

Übung 5 – Elektronische Schaltungen (ES)

Sommersemester 2020

Operationsverstärker

INSTITUT FÜR HOCHFREQUENZTECHNIK UND ELEKTRONIK



Aufgabe 1

- a) ges.: 3 wichtigsten Eigenschaften eines ideal OV's

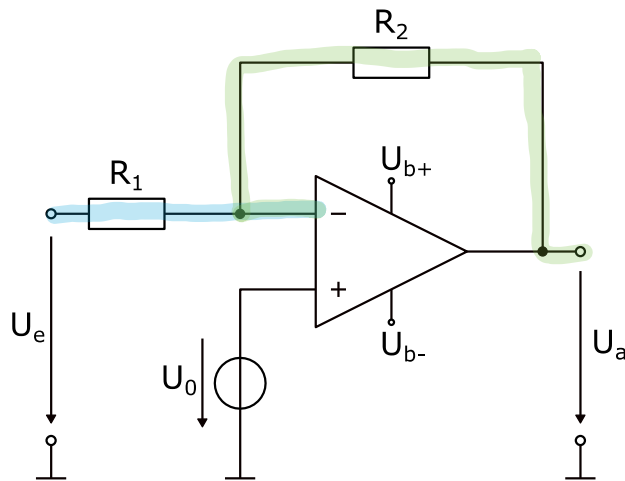
$$r_e \rightarrow \infty$$

$$r_a \rightarrow 0$$

$$A_D \rightarrow \infty$$

Aufgabe 1

■ b) ges.: Grundschialtung

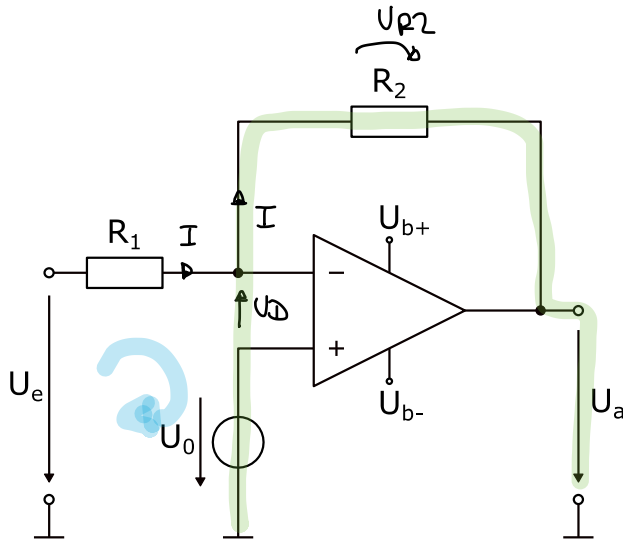


$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $U_b = \pm 15 \text{ V}$
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1. U_e : neg. Eingang \rightarrow invertierend
 2. Kopplung: Gegenkopplung
 3. Bauteile: Widerstände
- \rightarrow Invertierender Verstärker

Aufgabe 1

- c) ges.: $U_a(U_e)$ für $U_0 = 0V$



$$I: U_e = I \cdot R_1 - U_0 + U_0 = I \cdot R_1 + U_0 \rightarrow I = \frac{U_e - U_0}{R_1}$$

$$II: U_a = -I \cdot R_2 + U_0 = -\frac{U_e - U_0}{R_1} \cdot R_2 + U_0$$

$$= -\frac{R_2}{R_1} U_e + U_0 \left(1 + \frac{R_2}{R_1}\right)$$

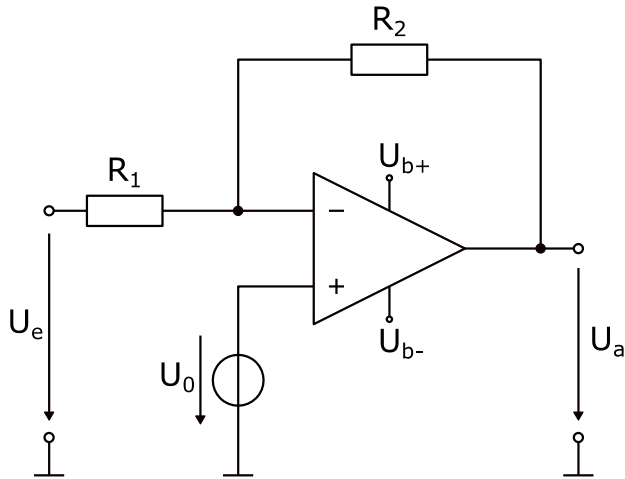
$$= -2 \cdot U_e + U_0 (1 + 2)$$

$$U_0 = 0V : U_a = -2 \cdot U_e$$

$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $U_0 = \pm 15 \text{ V}$
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Aufgabe 1

- d) ges.: $U_a(U_e)$ für $U_0 = 5V$



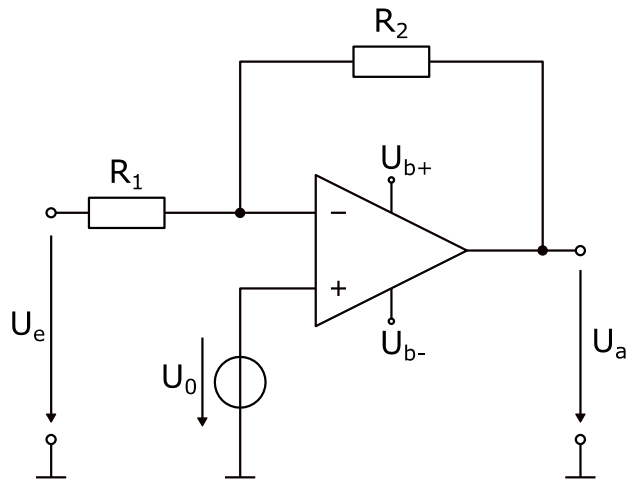
$$U_a = -2 \cdot U_e + U_0 (1 + 2)$$

$$U_a = -2 \cdot U_e + 15 V$$

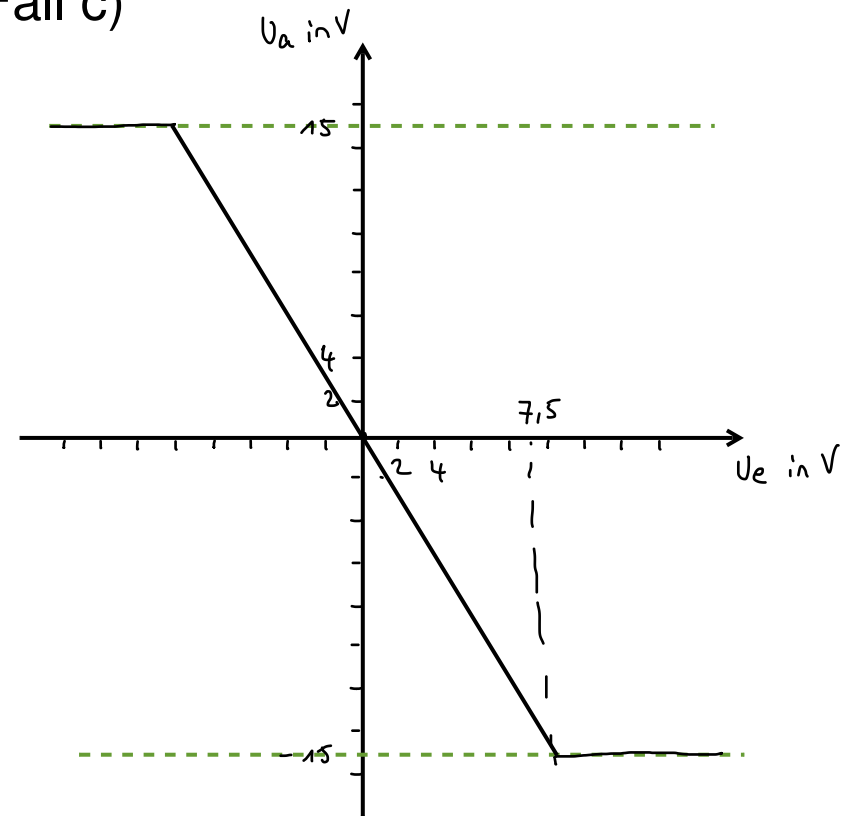
$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $U_b = \pm 15 \text{ V}$
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Aufgabe 1

- e) ges.: Übertragungskennlinie für Fall c)



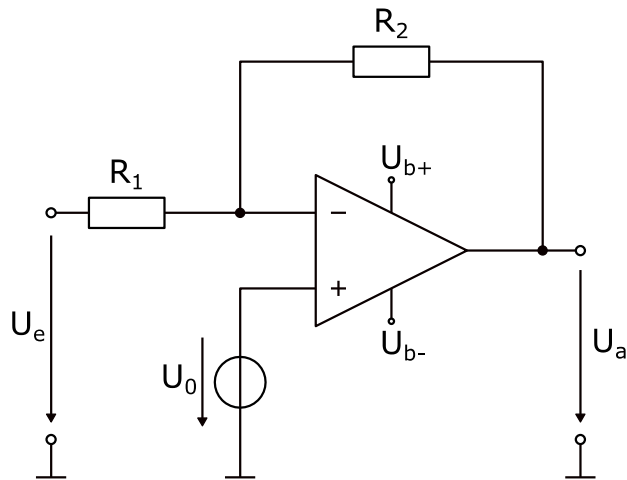
$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $U_b = \pm 15 \text{ V}$
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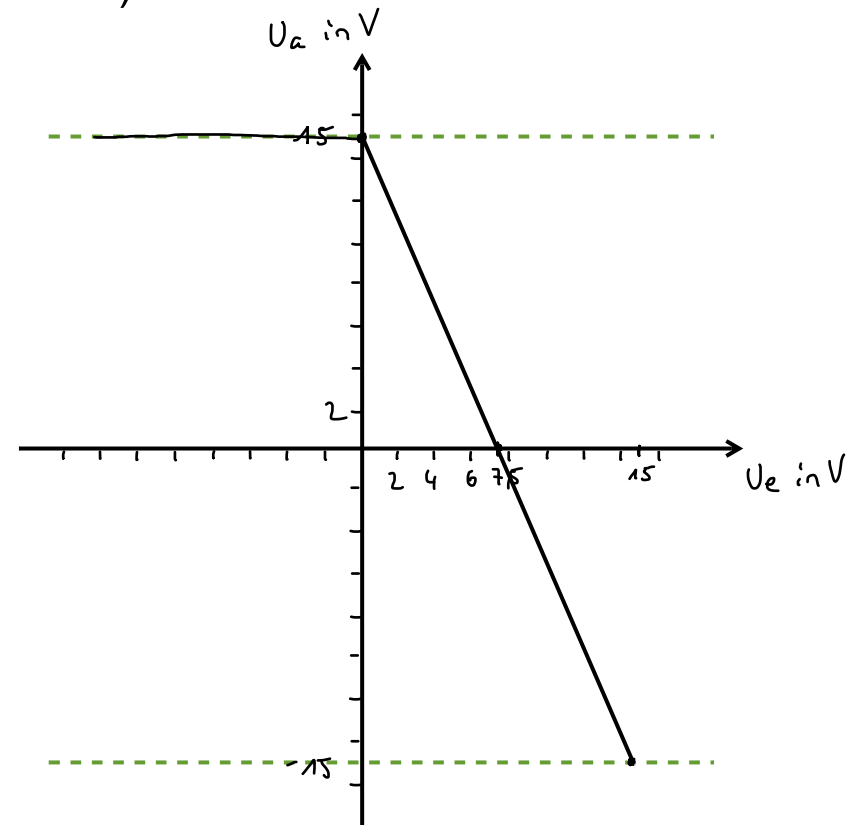
$$U_a = -2 \cdot U_e$$

Aufgabe 1

- e) ges.: Übertragungskennlinie für Fall d)



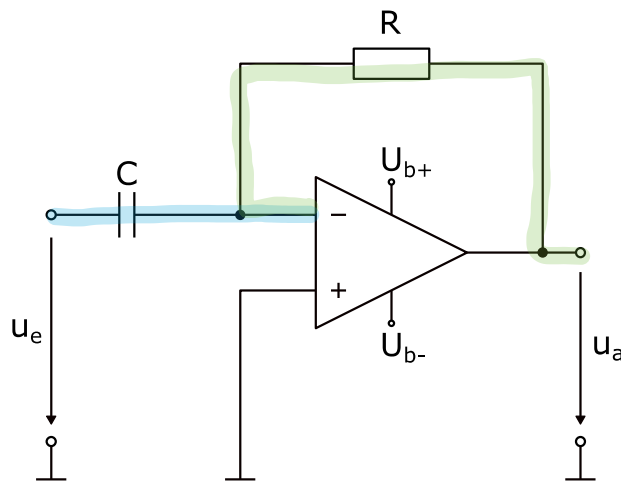
$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $U_b = \pm 15 \text{ V}$
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$$U_a = -2 \cdot U_e + 15 \text{ V}$$

Aufgabe 2

■ a) ges.: Grundschialtung

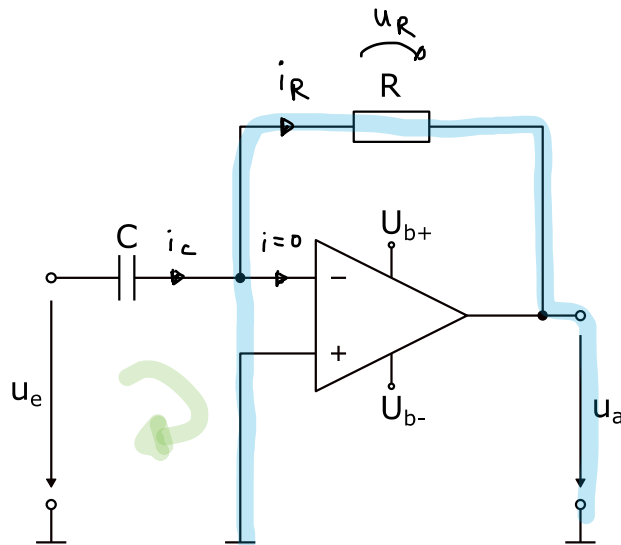


$R = 10 \text{ k}\Omega$ $C = 1 \text{ }\mu\text{F}$ $U_b = \pm 15 \text{ V}$

1. U_e : neg. Eingang des OV \rightarrow invertierend
2. Kopplung: Gegenkopplung
3. Bauteile: C, R
 \hookrightarrow Invertierender Differenzierer

Aufgabe 2

■ b) ges.: $u_a(u_e)$



$$u_a = -u_R = -i_R \cdot R$$

$$i_R = i_c$$

$$i_c(t) = C \cdot \frac{du_e(t)}{dt}$$

$$u_a(t) = -R \cdot C \cdot \frac{du_e(t)}{dt}$$

$$R = 10 \text{ k}\Omega$$

$$C = 1 \text{ }\mu\text{F}$$

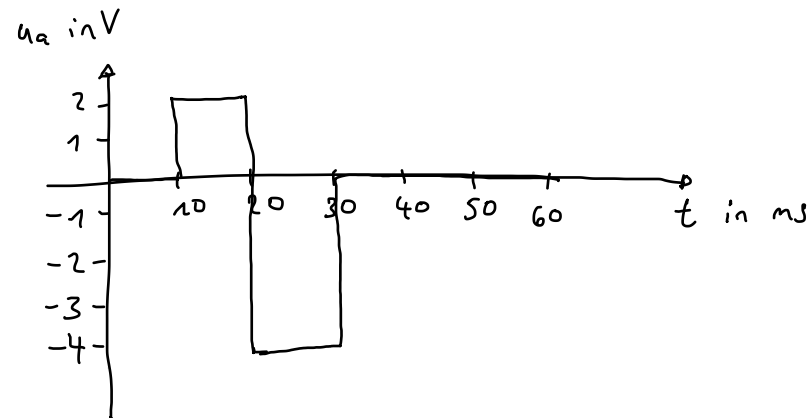
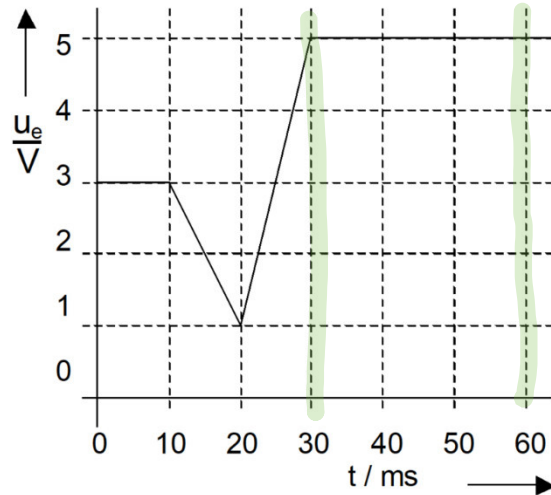
$$U_b = \pm 15 \text{ V}$$

Aufgabe 2

c) ges.: $u_a(t)$

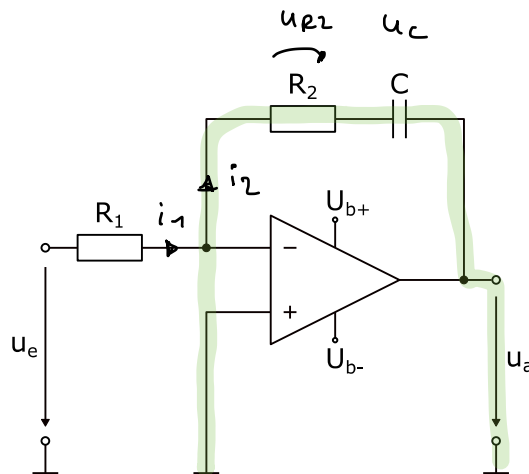
$$\begin{aligned}
 u_a(t) &= -R \cdot C \cdot \frac{d u_e(t)}{dt} \\
 &= -10 \text{ k}\Omega \cdot 1 \mu\text{F} \cdot \frac{d u_e(t)}{dt} \\
 &= -10 \text{ ms} \cdot \frac{d u_e(t)}{dt}
 \end{aligned}$$

zeitintervalle in ms	$\frac{d u_e(t)}{dt}$ in $\frac{\text{V}}{\text{ms}}$	u_a in V
$0 < t < 10$	0	0
$10 < t < 20$	$-\frac{2}{10}$	+2
$20 < t < 30$	$\frac{4}{10}$	-4
$30 < t < 60$	0	0



Aufgabe 2

■ d) ges.: $u_a(u_e)$



$R_1 = 10 \text{ k}\Omega$
$R_2 = 20 \text{ k}\Omega$
$C = 1 \text{ }\mu\text{F}$
$U_b = \pm 15 \text{ V}$
$u_c(t=0) = 0 \text{ V}$

$$u_a = -(u_{R2} + u_c) = -\left(i_2 \cdot R_2 + \frac{1}{C} \int_0^t i_2(\tau) d\tau + u_c(t=0)\right)$$

$$i_2 = i_1 = \frac{u_e}{R_1}$$

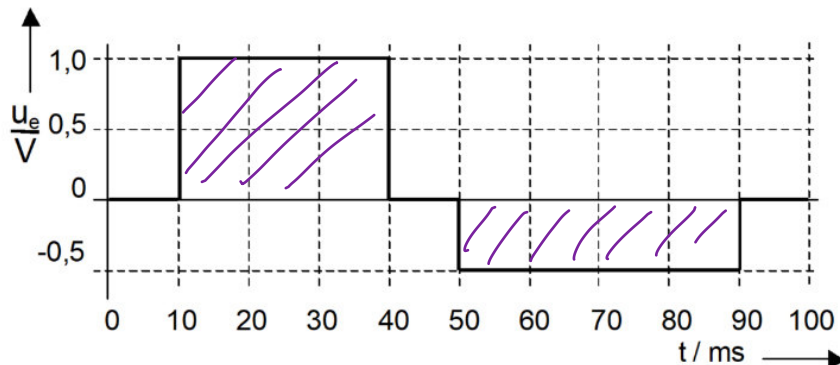
$$u_a(t) = \underbrace{-\frac{R_2}{R_1} \cdot u_e(t)}_{\text{inv. Verstärker}} - \underbrace{\frac{1}{C \cdot R_1} \int_0^t u_e(\tau) d\tau}_{\text{inv. Integrator}}$$

$$= -2 \cdot u_e(t) - \frac{1}{10 \text{ ms}} \int_0^t u_e(\tau) d\tau$$

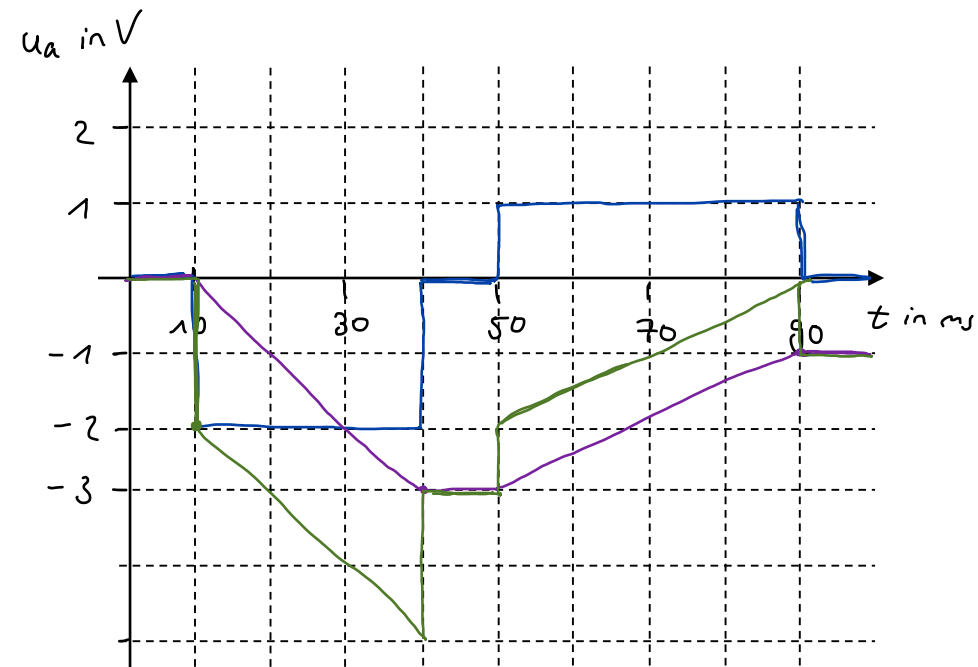
Aufgabe 2

■ d) ges.: $u_a(u_e)$

$$u_a(t) = -2 \cdot u_e(t) - \frac{1}{10\text{ms}} \int_0^t u_e(\tau) d\tau$$



$$-\frac{1}{10\text{ms}} (1\text{V} \cdot 30\text{ms}) - \frac{1}{10\text{ms}} (-0,5\text{V} \cdot 40\text{ms})$$



Aufgabe 2

■ d) ges.: $u_a(u_e)$ $u_a(t) = -2 \cdot u_e(t) - \frac{1}{10\text{ms}} \int_0^t u_e(\tau) d\tau$

$0 < t < 10\text{ms}$ $u_a(t) = -2 \cdot 0\text{V} - \frac{1}{10\text{ms}} \int_0^t 0\text{V} \cdot d\tau = 0\text{V}$

$10\text{ms} < t < 40\text{ms}$ $u_a(t) = -2 \cdot 1\text{V} - \frac{1}{10\text{ms}} \cdot \left[\int_0^{10\text{ms}} 0\text{V} d\tau + \int_{10\text{ms}}^t u_e(\tau) d\tau \right]$

$$= -2\text{V} - \frac{1}{10\text{ms}} \left[1\text{V} \cdot \tau \right]_{10\text{ms}}^t = -2\text{V} - \frac{1}{10\text{ms}} (1\text{V} \cdot t - 1\text{V} \cdot 10\text{ms})$$

$u_a(t=10\text{ms}^+) = -2\text{V}$ $u_a(t=40\text{ms}^-) = -2\text{V} - 3\text{V} = -5\text{V}$

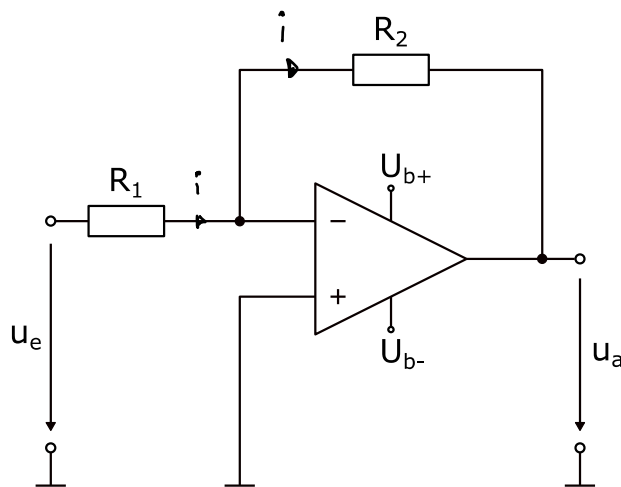
$40\text{ms} < t < 50\text{ms}$ $u_a(t) = -2 \cdot 0\text{V} - \frac{1}{10\text{ms}} \cdot \left[\int_0^{10\text{ms}} 0\text{V} d\tau + \int_{10\text{ms}}^{40\text{ms}} 1\text{V} d\tau + \int_{40\text{ms}}^t 0 d\tau \right]$

$$= -\frac{1}{10\text{ms}} \cdot \left[1\text{V} \cdot \tau \right]_{10\text{ms}}^{40\text{ms}} = -\frac{1}{10\text{ms}} \cdot [1\text{V} \cdot 40\text{ms} - 1\text{V} \cdot 10\text{ms}]$$

$= -3\text{V} = u_a(t=40\text{ms}^+) = u_a(t=50\text{ms}^-)$

Aufgabe 3 – Schaltung (a)

- a) ges.: Grundschtaltung & $u_a(u_e)$



$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$
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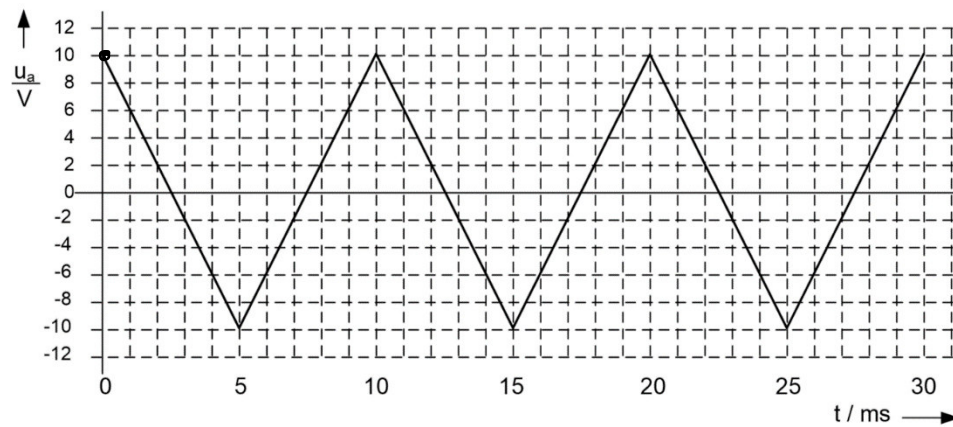
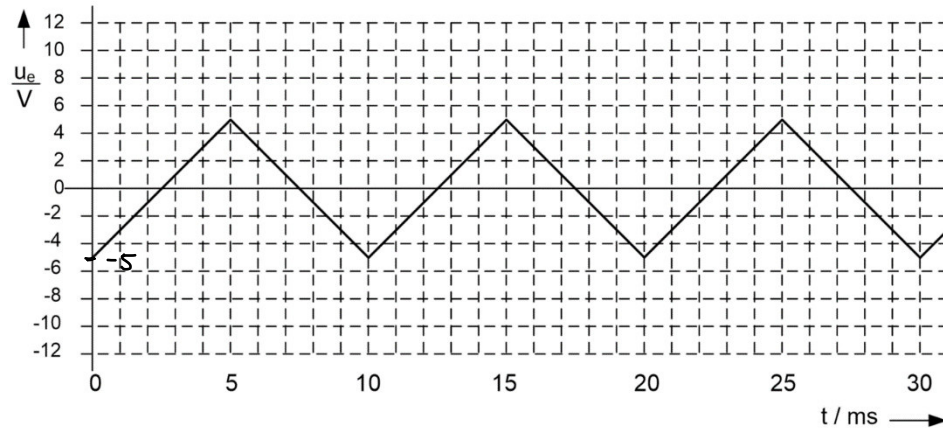
u_e : inv. Eingang 0V
 Kopplung: Gegenkopplung
 Bauteile: Widerstände

} Inv. Verstärker

$$\begin{aligned}
 u_a &= -i \cdot R_2 = -\frac{u_e}{R_1} \cdot R_2 \\
 &= -2 \cdot u_e
 \end{aligned}$$

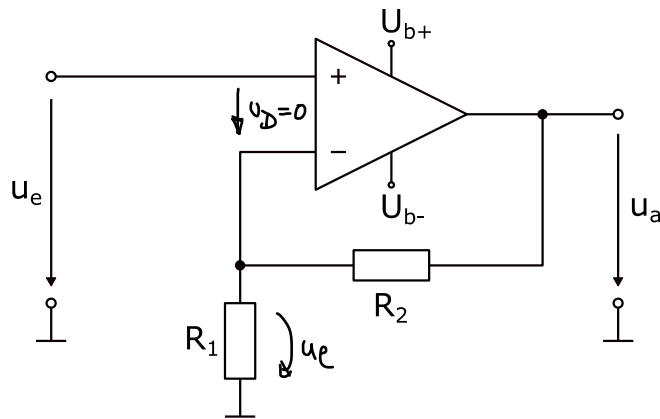
Aufgabe 3 – Schaltung (a)

■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (b)

- a) ges.: Grundschtaltung & $u_a(u_e)$



$$R_1 = 10 \text{ k}\Omega$$

$$R_2 = 20 \text{ k}\Omega$$

u_e : nicht inv. OV
 Kopplung: Gegenkopplung
 Bauteile: widerstände

}

Nicht inv. Verstärker

$$\frac{u_e}{u_a} = \frac{R_1}{R_1 + R_2} \rightarrow u_a = \frac{R_1 + R_2}{R_1} \cdot u_e$$

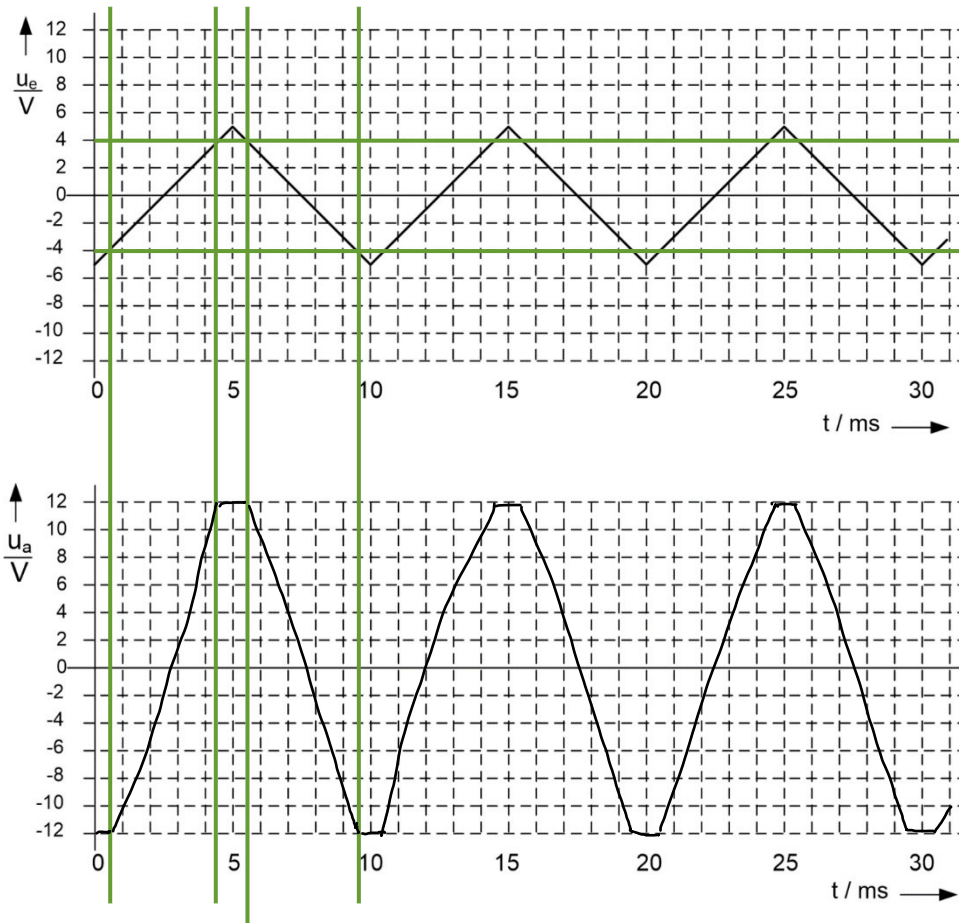
$$= 3 \cdot u_e \rightarrow -4V \leq u_e \leq 4V$$

$$u_a = 12V \rightarrow u_e = 4V$$

$$u_a = -12V \rightarrow u_e = -4V$$

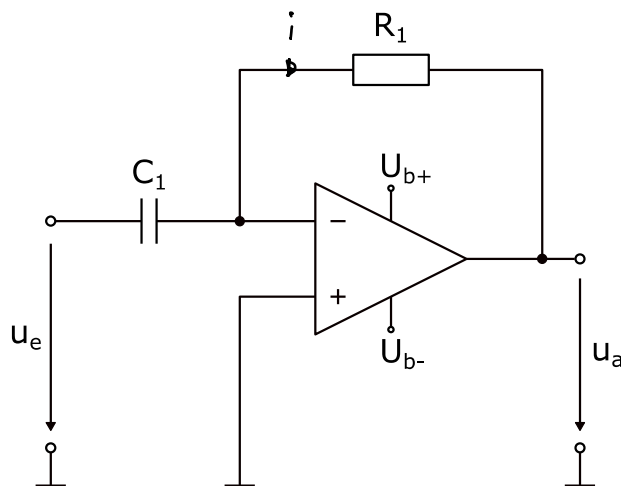
Aufgabe 3 – Schaltung (b)

■ b) ges.: $u_a(t) = 3 \cdot u_e(t) \quad -4V < u_e < 4V$



Aufgabe 3 – Schaltung (c)

- a) ges.: Grundsaltung & $u_a(u_e)$



$$R_1 = 10 \text{ k}\Omega$$

$$C_1 = 0,5 \text{ }\mu\text{F}$$

u_e : inv. Eingang des OVs
 Kopplung: Gegenkopplung
 Bauteil: C_1, R_1

}

inv. Differenzverstärker

$$u_a = -i R_1 \quad i = C_1 \cdot \frac{du_e}{dt}$$

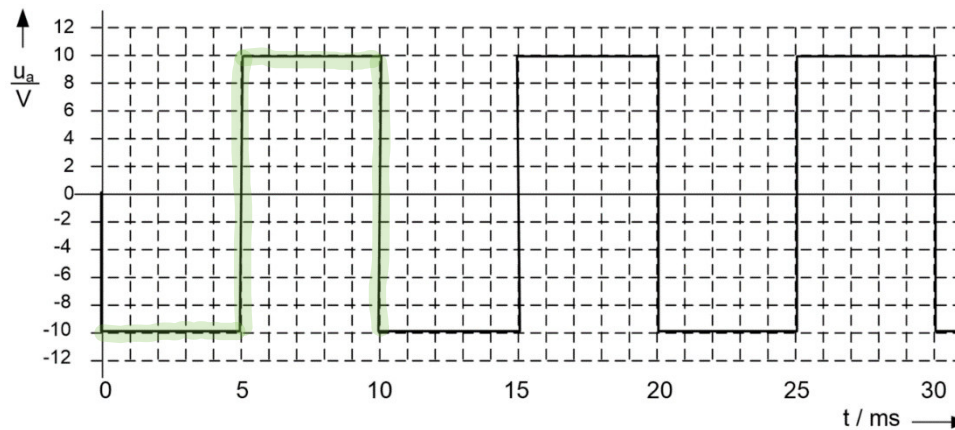
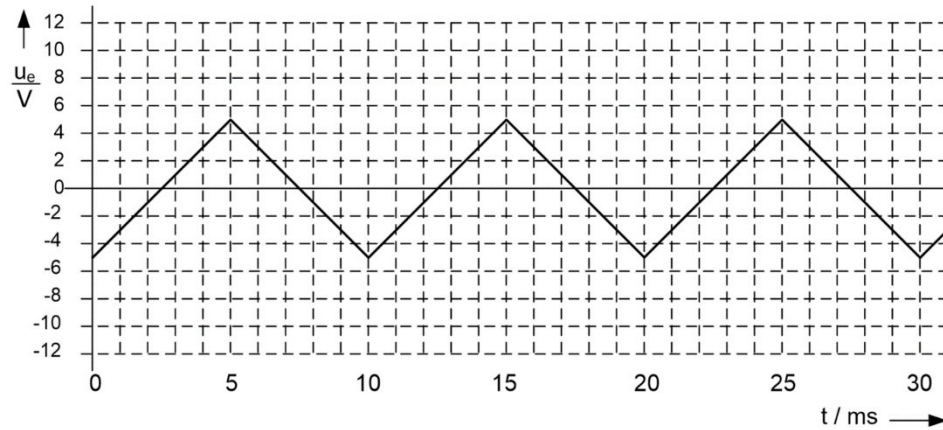
$$= -R_1 C_1 \frac{du_e}{dt} = -5 \text{ ms} \frac{du_e}{dt}$$

$$0 < t < 5 \text{ ms} \quad \frac{du_e}{dt} = \frac{10 \text{ V}}{5 \text{ ms}} = 2 \frac{\text{V}}{\text{ms}} \rightarrow u_a = -10 \text{ V}$$

$$5 \text{ ms} < t < 10 \text{ ms} \quad \frac{du_e}{dt} = -2 \frac{\text{V}}{\text{ms}} \rightarrow u_a = +10 \text{ V}$$

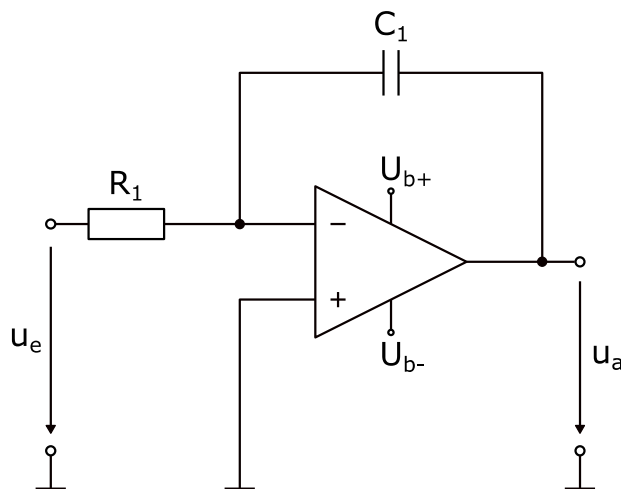
Aufgabe 3 – Schaltung (c)

■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (d)

- a) ges.: Grundsaltung & $u_a(u_e)$



$$R_1 = 10 \text{ k}\Omega$$

$$C_1 = 0,1 \text{ }\mu\text{F}$$

Inv. Integrator

$$u_a = - \frac{1}{C_1} \cdot \int_0^t i(\tau) d\tau + u_c(t=0) \quad , \quad i = \frac{u_e}{R_1}$$

$\stackrel{0V}{\leftarrow}$

$$= - \frac{1}{R_1 \cdot C_1} \cdot \int_0^t u_e(\tau) d\tau = - \frac{1}{1 \text{ ms}} \cdot \int_0^t u_e(\tau) d\tau$$

für $0 < t < 5 \text{ ms}$: $u_e(\tau) = 2 \frac{\text{V}}{\text{ms}} \tau - 5 \text{ V}$

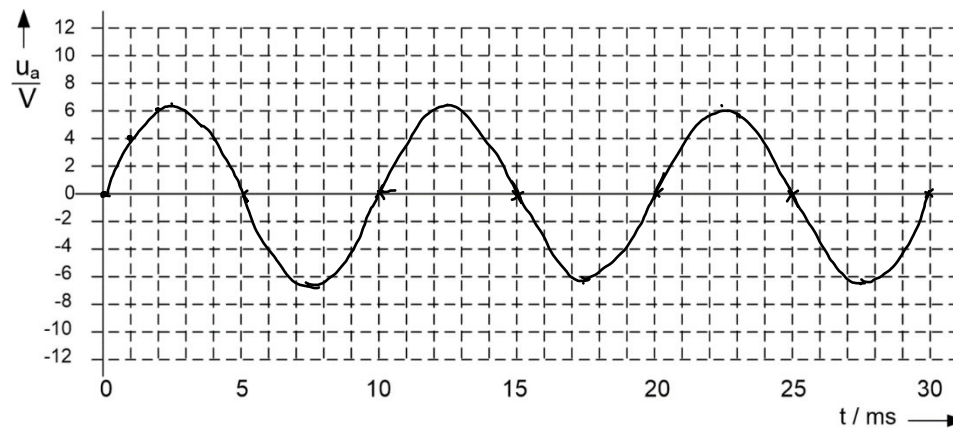
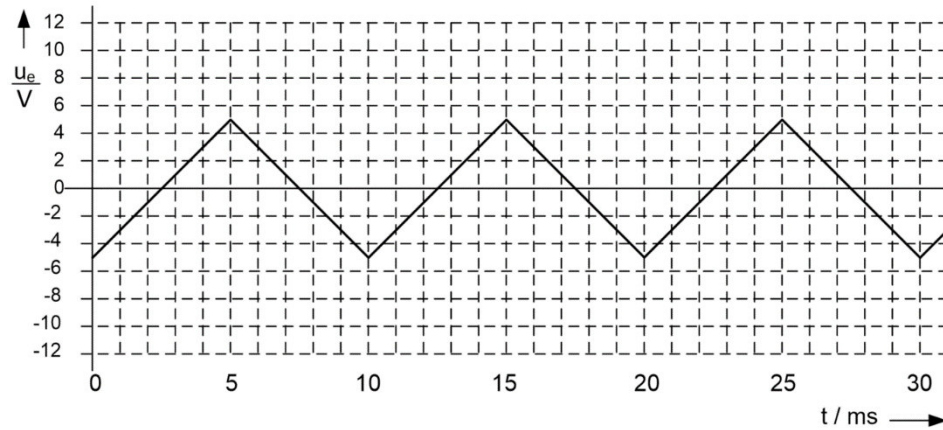
$$u_a = - \frac{1}{1 \text{ ms}} \cdot \int_0^t (2 \frac{\text{V}}{\text{ms}} \tau - 5 \text{ V}) d\tau = - \frac{1}{1 \text{ ms}} \left[1 \frac{\text{V}}{\text{ms}} \tau^2 - 5 \text{ V} \cdot \tau \right]_0^t$$

$$= - \frac{1}{1 \text{ ms}} \cdot \left(1 \frac{\text{V}}{\text{ms}} t^2 - 5 \text{ V} t \right)$$

t in ms	u _a in V
0	0
1	4
2	6
2,5	6,25
3	6
4	4
5	0

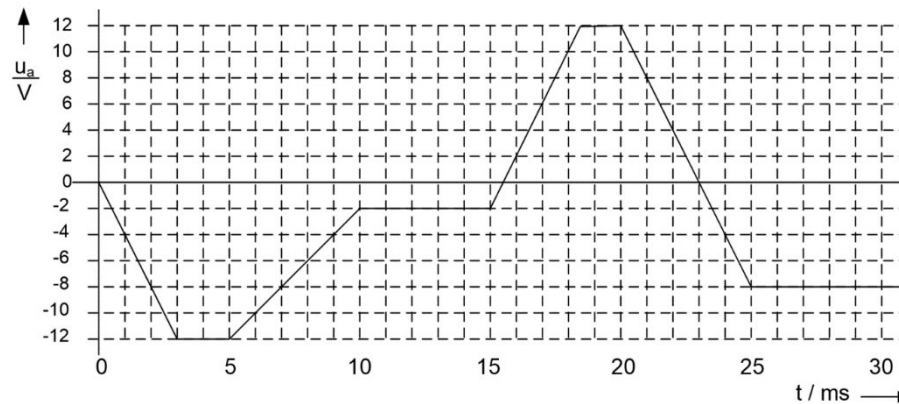
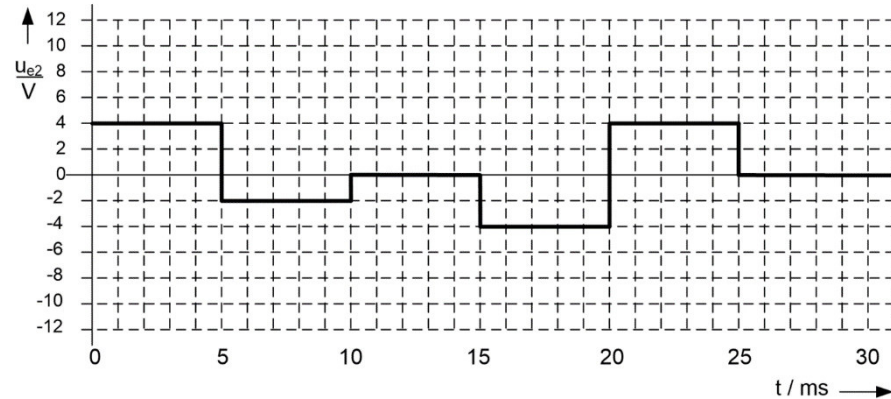
Aufgabe 3 – Schaltung (d) mit $u_e(t)$

■ b) ges.: $u_a(t)$



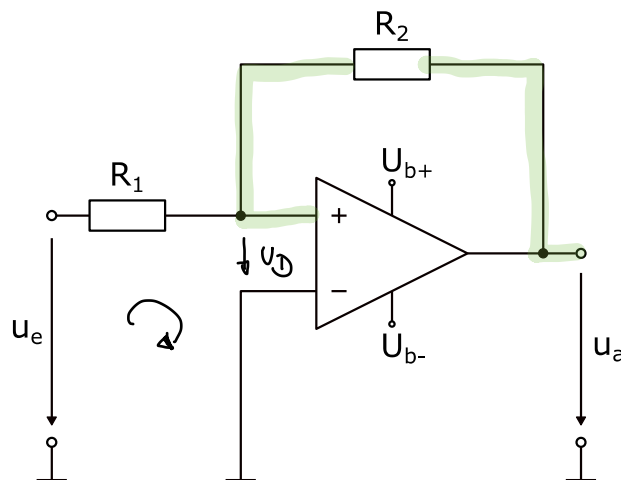
Aufgabe 3 – Schaltung (d) mit $u_{e2}(t)$

■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (e)

- a) ges.: Grundschialtung & $u_a(u_e)$



$$R_1 = 10 \text{ k}\Omega$$

$$R_2 = 30 \text{ k}\Omega$$

Kopplung: Mitkopplung

→ Nicht inv. Schmitt-Trigger

$$U_D = -i R_1 + u_e$$

$$U_D = i R_2 + u_a \rightarrow i = \frac{U_D - u_a}{R_2}$$

$$U_D = -\frac{U_D - u_a}{R_2} \cdot R_1 + u_e$$

$$U_D \left(1 + \frac{R_1}{R_2}\right) = \frac{R_1}{R_2} u_a + u_e \rightarrow U_D = \frac{R_2}{R_1 + R_2} \cdot \frac{R_1}{R_2} u_a + \frac{R_2}{R_1 + R_2} u_e$$

$$= \frac{R_1}{R_1 + R_2} u_a + \frac{R_2}{R_1 + R_2} u_e$$

Schaltsschwellen: $U_D = 0$

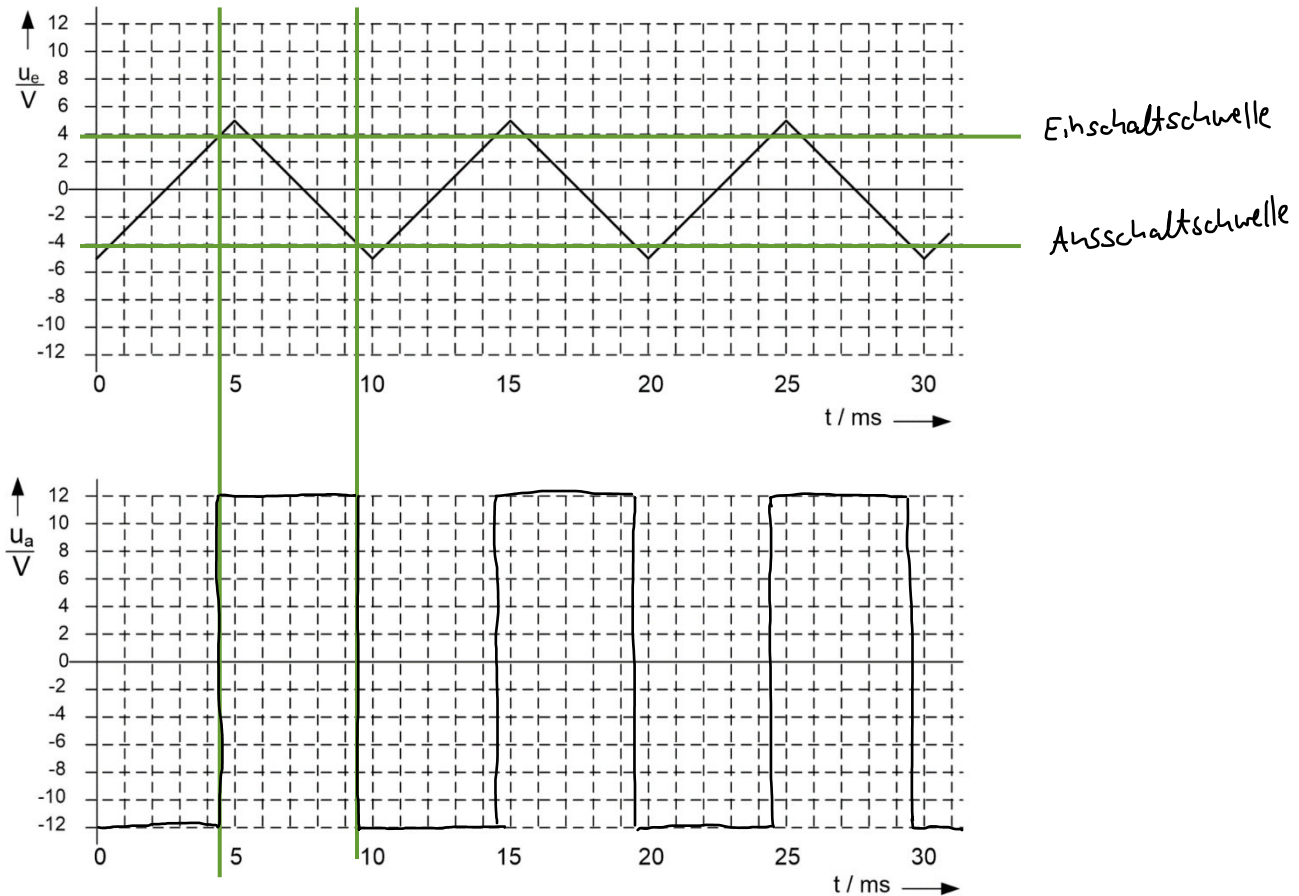
$$u_e = -\frac{R_1 + R_2}{R_2} \cdot \frac{R_1}{R_1 + R_2} u_a = -\frac{R_1}{R_2} u_a$$

$$u_a = U_{b-} = -12V : \text{Einschaltsschwelle: } u_e = -\frac{1}{3} \cdot (-12V) = 4V$$

$$u_a = U_{b+} = 12V : \text{Aus Schaltsschwelle: } u_e = -4V$$

Aufgabe 3 – Schaltung (e)

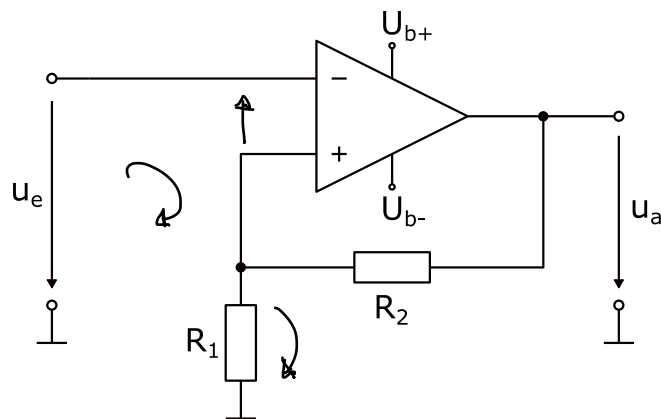
■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (f)

- a) ges.: Grundschtaltung & $u_a(u_e)$

Inv. Schmitt-Trigger



$$u_e = -u_D + U_{R1}$$

$$U_{R1} = \frac{R_1}{R_1 + R_2} \cdot u_a$$

$$\left. \begin{array}{l} u_e = -u_D + U_{R1} \\ U_{R1} = \frac{R_1}{R_1 + R_2} \cdot u_a \end{array} \right\} u_e = -u_D + \frac{R_1}{R_1 + R_2} \cdot u_a$$

$$u_D = 0$$

$$u_a = U_{b-} \rightarrow \text{Einschaltsschwelle: } u_e = \frac{1}{4} \cdot (-12V) = -3V$$

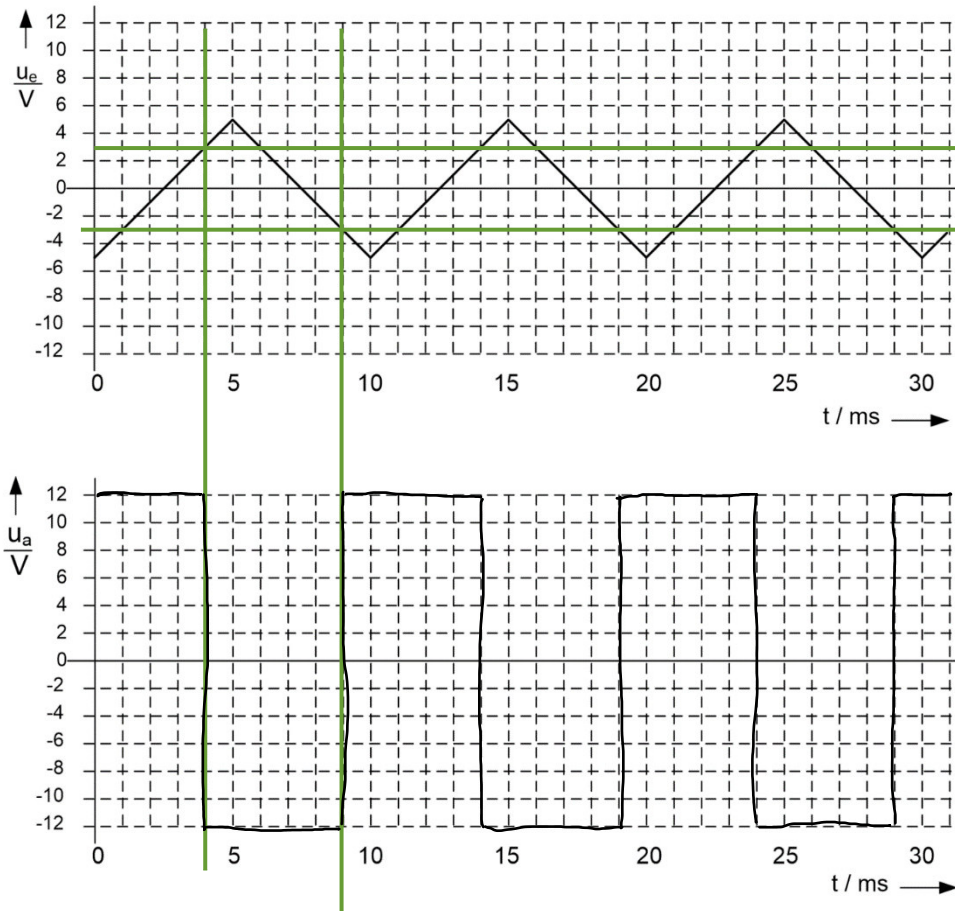
$$u_a = U_{b+} \rightarrow \text{Aus Schaltsschwelle } u_e = \frac{1}{4} \cdot (12V) = 3V$$

$$R_1 = 10 \text{ k}\Omega$$

$$R_2 = 30 \text{ k}\Omega$$

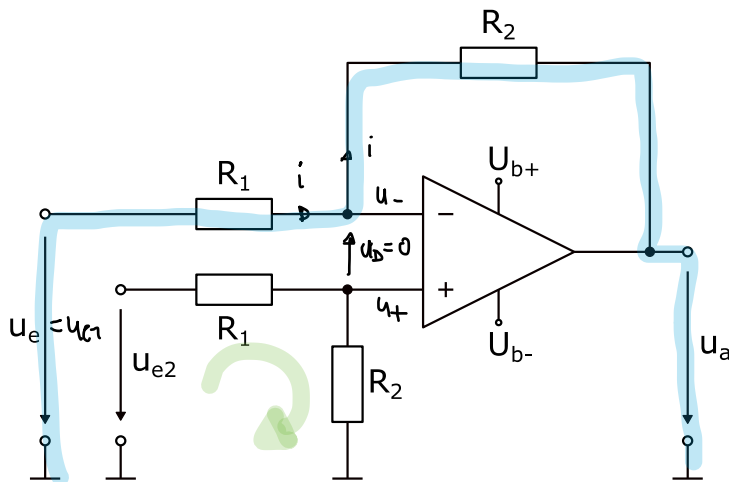
Aufgabe 3 – Schaltung (f)

■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (g)

- a) ges.: Grundschtaltung & $u_a(u_e)$



$R_1 = 10 \text{ k}\Omega$ $R_2 = 20 \text{ k}\Omega$ $u_{e1} = u_e$
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Subtrahierer

$$u_+ = \frac{R_2}{R_1 + R_2} \cdot u_{e2} = u_-$$

$$i = \frac{u_{e1} - u_-}{R_1} = \frac{u_{e1} - u_+}{R_1} = \frac{u_{e1}}{R_1} - \frac{R_2}{R_1 \cdot (R_1 + R_2)} \cdot u_{e2}$$

$$u_a = u_{e1} - i \cdot (R_1 + R_2)$$

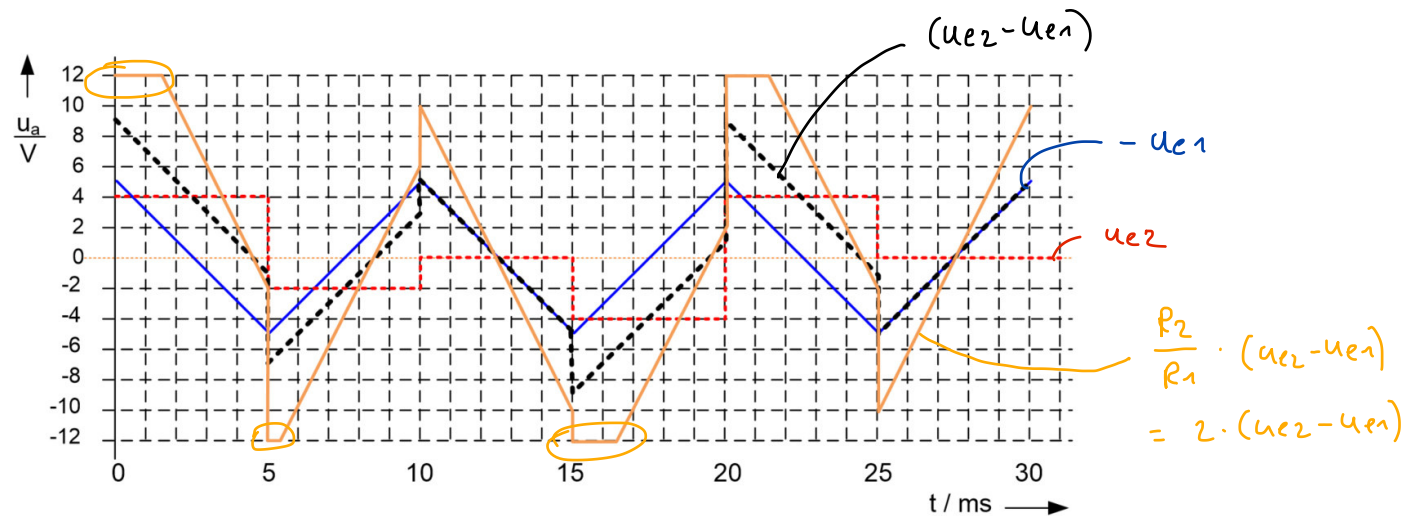
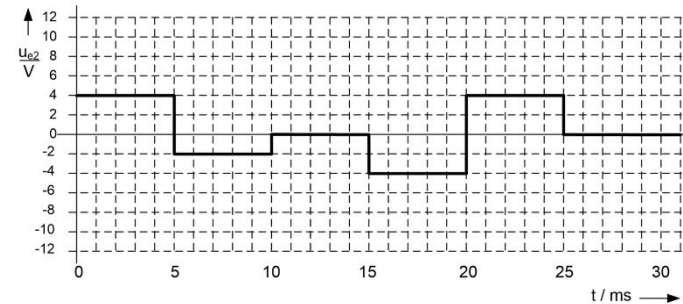
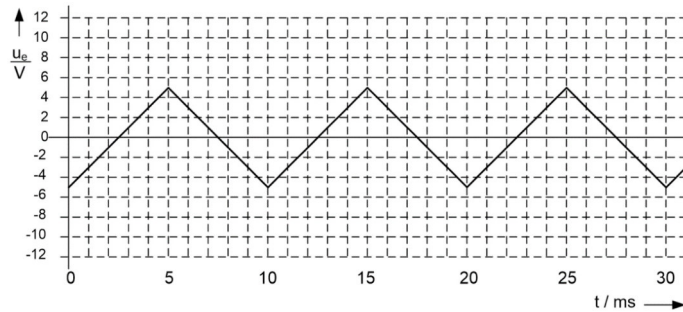
$$= u_{e1} - \frac{(R_1 + R_2)}{R_1} \cdot u_{e1} + \frac{R_2 \cdot (R_1 + R_2)}{R_1 \cdot (R_1 + R_2)} \cdot u_{e2}$$

$$= -\frac{R_2}{R_1} u_{e1} + \frac{R_2}{R_1} \cdot u_{e2} = \frac{R_2}{R_1} \cdot (u_{e2} - u_{e1})$$

$$= 2 \cdot (u_{e2} - u_{e1})$$

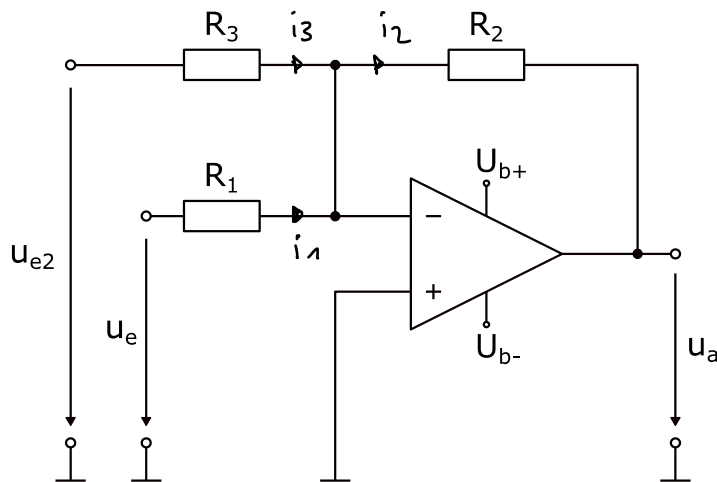
Aufgabe 3 – Schaltung (g)

■ b) ges.: $u_a(t)$



Aufgabe 3 – Schaltung (h)

- a) ges.: Grundschtaltung & $u_a(u_e)$



Inv. Addierer

$$i_1 = \frac{u_e}{R_1} = \frac{u_{e1}}{R_1}$$

$$i_3 = \frac{u_{e2}}{R_3}$$

$$i_2 = -\frac{u_a}{R_2}$$

$$i_1 + i_3 = i_2$$

$$\frac{u_{e1}}{R_1} + \frac{u_{e2}}{R_3} = -\frac{u_a}{R_2}$$

$$u_a = -R_2 \cdot \left(\frac{1}{R_1} u_{e1} + \frac{1}{R_3} u_{e2} \right)$$

$$= -2 u_{e1} - 1,5 u_{e2}$$

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$$R_1 = 10 \text{ k}\Omega$$

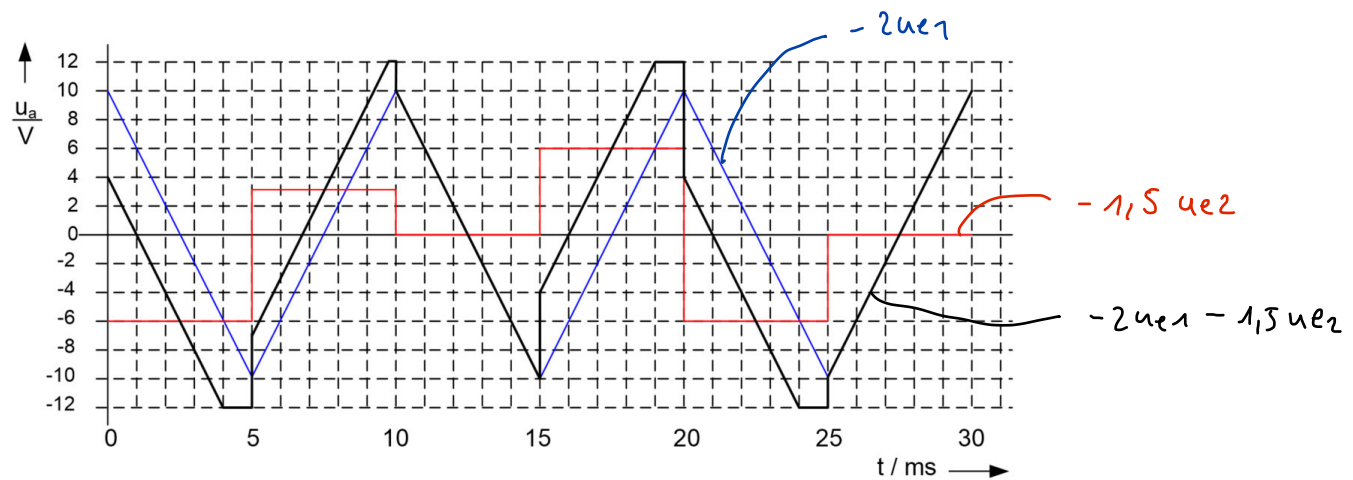
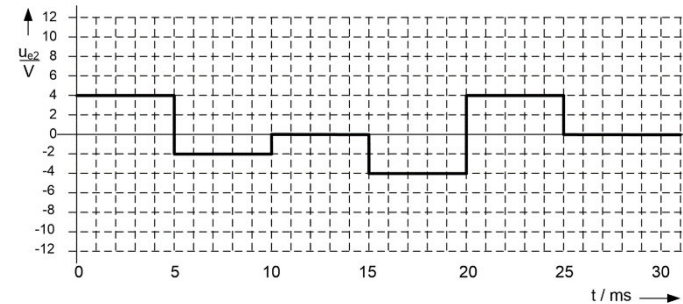
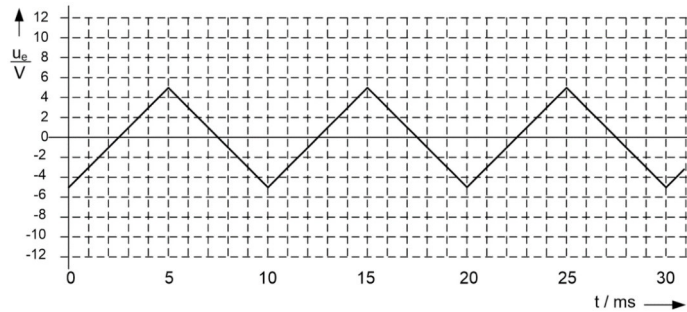
$$R_2 = 30 \text{ k}\Omega$$

$$R_3 = 20 \text{ k}\Omega$$

$$u_{e1} = u_e$$

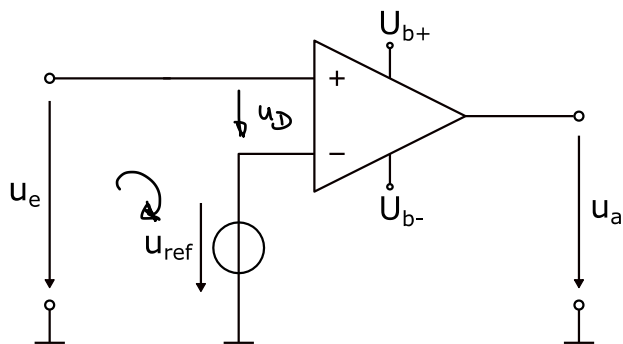
Aufgabe 3 – Schaltung (h)

■ b) ges.: $u_a(t) = -2 u_{e1} - 1,5 u_{e2}$



Aufgabe 3 – Schaltung (i)

- a) ges.: Grundschtaltung & $u_a(u_e)$



$$u_{\text{ref}} = 2 \text{ V}$$

Komparator

$$u_a = u_D \cdot A_D = (u_e - u_{\text{ref}}) \cdot A_D$$

$$u_a = -12 \text{ V} \quad u_e < u_{\text{ref}}$$

$$u_a = 12 \text{ V} \quad u_e > u_{\text{ref}} = 2 \text{ V}$$

Aufgabe 3 – Schaltung (i)

■ b) ges.: $u_a(t)$

