1.1 Low-voltage ultra-low-power analog IC design principles

Design principles for low-voltage low-lower analog integrated circuits

by Wouter A. Serdijn

Today's problem

- *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.
- ⇒The combination of *transfer quality, low voltage and low power* must be considered during the whole design process.

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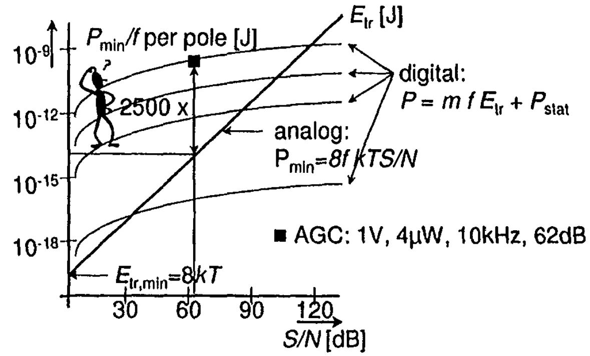
Today's challenge



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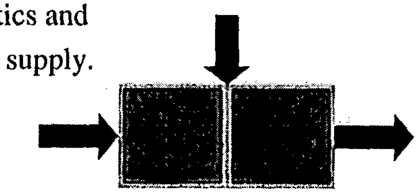
Considerations

- the system's input and output signals,
- the signal processing inside the system,
- the circuit topology,
- the parasitics and
- the power supply.



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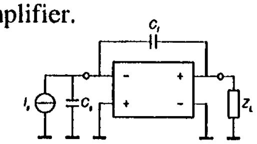
Source and load quantities

Example (I): a piezo-electric pressure transducer

- 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.



Choose the correct source and load quantities

Example (II): an electret microphone

- voltage sensing
  $Q_{quiescent} = Q_{active}$
  $CU_0 = (C + \delta C)(U_0 + \delta U)$
  $u_{mikro} = -\delta U = \frac{U_0 \delta C}{C + \delta C}$
- current sensing; virtual ground
  $U_0 = Q_0 / C = Q/C|_{active}$
  $Q_0 / C = \frac{Q_0 + \delta Q}{C + \delta C}$
  Charge amplifier yields:
  $u_{out} = \frac{U_0 \delta C}{C_{amplifier}}$
- Since $\delta C << C$, none of both methods is (theoretically) preferred above the other. *Current* sensing is less disturbed by cable capacitances and is therefore preferred in practice

Signal processing inside the system

Which electrical quantities are best suited for a particular signal-processing function inside the system?

- addition/subtraction ⇒ *currents*
- distribution ⇒ *voltages*
- desired non-linear transfer of devices ⇒ *interplay of current and voltages*

Accurate transfer (I): direct feedback

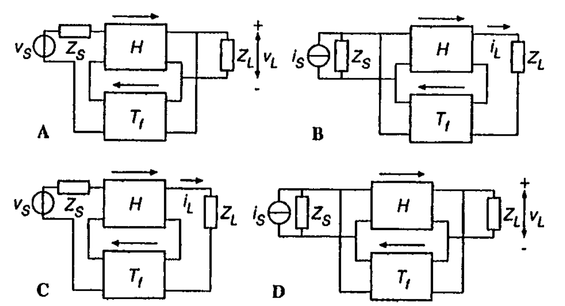


Figure 1. Four basic direct negative-feedback amplifiers: a voltage amplifier (A), a current amplifier (B), a transconductance amplifier (C) and a transimpedance amplifier (D)

Example

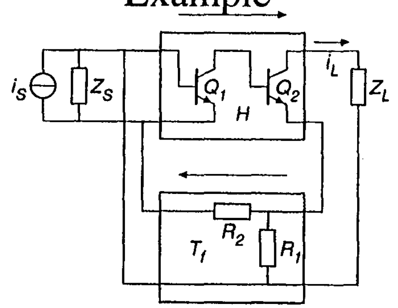


Figure 2. Possible embodiment of a direct-feedback current amplifier. Transistors Q_1 and Q_2 perform the nullor function. The feedback network is implemented by resistors R_1 and R_2.

Accurate transfer (II) at low supply voltage: indirect feedback (I)

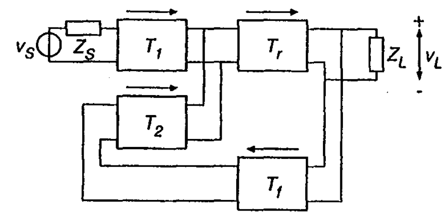


Figure 3. A voltage amplifier with negative feedback and indirect voltage comparison

Indirect feedback (II)

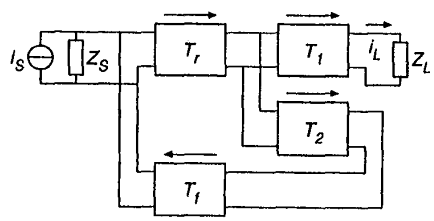


Figure 4. A current amplifier with negative feedback and indirect current sensing

Indirect feedback (III)

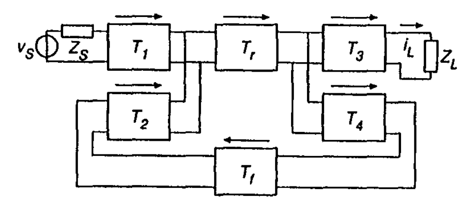


Figure 5. A transconductance amplifier with negative feedback and indirect current sensing and indirect voltage comparison

Example

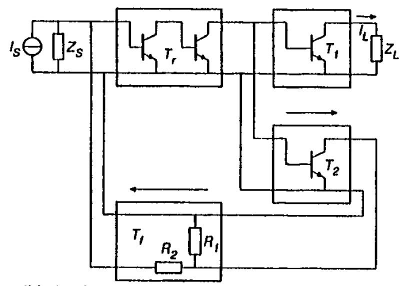
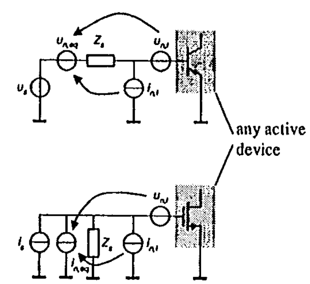


Figure 6. Possible implementation of the indirect-feedback current amplifier. Two cascaded transistors inside T_r perform the nullor function. The feedback network is implemented by the resistive divider (R_1 and R_2). The indirect outputs are provided by T_1 and T_2.

Noise



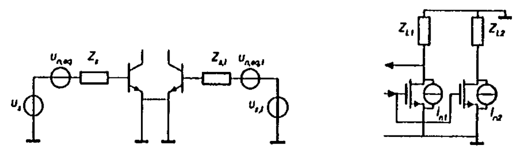
$$u_{n,eq} = u_n + i_n Z_s$$

$$i_{n,eq} = \frac{u_n}{Z_s} + i_n$$

$|Z_s| \downarrow 0 : u_n$ dominates

$|Z_s| \to \infty : i_n$ dominates

Circuit topology (I)



- *Indirect voltage comparison* results in a doubled power density spectrum of the equivalent noise voltage at the *input*.
- *Indirect current sensing* results in a doubled power density spectrum of the noise current at the *output*.
- In many situations, the noise at the input is more important than the noise at the output (e.g., in an LNA) ⇒ preference for the choice of *current* as the information-carrying quantity.

Circuit topology (II)

- When the circuits are *voltage-driven*, i.e., from a low-impedance source, using *indirect voltage comparison*, 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*.
- When the circuits are *current-driven*, i.e., from a high-impedance source, using *indirect current sensing*, the equivalent input noise current is predominantly the result of the input noise *current* of *only one* input stage. For bipolar transistors, this input noise current is proportional to the bias (collector) current, and thus, in order to obtain a low input noise *current*, this bias current must be rather *small*.
- ⇒ preference for the choice of *current* as the information-carrying quantity.

Circuit topology (III)

- Another disadvantage of *indirect voltage comparison* is that, in order to compensate each other, the non-linearities 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 non-linearities. 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.

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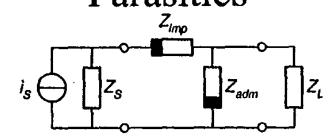
Parasitics



- 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.

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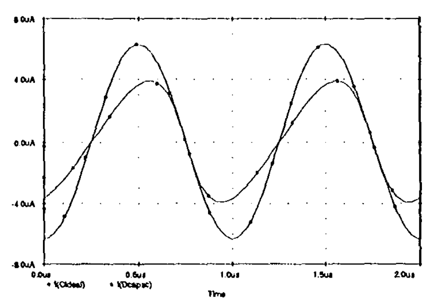
Example of a parasitic admittance: a junction capacitance



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Parasitics, cont'd

- 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.
- ⇒ terminate the signal paths with low impedances as much as possible ⇒ choose *current* as the information-carrying quantity.

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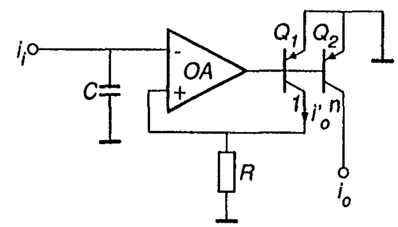
Power supply

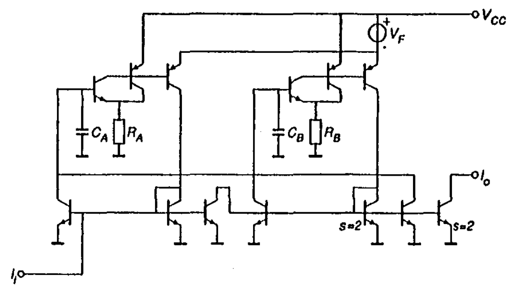
- In practice, the power supply is a voltage source (battery), giving a limitation in voltage.
- The limitation in current is only indirectly given by a limitation in the energy of the battery and might be less restricting than that of the voltage.
- This favors the choice of *current* as the information-carrying quantity.

Application: integrators in filters (I)

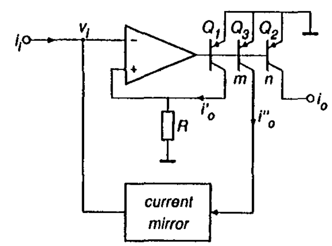


$$\frac{i_o}{i_i} = \frac{n}{j\omega RC}$$

Application: integrators in filters (II)



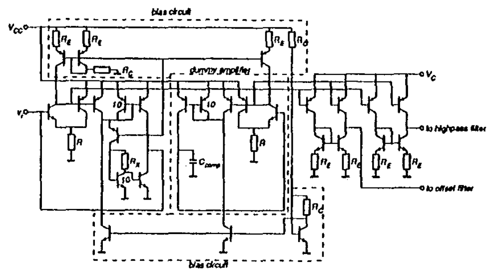
Application: a controlled microphone preamplifier (I)



$$R_i = \frac{v_i}{i_i} = \frac{R}{m}$$

$$G = \frac{i_o}{v_i} = \frac{n}{R}$$

Application: a controlled microphone preamplifier (II)



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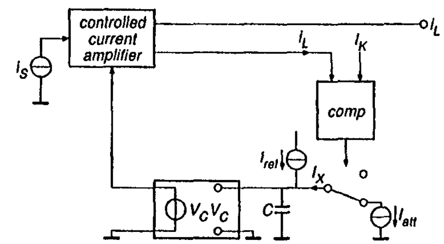
Application: an automatic gain control (I)



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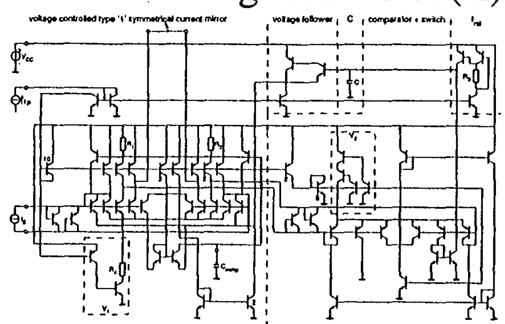
Application: an automatic gain control (II)



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Circuit principles

1. Dynamic Translinear Circuits
2. Switched MOSFET technique

⇒ further on