Analog Integrated Circuits and Signal Processing, 8, 115–120 (1995)

Design Principles for Low-Voltage Low-Power Analog Integrated Circuits

WOUTER A. SERDIJN, ALBERT C. VAN DER WOERD, ARTHUR H. M. VAN ROERMUND AND JAN DAVIDSE

Delft University of Technology, Faculty of Electrical Engineering, Electronics Research Laboratory Mekelweg 4, 2628 CD Delft, the Netherlands

W.A.Serdijn@et.tudelft.nl

Abstract. In this paper it is argued that there are good reasons to choose current as the information-carrying quantity in the case of low-voltage low-power design constraints. This paper focuses on the influence of the transfer quality on that choice. To obtain power-efficient transfer quality, indirect feedback is shown to be a good alternative to traditional feedback techniques.

Keywords: Low voltage, Low power, Integrated circuits, Design theory

Introduction

Low-voltage circuit techniques are applied in the area of battery-operated systems. For portability reasons, the size of the equipment must be small, which necessitates the maximum integration of the signal processing circuitry. However, as the size of batteries is now becoming the limiting factor, the reduction of the power dissipation has become an extra design constraint. As a consequence, the key point is to develop, simultaneously, both low-voltage (i.e. 1–1.5 V) and low-current (i.e. $< 100\ \mu$A) operating integrated circuits in order to reduce the battery size.

Another design criterion that must be fulfilled is transfer quality. This quality is influenced by two different kinds of errors: stochastic ones and systematic ones. By stochastic errors we mean inaccuracies in the input-output relation caused by noise or interference. Though impossible to eliminate, their influence can be minimized by a proper design strategy.

Systematic errors arise from network imperfections, such as offset, non-linearity, inaccuracy of the device parameters, drift and temperature dependence. Probably the most effective method to reduce their influence, and thus to obtain an accurate transfer function, is by means of applying negative feedback, which allows us to exchange the large gain provided by the (highly non-linear) active devices for quality provided by (usually linear) passive devices.

Design strategies for the reduction of stochastic errors and systematic errors are normally not consistent with design strategies which take into account power dissipation, voltage range and current range. Therefore, it is the combination of transfer quality, low voltage and low power that must be considered during the whole design process.

In the following sections, attention is paid to five design aspects that all have an important influence on the overall system transfer quality: the system's input and output signals, the signal processing inside the system, the available technology, the parasitics and the power supply. It is shown that current becomes more favorable than voltage as the information-carrying quantity in a low-voltage low-power environment.

System Requirements

The first step in the design process is to determine how the communication of the system with the external world, carried out by the source at the input and the load at the output, must be performed. Source and load are generally formed by other electronic systems or transducers. Depending on these, current or voltage (or a combination of these two), or linearly related quantities, such as charge or flux, must be chosen on the basis of the best reproducing relation to their physical input or output quantity [1].

The importance of choosing the correct source and load quantities can be illustrated by an example: a piezo-electric pressure transducer. A piezo-electric transducer, such as a piezo-electric microphone, converts pressure into charge. Since charge is linearly related to current ($i = dq/dt$), the output current of the sensor must be chosen as the electrical input quantity of the amplifier. The result is a charge amplifier. Yet, for many decades, voltage was chosen as

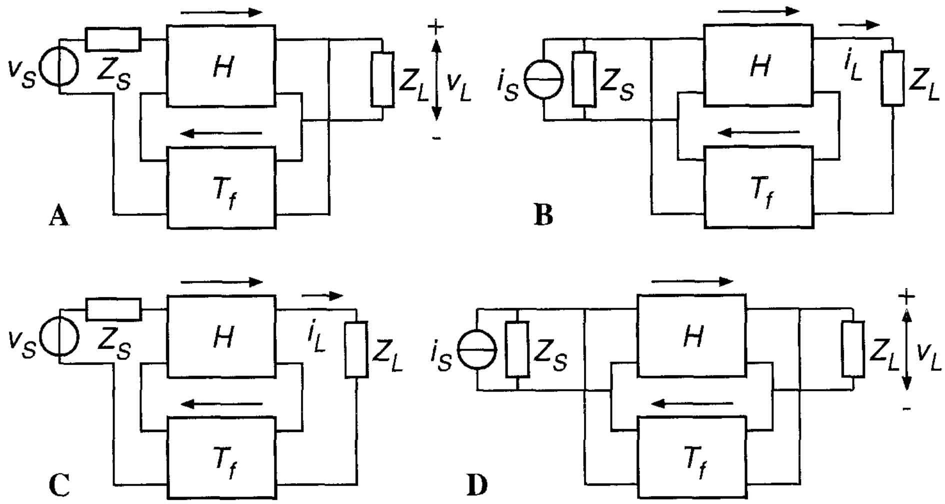


Fig. 1. Four basic direct negative-feedback amplifiers: a voltage amplifier (A), a current amplifier (B), a transconductance amplifier (C) and a transimpedance amplifier (D).

the information-carrying quantity—the amplifier being a voltage amplifier—which caused the piezo-electric microphone to be considered inferior to its magneto-dynamic counterpart.

Signal Processing

Assuming that the input and output quantities of the system have been determined by the foregoing system requirements, the next step in the design process is to decide which electrical quantities are best suited for a particular signal-processing function inside the system. When, e.g., signals coming from several subcircuits with a common terminal have to be added, current is a better choice for the information-carrying quantity than voltage. Currents can be added by simply connecting the output terminals of the subcircuits in parallel. When, however, a signal has to be distributed to several subcircuits, voltage is a better choice for the information-carrying quantity than current. Voltages can be distributed by simply connecting the input terminals of the subcircuits in parallel. For this reason, most of today's measurement instruments communicate by means of voltages, not currents.

Another example of choosing the correct electrical quantities is the use of a simple bipolar transistor when an exponential function over a wide range is required. Since the collector current is proportional to the exponent of the base-emitter voltage over a large range of collector currents, one device can do the job, if we are willing to choose voltage at the input and current at the output as the information-carrying quantity.

Indirect Feedback

As mentioned earlier, systematic errors can be reduced by means of negative feedback. Figure 1 shows the four basic ways of applying (single-loop) direct feedback by means of two two-ports. If all the transfer parameters of two-port H approach infinity, i.e., H is a nullor, the output signal (v_L or i_L) is related to the input signal (v_S or i_S) as the inverse transfer function of the feedback network T_f.

In low-voltage circuits, however, due to the restricted voltage swing, it is often not possible, or at least not preferable, to connect two ports of these two-port networks in series, thus to sense the output current or to compare the input voltage of a circuit directly. This occurs in configurations A (at the input), B (at the output) and C (at both input and output). Hence, all direct-feedback configurations, except the transimpedance amplifier (configuration D), are less suited for low-voltage applications.

To clarify the disadvantage of connecting two ports in series, let's consider the configuration shown in Figure 1B, of which a possible embodiment is given in Figure 2. Here, the two cascaded transistors Q_1 and Q_2 perform the nullor function while the feedback network is implemented by the resistive divider (R_1 and R_2). Clearly, the maximum output voltage swing, and

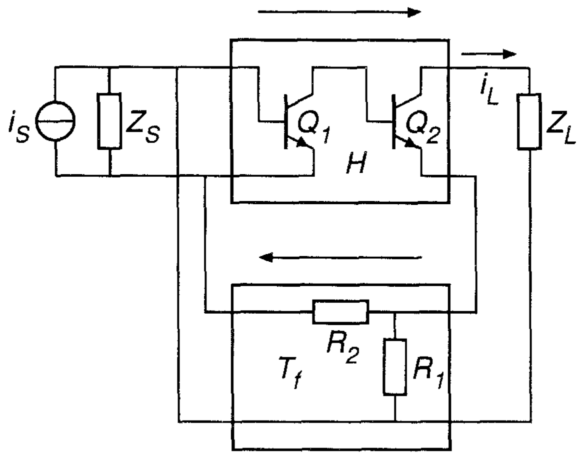


Fig. 2. Possible embodiment of a direct-feedback current amplifier. Transistors Q_1 and Q_2 perform the nullor function. The feedback network is implemented by resistors R_1 and R_2.

therefore the maximum output current swing, is limited by the supply voltage (not shown), the voltage across the output port of the nullor (the collector-emitter voltage of Q_2) and the voltage across the input port of the feedback network (R_1). There are similar problems related to the low supply voltage for the configurations shown in Figure 1A and C.

To realize voltage, current and transconductance amplifiers, a useful alternative to direct negative feedback may be a technique called indirect negative feedback. In an indirect-negative-feedback circuit, the output and/or the input stage is copied, so that it has an equivalent input-output relation, and the feedback signal is taken from and/or fed back to that copy. Thus, it is possible to obtain a circuit response which is determined by the feedback network only, assuming that the copying does not introduce errors. A voltage amplifier, a current amplifier and a transconductance amplifier, all using the indirect negative-feedback principle, are depicted in Figures 3, 4 and 5. It can be seen that series-connected ports are now avoided in all configurations.

Again, if all the transfer parameters of two-port T_r approach infinity, $T_2 = T_1$ and $T_4 = T_3$, the output signal (v_L or i_L) is related to the input signal (v_S or i_S) as the inverse transfer function of the feedback network T_f.

As an example of the advantage of using indirect negative feedback in low-voltage circuits, let's consider the configuration shown in Figure 4, of which a possible embodiment is given in Figure 6. Two cascaded transistors inside T_r perform the nullor function

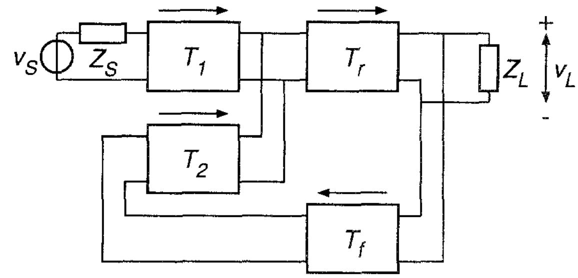


Fig. 3. A voltage amplifier with negative feedback and indirect voltage comparison.

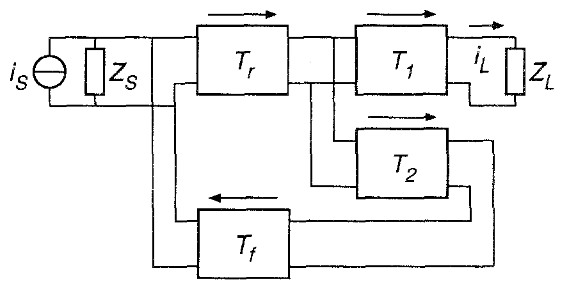


Fig. 4. A current amplifier with negative feedback and indirect current sensing.

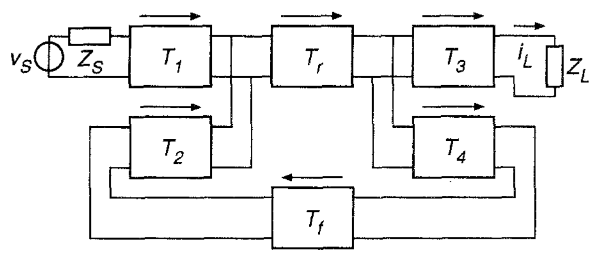


Fig. 5. A transconductance amplifier with negative feedback and indirect current sensing and indirect voltage comparison.

and the feedback network is implemented by the resistive divider (R_1 and R_2). The indirect outputs are provided by T_1 and T_2. Clearly, now the maximum output voltage swing, and therefore the maximum output current swing, is limited only by the supply voltage (not shown) and the voltage across the output port of T_1 (the collector-emitter voltage). Similar arguments hold for the configurations of Figure 3 and 5.

The Available Technology

As third step in the design process, we now investigate how applying indirect negative feedback relates to the choice of the electrical quantities inside the system. In

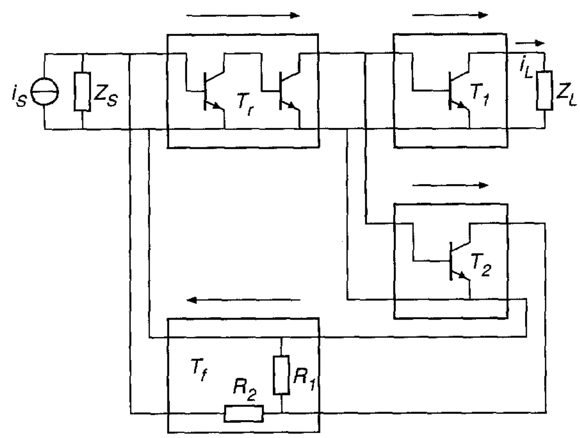


Fig. 6. Possible implementation of the indirect-feedback current amplifier. Two cascaded transistors inside T_r perform the nullor function. The feedback network is implemented by the resistive divider (R_1 and R_2). The indirect outputs are provided by T_1 and T_2.

electronic circuits, indirect voltage comparison results in a doubled power density spectrum of the equivalent noise voltage at the input, because the direct and indirect input are connected in series. Indirect current sensing results in a doubled power density spectrum of the noise current at the output, because the direct and indirect output are placed in parallel. In practice, often the noise is most critical at the input, so on that ground there may be a preference for current sensing and thus for current as the information-carrying quantity.

Another disadvantage of the use of voltage as the information-carrying quantity is that, when the circuits are 'voltage-driven', i.e., from a low-impedance source, the equivalent input noise voltage is predominantly the result of the input noise voltage of both input stages. For bipolar transistors and CMOS transistors in weak inversion, this input noise voltage is inversely proportional to the bias (collector or drain) current, and thus, in order to obtain a low input noise voltage, these bias currents must be rather large. This, of course, is in sharp contrast with our low-power requirement.

When, however, the circuits are 'current-driven', thus with a high impedance, the equivalent input noise current is mainly determined by the input noise current of the input stage. Since the input noise current of bipolar transistors and CMOS transistors in weak inversion is proportional to the bias current, this calls for small bias currents, which is in line with the low-power requirement. This favors the choice of current as the information-carrying quantity.

A third disadvantage of indirect voltage comparison is that, in order to compensate each other, the nonlinearities of the two input stages must be *symmetrical* or *opposite*, because the sum of their output currents must be nullified by the nullor. In practice, this requires either two balanced input stages or two complementary stages in a complementary IC process. The use of two balanced input stages, since their input noise voltages are placed in series, again doubles the power density spectrum of the equivalent input noise voltage. A complementary IC process is often not available and, moreover, exact complementarity can never be accomplished.

Indirect feedback at the output, however, calls for two *identical* output stages, to compensate for the nonlinearities. These can easily be made in any ordinary IC process. For this reason there again may be a preference for current sensing and thus for current as the information-carrying quantity.

Parasitics

Let us now, as fourth step in our design considerations, address the influence of parasitic immitances. The influence of parasitic *admittances* in parallel with the signal path can be reduced by terminating the signal path with a *low* impedance. The parasitic admittances then have no voltages across their terminals and thus no current flows in them. The influence of parasitic *impedances* in series with the signal path can be reduced by terminating the signal path with a *high* impedance. Then no current flows in the parasitic impedances and thus there is no voltage across their terminals.

In low-power integrated circuits, often the parasitic admittances, i.e., the node capacitances, e.g., the transistors' junction capacitances, due to their (non-linear) voltage dependency, have more influence on the signal behavior than the parasitic impedances, i.e., the branch inductances and resistances, e.g., the transistors' bulk resistances. Therefore it is convenient to terminate the signal paths with low impedances as much as possible. In this situation it is best to choose current as the information-carrying quantity.

This argument is also at the base of the popularity of 'current-mode', 'switched-current' and 'switched-transconductance' techniques [2], [3], [4], of which it is rightly stated that they have an inherent ability to exhibit good high-frequency properties.

Power Supply

Finally, we have to consider the power supply. In practice, this power supply is a voltage source (battery), giving a limitation in voltage. The limitation in current is only indirectly given by a limitation in the power of the battery and might be less restricting than that of the voltage. This favors the choice of current as the information-carrying quantity. However, not using the total range of this supply voltage for signal swing gives rise to waste of power [5].

Conclusions and Applications

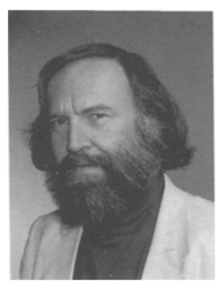
From the above discussion it will be clear that for low-voltage low-power analog ICs the total design process must be considered, in which transfer quality plays a dominant role. The theory was verified in several practical applications, such as circuits for hearing instruments, which, for the sake of brevity, cannot be discussed here. See, e.g., [6]–[8]. Our designs, based on the design principles shown above, confirm that current becomes more favorable than voltage as the information-carrying quantity and that indirect feedback is to be preferred in a low-voltage low-power environment.

References

1. E. H. Nordholt, *Design of High-Performance Negative-Feedback Amplifiers*, Elsevier: Amsterdam, 1983.
2. C. Toumazou, F. J. Lidgey and D. G. Haigh (eds.), *Analogue IC Design: The Current-Mode Approach*, Peter Peregrinus: London, 1990.
3. C. Toumazou, J. B. Hughes and N. C. Battersby (eds.), *Switched Currents: An Analogue Technique for Digital Technology*, Peter Peregrinus: London, 1993.
4. C. Toumazou and N. C. Battersby, "Switched-transconductance techniques: A new approach for tuneable, precision analogue sampled-data signal processing," in *Proc. IEEE ISCAS*, Chicago, May 1993.
5. E. A. Vittoz: "Low-power design: ways to approach the limits," in *Proc. IEEE ISSCC*, February 1994, pp. 14–18.
6. A. C. van der Woerd and W. A. Serdijn: "Low-voltage low-power controllable preamplifier for electret microphones," *IEEE J. Solid-State Circuits* vol. 28 no. 10 pp. 1052–1055, October 1993.
7. W. A. Serdijn, A. C. van der Woerd, J. Davidse and A. H. M. van Roermund, "A low-voltage low-power fully-integratable automatic gain control for hearing instruments," *IEEE J. Solid-State Circuits* vol. 29 no. 8, August 1994, pp. 943–946.
8. W. A. Serdijn, "The design of low-voltage low-power analog integrated circuits and their applications in hearing instruments," Delft University Press, Delft, 1994.

Wouter Serdijn was born in Zoetermeer, the Netherlands, in 1966. He started his course at the Faculty of Electrical Engineering at the Delft University of Technology in 1984, and received his 'ingenieurs' (M.Sc.) degree in 1989.

Subsequently, he joined the Electronics Research Laboratory of the same university where he received his Ph.D. in 1994. His research includes developing a formal design theory for low-voltage low-power analog integrated circuits along with the development of circuits for hearing instruments.

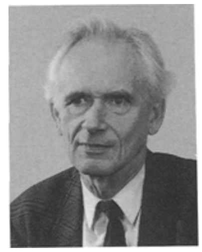


Albert C. van der Woerd was born in 1937 in Leiden, the Netherlands. In 1977 he received his 'ingenieurs' (M.Sc.) degree in electrical engineering from the Delft University of Technology, Delft, the Netherlands. He was awarded Ph.D. in 1985.

From 1959 to 1966 he was engaged in research on and development of radar and TV circuits at several industrial laboratories. In 1966 he joined the Electronics Research Laboratory of the Faculty of Electrical Engineering of the Delft University of Technology. During the first 11 years he carried out research on electronic musical instruments. For the next 8 years his main research subject was carrier domain devices. More recently he has specialized in the field of low-voltage low-power analog circuits and systems. He teaches design methodology.

Arthur H. M. van Roermund was born in Delft, The Netherlands in 1951. He received his M.Sc. degree in Electrical Engineering in 1975 from the Delft University of Technology and his Ph.D. in Applied Sciences from the K. U. Leuven, Belgium, in 1987.

From 1975 to 1992 he was with the Philips Research Laboratories in Eindhoven. First he joined the Consumer Electronics Group, where he has been involved with the design and integration of analog circuits and systems, especially switched-capacitor circuits. In 1987 he joined the Visual Communications Group where he has been engaged in video architectures and digital video signal processing. From 1987 to 1990 he was project leader of the Video Signal Processor project and from 1990 to 1992 of a Multi-Window Television project. Since 1992 he is a full professor at the Faculty of Electrical Engineering of the Delft University of Technology. He heads the Electronics Laboratory, which is part of DIMES: the Delft Institute of Micro Electronics and Submicron Technology.



Jan Davidse received his M.Sc. degree in Electrical Engineering from the Delft University of Technology in 1953 and subsequently his Ph.D. from the Eindhoven University of Technology.

He was research scientist with Philips Research Laboratories and received a full professorship in electronics at the Delft University of Technology in 1964. From 1964 to the present, he has been head of the Laboratory for Electronics at this university. He is the author of numerous papers and holds several patents in his field of interest. He is the author of ten books, among which is Analog Electronic Circuit Design, Englewood Cliffs, N.J.: Prentice Hall, 1991.