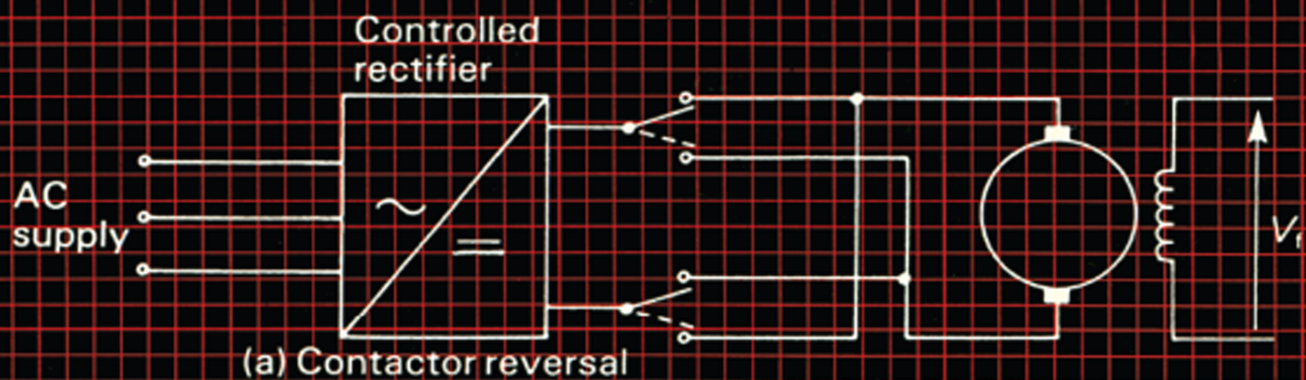
TUTORIAL GUIDES IN ELECTRONIC ENGINEERING 11

Power Electronics

Second edition

D. A. Bradley



Power Electronics

TUTORIAL GUIDES IN ELECTRONIC ENGINEERING

Series editors
Professor G.G. Bloodworth, *University of York*
Professor A.P. Dorey, *University of Lancaster*
Professor J.K. Fidler, *University of York*

This series is aimed at first- and second-year undergraduate courses. Each text is complete in itself, although linked with others in the series. Where possible, the trend towards a 'systems' approach is acknowledged, but classical fundamental areas of study have not been excluded. Worked examples feature prominently and indicate, where appropriate, a number of approaches to the same problem.

A format providing marginal notes has been adopted to allow the authors to include ideas and material to support the main text. These notes include references to standard mainstream texts and commentary on the applicability of solution methods, aimed particularly at covering points normally found difficult. Graded problems are provided at the end of each chapter, with answers at the end of the book.

1. Transistor Circuit Techniques: discrete and integrated (2nd edition) — G.J. Ritchie
2. Feedback Circuits and Op Amps — D.H. Horrocks
3. Pascal for Electronic Engineers — J. Attikiouzel
4. Computers and Microprocessors: components and systems — A.C. Downton (3rd edition)
5. Telecommunication Principles — J.J. O'Reilly
6. Digital Logic Techniques: principles and practice (2nd edition) — T.J. Stonham
7. Instrumentation Transducers and Interfacing — B.R. Bannister and D.G. Whitehead
8. Signals and Systems: models and behaviour — M.L. Meade and C.R. Dillon
9. Electromagnetism for Electronic Engineers — R.G. Carter (2nd edition)
10. Power Electronics — D.A. Bradley (2nd edition)
11. Semiconductor Devices: how they work — J.J. Sparkes
12. Electronic Components and Technology: engineering applications — S.J. Sangwine
13. Control Engineering — C. Bissell
14. Basic Mathematics for Electronic Engineers: models and applications — J.E. Szymanski
15. Integrated Circuit Design Technology — M.J. Morant

Power Electronics

Second edition

D.A. Bradley

Engineering Department
School of Engineering, Computing and Mathematics
Lancaster University, UK

CRC Press
Taylor & Francis Group
Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an informa business

CRC Press
6000 Broken Sound Parkway, NW
Suite 300, Boca Raton, FL 33487

270 Madison Avenue
New York, NY 10016

2 Park Square, Milton Park
Abingdon, Oxon OX14 4RN, UK

Typeset in 10/12pt Times by Compuscript Ltd, Co. Clare, Ireland
Printed in England by Clays Ltd, St Ives plc.

ISBN 0 412 57100 5

A catalogue record for this book is available from the British Library

Library of Congress Catalog Card Number: 94-71066

Printed on acid-free text paper, manufactured in accordance with ANSI/NISO Z39.48-1992 and ANSI/NISO Z39.48-1984 (Permanence of Paper).

Contents

Preface

The subject of power electronics originated in the early part of the twentieth century with the development and application of devices such as the mercury arc rectifier and the thyratron valve. Indeed many of the circuits currently in use and described in this book were developed in that period. However, the range of applications for these early devices tended to be restricted by virtue of their size and problems of reliability and control.

With the development of power semiconductor devices, offering high reliability in a relatively compact form, power electronics began to expand its range and scope, with applications such as DC motor control and power supplies taking the lead. Initially, power semiconductor devices were available with only relatively low power levels and switching speeds. However, developments in device technology resulted in a rapid improvement in performance, accompanied by a corresponding increase in applications. These now range from power supplies using a single power MOSFET to high voltage DC transmission where the mercury arc valve was replaced in the 1970s by a solid-state 'valve' using thyristor stacks.

Developments in microprocessor technology have also influenced the development of power electronics. This is particularly apparent in the areas of control, where analogue controllers have largely been replaced by digital systems, and in the evolution of the 'smart power' devices. These developments have in turn led to system improvements in areas such as robot drives, power supplies and railway traction systems.

To a professional electrical engineer, power electronics encompasses all of the above, from the mercury arc rectifier systems still operational to the microprocessor-controlled drives on a robot arm. However, to deal with all of these topics is outside the scope of this book which concentrates on providing the reader with an introduction to the subject of power electronics. Following a discussion of the major power electronic devices and their characteristics, with relatively little consideration given to device physics, the emphasis is placed on the systems aspects of power electronics and on the range and diversity of applications. For this reason, a number of 'mini case studies' are included in the chapters on applications. These case studies cover topics from high-voltage DC transmission to the development of a controller for domestic appliances such as washing machines and are intended to place the material under discussion into a practical context.

As the text is intended for instruction and learning rather than for reference, each chapter includes a number of worked examples for emphasis and reinforcement. These worked examples are supported further by a number of exercises at the end of each chapter.

The production of a book of this type does not proceed in isolation and many people have contributed to it, either by the provision of material or with encouragement and advice. From among my colleagues at Lancaster

University I would particularly like to thank Professor Tony Dorey, who encouraged me to undertake the project and in the first instance provided much helpful advice.

As this book is one of a series of related texts, its relationship with the other texts in the series is important. I am therefore grateful to Professor John Sparkes of the Open University for his help in this respect, particularly with Chapter 1.

I would also like to thank Mr. A. Woodworth of Mullard, Mr. J.M.W. Whiting of GEC Traction, Mr. I.E. Barker of GEC Power Transmission and Distribution Projects, Mr. T.G. Carthy, Mr. A. Polkinghorne and Professor P. McEwan, all of whom helped with the provision of material.

As the book is intended for students, a student's viewpoint at an early stage proved particularly valuable and I repeat my thanks to Michael Anson for having diverted himself from his studies for a time to help me in that respect. Finally, but by no means least, my thanks go to Professor G. Bloodworth of York University for his efforts, constructive comments and assistance in this project.

1
Power semiconductors

Objectives

- □ To introduce the major power electronic devices.
- □ To define their operating regimes and modes of operation.
- □ To establish their ratings.
- □ To consider losses and heat transfer properties.
- □ To examine means of protection.

An intrinsic semiconductor is defined as being a material having a resistivity which lies between that of insulators and conductors and which decreases with increasing temperature. The principal semiconductor material used for power electronic devices is silicon, a member of Group IV of the periodic table elements which means it has four electrons in its outer orbit.

If an element of Group V, such as phosphorus, with five electrons in its outer orbit is added to the silicon, each phosphorus atom forms a covalent bond within the silicon lattice, leaving a loosely bound electron. The presence of these additional electrons greatly increases the conductivity of the silicon and a material doped in this way is referred to as an n-type semiconductor.

By introducing an element from Group III as impurity, a vacant bonding location or hole is introduced into the lattice. This hole may be considered to be mobile as it can be filled by an adjacent electron, which in its turn leaves a hole behind. Holes can be thought of as carriers of positive charge and a semiconductor doped by a Group III impurity is referred to as a p-type semiconductor.

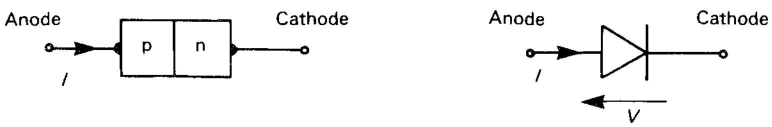
The extra, mobile electrons introduced by doping into the n-type material and the equivalent holes in the p-type material are referred to as the majority carriers. In an n-type material there is a small population of holes and in a p-type material a small population of electrons. These are called the minority carriers.

Diode

The semiconductor junction diode shown in Fig. 1.1 is the simplest semiconductor device used in power electronics. With no external applied voltage the redistribution of charges in the region of the junction between the p-type and n-type materials results in an equilibrium condition in which a potential

Ghandi, S.K. (1977). *Semiconductor Power Devices*. Wiley Interscience.

Sparkes, J. *Semiconductor Devices*. (1987). Van Nostrand Reinhold.



(a) Construction

(b) Circuit symbol

Fig. 1.1 The diode.

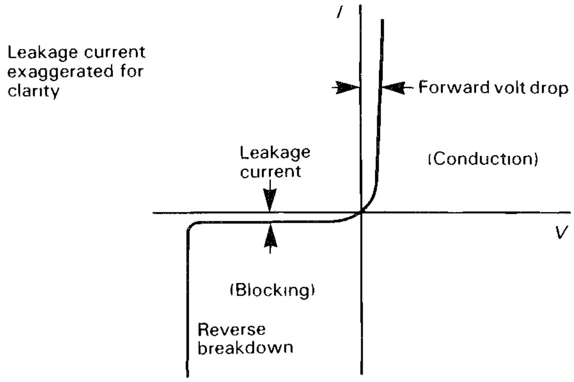


Fig. 1.2 Diagrammatic representation of the diode static characteristic. (Note: forward and reverse voltage scales are unequal. The forward voltage drop is of the order of 1 V while the reverse breakdown voltage varies from a few tens of volts to several thousand.)

The region over which the potential barrier exists is known as the depletion or transition layer.

The magnitude of the reverse leakage current can vary from a few picoamperes for an integrated circuit diode to a few milliamperes for a power diode capable of carrying several thousand amperes in the forward direction.

Avalanche diodes are designed to operate safely under reverse breakdown conditions and are used for device overvoltage protection (section on protection, p. 32).

barrier is established across a narrow region depleted of charge carriers on each side of the junction. This equilibrium may be disturbed by the application of an external applied voltage of either polarity.

If a reverse voltage – cathode positive with respect to anode – is applied, the electric field at the junction is reinforced, increasing the height of the potential barrier and increasing the energy required by a majority carrier to cross this barrier. The resulting small reverse leakage current shown in the diode static characteristic of Fig. 1.2 is due to the flow of minority carriers across the junction. The magnitude of the reverse leakage current increases with temperature because the number of minority carriers available increases with the temperature of the material.

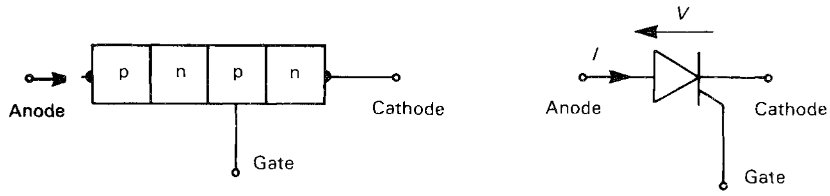
The reverse current will be maintained with increasing reverse voltage up to the point at which reverse breakdown occurs, which will not cause the destruction of the diode unless accompanied by excessive heat generation.

When a forward voltage – anode positive with respect to cathode – is applied to the diode the height of the potential barrier is reduced, giving rise to a forward current resulting from the flow of majority carriers across the junction. As the forward voltage is increased, the forward current through the diode increases exponentially. The overall current–voltage characteristic of the diode is given approximately by

$$I = I_s\left[\exp(qV_j/kT) - 1\right] \tag{1.1}$$

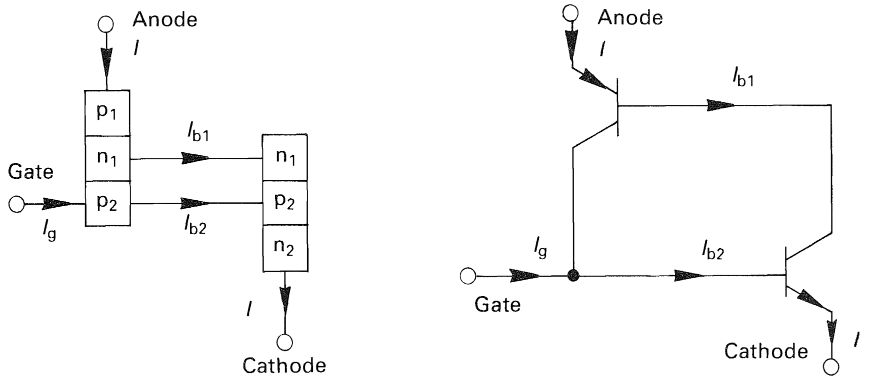
where I_s is the reverse leakage current
q is the electronic charge (1.602×10^{-19} C)
k is Boltzmann's constant (1.38×10^{-23} J K^{-1})
V_j is the voltage applied to the junction
and T is the temperature (K)

giving the forward or conducting part of the diode characteristic of Fig. 1.2. The forward voltage (V_j) applied to the junction is of the order of 0.7 V but because of internal resistances in series with the junction, the voltage (V) across the terminals of a practical power diode will be of the order of 1 V,



(a) Construction (b) Circuit symbol

Fig. 1.3 The thyristor.



(a) Structure (b) The two-transistor model of a thyristor

Fig. 1.4 The two-transistor model of a thyristor.

with the actual value being determined by the magnitude of the forward current and device temperature.

Thyristor

The thyristor is a four-layer, three-terminal device as suggested by Fig. 1.3. The complex interactions between three internal p–n junctions are then responsible for the device characteristics. However, the operation of the thyristor and the effect of the gate in controlling turn-on can be illustrated and followed by reference to the ***two-transistor model*** of Fig. 1.4. Here, the p_1–n_1–p_2 layers are seen to make up a p–n–p transistor and the n_2–p_2–n_1 layers an n–p–n transistor with the collector of each transistor connected to the base of the other.

With a reverse voltage, cathode positive with respect to the anode, applied to the thyristor the p_1–n_1 and p_2–n_2 junctions are reverse biased and the resulting characteristic is similar to that of the diode with a small reverse leakage current flowing up to the point of reverse breakdown as shown by Fig. 1.5(a).

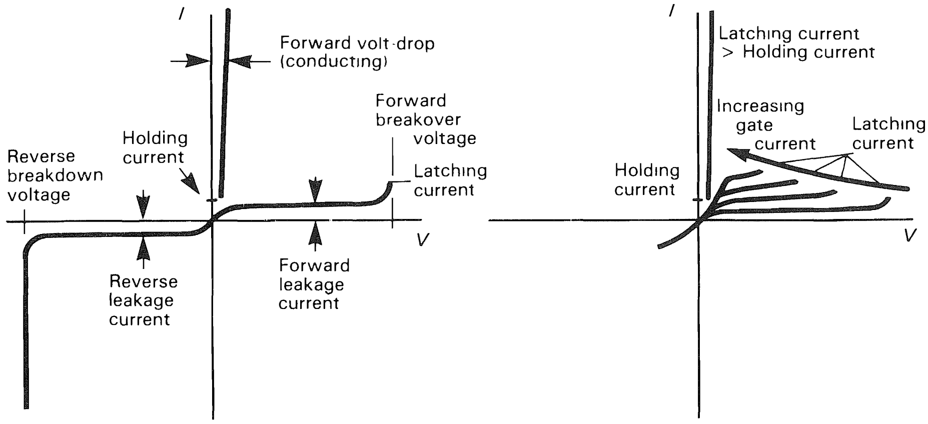
With a forward voltage, anode positive with respect to the cathode, applied and no gate current, the thyristor is in the ***forward blocking*** mode. The emitters of the two transistors are now forward biased and no conduction occurs. As the applied voltage is increased, the leakage current through the transistors increases to the point at which the positive feedback resulting

Taylor, P.D. (1987). *Thyristor Design and Realisation.* John Wiley.

Richie, G.J. (1983). *Transistor Circuit Techniques,* Van Nostrand Reinhold gives a discussion of transistor types.

Silicon Controlled Rectifier Manual. General Electric (1979).

Power Semiconductor Handbook. Semikron (1980).



(a) Thyristor characteristic with zero gate current

(b) Switching characteristic

Fig. 1.5 Thyristor characteristics.

This is the forward breakover condition.

The latching current is the minimum current required to ensure conduction is maintained.

The holding current is less than the latching current.

Once conduction has been established in the thyristor the gate current may be reduced to zero.

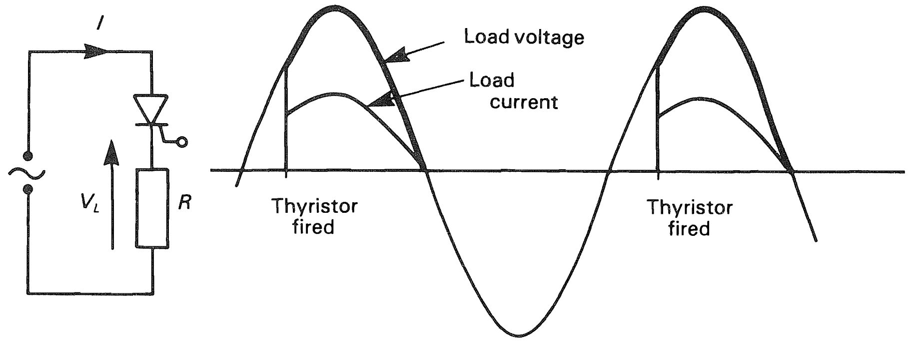
from the base/collector connections drives both transistors into saturation, turning them, and hence the thyristor, on. The thyristor is now conducting and the forward voltage drop across it falls to a value of the order of 1 to 2 V. This condition is also shown in the thyristor static characteristic of Fig. 1.5(a).

If a current is injected into the gate at a voltage below the breakover voltage, this will cause the n–p–n transistor to turn on when the positive feedback loop will then initiate the turn on of the p–n–p transistor. Once both transistors are on, the gate current can be removed because the action of the positive feedback loop will be to hold both transistors, and hence the thyristor, in the on state. The effect of the gate current is therefore to reduce the effective voltage at which forward breakover occurs, as illustrated by Fig. 1.5(b).

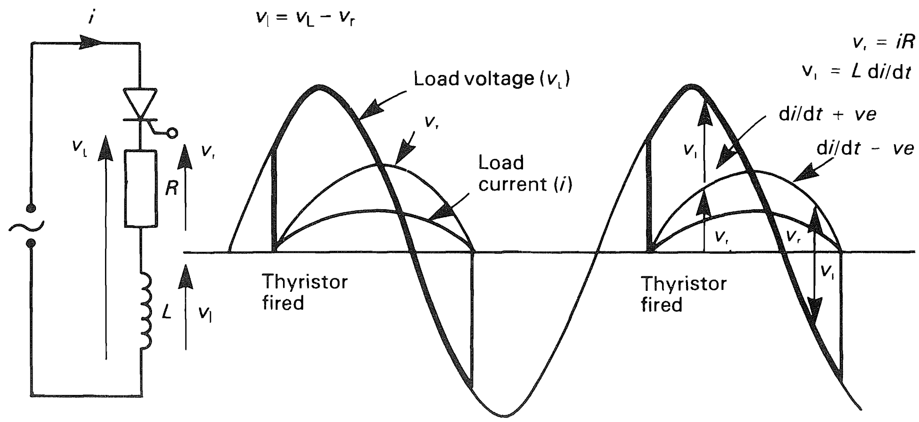
Once the thyristor has been turned on it will continue to conduct as long as the forward current remains above the holding current level, irrespective of gate current or circuit conditions. Figures 1.6(a) and 1.6(b) show a single, ideal thyristor supplying a resistive and an inductive load respectively. In each case the thyristor is being turned on after a delay of about a quarter of a cycle after the voltage zero. In the case of the resitive load the load current follows exactly the load voltage. However, in the case of the inductive load the load voltage is made up of two components, the voltage across the inductance (v_i) and the voltage across the resistance (v_r). The current through the thyristor has an initial value of zero. The current then rises to a maximum at which point di/dt and hence the voltage across the inductance (v_i) becomes zero and the load voltage (v_L) equals the voltage across the resistor (v_r). The slope of di/dt then becomes negative, changing the polarity of v_i, and thus maintains the forward voltage drop across the thyristor until the stored energy in the inductance has been dissipated.

Turn-on

Following the initiation of forward breakover by the gate current the process of establishing conduction is independent of the gate conditions once the



(a) Resistive load



(b) Inductive load

Fig. 1.6 Thyristor with different loads.

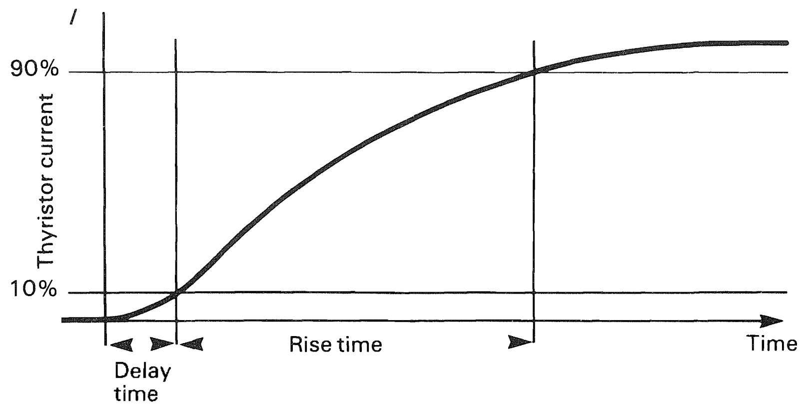


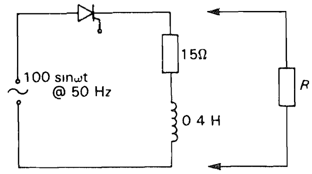
Fig. 1.7 Thyristor current on turn-on.

Instantaneous power = Voltage across thyristor × Current through thyristor.

thyristor current has reached the latching current level. The time taken for the thyristor current to reach the latching current level therefore establishes the minimum period over which the gate current must be maintained.

The time interval between the application of the gate current and the point at which the thyristor current reaches 90% of its final value is referred to as the ***turn-on time***. This time is made up of two components, the ***delay time***, which is the time taken for the current to reach 10% of its final value, and the ***rise time***, which is the time for the current to increase from 10% to 90% of its final value. The relationship between these values is illustrated by Fig 1.7 (pg. 5). The rate of rise of current in the thyristor is influenced by the load inductance, with increasing inductance extending the turn-on time.

Worked example 1.1



Example 1.1

A thyristor with a latching current of 40 mA is used in the circuit shown. If a firing pulse of 50 μs is applied at the instant of maximum source voltage, show that the thyristor will not be turned on. What value of resistance R' connected as shown will ensure turn-on?

Following the application of the gate pulse

$100 \cos \omega t = iR + L\mathrm{d}i/\mathrm{d}t$

Using Laplace transforms

$i = 100\,[\cos(\omega t - \phi) - \cos\phi.\exp(-Rt/L)]/(R^2 + \omega^2 L^2)^{1/2}$

$\phi = \tan^{-1}\omega L/R = 83.19° = 1.452\,\text{rad}$

$(R^2 + \omega^2 L^2)^{1/2} = 126.6$

After 50 μs, by substituting in equation for i

$i = 0.0124\,\text{A}$

Hence thyristor fails to turn on.

Connecting R' then current in R' is i' when

Current in thyristor $= i_t = i + i'$

For turn-on

$i + i = 0.04\,\text{A}$

$\therefore\ i' = 40 - 12.4 = 27.6\,\text{mA}$

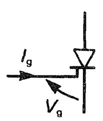
Maximum value of R' is thus

$100 \cos(100\pi \times 50 \times 10^{-6})/0.0276 = 3623\,\Omega$

The turn-on time will also be limited by the need to avoid conditions of high rate of rise of current at high forward voltage levels as the instantaneous product of current and voltage (power) can be high, resulting in damage to the thyristor by thermal effects. Figure 1.8 shows a typical power relationship for a 150 A thyristor.

The gate resistance curve.

Thyristor gate current and voltage.



The gate signal required to turn on a thyristor is influenced by the gate voltage versus gate current relationship for the particular thyristor. The actual characteristic for a given type of thyristor will lie between the definable limits of the gate high resistance and gate low resistance lines of Fig. 1.9. Further constraints are placed on the gate signal by the limiting values of gate current, gate voltage, gate power and temperature. Combining these limits gives the full gate characteristic of Fig. 1.9.

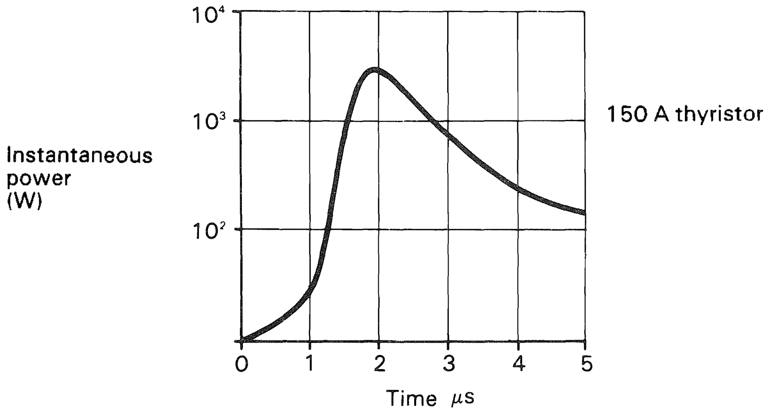
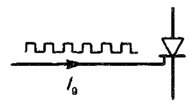


Fig. 1.8 Instantaneous power in thyristor during turn-on.

Firing of a thyristor by a pulse train.



The actual operating point is obtained from consideration of the circuit of Fig. 1.10. This circuit defines the gate load line (slope = $-R_G$), the intersection of which with the thyristor gate resistance characteristic determines the gate operating point.

Typically, thyristor firing circuits use pulse techniques which allow a precise control of the point-on-wave at which the thyristor is fired and which dissipate less energy in the gate than a continuous current. Reliance is not usually placed on a single pulse to fire the thyristor but instead the firing circuit is arranged to generate a train of pulses.

The connection of the gate signal to a thyristor often makes use of a pulse transformer as in Fig. 1.11(a) to provide isolation and remove the need for a floating gate power supply. The circuit of Fig. 1.11(a) may be simplified to that of Fig. 1.11(b) in which case, the effective voltage applied to the gate can be shown to be

$$V_g = \frac{1}{n}\frac{V_s R'_g}{(R_s + R'_g)}\exp(-t/\tau) \qquad (1.2)$$

Pulse transformers are typically constructed around a low-loss core and characteristically have negligible leakage inductance and a relatively high winding resistance.

R'_g in Fig. 1.11(b) is the effective impedance of the gate circuit transferred across the pulse transformer.

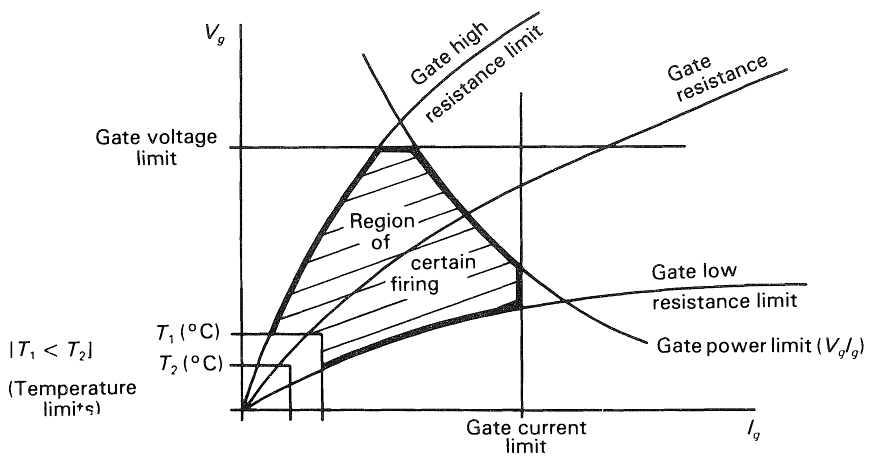


Fig. 1.9 Thyristor gate characteristic.

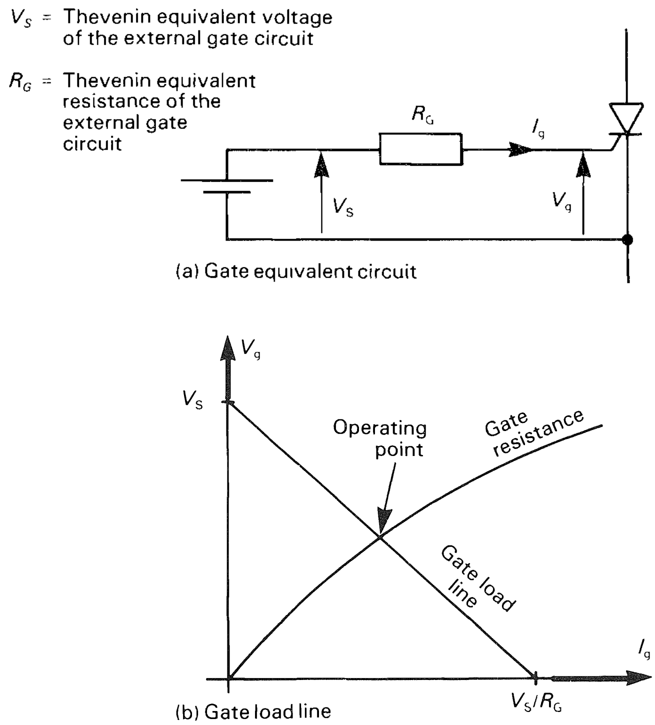


Fig. 1.10 Gate operation.

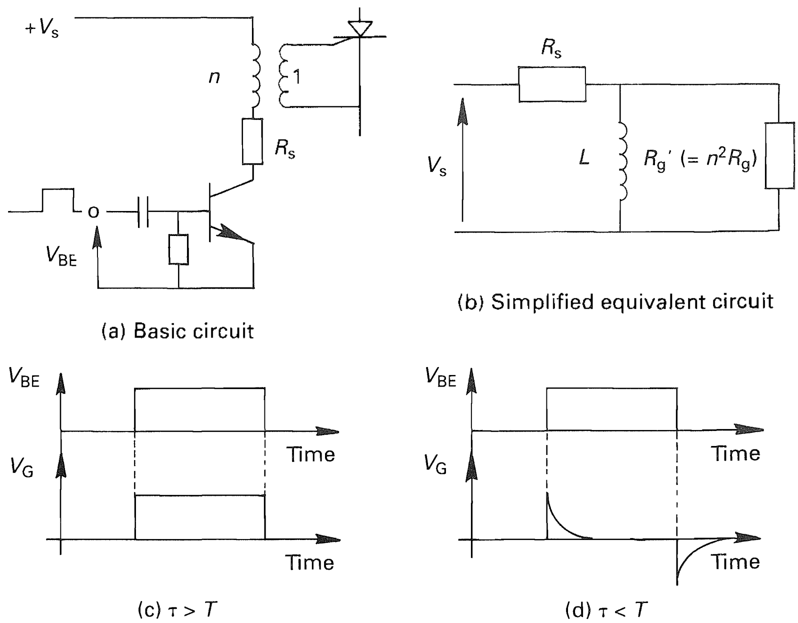


Fig. 1.11 Thyristor firing using a pulse transformer circuit.

where n is the turns ratio of the pulse transformer
and

$$R'_g = n^2 R_g$$

where R_g is the gate circuit resistance of the thyristor

$$\tau = \frac{R_e}{L} \text{ and } R_e = \frac{R_s R'_g}{(R_s + R'_g)}$$

For those cases where the system time constant (τ) is much greater than the pulse width T the pulse will be correctly transmitted as in Fig. 1.11(c). However, if the system time constant is much less than the pulse width the response will be as shown in Fig. 1.11(d). This has the advantage that the resulting gate waveform enables the injection of a large initial charge without significant heating of the gate permitting a high $\mathrm{d}i/\mathrm{d}t$ value in the thyristor immediately after firing.

Typically $\tau > 10T$.

Typically $\tau < T/10$.

Where the same pulse is to be used to fire multiple devices, the value of V_S must be chosen to ensure the firing of the least sensitive of these devices.

Isolation is also required when the gate signal is derived from a microprocessor in which case an opto-isolated device can be used in the gate circuit. Indeed, it is possible to obtain thyristors with integral opto-isolation. Such thyristors tend to be relatively low power devices but can be used to provide isolation in the gate circuit of a larger device as in Fig. 1.12(a). Figure 1.12(b) shows an alternative approach using an optically coupled transistor.

Turn-off

Turn-off of a thyristor begins when the forward current falls below the holding current level of Fig. 1.5(a) with no gate current applied. Turn-off performance depends on device characteristics, the forward current prior to turn-off, the peak reverse current and the rate of rise of forward voltage as

Details of forced commutation circuits are given in Chapter 3.

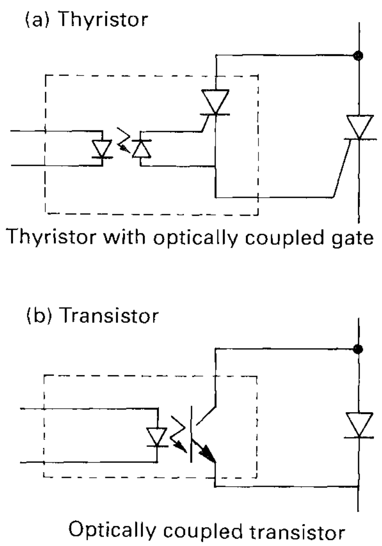


Fig. 1.12 Gate isolation using optically coupled devices.

well as temperature effects. Once the current has fallen to zero the thyristor must be placed into the reverse blocking state with a reverse voltage applied across the thyristor for sufficient time to allow the potential barriers to be re-established, completing the turn-off.

The dynamic behaviour of the thyristor during turn-off is shown in Fig. 1.13. Initially, the forward current falls, reaching zero at time t_0 and then reverses. From t_0 to t_1 the reverse current is sustained by the large numbers of carriers previously injected into the thyristor and device voltage drop is small. The build-up of the potential barriers at the junctions between and the removal of charge carriers by the action of the reverse current in the interval from t_1 to t_2 means that at time t_2 the reverse current can no longer be sustained and it begins to reduce. At this point the full reverse voltage appears across the junction, and as the circuit is slightly inductive this voltage will overshoot slightly, driving the reverse current down to the level of the reverse leakage current.

This occurs with all p-n junctions when changing from a forward biased to a reverse biased condition. (Sparkes, J. *Semiconductor Devices* (1987). Van Nostrand Reinhold.)

The carrier stored charge recovered during this period is shown as the shaded area of Fig. 1.13 and is referred to as the ***reverse recovery charge*** (Q_{rr}). Although the reverse recovery period is completed at time t_3, the reverse voltage must be maintained until time t_4 to ensure that the carrier density in the region of the central junction is reduced to a sufficiently small level to prevent the possibility of turn-on occurring when a forward voltage is reapplied. The total time for turn-off will vary according to the thyristor but will typically lie in the range 10 to 100 μs.

These conditions for turn-off occur automatically in a naturally commutated converter such as those described in Chapter 2. There is, however, a range of circuits operating from a DC voltage source in which additional circuitry must be used to turn the thyristor off. These additional, forced commutation circuits first force a reverse current through the thyristor for a short time to reduce the forward current to zero and then maintain the reverse voltage for the necessary time interval to complete the turn-off.

Details of forced commutation circuits are given in Chapter 3.

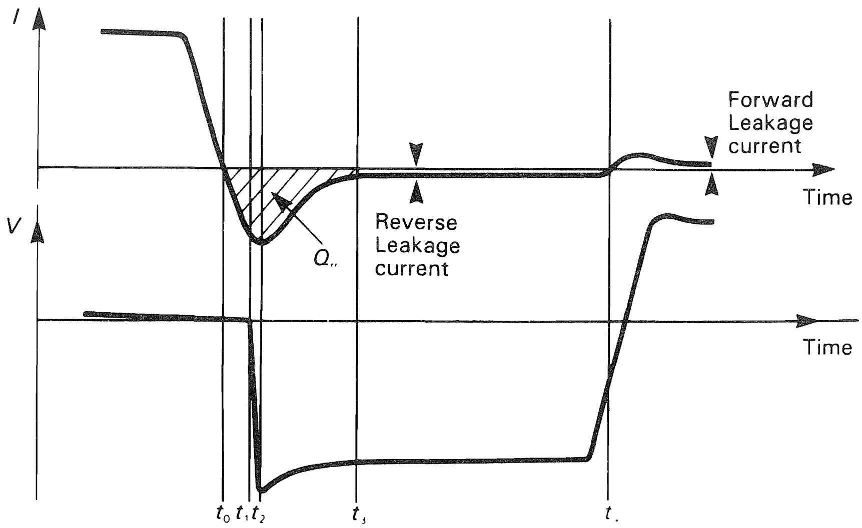


Fig. 1.13 Thyristor current and voltage during turn-off with zero gate current.

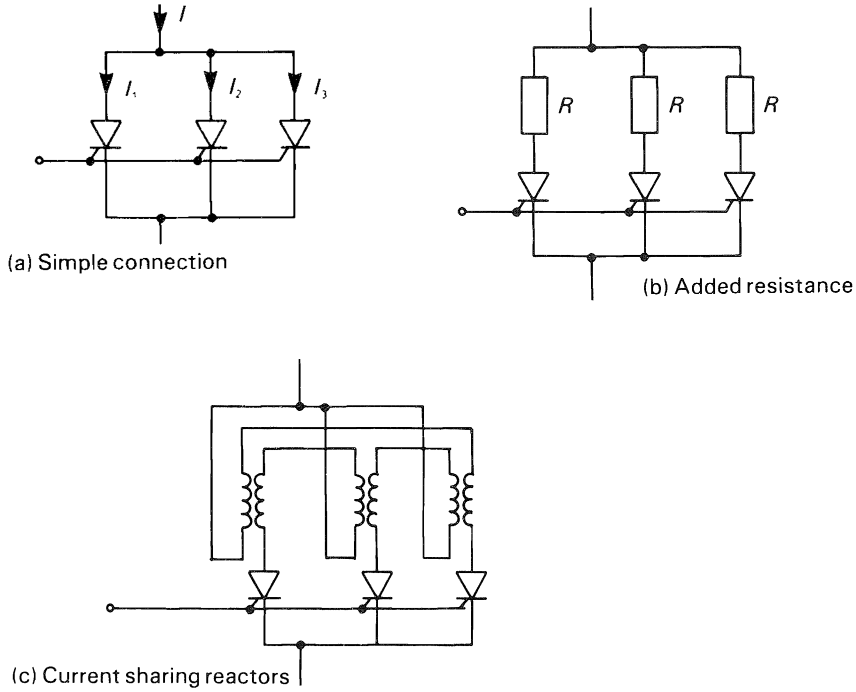


Fig. 1.14 Parallel connection of thyristors.

Parallel and series operation of thyristors

To accommodate high load currents a parallel connection of thyristors can be used. If the simple connection of Fig. 1.14(a) is used then differences in the individual thyristors will result in an unequal sharing of current between them. This sharing can be evened out by careful selection of matched devices, by the use of series resistance, as in Fig. 1.14(b), or by including current-sharing reactors as in Fig. 1.14(c).

Worked example 1.2

Two thyristors are connected as in the margin figure and have forward characteristics when conducting of the form

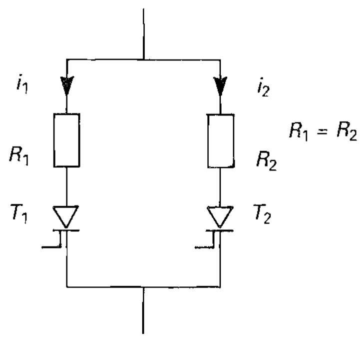
Thyristor 1	$v = 0.96 + 2.52 \times 10^{-4} i$
Thyristor 2	$v = 0.92 + 2.4 \times 10^{-4} i$

What will be the current distribution between the two thyristors when the total current is 1400 A?

$$v = 0.96 + 2.52 \times 10^{-4} i_1 = 0.92 + 2.4 \times 10^{-4} i_2$$

and

$$i_1 + i_2 = 1400$$



Example 1.2

Hence

$$0.96 + 2.52 \times 10^{-4} i_1 = 0.92 + 2.4 \times 10^{-4}(1400 - i_1)$$

when

$$i_1 = 601.6\,\text{A and } i_2 = 798.4\,\text{A}$$

What value of resistance added in series with each thyristor will result in the thyristors being within 5% of each other for the same total current?

$$0.96 + (2.52 \times 10^{-4} + R)i_1 = 0.92 + (2.4 \times 10^{-4} + R)(1400 - i_1)$$

For a 5% relationship, let $i_1 = 682.5\,\text{A}$ when from the above equation

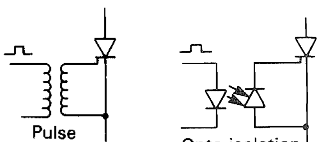
$$R = 1.14\,\text{m}\Omega$$

At turn-on the thyristor gate circuits must all be driven from the same source to force a simultaneous turn-on of all devices. To prevent any individual thyristor from turning off if its current falls below its holding level a continuous gate signal is normally used to ensure immediate re-firing.

Where high voltage levels are encountered thyristors can be connected in series to share the voltage. If the connection of Fig. 1.15(a) is used then the differences between the individual devices can result in an unequal voltage sharing between them. Allowance must also be made for any difference in recovery times to ensure that all thyristors are left able to withstand the reapplication of forward voltage.

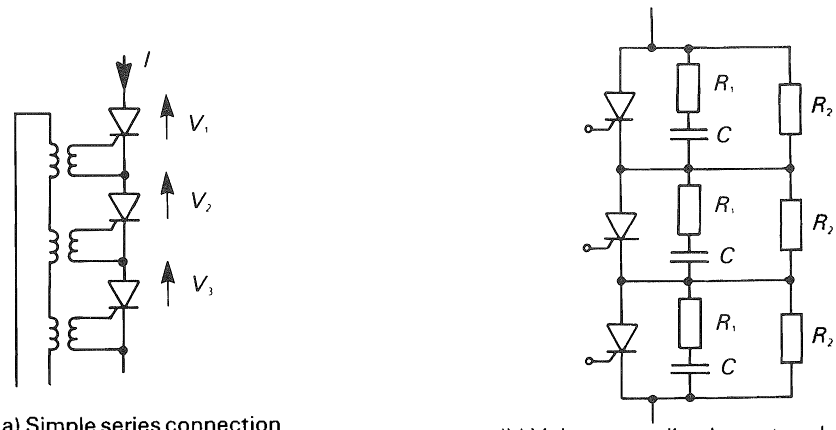
Voltage sharing can be achieved by using equalization networks such as that of Fig. 1.15(b). The capacitors ensure that each thyristor recovers fully on turn-off, while the resistor R_1 prevents an excessive di/dt on turn-on and resistor R_2 provides for equal steady-state sharing of voltage.

Gate circuit isolation.



As the gates of the individual thyristors can be separated by potentials of several thousand volts, a gate pulse must be provided from a common source via some means of isolation such as transformers, optically coupled diodes or transistors and fibre-optic light guides.

Chapter 5, case study of the Cross-Channel HVDC link.



(a) Simple series connection

(b) Voltage equalization network

Fig. 1.15 Series connection of thyristors.

The operation of all power semiconductors is limited by a series of ratings which define the operating boundaries of the device. These ratings include limits on the peak, average and RMS currents, the peak forward and reverse voltages for the devices, maximum rates of change of device current and voltage, device junction temperature and, in the case of the thyristor, the gate current limits.

Comparisons of power semiconductor device ratings are given in Fig. 1.49 and Table 1.2.

The current ratings of a power semiconductor are related to the energy dissipation in the device and hence the device junction temperature. The maximum value of ***on-state current*** ($I_{av(max)}$) is the maximum continuous current the device can sustain under defined conditions of voltage and current waveform without exceeding the permitted temperature rise in the device. The ***RMS current rating*** (I_{RMS}) is similarly related to the permitted temperature rise when operating into a regular duty cycle load such as that of Fig. 1.16.

Different manufacturers may adopt slightly different formats to those given in the text for a number of these standard values.

In the case of transient loads, as the internal losses and hence the temperature rise in a power semiconductor are related to the square of the device forward current, the relationship between the current and the permitted temperature rise can be defined in terms of an $\int i^2 dt$ rating for the device.

On turn-on, current is initially concentrated into a very small area of the device cross-section and the devices is therefore subject to a di/dt rating which sets a limit to the permitted rate of rise of forward current.

Typically, inductance would be added in series with the load to limit di/dt where the load inductance by itself was insufficient.

The voltage ratings of a power semiconductor device are primarily related to the maximum forward and reverse voltages that the device can sustain. Typically, values will be given for the ***maximum continuous reverse voltage*** ($V_{RC(max)}$), the ***maximum repetitive reverse voltage*** ($V_{RR(max)}$) and the ***maximum transient reverse voltage*** ($V_{RT(max)}$). Similar values exist for the forward voltage ratings.

$V_{RT(max)}$ is greater then $V_{RR(max)}$.

Equivalent forward voltage ratings are $V_{FC(max)}$, $V_{FR(max)}$ and $V_{FT(max)}$.

The presence of a fast transient of forward voltage can cause a thyristor to turn on and a dv/dt rating is therefore specified for the device. The magnitude of the imposed dv/dt can be controlled by the use of a snubber circuit connected in parallel with the thyristor. Figure 1.17 shows the basic series RC snubber together with some more complicated variations.

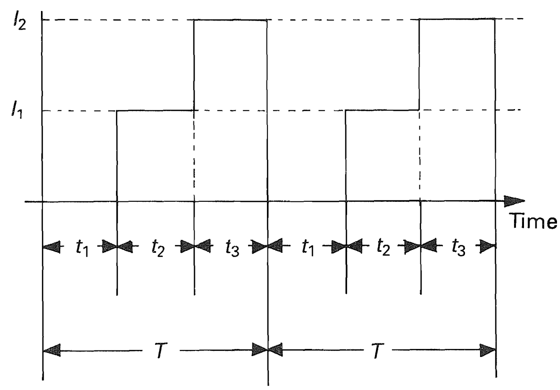


Fig. 1.16 Duty cycle load.

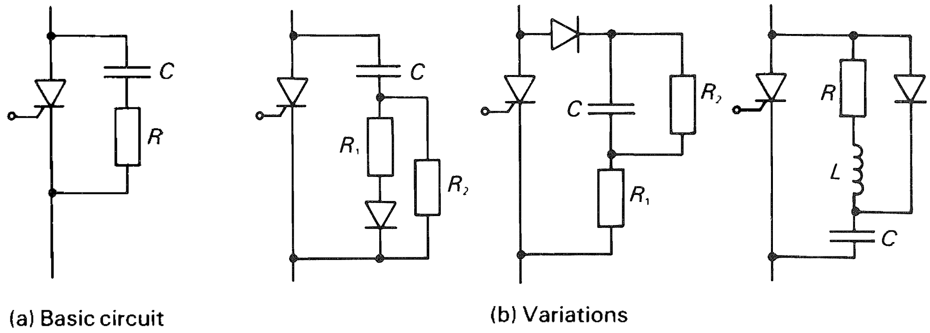


Fig. 1.17 Snubber circuits.

Snubber circuits

Software is now available for the calculation and optimization of snubber circuits.

Consider the circuit of Fig. 1.18(a) in which a thyristor is being used to supply a resistive load. With the thyristor turned off, the effective load is as shown in Fig. 1.18(b). If a voltage step (V_s) is now applied the current through the capacitor becomes

$$i_S = \frac{V_S}{R}\exp(-t/CR) \tag{1.3}$$

The voltage across the capacitor is then

$$v_C = V_S(1 - \exp(-t/CR)) \tag{1.4}$$

when

$$\frac{dv_C}{dt} = \frac{V_S}{CR}\exp(-t/CR_S) \tag{1.5}$$

If the dv/dt rating of the thyristor is not to be exceeded then, from Equation 1.5,

$$C > \frac{V_S}{R\left[\dfrac{dv_C}{dt}\right]_{max}} \tag{1.6}$$

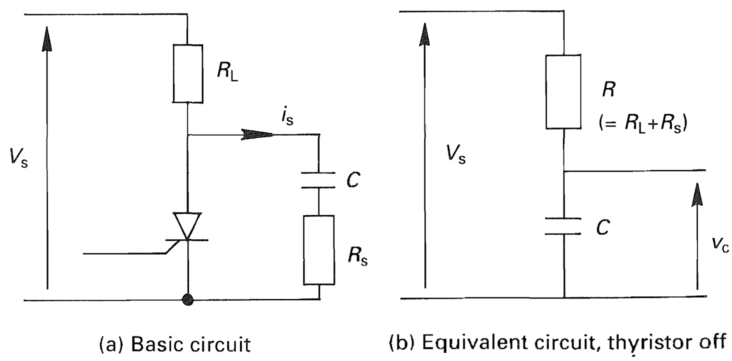


Fig. 1.18 Snubber operation with a resistive load.