Power Electronics

THIRD EDITION

Cyril W. Lander

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PREFACE

The application of semiconductor devices in the electric power field has been steadily increasing, and a study of power electronics (as it is commonly called) is now a feature of most electrical and electronic engineering courses.

The power semiconductor devices, such as the diode, thyristor, triac, and power transistor, are used in power applications as switching devices. The development of theory and application relies heavily on waveforms and transient responses, which distinguishes the subject of power electronics from many other engineering studies. The aim of the author has been to produce a student text which explains the use of the power semiconductor devices in such applications as rectification, inversion, frequency conversion, d.c. and a.c. machine control, and the many non-motor applications.

In choosing material to include in this text, it was decided that material relating to the physics of semiconductor devices, electronic control circuitry involved in (for example) firing circuits, and control system theory is adequately covered elsewhere and would unnecessarily lengthen the book. Material relating to these areas has only been included where it is essential to the proper understanding of the applications of, and circuits used in, power electronic systems.

The treatment and level of the material in this book is intended for students following courses ranging from the higher technician level to final-year first degree. This book will also provide useful background material for post-graduate master's degree courses.

Engineers concerned with the supply and utilization of electricity need to be aware of the effects which power electronics equipment has on both the supply and load. It is hoped that this text will fulfil this need, particularly for those whose student days date back to the era before the development of the power semiconductor devices.

It is the author's view that a technical book requires worked examples to reinforce the understanding of the subject, and to this end 167 worked examples have been included. It is suggested that initially readers attempt the worked examples without reference to the solution, as this will identify gaps in their knowledge. Much of the routine arithmetic has been omitted from the solutions, as this should be within the competence of readers to solve. All the mathematical work in the solutions has been carried out with the aid of an electronic hand calculator. All the worked examples and problems have been devised by the author.

The order of the chapters is that in which the author has taught the subject to final-year BSc students, although it is recognized that protection may well be included at an earlier stage. A glossary of terms in use in power electronics has been included.

I am grateful to my wife Audrey and children Karen and Stephen for the patience they have shown during the long hours spent at home in preparing the manuscript for this book. My grateful thanks are also extended to all those teachers, colleagues, students, and friends who over the years have inspired and helped me.

CYRIL LANDER

PREFACE TO THE SECOND EDITION

Since the original edition was published, new devices have become commercially available and are being used in power electronic equipment. Also, further developments have taken place in the applications of the power electronic devices. The opportunity has been taken in this new edition to include the new devices and applications as additional material, retaining all of the original material from the first edition.

I am grateful for the many encouraging and favourable comments received from lecturers and students who are using my book, and hope that the updating of the material will enhance its value in the study of power electronics. I would also like to acknowledge with thanks the help and assistance received from the staff of McGraw-Hill, the publishers of this book.

CYRIL LANDER

PREFACE TO THE THIRD EDITION

In the six years since the second edition, further developments have taken place in power electronics. These developments in both the devices and their applications have been included in this edition. Some extra worked examples are included to aid the understanding of the new material.

I continue to be grateful for the encouraging and favourable comments received from lecturers and students who use my book and hope the further updating in this edition enhances its value in the study of power electronics. As with the earlier editions my wife Audrey has continued to be very patient and supportive during the many hours spent at home preparing the manuscript for the new edition. Finally, I would like to again acknowledge with many thanks the help and assistance received from the staff of McGraw-Hill, the publishers of this book.

CYRIL LANDER

CHAPTER
ONE
RECTIFYING DEVICES

A rectifying device is one which permits current flow in one direction only, being able to withstand a potential difference without current flow in the opposite direction. The major devices in power rectification are the diode, conventional thyristor, triac, gate turn-off thyristor, bipolar power transistor, power MOSFET, and the insulated gate bipolar transistor. Other than the diode all of these devices can withstand a potential difference in the forward direction and are thus controllable rectifying devices.

1-1 THE DIODE

The active material from which the semiconductor power diode is formed is silicon, a semiconducting material, that is, a material which is classified as being between the insulating and conducting materials, its resistance decreasing with temperature rise.

Silicon is an element in group IV of the periodic table, and has four electrons in the outer orbit of its atomic structure. If an element from group V is added, that is, an element having five outer orbit electrons, then a free electron is present in the crystal structure. The free electrons allow greatly increased conduction, and as the electron is negatively charged such a material is known as an *N*-type semiconductor.

If to silicon is added an impurity element from group III, that is, an element having three outer orbit electrons, then a gap or hole appears in the crystal structure which can accept an electron. This gap can be considered to provide a positively charged carrier known as a *hole*, which will allow greatly increased conduction, the material so doped being known as a *P*-type semiconductor.

The order of doping (addition of impurity) is in the order of 1 part in 10^7 atoms. In *N*-type semiconductors, the majority carriers of current are electrons, the minority carriers being holes. The reverse applies to the *P*-type semiconductor. Depending on the degree of doping, the conductivity of the *N*- or *P*-type semiconductor is very much increased compared to the pure silicon.

The diode shown in Fig. 1-1 is formed by the junction within a single crystal of *P*- and *N*-type materials. At the junction, the free electrons of *N* and the free holes of *P* combine, leaving the *N* side with a positive charge and the *P* side

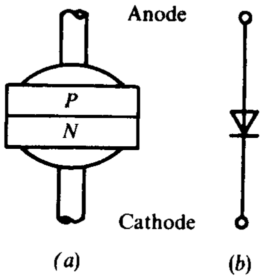

Figure 1-1 The diode. (*a*) Structure. (*b*) Symbol.

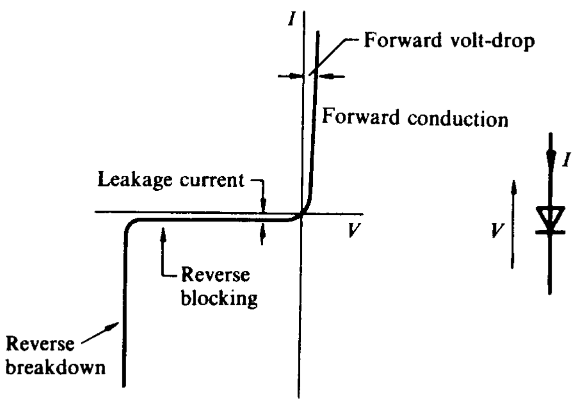

Figure 1-2 Diode characteristic.

with a negative charge. Hence, a potential barrier exists across the junction having a value of the order of 0.6 V.

The diode characteristic is shown in Fig. 1-2, and with reference to Fig. 1-1*a*, a positive voltage applied to *P* (the anode) with respect to *N* (the cathode) will result in current flow once the potential barrier of 0.6 V is overcome, giving an overall forward volt-drop of the order of 0.7 V at its rated current. The application of a reverse voltage will move the mobile carriers of holes and electrons away from the junction in the *P* and *N* sides respectively, hence preventing current flow and allowing the junction to withstand the applied voltage without conduction. The junction experiences a high electric field gradient and hence can be considered as having capacitance. Thermal agitation does rupture some of the bonds in the crystal, resulting in minority carriers which permit a small reverse current flow shown as a leakage current. An increase in the reverse voltage will lead to an increase in the acceleration rate of the minority carriers across the junction. Eventually the minority carriers have sufficient energy to remove others by collision, when avalanche multiplication takes place and the junction is broken down, giving the reverse breakdown characteristic. Typically the leakage current is a few milliamperes.

1-2 THE THYRISTOR

The device described in this section is that which was originally developed and can be described as the conventional thyristor to distinguish it from the gate turn-off thyristor described in Sec. 1-4. The thyristor is a four-layer *P-N-P-N* device, with a third terminal, the gate, as shown in Fig. 1-3. A 2000 V, 300 A device would typically be a silicon wafer of diameter 30 mm and thickness 0.7 mm.

The characteristic of the *P-N-P-N* device without any external connection to the gate is shown in Fig. 1-4. The thyristor in this condition may be considered

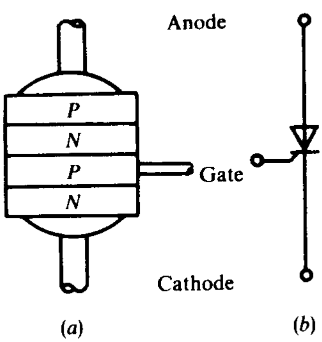

Figure 1-3 The thyristor. (*a*) Structure. (*b*) Symbol.

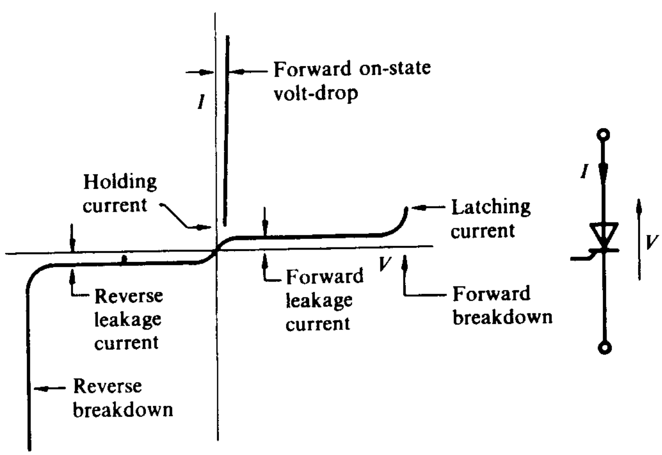

Figure 1-4 Thyristor characteristic with no gate current.

as three diodes in series, with directions such as to prevent conduction in either direction. The reverse characteristic, that is, with the cathode positive, exhibits similar features to the diode. The forward characteristic, that is, with the anode positive, exhibits no current flow other than leakage until the breakover voltage of the centre control junction is exceeded. The forward and reverse breakover voltages are similar in magnitude, due to, in the reverse blocking state, almost all the voltage appearing at the anode *P-N* junction, the cathode *P-N* junction breaking over at about 10 V. Once breakover in the forward direction occurs, the centre *P* slice is neutralized by the electrons from the cathode, and the device acts as a conducting diode having two junctions giving a forward volt-drop approximately double that of the diode. In order for the thyristor to attain and retain the on-state, the anode current must reach its latching level, and not fall below its holding level as shown in Fig. 1-5. The latching current is typically double the holding current, but both are low, being much less than 1 per cent of the full-load rated value.

The thyristor, when forward-biased (anode positive), can be switched into the on-state by injecting current into the gate terminal relative to the negative cathode, as illustrated in Fig. 1-5. The action of the gate current is to inject holes into the inner *P* slice, which, together with the electrons from the cathode *N* layer, breakover the centre control junction, switching the thyristor into the on-state. Once the anode current has exceeded the latching level, the gate current can cease, the thyristor remaining in the on-state, irrespective of conditions in the gate circuit.

To turn off the thyristor, the anode current must be reduced below the holding level, and a relatively long time allowed to elapse for the thyristor

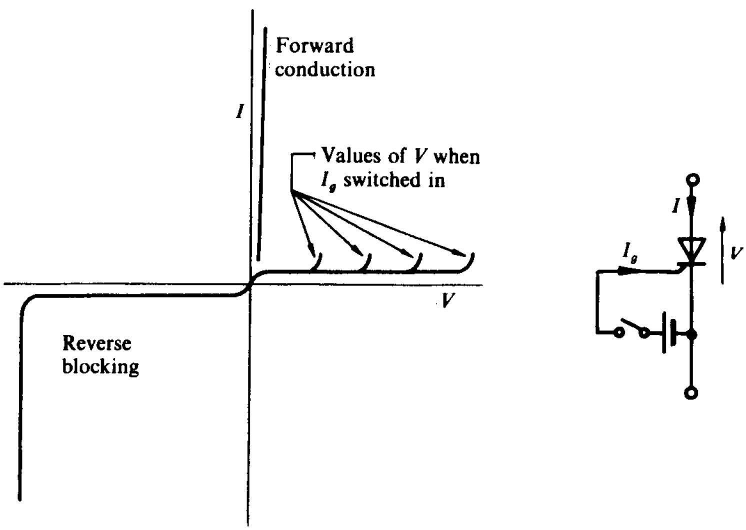

Figure 1-5 Thyristor characteristic with gate current.

control junction to recover its blocking state, before a forward voltage can again be applied without conduction. More typically, to turn off the thyristor, the anode current is driven into reverse by the external circuitry, when for a very brief period a reverse current flows as shown in Fig. 1-6, permitting charge movement within the *PN* layers, allowing the two outer junctions to block any further reverse current after the storage charge has been recovered. The stored charge is due to the presence of the current carriers in the junction region. The central control junction will, however, not block the re-application of a forward voltage until a further time has elapsed, sufficient to allow recombination of the carriers at this junction. Typically 10 to 100 μs must elapse before the forward voltage can again be applied without breakdown. The storage charge could typically be 20 μC for a 20 A thyristor.

The thyristor described in this section is that which was the first to be developed, and can be referred to as the conventional thyristor. More recent developments have seen the introduction of the gate turn-off thyristor which can be turned off by removal of current from the gate, unlike the conventional thyristor which can only be turned off by reduction of its anode current to near zero. The gate turn-off thyristor is described fully later in Sec. 1-4.

A further device which has been developed is the combination of a thyristor with a reverse conducting diode on one silicon wafer. This device will always conduct in the reverse direction, but is controllable (as with the normal thyristor) in the forward direction. Applications of this reverse conducting thyristor are in inverter circuits such as that shown in Fig. 5-20, where this single device can be used instead of the parallel connection of one thyristor and one diode.

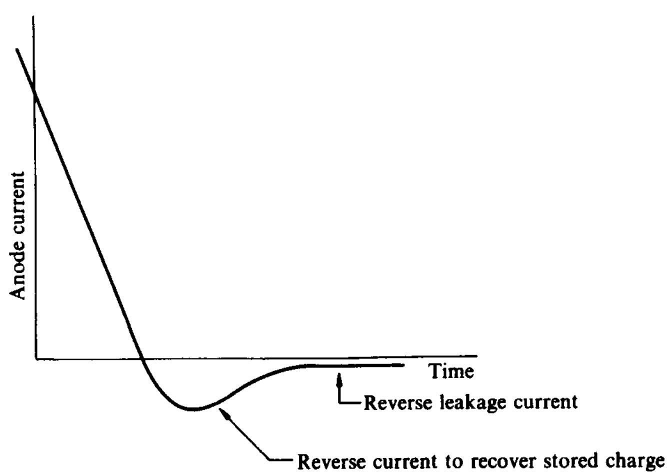

Figure 1-6 Typical current waveform during turn-off.

1-2-1 Thyristor gating requirements

The gate-cathode characteristic of a thyristor is of a rather poor *P-N* junction. There will be a considerable range of characteristic within a given production batch, individual thyristors having characteristics as shown in Fig. 1-7*a*. All thyristors can be assumed to have a characteristic lying somewhere between the low and high resistance limits. The minimum level of current and voltage required to turn on the thyristor is a function of the junction temperature; an indication of these minimum levels is shown in Fig. 1-7*a*.

The current into, and the voltage at, the gate are both subject to maximum values, but turn-on requirements demand they also exceed certain minimum

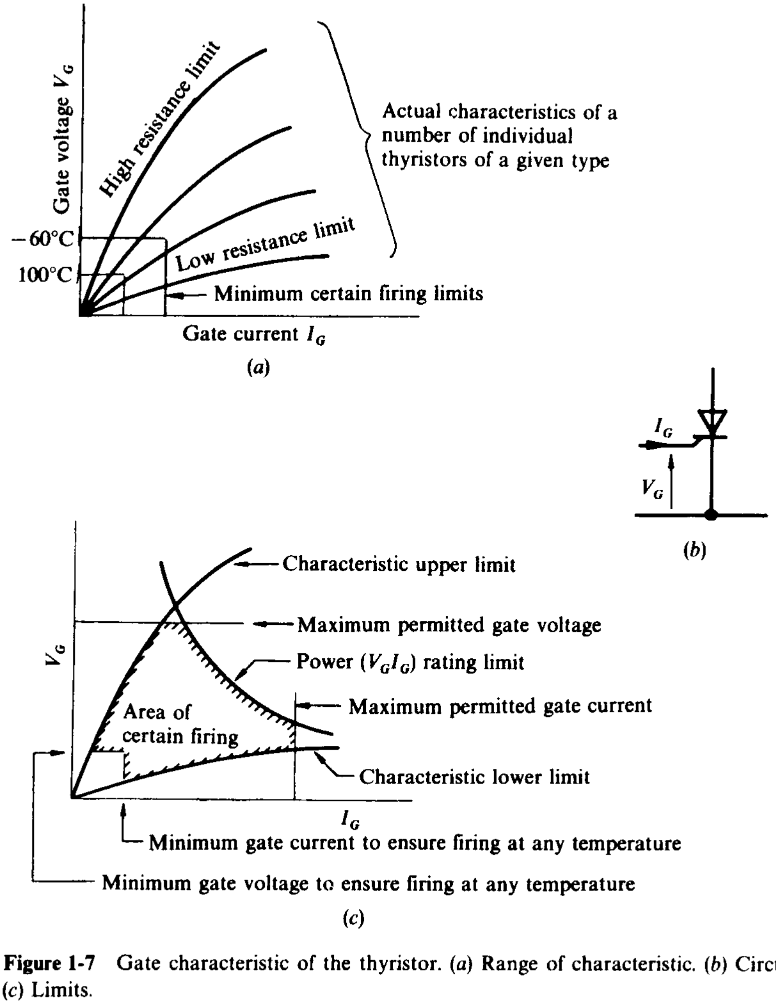

Figure 1-7 Gate characteristic of the thyristor. (*a*) Range of characteristic. (*b*) Circuit reference. (*c*) Limits.

levels. The product of gate voltage and current gives a power level to which a maximum is set. Fig. 1-7*c* shows these limits imposed on the gate-cathode characteristic, giving the area into which must be fitted the gate firing signal for certain firing into the on-state to take place.

The final stage of the gate firing (triggering) network shown in Fig. 1-8*a* will consist of a transformer for isolation, a resistance R_1 to limit the gate

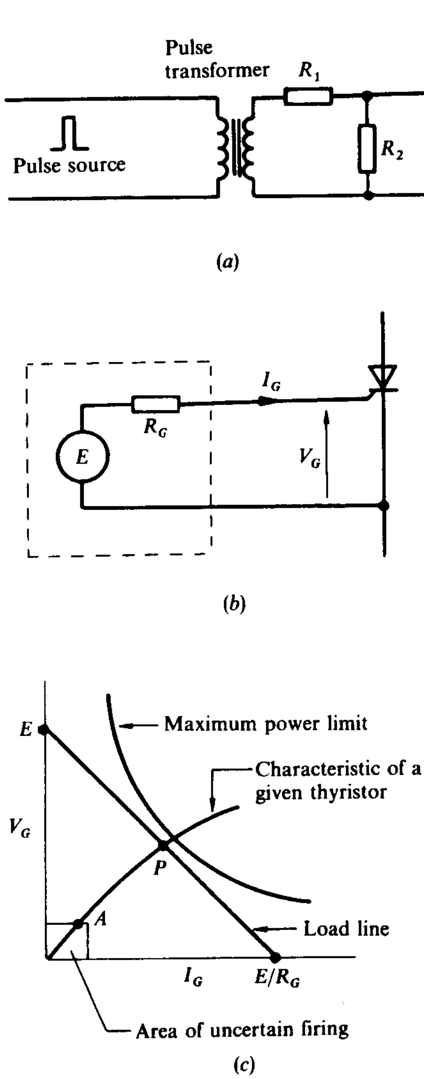

Figure 1-8 Firing (trigger) network. (*a*) Desirable network connection. (*b*) Thévenin's equivalent circuit for firing network. (*c*) Firing network load line.

current, and a resistance R_2 to limit the gate voltage when the thyristor is in the off-state.

The Thévenin equivalent circuit of the firing network, shown in Fig. 1-8*b*, is taken as a voltage E in series with a resistance R_G.

The relationship in the steady state between the gate voltage V_G and the gate current I_G is defined by the values of E and R_G along the load line shown in Fig. 1.8*c*. When the firing signal is initiated, the gate current will grow along the line of the characteristic for that thyristor until in the steady state the load line at point P is reached. However, before point P is reached, the thyristor will have turned on, most likely in the region of point A. The parameters of the firing network must be so chosen that the load line is above A but within the maximum power limit. Typically the value of E will be 5 to 10 V, having an associated maximum current of 0.5 to 1 A.

1-2-2 Requirements of firing circuits

To turn on a thyristor positively in the shortest time, it is desirable to have a gate current with a fast rise time up to the maximum permitted value. This rise time is best achieved by pulse techniques, where the firing circuit generates a fast rise pulse of sufficient length to allow the anode current enough time to reach its latching value. The advantage of the pulse is that much less power is dissipated in the gate compared to a continuous current, and the instant of firing can be accurately timed.

Reference to the simple rectifying circuit of Fig. 2-4 shows that an essential requirement of the firing circuit in a.c. supply applications is that the thyristor shall be turned on at a time related to the a.c. supply voltage phase. Also, the phase of the firing pulse in relation to the a.c. supply voltage zero must be capable of variation.

A practical commercial firing circuit will typically have a characteristic pulse such as in Fig. 1-9*a*, a rise time of 1 μs from a voltage source of 10 V, capable of delivering 1 A, the peak pulse load line being as shown in Fig. 1-9*b*. A pulse length of 10 μs with a rise to 2 V in 1 μs may suffice for many applications, whereas other applications may require lengths up to 100 μs. The firing circuit will normally reset itself after the first pulse, to give a succession of pulses spaced (say) 400 μs up to the end of the half cycle as shown in Fig. 1-9*c*. In the rectifier circuit, conditions may not be right for conduction to take place at the first pulse, the second and successive pulses being available to turn on the thyristor.

Many rectifier configurations require the simultaneous firing of two thyristors, the cathodes of which are at different potentials. To overcome this problem, the final stage of the firing circuit will be a transformer with two or more isolated outputs.

Reverse gate current must be prevented to avoid excessive gate power dissipation. Also, injection of gate current when the thyristor is reverse-biased will increase the leakage current, and is best avoided.

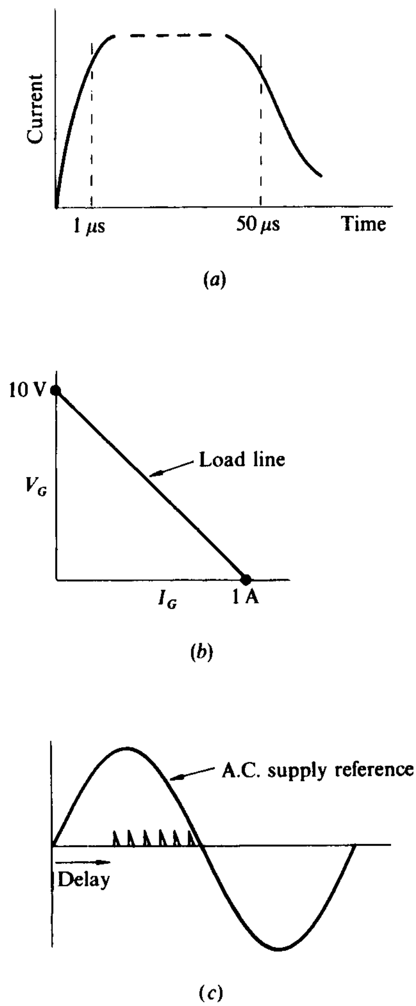

Figure 1-9 Typical firing circuit output pulse characteristic. (*a*) Pulse shape. (*b*) Load line. (*c*) Firing pulse reference to a.c. supply.

1-2-3 Typical firing circuits

Figure 1-10*a* shows a crude firing arrangement, the object of which is to control the load voltage to the waveform shape of Fig. 1-10*b*. The gate current $i_g \simeq (v_{\text{supply}})/R$ and, as the sinusoidal voltage rises from zero, the gate current will eventually reach a level such as to turn on the thyristor, this occurring at (say) the angle α shown in Fig. 1-10. Variation of the firing delay angle α will vary the load power. This simple firing arrangement has so many shortcomings

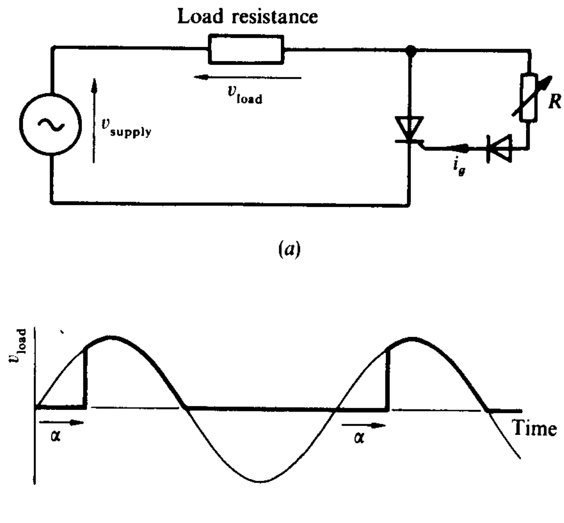

Figure 1-10 Simple rectifier circuit. (*a*) A crude firing arrangement. (*b*) Single-phase control using one thyristor.

that its practical use is negligible. The turn-on angle will vary from cycle to cycle as temperature and other changes occur in the thyristor. Further, the turn-on will be slow and will not occur near the zero voltage, nor will extend beyond the supply voltage maximum ($\alpha = 90°$). This demonstrates a clear need for firing circuits giving a pulse output timed to the a.c. cycle as shown in Fig. 1-9*c*.

Simple but practical firing circuits are those using the switching action of a transistor as in Fig. 1-11. Both circuits are supplied from the a.c. source, which is clipped by the Zener diode *Z* to give a level voltage to the $R_1 C_1$ series circuit. Resistance R_2 drops the voltage difference between the supply and the Zener diode. In both circuits the voltage on the capacitor C_1 will rise exponentially at a rate determined by the value of R_1.

In the circuit of Fig. 1-11*a*, the reference voltage to the base of the transistor is determined by the resistor chain *S*. Initially with zero voltage on C_1 the transistor is held off but, when the voltage on C_1 at the emitter reaches a high enough level, the transistor starts to conduct. Feedback action via the transformer winding raises the base current so the transistor turns hard on, discharging C_1 rapidly into the thyristor gate via the transformer. The unijunction transistor of Fig. 1-11*b* exhibits a characteristic of no conduction until the voltage on C_1 reaches a particular value, then the unijunction transistor will change to its conducting state, allowing C_1 to discharge into the thyristor gate. The rapid discharge of C_1 gives a fast rise pulse into the thyristor gate.

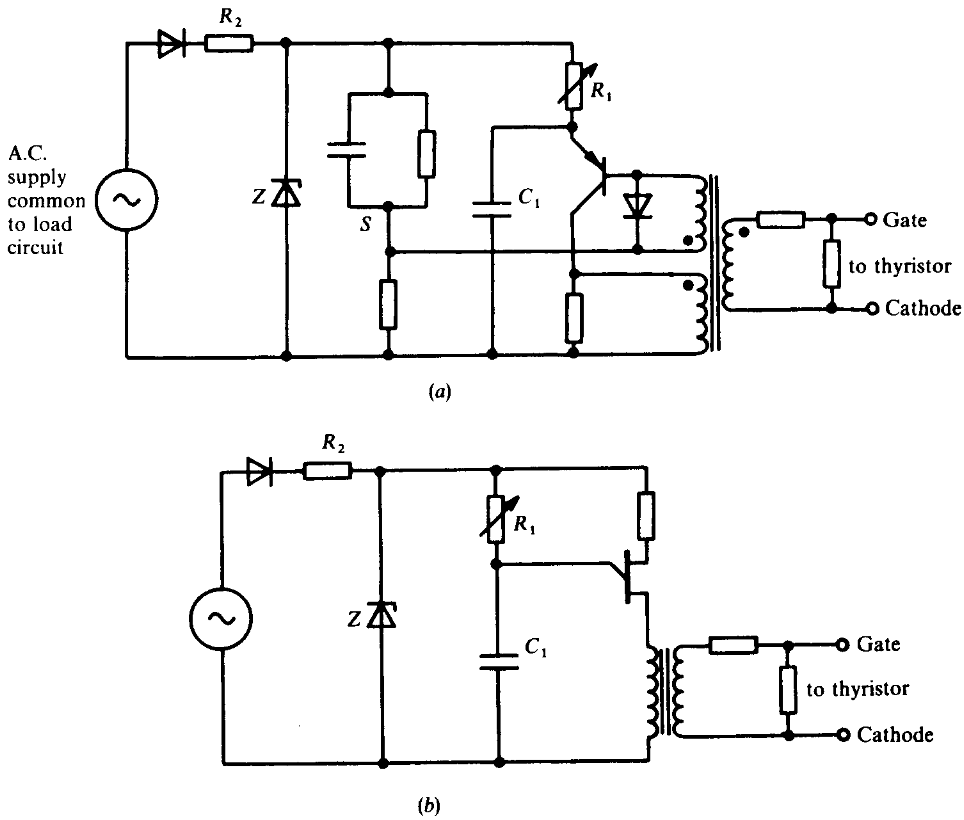

Figure 1-11 Simple firing circuits using transistors. (*a*) Using transistor. (*b*) Using unijunction transistor.

Both of the transistor firing circuits will reset after C_1 is discharged, building up to give a second and further pulses. At the zero point in the a.c. supply cycle, the circuit will completely discharge, hence the initial growth of voltage at C_1 is timed from the supply zero. By adjustment of R_1, the time of the first output pulse can be controlled up to 180° delay in a waveform such as shown in Fig. 1-10*b*.

The simple circuits of Fig. 1-11 give a pulse length and rise time which is adequate for most passive resistive loads, where small variations in firing angle from cycle to cycle can be tolerated. Additional circuits can be added in series with R_1 to inhibit firing by preventing charging current flow to C_1, or to incorporate some desired remote automatic control.

The more sophisticated firing circuits contain many more stages in their electronic circuitry. Such circuits may, for example, rely on the interrelationship

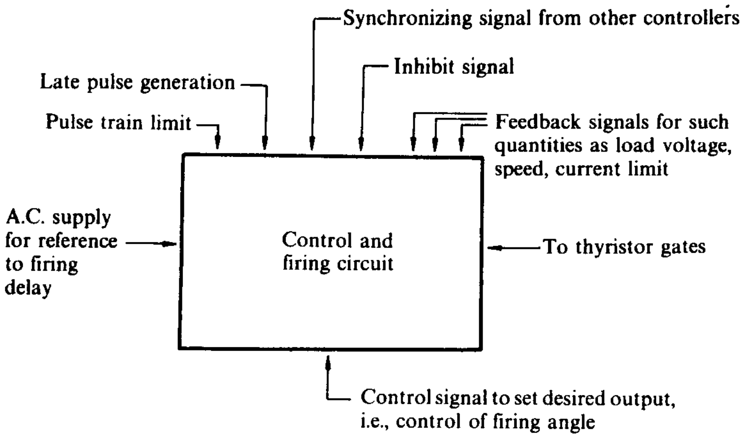

Figure 1-12 Typical features required in a more complex a.c. converter system.

between a ramp voltage and the external control voltage to initiate accurately, at the same time in each cycle, the start of the pulse generator.

For applications other than those connected with a fixed frequency supply, the firing circuits include oscillators to initiate the pulse starts and finishes.

1-2-4 Control features of firing circuits

The more complex systems utilizing thyristors as the power control elements will include, for example, closed-loop links, polyphase supply, automatic control of current or motor torque level, inhibiting loops to ensure against malfunction of operation due to simultaneous firing of different groups. The control characteristic is designed to give a defined relationship between firing delay angle and input voltage, say, either linear or cosine. These aspects are shown diagrammatically in Fig. 1-12 which can include (as shown) inputs to limit the length of the pulse train, or to ensure a pulse will appear at the thyristor gate at a given angle, in particular, just before the time when control would be lost in the inverting mode of converter operation.

The example given above relates to a.c. converter systems, but similar control features will be required in the many other systems involving d.c. supply, or variable-frequency supply with the many varied load features. The later chapters will describe many of these systems.

1-3 THE TRIAC

The triac is a five-layer device, as shown in Fig. 1-13, having a *P-N-P-N* path in either direction between terminals T_1 and T_2, and can hence conduct in

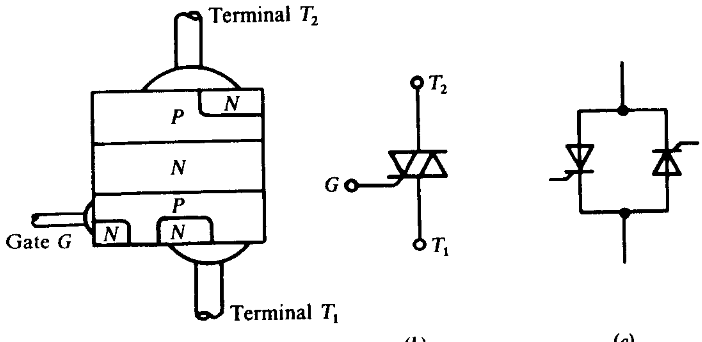

Figure 1-13 The triac. (*a*) Structure. (*b*) Symbol. (*c*) Thyristor equivalent.

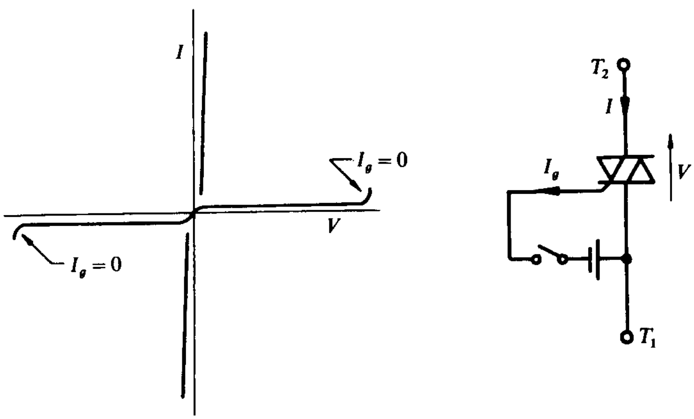

Figure 1-14 Triac characteristic.

either direction as the symbol clearly indicates. Electrically, the triac performs in one device that which would require two thyristors in the inverse-parallel connection shown in Fig. 1-13*c*.

The triac can be switched into the on-state by either positive or negative gate current, but is most sensitive if positive current is injected when T_2 is positive, and negative current when T_1 is positive. However, in practice, negative gate current is always used as shown with the characteristic in Fig. 1-14.

Both the maximum steady-state and transient ratings described in Sec. 1-9 are inferior to those of the thyristor.

1-4 GATE TURN-OFF THYRISTOR

The conventional thyristor as described in Sec. 1-2 has over the years been developed such that two new devices of the thyristor family are now available, the asymmetrical thyristor and the gate turn-off (GTO) thyristor.

The conventional thyristor has two *P-N* junctions which can block high voltages in one or other direction, this being an essential requirement for applications in the rectifier circuits described in Chapter 2. However, for the inverter circuits described in Chapter 5 the reverse blocking capability is not needed.

To reduce the time taken for the thyristor to recover its blocking state after turn-off the silicon can be made thinner at the expense of it losing its ability to block a reverse voltage, this device now being known as the asymmetrical thyristor. In the inverter circuits a diode is connected in parallel with the thyristor so the loss of the reverse blocking capability is of little consequence, but the switching time is reduced to a few microseconds compared to the tens of microseconds for the conventional thyristor.

The conventional thyristor can only be turned off by effectively reducing the anode current to zero, but the gate turn-off thyristor, as its name implies, has a structure such that it can be turned off by removing current from the gate. Turn-on is achieved by injecting current into the gate as in the conventional thyristor.

The more complex structure of the gate turn-off thyristor compared to the conventional thyristor is shown in Fig. 1-15. The circuit symbol for the gate turn-off thyristor is an extension from the conventional thyristor showing the

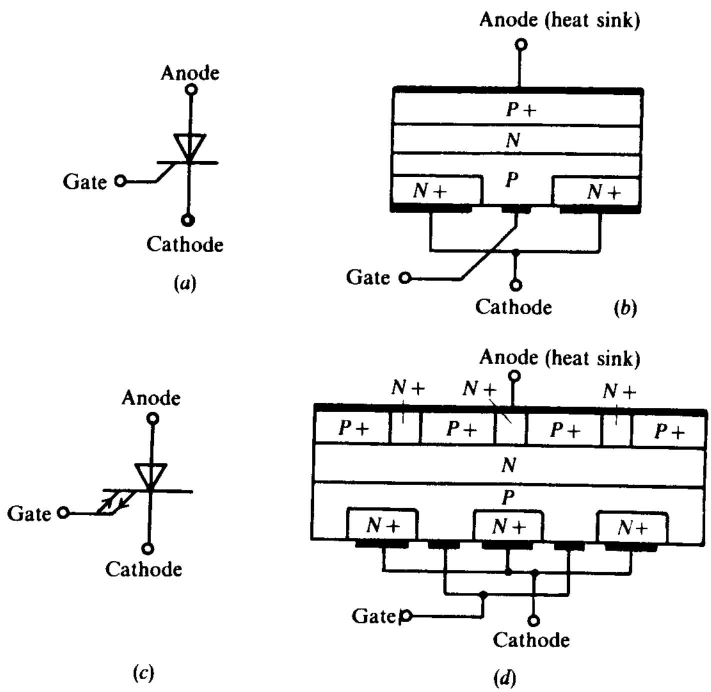

Figure 1-15 Thyristor structure. (*a*) Conventional thyristor symbol. (*b*) Conventional thyristor *P-N-P-N* structure. (*c*) Gate turn-off thyristor symbol. (*d*) Gate turn-off thyristor structure.

dual role of the gate terminal. Referring to Fig. 1-15*d*, the gate turn-off thyristor has highly doped *N* spots in the *P* layer at the anode, the plus sign indicating high doping levels. The gate-cathode structure is interdigitated, that is, each electrode is composed of a large number of narrow channels closely located.

With the gate turn-off thyristor, in the absence of any gate current, a positive voltage at the anode with respect to the cathode is withstood at the centre *N-P* junction in a like manner to the conventional thyristor, but a reverse voltage with the cathode positive will break down the anode junction at a low level in a similar manner to the asymmetrical thyristor. Reverse blocking GTOs are available, but at the expense of the other rating features, an example of application being a resonant load. With a resonant load the GTO is being used like a conventional thyristor but achieves a very fast turn-off.

The turn-on conditions for the gate turn-off thyristor are similar to the conventional thyristor, but because of the differing structure the latching current is higher. The interdigitated nature of the gate results in a very rapid spread of conduction in the silicon, but it is necessary to maintain the gate current at a high level for a longer time to ensure that latching takes place. To minimize the anode-cathode voltage drop it is advantageous to maintain a low level of gate current throughout conduction otherwise the on-state voltage and hence conduction losses will be slightly higher than necessary.

The thyristor remains on after removal of the gate current because the internal mechanism of carrier multiplication is self-maintaining provided the anode current is above the latching level. With the gate-off thyristor it is possible to cause the carrier multiplication to cease by removing holes from the *P* region, which causes the conducting area to be squeezed towards the anode *N* spots into the area under the cathode electrode furthest from the gate electrode, until all the conducting paths are extinguished. Once the cathode current has ceased a gate-anode current persists for a short time until the device gains its blocking state. The magnitude of the gate current for turn-off is of the order of one-fifth to one-third of the anode current; hence it is considerably higher than the turn-on magnitude. The time of turn-off is shorter than with the other thyristors.

The gating requirements of the gate turn-off thyristor are summarized by the circuit shown in Fig. 1-16*a*. At turn-on a current is injected into the gate. At turn-off a negative voltage is placed across the gate-cathode of the order of 10 V, thus removing current from the gate. The turn-off voltage must be less than the gate-cathode reverse breakdown but high enough to extract the charge necessary to bring about turn-off. The turn-off physics of the device is complex but basically the gate charge must be extracted rapidly with a peak gate current value near to the value of the anode current, this current being established in much less time than one microsecond. To limit the rate at which the anode voltage rises at turn-off a snubber capacitor is connected across the thyristor.

A simple gate control circuit is shown in Fig. 1-16*b*. Positive current to the base of transistor T_1 allows current flow into the gate via R_1 and C_1, with the initial value being set by R_1. The Zener diode D_1 conducts when its breakdown