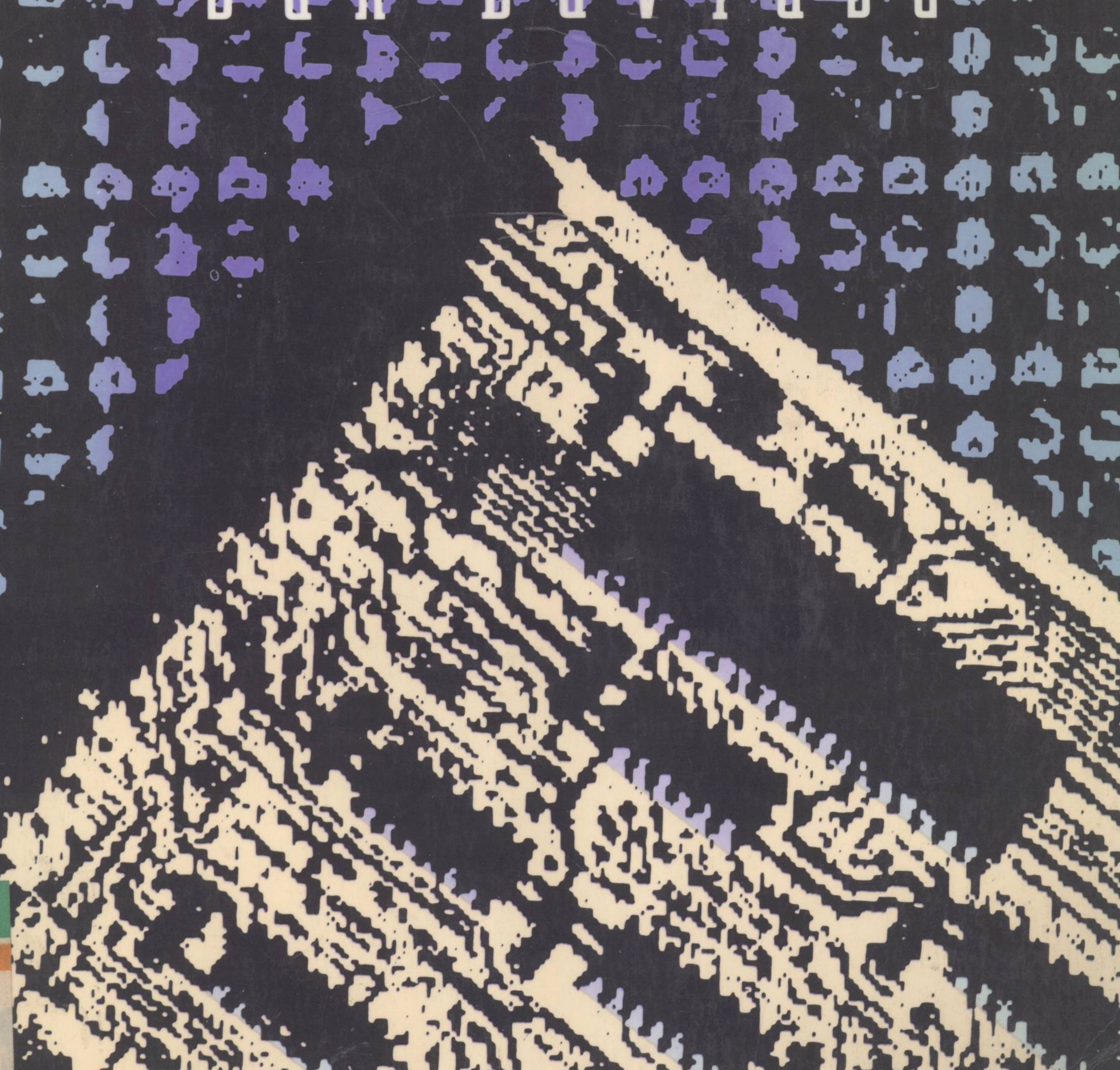
ANALOG ELECTRONIC CIRCUIT DESIGN

Jan Davidse



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Preface

Analogue electronics is the oldest branch in the field of electronics. Although much signal processing is done digitally at the present time, analogue electronics remains an indispensable discipline. The field has constantly been in a process of rejuvenation and, with monolithic technology as the driving force, this process has more gained speed during the last decade, than in any preceding period.

At present, analogue electronics is a wide field. Full coverage within the bounds of a single volume is illusory and any author of a textbook has to take decisions with regard to the selection of the subjects to be included and to the depth of their treatment. In writing this book I have adopted two guiding principles. First, emphasis should be on the pursuit of high performance in integrated implementations of analogue signal-processing circuits. Hence, subjects such as the judicious application of negative feedback and the mastering of noise in circuit design have obtained more attention than they get in most textbooks. Low-noise design is nearly always of the essence in high-performance signal processing, but experience reveals that suboptimal designs are not uncommon. Second, topics of a specialist nature have been omitted or only touched upon. As criteria for declaring a topic to be of a specialist nature, the availability of modern specialized books devoted to the particular subject has been taken. Examples in this category are A-to-D and D-to-A converters, signal processing with charge-coupled devices, switched-capacitor filters and phaselock loops.

The book has grown from course material which I taught for many years in graduate and upper undergraduate courses. Hence, most of the material has been tried out extensively on generations of students. The reader is assumed to possess basic knowledge of elementary network and signal theory and of electronic devices and circuits. In order to support readers whose knowledge of these topics is lacking to some extent, the first three chapters survey the prerequisites for fruitful study of the subsequent chapters.

A collection of problems, together with elaborated solutions is available from the publisher in a separate booklet. This material has been especially devised for the benefit of readers who use the book for self-study and who lack everyday guidance by a teacher. I believe that much of the material included in this book is valuable for analogue circuit designers who are willing to extend or to update their knowledge.

I headed the electronics laboratory of the Department of Electrical Engineering of the Delft University of Technology for many years. Acknowledgements are due to all members of the staff of this laboratory. Special thanks go to Leo de Jong, Gerard Meijer, Kees Wissenburgh and Albert van der Woerd for reading and commenting on the manuscript. They have saved me from many pitfalls, and their comments have contributed considerably to the final shape of the text. I am very grateful to Mrs Olfien Lefèbre-van den Broeke who undertook the enormous amount of typing work involved in the preparation and finalization of the text, and to Rob Janse, who prepared all the drawings using his self-developed drawing program 'tekplot'. Finally, I wish to thank the many generations of students who have continually challenged my didactic qualities and who, in a process of mutual interaction, in one sense were also my teachers.

Jan Davidse
Delft, September 1990

Contents

1 Signals and signal handling

1.1 Types of electrical signals

Electronics is the art of handling information-carrying electrical signals. The electrical quantity constituting the signal can be electrical charge, magnetic flux, current or voltage. Nearly always, the primary information is not available in the form of an electrical quantity but is available, for example, in the form of an optical, acoustic, thermal or chemical signal. To render these signals manageable by electronic devices and circuits they must be converted into electrical signals. The devices serving this purpose are called *input transducers* or *sensors*. After being transported and/or processed in an electronic system, the output signals of these systems must, in most cases, be converted again into the physical quantities that are appropriate to the final representation of the information. This is accomplished by devices called *output transducers* or *actuators*.

Figure 1.1 depicts the structure of a generalized system for the transport and/or processing of information. The link between the input transducer and the electronic processing system is called the 'front interface' of the system. Similarly, the corresponding link at the output side is called the 'rear interface'. A television system can serve as an example of an electronic system for the transport and processing of information. The primary information source is an optical image.

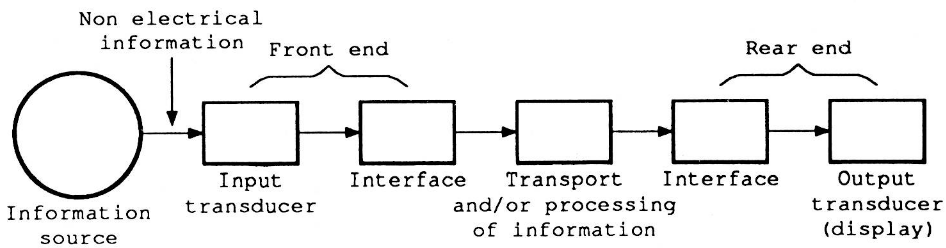

Fig. 1.1 *Generalized electronic system for the transport and/or processing of information.*

The signal obtained from the camera is amplified and modified in such a way that it can be transmitted by a television transmitter. At the reception site, the signal is picked up, amplified and processed for appropriate driving of the display system that reconverts the signal into an optical image.

The question may arise as to why the detour is needed for the employment of electronic means for the manipulation of the information. The reason is the unparalleled flexibility of electronic means. Electronic signal handling can be extremely fast. In addition, it can be achieved at the cost of very little power and material consumption. Microwatts and nanowatts are current power measures in electronics. The material of greatest interest in electronics is silicon, which is the second most abundant chemical element on earth. Even if the preferred material were not so ubiquitous, this would not be a problem since in modern electronics most circuits are realized in the form of chips, tiny pieces of material whose volume rarely exceeds 1 mm^3. The physical basis of the extreme versatility of electronic means is the very large specific charge (ratio of charge and mass) of the electron, viz. 1.76×10^{11} C kg^{-1}. It is therefore possible to exert large forces on the electron with very small fields and, hence, at the expense of very little power consumption.

The signals generated by the sources of primary information are almost always continuous-time signals, and the same holds for the electrical signal produced by the input transducer. The signal, as a function of time, corresponds to the time-dependent physical phenomenon providing the primary information. Such an electrical signal is an analogue of the primary information stream; it is, therefore, called an *analogue signal*. For example: the signal generated by a microphone is an electric analogue of the sound signal picked up by the device. It is characteristic of a true analogue signal that its value is relevant at any moment. However, the possible rate of change dS/dt of a signal $S(t)$ is always finite. In spectral terms this is expressed by the finite nature of the spectral bandwidth of the signal. Information theory states that a signal confined within a spectral bandwidth B is fully determined by $2B$ samples per second. Hence, without loss of information, a continuous-time signal can be converted into a discrete-time sampled data signal, provided the samples are taken at equal time intervals and at a rate exceeding $2B$ per second. For instance, a video signal confined to 5 MHz bandwidth can be fully specified by 10^7 samples per second. Figure 1.2 sketches both types of signals.

Though a sampled-data signal is discrete in time, the succession of sampled values is still an analogue of the primary information. A further step in discretizing the information is to measure the magnitude of each sample and to represent the results by means of a number. Thus the information stream is coded in the form of a sequence of numbers. This way of formatting is called 'digitizing' and the signal obtained is called a 'digital signal'. The number representation most often used is the binary representation, which uses only two digits, 0 and 1. A convenient electrical representation is in the form of pulses where, for example, no pulse denotes 0 and a pulse denotes 1. In present-day electronics, digital signal processing plays a dominant role. It has many attractive features, the most obvious being its robustness. Only two signal values can exist and, hence, noise and interference have

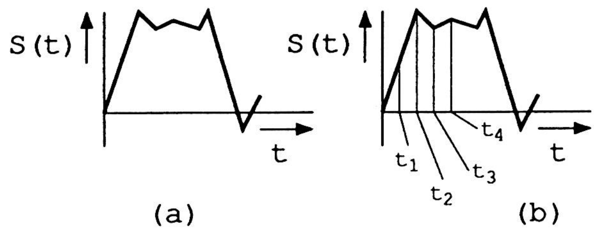

Fig. 1.2(a) *Example of an analogue signal.* (b) *Sampling of the signal at discrete time intervals.*

little grip on the signal. Moreover, circuits for handling digital signals are excellently suited to integrated-circuit (IC) implementation and to computer-aided circuit design (CACD) methods. A digital signal-processing system can, in principle, be entirely built up out of one type of elementary circuit, the logic decision circuit, and there is always a direct relationship between the function to be performed and the structure of the circuit implementing the function. The circuits can be built using transistors only, sometimes augmented with resistors. The transistors operate as switches and, in essence, only their switching behaviour is involved. In the days of discrete device electronics, the vast number of transistors needed to implement the desired functions was considered to be a drawback, but in the era of IC-electronics this is no problem at all, since hundreds of thousands of transistors can be accommodated within the confines of a single chip. There is no doubt that digital signal processing will continue to prevail wherever feasible. However, in certain areas analogue signal processing remains indispensable or desirable. These areas will be outlined in the following section.

1.2 When and where analogue signal processing is needed

The outside world, as it presents itself to a human observer, is essentially of an analogue nature. Our senses are organized for communicating with this analogue world. The signals delivered by the sensors at the front end of an electronic signal-processing system are almost always in analogue format. Customarily, these signals are very weak and therefore prone to noise and interference. 'Noise' is the term generally used to indicate the stochastic variations that fundamentally accompany all physical processes. These stochastical phenomena are a direct consequence of the second law of thermodynamics, which implies that they cannot be avoided. Hence, any primary signal is contaminated with noise and any signal handling adds noise to the signal. The ratio of signal power to noise power is called the 'signal-to-noise ratio' (S/N). This quantity is a measure of the accuracy with which the information content of a signal can be recovered. The reduction of S/N that accompanies any signal processing is insignificant when signal power is large in comparison with the noise added by the signal handling. Hence, the weak primary signal delivered by the transducer has to be amplified at the earliest possible stage of the signal handling. Accurate and low-noise amplification is an important task of the interface electronics (Figure 1.1). This interface has to cope with analogue signals. Since sensor properties vary widely, depending on the type of transduction process involved, interface electronics circuitry must always be designed to measure. Standard solutions are rarely applicable. From the foregoing, it will be clear that low-noise design is at a premium at this stage. In fact it is of great importance in electronic design in general, and for this reason much attention is given to the topic in this book.

Having obtained robust signals, one can choose between digital or analogue processing, whichever is most practical in the relevant situation. At the rear end of the chain the signal is applied to an actuator or a display system. Frequently, the final presentation of the information will be in analogue format again, for instance a sound signal or an optical image. At this rear end interface, noise will rarely be a problem because signal power can be made large. Here, the main requirements are usually the accuracy and power efficiency of the information transfer. In summary, it can be stated that analogue signal processing is nearly always indispensable in the front end and the rear end sections of the signal-processing system. Moreover, these analogue parts have to comply with critical and application-specific requirements.

A further area in which analogue signal processing is and remains of the essence is in systems where spectral bandwidth is a fundamentally scarce commodity, as is the case in non-directed communications, such as broadcasting. Given the amount of information to be handled, a digital signal has a much larger spectral width than an analogue signal. According to information theory, the information capacity C of a communication channel is given by

$$C = B\,.\,{}^{2}\log\left(1 + \frac{S}{N}\right) \text{ bit s}^{-1} \tag{1.1}$$

where B is the bandwidth of the channel and S/N the ratio of signal power to noise power under the assumption of Gaussian noise. Conversion of an analogue signal to a digital signal implies a large increase in spectral width. As a consequence, the required capacity is obtained with low S/N. The analogue format requires minimum spectral bandwidth but, according to eq. (1.1), this implies that S/N should be high. Obviously, bandwidth and power can be exchanged within certain bounds and analogue signal processing minimizes bandwidth.

An important quantity related to signals and systems is the *dynamic range* of the signal involved.This is the ratio of the maximum and minimum signal levels that can occur. The maximum level that can be handled by a system is usually determined by its power handling capability; the minimum is determined by the noise with which the signal is contaminated. In certain systems the dynamic range encompassed by the signals to be processed can be quite large. An example is the signal delivered by an antenna for the medium wave broadcast band (bandwidth ≈ 1.5 MHz). The dynamic range in the relevant spectrum encompasses about 130 dB. The minimum signal level is on the microvolt level. Conversion into a digital signal would involve about 23 bits per sample, with the least significant bit at the level of, say, 10^{-7} V, which is far beyond present capabilities. A similar conclusion applies to the analogue-to-digital conversion of signals of extremely large spectral width. Bit rates in excess of some hundreds of Mbit s^{-1} are hardly feasible, given the present state of the art. The feasibility limit will increase in the course of time, but there will continue to be a limit.

Finally, note that in certain situations where, in principle, both digital and analogue signal processing are viable options, the analogue approach leads to much simpler solutions. The choice for the digital option implies the requirement of analogue-to-digital conversion (A/D-conversion), and vice versa. An accurate converter is a rather complex subsystem and its cost effectiveness can be disputed, particularly in cases where a modest amount of signal processing is required. Whether the analogue or the digital approach provides maximum cost effectiveness depends, of course, on the state of the art both in digital and in analogue techniques, and is, therefore, subject to change.

It is common practice to use the terms 'analogue electronics' and 'digital electronics'. Strictly speaking, digital electronics is a nonsense term in contrast to the term 'digital signal processing'. The latter applies to the system level where it is an appropriate indication of the signal format involved. Electronics is the art of manipulating electrons. On fundamental grounds, it is impossible to change the operation of an electronic device or circuit between two discrete states within an infinitely short time interval. Any change from the 0-state to the 1-state involves the passing of an infinitely large amount of intermediate states. In other words: during the transient from 0 to 1, the signal is a continuous-time or analogue signal. For the proper control of the transient situation, knowledge of analogue signal behaviour is indispensable. Admittedly, trying to banish the term 'digital electronics' would be an exercise in futility but, on the other hand, it must be stated that the designer of 'digital circuits' should be aware of the intricacies of transient behaviour, since these can to a large extent determine the ultimate performance of the designer's circuits.

1.3 Time domain and frequency domain

Any signal, whether analogue, sampled analogue or digital, is a function of time. In many cases it can and should be treated as such. Alternatively, a function of time can be described in an indirect way by applying a mathematical transform. One that has found widespread use is the Fourier transform. The Fourier transform $F(\omega)$ of a time-dependent signal $S(t)$ is defined by

$$F(\omega) = \int_{-\infty}^{+\infty} S(t) \exp(-j\omega t) \, dt \tag{1.2}$$

with the inverse transform

$$S(t) = \frac{1}{2\pi} \int_{-\infty}^{+\infty} F(\omega) \exp(j\omega t) \, d\omega \tag{1.3}$$

Equation (1.3) can be interpreted by stating that $S(t)$ is the superposition of an infinite number of sinusoidal signals with different frequencies. Thus the signal is represented by a spectral function. As has already been stated, the rate of change of a signal is always limited. In spectral terms this implies that the spectral bandwidth is limited. The relation between the two representations will be taken up again in Chapter 3.

The two ways of specifying signals have given rise to the terms *time domain representation* and *spectral domain* or *frequency domain representation*. One advantage of using the frequency domain approach is that, usually, the response of a circuit to a sinusoidal signal as a function of frequency is easily found. This applies to the majority of circuits of analogue electronics, and particularly to filter networks, modulators and frequency converters. The signal-processing operations that these last-mentioned circuits perform are essentially spectral manipulations. Describing their behaviour in terms of time domain signal processing usually leads to cumbersome calculations and formulas.

In frequency domain considerations, the quantity commonly used to specify frequency is the angular frequency ω. The relation between frequency f and angular frequency ω is $\omega = 2\pi f$. Strictly speaking, where ω is referred to, the term 'angular frequency' should be used. We will not stick to this tribute to accuracy in terminology. Instead, we will loosely use the term 'frequency' for either of the quantities f and ω, unless confusion would possibly be invoked by this mild form of sloppiness.

Readers who are not familiar with the various transforms used in signal theory are advised to consult one of the many textbooks dealing with this topic. For a quick refresher the compact survey in Gregorian and Themes (1986) may be useful.

1.4 Symbols and sign conventions

The conventions concerning the use of symbols in textbooks and papers are fairly well standardized, but in practice some variability can be observed. For the sake of completeness, a survey is given here on the conventions used in this book. Figure 1.3 shows the most important symbols used. For resistors, impedances and their reciprocals (conductor and admittance) the same symbol (Figure 1.3a) is used. Which meaning is applicable follows from the context. For the symbols used for field-effect transistors reference is made to Chapter 2. Wherever the type of field-effect transistor involved is irrelevant in principle, the general symbols of Figure 1.3g will be used. The symbols for voltage sources and for current sources are in agreement with international standardization, although many books and papers use alternative symbols. The symbols used here are logical and self-explanatory and they should therefore be preferred.

As to sign conventions: the plus- and minus-signs at the terminals of voltage sources or electronic circuits indicate which polarity is considered to be positive or negative. In order to prevent any confusion: plus does not mean 'this terminal is

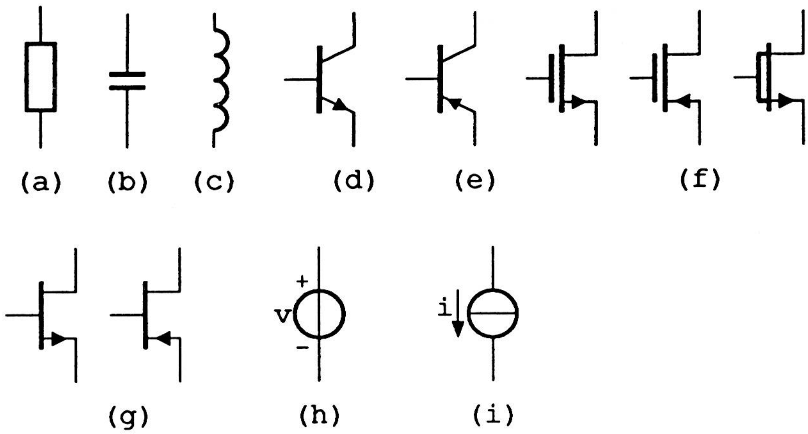

Fig. 1.3 *Symbols for circuit elements and electronic devices:* (a) *resistance or impedance;* (b) *capacitance;* (c) *inductance;* (d) *npn-bipolar transistor;* (e) *pnp-bipolar transistor;* (f) *various symbols for MOS field-effect transistors;* (g) *symbols for junction field-effect transistors and general symbols for field-effect transistors;* (h) *voltage source;* (i) *current source.*

positive with respect to the terminal carrying the minus sign', but rather 'if this terminal is positive with respect to the terminal with the minus sign, the voltage is labelled positive'. In like manner for currents: the direction of the arrow does not mean 'the current flows in the direction of the arrow', but rather 'if the current flows in the direction of the arrow it is labelled positive'. Further, in agreement with the conventions usually followed in treatments on circuit theory, positive current direction will be chosen to correspond with the direction *into* the network. Admittedly, this convention can lead to formulas that at first sight lack logic. Figure 1.4 gives a simple example. For this network,

$$\frac{i_o}{i_i} = -\frac{R_3}{R_2 + R_L + R_3}$$

hence, if $R_3 \to \infty$, $i_o/i_i = -1$, though it is obvious that the physical output current

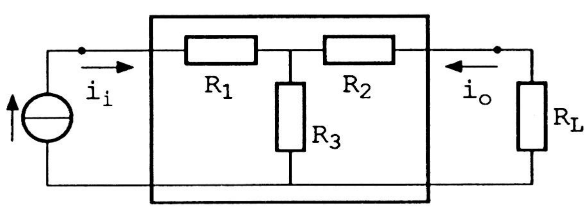

Fig. 1.4 *Current transfer in a simple resistive network.*