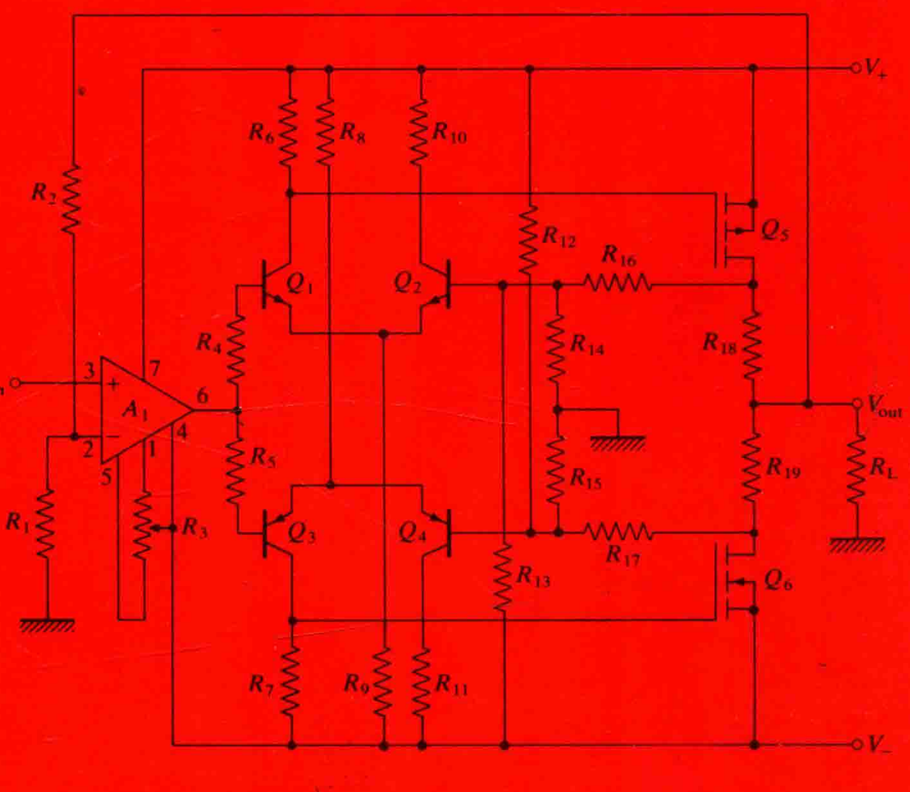
Electronic circuit design

art and practice

T.H. O'DELL



Electronics texts for engineers and scientists

Electronic Circuit Design:
Art and Practice

T.H.O'DELL
Reader Emeritus, University of London

The right of the University of Cambridge to print and sell all manner of books was granted by Henry VIII in 1534. The University has printed and published continuously since 1584.

CAMBRIDGE UNIVERSITY PRESS
Cambridge
New York New Rochelle Melbourne Sydney

Published by the Press Syndicate of the University of Cambridge
The Pitt Building, Trumpington Street, Cambridge CB2 1RP
32 East 57th Street, New York, NY 10022, USA
10 Stamford Road, Oakleigh, Melbourne 3166, Australia

First published 1988

Printed in Great Britain at the University Press, Cambridge

British Library cataloguing in publication data

O'Dell, T. H.
Electronic circuit design:
art and practice – (Electronics tests for
engineers and scientists).
1. Electronic circuit design
I. Title II. Series
621.38 15'3 TK7867

Library of Congress cataloguing in publication data

O'Dell, T. H. (Thomas Henry)
Electronic circuit design: art and practice / T.H. O'Dell.
172 pp. cm. -- (Electronics texts for engineers and scientists)
Includes bibliographies and indexes.
ISBN 0-521-35329-7. ISBN 0-521-35858-2 (pbk.)
1. Electronic circuit design. I. Title. II. Series.
TK 7867.028 1988
621.3815'3 -- dc 19 87-32903 CIP

ISBN 0 521 35329 7 hard covers
ISBN 0 521 35858 2 paperback

MCP

Electronics texts for engineers and scientists

Editors

H. Ahmed, *Reader in Microelectronics, Cavendish Laboratory, University of Cambridge*

P. J. Spreadbury, *Lecturer in Engineering, University of Cambridge*

Electronic circuit design: art and practice

Preface

This book has grown out of the experience I gained while involved with a laboratory course in electronic circuit design for the final year undergraduates in the Department of Electrical Engineering, Imperial College, University of London. The book is intended to provide a selection of ideas for such a course, more material being described than could be fitted into a single option during one academic year, and much being suitable for the earlier years of a degree course.

The book is also intended for a far wider range of readers who have access to a simple electronics laboratory: those undergraduates, graduates, research assistants, and technicians in all fields of the hard and soft sciences who, as Horowitz and Hill put it in the Preface to their *Art of Electronics*, 'suddenly find themselves hampered by their inability to "do electronics"'.

The point which is emphasised here is that electronic circuit design can only be learnt by doing. Theoretical knowledge is, of course, essential and this book must be used with a good foundation text for the fundamental principles of electronics. Horowitz and Hill is an excellent choice for this, and the book by Gray and Meyer will cover any more advanced theory which is needed. Details of these two books will be found in note 2 of Chapter 3 here.

There is something more to electronic circuit design, however, than a good theoretical foundation coupled with a considerable amount of experience in the laboratory. This something more is the question of design itself: where do *new* circuit ideas come from? This problem is discussed in the first chapter 'What is design?', and the discussion is maintained throughout the following eight chapters, which deal with high and low frequency small signal circuits, opto-electronic circuits, digital circuits, oscillators, translinear circuits, and power amplifiers. In each chapter there are one or more experimental circuits for the reader to construct and make measurements on, a total of thirteen small project exercises in all. This practical work of construction, followed by the observation of waveforms, voltage and current levels, non-linearities, thermal effects, and so on, is the way to understand how new circuit ideas develop and why electronic circuits take the shape that they do. Then, readers will find themselves inventing new circuits of their own; new, perhaps, only to them, but that is no problem. To discover new techniques for yourself in the only valid way to keep up to date.

The final chapter 'Theory and practice' draws some brief conclusions on the fundamental problem of design, in the light of the growing literature about it and in the light of the circuits which have been dealt with in the book.

In writing this book I have made use of many ideas which have come out of discussions with colleagues, or during project and laboratory work with students. I should like to thank them all. Thanks are also due to Dr B. A. Unvala, of Imperial College, and to Mr Francis Saba, who both read the text and suggested many improvements.

T. H. O'Dell
London, January 1987

Contents

1

What is design?

1.1 Design and synthesis

As the word 'design' is used in electronic engineering rather freely it seems essential, for a beginning to our discussion of electronic circuit design, to be clear what is meant. The production of a piece of electronic hardware, starting of course with a clear idea of what that hardware is supposed to do, really involves two stages before the work of manufacture or construction can begin. At first, we must outline how we are going to solve the problem. We need a preliminary sketch of the circuit. Secondly, we need to calculate the exact component values, or values of the parameters which enable us to construct or process the circuit. Here, we shall call these two steps design and synthesis. It is not, of course, possible to separate these two steps. They interact with one another and the complete engineering process involves a continuous shift from design to synthesis and then back to design. This is what 'computer aided design' should mean.

For electronic circuits, the design step is primarily a choice of what we shall call circuit shape. The word 'shape' has been chosen with the German word for shape, *die Gestalt*, in mind because this has now come into the English language [1] to mean 'an organised whole in which each individual part affects every other, the whole being more than the sum of its parts'. Such an attribution is meant here by circuit shape, and this should become clear below when we look at some examples. Even more is involved, however, because it is not just the individual parts of a circuit, and the way in which these are connected up, which are important. As Baxandall [2] has remarked, the way a circuit is actually drawn has a very strong influence upon the way one thinks about how it works.

1.2 Choosing a circuit shape

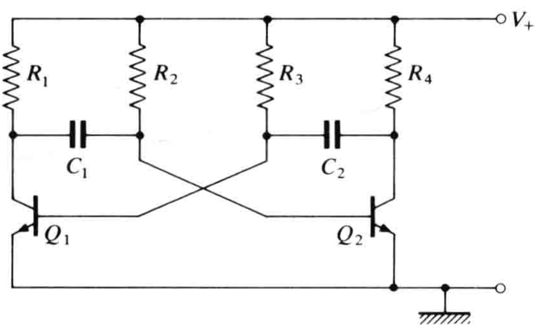
Fig. 1.1 shows an electronic circuit, a relaxation oscillator, a circuit shape which will have been made repeatedly familiar to electrical engineering students over the past sixty years. This is an historical fact because the circuit, as a shape, probably first appeared as Fig. 62 on page 158 of a 'secret' document dated April 1918, complete with all the differential equations describing its operation [3]. At that time the circuit used two triodes and worked extremely well with these devices because, in the circuit shape of Fig. 1.1, nearly the full supply voltage, V_+, is available to reverse bias the grid with respect to the cathode when either triode has to be turned off.

Using transistors, the circuit shape shown in Fig. 1.1 is not a good choice for a design. The reason is that, in contrast to a triode, a bipolar transistor can have no reverse bias across its emitter junction until it *has* been turned off. Furthermore, while the positive supply voltage, V_+ in Fig. 1.1, may be only about 15 V, this is quite enough to break down the emitter junction of a silicon planar transistor. Fig. 1.1 may well have worked when it was first tried out with germanium transistors, but it is surprising to find that it is still presented as a worthwhile design today [4].

Consider an alternative circuit shape for a multivibrator: the circuit shown in Fig. 1.2. Like Fig. 1.1, this is a two stage amplifier with its output fed back to its input. The first stage, Q_1, is in grounded base connection, and the second stage, Q_2, is in grounded collector connection, as far as the oscillator loop is concerned. Q_2 is also used as an output buffer amplifier, which is a good idea compared to simply omitting R_4 and taking the output from the collector of Q_1.

The advance in technique, as far as making effective use of the bipolar transistor is concerned, in going from Fig. 1.1 to Fig. 1.2, cannot be over-emphasized [5]. In Fig. 1.2 use is made of the small voltage across the

Fig. 1.1.



emitter junctions of Q_1 and Q_2, when these devices are conducting, to enable us to define the operating currents of Q_1 and Q_2 by means of resistor values. The transistors do not saturate in this circuit; it was the fact that Q_1 and Q_2 were allowed to saturate in Fig. 1.1 which defined the operating currents in that circuit. Full details of Fig. 1.2 are given in the Appendix because this is an interesting circuit to experiment with.

Let us look at a third possible shape for a multivibrator or relaxation oscillator circuit. This is shown in Fig. 1.3, and is the kind of circuit shape which might be found in a silicon integrated circuit [6].

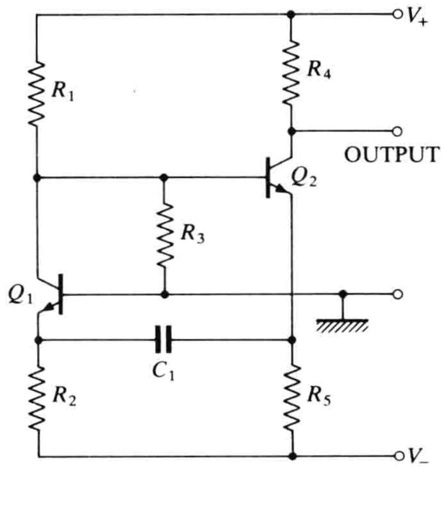
Often described as an emitter coupled multivibrator, Fig. 1.3 is, in fact, more complicated than Fig. 1.2 because it includes some of the ideas shown in Fig. 1.1. We do not discuss the way these circuits work here, they are all well known. We are only proposing different circuit shapes which all can, with different advantages and disadvantages, provide the solution should we need a relaxation oscillator, or at least provide a basis to build on for a good final design.

1.3 Method in design

Is there any method that can be followed in order to come up with new circuit ideas? When the circuits shown here as Figs. 1.1, 1.2, and 1.3 were first drawn, they were without question quite new conceptions. How was it done? How can we continue to come up with good new circuit ideas?

There have been attempts in the past to find a method in the design of electronic circuits, and by design we again mean the invention of the shape of a circuit, the step which must take place before any problems concerned

Fig. 1.2.

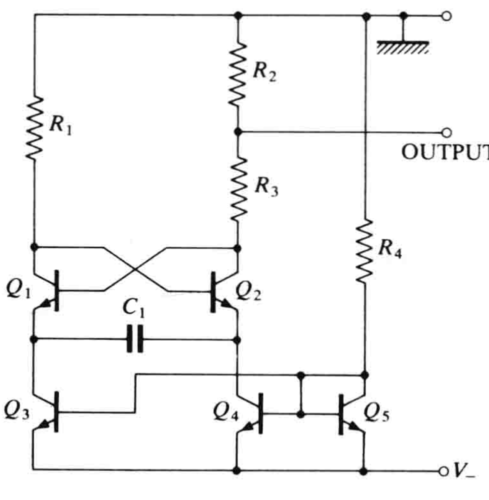


with component values, that is with synthesis, come up. The use of signal flow graphs and network topology was at one time considered a step in the right direction, but both these techniques, while making important advances which helped with analysis and synthesis [7], contributed nothing to our understanding of the design process. It is, perhaps, interesting to look at one of the texts which introduced signal flow graphs and network topology to the main stream of electronic engineers, and to quote from the preface of the first edition, dated 1960:

> The laws of physics provide basic models of charge motion, in terms of which we explain the observed terminal behaviour of elementary components and devices . . . From physical models and observed terminal characteristics, we make circuit models that lead to simple circuits capable of performing basic operations. . . . These operations . . . serve as elementary building blocks or models with which we can construct models of more general systems [8].

This is a very good example of the feeling that technology is just a matter of applying science, a feeling which was very much the accepted one in the middle of this century. Today, we know little more about the problem except that it is far more complicated. Technology is certainly not just applied science, but, as Mayr has written [9], 'the problem of the science–technology relationship . . . has eluded all who have tried to grasp it', and he goes on to list the great variety of people who have tried. In their very interesting book, *The Sources of Invention*, Jewkes, Sawers and Stillerman consider an even wider field and write 'The interactions between science, technology and economic growth are much more complicated than was

Fig. 1.3.



ever imagined by those who have dominated opinion and influenced public policy upon these matters in recent years' [10].

So we are left with our original difficulty when we ask where new circuit shapes, new circuit ideas, actually come from. This difficulty might be answered with one word: '*eureka*', 'I have found it'. However, we must be careful not to then make the assumption that there is one particular person responsible for any new circuit idea. The truth is far more likely to be that a new circuit shape has appeared in a number of different places, all at about the same time, simply because so many workers in the field have been thinking along the same lines. T. S. Kuhn has written about the same thing happening with scientific innovation [11], as opposed to the technological innovation we are concerned with here.

In the following chapters we shall be looking at some of the interesting circuit shapes that various people have come up with, often trying to trace the origin of these new circuits by looking at the kind of circuit shapes which were used earlier. As far as possible, circuits have been chosen so that the reader can construct them in a laboratory which has only the simplest facilities. This has been done because an experimental point of view seems to be essential for making progress in circuit design, for beginning to find new circuit shapes even if these are new only to the experimentalist. From the point of view which is taken in this book, a circuit designer comes from the laboratory, not from the lecture theatre.

1.4 Working with circuit shapes

While there appears to be no clear method behind the invention of a completely new circuit, it does seem possible, in some cases, to find a pattern in the development of a new idea.

This pattern can take its form from simply adding simpler circuits together. We have an example here already in Figs. 1.1, 1.2, and 1.3: the idea of two stages of common emitter amplification, Fig. 1.1, and the idea of emitter coupling via a capacitor, Fig. 1.2, both appear in Fig. 1.3. It might be said that the circuit shape of Fig. 1.3 comes from embedding Fig. 1.2 into Fig. 1.1. This idea of embedding one circuit into another is explored further in Chapter 3. The simpler idea of just adding circuits, one after another, is looked at first, in Chapter 2, and also in Chapter 4 where we look at the kind of new circuits people have come up with by simply adding operational amplifier circuits together.

The idea of working with circuit shapes may be taken even further when integrated circuits are considered. This comes about because the idea of adding circuits together, or embedding one circuit into another, takes on a far deeper meaning when we deal with silicon, n^+, n, i, p and p^+, and not just with the nodes, or input and output terminals, of circuits which, while they may not be discrete component circuits, are still thought of in a discrete way. Some very interesting examples of this kind of work with circuit shapes come up in Chapter 6 when we look at the invention of integrated injection logic and substrate fed logic.

1.5 Construction and manufacture

The way a circuit is going to be made has a very great effect on the kind of circuit shape we may finally end up with. Of our examples so far, Figs. 1.1 and 1.2 are classical discrete component circuits, while Fig. 1.3 would be much better made as an integrated circuit, or at least by using an array of transistors [12], because Q_3, Q_4 and Q_5 need to be in close thermal contact.

It is from this aspect, constructional and manufacturing technique, that development and technical change in electronics are most apparent. However, while references given to particular devices, and even to kinds of device, will always become rapidly out of date, the central problems of electronic circuit design have been surprisingly constant for a very long time. Unless we have just entered a 'post historical' era [13], the electronic hardware of today should look as old fashioned, to the electronic engineer of fifty years from now, as the electronic hardware of World War II looks to us when we see it in our museums today. Whatever devices or constructional techniques we may use in the future, we shall still be building on the theory which has its foundations in the past, and we shall probably still be trying to understand how people come up with such elegant and simple ideas, ideas which, with hindsight, make us feel that the whole problem is quite easy and must be obvious.

Notes

1 **Oxford Concise Dictionary,** Oxford, 1970, p. 513.

2 P.J. Baxandall, *Radio and Electronic Eng.*, **29**, 229–46, 1965.

3 This document is the remarkable 'Notice sur les lampes – valves à 3 électrodes et leurs applications', Ministère de la Guerre, Establissement Central du Matérial de la Radiotélégraphie Militaire, Avril 1918. Copies of this are held in the Centre de Documentation d'Histoire des Techniques in Paris, ref. DOC 1359, and in the IEE Archives in London, ref. NAEST 46/9.

4 In an issue of *IEEE Spectrum*, No. 11, 1984, which is devoted to contemporary education, the circuit shown in Fig. 1.1 appears on page 48 as a photograph which has been taken from the VDU display of a 'Circuit Analysis Program' designed for students.

5 The circuit shown in Fig. 1.2 may have been first described by R.C. Bowes,

Proc. IEE, **106B**, *Suppl.* 15–18, 793–800, May 1959. Bowes gives some comments on the possible origin of this circuit.

6 The circuit shown in Fig. 1.3 is a very much simplified version of the one used in the 560 series of phase locked loops introduced in 1970 by Signetics: *Linear Integrated Circuits*, Signetics Int. Corp., London, 1972, p.260.

7 F.D. Waldhauer, *Bell Syst. Tech. J.*, **56**, 1337–86, 1977.

8 S.J. Mason and H. Zimmerman, *Electronic Circuits, Systems and Signals*, John Wiley, New York, 1960. This book covers network topology in Ch. 3 and signal flow graphs in Chs. 4 and 6.

9 O. Mayr, *Tech. and Culture*, **17**, 663–73, 1976.

10 J. Jewkes, D. Sawers and R. Stillerman, *The Sources of Invention*, Macmillan, London, 1969, 2nd edition, p.226.

11 T.S. Kuhn, *Hist. Studies Phy. Sciences*, **14**, 231–52, 1984, particularly pp.250–1.

12 A variety of these are available with up to seven devices (CA3081), using bipolar devices of one or the other polarity, or even mixed (CA3096). There are also arrays of MOS transistors (CA3600).

13 In his very interesting paper, 'Historians and Modern Technology', *Tech. and Culture*, **15**, 161–93, 1974, Reinhard Rürup warns against a 'technological mode of thinking – a way of thinking according to which man's hope and future lie in the end of history'. Just such a mode of thinking is to be found in Dennis Gabor's *Inventing the Future*, Secker and Warburg, 1963: Chapter 10 is subtitled 'History must have a stop'.