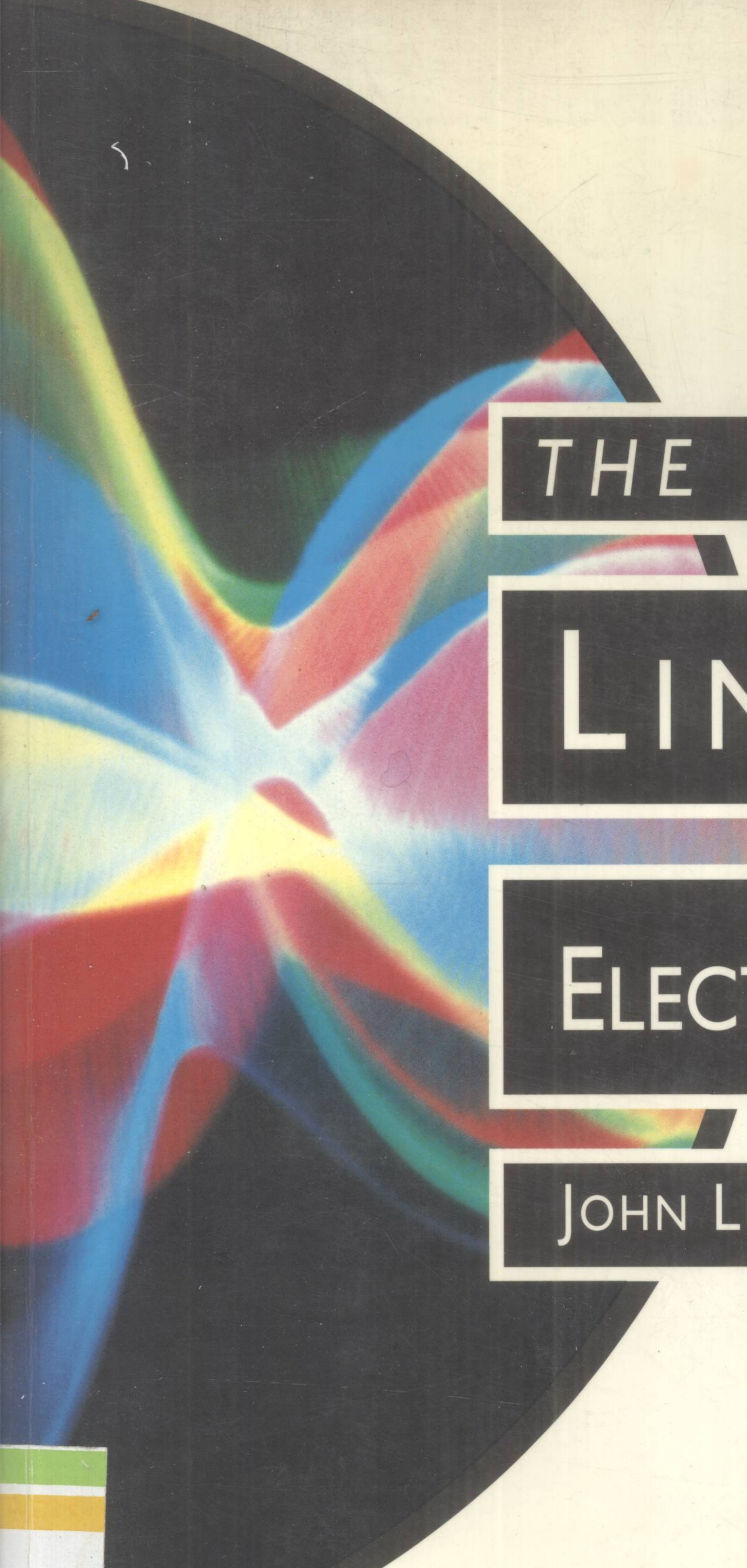

THE ART OF LINEAR ELECTRONICS

JOHN LINSLEY HOOD

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BUTTERWORTH HEINEMANN

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Preface

The past decades have seen a number of changes in the nature of electronics. Of these, few have had a greater impact than the continuous growth of digital circuit technology, with its extensions into electronic computation, data handling and numerical storage.

The enormous potential of digital circuit techniques has fascinated most of those who have become acquainted with them, and it is therefore a matter of little surprise that such a large proportion of studies in the field of electronics at universities and colleges relate almost exclusively to systems based on digital electronic components and circuitry.

However, circuit design in this field is largely restricted to the interconnection of various commercially available circuit building blocks in ways which are largely predetermined by their manufacturers.

While it is obviously essential for the digital circuit engineer to understand the specific functions of the complex circuit blocks he is joining together, it is unnecessary for him to know what actually happens within these blocks of 'integrated circuitry' when these are fed with well defined input pulses at logic level amplitudes, nor to concern himself with the problems which can and do arise in the handling of input signals of minute, indeterminate, or variable size, irregular waveform shape, or uncertain frequency.

This situation is now leading to an increasing shortage of engineers who have any skills in the equally wide field of linear electronic circuit design, and has shut off many competent engineers, quite familiar with the methods of digital circuitry, from the pleasure of creating simple and possibly unique functional circuits from discrete electronic components.

Moreover, while it is increasingly possible for almost any electronic circuit requirement to be met by digital techniques, all the methods which allow contact with the phenomena of nature, normally referred to as transducers, operate with variable signals of a wide range of amplitudes and frequencies, so any digital manipulation of these signals will depend on the availability of some linear 'interface' device to convert the input or output signal to or from its digital form.

While it is far too big a field for any single book to give more than a brief summary of linear electronic circuits and techniques, it does seem to me to be possible to cover the principal aspects of the subject in outline, so that those who would like a rather fuller knowledge of any particular part of the field could then refer to more specialized books for further information, without feeling lost in a totally unfamiliar world.

It is my hope that I will also have provided enough basic information within the chapters of this book for someone, starting with very little previous experience of this subject, to be able, having read it, to do some linear circuit design for himself. For this reason, I have tried not to presume too high a degree of existing knowledge on the part of the reader, and to explain, where I can, the reasons why things are done in the way that they are. I have also tried, particularly in the earlier chapters, to explain the various bits of technical jargon used in this field, since I know, from experience, how frustrating it is to read a text in which all sorts of unknown things are referred to by unfamiliar names or groups of inexplicable initials. I ask the more experienced readers to put up with this, or skip these introductory chapters altogether.

However, in the later chapters, my intention has been, where I can, to include aspects of the subject which I have found, to my regret, are not well covered in the bulk of contemporary textbooks, and which may therefore be interesting, informative, or useful to the experienced engineer as well.

It is not easily possible to sustain a simple and fully explanatory approach through those chapters dealing with moderately complex aspects of the subject, so I have sought to grade the extent of presumed existing knowledge, so that the later chapters lean on those things which I hope the reader will have gathered from the earlier ones.

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Acknowledgements

I would like to thank my many friends for their help and encouragement. In particular, I would like to record my debt to Colin Green, for his great help in ploughing his way through some of the more turgid parts of my prose, to point out obscurities, ambiguities, spelling mistakes and technical errors, and without whose advice the text would have been even less elegant.

Contents

1

Electronic component symbols and circuit drawing

Introduction

The normal way by which an electronics engineer will explore the function of an electronic circuit, or will describe his own designs, is by way of a 'theoretical' circuit drawing. In order to be able to understand what he sees or to be able to make his own drawings, it is necessary for him to know what the conventional circuit symbols mean, and which symbols are appropriate for a given device.

It is all too often taken for granted that the reader will understand this, without further explanation. This can be frustrating if some of the symbols used are unfamiliar, or if unexplained conventions are employed as a means of simplifying the drawing.

I have therefore tried, in the following pages, to show the most common graphical forms by which specific components are represented. Although there is a fairly wide agreement on these styles, individual design offices may still employ symbols which are unique to themselves, where some guesswork may be needed. The experienced engineer can skip this chapter without loss.

Basic design philosophy

The purpose of a circuit drawing is to give a rapid visual explanation to the viewer of how the circuit works, and how the individual component parts relate to one another. Unfortunately, in practice, drawings are often made with the sole aims of showing the connections between the components in an accurate manner and of producing a neat looking final result. Whether or not the actual interconnections are easy to follow, or how readily the engineer can discover the way the circuit operates, may not be a particularly high priority at the time the drawing is made.

Certain ground rules will help to keep the drawing simple in appearance and easy to follow. These are:

1. Adopt a consistent policy for the flow direction of signals, such as 'inputs' on the left-hand side of the drawing, moving across to 'outputs' on the right-hand side.
2. Keep positive supply lines at the top of the drawing, and negative supply lines, if present, at the bottom. Also, where polarity sensitive components are employed, try to position these so

that the potential appearing across them has the same orientation as that of the supply lines. If there is an 'earth' or '0V' line this should be positioned between the +ve and –ve lines.

3. Where the proliferation of supply lines will tend to confuse the picture, because of their frequent crossing of signal lines, use conventional symbols, as shown in Figure 1.1, to indicate their destinations. The convention here is that Figure 1.1a denotes a connection to a '0V' supply line, which may or may not be connected to the chassis of the equipment, while that of Figure 1.1b will indicate a direct connection to a metal chassis and Figures 1.1c or 1.1d will denote an earth connection.
   The symbols of Figures 1.1e and 1.1f will imply a connection to the positive and negative supply lines. The drawing can frequently be greatly simplified by this technique, and if there are several different power supply or '0V' return lines the appropriate ones can easily be indicated by numbers or letters.

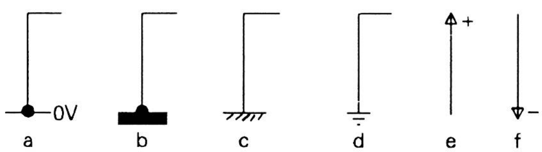

Figure 1.1

4. Avoid groups of connections drawn as closely spaced bundles of parallel lines. Although these can give a drawing a tidy appearance, it is very easy for the reader to lose track of the connection he is tracing through the circuit. It is much better to use labels or supply sign conventions instead.

A comparative example is shown in Figures 1.2a and 1.2b, in which the latter drawing is not only simpler, and easier to follow, but actually gives more information about the operation of the circuit than Figure 1.2a. In view of the complexity which can arise in showing the interconnections of just five components, it is easy to see how confusing the circuit drawings for more complicated systems may become, unless some care is taken to make them easy to follow.

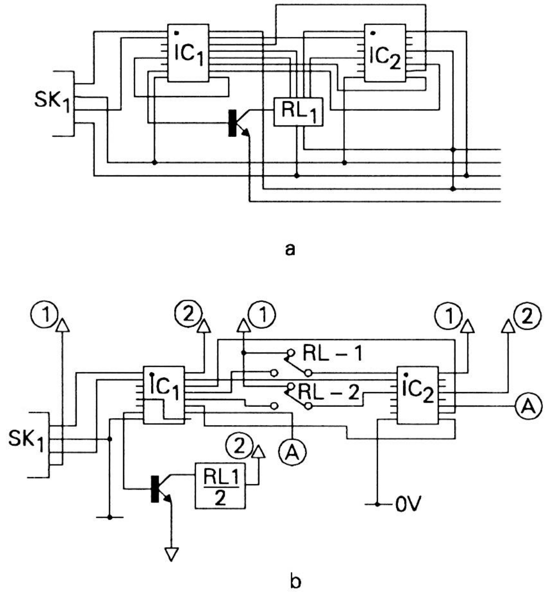

Figure 1.2

Avoidance of ambiguities

The most common source of ambiguity in circuit diagrams concerns wiring connections which join, or which cross without joining. Several conventions exist in this area. Of these the most common is the use of a 'blob' on a junction of two wires, as shown in Figure 1.3a, to distinguish this from a crossing without junction, shown in Figure 1.3b.

Unfortunately, in printing or subsequent reproduction, spurious 'blobs' can appear because of ink accumulations where lines cross, giving a wrong indication of circuit function. To avoid this type of mistake, it is good practice to make sure that junctions are never shown as simple crossings with 'blobs' but as staggered connections as shown in Figures 1.3c or 1.3d. Alternatively, a loop can be inserted where lines cross without connection, as shown in Figure 1.3e.

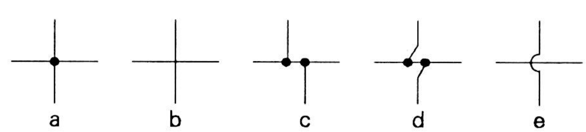

Figure 1.3

The other major uncertainty arises where earth or '0V' line connections are specified. Quite often the performance of the circuit depends critically upon the position of the 0V or earth line returns, and a simple connection to an earthed chassis may not be acceptable. In this case the forms of connection should be distinguished from one another by the use of the symbols shown in Figure 1.1, and where separate 0V or earth line returns are necessary these should be labelled numerically.

Conventional assumptions

Some conventions can cause difficulties to the inexperienced. One of these, as noted below, in Figure 1.13a, in relation to operational amplifiers, is that these ICs are normally powered by stabilized +/–15V DC supply lines – unless otherwise specified – so it may be taken for granted that the IC will be connected to its appropriate supply lines without these connections being shown at all on the circuit diagram.

A similar convention is often assumed with logic ICs, which will usually be connected between the 0V rail and a fixed +5V line. The existence of such a supply line is frequently taken for granted, and not shown in the circuit drawing, as is the presence of a small ceramic 'by-pass' capacitor, to decouple the supply to the 0V line at its point of connection to the IC, as shown in Figure 1.14n. However, there may be exceptions to this rule, and the fact that no connections are shown may not always mean that a +5V rail is used.

Block diagrams

It is often helpful when explaining the function of a relatively complex circuit – or group of circuits – to make use of 'block diagrams', in which the function of each block is described within its outlines, to show how the several parts of the circuit relate to one another. An example based on an audio amplifier and preamplifier is shown in Figure 1.4.

The specific circuit layout of the individual function blocks can then be shown separately at a later stage in the circuit description, when required.

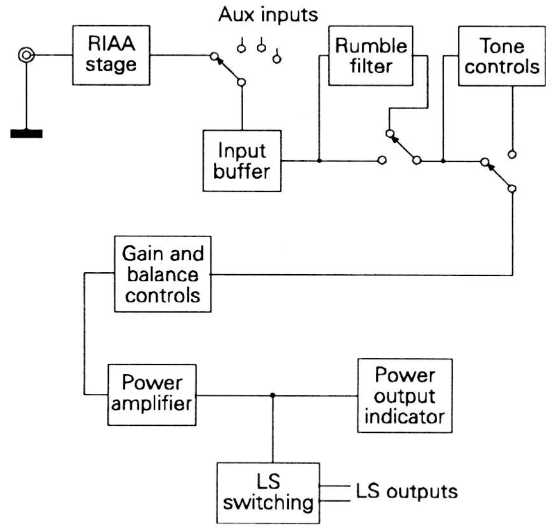

Figure 1.4

The theoretical circuit

In addition to providing an illustration of the way in which the various components of the circuit relate to one another, and an indication of the flow of the signal path and the currents drawn from the power supply lines, the circuit diagram also allows the types and values of the separate components to be shown. It may also be helpful, as an aid to understanding of the circuit function, or subsequent fault diagnosis, if the nominal currents flowing in the various supply line paths are also indicated.

Although designers are traditionally assumed to set down their thoughts on the backs of envelopes, from which a fully-fledged design may spring into existence – and, indeed there may be designers who really do work like this – there is little doubt that the extra time spent, at the design stage, in producing a fully labelled circuit drawing, greatly facilitates the calculation of circuit performance, and allows thermal dissipations and other characteristics of the design to be assessed before the prototype is assembled.

Technical terms

As I explained in the preface, it is my hope that this book will be useful to engineers with little existing knowledge of electronics. To this end, I have tried to explain technical terms as they arise. However there are cases where this would make the text unduly lengthy, so, where I have omitted explanations, I would refer the reader to the chapter which deals with the component or technique in question.

Circuit symbols and useful conventions

In the beginning, most of the circuit symbols were simplified representations of the actual components themselves: such as that for a resistor being shown as a piece of resistive wire laid down in a zigzag path to increase its length, or a capacitor as a nominal pair of parallel conductive plates, in proximity to one another, but separated by an air gap, or a transformer being represented by two coils of wire wound on a laminated iron core.

However, the growth of different forms of these basic component types has led to the adoption of various conventional styles of representation of these sub-species, and it helps greatly in understanding the diagram if these individual variations can be recognized instantly.

In addition, some 'shorthand' forms of symbol have emerged to denote such things as 'current mirrors' or 'constant current sources' – circuit function blocks which will normally be made up from groups of separate components – as well as for the wide variety of integrated circuits which are now available.

The diagrams used to represent the most commonly found types of components, together with some of these 'shorthand' symbols, are illustrated in Figures 1.5 – 1.16.

Capacitors

These are used in various forms. Of these, the simplest is the fixed value component, with either air or some polarity-insensitive dielectric between its plates, for which the circuit symbol is as shown in Figure 1.5a. The actual type of capacitor may not be specified by the drawing used. If this is critical to the function of the circuit, it will then be labelled so that this will be known.

With capacitors, as with most other circuit components, the capacitance value, together with the work-

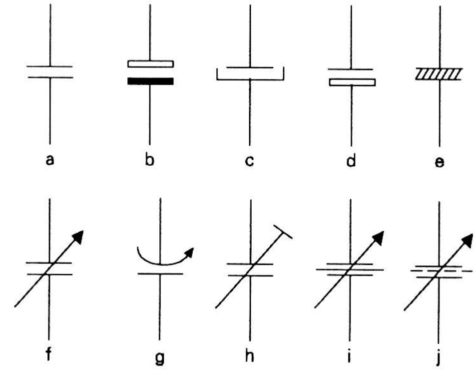

Figure 1.5

ing voltage and the required precision of value, where these are important or non-standard, will be appended as a label, such as 2μ2F/64V/10%. (It is becoming normal practice for the magnifier symbol, such as 'p' or 'μ' or 'k' or 'M' to be used instead of the decimal point, as in the previous example.)

Electrolytic capacitors, that is to say capacitors in which a thin insulating layer of metallic oxide has been formed within the component by electrolytic action, and which must therefore be connected in the circuit so that the applied voltage across its terminals has the correct polarity, are shown in the several forms illustrated in Figures 1.5b, 1.5c, or 1.5d, the actual symbol used depending on design office or national preferences.

Regrettably, the diagram of Figure 1.5c is also sometimes used to denote a non-polar capacitor, as an alternative to that of Figure 1.5a. This source of ambiguity could be avoided if a '+' polarity sign is always appended to the positive terminal of an electrolytic component. In some drawings of Japanese origin, electrolytic capacitors are depicted by the symbol shown in Figure 1.5e.

Capacitors in which the value can be manually adjusted, known as 'variable capacitors', are shown in the forms illustrated in Figures 1.5f – 1.5k. A convention which is worth remembering, because it is used with many other component symbols, is that an arrow with a point on its end usually implies that the component is intended to be adjusted frequently, for some operational or control purpose, whereas an arrow with a square end implies a pre-set component, which might be adjusted once, on setting up the equipment, and thereafter left alone.

Figures 1.5g and 1.5h frequently imply small value 'trimmer' capacitors, whereas Figure 1.5f would be used most commonly to represent a larger value variable capacitor, used as the 'tuning' control in a radio receiver. A special form of tuning capacitor, used in transmitters and short-wave receivers, is the 'split stator' type, in which two insulated plates are separated by a central earthed plate. This is denoted by the diagram of Figure 1.5j.

Where several variable capacitors are 'ganged' together, so that several sections can be adjusted simultaneously from the same control spindle, this fact is usually represented by the use of a dotted line joining the rear ends of the arrows together. The same dotted line convention is used to denote ganged sections of potentiometers and switches.

A similar diagram to that of Figure 1.5j, shown in Figure 1.5k, is used to denote a variable capacitor in which a sheet of some thin insulating material has been inserted between the plates so that these can be operated at much closer spacings, which allows a more compact component to be made, without the likelihood of an inadvertent short circuit occurring between the plates.

Resistors and potentiometers

The normal symbol for a fixed resistor is that shown in Figures 1.6a or 1.6b. The latter is becoming more popular because it is easier to draw neatly, but is slightly more ambiguous in its appearance. A two-terminal continuously variable resistor is represented by either of the Figures 1.6c or 1.6d, while a preset variable resistor is illustrated in Figures 1.6e or 1.6f.

The label applied to a resistor will specify its ohmic value, and may also denote its type, for example wirewound (ww), metal film (mf) or metal oxide film (mo) as well as its power rating and precision in value, giving a description such as 2k2/3W/5%/ww.

A three-terminal potential divider (potentiometer) is shown by either Figure 1.6g or 1.6h, depending on whether it is of a continuously variable or preset form. Note again the 'arrow head' convention. Using the oblong box type of resistor diagram, a continuously variable potentiometer would be shown as in Figure 1.6k.

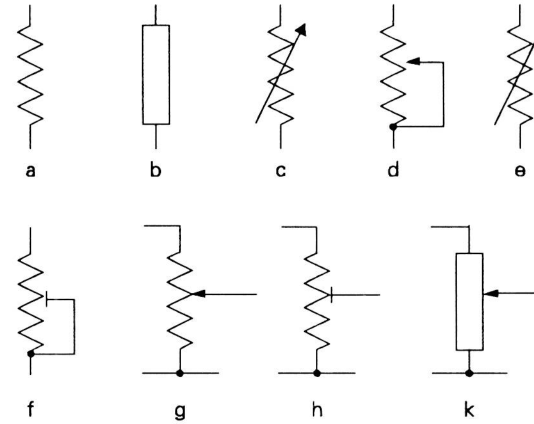

Figure 1.6

Coils and transformers

The simplest form, that of a fixed value air cored coil, is illustrated in Figure 1.7a. For RF use, in order to make the component more compact, a powdered iron core may be used, which will give the coil a higher inductance value for the same number of turns of winding. This is indicated by the use of the dotted line core shown in Figure 1.7b. Figures 1.7c and 1.7d denote dust iron cored, or similar, coils in which the inductance can be adjusted by a preset or continuously variable position for the core.

The use of a laminated sheet iron core, for a low frequency choke, is indicated by Figure 1.7e.

Radio frequency transformers are illustrated in Figures 1.7f, 1.7g and 1.7h, using air cores, and fixed and variable dust iron cores respectively. The diagram used in Figure 1.7j is sometimes used to denote a variable dust iron core position, as an alternative to that of Figure 1.7h. Where the coil or RF transformer is enclosed in a screening can, a box is drawn around it, as in Figure 1.7k.

Where coils are inductively coupled, though not shown close to each other, this is indicated by a curving line drawn through both, as shown in Figure 1.7m, and where the extent of such coupling is adjustable, this would be indicated by the arrow head symbol of Figure 1.7n.

Low frequency power transformers, such as those used for mains power inputs, are depicted by the drawings of Figures 1.7p, 1.7q and 1.7r, of which the last two represent tapped and separated winding types.

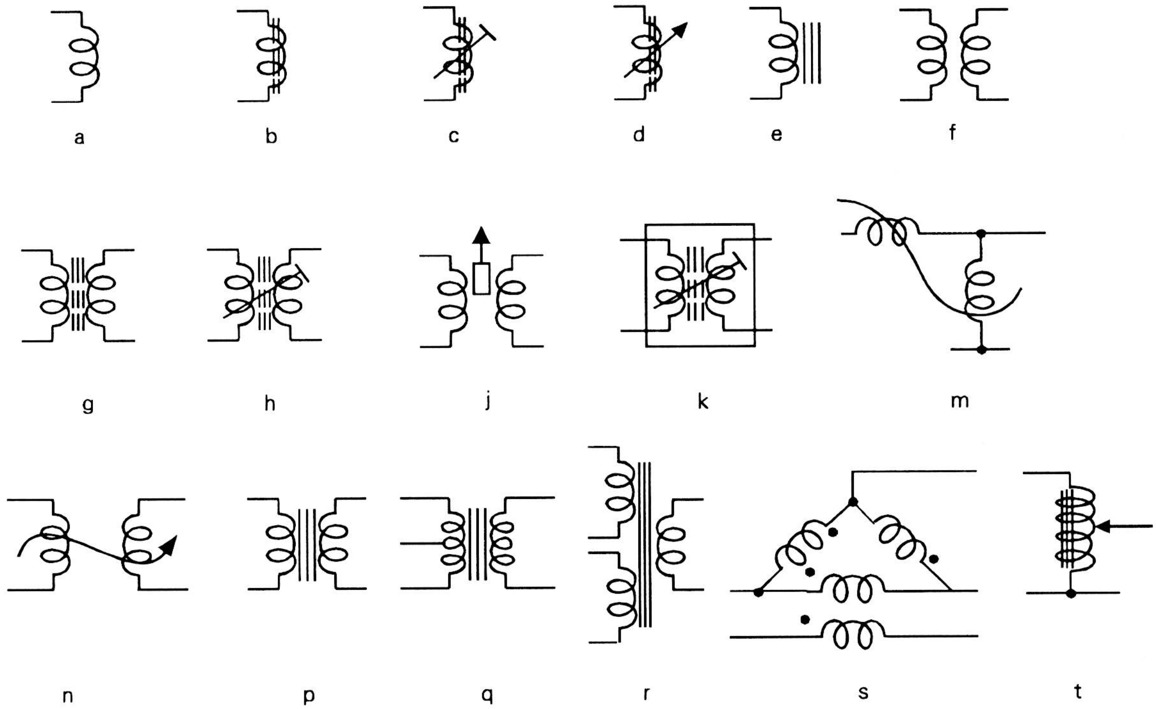

Figure 1.7

If the direction of winding in a coil or transformer is important, the 'top' ends of all windings made in the same direction will be marked by a 'dot', as in Figure 1.7s. By analogy with the symbol for a potentiometer, a 'Variac', or variable transformer, would be drawn as in Figure 1.7t.

Switches

These are mainly drawn in a manner which closely follows their mechanical function, as for example the two-way switch of Figure 1.8a and the five-way rotary switch shown in Figure 1.8b. It is conventional to indicate the moving arm by an arrow head symbol. In normally closed, and normally open forms, this may be indicated by an offset arrow head, as in Figures 1.8c and 1.8d.

Switches with ganged segments, such as the main power on/off switch for a piece of equipment, are commonly denoted by a dotted line linking the moving arms, as in Figure 1.8e.

A momentary contact switch of the kind which makes contact only when the actuating button is depressed is shown as in Figure 1.8f. One in which the operation of the switch momentarily breaks the circuit would be drawn as in Figure 1.8g.

Relays

These are a special category of switches, in which the mechanical operation of the switch arm is performed by an electromagnetic actuator driven by a wound coil. Showing the coil in physical proximity to the switch mechanism, as illustrated in Figure 1.8h – which might depict a 'reed' relay, with an air-cored operating coil – tends to clutter up the circuit diagram, so it is more common to separate these, as shown in Figure 1.8j.

The relay operating coil can then be drawn as a simple box, on which, for example, the legend $\frac{\text{'RL1'}}{2}$ denotes that relay No. 1 has two operating

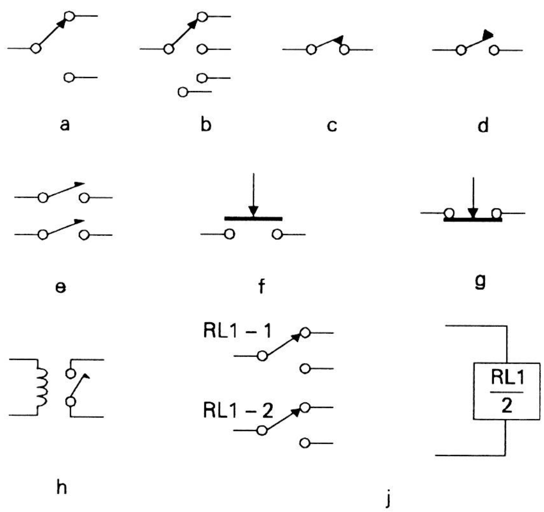

Figure 1.8

switch contacts. This then allows the switch elements which are operated by this relay to be placed anywhere convenient in the circuit drawing, and labelled 'RL1–1' and 'RL1–2' to show how they are operated.

It is good practice to append 'nc' or 'no' signs against such relay switch contacts to show they are 'normally open' or 'normally closed' – when the relay operating coil is unenergized.

Transistors and diodes

The normal semiconductor junction diode is represented by one or other of the equivalent forms shown in Figs 1.9a or 1.9b. No specific notation is used to distinguish between a low-power, 'small signal', diode and a high-power rectifier device, so the engineer must infer this distinction from the part of the circuit in which the device is placed.

'Bridge' rectifiers, or a group of diodes arranged to form a full-wave rectifying block, are conventionally shown as in Figure 1.9c. However, the diode symbols are sometimes omitted from the drawing entirely, giving the picture shown in Figure 1.9d, which relies for its interpretation on the presence of the '+', '–' and '~' (AC input) signs at the corners of the diagonal square. This may be simplified even further to the symbol of Figure 1.9e, in which a diode is shown within the square, and even the '+', '–' and '~' symbols are left out.

'Zener' or voltage regulator diodes are denoted by the symbols of Figure 1.9f or 1.9g. A similar symbol is sometimes used to denote a 'hot-carrier' or 'Schottky' type of point contact diode. A preferred symbol for this device is shown in Figure 1.9h.

Normal NPN junction transistors are drawn as shown in Figures 1.9j – 1.9m, according to the preference of the draughtsman. Enclosing the transistor symbol with a ring, to indicate the physical boundary of the device, as in Figure 1.9m, allows the envelope to be extended, as for example in Figure 1.9n, to denote a dual or multiple device mounted within the same housing. Such a symbol probably implies that both devices are fabricated on the same chip, so that both sections will have closely similar operating characteristics.

In both NPN and PNP junction transistors, the emitter lead is denoted by the line with the arrow head; pointing towards the 'base' in the case of a PNP device, and away from it in the case of the NPN version. The angled line without the arrow head denotes the collector junction. The line joining at a 'T' refers to the base of the transistor. Symbols for PNP junction transistors are depicted in Figures 1.9p, 1.9r and 1.9s.

The line or bar denoting the base area of the transistor should be blocked in. Where this is left as an open rectangle, as in Figure 1.9t, it is usually taken to mean that the device is of the 'super-Beta' type, having a very high current gain but a very low collector–emitter or base–emitter breakdown voltage. These types of transistor are normally only found in integrated circuits.

The drawings shown in Figures 1.9u or 1.9v are sometimes found as a representation of a junction transistor. This is a more logical analogy for the devices now made than the symbols of Figs 1.9j or 1.9p – which typified the early, and now obsolete, point contact devices. However, this more accurate symbol has never been widely adopted, and remains a somewhat eccentric variation.

Field effect devices

These exist as junction types, and as 'MOSFET' or 'insulated gate' (static charge operated) field effect devices. The symbols used to represent junction FETs are as shown in Figures 1.10a and 1.10b, which denote