ELEC-E3530

Integrated Analog Systems L4
SC Ladder Filters

SC-ladder filters

- The LC-ladder filters' sensitivity for component spread is zero at the maximum of the transfer function

- Close to the maximum the sensitivity is relative to the reflection coefficient i.e. sensitivity is small

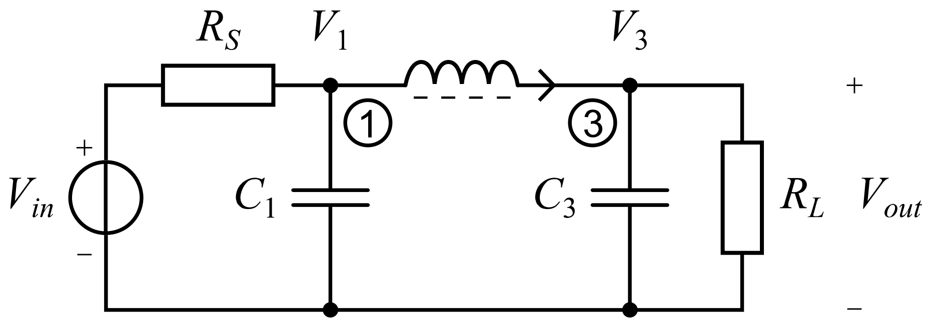
- Sensitivity for the source and load resistors (R_s=R_L) spread is constant i.e. frequency independent constant error

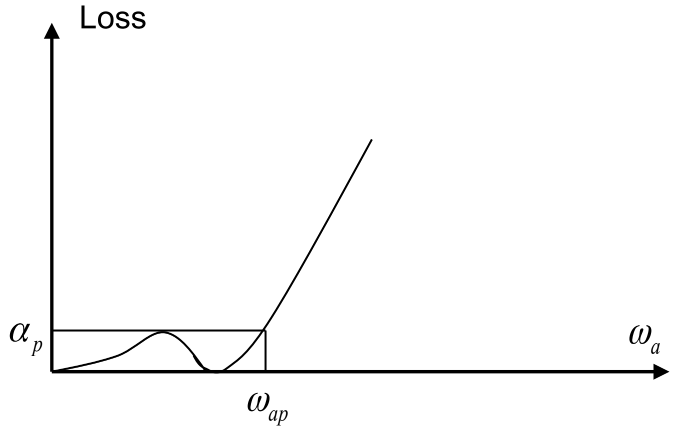
⇒ filters with a high Q value can be implemented

The LC-filter's sensitivity characteristics will be inherited by the SC equivalent IF

1) the transfer functions are the same

2) the filters coefficients will be determined by one-to-one mapping

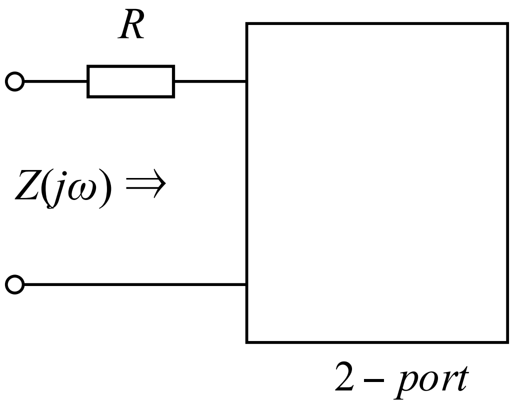




Losses in the LC-two ports

$$\varepsilon_L(\omega) = 1 - \frac{\Delta L}{L} + j\frac{1}{Q(\omega)}$$

$$Q(\omega) = \frac{\omega L}{R_L}$$

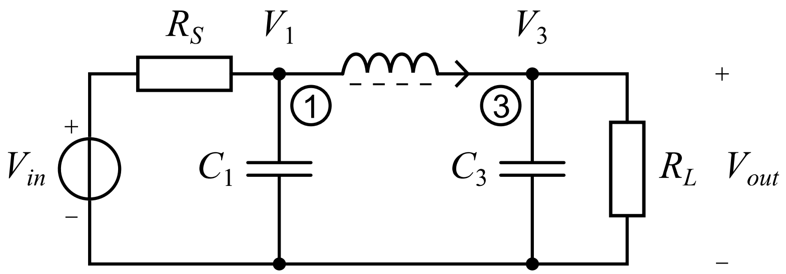


The attenuation on the pass-band:

$$\left|\Delta a(\omega)\right| < \frac{\left|\varepsilon_{L1} cr(\omega)\right|}{1 - \left|r(\omega)\right|^2}\,\omega i(\omega)$$

$$r(\omega) = \frac{z(j\omega) - R}{z(j\omega) + R}$$

$i(\omega)$ = group delay time
$r(\omega)$ = reflection coefficient



Active SC integrator:

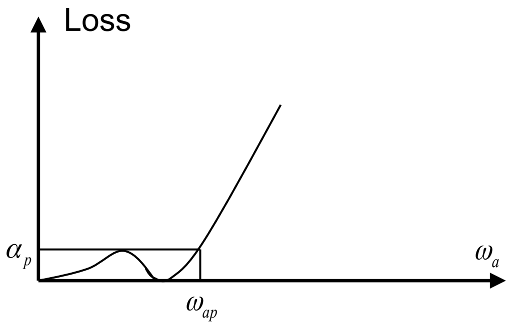
$$H\left(e^{j\omega T}\right) = \frac{1}{j\omega R x_i}\left(1 + m(\omega)\right)e^{jp(\omega)}$$

$$\approx \frac{1 + m(\omega) + jp(\omega)}{j\omega R x_i}$$

$m(\omega)$ = gain error
$p(\omega)$ = phase error

$$\Rightarrow m(\omega) \Rightarrow -\frac{\Delta L}{L}$$

$$p(\omega) \Rightarrow -\frac{1}{Q_L(\omega)}$$



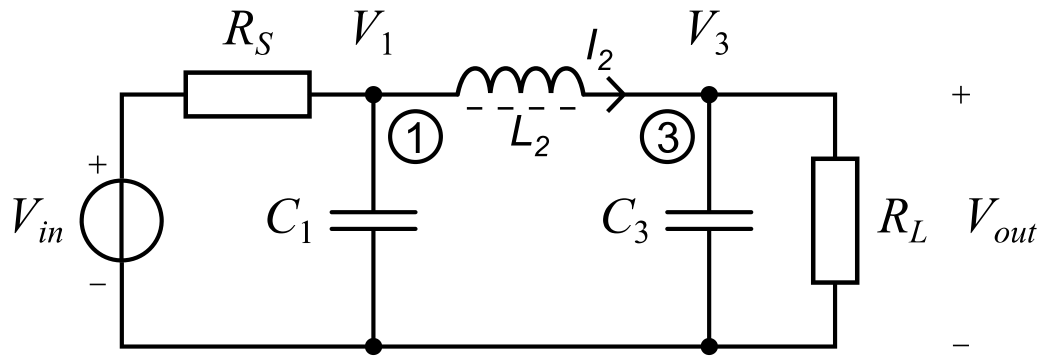
Ladder filter design

For a capacitor:

$$V_c(s) = \frac{1}{sC} I_c(s)$$

For an inductor:

$$I_L(s) = \frac{1}{sL} V_L(s)$$



- Thus the capacitor voltage is obtained by integrating the capacitor current.
- The inductor current is obtained by integrating the inductor voltage

$\Rightarrow$ select the state variables to be

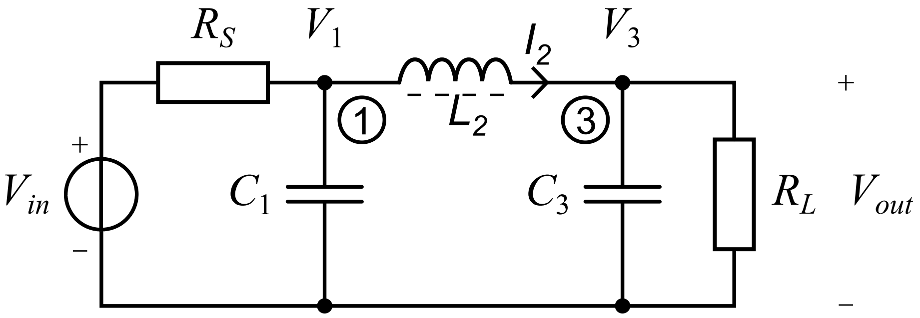
* the capacitor voltage

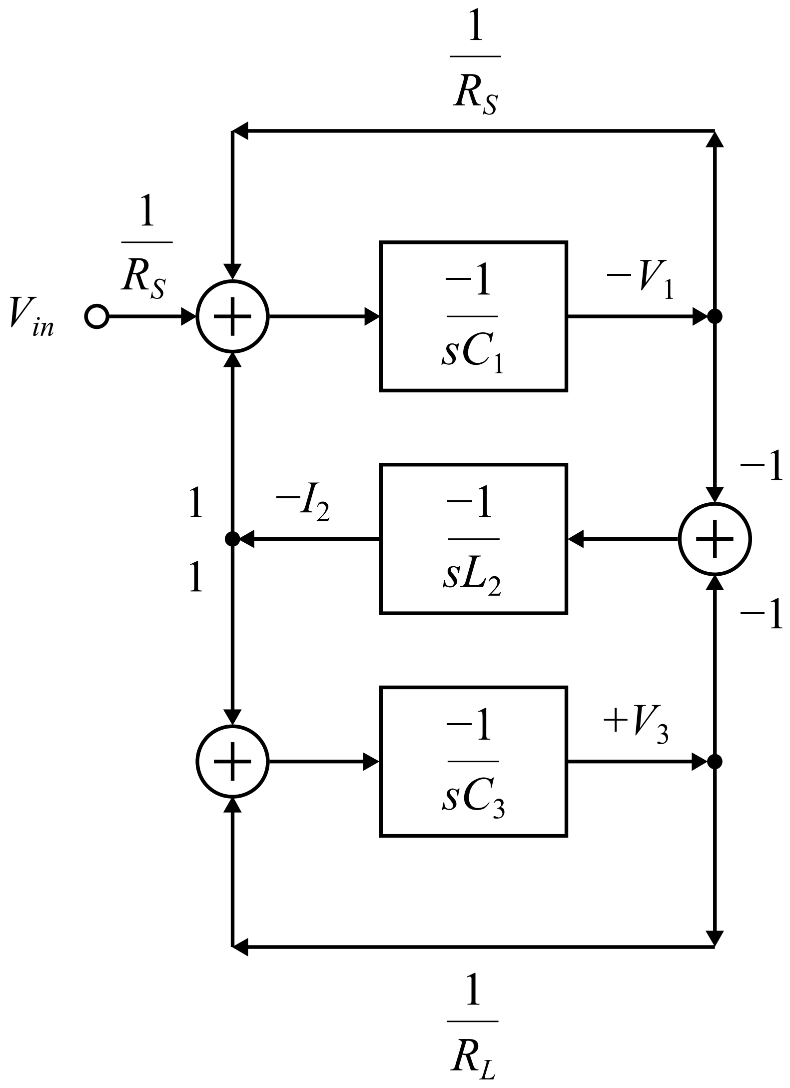
* the inductor current

We select the state variables to be:

V_1, I_2, V_3

Signal-flow graph





The state equations are:

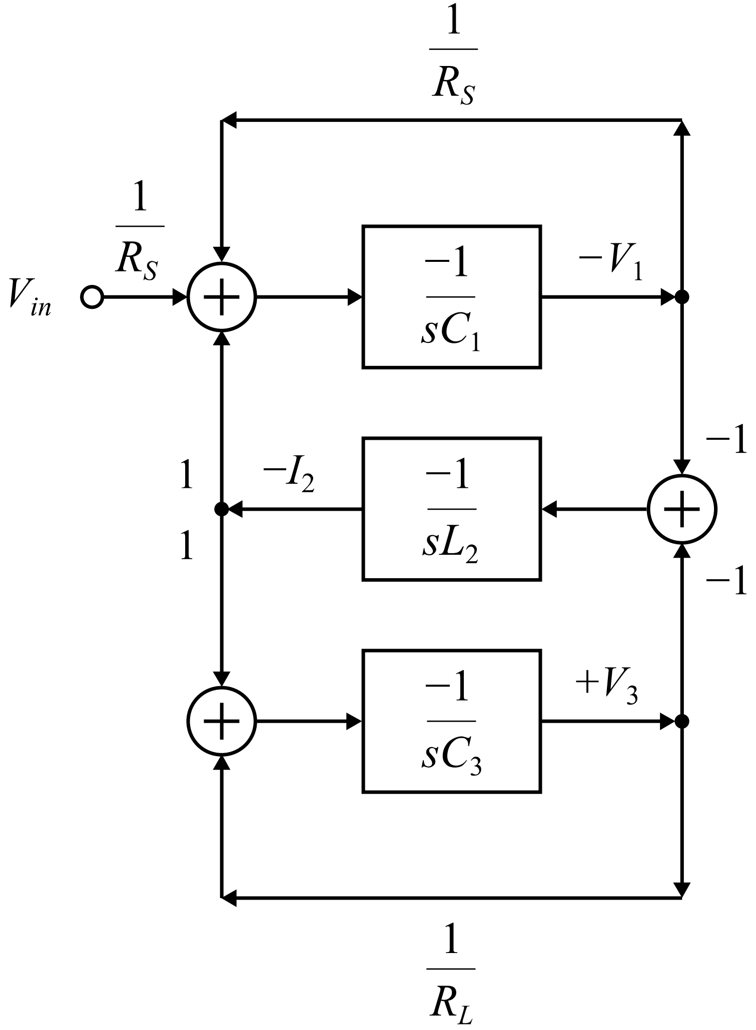
$$-V_1 = \frac{-1}{sC_1}\left(\frac{V_{in} - V_1}{R_s} - I_2\right)$$

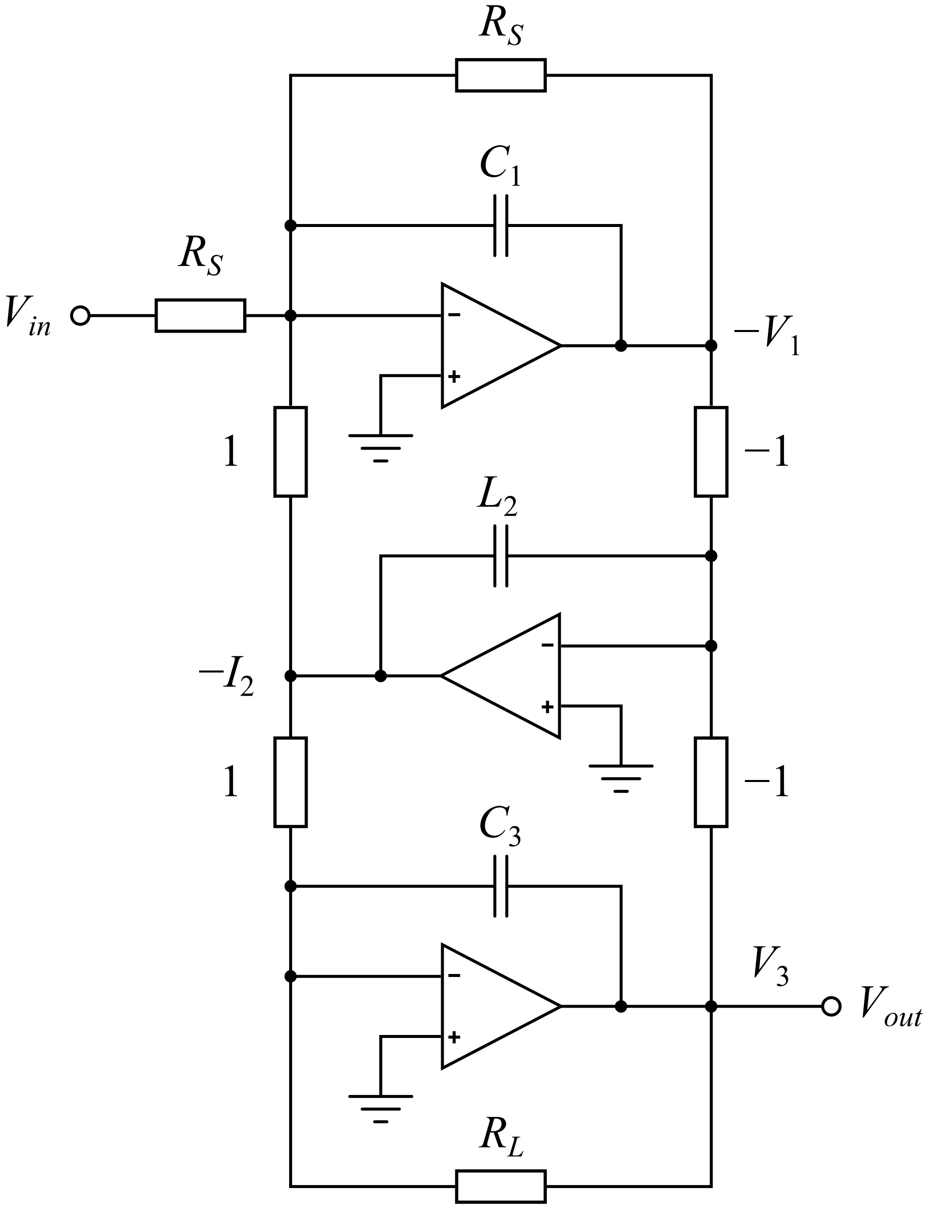
$$-I_2 = \frac{-1}{sL_2}\left(V_1 - V_3\right)$$

$$V_3 = \frac{-1}{sC_3}\left(-I_2 + \frac{V_3}{R_L}\right)$$

The sign convention is selected by the requirement that the integrators are realized with the **negative feedback amplifiers i.e. H(s) = -1/s !!**

RC-active realization





Scaling the middle integrator

$$-I_2 = \frac{-1}{sL_2}\left(V_1 - V_3\right)$$

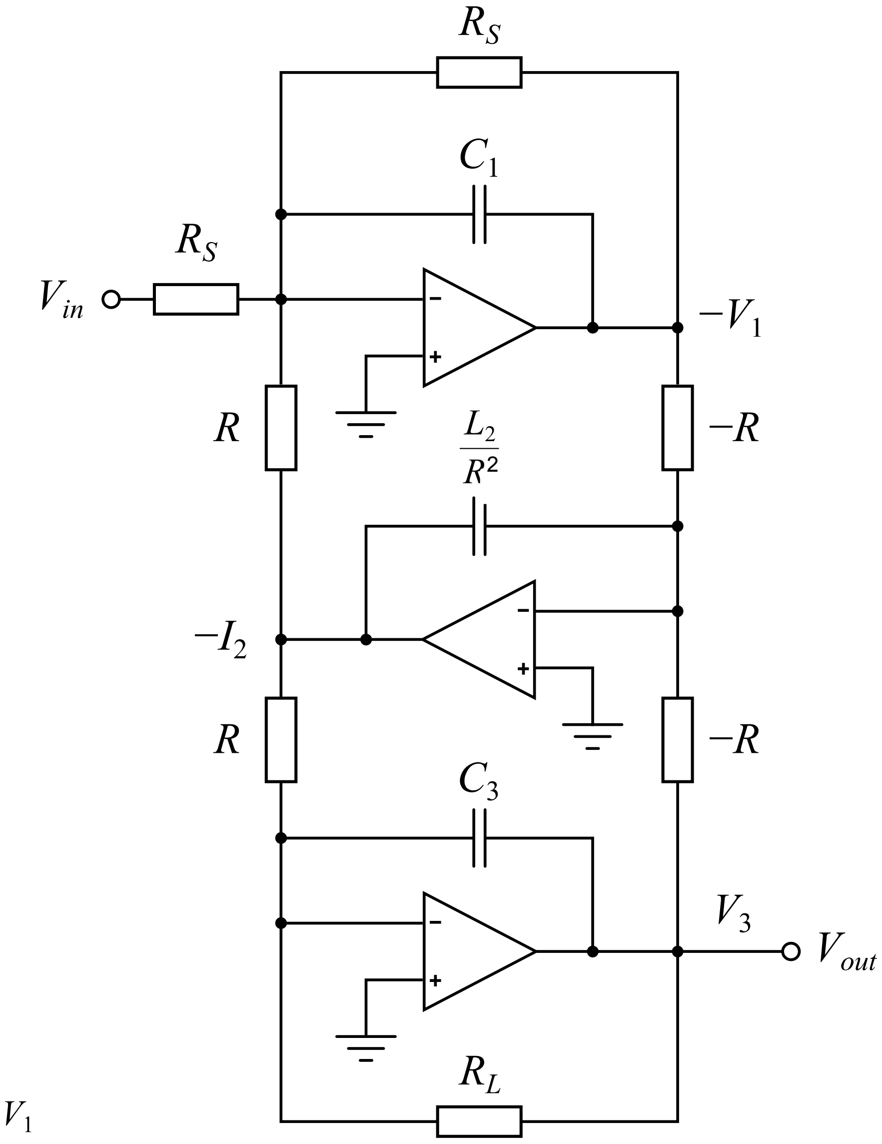
Scaling the input with R

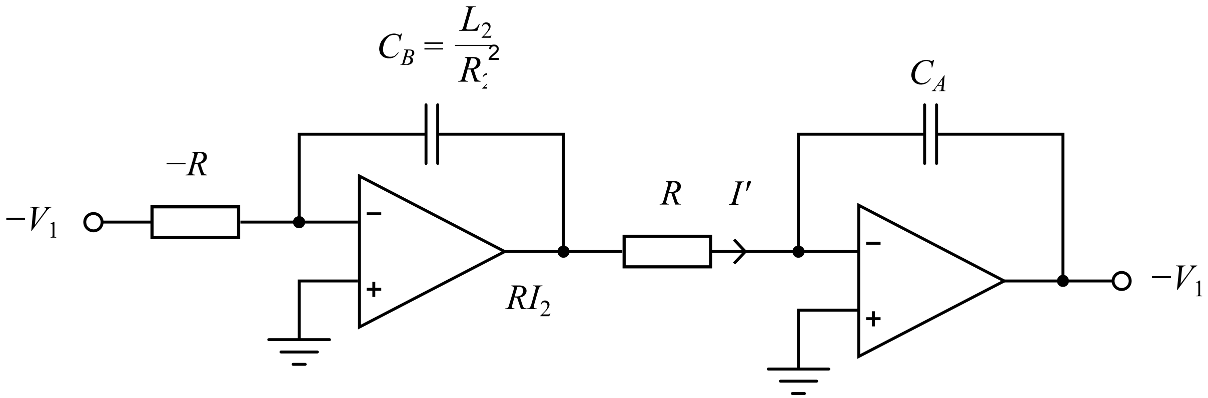
$$-I_2 = \frac{-R}{sL_2}\left(\frac{V_1}{R} - \frac{V_3}{R}\right)$$

Scaling the output with R (transforming $-I_2$ into voltage)

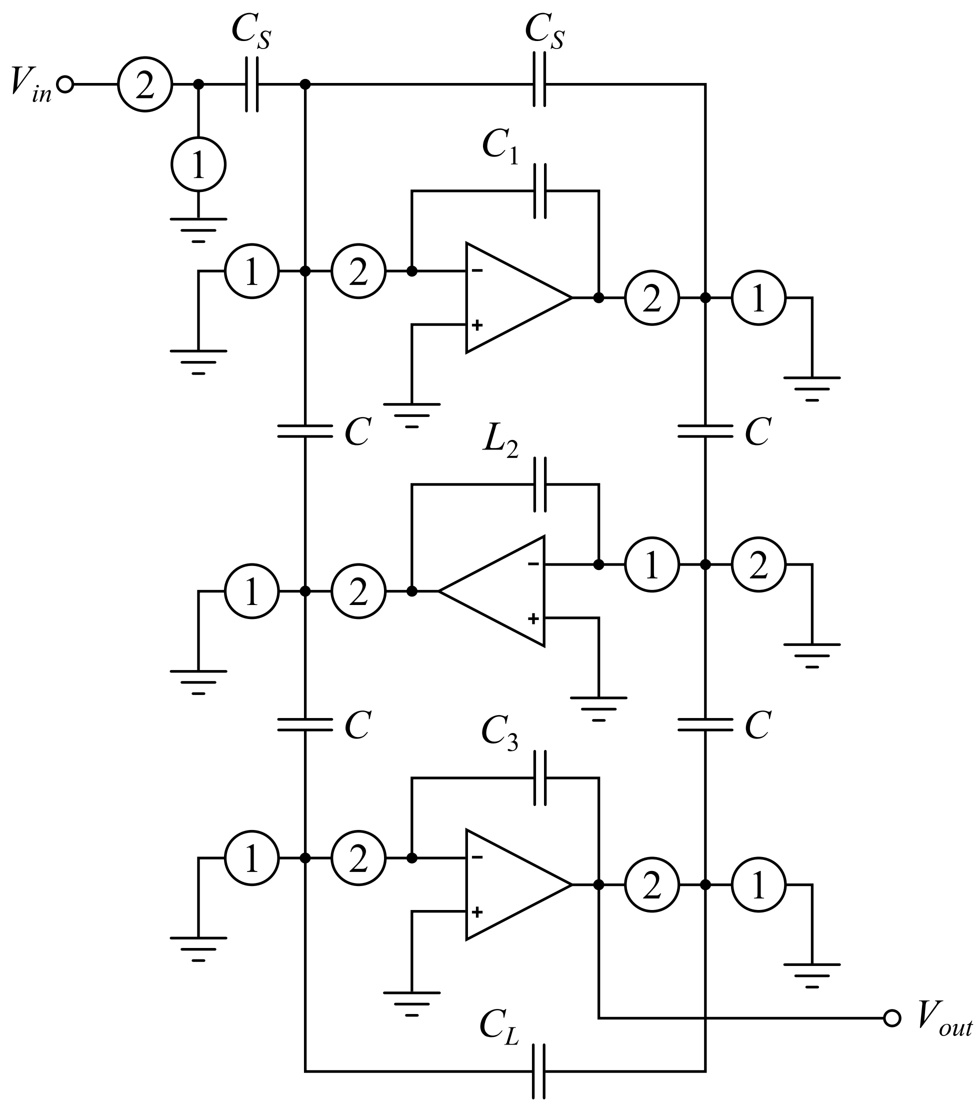
$$\left(-V_2\right) = -I_2 R = \frac{-R^2}{sL_2}\left(\frac{V_1}{R} - \frac{V_3}{R}\right)$$

Also all other impedancies connected to
the output branch have to be scaled with R





SC realization of LC-ladder filter



The capacitor values for SC realization:

$$R_{SC} = \frac{T}{C_{SC}} \Rightarrow C_{SC} = \frac{T}{R_{SC}}$$

$$\Rightarrow \quad C_s = \frac{T}{R_s}$$

$$C = \frac{T}{1} = T$$

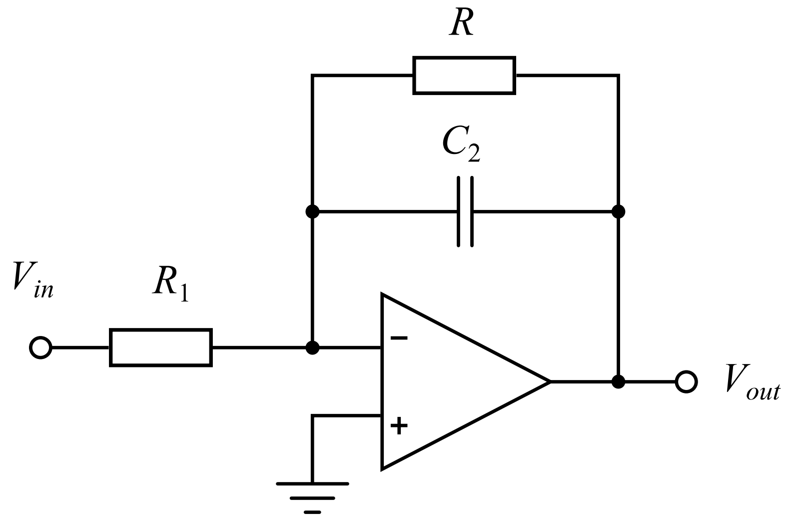
$$C_L = \frac{T}{R_L}$$

<u>Comments on one-to-one mapping:</u>

SC realization requires two capacitors to realize R_s. It also has four switched capacitors with value C=T. ⇒ Sensitivity behaviour is not as good as in the passive LC-prototype.

IF the losses at the pass-band are < 0,1 dB , the sensitivity characteristics are still very good !!

Losses in SC integrator



The transfer function for the SC integrator:

$$H(z) = -\frac{C_1}{C_2}\frac{1}{1-z^{-1}}$$

$$z = e^{j\omega T}$$

$$H\left(e^{j\omega T}\right) = -\frac{C_1}{C_2}\frac{1}{1-e^{-j\omega T}} \approx -\frac{C_1}{C_2}\frac{T}{j\omega - \omega^2\frac{T}{2}}$$

This is a lossy integrator.

The transfer function of lossy RC integrator:

$$H(\omega) = -\frac{R}{R_1}\frac{1}{1+j\omega C_2 R} = -\frac{1}{R_1 C_2}\frac{1}{j\omega - \frac{1}{RC_2}}$$

equating gain coefficients and the lossy terms

$$\frac{C_1}{C_2} = \frac{1}{R_1 C_1} \qquad \frac{1}{RC_2} = \omega^2\frac{T}{2}$$

$$\Rightarrow R_1 = \frac{T}{C_1} \qquad R = \frac{2}{\omega^2 T C_2}$$

the Q - factor is

$$\Rightarrow Q = \omega C_2 R = \frac{2}{\omega T}$$

Note: typically $\omega T << 1 \Rightarrow Q >> 1$

The approximation caused by the Z-transformation is equivalent to the losses in the L and C components in the passive filter.

Losses of SC-ladder filter

The transfer function of the middle integrator

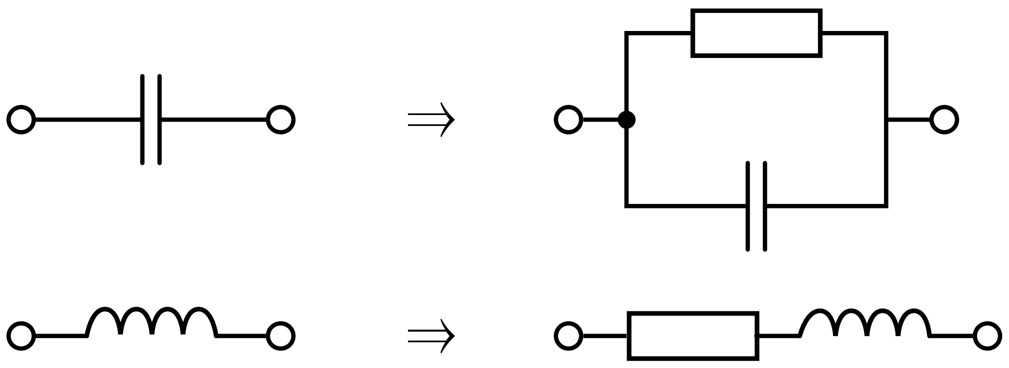
$$H(z) = \frac{C_1}{C_2} \frac{z^{-1}}{1 - z^{-1}}$$

$$H\left(e^{j\omega T}\right) = \frac{C_1}{C_2} \frac{1}{e^{j\omega T} - 1}$$

$$\approx \frac{C_1}{C_2} \frac{1}{j\omega T - \omega^2 \frac{T^2}{2}}$$

This is a lossy integrator $\Rightarrow Q_L = -\frac{2}{\omega T}$

Thus the approximation caused by the z-transformation can be described by the losses of the passive L and C elements in the prototype.

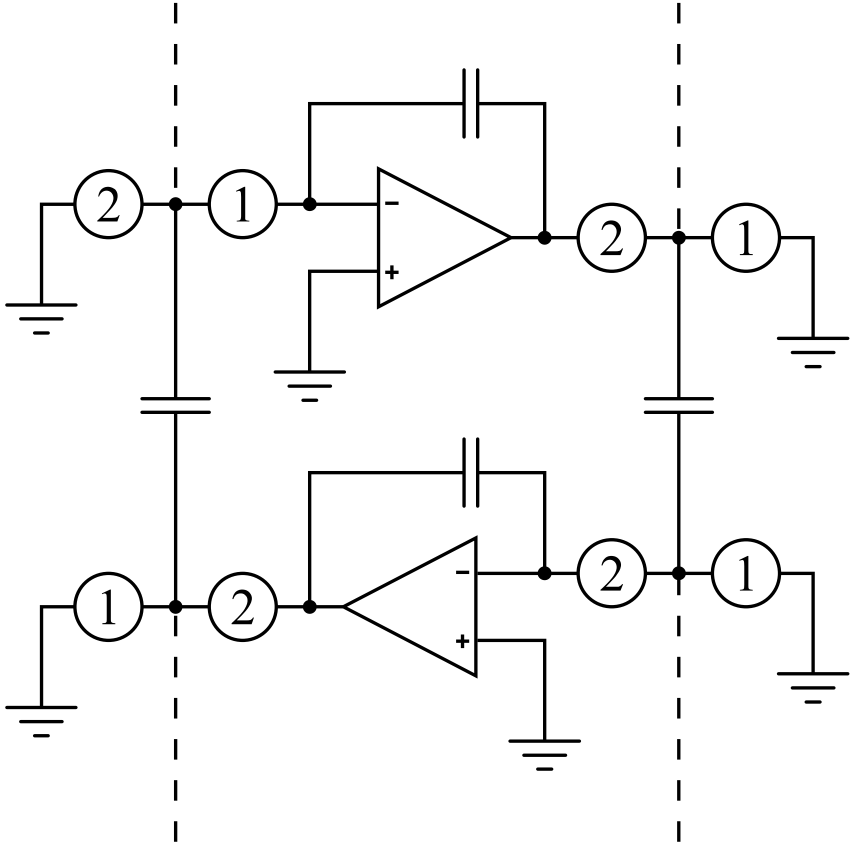


However, the Q-values of the L and C elements have opposite signs

$\Rightarrow$ in the loop connection they compensate each other's effect

Lossless discrete integrators (LDI)

The SC-ladder implementation has inverting and non-inverting integrators alternating



Transfer functions of inverting and non-inverting integrators:

$$H(z)_{inv} = -\frac{\left(\frac{C_1}{C_2}\right)}{1 - z^{-1}}$$

$$H(z)_{noninv} = \frac{\left(\frac{C_1}{C_2}\right) z^{-1}}{1 - z^{-1}}$$

Transfer function of the loop connection:

$$H(z) = H(z)_{inv} \cdot H(z)_{noninv} = -\frac{\left(\frac{C_1}{C_2}\right)}{1 - z^{-1}} \frac{\left(\frac{C_1}{C_2}\right) z^{-1}}{1 - z^{-1}}$$

$$= \frac{-K^2 z^{-1}}{\left(1 - z^{-1}\right)^2} = \frac{-K^2}{\left(z^{\frac{1}{2}} - z^{-\frac{1}{2}}\right)^2}$$

Inserting $z=e^{j\omega T}$ we obtain

$$H\left(e^{j\omega T}\right)=\frac{K^2}{4\sin^2\left(\frac{\omega T}{2}\right)}$$

This is real thus the loop connection does not have **losses**!
Comparing with s-domain integrators

$$H_1(s)H_2(s)=-\frac{1}{j\omega RC}\frac{1}{j\omega RC}=\frac{1}{\omega^2(RC)^2}$$ this is real!

Thus only frequency distortion occurs! $(\omega \rightarrow \sin\frac{\omega T}{2})$
Let us reform H(z) as follows:

$$H(z)=\frac{-K^2}{\left(z^{\frac{1}{2}}-z^{-\frac{1}{2}}\right)^2}=\frac{-K}{\left(z^{\frac{1}{2}}-z^{-\frac{1}{2}}\right)}\frac{K}{\left(z^{\frac{1}{2}}-z^{-\frac{1}{2}}\right)}$$

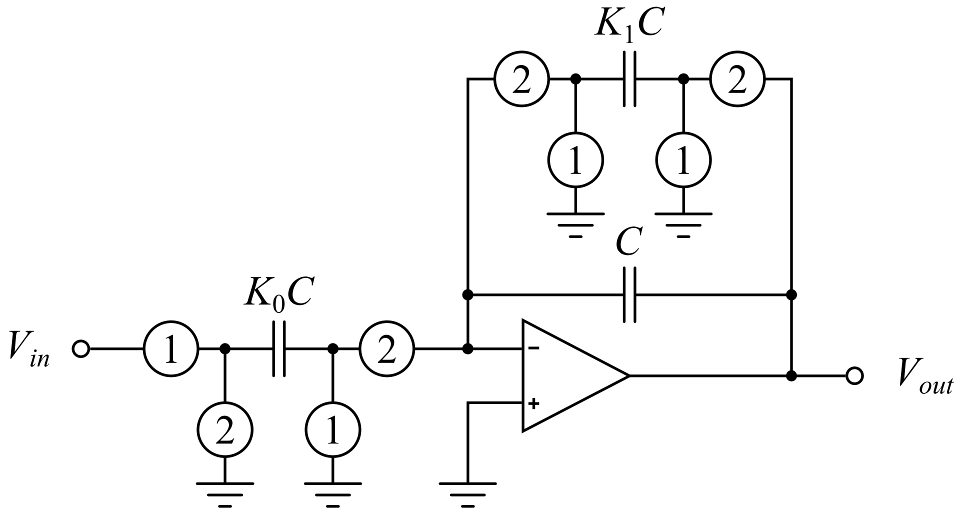
LDI-integ. LDI-integ.

These are called Lossless-discrete-integrators.

Notice: The realization of the termination impedances R_s and R_L is not exact!
(i.e. LDI-transformation)

Lossy integrators realizing terminating impedances R_s and R_L

Lossy SC integrator:



Transfer function

$$H(z) = \pm \frac{K_0 z^{-\frac{1}{2}}}{1 + K_1 - z^{-1}}$$

Correct transfer function with LDI-transformation

$$H(z) = \pm \frac{K_0 z^{-\frac{1}{2}}}{1 + K_1 z^{-\frac{1}{2}} - z^{-1}}$$

Term $K_1 z^{-1/2}$ not realizable

Let us insert $z = e^{j\omega t}$

$$H\left(e^{j\omega T}\right) = \pm \frac{K_0}{j2\sin\frac{\omega T}{2} + K_1\left[\cos\frac{\omega T}{2} + j\sin\frac{\omega T}{2}\right]}$$

K_1 produces a real part and an imaginary part to the denominator $\Rightarrow$ not accurate i.e. not lossless

Equating K_1 and K_0 at the polefrequency ω_1

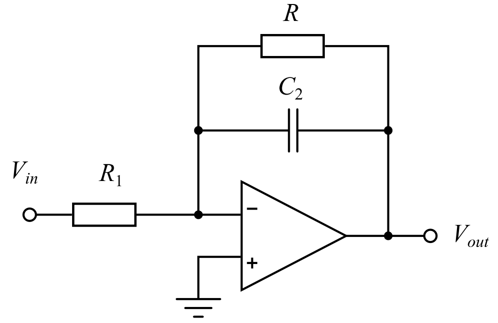
$$K_1 = \frac{2\sin\frac{\omega_1 T}{2}}{\cos\frac{\omega_1 T}{2} - \sin\frac{\omega_1 T}{2}}$$

$$K_0 = GK_1\cos\frac{\omega_1 T}{2}$$

for which $G = \frac{R}{R_1}$, $\omega_1 = \frac{2\pi}{\tau_1}$ and $\tau_1 = R_1 C_2$ in lossy RC-integrator

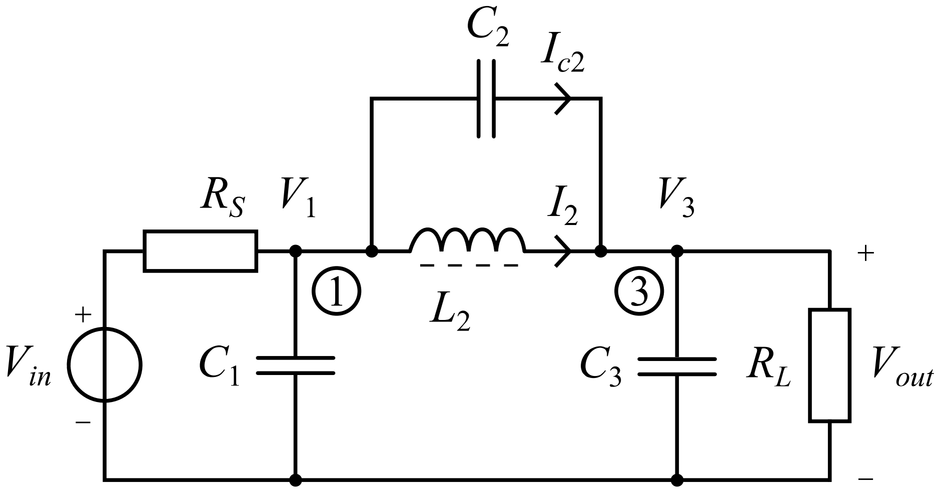
The transfer function of lossy RC integrator:

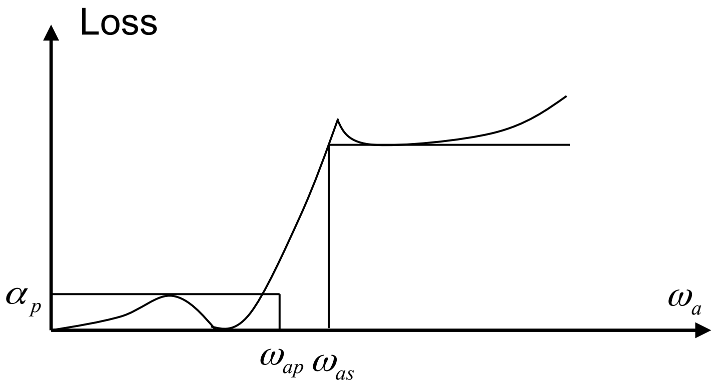
$$H(\omega) = -\frac{R}{R_1}\frac{1}{1 + j\omega C_2 R} = -\frac{1}{R_1 C_2}\frac{1}{j\omega - \frac{1}{RC_2}}$$



Transfer zeros (elliptical filters)

3rd order elliptical low-pass filter





State-variables
- capacitor voltages
- inductor currents

⇒ 4 state equations but only 3 needed

The voltage of C_2 is already given as the difference of the two state-variables V_1 and V_3.

The capacitor C_2 has a current given as:

$$I_{c2} = sC_2(V_1 - V_3)$$

The state equations are obtained from the current equation at nodes 1 and 3 and from the current equation of L_2.

State equations

Select state variables to be V_1, I_2, V_3.
Solve current equation at node 1

$$\left(V_{in} - V_1\right)\frac{1}{R_S} = sC_1V_1 + \left(V_1 - V_3\right)sC_2 + I_2$$

Form an integrator

$$s\left(C_1 + C_2\right)V_1 = \frac{1}{R_S}V_{in} - \frac{1}{R_S}V_1 + sC_2V_3 - I_2$$

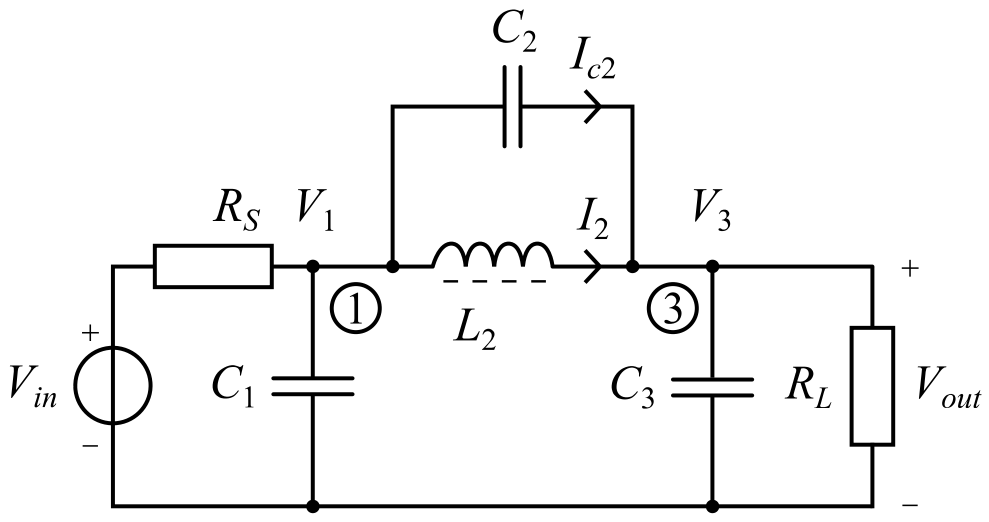
$$-V_1 = \frac{-1}{s\left(C_1 + C_2\right)}\left[\frac{1}{R_S}V_{in} - \frac{1}{R_S}V_1 - I_2 + sC_2V_3\right]$$

Solve V_3 from the current equation at node 3

$$\left(V_1 - V_3\right)sC_2 + I_2 = sC_3V_3 + \frac{1}{R_L}V_3$$

$$s\left(C_2 + C_3\right)V_3 = sC_2V_1 + I_2 - \frac{1}{R_L}V_3$$

$$V_3 = \frac{-1}{s\left(C_2 + C_3\right)}\left[-sC_2V_1 - I_2 + \frac{1}{R_L}V_3\right]$$



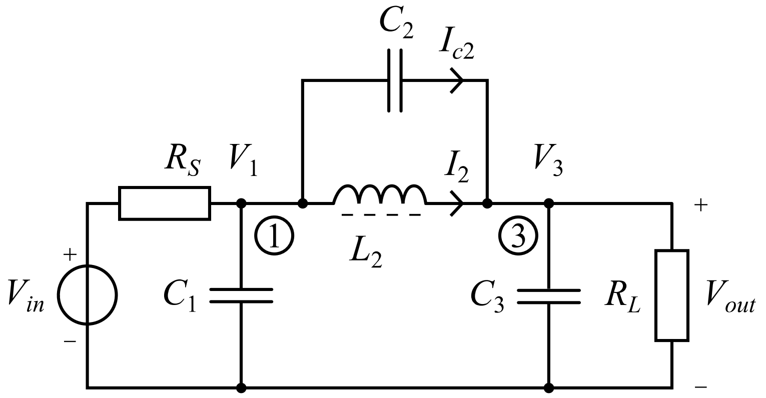
Inductor L_2 current

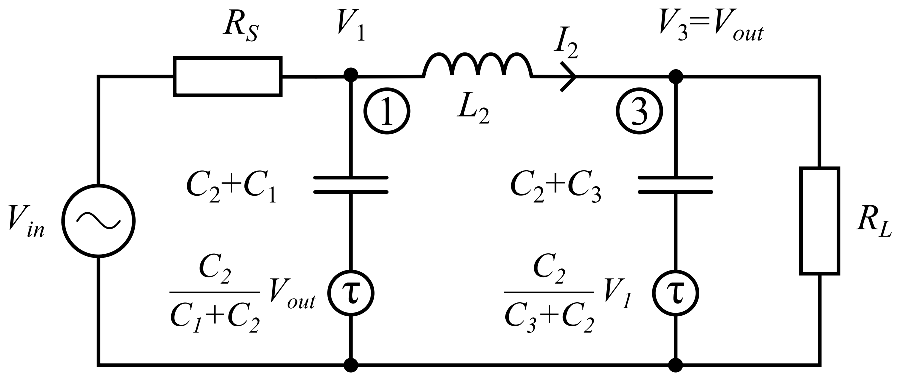
$$V_1 - V_3 = sL_2I_2$$

$$-I_2 = \frac{-1}{sL_2}\left(V_1 - V_3\right)$$

Note: sign-convention according to negative feedback realization.

Circuit transformation method to find state-equations





Currents in nodes 1 and 3:

1 $$(V_{in}-V_1)\frac{1}{R_S} = (V_1-V_3)sC_2 + (V_1-V_3)\frac{1}{sL_2} + sC_1V_1$$

3 $$(V_1-V_3)sC_2 + (V_1-V_3)\frac{1}{sL_2} = V_3\cdot sC_3 + V_3\cdot\frac{1}{R_L}$$

again in a changed coupling

1 $$(V_{in}-V_1)\frac{1}{R_S} = (V_1-V_3)\frac{1}{sL_2} + \left(V_1 - \frac{C_2}{C_1+C_2}\cdot V_3\right)s(C_1+C_2)$$

$$= (V_1-V_3)\frac{1}{sL_2} + V_1 s(C_1+C_2) - V_3 sC_2$$

$$= (V_1-V_3)\frac{1}{sL_2} + V_1 sC_1 + (V_1-V_3)sC_2$$

3 $$\frac{1}{sL_2}(V_1-V_3) = \left(V_3 - \frac{C_2}{C_2+C_3}V_1\right)s(C_2+C_3) + V_3\frac{1}{R_L}$$

$$= V_3 s(C_2+C_3) - V_1 sC_2 + V_3\frac{1}{R_L}$$

$$= (V_3-V_1)sC_2 + V_3 sC_3 + V_3\frac{1}{R_L}$$

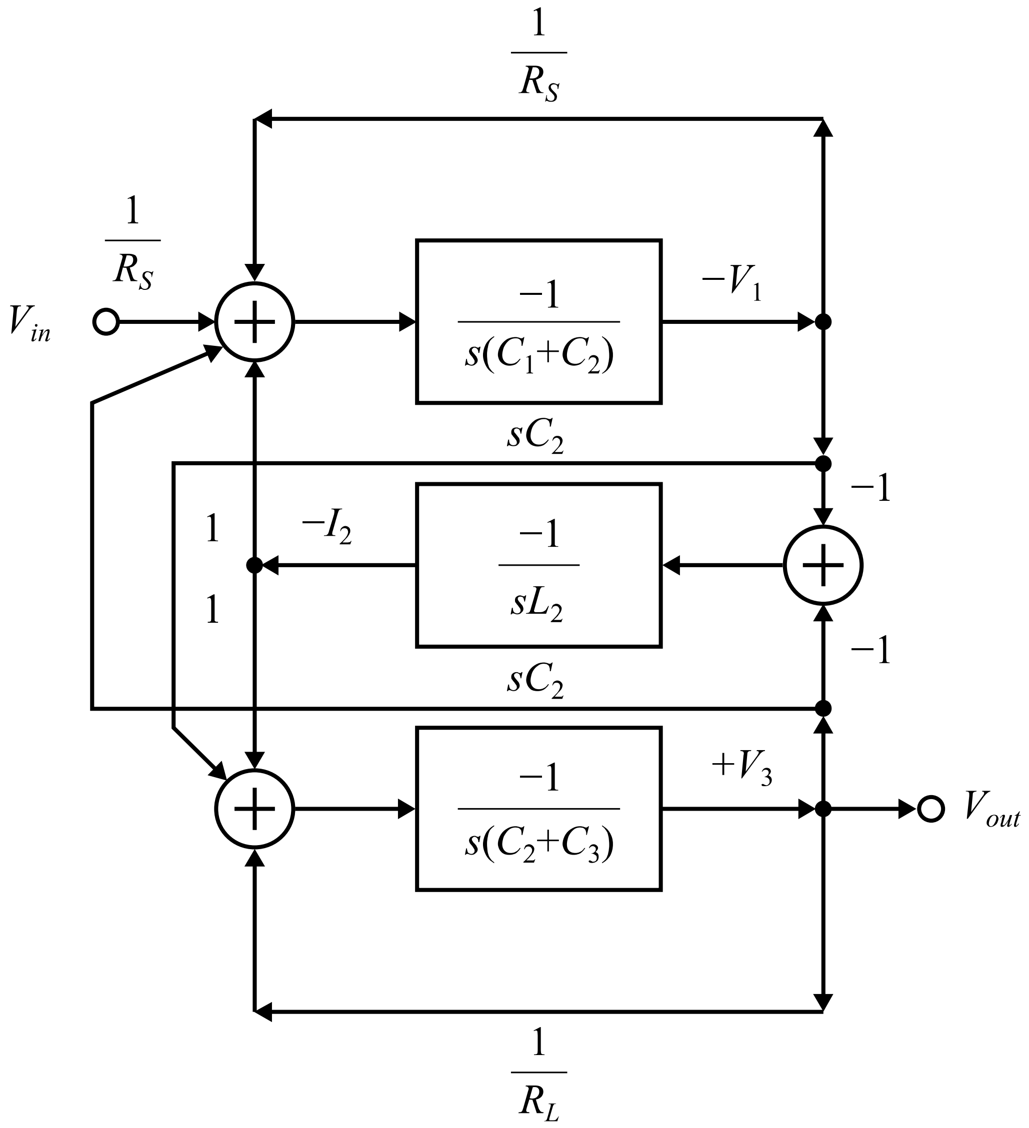
Signal-flow graph

State-equations

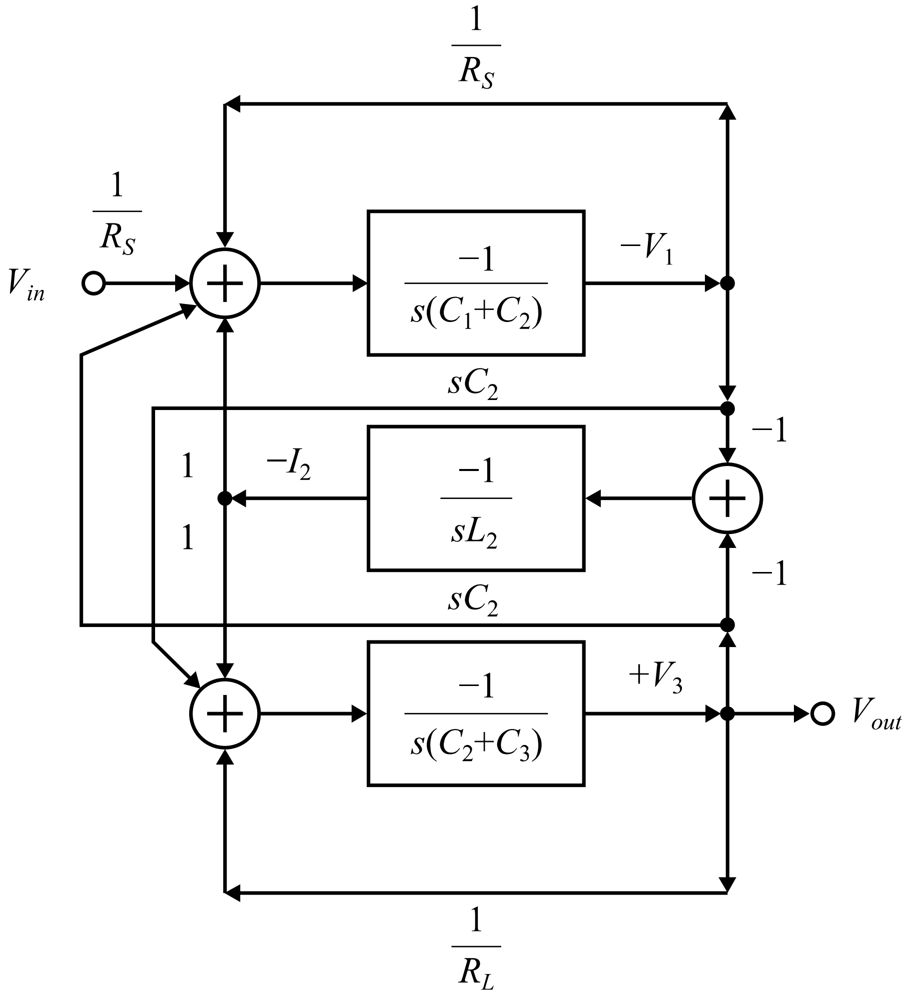
$$-V_1 = \frac{-1}{s(C_1 + C_2)}\left(\frac{V_{in} - V_1}{R_S} + sC_2V_3 - I_2\right)$$

$$-I_2 = \frac{-1}{sL_2}(V_1 - V_3)$$

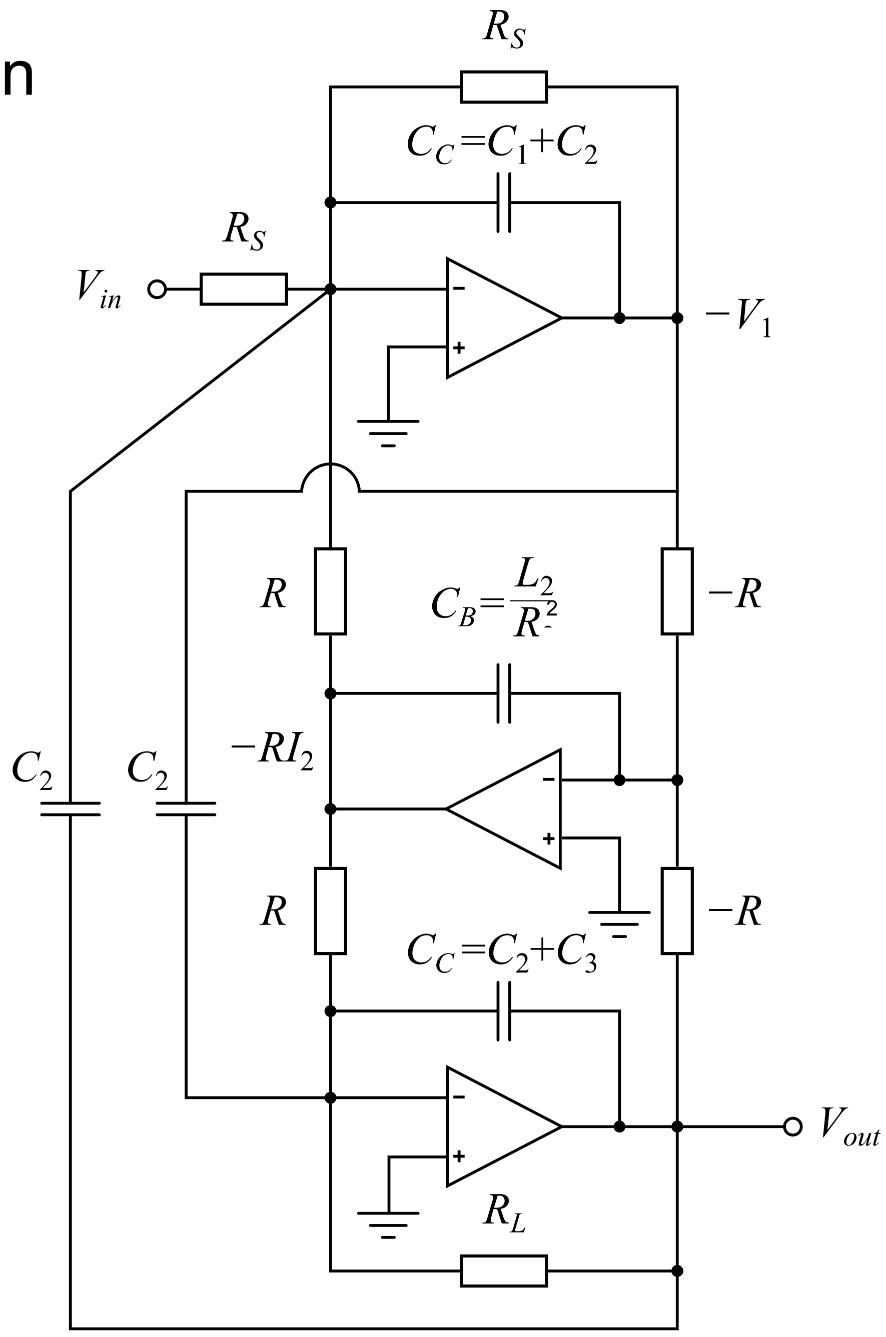
$$V_3 = \frac{-1}{s(C_2 + C_3)}\left(-sC_2V_1 - I_2 + \frac{V_3}{R_L}\right)$$



RC-active realization



Impedance scaling of middle integrator:



Elliptical SC-filter

The switched-capacitors are given by:

$$R_{sc} = \frac{T}{C_{sc}} \Rightarrow C_{sc} = \frac{T}{R_{sc}}$$

Thus:

$$C_s = \frac{T}{R_s}$$

$$C = T$$

$$C_L = \frac{T}{R_L}$$

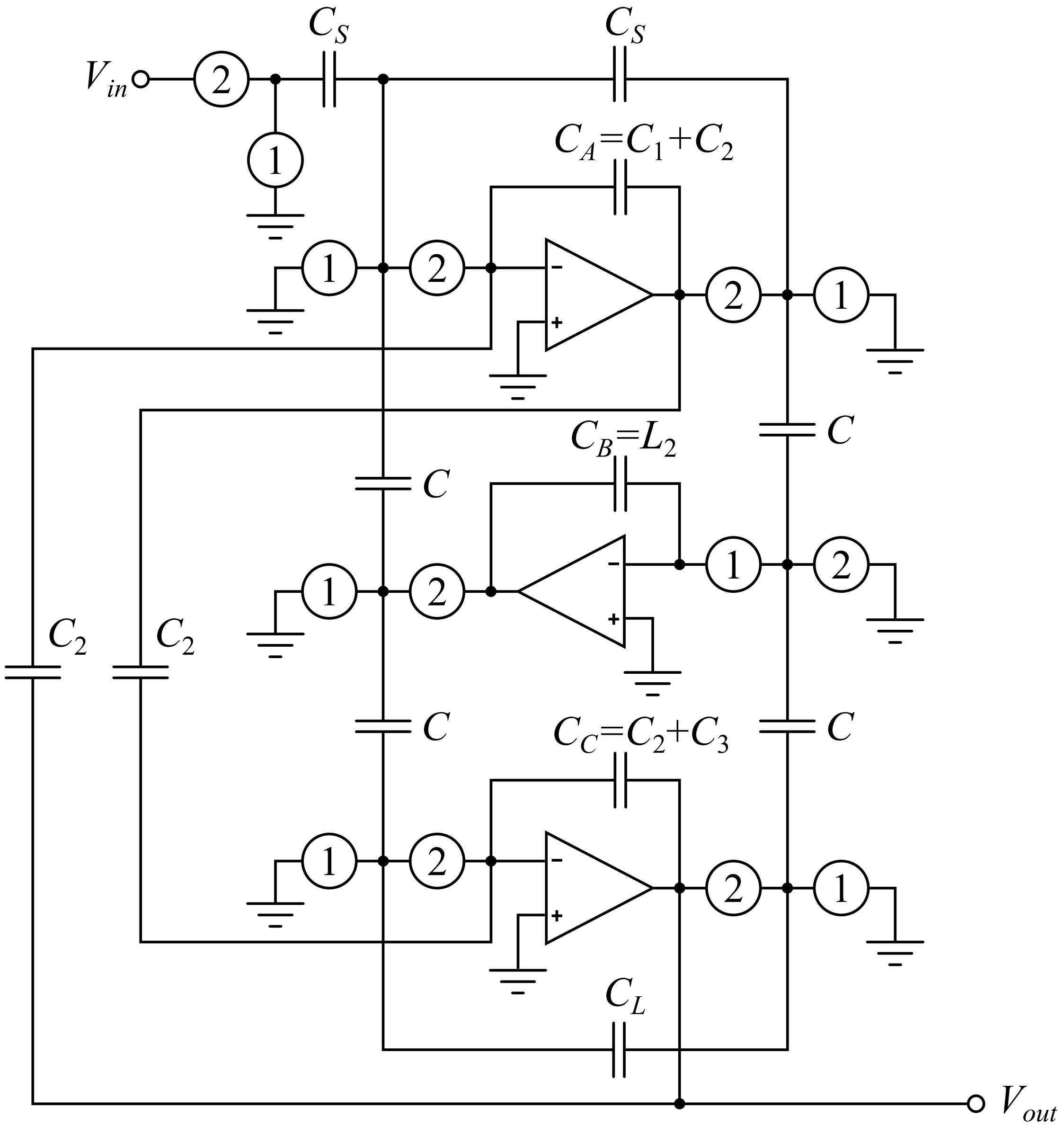
and the integrator capacitors are

$$C_A = C_1 + C_2$$

$$C_B = L_2$$

$$C_C = C_2 + C_3$$

C_2 is included in four different capacitors, while in the passive LC-ladder filter it appears only once → effects sensitivity!



Exact design of SC-ladder filter

The errors caused by the LDI-transform can be avoided by using the *bilinear transform*:

$$s = \frac{2}{T}\frac{z-1}{z+1}$$

A 3rd-order LCR-filter implementation by using the bilinear transformation

For the bilinear transformation the state equations have to be changed as follows:

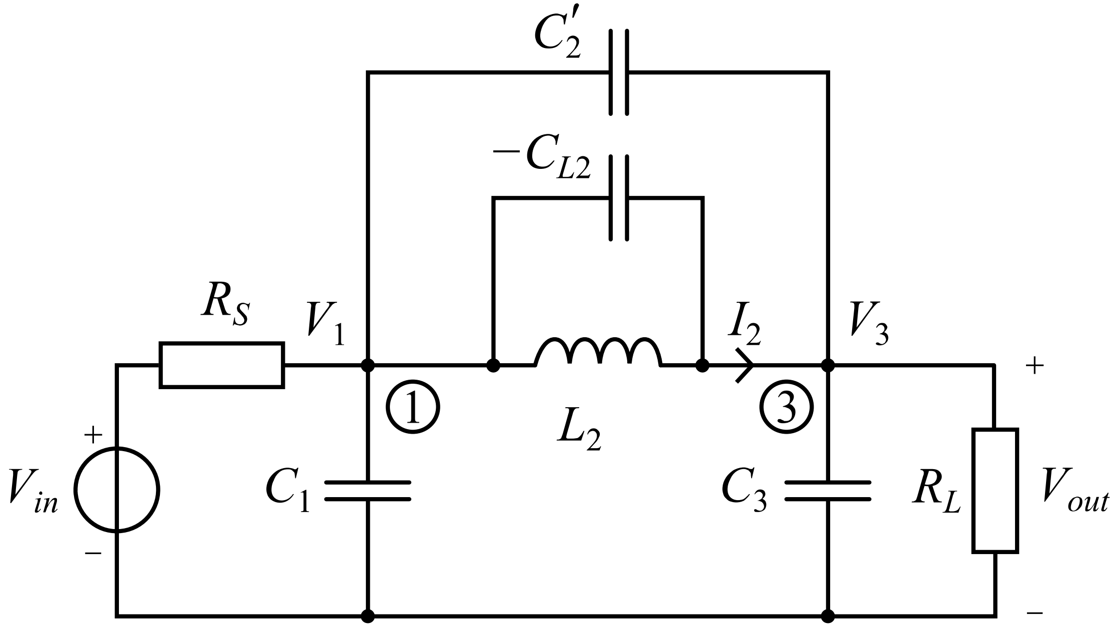
$$\left.\begin{aligned} C_2' &= C_2 + C_{L2} \\ -C_{L2} &= \frac{-T^2}{4L_2} \end{aligned}\right\} \Rightarrow C_2 = C_2' - C_{L2}$$

The new state equations:

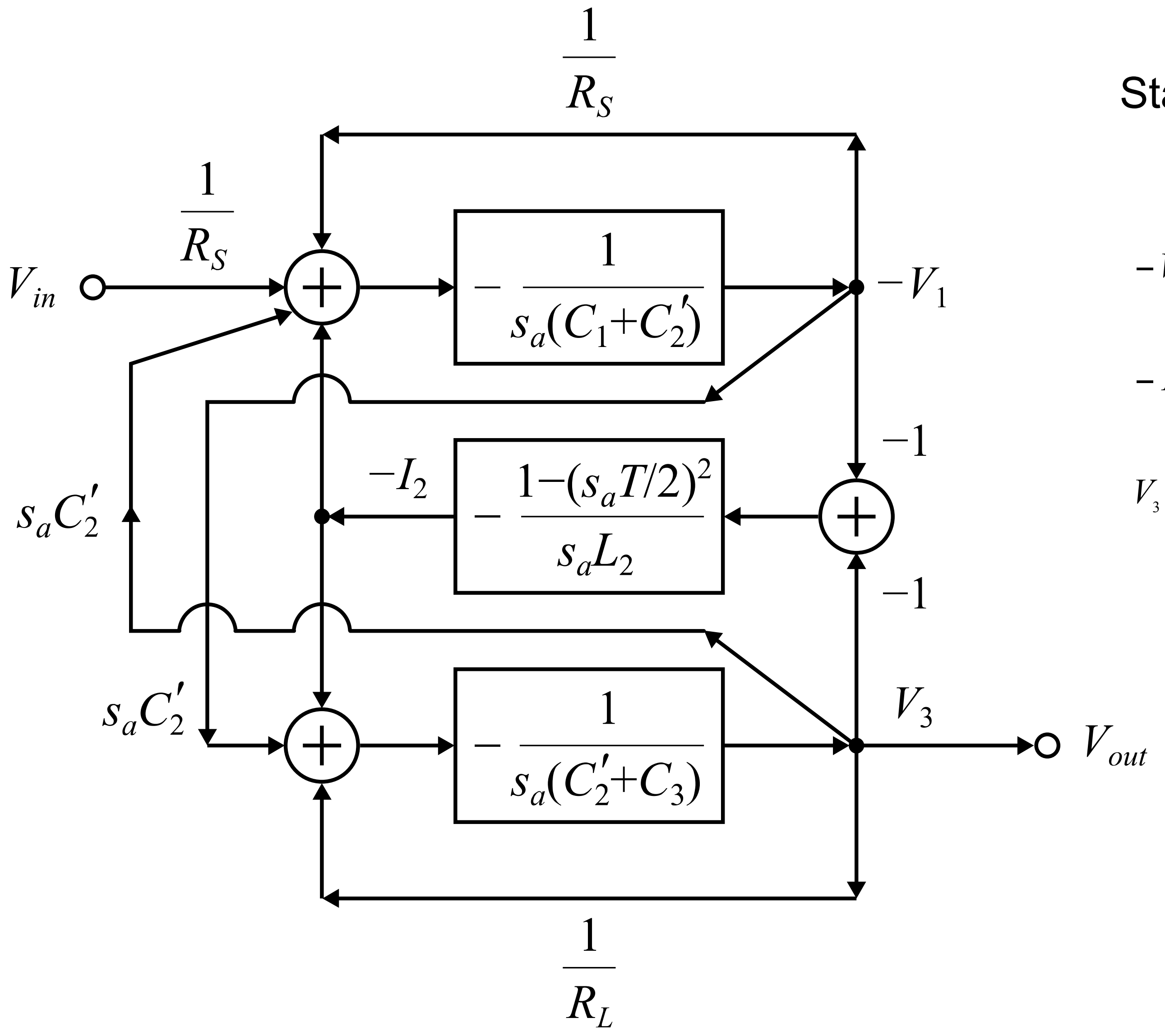
$$-V_1 = \frac{-1}{s_a\left(C_1 + C_2'\right)}\left[\frac{V_{in} - V_1}{R_s} + sC_2'V_3 - I_2\right]$$

$$-I_2 = -\left[-s_a\left|C_{L2}\right| + \frac{1}{s_aL_2}\right]\left[V_1 - V_3\right] \stackrel{\Delta}{=} -\frac{1-\left(s_aT/2\right)^2}{s_aL_2}\left[V_1 - V_3\right]$$

$$V_3 = \frac{-1}{s_a\left(C_2' + C_3\right)}\left[-s_aC_2'V_1 - I_2 + \frac{V_3}{R_L}\right]$$



Signal-flow graph



State equations:

$$-V_1 = \frac{-1}{s_a\left(C_1 + C_2'\right)}\left[\frac{V_{in} - V_1}{R_s} + sC_2'V_3 - I_2\right]$$

$$-I_2 = -\left[-s_a\left|C_{L2}\right| + \frac{1}{s_aL_2}\right]\left[V_1 - V_3\right] \triangleq -\frac{1-\left(s_a T/2\right)^2}{s_aL_2}\left[V_1 - V_3\right]$$

$$V_3 = \frac{-1}{s_a\left(C_2' + C_3\right)}\left[-s_aC_2'V_1 - I_2 + \frac{V_3}{R_L}\right]$$

Implementation of the middle segment:

$$Q(s_a) = \frac{-I_2}{s_a} = -\frac{1-(s_a T/2)^2}{s_a^2 L_2}\left[V_1 - V_3\right]$$

Bilinear transformation ⇒

$$Q(z) = -\frac{1-\left[\dfrac{z-1}{z+1}\right]^2}{\dfrac{4L_2}{T^2}\left[\dfrac{z-1}{z+1}\right]^2}\left[V_1(z)-V_3(z)\right] = -\frac{z4C_{L2}}{(z-1)^2}\left[V_1(z)-V_3(z)\right]$$

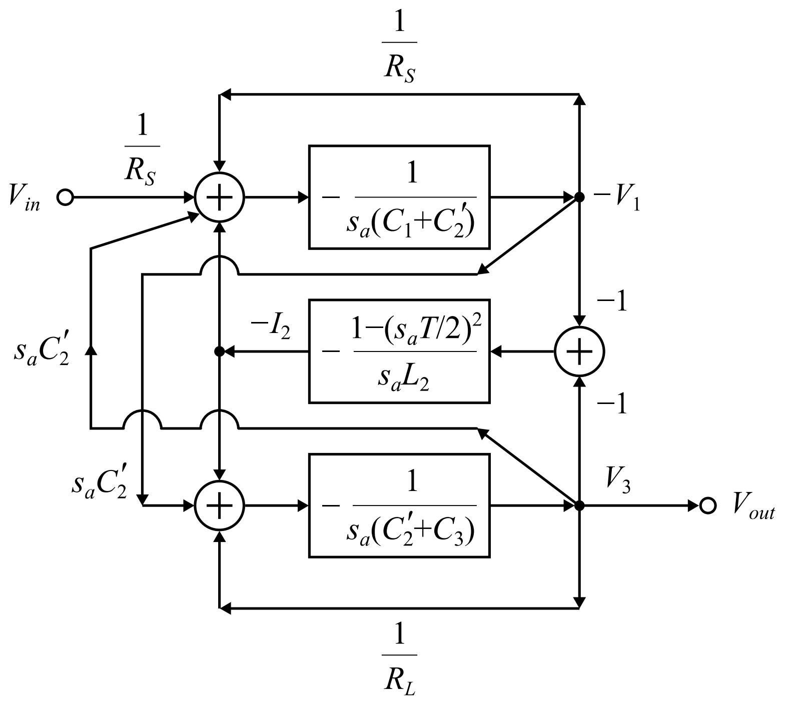
$$\Rightarrow (1-z^{-1})Q(z) = \frac{z^{-1}4C_{L2}}{1-z^{-1}}(V_3 - V_1)$$

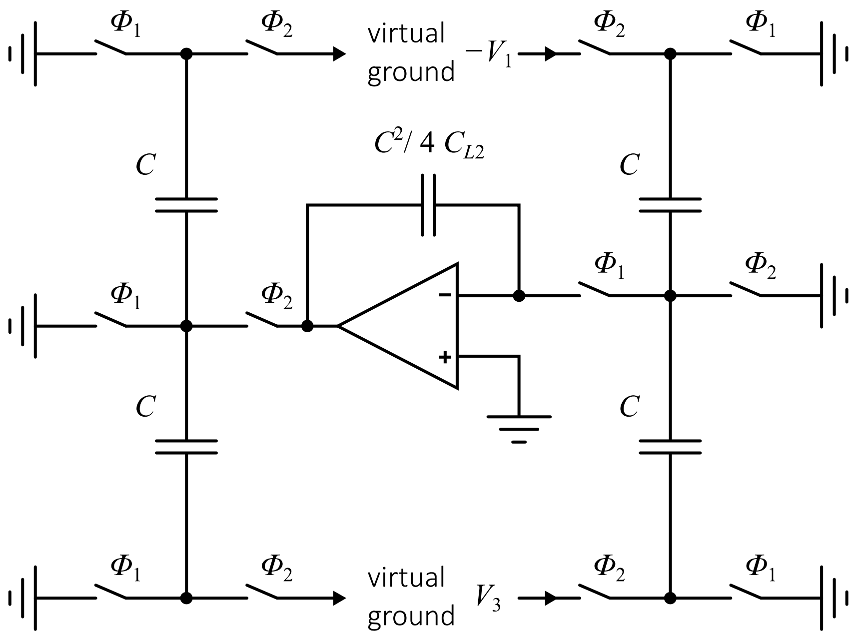
Notice!

$$(1-z^{-1})Q(z) \triangleq q(t_n) - q(t_{n-1}) = \Delta q$$

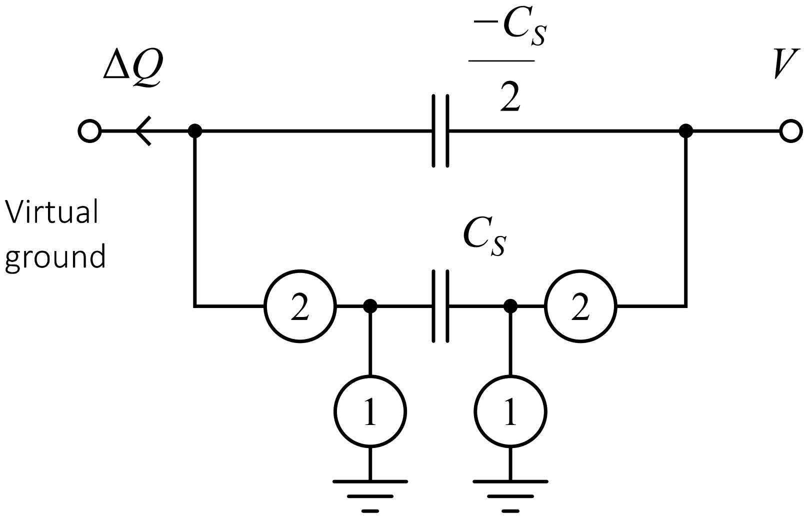
$$\Rightarrow (1-z^{-1})Q(z) = C\left[\frac{-4C_{L2}/C^2}{1-z^{-1}}\underbrace{\left(Cz^{-1}\left[V_3 - V_1\right]\right)}_{Q}\right]$$

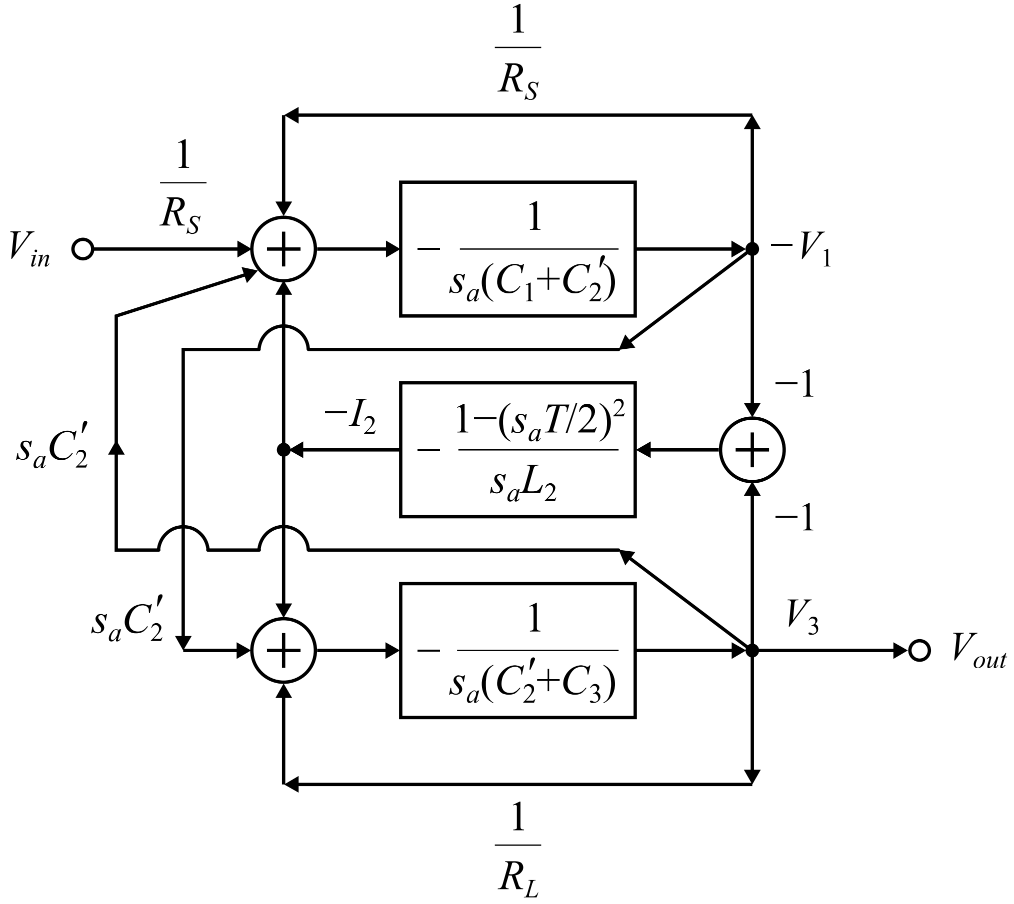
$Q = VC \quad V = \dfrac{Q}{C}$





Feedback loops $1/R_S$ and $1/R_L$





$$\frac{\Delta Q}{V} = -\frac{C_S}{2}\left(1-z^{-1}\right)+C_s = \frac{C_S}{2}\left(1+z^{-1}\right)$$

$$\Delta q = q\left(t_n\right)-q\left(t_{n-1}\right)$$

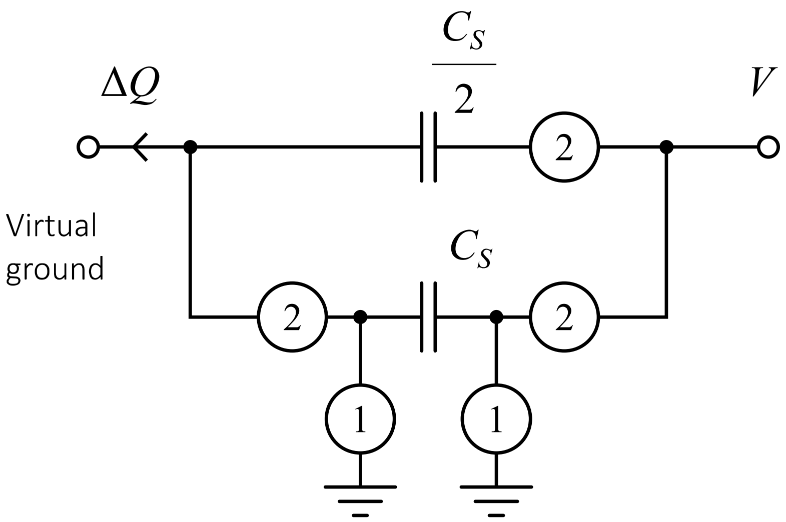
$$\Delta Q = \left(1-z^{-1}\right)Q\left(z\right) = \frac{C_S}{2}\left(1-z^{-1}\right)V\left(z\right)$$

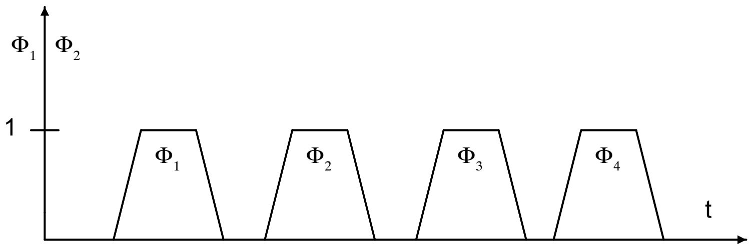
Reverse transformation (bilinear)

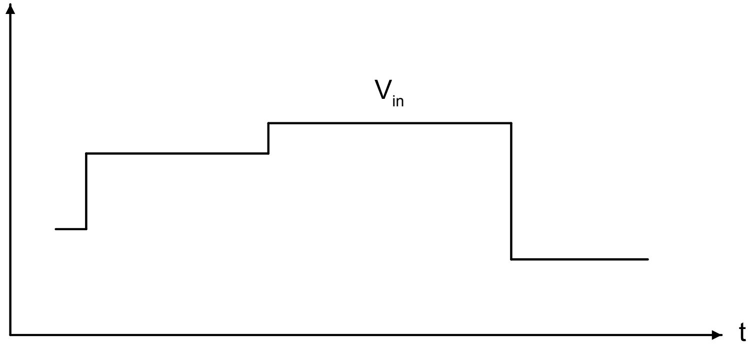
$$C_S = \frac{T}{R_S} \qquad Q\left(z\right) = \frac{T}{2R_S}\frac{1+z^{-1}}{1-z^{-1}}V\left(z\right)$$

$$Q\left(s\right) = \frac{V\left(s\right)}{sR_s}$$

Optional implementation of feedback resistor with bilinear transformation:

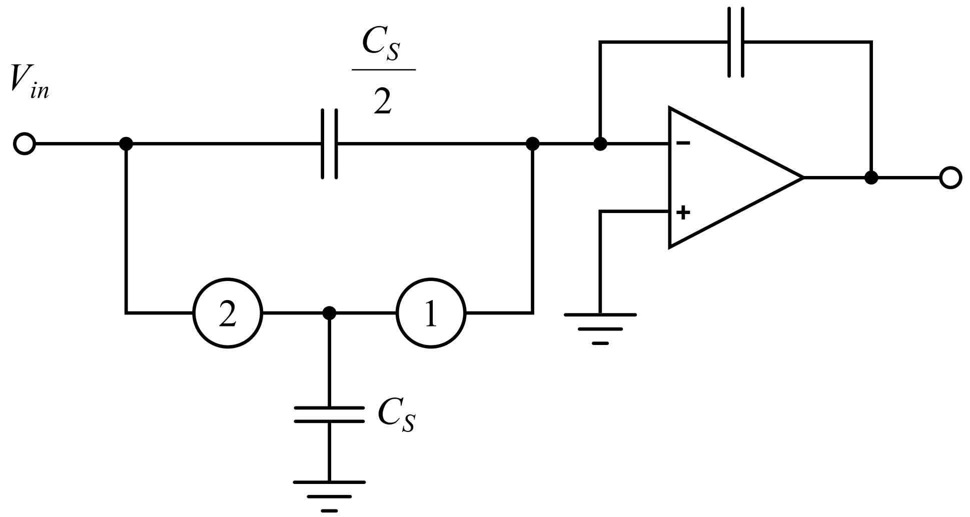






The movement of the charge in the input branch:

$$I_{IN} = \frac{dQ_{IN}}{dt} = \frac{V_{IN}}{R_S} \Rightarrow Q_{IN}(s_a) = \frac{V_{IN}}{s_a R_S}$$



Bilinear transformation:

$$Q_{IN}(z) = \frac{T}{2}\frac{z+1}{z-1}\frac{V_{IN}(z)}{R_S}$$

$$\left(1-z^{-1}\right)Q_{IN}(z) = \frac{T}{2R_S}\left(1+z^{-1}\right)V_{IN}(z)$$

In time-domain:

$$\Delta q_{IN} = q_{IN}(t_n) - q_{IN}(t_{n-1}) = \frac{C_S}{2}\left[v_{IN}(t_n) + v_{IN}(t_{n-1})\right]$$

$$= \frac{C_S}{2}\left[v_{IN}(t_n) - v_{IN}(t_{n-1})\right] + C_S v_{IN}(t_{n-1})$$

• transfer function zeros $s_a C_2'$:

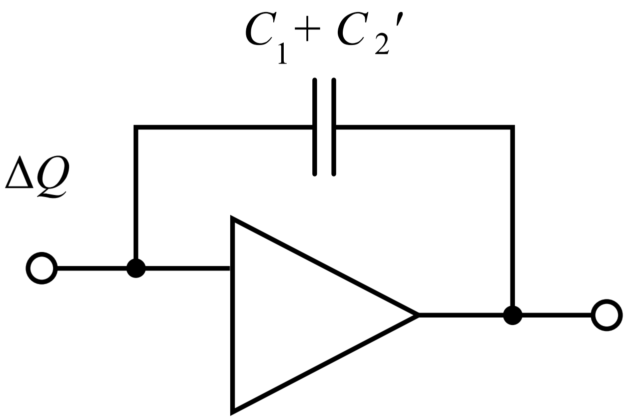
$$\frac{Q}{V} = C_2'$$

Implementation with non-switched capacitors C_2'

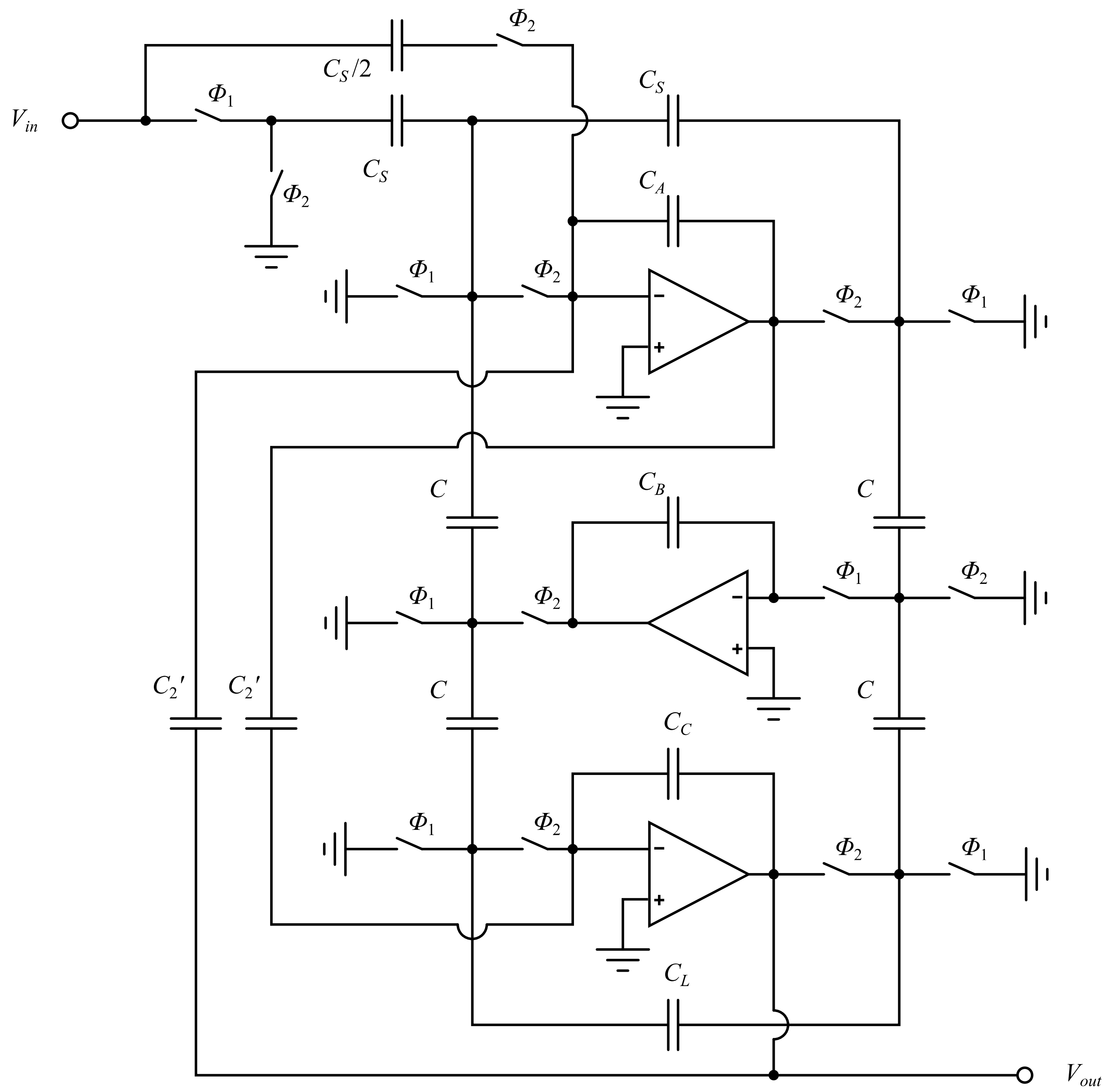
• current to voltage conversion

$$-\frac{1}{C_1 + C_2'}$$

Implementation with integrator (amplifier + feedback capacitor)

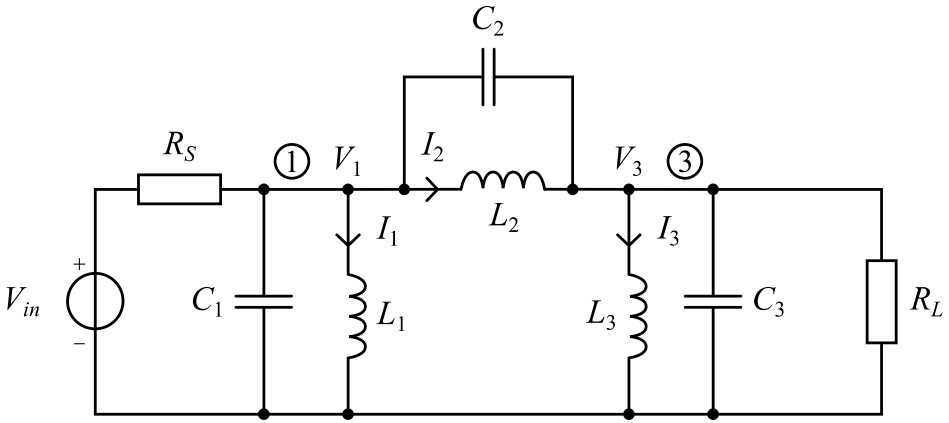


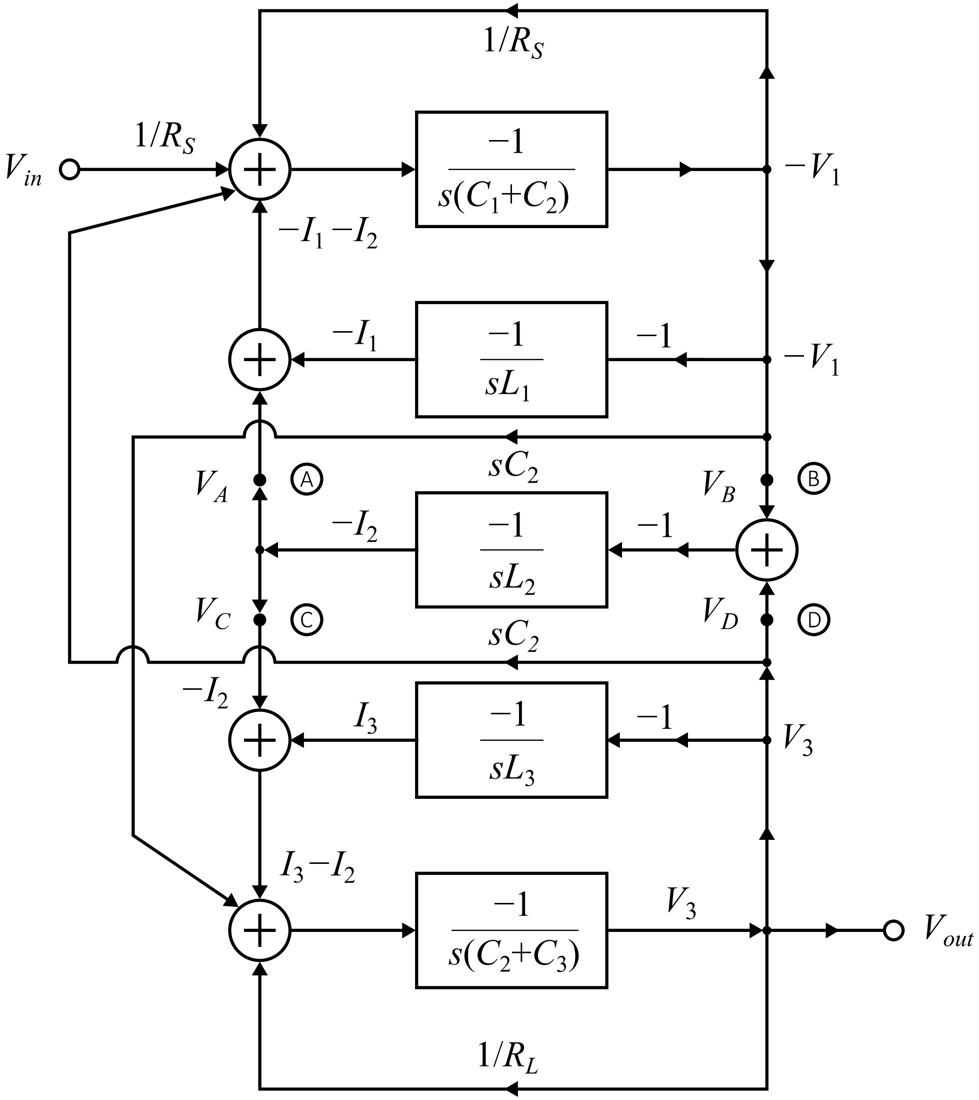
$$V_1 = \frac{\Delta Q}{C_1 + C_2'}$$



V_{in}
Φ_1
Φ_2
$C_S/2$
C_S
C_A
C_B
C_C
C_L
C
C_2'
V_{out}

Band-pass filters





State equations:

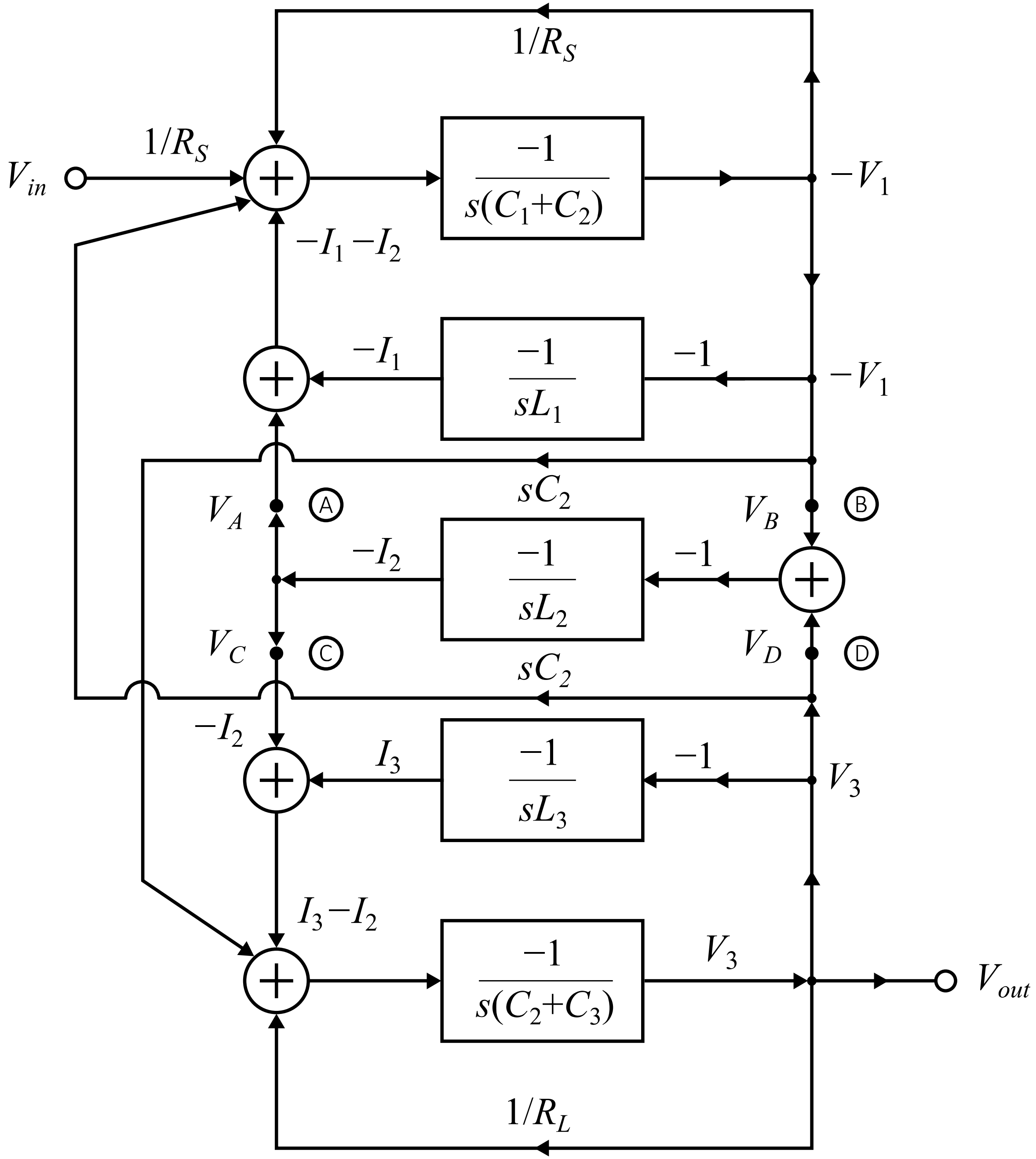
$$-V_1 = \frac{-1}{s(C_1+C_2)}\left[\frac{V_{in}-V_1}{R_S} + sC_2V_3 - I_1 - I_2\right]$$

$$-I_1 = \frac{-V_1}{sL_1}$$

$$-I_2 = \frac{-V_1+V_3}{sL_2}$$

$$-I_3 = \frac{-V_3}{sL_3}$$

$$V_3 = \frac{-1}{s(C_2+C_3)}\left[-sC_2V_1 + I_3 - I_2 + \frac{V_3}{R_L}\right]$$



1/R_S
V_in
1/R_S
−1
s(C1+C2)
−V1
−I1 −I2
−I1
−1
sL1
−1
−V1
V_A
A
sC2
V_B
B
−I2
−1
sL2
−1
V_C
C
sC2
V_D
D
−I2
I3
−1
sL3
−1
V3
I3−I2
−1
s(C2+C3)
V3
V_out
1/R_L

Offset-voltages cause a problem of DC-instability!

$$H_{AB} = \frac{V_B}{V_A} = \frac{-sL_1}{s^2 L_1 (C_1 + C_2) + \frac{sL_1}{R_S} + 1}$$

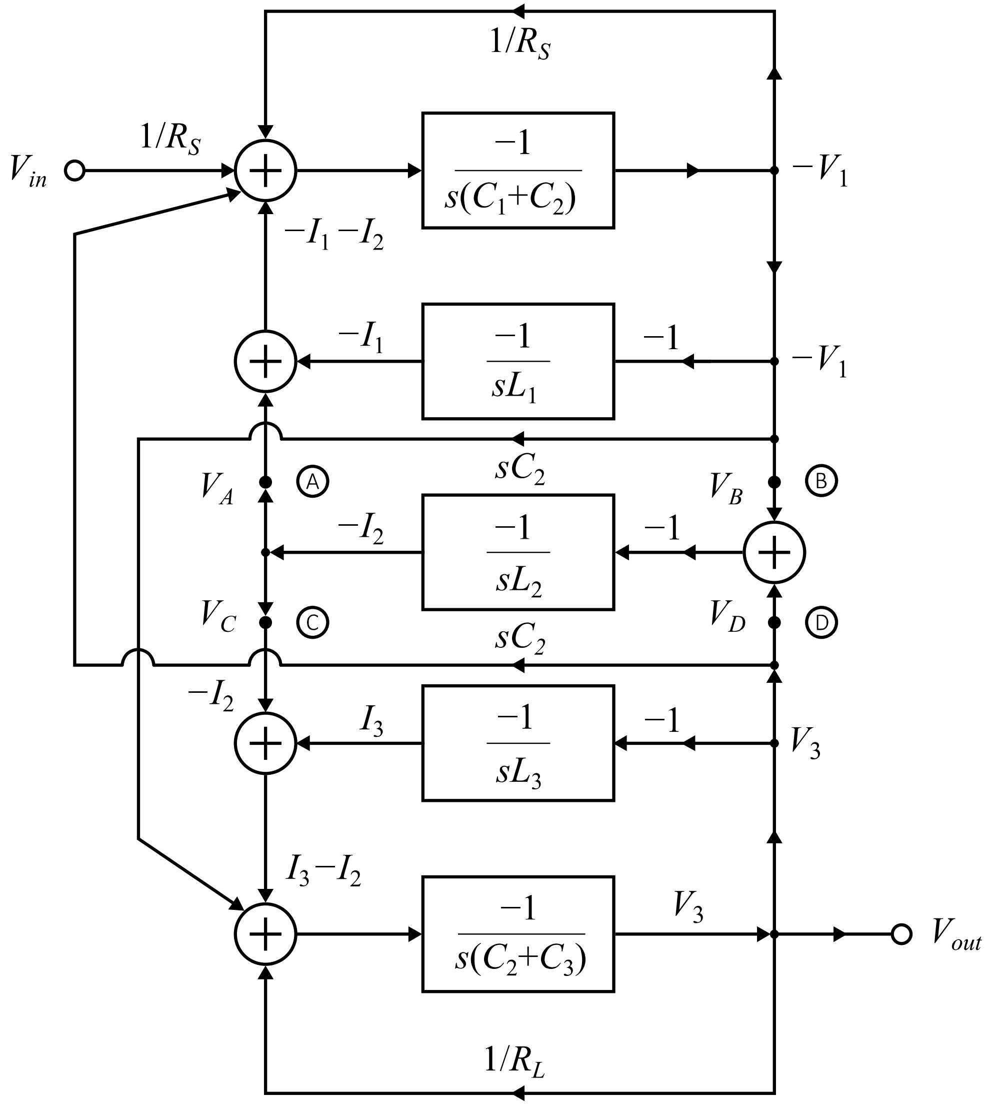
$$H_{CD} = \frac{V_C}{V_D} = \frac{-sL_3}{s^2 L_3 (C_2 + C_3) + \frac{sL_3}{R_L} + 1}$$

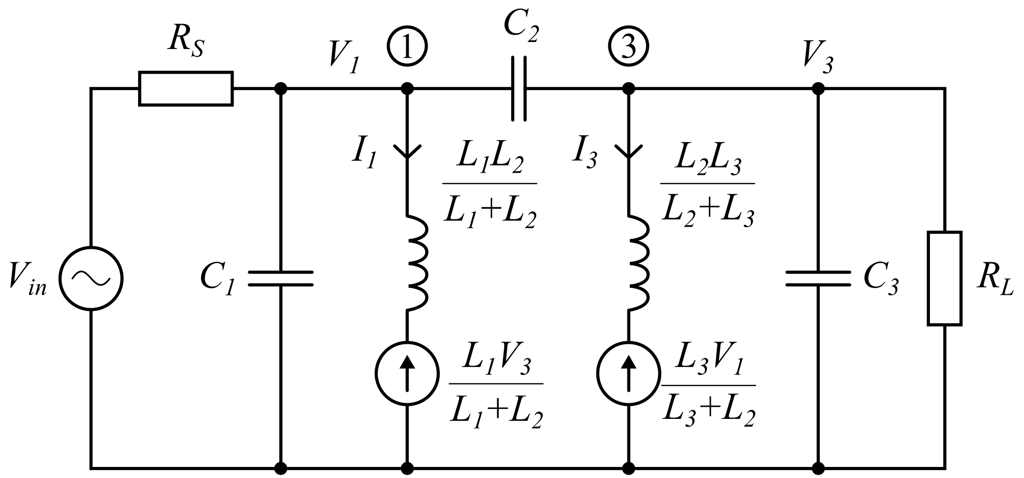
$nyt\ \ \mathrm{s} \rightarrow 0 \Rightarrow \mathrm{H_{AB}} \rightarrow 0$ ja $\mathrm{H_{CD}} \rightarrow 0$

$\Rightarrow -\frac{1}{sL_2}$ - integrator has no DC - feedback!!

$\Rightarrow$ saturates!!

Also $\frac{1}{\mathrm{sL_1}}$ - and $\frac{1}{sL_3}$ - integrators saturate!





Current equation of node 1

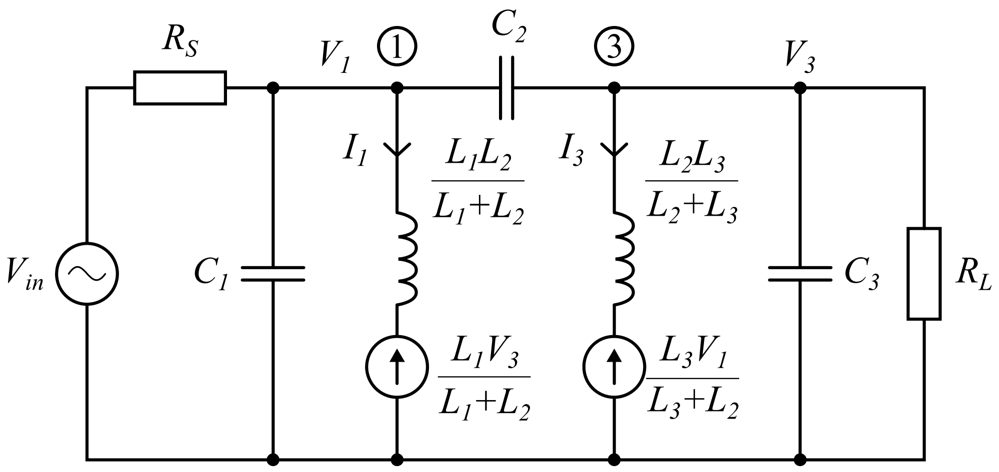
$$0 = \frac{V_{in} - V_1}{R_S} - sC_1V_1 - sC_2\left(V_1 - V_3\right) - \frac{1}{\frac{sL_1L_2}{L_1 + L_2}}\left(V_1 - \frac{L_1V_3}{L_1 + L_2}\right)$$

$$= \ldots\ldots \qquad - \left[\frac{1}{\frac{sL_1L_2}{L_1 + L_2}}V_1 - \frac{1}{sL_2}V_3\right]$$

$$= \qquad \ldots\ldots \qquad - \left[\left(\frac{1}{sL_2} + \frac{1}{sL_1}\right)V_1 - \frac{1}{sL_2}V_3\right]$$

$$= \qquad \ldots\ldots \qquad - \left[\frac{1}{sL_1}V_1 + \frac{1}{sL_2}\left(V_1 - V_3\right)\right]$$

$$0 = \frac{V_{in} - V_1}{R_S} - sC_1V_1 - \frac{V_1}{sL_1} - sC_2\left(V_1 - V_3\right) - \frac{1}{sL_2}\left(V_1 - V_3\right)$$



new state equations:

$$-V_1 = \frac{-1}{s(C_1+C_2)}\left[\frac{V_{in}-V_1}{R_S} + sC_2V_3 - I_{(1)}\right],$$

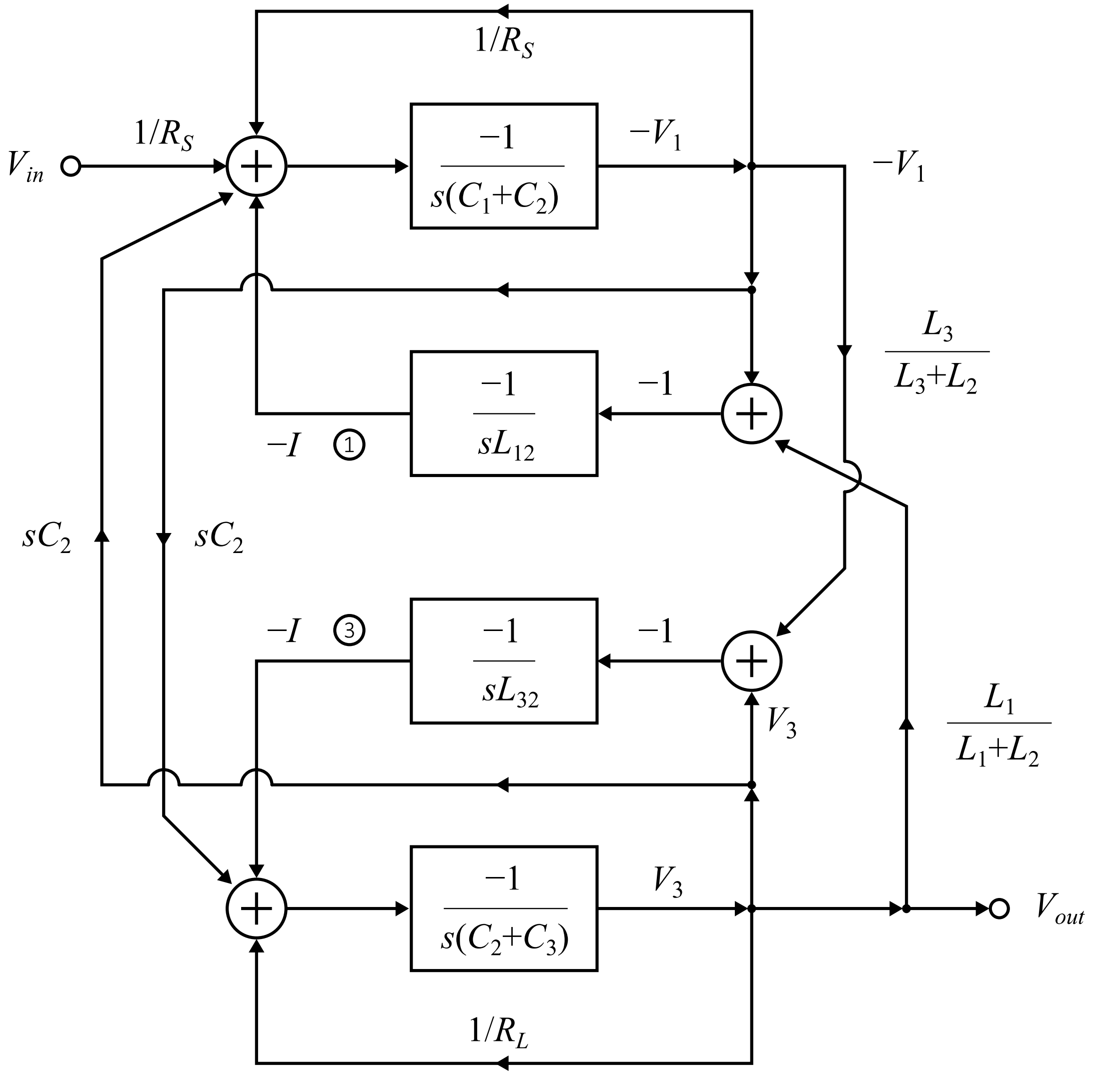
$$-I_{(1)} = -(I_1+I_2) = \frac{-1}{sL_{12}}\left[V_1 - \frac{L_1V_3}{L_1+L_2}\right],$$

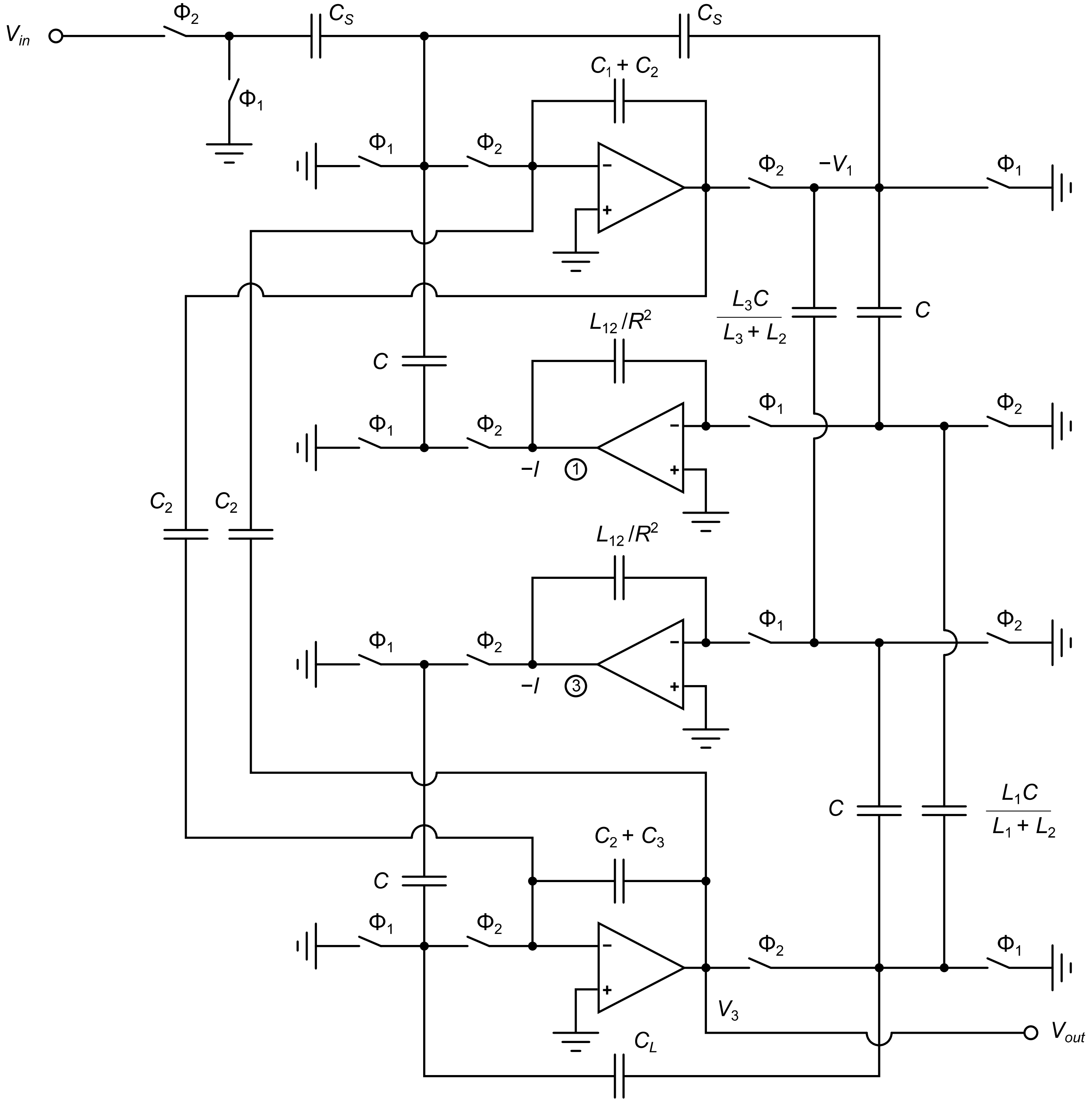
$$V_3 = \frac{-1}{s(C_2+C_3)}\left[-sC_2V_1 - I_{(3)} + \frac{V_3}{R_L}\right],$$

$$-I_{(3)} = I_3 - I_2 = \frac{-1}{sL_{32}}\left[-V_3 + \frac{L_3V_1}{L_3+L_2}\right],$$

where $L_{12} = L_1 \| L_2 = \frac{L_1L_2}{L_1+L_2}$.

$L_{32} = L_3 \| L_2$





V_{in}
Φ_2
C_S
C_S
Φ_1
$C_1 + C_2$
Φ_1
Φ_2
Φ_2
$-V_1$
Φ_1
$\frac{L_3C}{L_3 + L_2}$
C
L_{12}/R^2
C
Φ_1
Φ_2
Φ_1
Φ_2
$-I$
1
C_2
C_2
L_{12}/R^2
Φ_1
Φ_2
Φ_1
Φ_2
$-I$
3
C
$\frac{L_1C}{L_1 + L_2}$
$C_2 + C_3$
C
Φ_1
Φ_2
Φ_2
Φ_1
V_3
C_L
V_{out}