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PROGETTAZIONE DI UN CONVERTITORE BOOST



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Specifiche da rispettare

Boost-B

Tensione di ingresso nominale	10 V
Ripple della tensione di ingresso (picco-picco)	1 V a 100 Hz
Tensione di uscita regolata	20 V
Frequenza di switching (fsw)	500 kHz
Ripple della tensione di uscita (a fsw)	< 0.01×Vo
Resistenza di carico (min, max)	[40, 120] Ω
Banda (fc)	0.6 kHz < fc < 6 kHz
Margine di fase	$\pi/2$ (+/-10%)
Reiezioni ai disturbi: variazione della tensione di uscita rispetto al ripple della tensione di ingresso	ΔV_o (picco-picco) < 200 mV
Tensione di riferimento V_{REF}	2 V
V_M (PWM)	1 V



Obiettivi

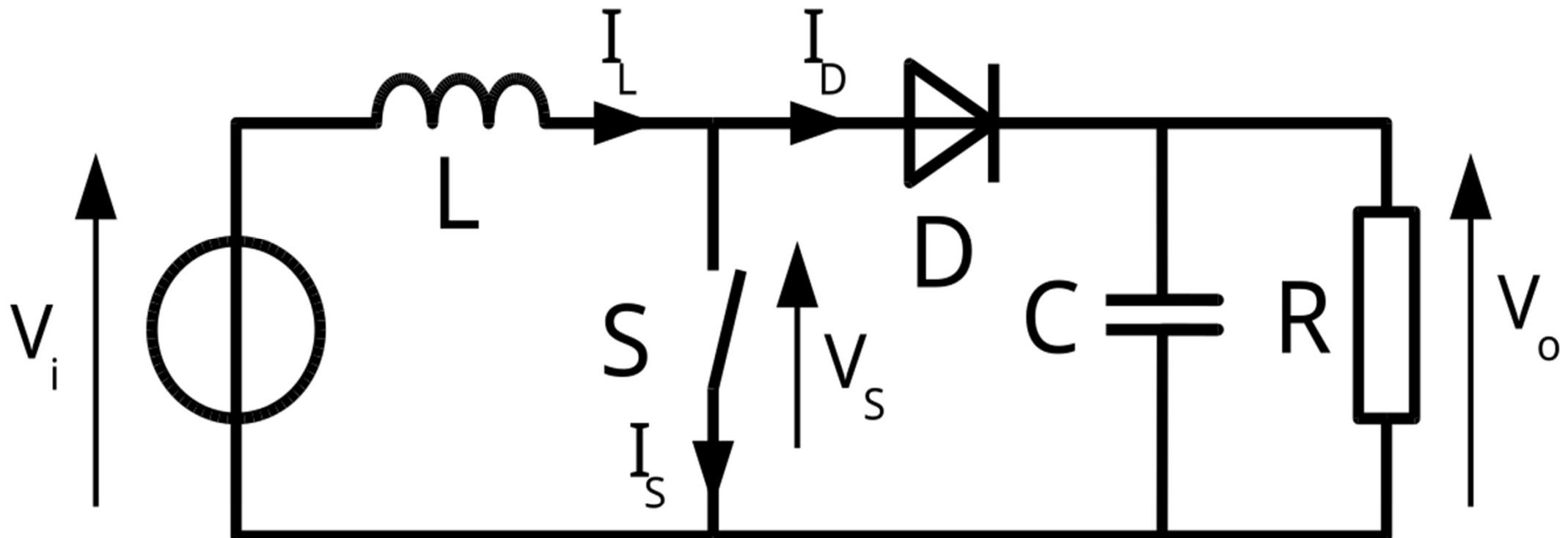
Verificare le prestazioni del convertitore:

- In feedback con i modelli di piccolo segnale (FDT), utilizzando la descrizione a blocchi con le librerie **Xcos**. Confrontare i risultati con la configurazione a loop aperto (D costante).
- In feedback, **LTspice**, utilizzando una descrizione circuitale per la configurazione del convertitore.
- Stimare con **LTspice** l'efficienza del convertitore in open loop al variare della corrente di carico.

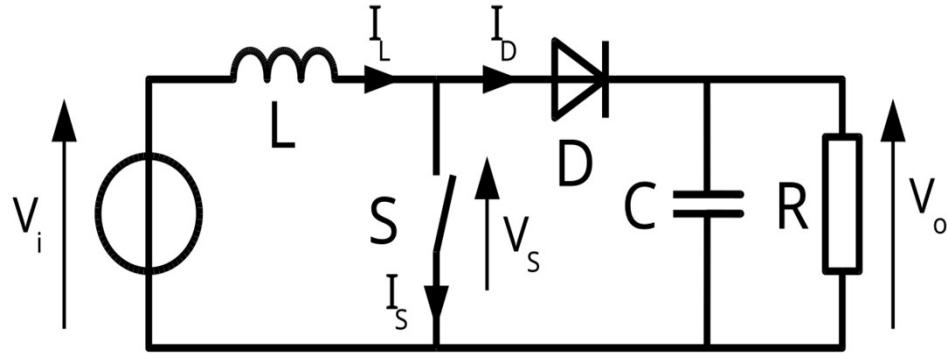


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Modello steady state senza perdite



Modello steady state senza perdite



$$\langle V_L \rangle_{T_{SW}} = 0$$

$$\frac{V_o}{V_{IN}} = \frac{1}{1-D} (> 1)$$

D=0.5

Indipendentemente dalle perdite, si ha:

$$\frac{I_o}{I_{IN}} = (1 - D)$$

perché

$$\langle I_C \rangle_{T_{SW}} = 0$$

Nel convertitore Boost il ripple della tensione di uscita dipende da C e non da L (filtro del primo ordine RC). Per rispettare la **specifica sul ripple** si impone quindi:

$$\frac{D}{F_{SW} * R_{min} * C_{min}} < 1\% \quad \longrightarrow \quad C > C_{min} = 2.5 \mu F$$

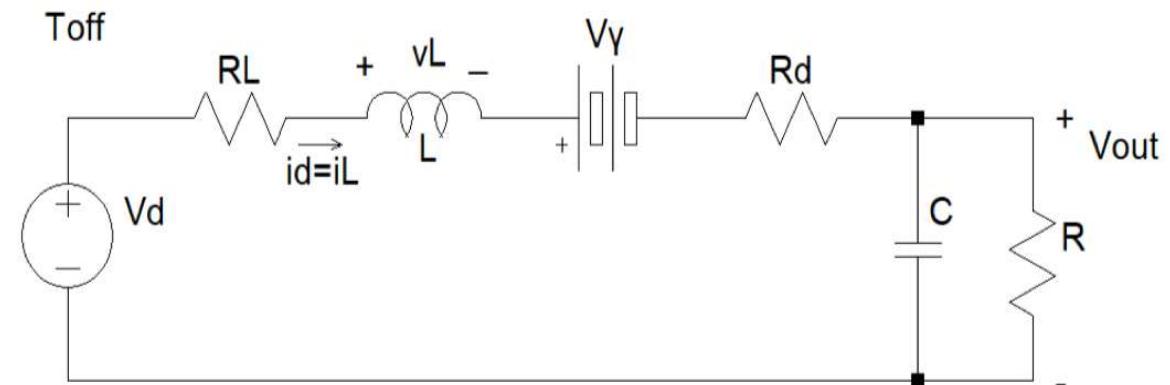
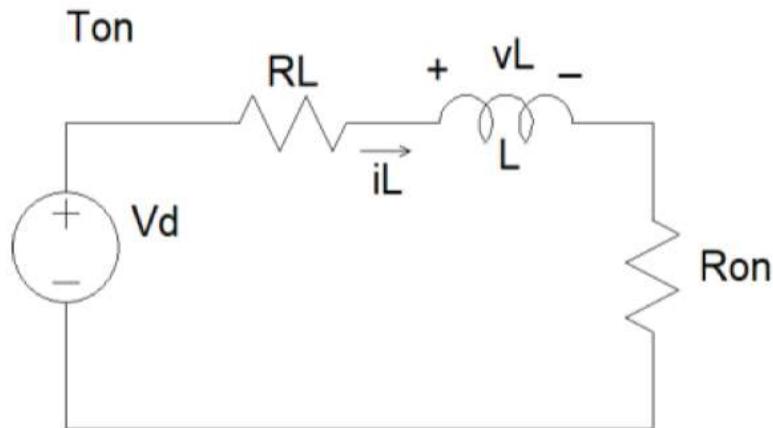
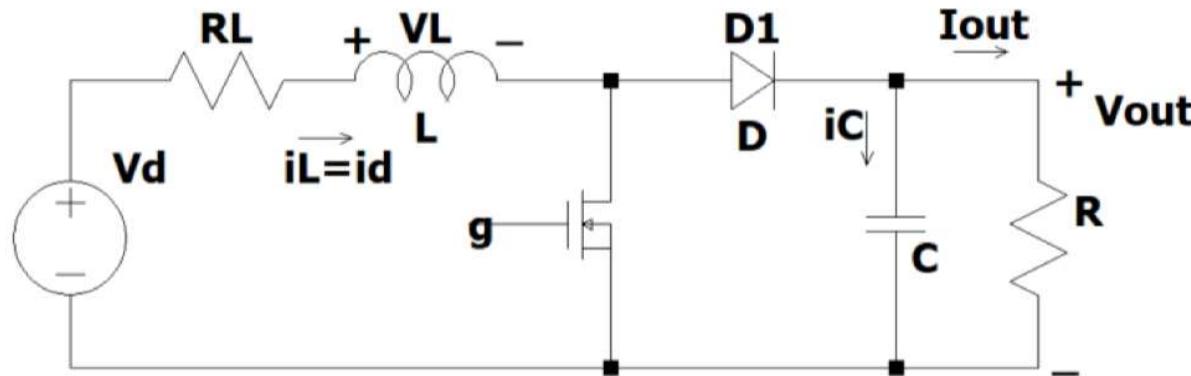
Per fare in modo che il convertitore lavori sempre in **modalità continua** invece impongo che:

$$I_o > I_{OB} \quad \forall t \quad \longrightarrow \quad \frac{V_o}{R_{max}} > \frac{V_o * (1 - D)^2 * D * T_{SW}}{2 * L_{min}} \quad \longrightarrow \quad L > L_{min} = 15 \mu H$$

$$\Delta i_L \leq 20\% * I_L \quad \longrightarrow \quad L > L_{min} = 75 \mu H$$



Modello steady state con perdite

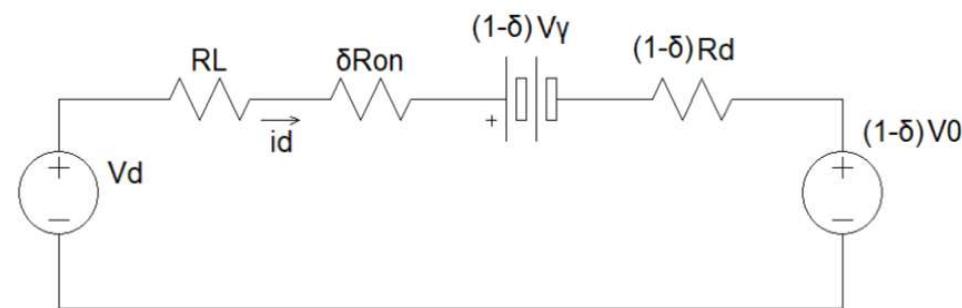


Modello steady state con perdite

Perdite per conduzione

Stima delle perdite su ogni componente: si **trascura** il ripple sulla tensione di uscita e la resistenza serie del condensatore

Dai calcoli effettuati sul circuito equivalente riportato a fianco
si ottiene:



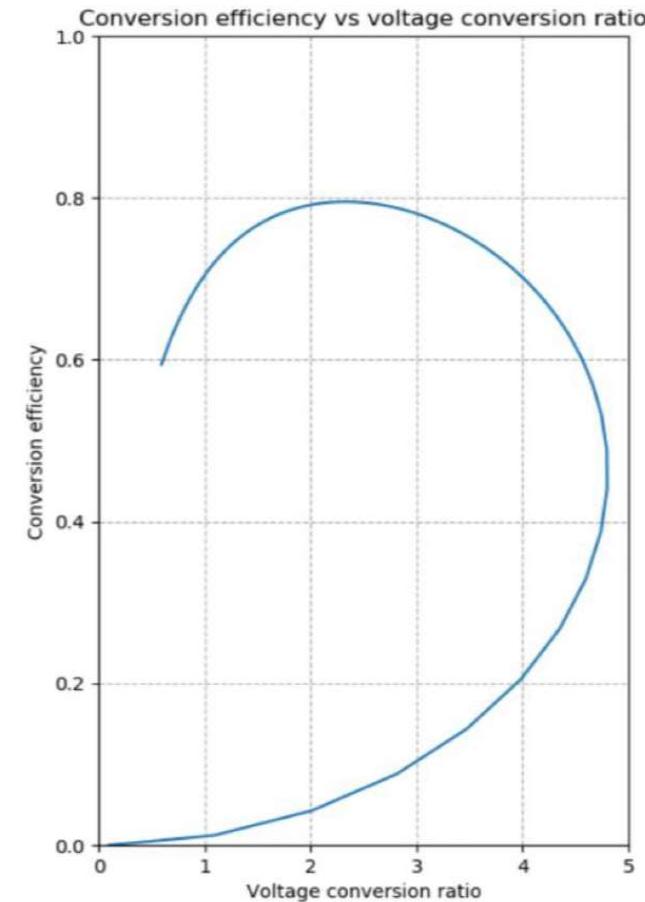
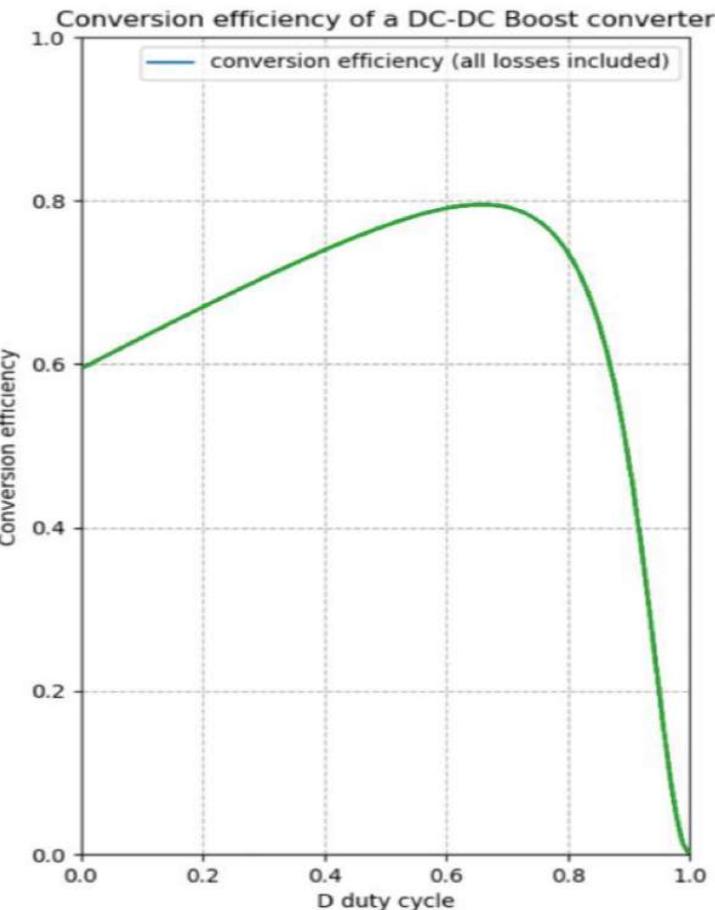
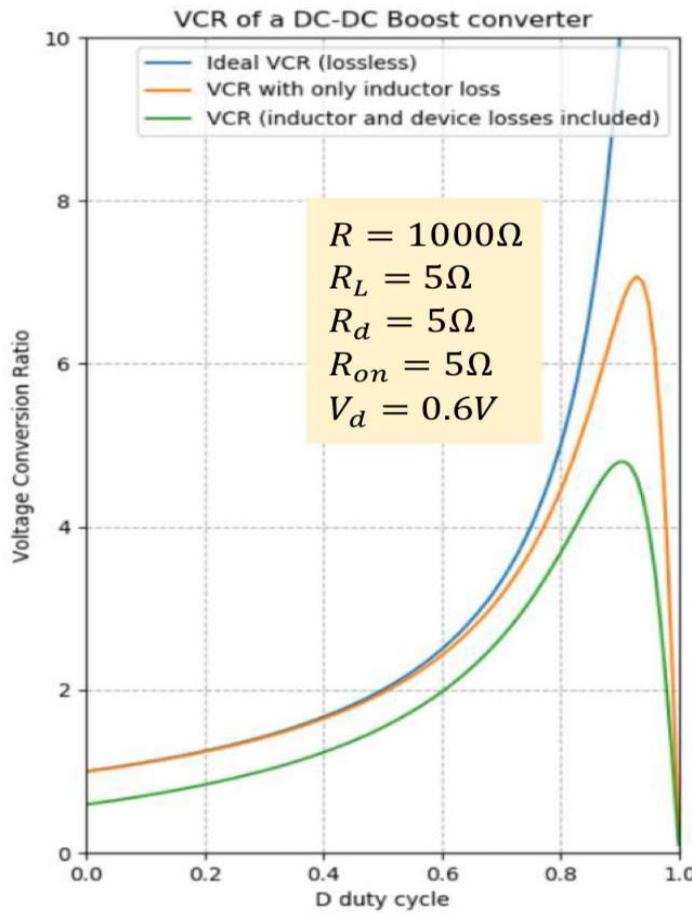
$$VCR = \frac{V_o}{V_{IN}} = \frac{1}{1-D} * \frac{1 - \frac{(1-D)V_\gamma}{V_{IN}}}{1 + \frac{R_L + DR_{ON} + (1-D)R_D}{R(1-D)^2}}$$

$$\eta = \frac{V_o I_o}{V_{IN} I_{IN}} = \frac{1 - \frac{(1-D)V_\gamma}{V_{IN}}}{1 + \frac{R_L + DR_{ON} + (1-D)R_D}{R(1-D)^2}}$$

$$VCR = \frac{1}{1-D} * \eta(D)$$



Grafici di VCR e η



Modello steady state con perdite

Perdite totali

Induttore

$$P_{induttore} = R_L * {I_{IN}}^2$$

Mosfet

$$P_{mosfet} = R_{ON} * D * {I_{IN}}^2$$

Diodo

$$P_{diodo} = (1 - D) * (V_\gamma I_{OUT} + R_D {I_{OUT}}^2)$$

Condensatore

$$P_{condensatore} = R_{C_{ESR}} * \frac{{\Delta I_C}^2}{2} \quad (\text{sovraffima})$$

Switching losses

$$P_{switching} = f_{sw} [C_{GS} {\Delta V_{GS}}^2 + C_{GD} {\Delta V_{GD}}^2 + C_{DS} {\Delta V_{DS}}^2]$$

$$P_{loss_{tot}} = P_{loss_{switching}} + P_{loss_{cond}}$$



$$\eta = \frac{P_{out}}{P_{out} + P_{loss_{tot}}}$$

Modello steady state con perdite

Scelta dei componenti



Induttore

Coilcraft RFC1010B-823

$L_{nom} = 82 \mu H$ (10%) con $R_{L_{max}} = 0,125 \Omega$



Condensatore

NIC Components Corp NMC1210X7R106K25TRPLPF

$C_{nom} = 10 \mu F$ (10%) con $R_{C_{ESR}} = 0,010 \Omega$



Mosfet

Infineon IRLML6346 con $R_{ON_{max}} = 63 m\Omega$ @ $V_{GS} = 4,5 V$

$C_{iss} = 270 pF, C_{oss} = 32 pF, C_{rss} = 21 pF$



Diodo Schottky

Rohm Semiconductor RB058LAM-30

$V_D = 0.42 V$ @ $I_F = 1 A$

$R_D = 5,5 m\Omega$

Osservazione: nella scelta dei componenti si è tenuto conto di una tollerabilità del 20% e anche del fattore costo



Modello steady state con perdite

Risultati

Calcoli effettuati con (**worst case**):

$$R_{load} = R_{min} = 40 \Omega, I_O = \frac{20 V}{40 \Omega} = 0.5 A, I_{IN} = \frac{I_O}{(1 - D)} = 1 A, P_{out} = \frac{V_O^2}{R_{min}} = 10 W$$

Risulta:

$$P_{induttore} = 118 \text{ mW} \quad P_{mosfet} = 35 \text{ mW} \quad P_{diodo} = 117 \text{ mW} \quad P_{condensatore} = 2,6 \text{ mW}$$

$$P_{switching} = 11 \text{ mW}$$

$$P_{loss_{tot}} = 283 \text{ mW}$$

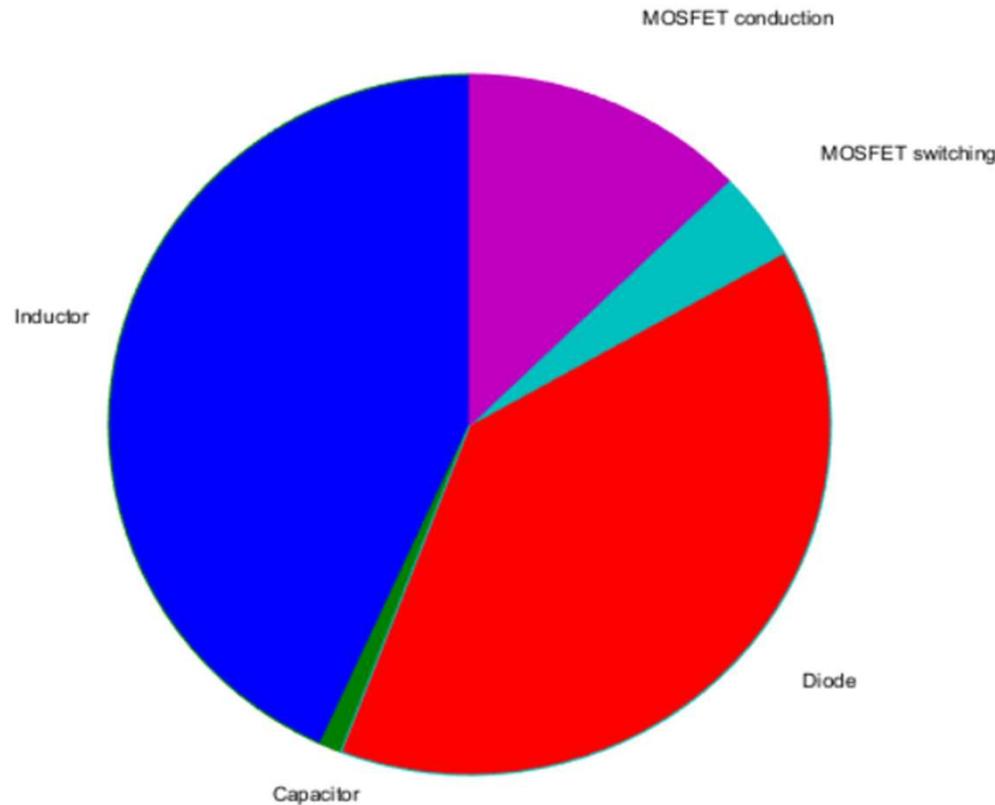
$$\eta = \frac{P_{out}}{P_{out} + P_{loss_{tot}}} = \frac{10 W}{10 W + 283 \text{ mW}} = 97,2\%$$

Duty cycle effettivo:
D=0,515



Modello steady state con perdite

Grafico



$$R_{load} = R_{min} = 40 \Omega$$

Inductor
Capacitor
Diode
MOSFET switching
MOSFET conduction



Modello steady state con perdite

Risultati

Calcoli effettuati con (**best case**):

$$R_{load} = R_{max} = 120 \Omega, I_O = \frac{20 V}{120 \Omega} = 0,166 A, I_{IN} = \frac{I_O}{(1 - D)} = 0,332 A, P_{out} = \frac{V_O^2}{R_{max}} = 3,3 W$$

Risulta:

$$P_{induttore} = 12,8 \text{ mW} \quad P_{mosfet} = 9,1 \text{ mW} \quad P_{diodo} = 29,8 \text{ mW} \quad P_{condensatore} = 290 \text{ uW}$$

$$P_{switching} = 8 \text{ mW}$$

$$\mathbf{P_{loss_{tot}} = 60 \text{ mW}}$$

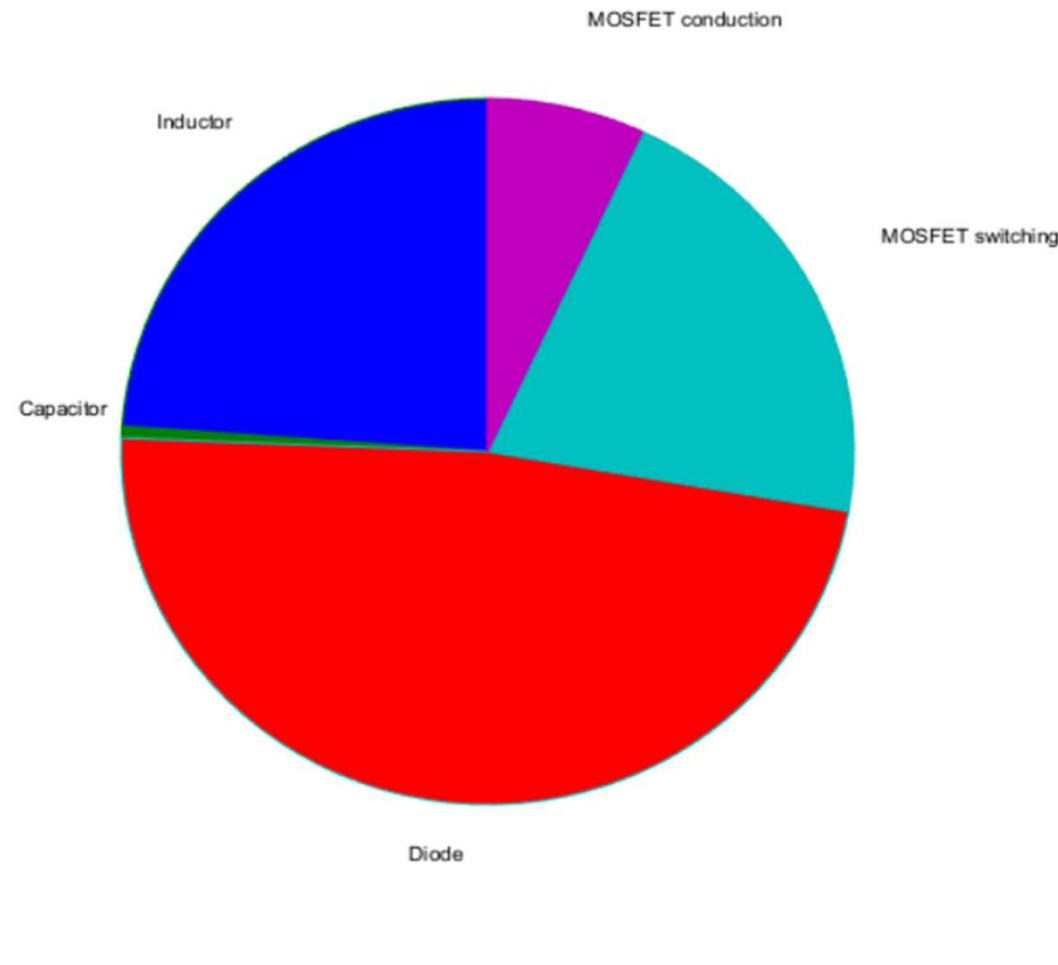
$$\eta = \frac{P_{out}}{P_{out} + P_{loss_{tot}}} = \frac{3,3 \text{ W}}{3,3 \text{ W} + 60 \text{ mW}} = 98,2\%$$



*Duty cycle effettivo:
D=0,511*

Modello steady state con perdite

Grafico



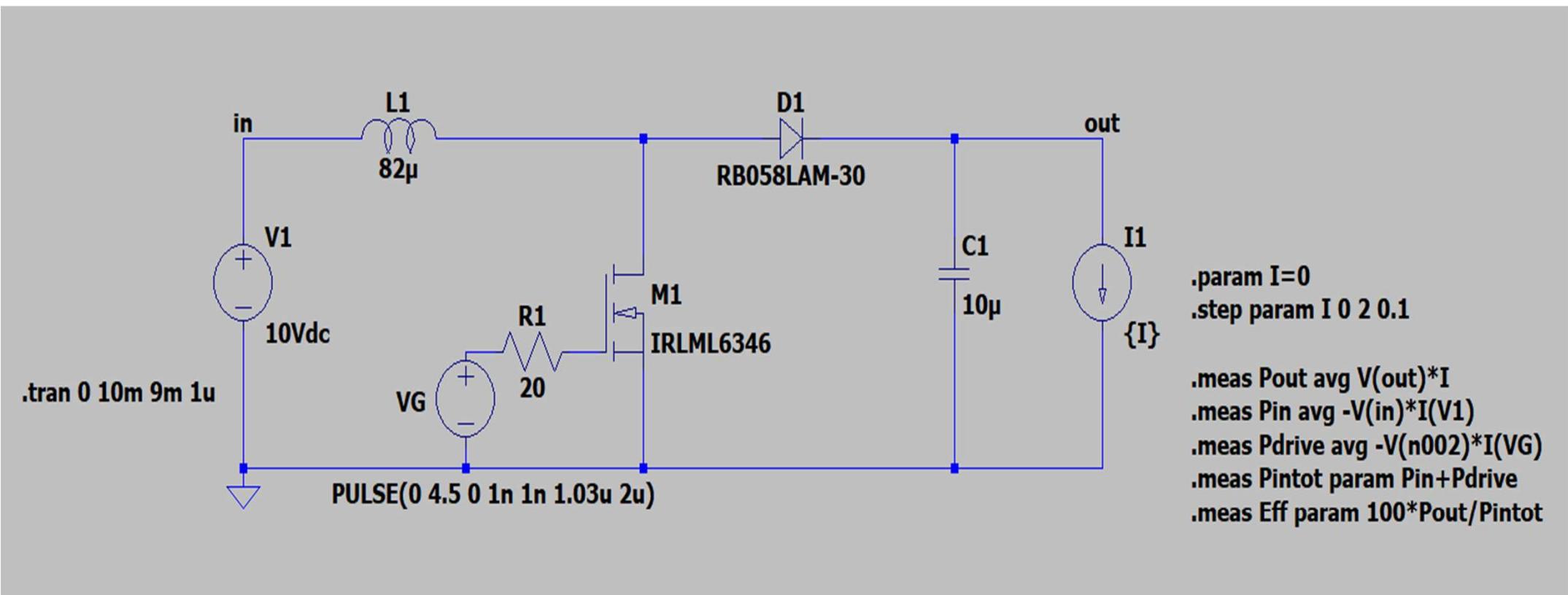
$$R_{load} = R_{max} = 120 \Omega$$

Inductor
Capacitor
Diode
MOSFET switching
MOSFET conduction



Modello steady state con perdite: LTspice

Efficienza al variare della corrente di uscita

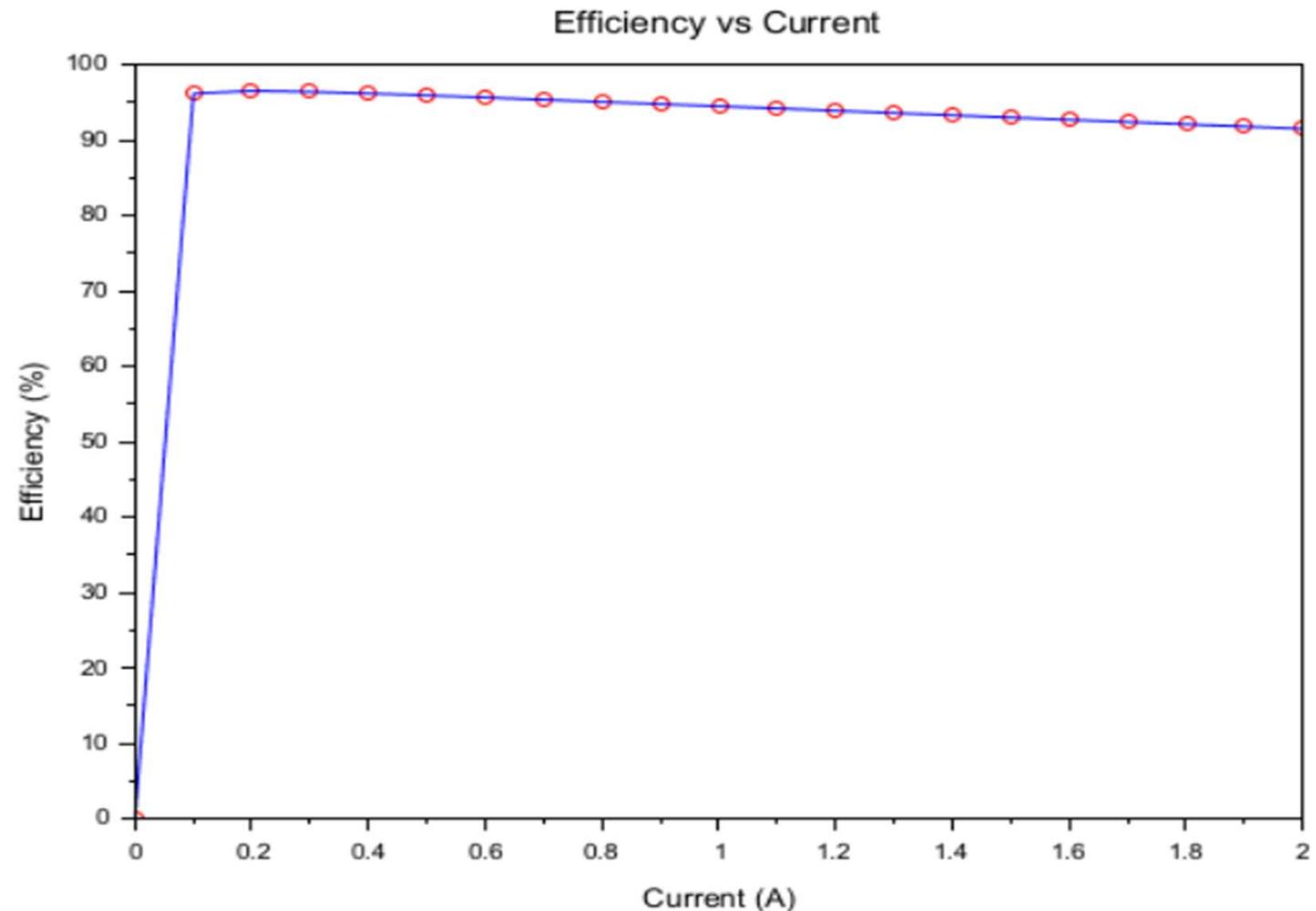


Modello steady state con perdite: LTspice

Efficienza al variare della corrente di uscita

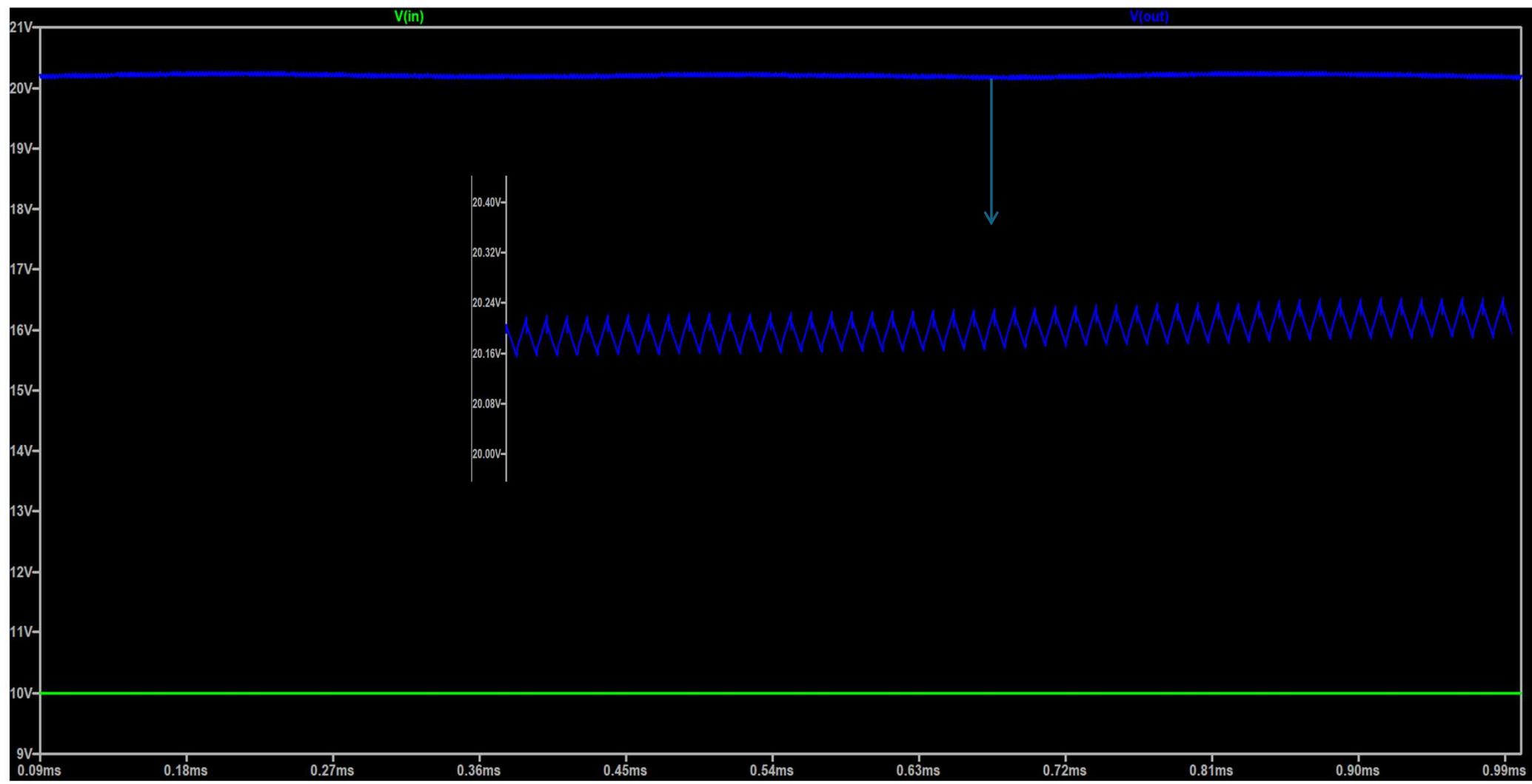
Measurement: Eff

step	100* Pout/Pintot
1	0
2	96.1490574175
3	96.5026384807
4	96.3839661359
5	96.1657610208
6	95.9068658878
7	95.6294755499
8	95.3348811906
9	95.0419754673
10	94.7544682763
11	94.4664206409
12	94.1780062576
13	93.8711584278
14	93.56544404
15	93.2704488956
16	92.9705737722
17	92.6724792714
18	92.3763079468
19	92.0717454265
20	91.7750701462
21	91.4721676193



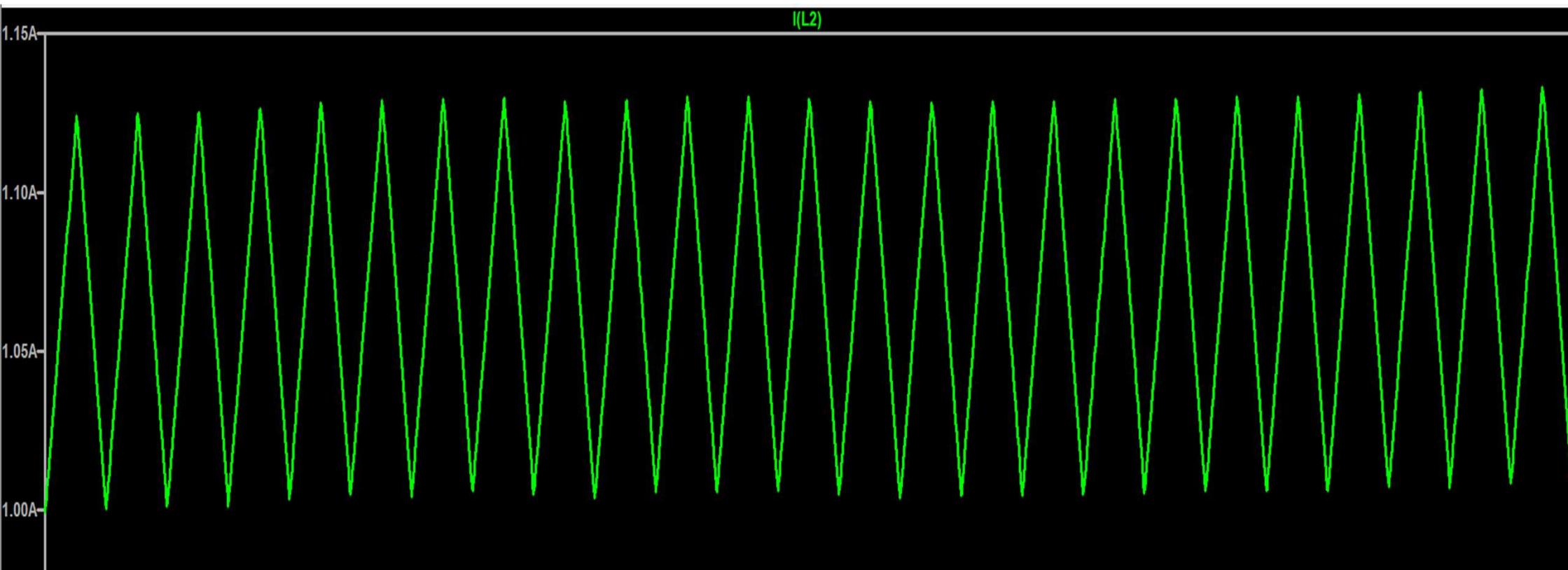
Modello steady state con perdite: LTspice

Andamenti di V_{in} e di V_{out}



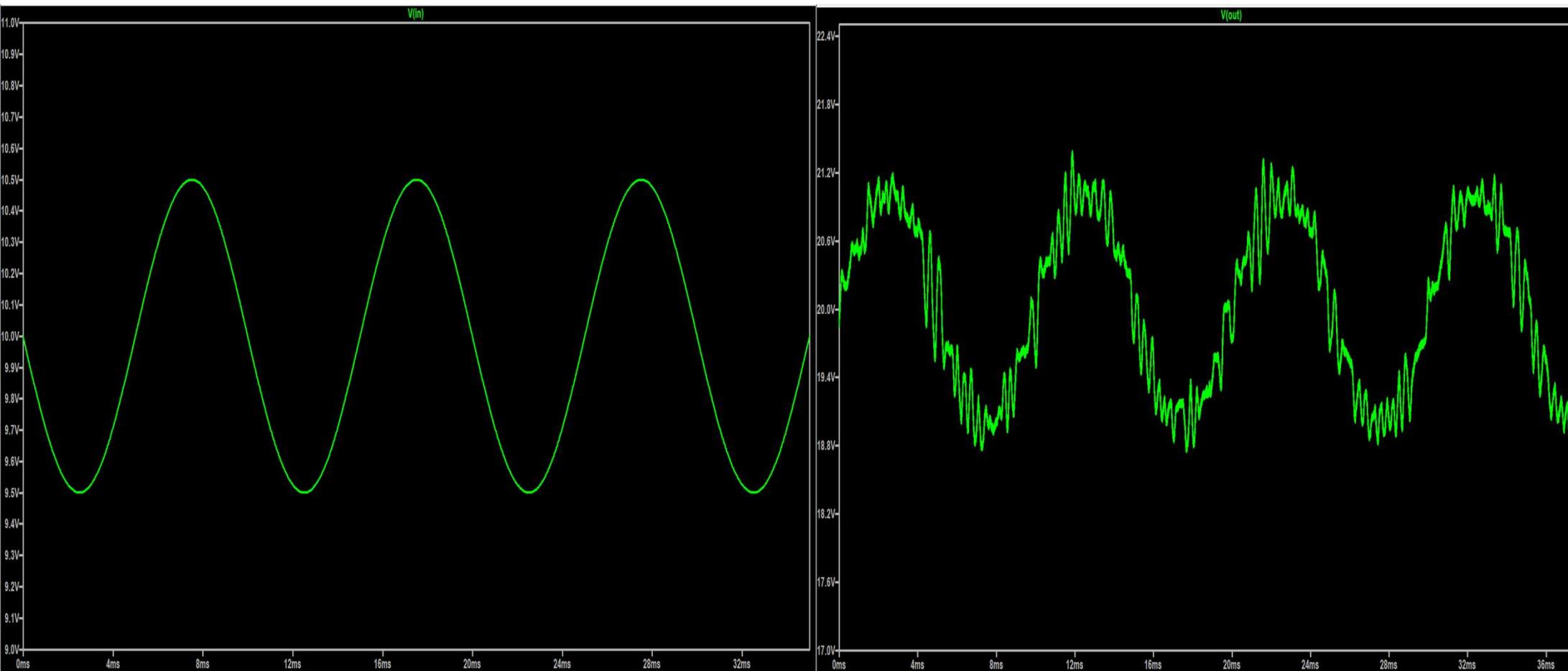
Modello steady state con perdite: LTspice

Corrente nell'induttore



Modello steady state con perdite: LTspice

Ripple di V_{out} dovuto al ripple di V_{in}



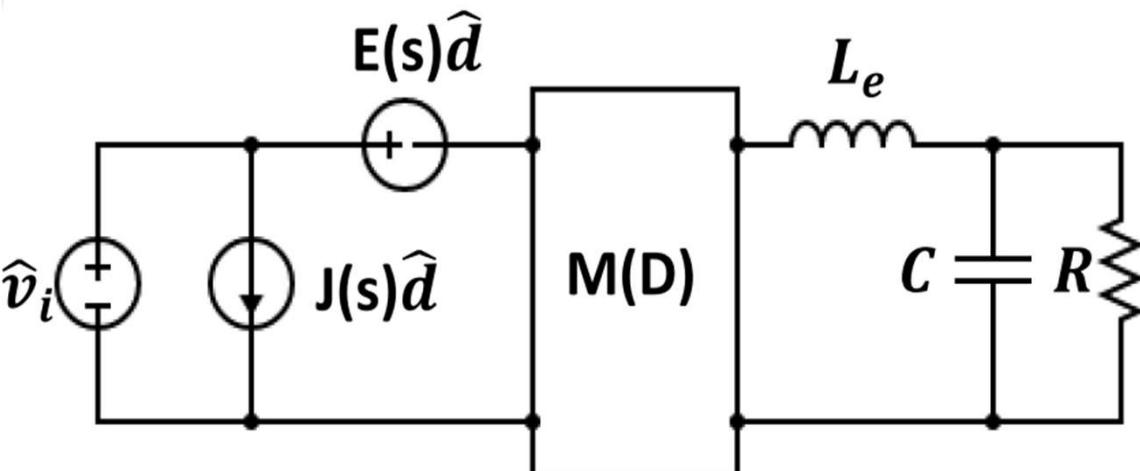
Modello dinamico

Modello ideale senza perdite, lineare tempo invariante

Approssimazioni:

- Considero il valor medio delle grandezze nel periodo di switching
- Approssimazione di piccolo segnale (si trascurano i termini in AC del 2° ordine)
- Senza perdite

Dal circuito in *forma canonica* si ottiene:



$$G_{v_d} = \left. \frac{\hat{v}_o}{\hat{d}} \right|_{\begin{array}{l} \hat{v}_i = 0 \\ \hat{i}_{load} = 0 \end{array}} = E(S) * M(D) * LPF(S)$$

$$G_{v_g} = \left. \frac{\hat{v}_o}{\hat{v}_i} \right|_{\begin{array}{l} \hat{d} = 0 \\ \hat{i}_{load} = 0 \end{array}} = M(D) * LPF(S)$$

$$Z_{out} = - \left. \frac{\hat{v}_o}{\hat{i}_o} \right|_{\begin{array}{l} \hat{v}_i = 0 \\ \hat{d} = 0 \end{array}} = sL_{eq} * LPF(S)$$

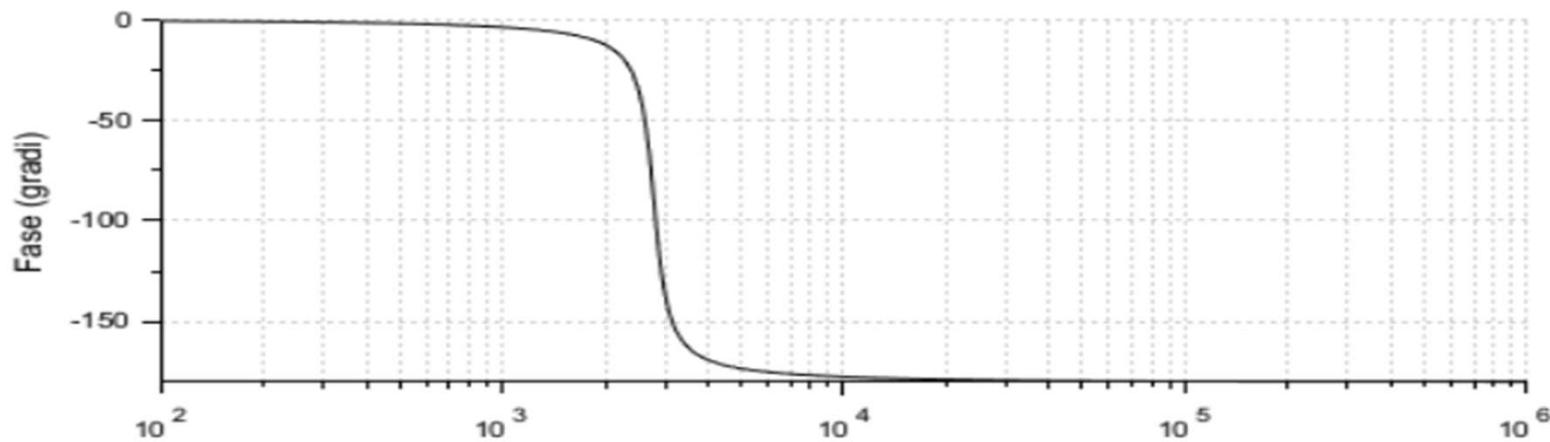
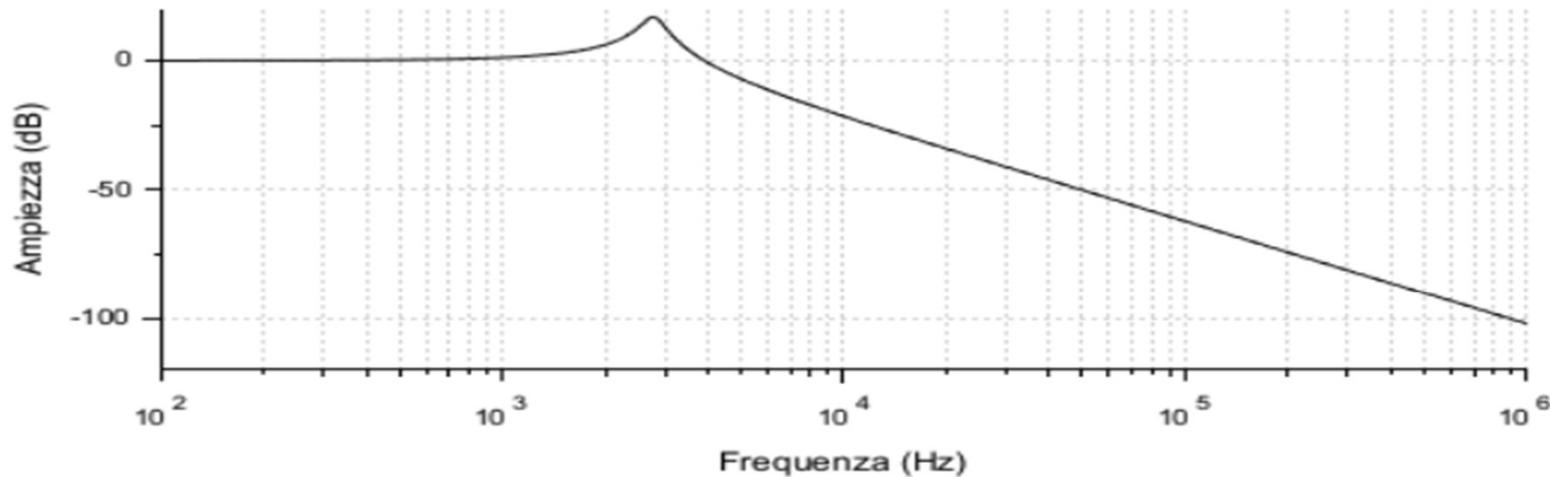
Modello dinamico

$$LPF(s) = \frac{1}{1 + \frac{s}{Qw_0} + (\frac{s}{w_0})^2}$$

$$w_0 = \frac{(1 - D)}{\sqrt{LC}}$$

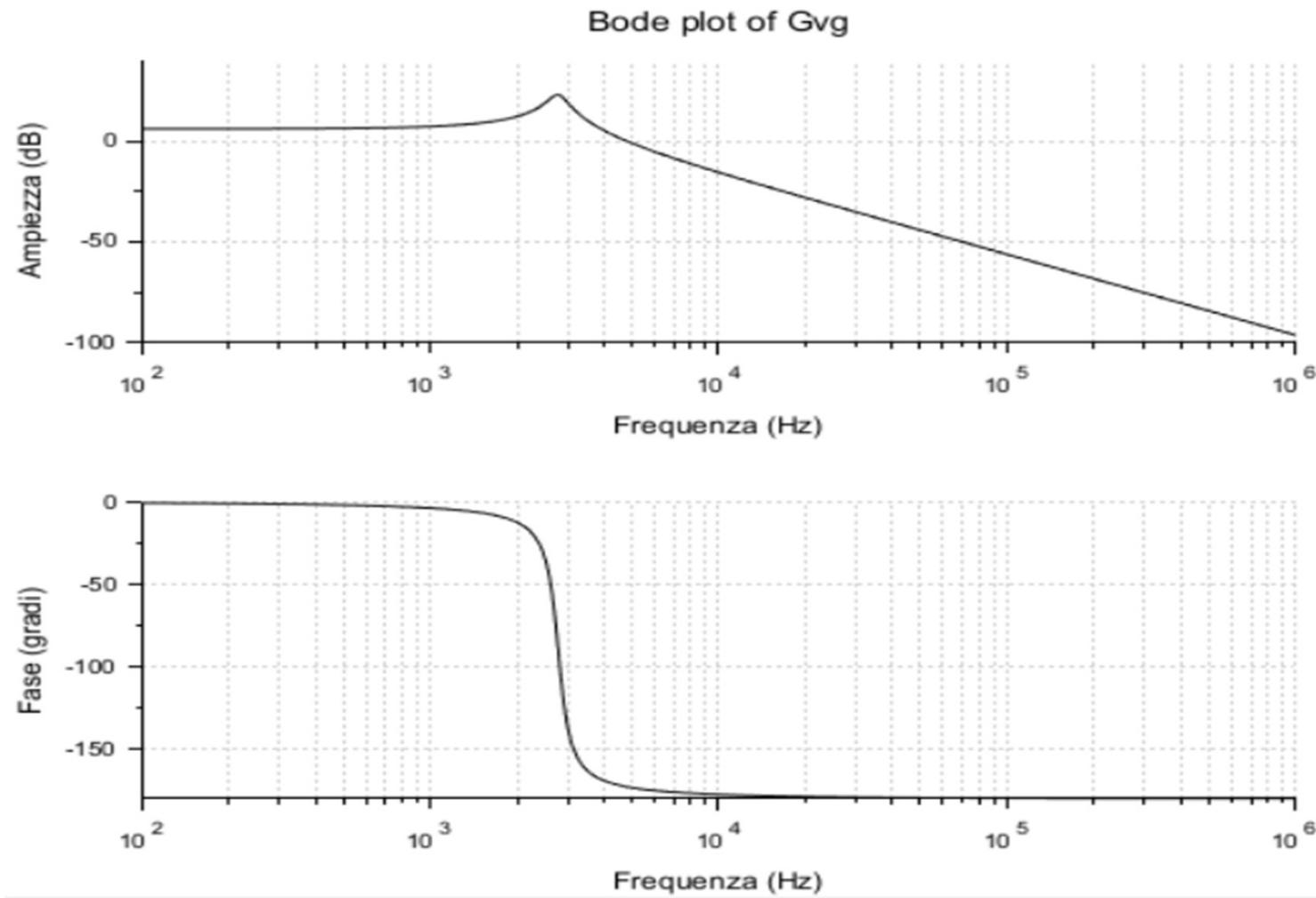
$$Q = R(1 - D) \sqrt{\frac{C}{L}}$$

Bode plot of LPF



Modello dinamico

$$G_{vg}(s) = \frac{1}{(1-D)} \frac{1}{1 + \frac{s}{Qw_0} + (\frac{s}{w_0})^2}$$

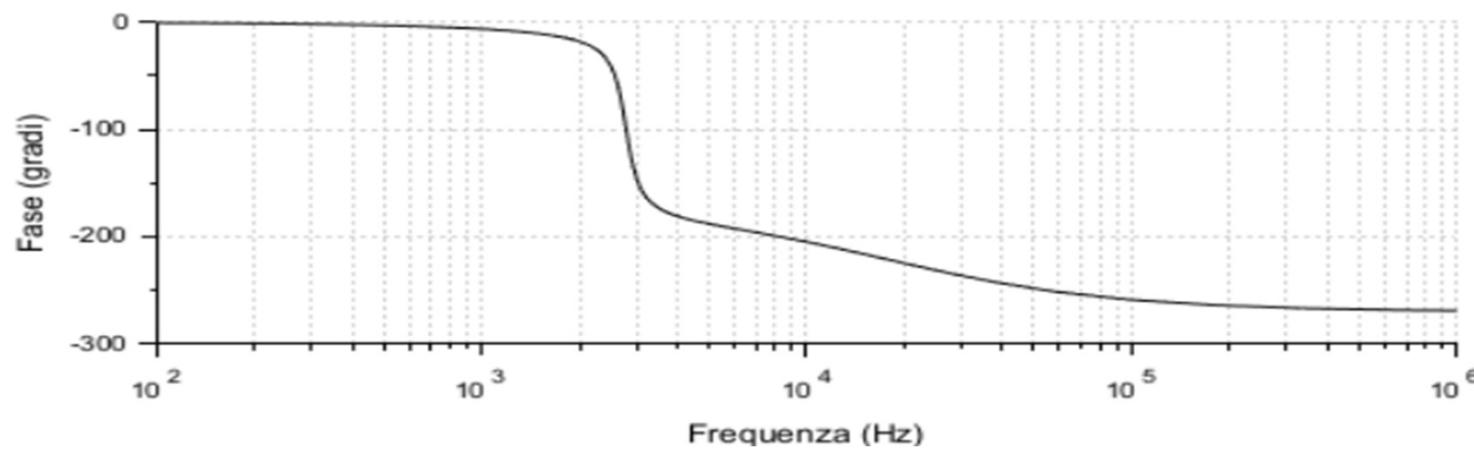
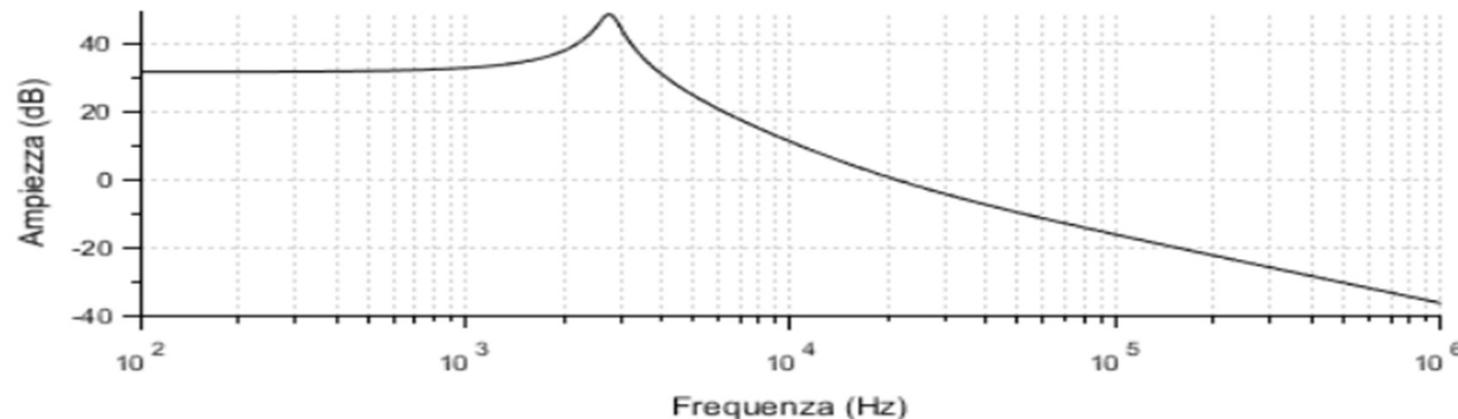


Modello dinamico

$$G_{vd}(s) = \frac{V_{out}}{(1 - D)} \frac{1 - \frac{s}{w_z}}{1 + \frac{s}{Qw_0} + (\frac{s}{w_0})^2}$$

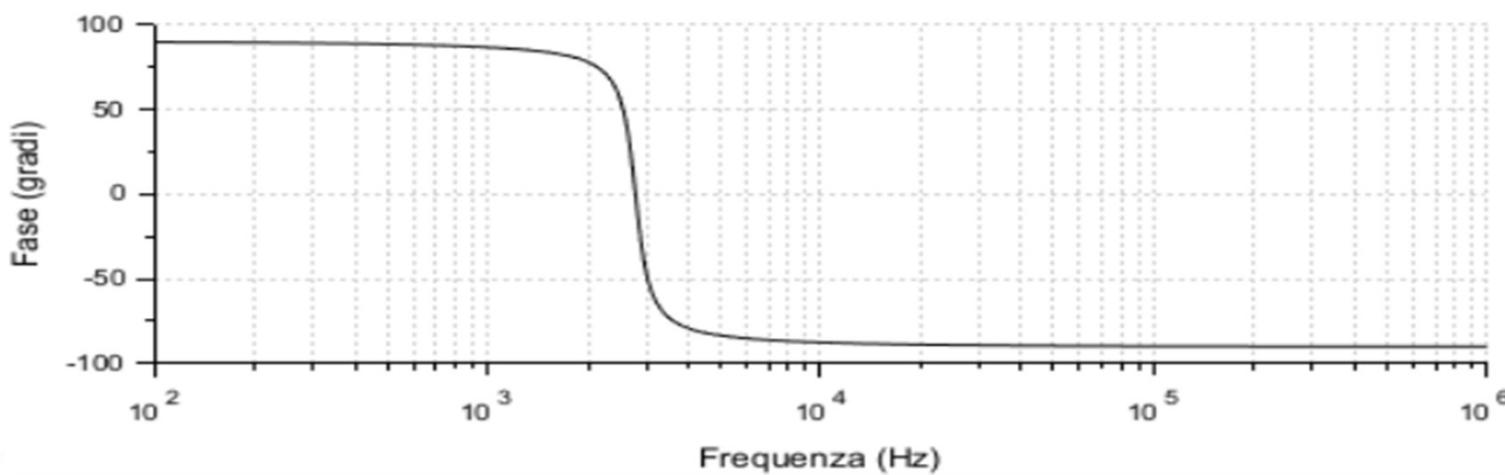
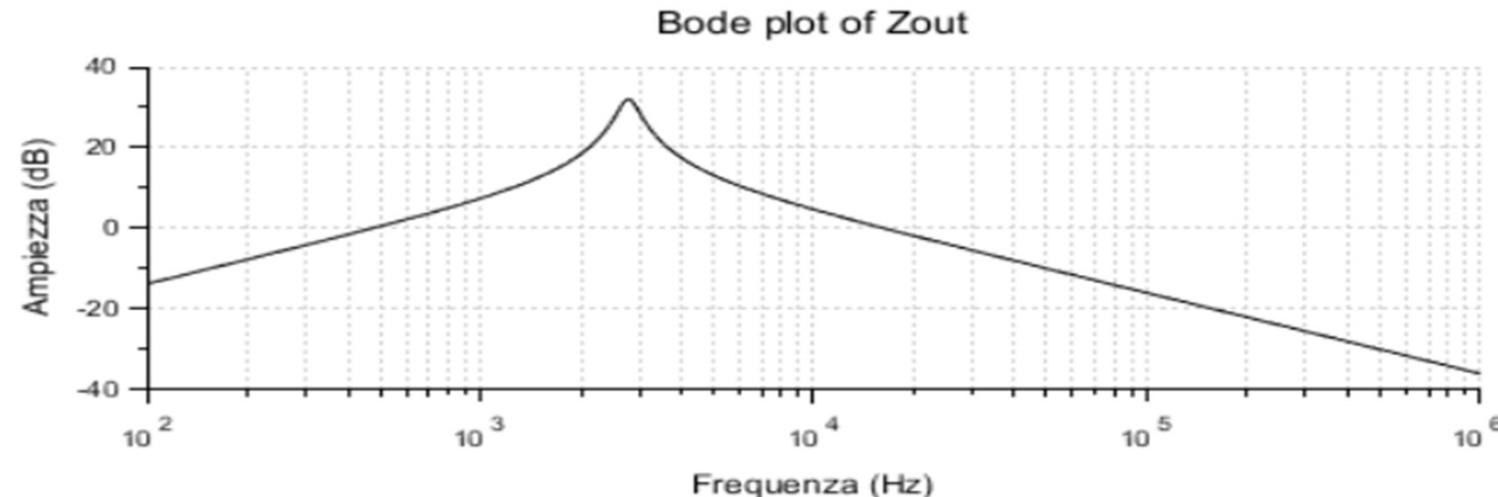
$$w_z = \frac{V_{out}(1 - D)}{L * I_L}$$

Bode plot of Gvd

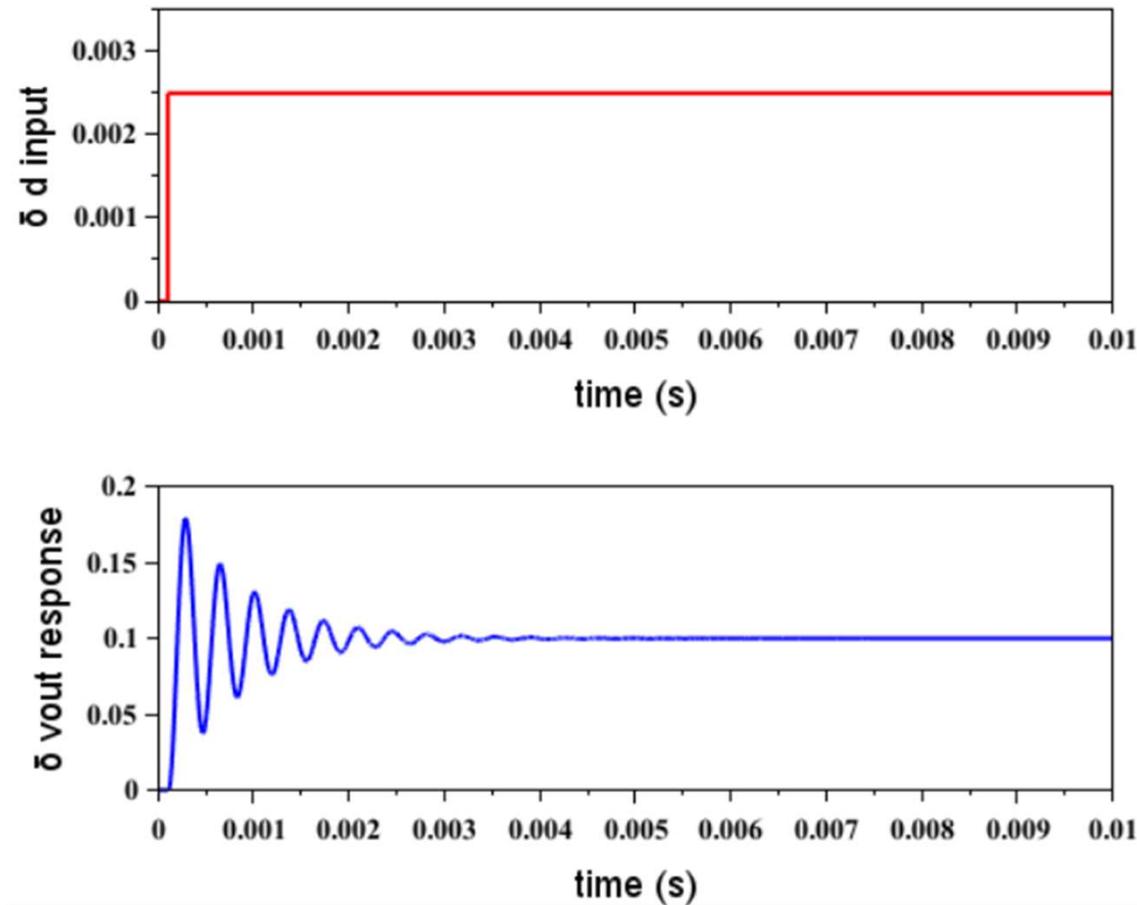
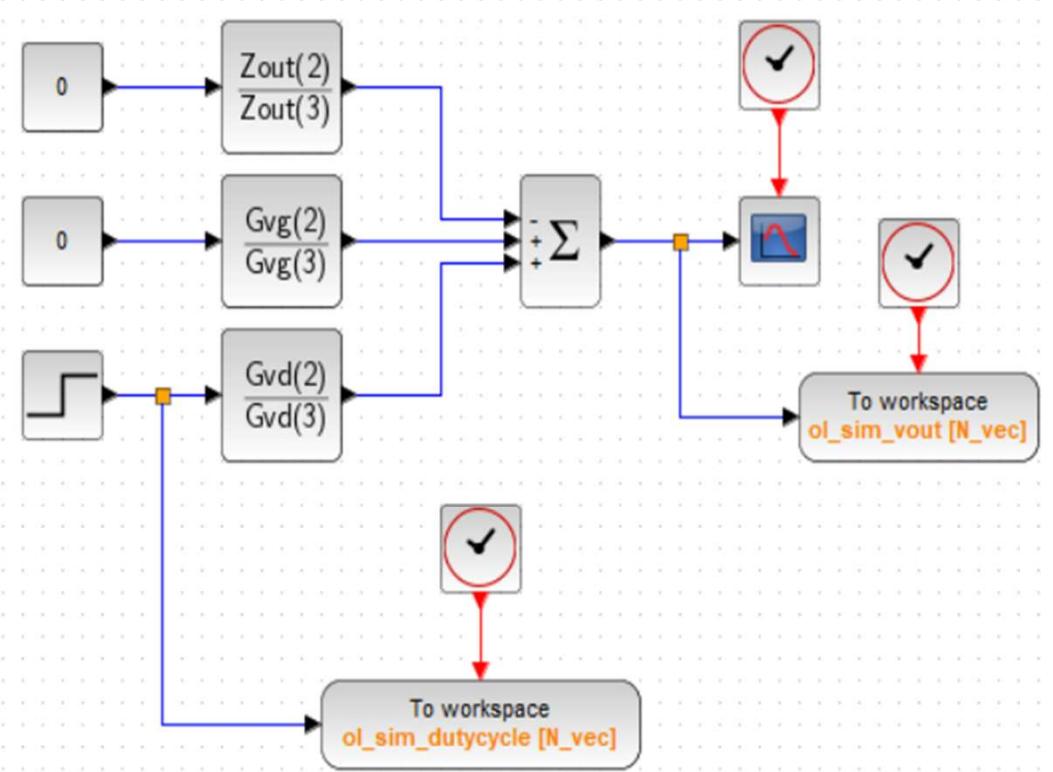


Modello dinamico

$$Z_{out}(s) = \frac{sL}{(1-D)^2} \frac{1}{1 + \frac{s}{Qw_0} + (\frac{s}{w_0})^2}$$



Modello dinamico: simulazione open loop



Progettazione del feedback

Variazione della tensione di uscita a **loop chiuso**:

$$\hat{v}_{out} = \frac{T}{1+T} \frac{\hat{v}_{ref}}{H} + \frac{G_{vg}}{1+T} \hat{v}_i - \frac{Z_{out}}{1+T} \hat{i}_{load}$$

con T il **guadagno di anello**:

$$T = \frac{H}{V_M} G_{vd} C_G = T_U C_G$$

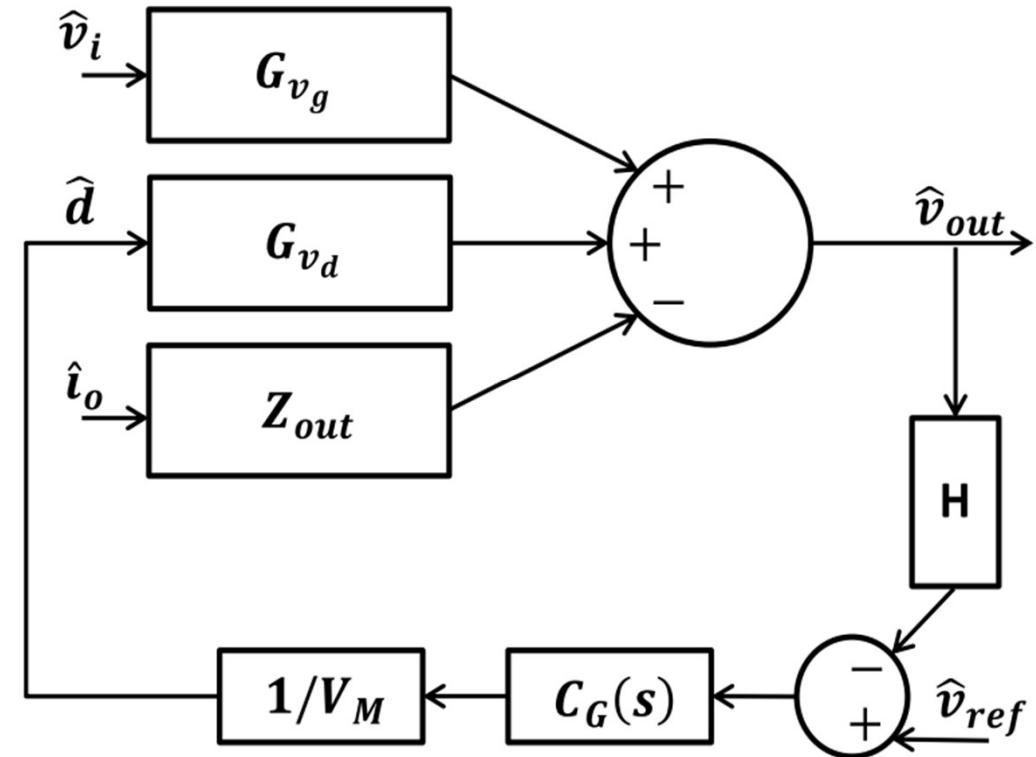
I criteri per la *progettazione* del compensatore C_G sono:

1. **Banda (f_C)** $\longrightarrow 0.6 \text{ kHz} < f_C < 6 \text{ kHz}$

con f_C la frequenza di crossover di T

2. **Margine di fase** $\longrightarrow M_\varphi = \frac{\pi}{2} (+/-10\%)$

3. **Reiezioni ai disturbi**: variazione della tensione di uscita rispetto al ripple della tensione di ingresso



$$\Delta v_o (\text{picco picco}) < 200 \text{ mV}$$

Con ripple della tensione di ingresso:

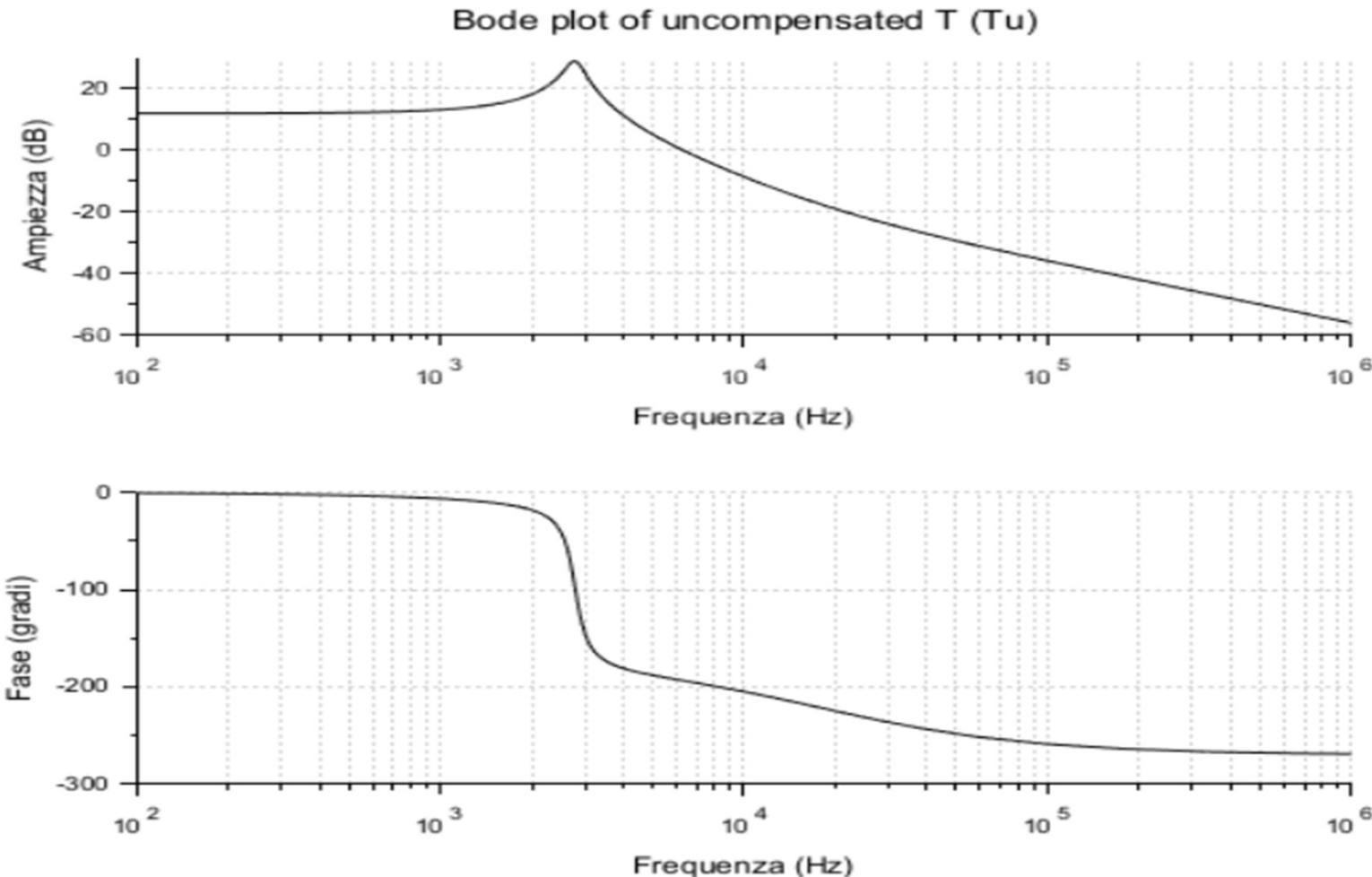
$$1 \text{ V} (\text{picco picco}) \text{ a } 100 \text{ Hz}$$

Progettazione del feedback

$$T_U(s) = T_{u_0} \frac{1 - \frac{s}{w_z}}{1 + \frac{s}{Qw_0} + (\frac{s}{w_0})^2}$$

$$T_{u_0} = \frac{H}{V_M} \frac{V_{out}}{(1 - D)}$$

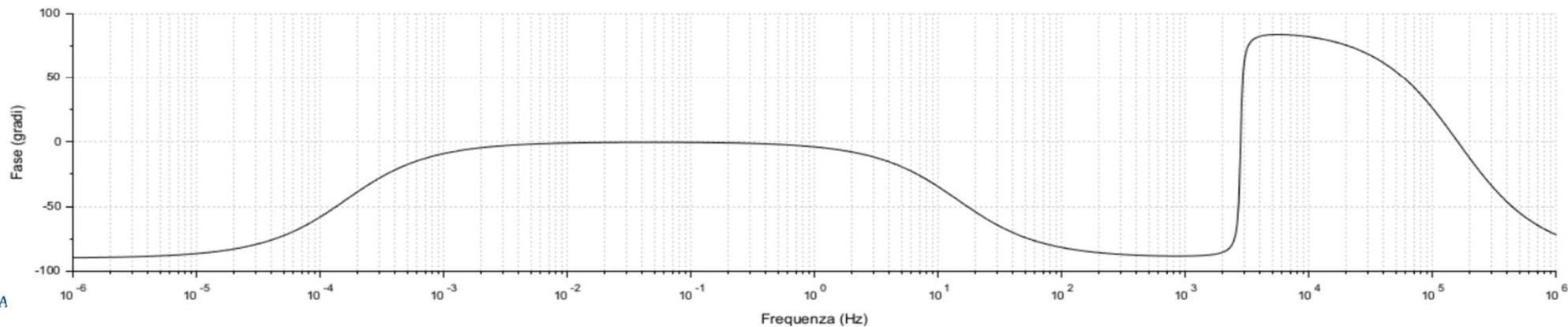
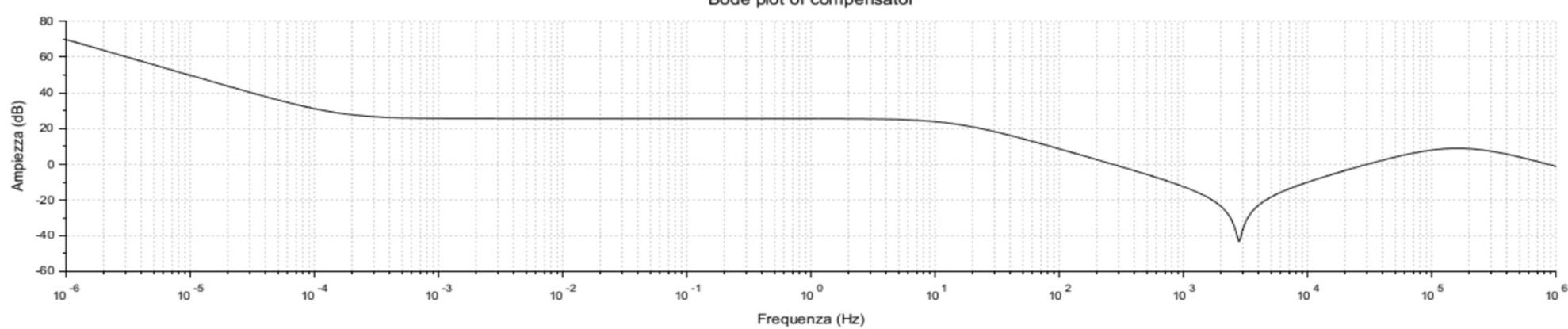
$$f_0 = 2.78 \text{ kHz}$$



Progettazione del feedback

$$C_G(s) = \frac{\left(\frac{w_{ib}}{s}\right)\left(1 + \frac{s}{w_{zb}}\right)(1 + \frac{s}{Q_c w_0} + (\frac{s}{w_0})^2)}{\left(1 + \frac{s}{w_{p1}}\right)(1 + \frac{s}{w_{p2}})^2}$$

$$\begin{aligned} w_{ib} &= 190 \cdot 10^{-4} \text{ rad/s} & w_{p1} &= 0.9 \cdot 10^2 \text{ rad/s} \\ w_{zb} &= 1 \cdot 10^{-3} \text{ rad/s} & w_{p2} &= 1 \cdot 10^6 \text{ rad/s} \\ Q_c &= 15 \end{aligned}$$



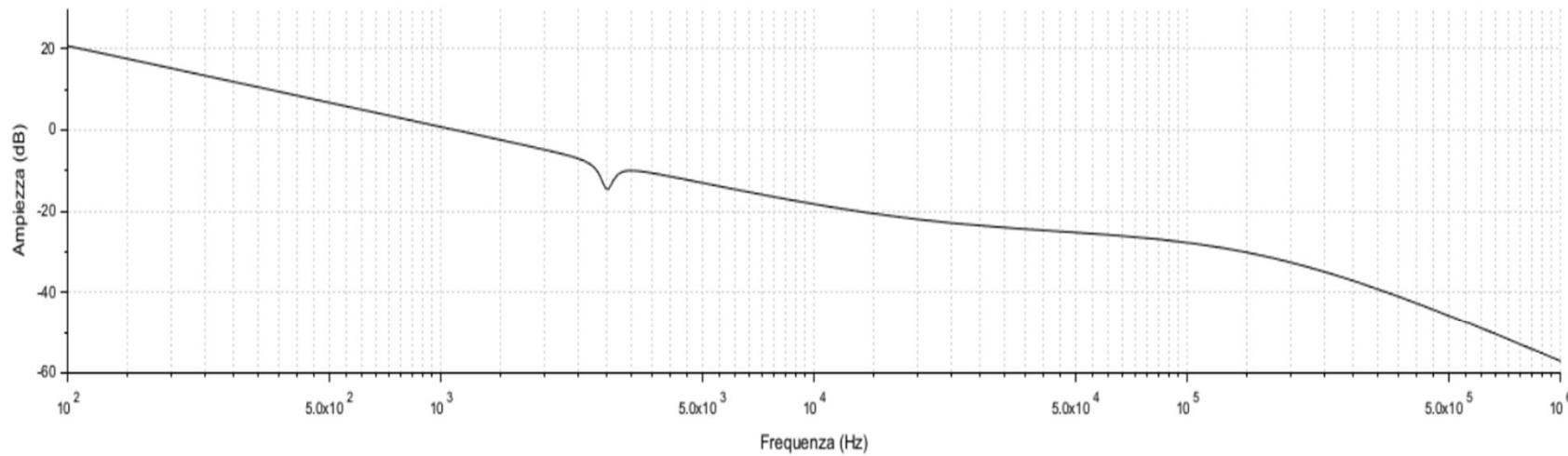
Progettazione del feedback

Bode plot of compensated T

$$R_{load} = R_{min} = 40 \Omega$$

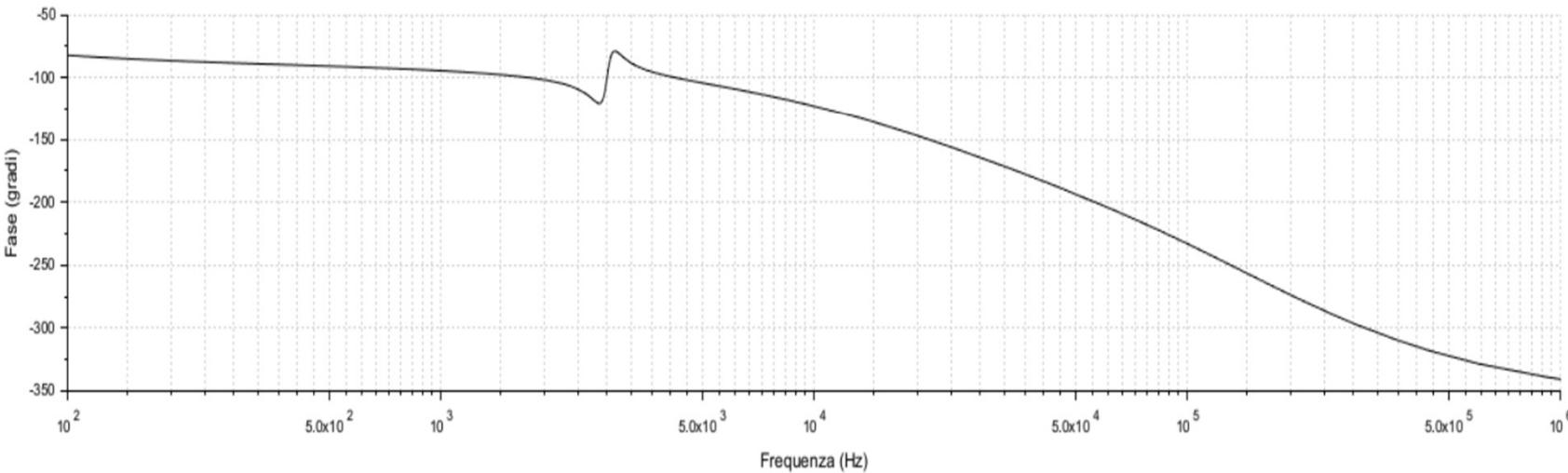
$$f_C = 1.08 \cdot 10^3 \text{ Hz}$$

$$M_\varphi = 84.7^\circ$$



Noise PWM at f_{sw} :

$$V_{noise} = 0.0015 \text{ V}$$



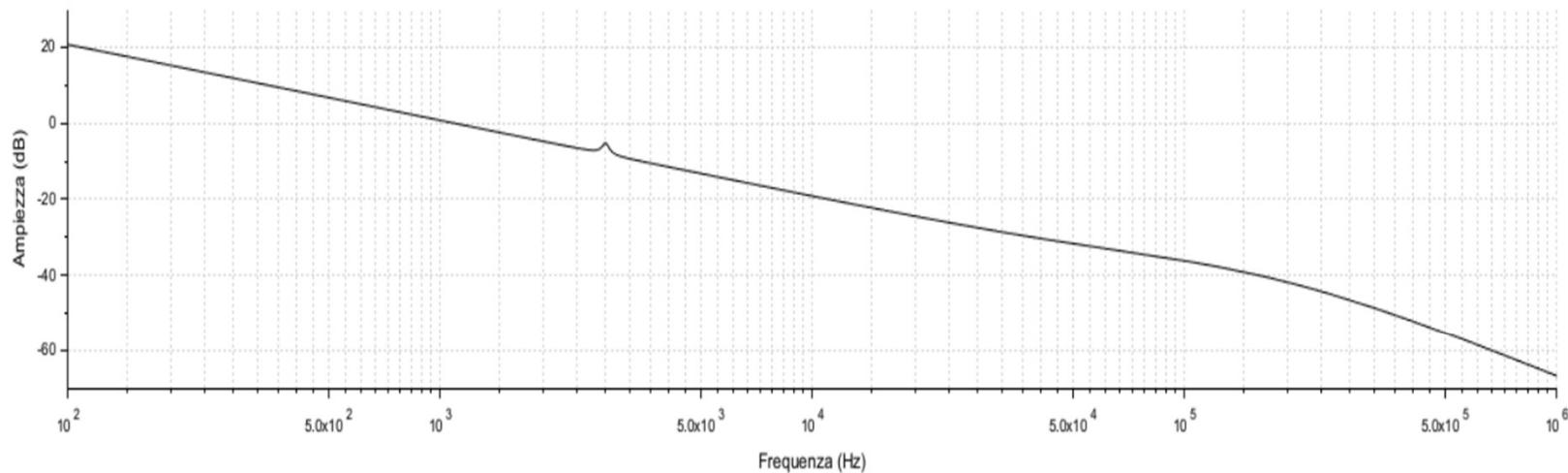
Progettazione del feedback

Bode plot of compensated T

$$R_{load} = R_{max} = 120 \Omega$$

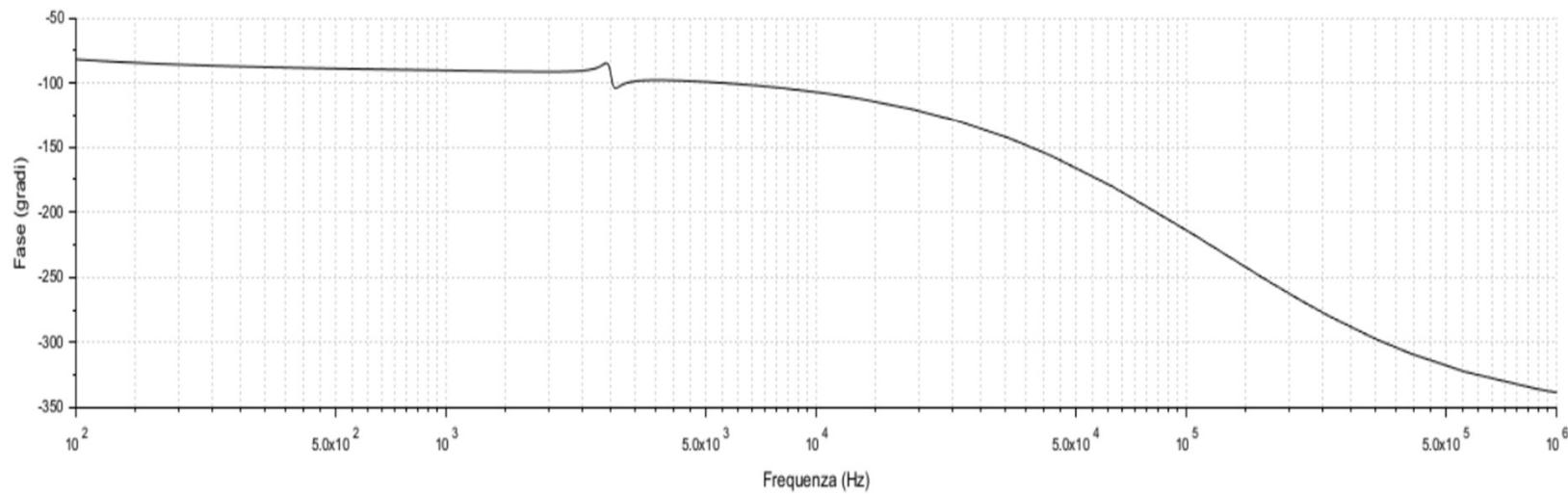
$$f_c = 1.08 \cdot 10^3 \text{ Hz}$$

$$M_\varphi = 89.4^\circ$$

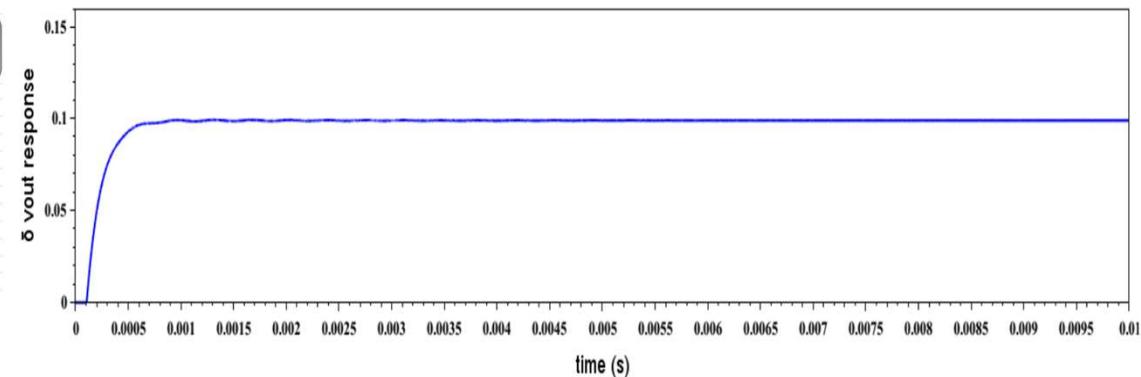
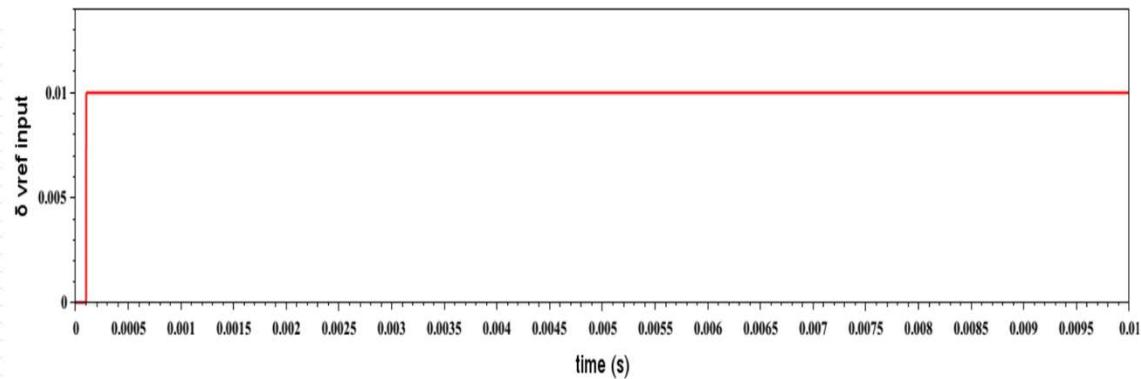
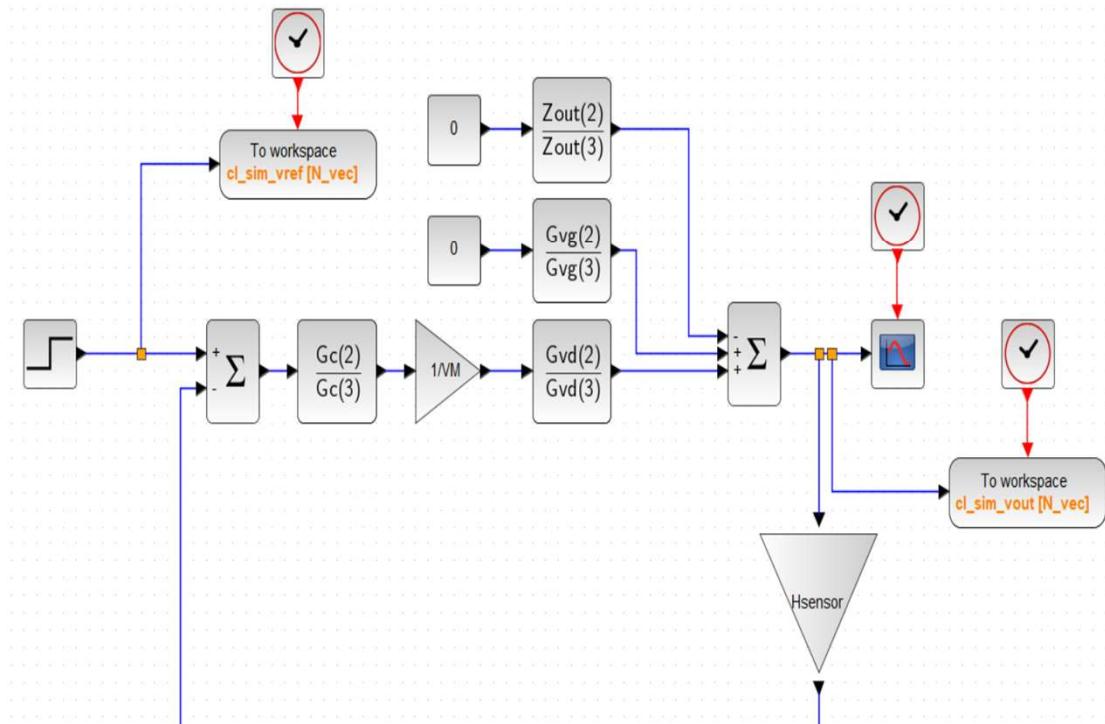


Noise PWM at f_{sw} :

$$V_{noise} = 0.0016 \text{ V}$$

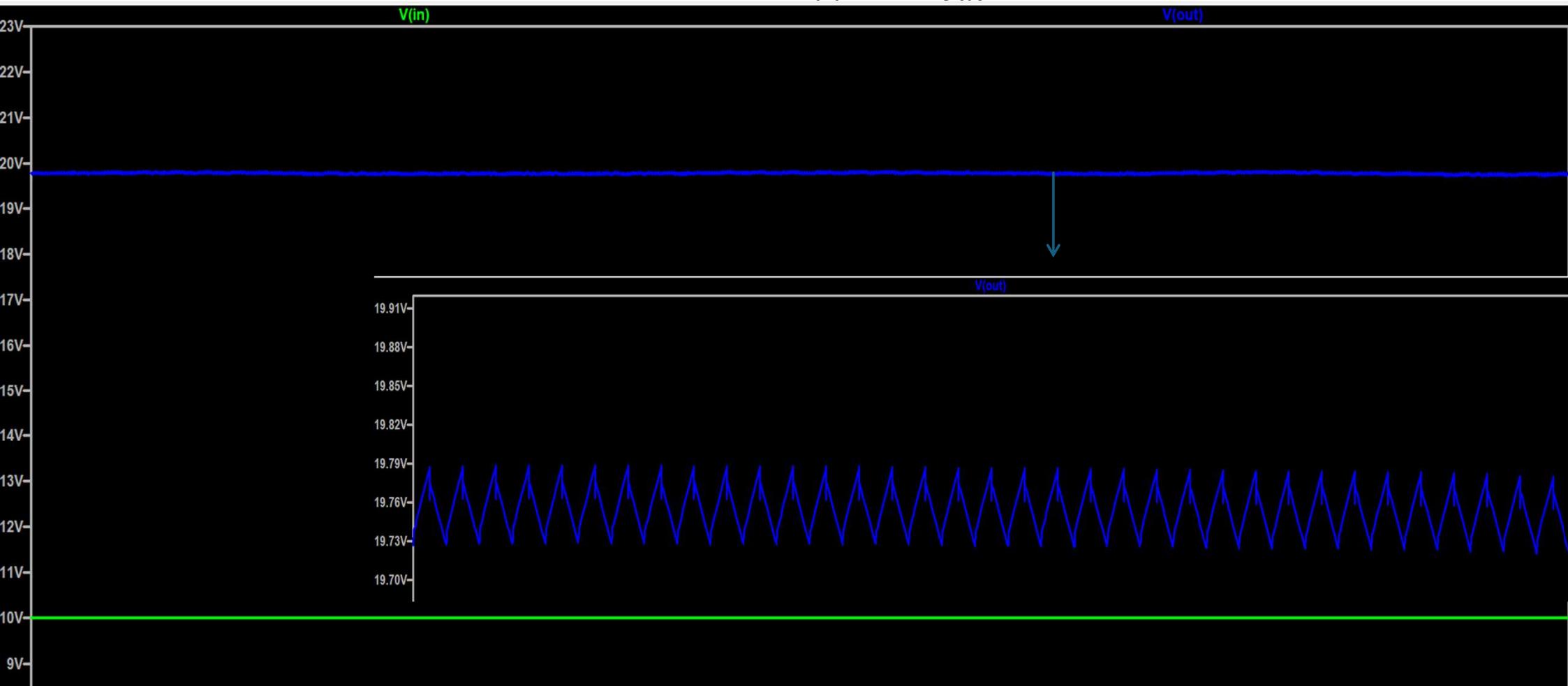


Progettazione del feedback: simulazione closed loop



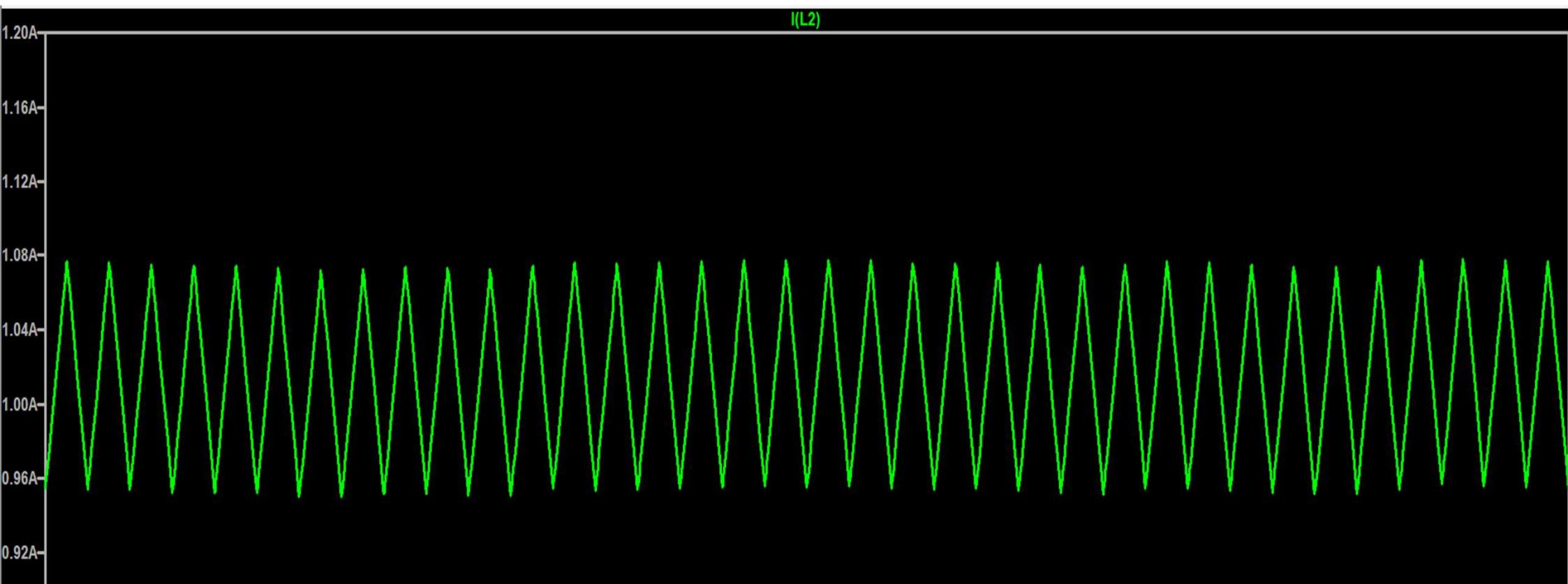
Simulazione closed loop: LTspice

Andamenti di V_{in} e di V_{out}



Simulazione closed loop: LTspice

Corrente nell'induttore



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Simulazione closed loop: LTspice

Ripple di V_{out} dovuto al ripple di V_{in}

