tegengekoppelde configuraties nauwkeurig te kunnen versterken worden *operationele versterkers* genoemd. Ze danken hun naam uit de tijd van de analoge computers, toen rekenbewerkingen (operaties) werden uitgevoerd met behulp van tegengekoppelde versterkers, waarvan de versterking nauwkeurig vast moest liggen.

De signalen s_g en s_o kunnen zowel stromen als spanningen voorstellen en we zullen nu onze beschouwen richten op het realiseren van de vier nauwkeurige overdrachten die hieruit voorvloeien.

6.3.5 The nullor

An important elementary active twoport that can be considered to be the ideal networktheoretical equivalent of the abovementioned high-gain amplifier A is the *nullor.* For a nullor, it holds that all four chain parameters A, B, C and D equal zero; the transfer parameters μ, γ, ζ and α are thus infinite. In case of finite output quantities u_o and i_o, the input quantities of the nullor, as a consequence, equal zero. Figure 6.10 depicts the used nullor symbol. From Equation 4.22 – 4.25 it follows that a nullor is not suitable to be used as an accurate amplifier. However, since the transfer parameters are infinitely large, the nullor is the obvious twoport to be used as the active part in a negative-feedback configuration. In the next subsection, we find that, by means of an amplifier with nullor properties and a feedback network consisting of passive network elements, always one of the four transfers can be determined accurately. It will be shown that of each of the by means of negative feedback created new twoports, one of the transfer quantities is determined accurately by the passive network elements, while the other three remain (infinitely) large and inaccurate.

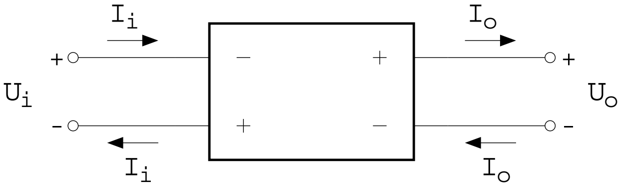

Figure 6.10: Used nullor symbol and its signal orientations.

6.3.6 Negative-feedback amplifier configurations

Passive two-port network elements that can be employed as feedback networks are

- the transformer,
- the gyrator,
- twoports that are constructed with one-port network elements, such as resistances, capacitances, inductances and diodes

Transformers are often overlooked since as components they are relatively expensive, not easily integrated onto silicon and do not pass dc. However, transformers ideally do not introduce noise, consume no power and therefore do play a role in radio-frequency (RF) circuits as can be found in today's and future wireless communication systems. Their transfer function can be described by

$$u_i = \frac{1}{n} \cdot u_o \tag{6.28}$$

$$i_i = n \cdot i_o \tag{6.29}$$

or

$$\begin{pmatrix} u_i \\ i_i \end{pmatrix} = \begin{pmatrix} \frac{1}{n} & 0 \\ 0 & n \end{pmatrix} \begin{pmatrix} u_o \\ i_o \end{pmatrix} \tag{6.30}$$

n being the ratio of the number of turns at the secondary side and the number of turns at the primary side, respectively.

Employing the transformer's accurate relation between input and output voltage or between input and output current, respectively, in a feedback configuration, it is thus possible to realize accurate voltage gain or current gain, respectively.

Similarly, if gyrators would exist as components, they would allow the realization of accurate voltage-to-current (transadmittance) and current-to-voltage (transimpedance) transfers.

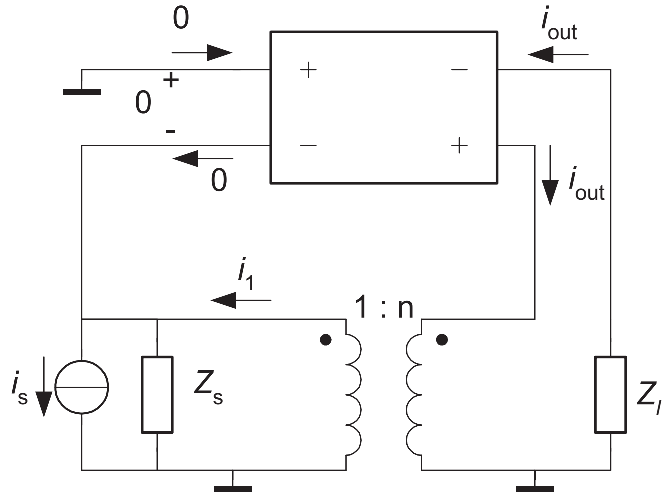

Figure 6.11: Negative-feedback current amplifier employing a transformer in its feedback path.

Figure 6.11 depicts the basic configuration of a negative-feedback current amplifier that employs a transformer in its feedback path. Its operation can be analyzed as follows. The output current i_{out} flows from the positive output terminal of the nullor, via the secondary side of the transformer (at right), via the load Z_l to the negative output terminal of the nullor. At the primary side of the transformer (at left), an n-times larger current is generated. Since the input *voltage* of a nullor equals zero, no current flows through the source impedance Z_s. As also the input *current* of a nullor equals zero, apparently the source current i_s and the primary current add up to zero. It therefore holds:

$$i_s = n \cdot i_{\text{out}} \tag{6.31}$$

and thus:

$$\frac{i_{\text{out}}}{i_s} = \frac{1}{n} \tag{6.32}$$

Note that indeed *negative* feedback is applied here, since the signals present at the *positive* output terminal and the *negative* input terminal of the nullor have identical signs. Note also that, since the input voltage of the current amplifier remains zero, the input impedance of the current amplifier equals zero, as should be for an ideal current amplifier. The source impedance Z_s thereby has no influence on the transfer function. Finally, note that the output current is independent of the load Z_l. The current amplifier thus has the desired infinite output impedance, as discussed in Section 4.4.

Often, however, the feedback network is composed of a combination of one-port network elements, such as resistances, capacitances, inductances and diodes.

The voltage-to-voltage converter or voltage amplifier

In the configuration depicted in Figure 6.12a, a fraction of the voltage u_l that appears across the load R_l, by means of a parallel connection at the output and a series connection at the input, is fed back to the input. The relevant transfer quantity is μ_t (index t denoting "tegenkoppeling," i.e., feedback), defined to be:

$$\mu_t = \frac{1}{A_t} = \frac{u_{o,t}}{u_{i,t}} ||_{i_{o,t}=0} \tag{6.33}$$

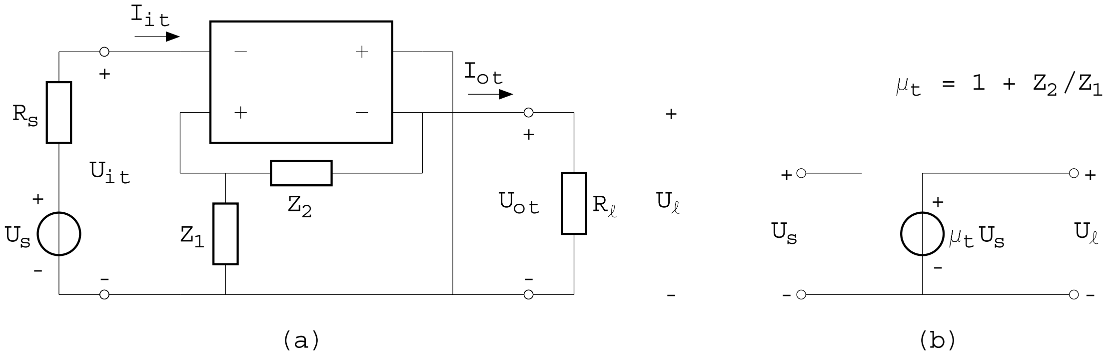

Figure 6.12: a. Negative-feedback voltage amplifier employing an impedance network in its feedback path; b. voltage-controlled voltage source.

Because of the nullor operation ($u_i = 0$ and $i_i = 0$), for $i_{o,t} = 0$ (assume $R_l = \infty$) it holds:

$$u_{i,t} = \frac{Z_1}{Z_1 + Z_2} \cdot u_{o,t} \tag{6.34}$$

and therefore

$$\mu_t = \frac{1}{A_t} = 1 + \frac{Z_2}{Z_1} \tag{6.35}$$

which is well defined by the passive feedback network. For the remaining chain parameters one readily finds: $B_t = C_t = D_t = 0$. The input and output impedances equal infinity and zero, respectively. This means that the amplifier does not load the source at all and acts like a voltage-controlled voltage source, as depicted in Figure 6.12b. In the special case that $Z_1 = \infty$ and/or $Z_2 = 0$, the voltage gain u_l/u_s becomes equal to 1 and one speaks of a *voltage follower.*

The voltage-to-current converter or transadmittance amplifier

In the configuration depicted in Figure 6.13a, the current i_l that flows through the load R_l, by means of series connections at both output and input, is converted into a voltage by impedance Z and fed back to the input. The relevant transfer quantity is γ_t, defined to be:

$$\gamma_t = \frac{1}{B_t} = \frac{i_{o,t}}{u_{i,t}} ||_{u_{o,t}=0} \tag{6.36}$$

Because of the nullor operation ($u_i = 0$ and $i_i = 0$), for $u_{o,t} = 0$ (assume $R_l = 0$) it holds:

$$u_{i,t} = -Z \cdot i_{o,t} \tag{6.37}$$

and therefore

$$\gamma_t = \frac{1}{B_t} = -\frac{1}{Z} \tag{6.38}$$

which is well defined by the passive feedback network. For the remaining chain parameters one readily finds: $A_t = C_t = D_t = 0$. The input and output impedances equal both infinity. This means that the amplifier does not load the source at all and acts like a voltage-controlled current source, as depicted in Figure 6.13b.

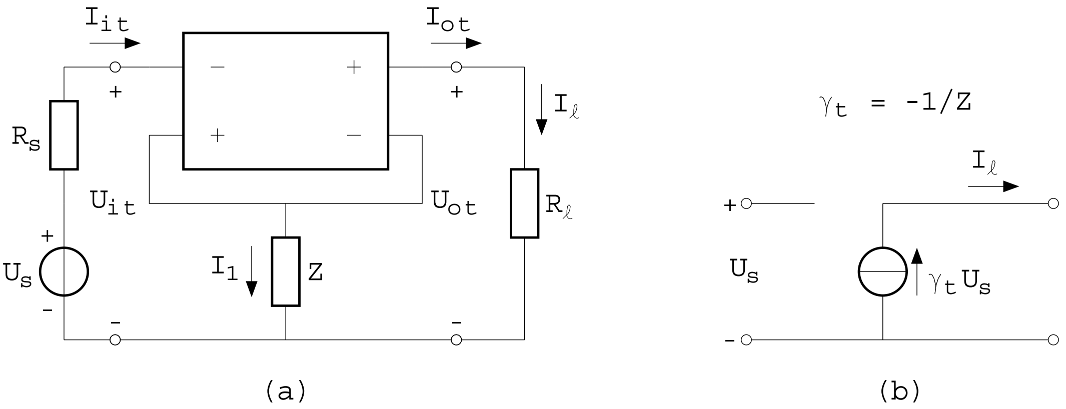

Figure 6.13: a. Negative-feedback transadmittance amplifier employing an impedance in its feedback path; b. voltage-controlled current source.

The current-to-voltage converter or transimpedance amplifier

In the configuration depicted in Figure 6.14a, the voltage u_l across the load R_l, by means of parallel connections at both output and input, is converted into a current by impedance Z and fed back to the input. The relevant transfer quantity is ζ_t, defined to be:

$$\zeta_t = \frac{1}{C_t} = \frac{u_{o,t}}{i_{i,t}} ||_{i_{o,t}=0} \tag{6.39}$$

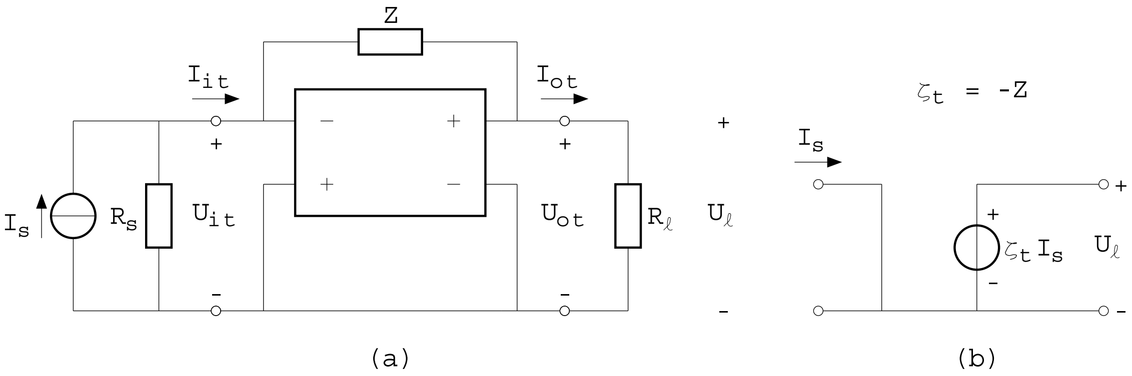

Figure 6.14: a. Negative-feedback transimpedance amplifier employing an impedance in its feedback path; b. current-controlled voltage source.

Because of the nullor operation ($u_i = 0$ and $i_i = 0$), for $i_{o,t} = 0$ (assume $R_l = \infty$) it holds:

$$i_{i,t} = -1/Z \cdot u_{o,t} \tag{6.40}$$

and therefore

$$\zeta_t = \frac{1}{C_t} = -Z \tag{6.41}$$

which is well defined by the passive feedback network. For the remaining chain parameters one readily finds: $A_t = B_t = D_t = 0$. The input and output impedances equal both zero. This means that the amplifier does not load the source at all and acts like a current-controlled voltage source, as depicted in Figure 6.14b.

The current-to-current converter or current amplifier

In the configuration depicted in Figure 6.15a, a fraction of the current i_l that flows through the load R_l, by means of a series connection at the output and a parallel connection at the input, is fed back to the input. The relevant transfer quantity is α_t, defined to be:

$$\alpha_t = \frac{1}{D_t} = \frac{i_{o,t}}{i_{i,t}}||_{u_{o,t}=0} \tag{6.42}$$

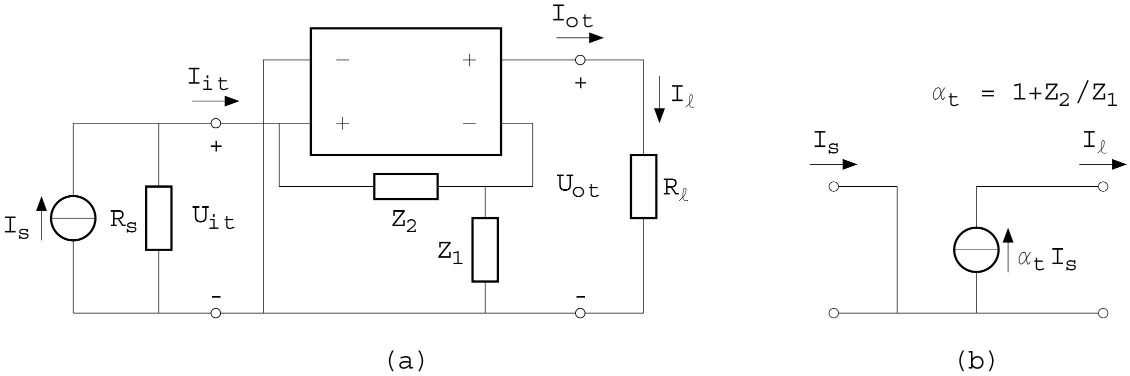

Figure 6.15: a. Negative-feedback current amplifier employing an impedance network in its feedback path; b. current-controlled current source.

Because of the nullor operation ($u_i = 0$ and $i_i = 0$), for $u_{o,t} = 0$ (assume $R_l = 0$) it holds:

$$i_{i,t} = \frac{Z_1}{Z_1 + Z_2} \cdot i_{o,t} \tag{6.43}$$

and therefore

$$\alpha_t = \frac{1}{D_t} = 1 + \frac{Z_2}{Z_1} \tag{6.44}$$

which is well defined by the passive feedback network. For the remaining chain parameters one readily finds: $A_t = B_t = C_t = 0$. The input and output impedances equal zero and infinity, respectively. This means that the amplifier does not load the source at all and acts like a current-controlled current source, as depicted in Figure 6.15b. In the special case that $Z_1 = \infty$ and/or $Z_2 = 0$, the current gain i_l/i_s becomes equal to 1 and one speaks of a *current follower*.

6.4 Learning objectives

After studying this chapter, the student:

1. is able to distinguish between linear and nonlinear with respect to components, networks and transfer functions
2. understands how a harmonic signal that passes through a nonlinear transfer function yields higher harmonics
3. is able to calculate the distortion of a signal, comprising first and higher harmonics
4. knows and understands the concept of additive and multiplicative compensation and negative feedback to linearize amplifiers
5. knows, understands and is able to apply the concept of negative feedback in general (Black's model)