still sufficiently high to allow huge current increments by the feedback mechanism. These increments proliferate, raising the thyristor current exponentially.

We now discuss reverse blocking characteristics. In the reverse operated thyristor, J_2 is forward biased while J_1 and J_3 absorb most of the thyristor voltage. The lowest doped zone exhibits the largest space-charge region. According to Fig. 1, this is the n_1 zone. Figure 3(e) shows the concentration profile of the reverse operated thyristor. An avalanche breakdown occurs if the electrical field strength in the depletion layer surmounts a certain value. A depletion layer punch-through occurs as soon as the right border of the depletion zone of J_1 contacts the left border of the space-charge region of J_2. It depends on the doping profile, whose effect appears first and thereby defines the reverse breakdown voltage. The device behaves quite similar to a diode that is operated in reverse direction.

TWO-TRANSISTOR ANALOG

Another approach to understanding the thyristor (in particular the switch-on process) is the two-transistor analog which is explained hereinafter. In Fig. 4(a), the dashed line marks the location where the device is (imaginarily) decomposed. The upper fragment represents an *pnp* transistor, the lower part a *npn*-transistor. Figure 4(b) shows the equivalent circuit that contains two complementary transistors. The voltages V_{J2} in transistor T_1 and V_{J2} in transistor T_2 are equal because wires connect the cuts laterally. A positive voltage V_{AK} biases J_2 in both transistors in the reverse direction and J_1 as well as J_3 in the forward direction. This means that n_1 of T_1 as well as p_2 of T_2 act as collectors. The wires between the cuts connect the base of each transistor with the collector of its complementary transistor. The application of the transistor theory provides the following equations:

$$\begin{aligned} I_{C2} &= \alpha_2 I_A + I_{C02} \\ \alpha_2 &= \text{common base current gain of transistor } T_2 \\ I_{C02} &= \text{collector-base reverse saturation current of } T_2 \end{aligned} \tag{1}$$

$$\begin{aligned} I_{B1} &= I_K(1-\alpha_1) - I_{C01} \\ \alpha_1 &= \text{common base current gain of transistor } T_1 \\ I_{C01} &= \text{collector-base reserve saturation current of } T_1 \end{aligned} \tag{2}$$

The usage of Kirchhoff's law gives:

$$I_{C2} + I_G = I_{B1} \tag{3}$$

$$I_A + I_G = I_K \tag{4}$$

Inserting Eqs. (1) and (2) into Eq. (3) and replacing I_K according to Eq. (4) yields

$$I_A = \frac{I_G \alpha_2 + I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)} \tag{5}$$

If no gate current is applied, Eq. (5) reads

$$I_{T0} = \frac{I_{CO1} + I_{CO2}}{1-(\alpha_1+\alpha_2)} \tag{6}$$

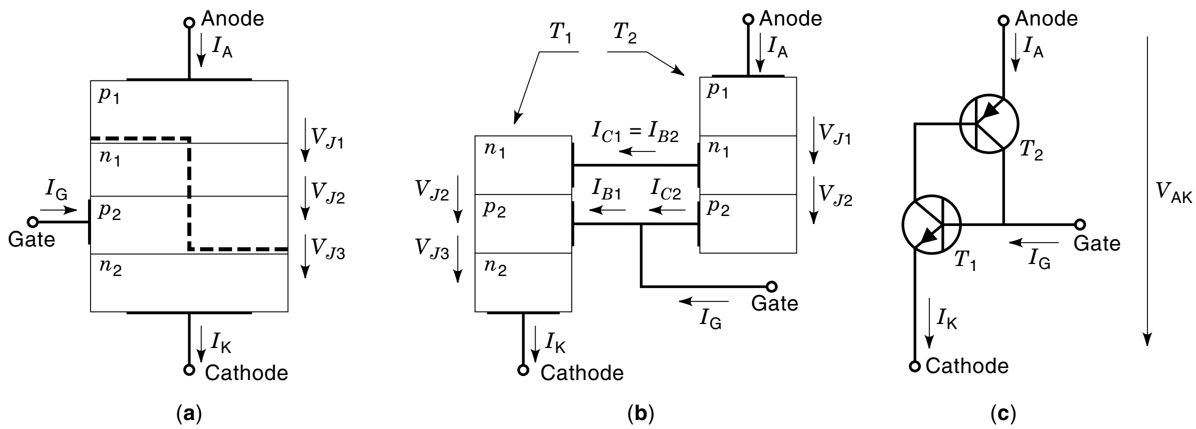

Figure 4. Two-transistor analog: (a) pnpn structure of a thyristor, dashed line marks the location where the device is imaginarily decomposed. (b) pnpn structure after decomposition, the pnp structure and the npn structure of the two resulting transistors can be recognized. (c) replacement of (b) by graphical symbols.

From Eq. (5) it is obvious that the thyristor current rises infinitely if the sum of $\alpha_1 + \alpha_2$ approaches unity. Besides this mathematical conclusion there is a physical explanation. Starting from the off state of the forward operated thyristor with $I_G = 0$, a gate current increment ΔI_G is applied. This current raises the base current of T_1

$$\Delta I_{B1} = \Delta I_G \tag{7}$$

and causes a collector current increment

$$\begin{aligned} \Delta I_{C1} &= \beta_1 \Delta I_{B1} = \beta_1 \Delta I_G \\ \beta_1 &= \text{common-emitter current gain of } T_1 \end{aligned} \tag{8}$$

Because I_{C1} equals I_{B2}, the current increment is amplified a second time and results in the collector current increment:

$$\begin{aligned} \Delta I_{C2} &= \beta_2 \Delta I_{B2} = \beta_1 \beta_2 \Delta I_G \\ \beta_2 &= \text{common-emitter current gain of } T_2 \end{aligned} \tag{9}$$

ΔI_{C2} drives T_1 and therefore I_{B1} rises to

$$I_{B1} = \Delta I_G (1 + \beta_1 \beta_2) \tag{10}$$

The original gate current has been amplified by this feedback mechanism. The additional current $\Delta I_G \beta_1 \beta_2$ will be amplified again by the factor $\beta_1\beta_2$. After the next cycle, I_{B1} can be calculated to be

$$I_{B1} = \Delta I_G (1 + \beta_1 \beta_2 + \beta_1^2 \beta_2^2) \tag{11}$$

After n cycles, I_{B1} will read

$$I_{B1} = \Delta I_G (1 + \beta_1 \beta_2 + \beta_1^2 \beta_2^2 + \cdots + \beta_1^n \beta_2^n) \tag{12}$$

If the product $\beta_1\beta_2$ equals unity, the base current I_{B1} rises linearly by time; if the product surmounts unity, I_{B1} rises exponentially by time. The thyristor current I_T rises along with the base currents I_{B1} and I_{B2} and the device switches to the on state. Using the relation

$$\beta = \frac{1}{\dfrac{1}{\alpha} - 1} \tag{13}$$

it can be derived that the condition $\beta_1\beta_2 > 1$ corresponds to

$$\alpha_1 + \alpha_2 > 1 \tag{14}$$

which was the mathematical condition for an infinite thyristor current in Eq. (5). The terms α_1, β_1, α_2, and β_2 depend on the carrier concentrations and rise with increasing current I_T. The gate current I_G is only necessary to increase the thyristor current to that value at which the sum of $\alpha_1 + \alpha_2$ exceeds unity. Henceforth I_T rises of itself. The gate current even can be switched off now because each transistor drives the base of the other transistor. The rising current causes an increasing voltage drop over the external resistance as well as over the bulk resistance. Consequently, the thyristor voltage subsides until J_2 becomes forward biased. Thereby, the transistors level off and the rise of current comes to an end.

ELECTRICAL PROPERTIES

The electrical properties of thyristors result from the forward and reverse blocking characteristic and from the on-state characteristic. Specified are allowable blocking voltages, maximum on-state currents under normal operation, and limits for surge and overcurrent. Electrical properties of thyristors are temperature dependent. It follows that electrical data given in data sheets are, in many cases, only valid in conjunction with the defined temperature data.

Forward direction is the direction from one main terminal to the other main terminal in which the thyristor has two stable states of operation, the off and on states [Fig. 2(a), direction anode-cathode)]. The forward characteristics consist of off-state and on-state regions; both regions are joined by the negative differential resistance region. Current and voltage values are defined as follows:

Forward off-state current I_D is the current that flows in the forward direction through the main terminals in the off-state condition of the thyristor.

Forward off-state voltage V_D is the voltage that is applied across the main terminals in the forward direction during the off-state condition of the thyristor.

Repetitive peak forward off-state voltage V_{DRM} is the maximum rated value of repetitive voltages in the forward off-state direction, including all repetitive transient voltages but excluding all nonrepetitive transient voltages. In view of transient voltages, which may be expected in operation, the thyristors are usually fed from a supply voltage whose peak value is equal to the limiting repetitive peak forward off-state voltages rating divided by a safety factor between 1.5 and 2.5.

Forward breakover voltages V_{BF} is the value of the off-state voltage at which for a given gate current the thyristor switches from the off state to the on state.

Holding current I_H is the minimum on-state current required to maintain the thyristor in the on state.

Latching current I_L is the minimum on-state current required to maintain the thyristor in the on state when the gate current decays with a fast rate of fall. It depends on the rate of rise, peak, and duration of the gate current and on the junction temperature.

On-state current i_T, I_{TAV} is the current that flows in the on state of the thyristor through both main terminals. Two values are distinguished: i_T = instantaneous value, I_{TAV} = average value.

On-state voltage V_T is the voltage between the main terminals at a defined on-state current. It depends on the junction temperature.

The forward on-state characteristic is the relation of the instantaneous values of on-state current and on-state voltage of a completely turned-on thyristor at given junction temperature.

A straight line approximation of the forward characteristic in the on state according to

$$V_T = V_{T(TO)} + I_T r_T \tag{15}$$

may be used to calculate the on-state power dissipation for the current range of interest [see Fig. 2(b)]. Thus with $V_{T(TO)}$ = threshold voltage and r_T = slope of resistance are specified.

The value of $V_{T(TO)}$ is determined by the intersection of straight-line approximation of the on-state characteristic and the voltage axis. r_T is calculated from the rate of rise of the straight line.

Maximum average on-state current I_{TAVM} is the maximum allowable continuous average value of current in a single-phase half-wave resistive load circuit at 40 to 60 Hz.

Maximum rms on-state current I_{TRMSM} is the maximum value of rms on-state current that the thyristor may conduct in view of the electrical, thermal, and mechanical stresses arising in the internal assembly parts of the devices. It must not be exceeded even under the best cooling conditions.

Surge (nonrepetitive) on-state current I_{TSM} is the maximum allowable instantaneous value of a single half-sinusoidal 50 Hz current pulse. Its value is given following no-load and following operation at maximum average on-state current, each without following voltage stress.

The $\int i^2 dt$ value is the maximum allowable value of the square of the instantaneous forward on-state current integrated over the time. This value provides a basis for the design of circuit protective devices. There is danger of destruction when exceeding the maximum allowable value.

Reverse direction is the direction from one main terminal to the other in which the thyristor has only one stable state of operation (namely, high resistance) (direction cathode to anode).

Reverse current I_R is the current flowing in reverse direction through the main terminals of the thyristor.

Reverse voltage V_R is the voltage applied across the main terminals of the thyristor in reverse direction.

Repetitive peak reverse voltage V_{RRM} is the maximum allowable instantaneous value of repetitive voltages in the reverse direction, including all repetitive, but excluding all nonrepetitive, transients.

SWITCHING BEHAVIOR

The dynamic properties describe the behavior of the thyristor during switching on and off as well as in a fast rate of rise of current and voltage. The most important are $(di/dt)_{cr}$, $(dv/dt)_{cr}$, and turn-off time t_q. After each change of current or voltage in the thyristor, a certain time passes before a new state of equilibrium is reached. As a result, delay times and switching power dissipations occur at turn-on and turn-off.

Turn-on is initiated at forward off-state voltage V_D by a gate current I_G having a rate of rise di_G/dt and a magnitude I_{GM}. It is sufficiently described by the terms *gate-controlled delay time* t_{gd} and *critical rate of rise of on-state current* $(di/dt)_{cr}$ (Fig. 5). Gate-controlled delay time t_{gd} is the time between the 10% value of a fast rising gate current and the 90% value of the decreasing main voltage. It is decreased by increasing gate current.

Critical Rate of Rise of On-State Current $(di/dt)_{cr}$

After the gate-controlled delay time has elapsed, a limited cathode area near the gate contact begins to conduct on-state current. This current-conducting area spreads out later on with a speed up to $v \approx 0.1$ mm/μs. The current-carrying capability of the system in the initial interval of time after turn-on is, therefore, heavily restricted. Endangering or even destroying the thyristor is, however, impossible if in practical use the value of the critical rate of rise of on-state current specified in the data sheet is not exceeded.

The critical rate of rise of off-state voltage $(dv/dt)_{cr}$ is the maximum permissible value of the rate of rise of a blocking voltage in forward direction, which rises nearly from 0 to 0.67 V_{DRM} at which the thyristor does not switch into the conducting state. It is valid for open gate and maximum allowable junction temperature. There is a danger of destruction when exceeding this limit.

Turn-off is normally initiated by applying a reverse voltage. The principal current does not cease when passing through zero but it continues to flow in reverse direction as

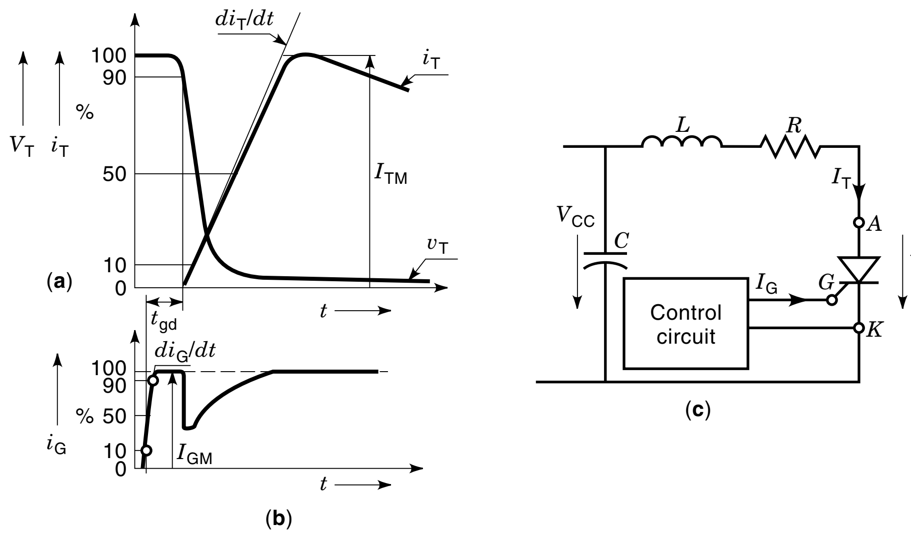

Figure 5. Schematic representation of turn on of thyristors: (a) Thyristor voltage and current at main current circuit turned on, (b) gate current at fast rising on-state current (dashed line is gate current under open main circuit), (c) turn-on circuit.

reverse recovery current as a result of the hole storage effect (Fig. 6). Recovered charge Q_r is the total amount of charge flowing out of the thyristor after switching from an on-state current to a defined operating condition with reverse direction. Q_r increases with rising junction temperature as well as with peak value and rate of fall of the on-state current.

Peak Reverse Recovery Current I_{RM}

Dependencies on operating conditions are corresponding to those of Q_r. Reverse recovery time t_{rr} is the time interval between the current passing through zero and the time when the extrapolated reverse recovery current reaches zero in a commutation process from forward to reverse direction.

Circuit commutated turn-off time t_q is the time interval between the instant when the decreasing on-state current passes through zero and the earliest reapplication of off-state voltage, after which the thyristor does not turn on again (Fig. 7). It depends mainly on the rate of fall of the on-state current, the rate of rise of the off-state voltage, and the junction temperature. For phase control thyristors t_q is on the order of 100 to 300 μs, in contrast to inverter thyristors, with t_q between 5 μs and 50 μs.

TRIGGERING PROPERTIES

Thyristors are predominantly triggered electrically. They are bipolar devices controlled by currents. Thyristors need positive gate current for turning on (Fig. 8). The following gate properties are defined:

Gate current I_G is the current flowing through the control path at positive gate voltage.

Gate voltage V_G is the positive voltage across gate terminal and cathode.

Gate trigger current I_{GT} is the value of gate current that causes the thyristor to trigger. It depends on the voltage across the main terminals and the junction temperature T_{vj}. At the given maximum value all thyristors of a given type of trigger.

Gate trigger voltage V_{GT} is the voltage that occurs across the gate terminal and cathode terminal when the trigger current flows.

In a normal case of application, the design of the control circuit should be oriented to gate data, which are given in con-

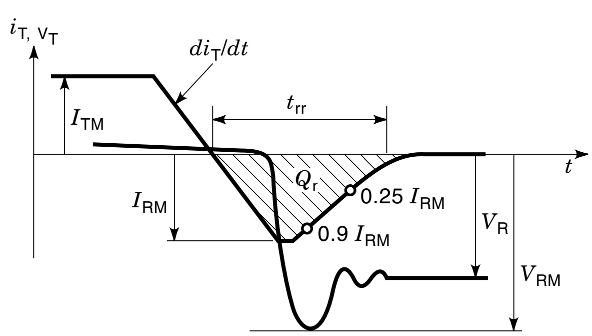

Figure 6. Schematic representation of reverse recovery current.

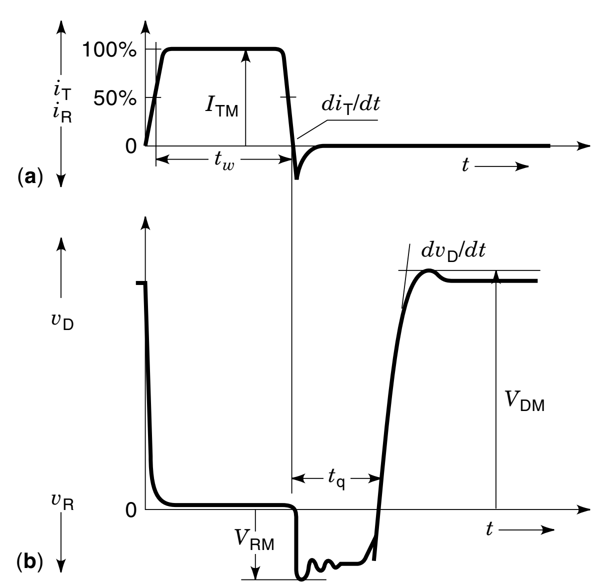

Figure 7. Schematic representation for the turn-off: (a) Thyristor current, (b) thyristor voltage, circuit turn-off time t_q.

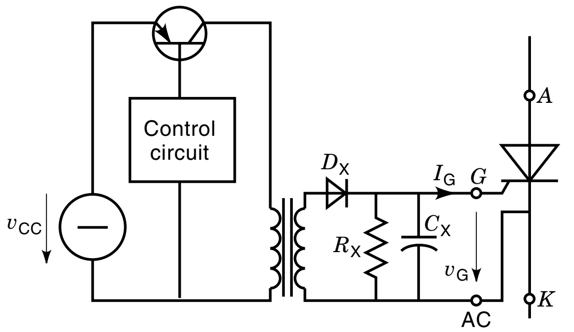

Figure 8. Basic circuit diagram for a trigger pulse generator for thyristors.

nection with the critical rate of rise of on-state current, gate-controlled delay time, and latching current. When thyristors are connected in parallel or in series, even higher and steeper as well as synchronous gate pulses are necessary (for instance, to keep the variation of the values of delay time low).

Light-Triggered Thyristor

Thyristors can also be triggered directly with light. Moreover, hybrid solutions are possible where a built-in auxiliary thyristor is light triggered first and fires then the main thyristor electrically.

Light-triggered thyristors are developed specially for applications in high-voltage equipment. These are large thyristors in disc cases that have a light-sensitive gate area triggering the thyristor when irradiated by photons. The light is guided by a fiber optic directly to the cathode area. By means of the fiber guide an isolation for the highest voltages is obtained without problems. The needed light power is at maximum on the order of 10 mW at the gate (6,7). Due to losses caused by damping in the light fiber and by coupling into and out of the fiber, a three to five times higher light power has to be generated in the control circuit. Snubbers consist of R and C networks with other possible components connected across the thyristor.

SNUBBER CIRCUITS

For protection against voltages and currents that are too high, thyristors need snubber circuits.

Overvoltage Protection

Overvoltages may occur in a power system (for instance, due to switching operations in the main supply, atmospheric effects, switching of a transformer at no load, switching of inductive loads, and delay characteristics of power semiconductors). Since thyristors can be damaged by voltage transients of a few microseconds, a careful selection of overvoltage protection is essential. When designing a suitable snubber circuit, the blocking capability (V_{DRM}, V_{RRM}) and the critical rate of rise of off-state voltage $(dv/dt)_{cr}$ have to be taken into consideration. As protection, RC snubbers, varistors, overvoltage limiters, and series inductances are usual.

Transient overvoltages will be caused through the delay characteristics of thyristors after reaching the peak reverse recovery current of the main circuit. They can effectively be reduced by a snubber circuit (R and C in series). For many applications the RC snubber circuits are sufficient (these are given to diagrams of the total energy and current load). Their suitability for the provided application should be checked.

Overcurrent Protection

Thyristors have a high current-carrying capability in continuous operation but allow only limited overcurrents due to their low thermal capacity. In case of a breakdown, an overcurrent protection device prevents destruction. In case of a short circuit, the protection must be laid out in such a way that in utilizing the $\int i^2 dt$ value or surge on-state current I_{TSM}, the thyristors may temporarily lose their blocking ability. The following typical breakdowns must be considered in projecting the protection: short circuit in the load circuit, bad triggering of a thyristor, destruction of a thyristor.

Series Inductances in the Main Circuit of Thyristors. In some applications the installation of linear or saturable inductances in series with a thyristor is necessary to keep the stress of current and voltage within given boundaries during turn-on and turn-off. This measure also reduces turn-on switching dissipation. In the case of a linear inductor, the current density in the spreading portion of silicon that is conducting will be reduced during the current rise. With saturable inductors (e.g., consisting of ring cores with rectangular hysteresis loops), the current rise takes only place after the step time has elapsed (that is, when already a larger area of the silicon pellet participates in current conduction).

PARALLEL AND SERIES CONNECTION

To increase the power of equipment, thyristors can be connected in parallel or in series.

Parallel Connection

When connecting thyristors in parallel, the distribution of the current in the arms of the converter should be as equal as possible. Reasons for deviations from the ideal distribution of current are different resistances in parallel arms. They are caused by the spread of the on-state characteristics of the thyristors and the construction details of the parallel circuit. Dynamic influences, such as spread of the gate-controlled delay time, differences in the turn-on behavior, and induced voltages caused by the construction of the circuit, also cause current deviations. In addition, all snubber circuits of parallel arms discharge through the thyristor triggering first. An equal current distribution in the parallel arms can be achieved by the use of thyristors with nearly equal on-state voltage and a large degree of correspondence of resistance in parallel arms. An additional resistance in series to each parallel thyristor, such as a fuse, improves the symmetry. The same is true for the use of current-balancing reactors and small spread of the values of the gate-controlled delay time. For that, triggering of the thyristors with synchronous, steep, and high gate pulses is necessary. After triggering of the first thyristor, the anode-cathode voltage of the parallel components also falls to the value of its on-state voltage. As a consequence, the voltage-dependent delay time of the thyristors triggering increases and the beginning of turn-on of these components is delayed correspondingly.

Especially with large and high voltage blocking thyristors there is a risk that some of them, after initial triggering, revert to the forward off state because of on-state current density that is too low. An overload of the current-conducting thyristors if the load increases can be avoided by retriggering. As a rule, one strives for currents unbalances of less than 15%.

Series Connection

When connecting thyristors in series, the applied voltages have to be divided as equally as possible. Reasons for the deviation from the ideal voltage division areas follows:

Different reverse and forward currents. Without a snubber circuit during the static reverse condition, a very unfavorable voltage distribution in both directions may occur as it depends on each individual thyristor at the uniform reverse current in the series connection.

At turn on spread of the gate controlled delay time can cause a considerably higher forward off-state voltage of the thyristors triggering at last.

The consequences of differences in the reverse recovered charge Q_r is different reverse recovery times t_{rr} and different peak reverse currents I_{RM}, which means that the thyristors begin to block reverse voltage at different times. The spread of the reverse recovered charge ΔQ_r of two thyristors connected in series effects a voltage deviation $\Delta V \approx \Delta Q_r/C$, where C is the capacitance of the parallel snubber circuit. Equal voltage distribution across thyristors in series may be achieved by snubber circuits. For this the RC components against carrier storage effects are often sufficient. However, for long-lasting direct current (dc) voltage an additional resistor parallel to each thyristor is necessary. It should carry about to two to five times the maximum reverse current of the applied thyristor at operation temperature.

To reduce the spread of the delay times, triggering of the thyristors with synchronous, steep, and high gate pulses is necessary ($di_G/dt \geq I_{GM}/1\mu s$, $I_{GM} \geq 4 \ldots 10\ I_{GT}$). Gate pulses like these reduce the spread of the delay time to $\Delta t_{gd} < 1\ \mu s$.

MECHANICAL DESIGN

The first thyristors were built in a ceramic and metal package and mounted by a stud or a clamp on a heatsink. The contacts of anode and cathode were soldered. This design is still valid for thyristors in the low and medium power fields. For mass application, thyristor modules have been developed. Modules can contain two or more thyristors (also in combination with diodes) to build up complete single- or three-phase bridge connections. For medium and high power, the disc case design (unit cell) is dominant. This design allows for mounting into different heatsinks as well as two-sided cooling (Fig. 9).

The proper and careful mounting of thyristors is mandatory for reliable and undisturbed operation, because both electrical and thermal contacts are produced by fixing the devices in place (e.g., on heatsinks). Stud-type thyristors are screwed in with a torque wrench. With flat base cases, the required clamping force is obtained with the spring clamp supplied with each device.

LOSSES IN THYRISTORS

Under operation, electrical losses occur in thyristors that have to be transferred into heatsinks. Different dissipations are distinguished: on-state dissipation, switching power dissipation, off-state dissipation, and dissipation in the gate circuit.

Forward off-state and reverse power dissipations P_D, P_R are the electrical power converted into heat in the off state in the

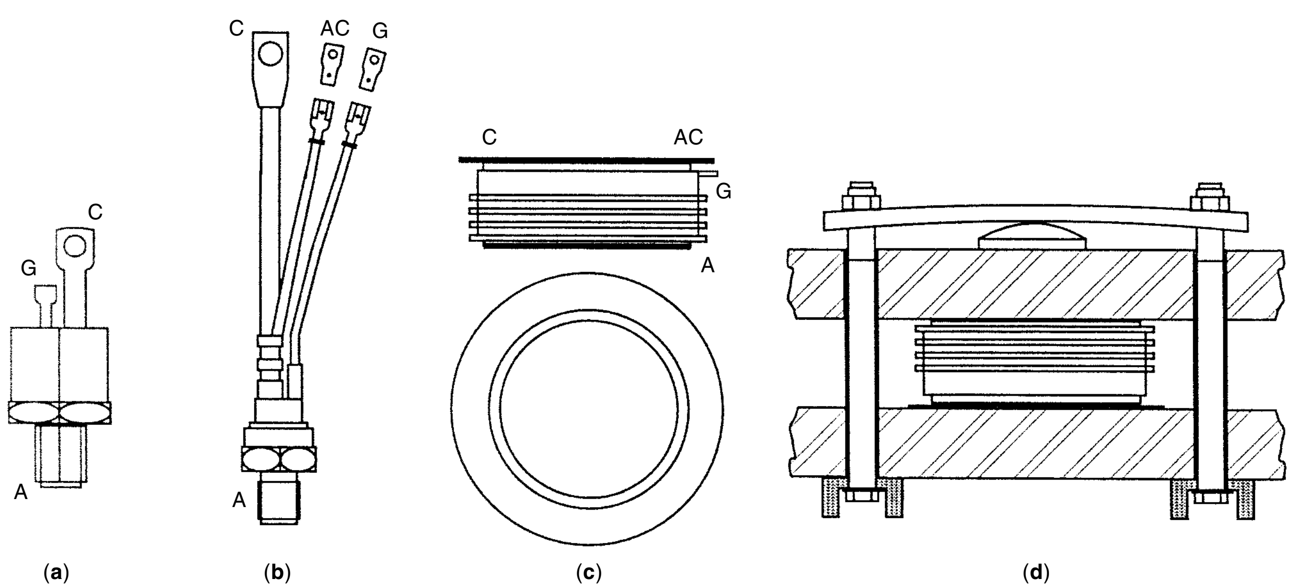

Figure 9. Representation of different thyristor cases: (a) Metal case with glass insulator, threaded stud, for small current (<50 A), (b) hermetic metal case with ceramic insulator, threaded stud, for medium current (<100 A), (c) capsule type metal-ceramic package with precious metal pressure contacts, for high current (>2000 A), (d) example for mounting under pressure and double-sided cooling.

forward direction (P_D) and reverse direction (P_R). These are mainly important for operating with predominant blocking voltage stress.

On-state power dissipation P_T is the electrical power converted into heat if only the forward conducting state is considered. The average on-state dissipation P_{TAV} can be approximately calculated using the following equation and the straight-line approximation with $V_{T(TO)}$ and r_T:

$$P_{\mathrm{TAV}} = V_{\mathrm{T(TO)}} \cdot I_{\mathrm{TAV}} + r_{\mathrm{T}} \cdot I^2_{\mathrm{TRMS}} \tag{16}$$

Switching power dissipations $P_{TT} + P_{RQ}$ are the electrical power converted into heat at turn-on (P_{TT}) and turn-off (P_{RQ}). The average switching dissipation increases at an increasing rate of rise and fall of on-state current when turning on and off as well as at increasing repetition frequency and must be taken into consideration. In application at mains frequency of 40 to 60 Hz, switching dissipation can be ignored compared to the on-state dissipation up to medium-size thyristors.

Turn-on switching power dissipation P_{TT} is heat developed in a thyristor during a turn-on process. It is caused, on the one hand, by the delay characteristic and, on the other hand, by the time required for the conducting area to spread out. To turn on a rather large area, fast thyristors are equipped with an amplifying gate.

Turn-off switching power dissipation P_{RQ} is caused by the delay characteristics and depends on the process of the recovered current as well as the height and the rate of rise of the reverse blocking voltage and can therefore be influenced by a snubber circuit.

COOLING

The heat generated within the thyristors by electrical losses must be transferred through heatsinks to the ambient. In general, the heatsinks are offered together with the thyristors by the manufacturers. Coolant air or liquids are applied. For liquid cooling, water is preferred (in special cases also oil). In traction converters, boiling liquid cooling has been applied for about one decade because of their very compact construction. Here the loss generating elements lie within a closed tank filled with a low-temperature boiling liquid (Freon). To protect the environment Freon cooling has been replaced in newly developed converters by water cooling or heat pipes. The heating produced by electrical losses can be calculated by using thermal equivalent circuits (Fig. 10).

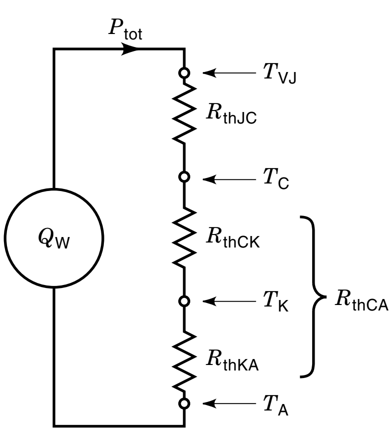

Figure 10. Thermal equivalent circuit for thyristors.

Thermal resistance is formally divided into single sections (i.e., thermal resistance junction to case and case to ambient). For the thyristors and heatsinks these thermal resistances are given in data sheets.

Junction temperature T_{vj}, T_{vjmax} is the most important reference for all fundamental electrical properties. It represents a mean spatial temperature and is therefore known more precisely as a virtual junction temperature. Observance of the maximum permissible junction temperature T_{vjmax} is important for the operation and reliability of the device. Exceeding it may change the properties permanently. Case temperature T_c or heatsink temperature T_K is the temperature at a spot of the thyristor case or of the heatsink close to the contact surface. Storage temperature T_{stg} is the temperature range within which the thyristor may be stored without any electrical stress.

The thermal resistance junction to case R_{thJC} is the relationship of the difference between the junction temperature T_{vj} and the case temperature T_c to the total power dissipation P_{tot}:

$$R_{\mathrm{thJC}} = \frac{T_{\mathrm{VJ}} - T_{\mathrm{C}}}{P_{\mathrm{tot}}} \tag{17}$$

The thermal resistance case to heatsink R_{thCK} is the ratio of the difference between temperature at the contact surfaces of thyristor and heatsink to the total power dissipation P_{tot}:

$$R_{\mathrm{thCK}} = \frac{T_{\mathrm{C}} - T_{\mathrm{K}}}{P_{\mathrm{tot}}} \tag{18}$$

The values given are valid at proper mounting only. The thermal resistance case to coolant R_{thCA} is the ratio of the difference between the case temperature T_C and the coolant temperature T_A to the total power dissipation P_{tot}:

$$R_{\mathrm{thCA}} = \frac{T_{\mathrm{C}} - T_{\mathrm{A}}}{P_{\mathrm{tot}}} \tag{19}$$

The total thermal resistance R_{thJA} is the ratio of the difference between the virtual junction temperature T_{vj} and T_A to the total power dissipation P_{tot}:

$$R_{\mathrm{thJA}} = \frac{T_{\mathrm{J}} - T_{\mathrm{A}}}{P_{\mathrm{tot}}} = R_{\mathrm{thJC}} + R_{\mathrm{thCA}} \tag{20}$$

For dynamic processes the thermal capacitances also have to be taken into account. The transient thermal impedance junction to case $Z_{(th)JC}$ is given in the individual data sheets for direct current (dc). This value allows one to calculate of the transient heating. In addition, the values R_{thn} and τ_n are given for the analytical function (8):

$$Z_{\mathrm{(th)JC}} = \sum_{n=1}^{n_{\max}} R_{\mathrm{th}n}(1 - e^{-T/\tau_n}) \tag{21}$$

Arrangement of Heatsinks

Thyristors with heatsinks for forced air cooling or water cooling can be mounted in any position as long as the flow of cooling medium will be maintained. In the case of natural convection cooling, the heatsinks have to be arranged so that

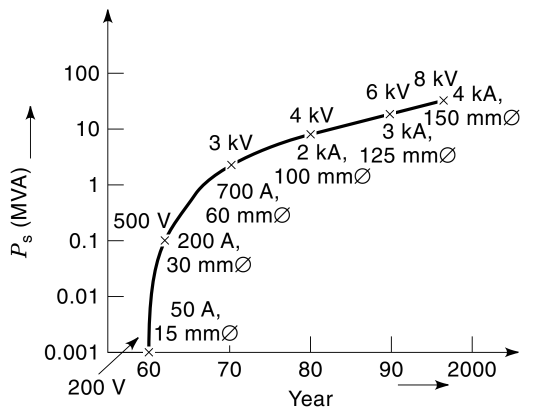

Figure 11. Development of maximum voltage and maximum current of phase control thyristors over four decades. Also given is the maximum diameter of silicon wafers.

their ribs are in vertical position to allow cooling air to pass unhindered. They have to be mounted a sufficient distance from the bottom or from other equipment. If a number of heatsinks are arranged on top of each other, a sufficiently great spacing has to be ensured (in particular, at natural convection cooling to prevent mutual heating). If thyristors and heatsinks are heated by other components (e.g., transformers) they have to be derated correspondingly. Heatsinks have the voltage of the attached thyristor and for this reason have to be mounted electrically insulated. Thyristors in disc cases enable any cooling configuration. Bore holes and clamping pins have to be provided in the clamping devices. A common configuration is shown in Fig. 9.

TYPICAL VALUES FOR THYRISTORS

Thyristors are available for a wide power range of applications from the kilowatt to the gigawatt range. The values of

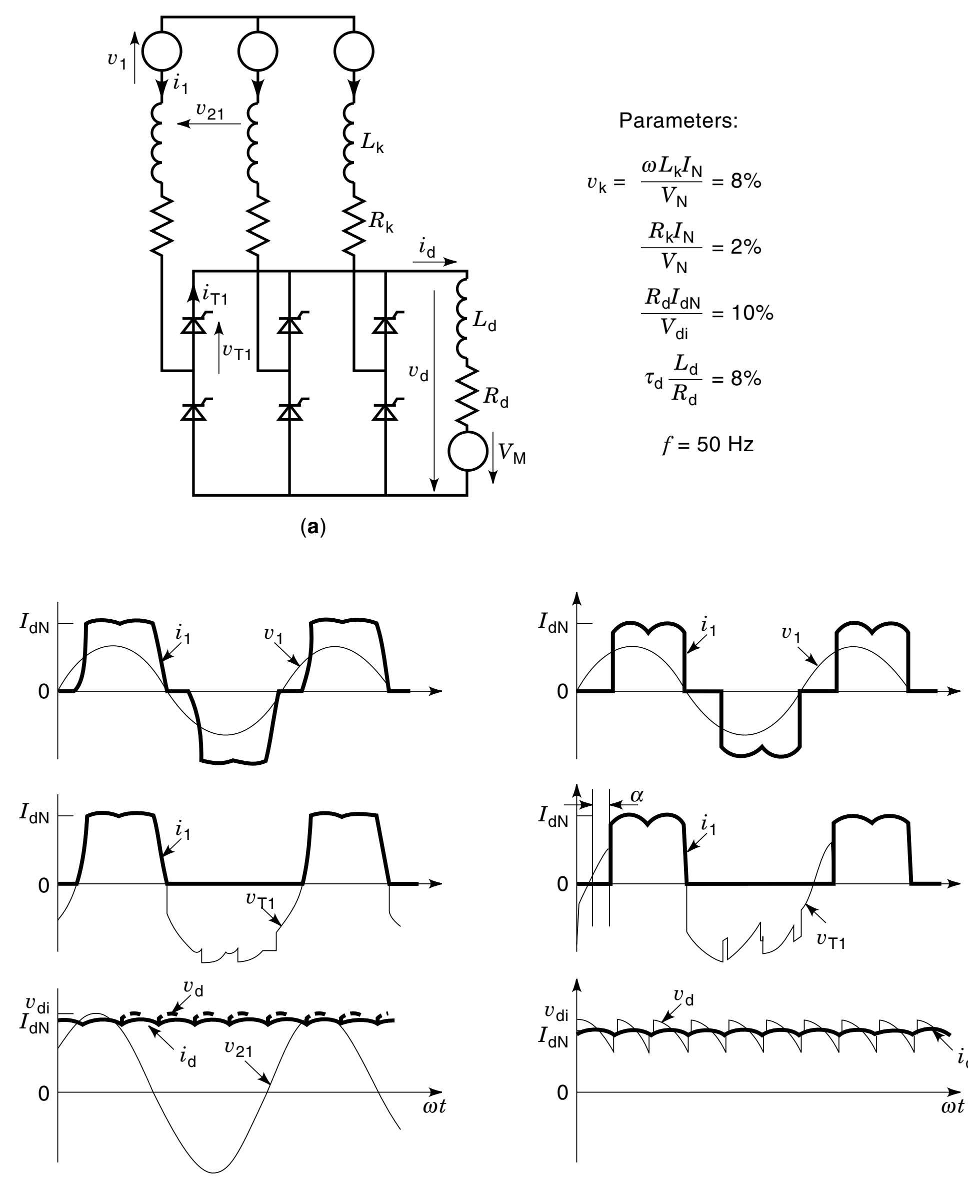

Figure 12. Phase control: (a) Three-phase bridge rectifier, (b) phase delay α = 0°, (c) phase delay α = 30°. Dc voltage can be changed by phase control: $V_{d\alpha} = V_{di} \cos \alpha$.

the blocking voltage are adapted to the connected main voltage. The maximum repetitive blocking voltage extends from several hundred volts to 10 kV for application in high-voltage areas. By series connection higher voltage values can be achieved. The same is true for current where thyristors of some amperes up to 4 kA are offered (9). The diameter of the round silicon disks determines the allowable current. With small thyristors the silicon disks have dimensions of some millimeters. For large thyristors the disks have reached 5 to 6 inches in diameter. Out of maximum blocking voltage and maximum on-state current a product can be formed that defines a fictitious switching power in megavolt-amperes. Figure 11 shows the increase of the maximum fictitious switching power of thyristors over time. The increase in current resulted mainly from the increase of the diameter of silicon crystals. The increase of blocking voltage was achieved by improving the homogeneity of the starting material, the dope profile, and by developing specially surface bevelled structures.

Only a fraction of the fictitious switching power of thyristors can be utilized in power electronic equipment due to necessary safety factors in protection against overcurrent and overvoltage.

MAIN APPLICATIONS OF PHASE CONTROL THYRISTORS

The principle of phase control in single- and three-phase ac circuits is given by the fact that the instant of triggering and thereby the start of conducting current can be controlled via the gate connection. This offers the opportunity to control electrical power continuously (Fig. 12). The start of current is determined by the triggering instant. After triggering the current flows dependent on the external connection under the influence of the ac commutating line voltage until it falls to zero and becomes extinct. The thyristor then switches from the on state to its blocking characteristic.

The main applications of phase control thyristors are controlled rectifiers and inverters. The connection most applied is the three-phase bridge connection. This application covers a power range of some kilowatts to more than 10 GW. With such converters drives, dc motors can be controlled in speed. The highest power installations are found in high-volt dc transmission (HVDC). Big HVDC plants reach power up to the Gigavolt-ampere range. Because of the high voltages (up to several hundred kilovolts dc) many thyristors have to be connected in series. Also, complete bridge connections have to be put in series. The thyristors can be electrically or light triggered.

Synchronous machines can be controlled in speed by phase control thyristors: converter-fed synchronous machines. With cycloconverters, low changeable frequencies can be generated from 50 to 60 Hz mains.

Antiparallel connected thyristors can be applied as an ac switch or for ac phase control. For low power, Triacs can be used for applications like lamp dimming.

DEVELOPMENT TRENDS

The development of phase control thyristors is mature. Nevertheless, steady improvements still take place. Monocrystalline silicon material is further enhanced with respect to homogeneity and diameter (6 inches are reached). For application in high-voltage installations, one tries to build thyristors for 10 kV and more. To improve the turn-on, gate structures are refined. A special concern is robustness against radiation, especially cosmic radiation, which may lead to flashover under high-voltage operation. Light-triggered thyristors will probably find wider application.

The material silicon dominates in semiconductor elements for power electronics. Worldwide there is research and development with other materials, like gallium arsenide and silicon carbide (10,11).

One task remains for application of phase control thyristors in the future: the replacement of mechanical switches in single- and three-phase ac systems. This is especially true for medium voltage grids, where better system quality can be achieved by semiconductor switches: synchronous switching, phase control if needed, no wear and tear, and fast turn-off in case of disturbance and short circuit. The key for broader application of phase control thyristors in this field is economy.

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