Corso di Elettronica Industriale (N. O.)

Prof. Ing. L. Masotti

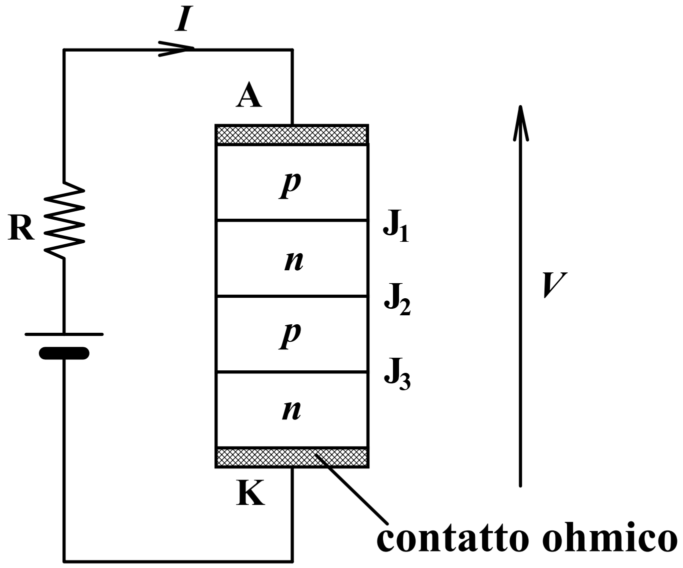
▪ Libri di testo

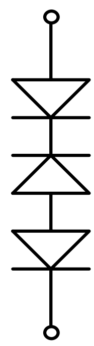
— Jacob Millman, Arvin Grabel:
Microelectronics
Mc Graw Hill, 1981

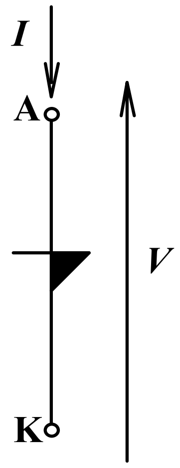
— Ulrich Tietze, Christoph Schenk:
Electronic circuits - Design and applications
Springer Verlag Heidelberg, 1991

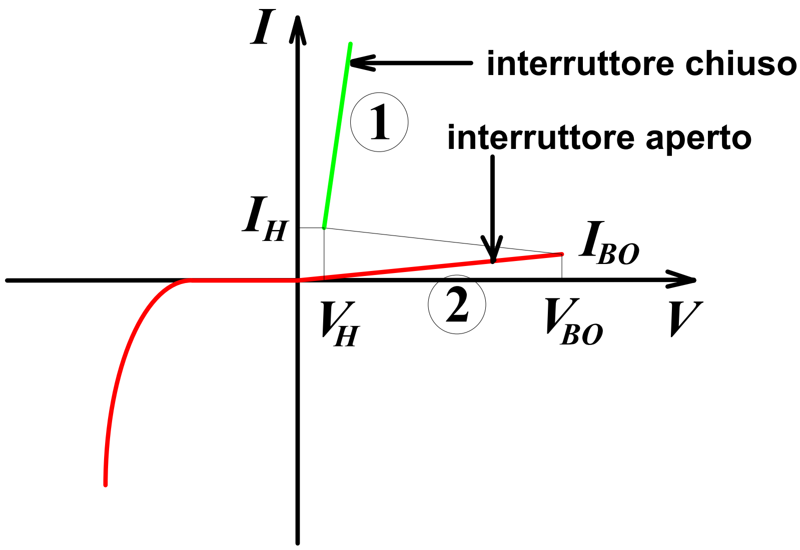
— John G. Kassakian, Martin F. Schlecht, George C. Verghese:
Principles of power electronics
Addison-Wesley Publishing Company, Inc., 1992

Dispositivo a 4 strati









$$I_H \cong 10 \div 1000\ \text{mA}$$

$$V_H \cong 0{,}5 \div 1\ \text{V}$$

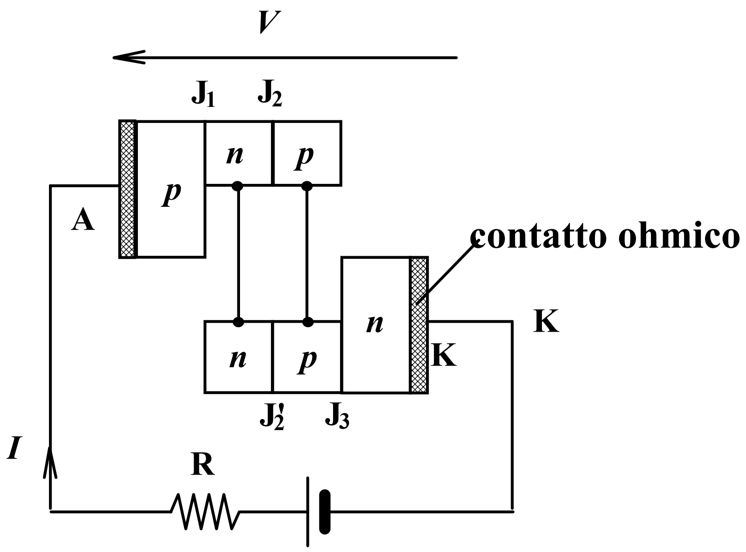
$$I_{BO} \cong \frac{1}{100} I_H$$

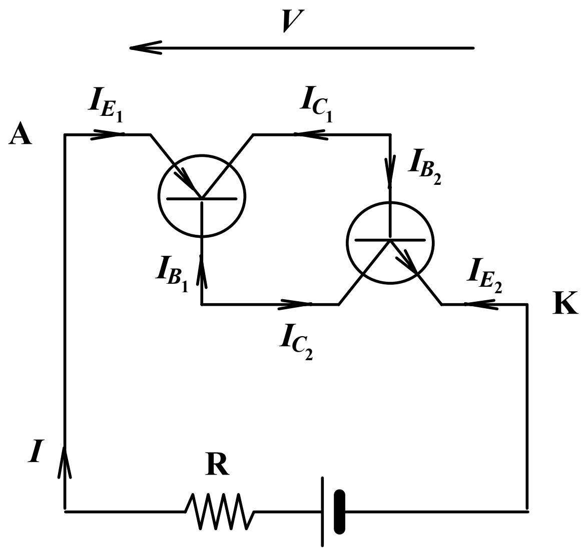
$$V_{BO} \cong 10 \div 100\ \text{V}$$

$$r_{d_{(on)}} \cong 1 \div 10\ \Omega$$

$$r_{d_{(off)}} \cong 10 \div 100\ \text{M}\Omega$$

Modello equivalente di Shockley





$$I_{E_1} + I_{C_1} + I_{B_1} = 0$$

$$I - \alpha_1 I_{E_1} + I_{C_{0,1}} + \alpha_2 I_{E_2} - I_{C_{0,2}} = 0$$

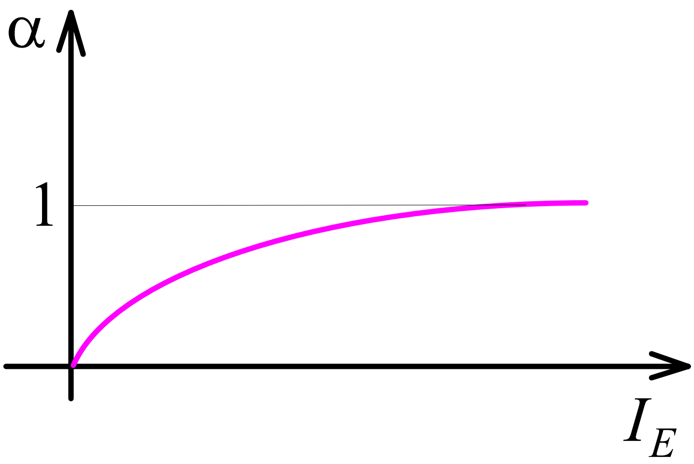
$$I(1 - \alpha_1 - \alpha_2) + I_{C_{0,1}} - I_{C_{0,2}} = 0$$

$$\boxed{I = \frac{I_{C_0}}{1 - (\alpha_1 + \alpha_2)}}$$

$$I_{C_1} = -\alpha_1 I_{E_1} + I_{C_{0,1}}$$
$$I_{C_2} = -\alpha_2 I_{E_2} + I_{C_{0,2}}$$

$$I_{E_1} = I$$
$$I_{B_1} = -I_{C_2}$$
$$I_{C_1} = -I_{B_2}$$
$$I_{E_2} = -I$$

$$I_{C_{0,1}} = -I_{C_{0,2}} = \frac{-I_{C_0}}{2}$$



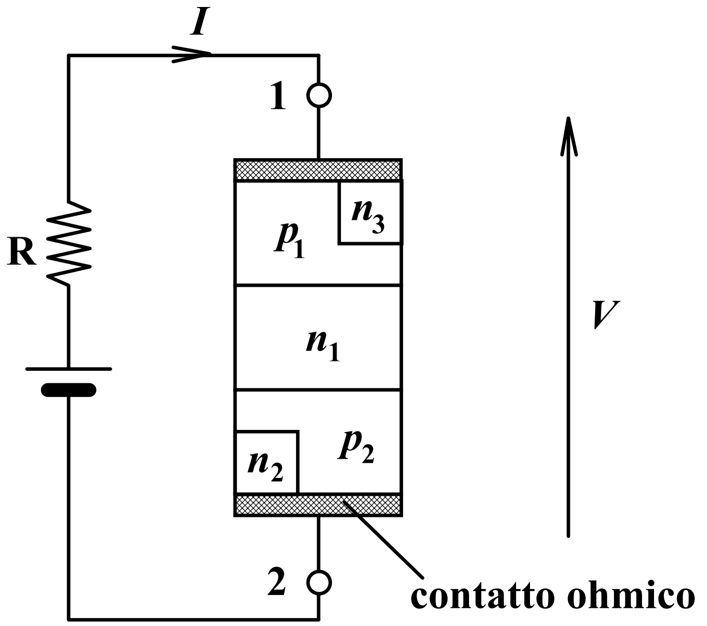
$$\boxed{V_H = 2V_{BE,sat} - V_{BC} - V_{bulk}}$$

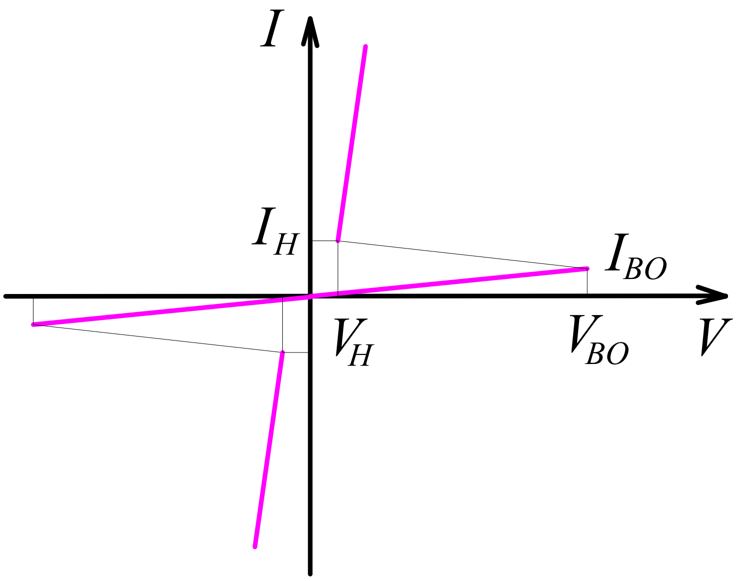
ê non sensibile alla T

<u>*Tempo di accensione*</u> *:* $\boldsymbol{t_{turn-on}}$ *(trascurabile)*

<u>*Tempo di spegnimento*</u> *:* $\boldsymbol{t_{turn-off}} \begin{cases} \mathbf{1 \div 15 \mu s (\textit{bassa potenza})} \\ \mathbf{15 \div 150 \mu s (\textit{elevata potenza})} \end{cases}$

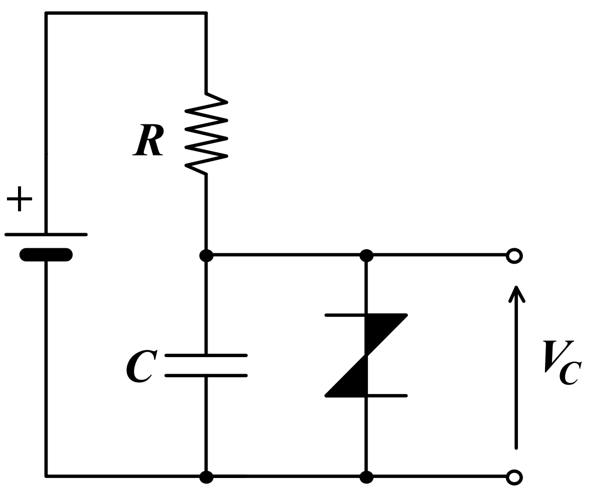
Diac

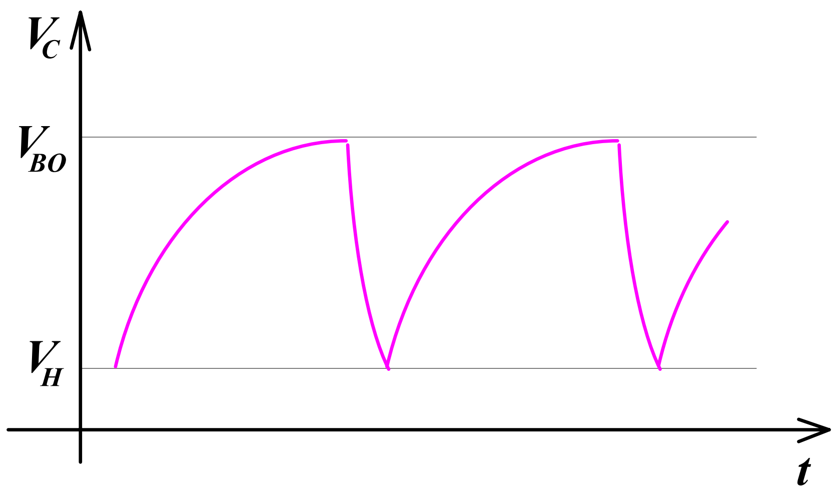




$$\boxed{|V_{bk}| > |V_{BO}|}$$

Oscillatore a rilassamento





SCR = Silicon Controlled Rectifier

SCS = Silicon Controlled Switch

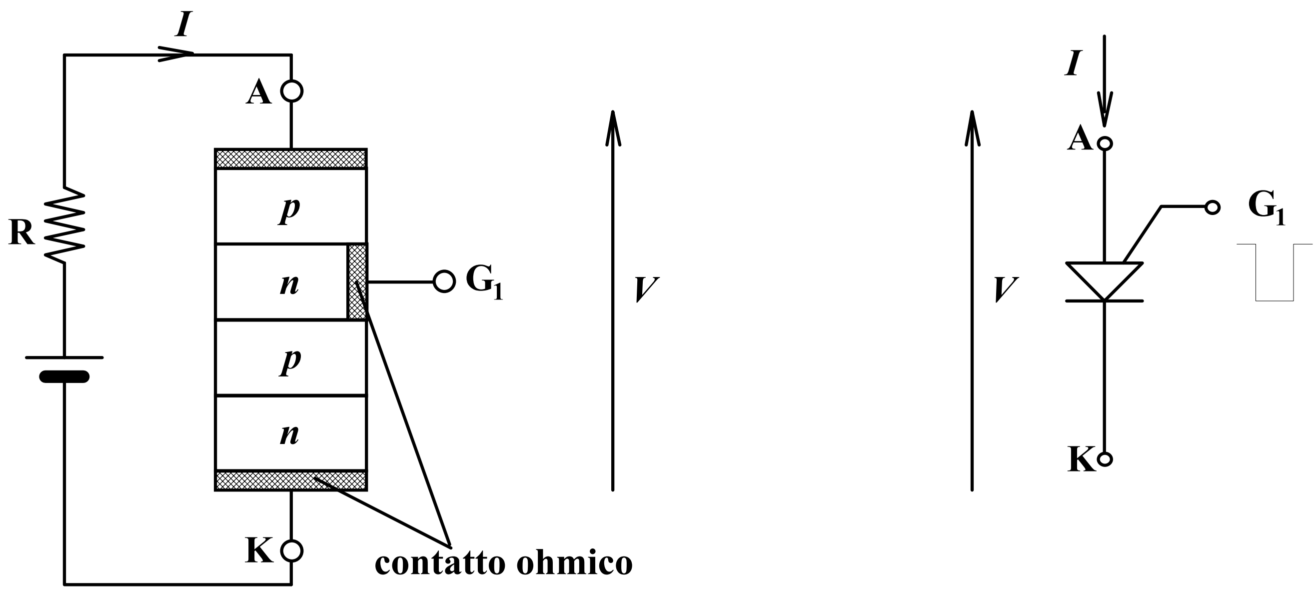
LAS = Light Activated Switch

GTO = Gate Thyristor Operator (Gate Turn off operating)

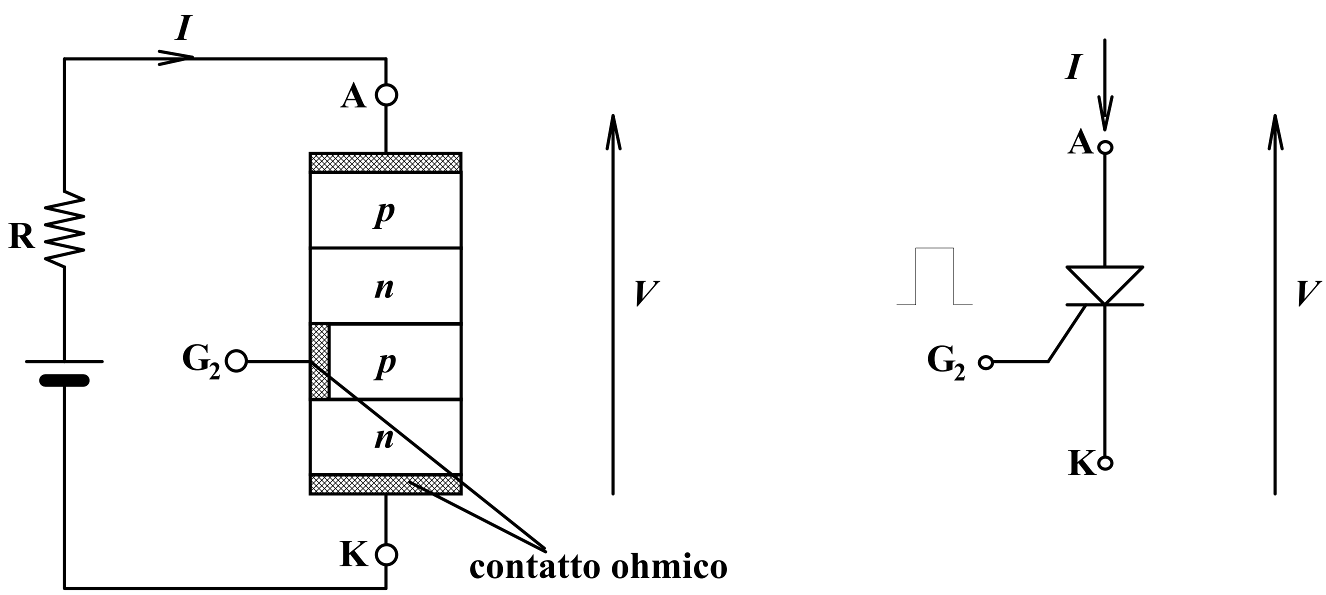
$\Downarrow$

Thyratron

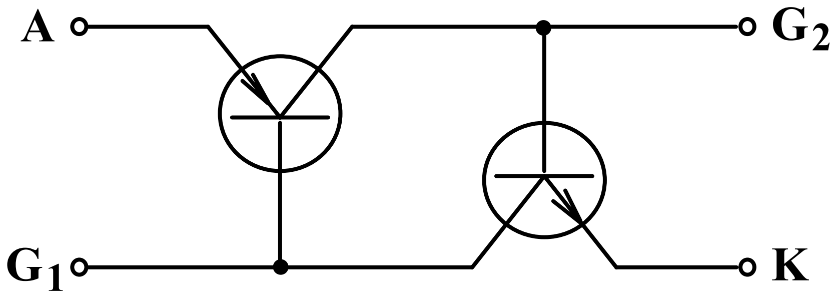
Tiristore a controllo di anodo



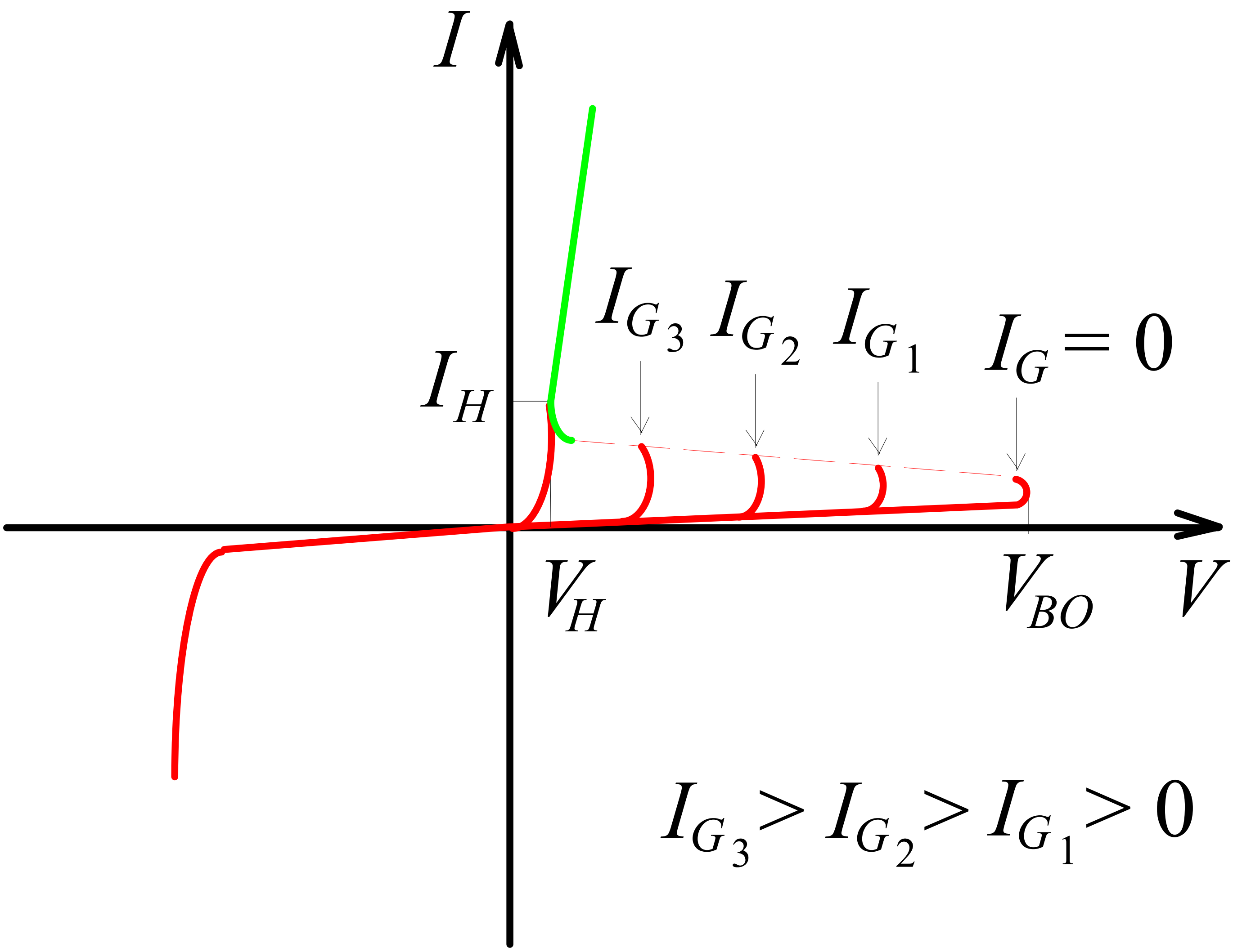
Tiristore a controllo di catodo



Modello equivalente

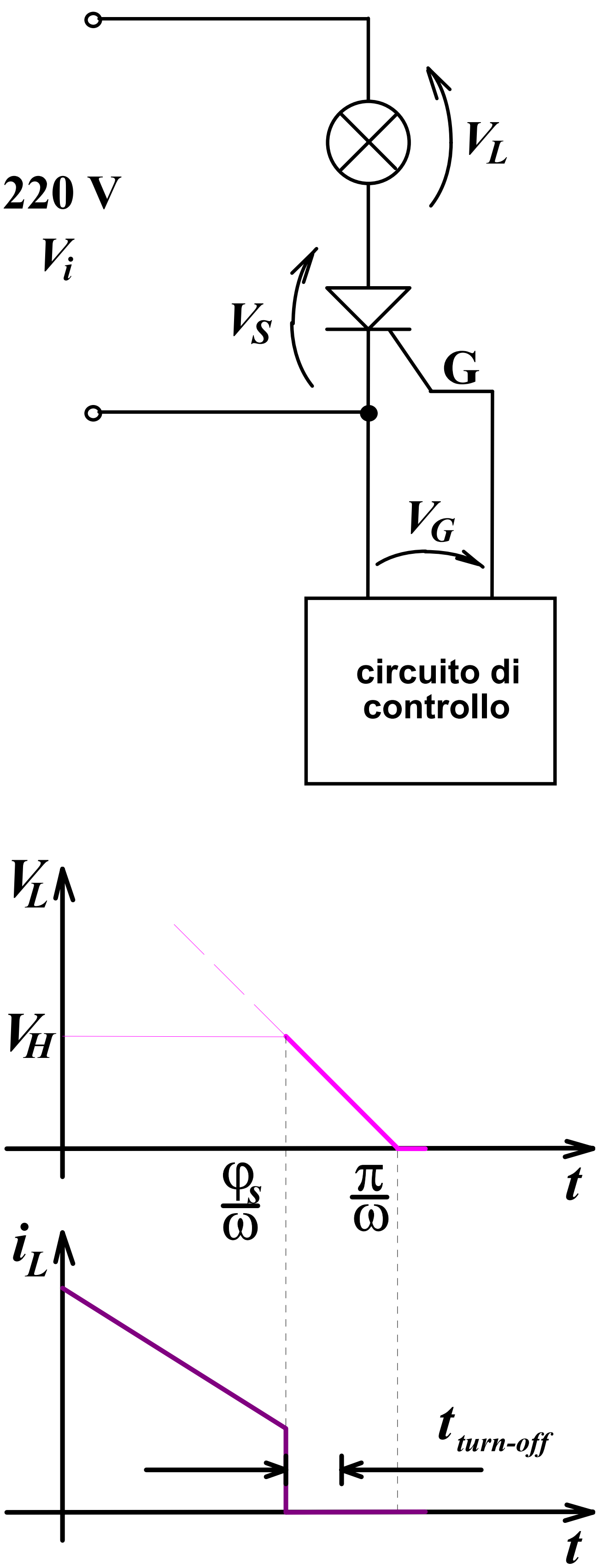


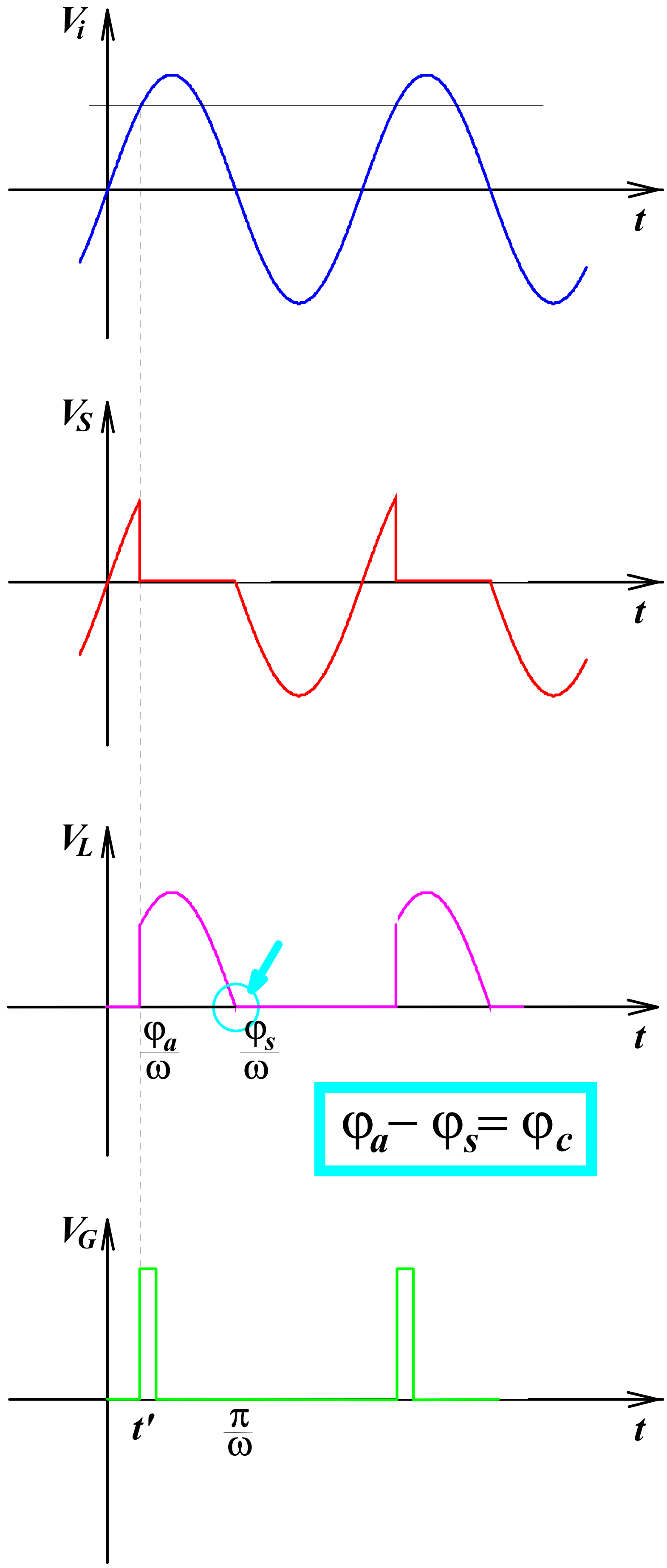
$$\boxed{I_B \uparrow \Rightarrow I_E \uparrow \Rightarrow \alpha \uparrow}$$



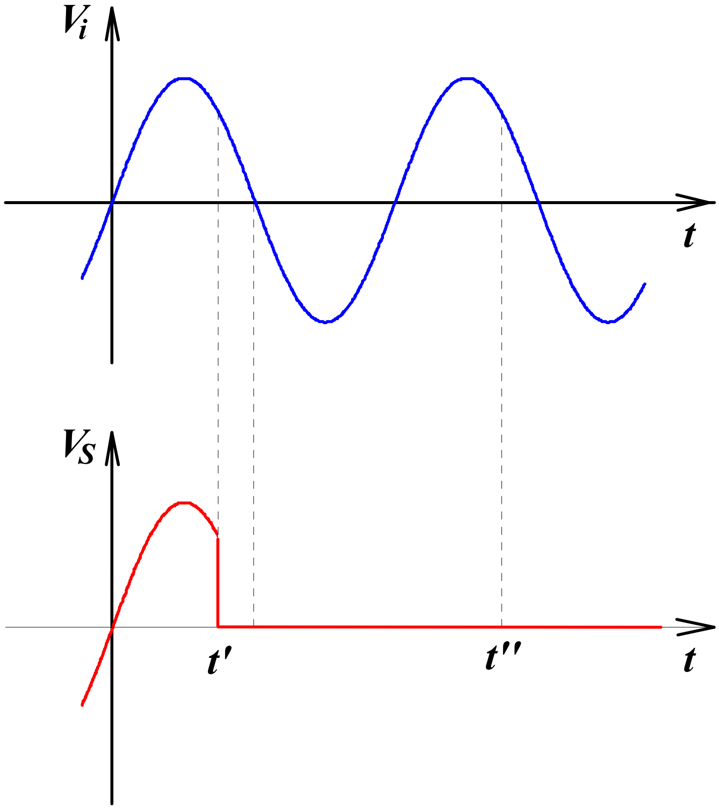
$$I_{G_3} > I_{G_2} > I_{G_1} > 0$$

Applicazione: dimmer





Problemi legati al tempo di turn-off



$$\boxed{f_{\max} < \frac{1}{2t_{turn-off}}}$$

Parzializzazione di conduzione sul carico

$$\overline{V_L} = \frac{1}{2\pi}\int_{\varphi_a}^{\varphi_s}(V_m \,\mathrm{sen}\,\omega t - V_H)d\omega t = \frac{V_m}{2\pi}\int_{\varphi_a}^{\varphi_s}\left(\mathrm{sen}\,\omega t - \frac{V_H}{V_m}\right)d\omega t$$

$$\Downarrow$$

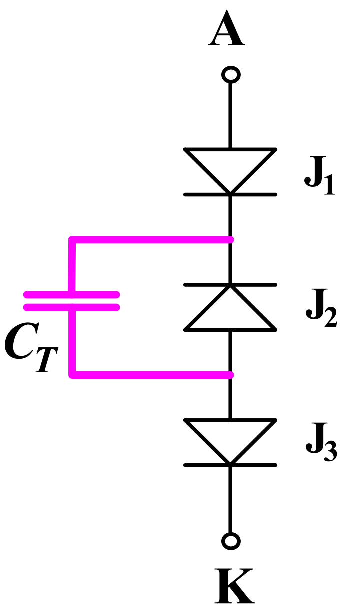
$$\frac{V_H}{V_m} \cong 0$$

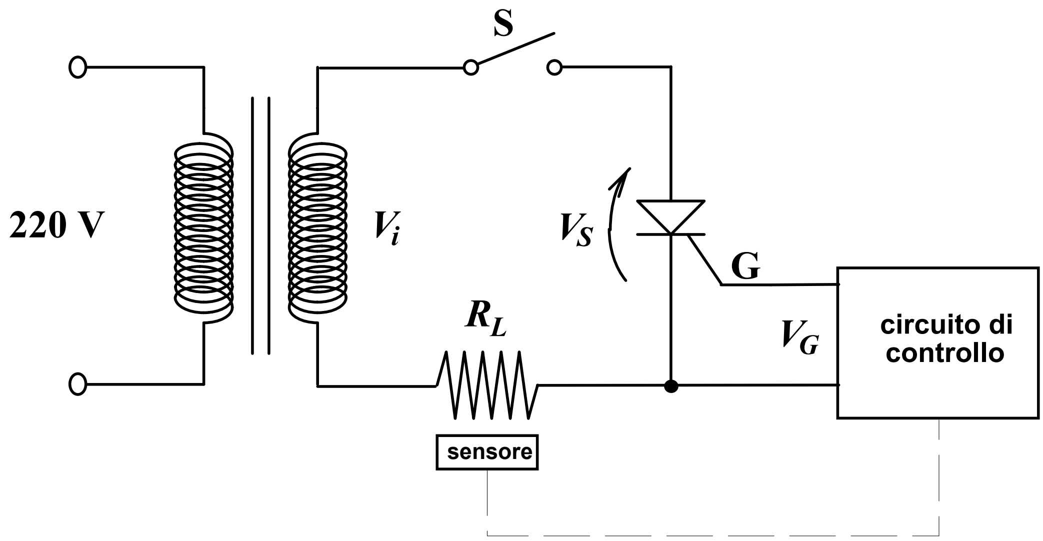
$$\Downarrow$$

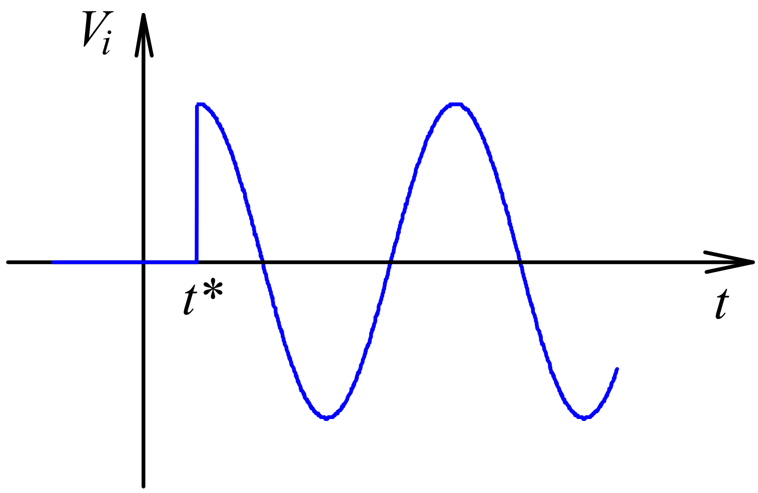
$$\overline{V_L} \cong \frac{V_m}{2\pi}\int_{\varphi_a}^{\varphi_s}\mathrm{sen}\,\omega t\, d\omega t = \frac{V_m}{2\pi}[-\cos\omega t]_{\varphi_a}^{\varphi_s} = \frac{V_m}{2\pi}(1+\cos\varphi_a)$$

Problematiche legate all'uso di scr

capacità di transizione e problemi causati all'<u>accensione del circuito</u> e per via di <u>disturbi impulsivi presenti in rete</u>





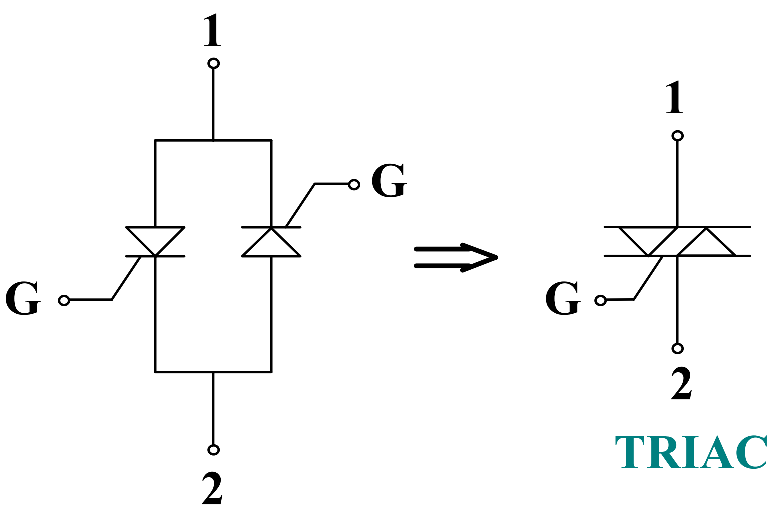


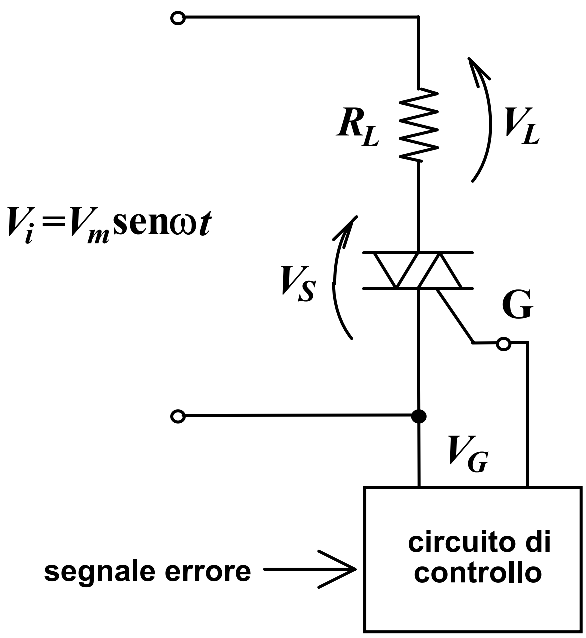
$$\boxed{i = C_T \frac{dV_{AK}}{dt}}$$

$$\frac{dV_{AK}}{dt} < 100 \frac{\mu V}{s}$$

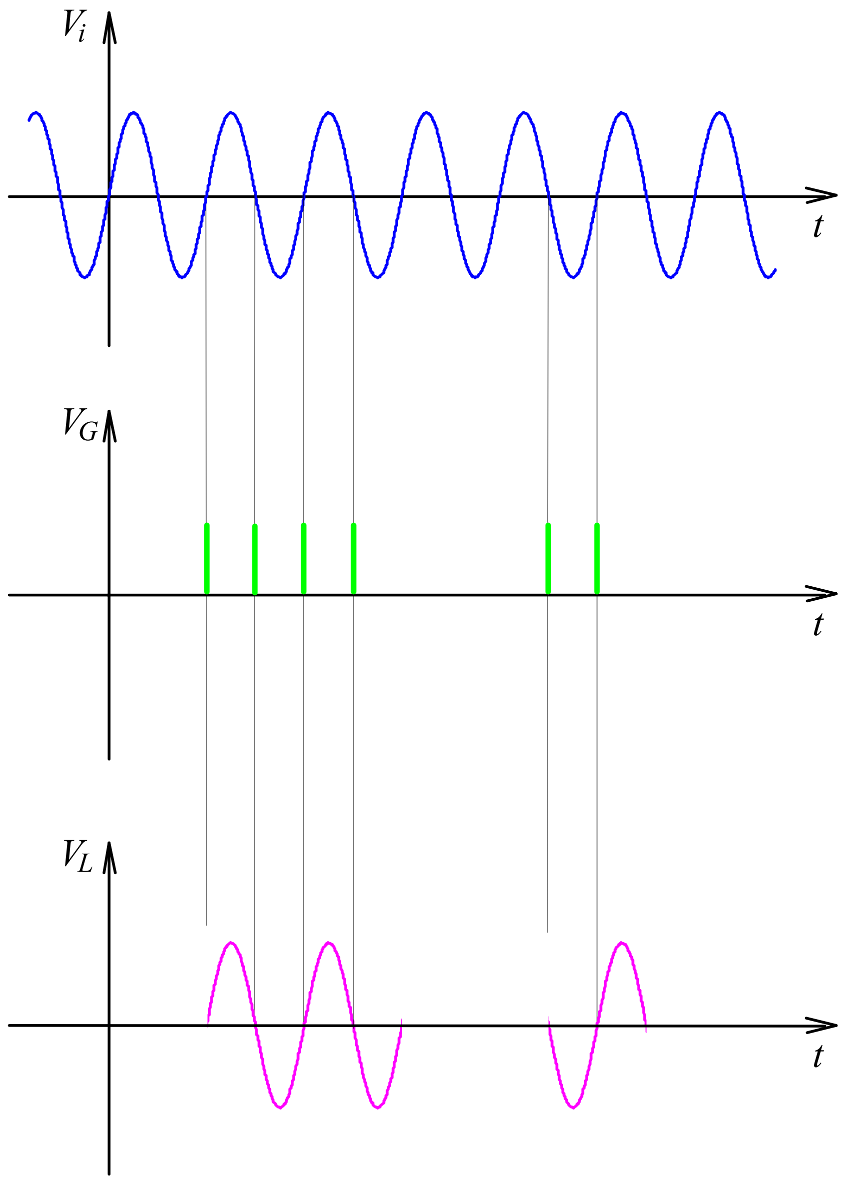
Deve inoltre essere limitata anche la $\frac{di}{dt}$ ***altrimenti si possono instaurare <u>punti caldi</u> oltre che <u>cadute di potenziale trasversali</u>***

Triac





- ***minore rendimento di pilotaggio rispetto agli scr in antiparallelo***
- ***dispositivi non di elevatissima potenza***



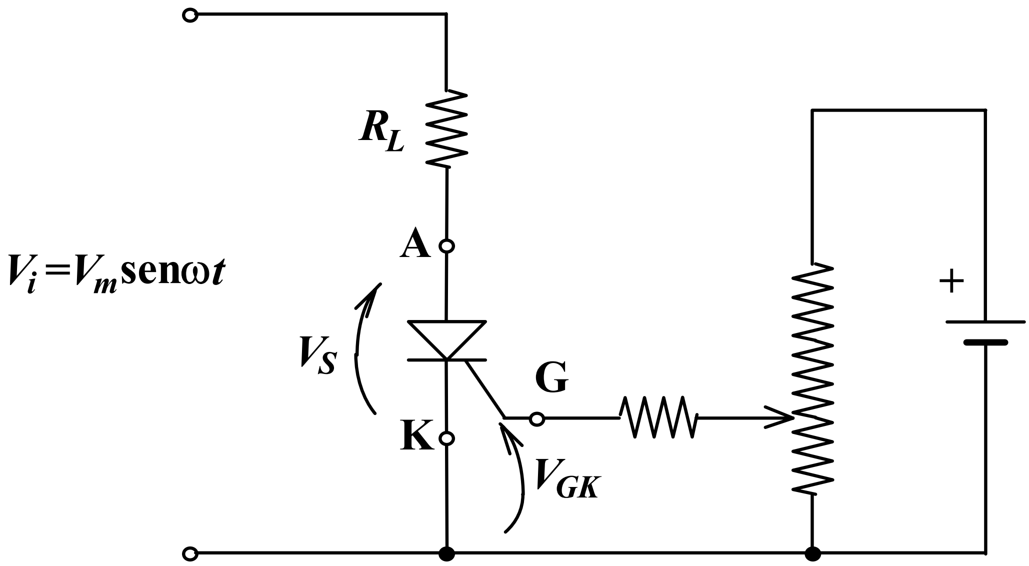
Controllo a "burst"

Modalità di pilotaggio

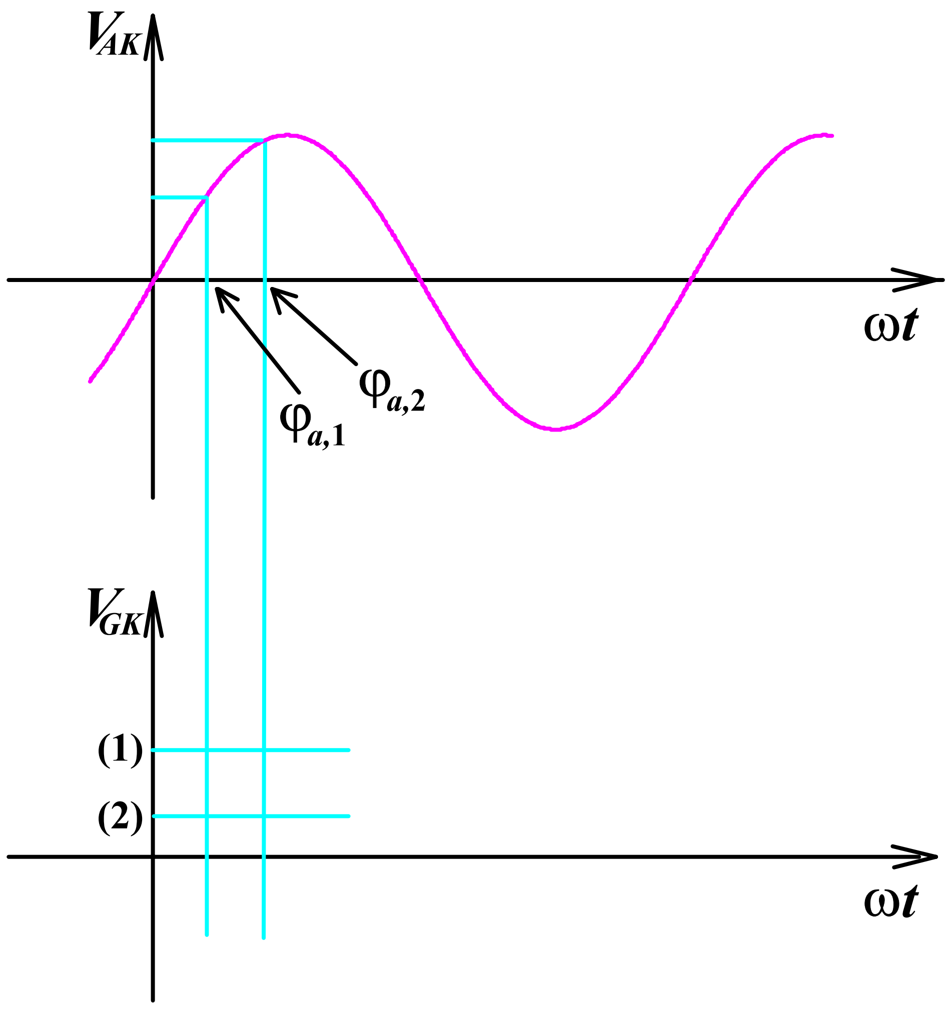
(a) in continua
(b) in alternata
(c) impulsivo

(a) in continua

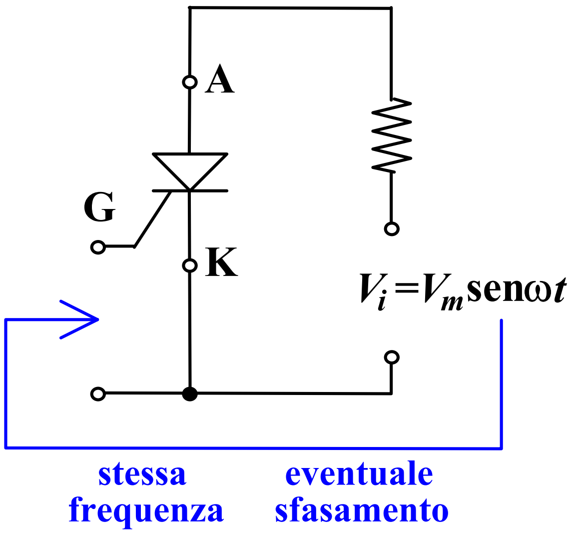
- ***basso rendimento***
- ***impreciso***
- ***sensibile alla temperatura***

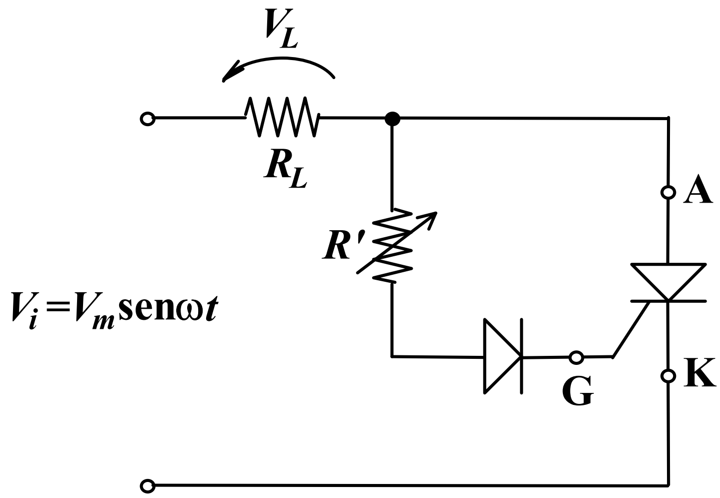


- $\varphi_a = 0 \div 90^{0}$



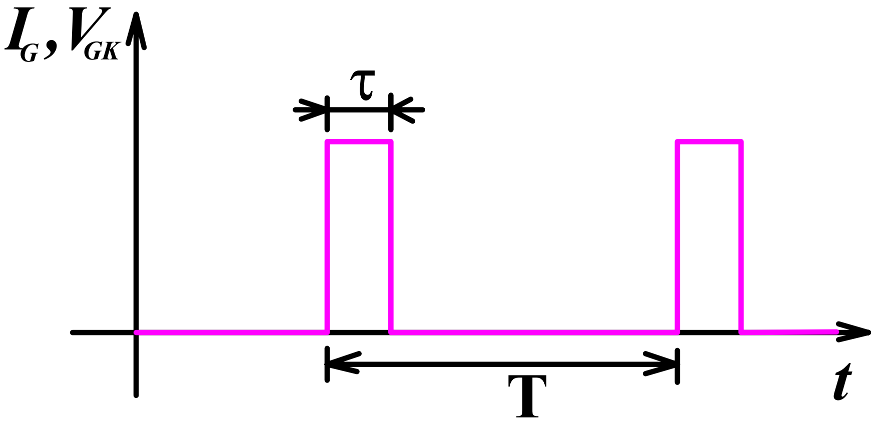
(b) in alternata





(c) impulsivo

- *maggiore precisione dell'istante di accensione*
- *indipendente dalla T*



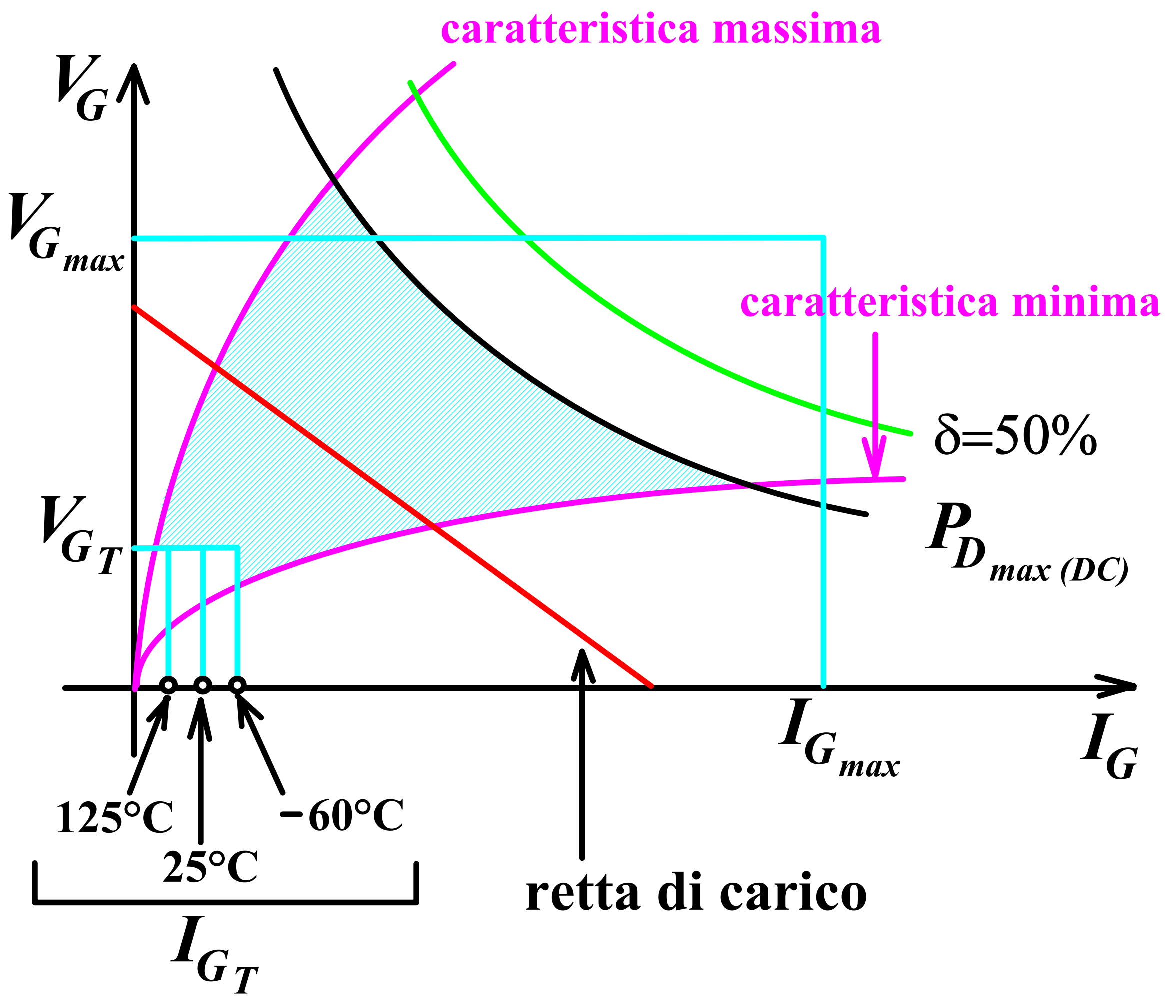
Duty cycle

$$P_D = I_G V_{GK} = \textit{potenza di picco}$$

$$P_D \cdot \tau = \textit{energia dissipata per impulso}$$

$$\overline{P}_D = P_m = \frac{\tau P_D}{T} \quad \Rightarrow \quad \boxed{\frac{\tau}{T} = \delta} \qquad \textit{(duty cycle)}$$

Problema della dissipazione di potenza



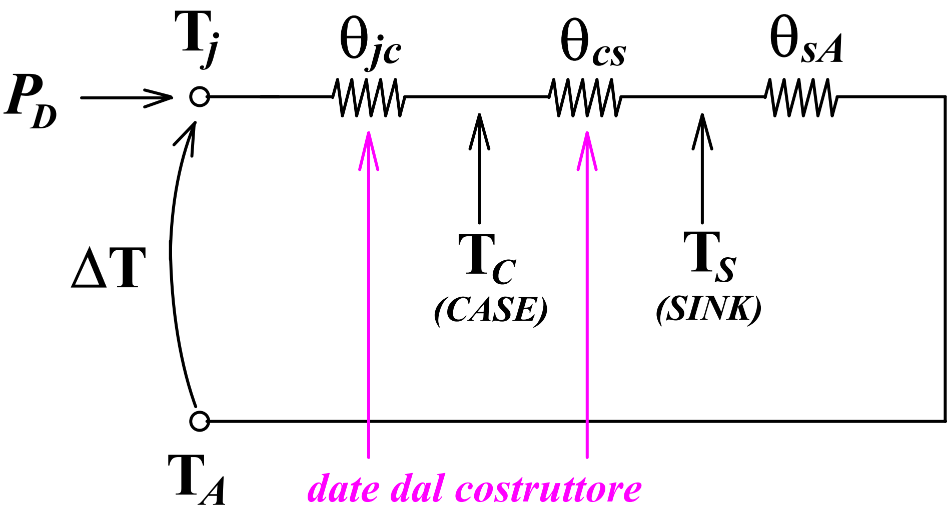
$\Delta T \Rightarrow \Delta V$

$P_D \Rightarrow I$

$\theta \Rightarrow R$

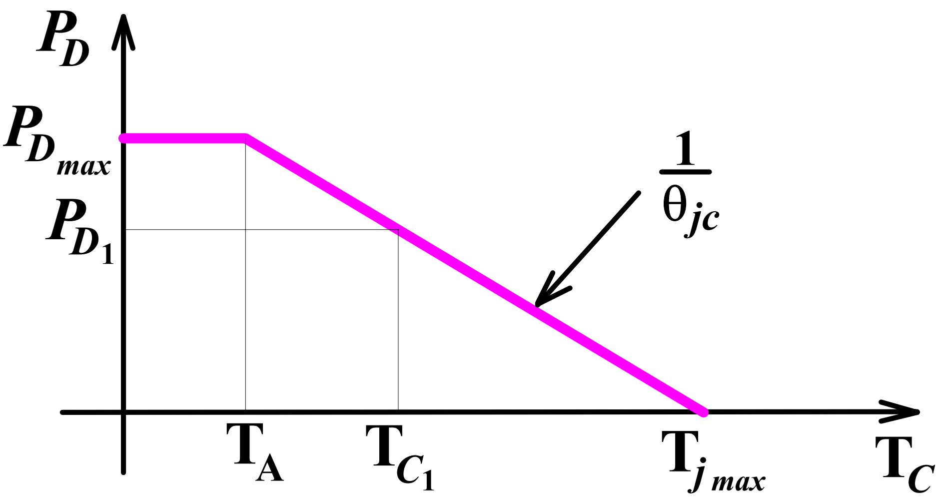
$$\boxed{\theta = \frac{\Delta T}{P_D} \quad \left[\frac{°C}{W}\right]}$$

Derating Curve



$$\theta_{sA} = ?$$

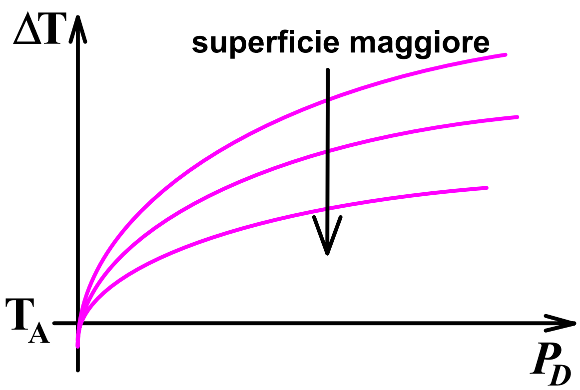
$$\boxed{\left|\frac{\Delta P_D}{\Delta T}\right| = \frac{1}{\theta_{jc}}}$$

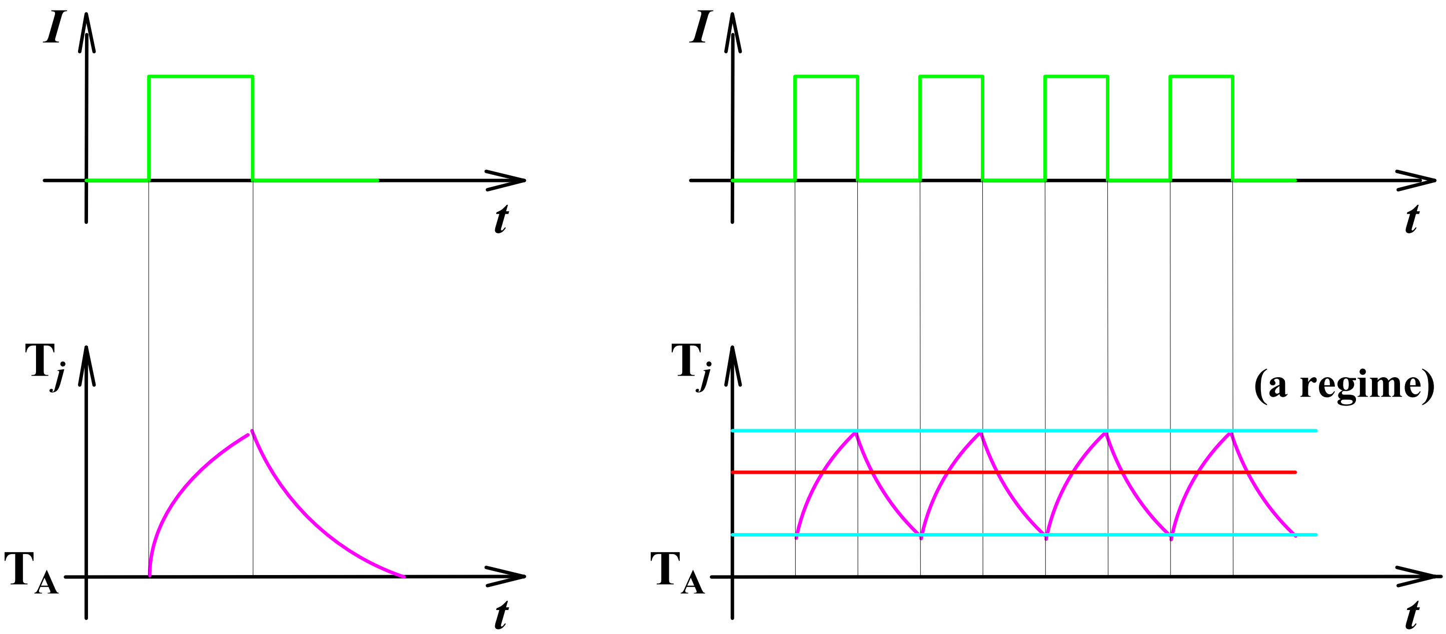


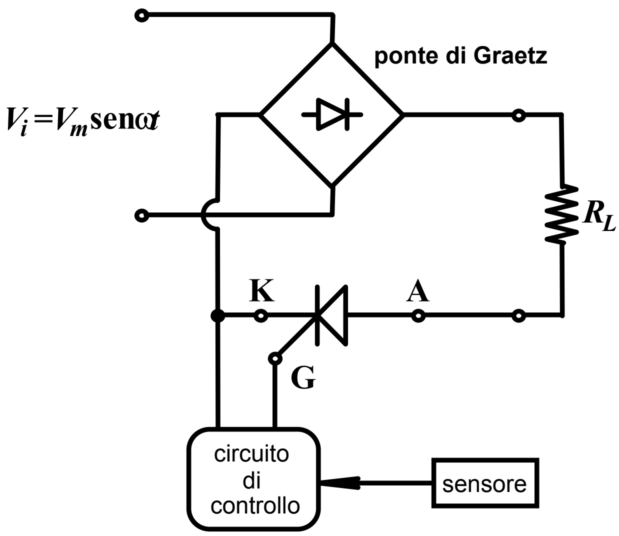
$$P_{D_1} = \frac{T_{C_1} - T_A}{\theta_{cs} + \theta_{sA}}$$

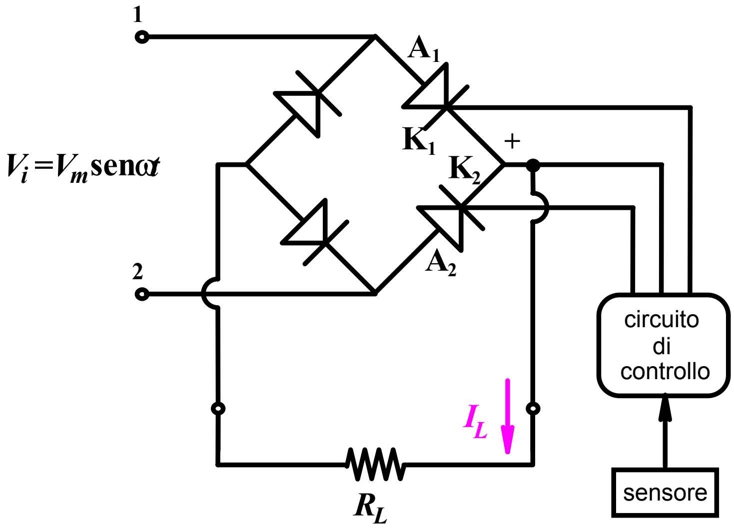
Le caratteristiche del dissipatore dipendono da:

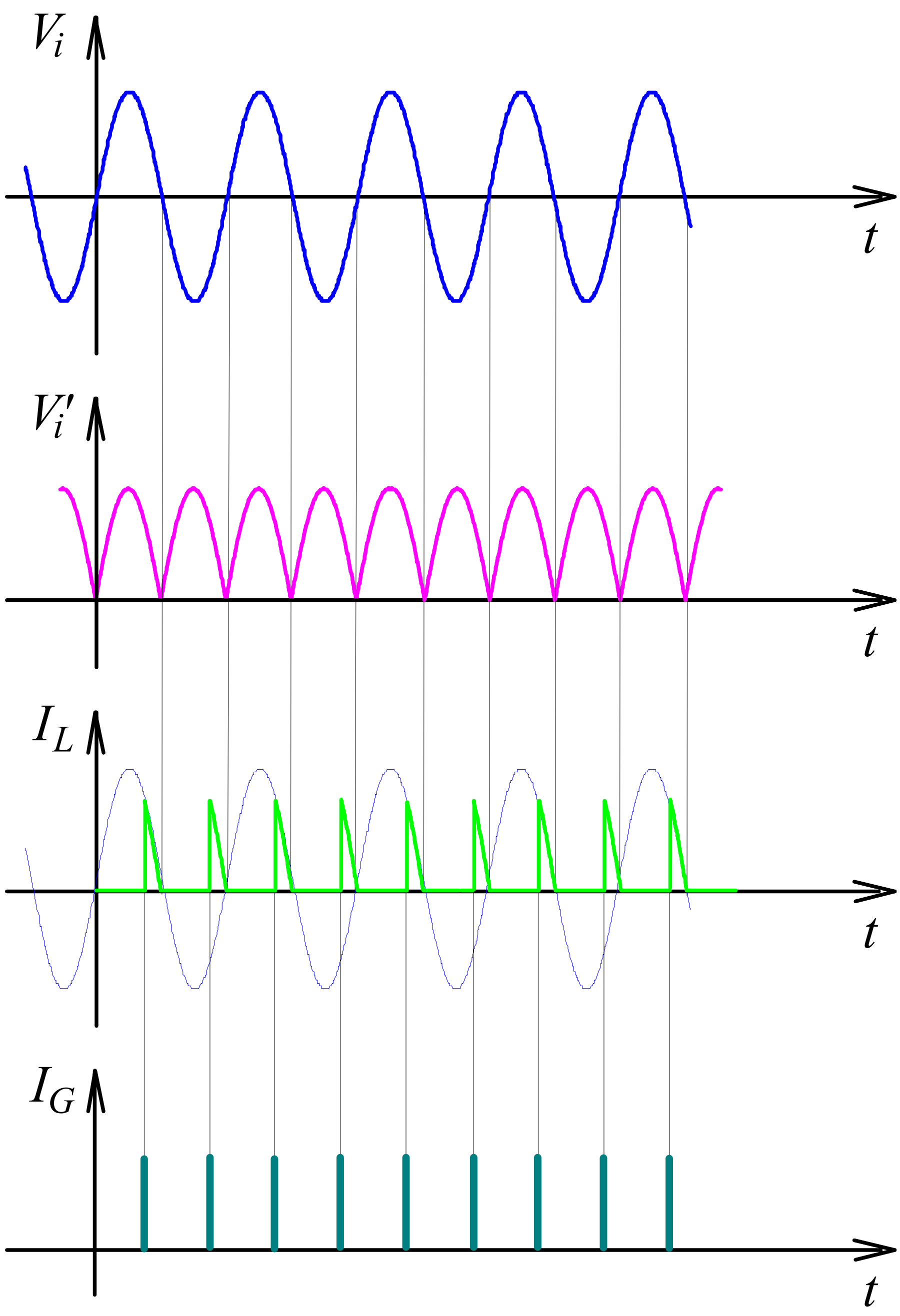
***- materiale** (conducibilità termica)*
***- dimensione** (estensione della superficie di scambio)*
***- stato della superficie** (liscia, sabbiata, verniciata)*
***- forma** (alettata, liscia, ecc.)*
***- tipo di scambio termico utilizzato** (conduzione, irradiazione, convezione naturale o forzata)*



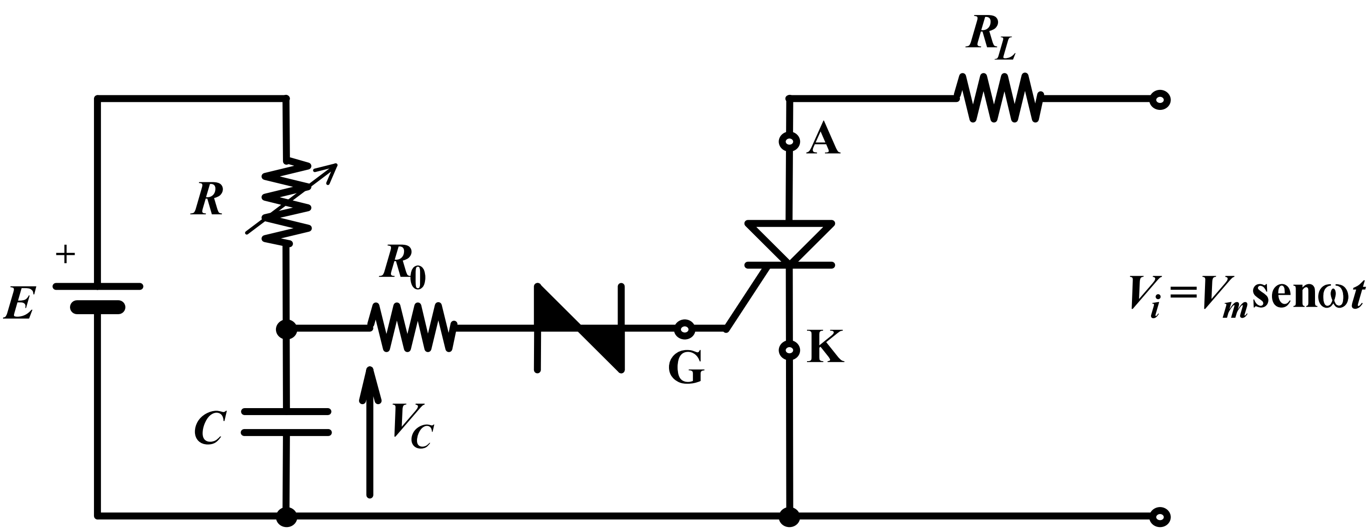



ponte di Graetz
$V_i = V_m \text{sen}\omega t$
R_L
K
A
G
circuito di controllo
sensore

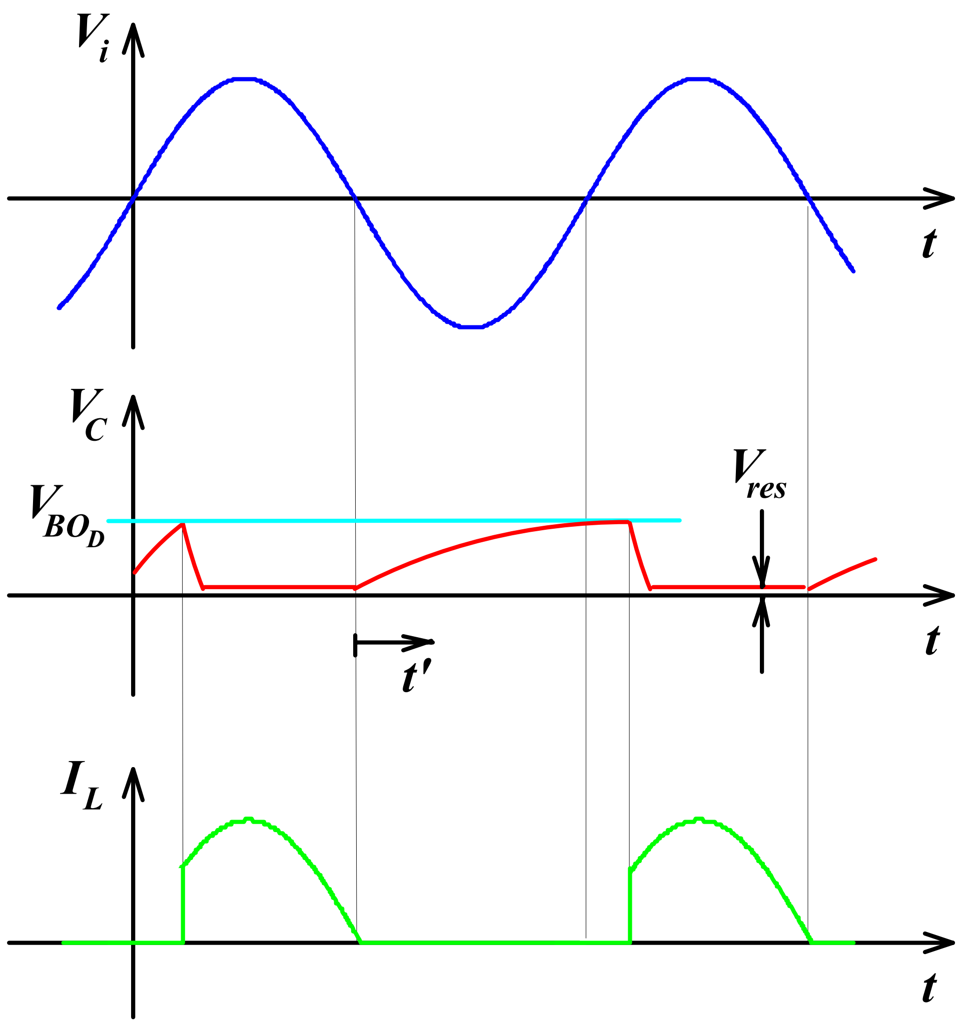

1
2
A_1
K_1
K_2
A_2
+
$V_i = V_m \text{sen}\omega t$
I_L
R_L
circuito di controllo
sensore


V_i
t
V_i'
t
I_L
t
I_G
t

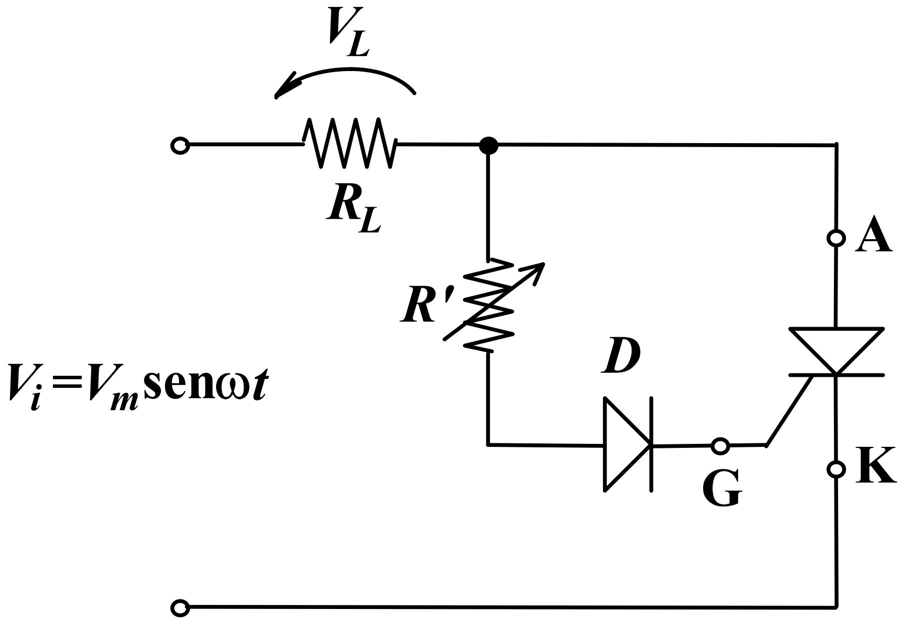
Esempio

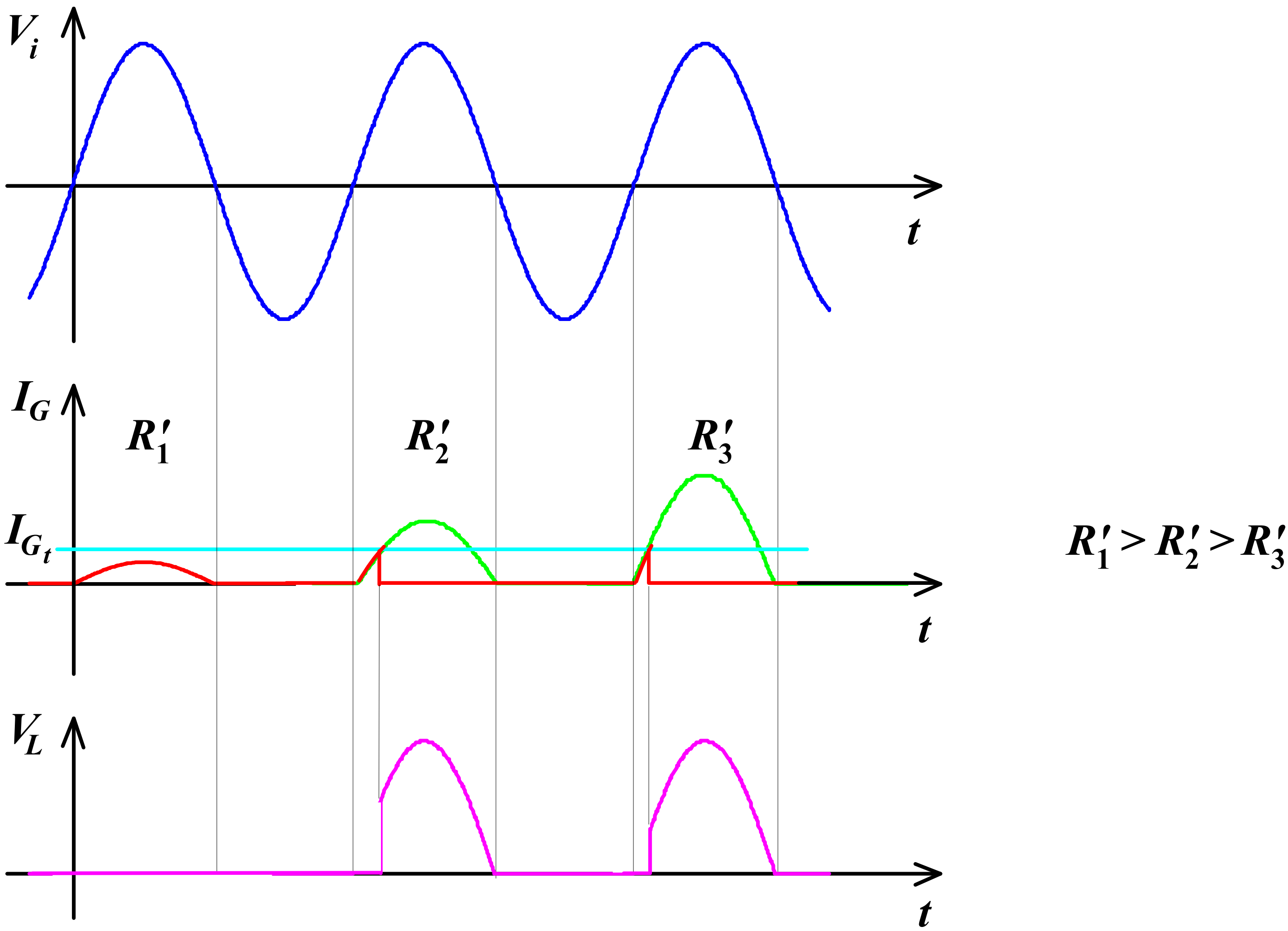


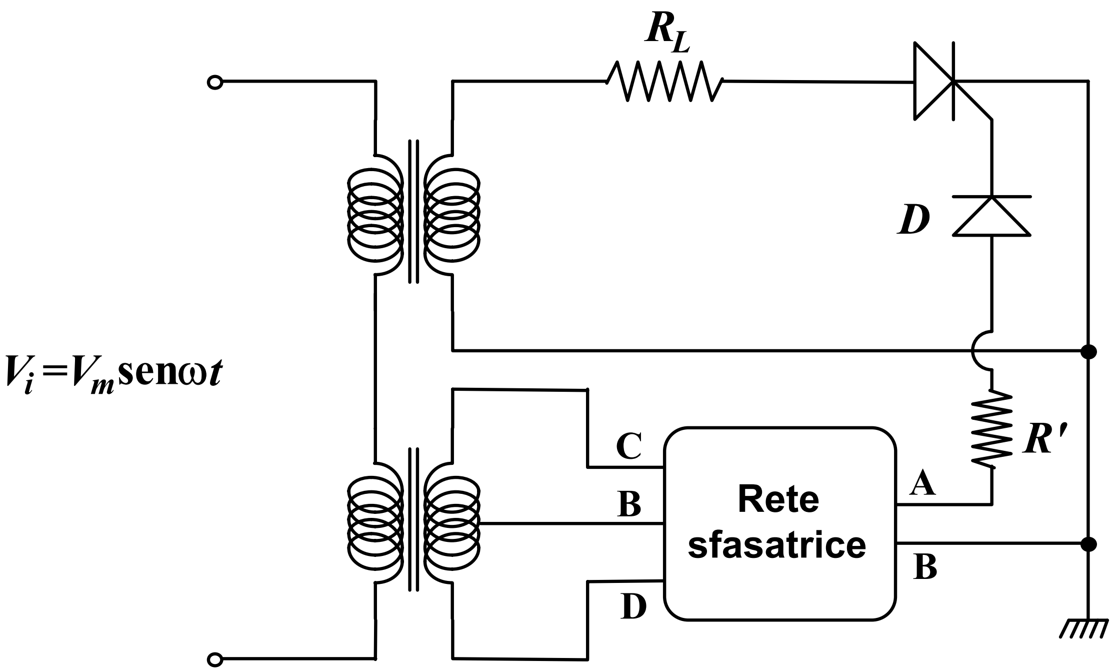
$$V_C - V_{res} = (E - V_{res})\left(1 - e^{-\frac{t'}{RC}}\right)$$



Utilizzo di una rete sfasatrice





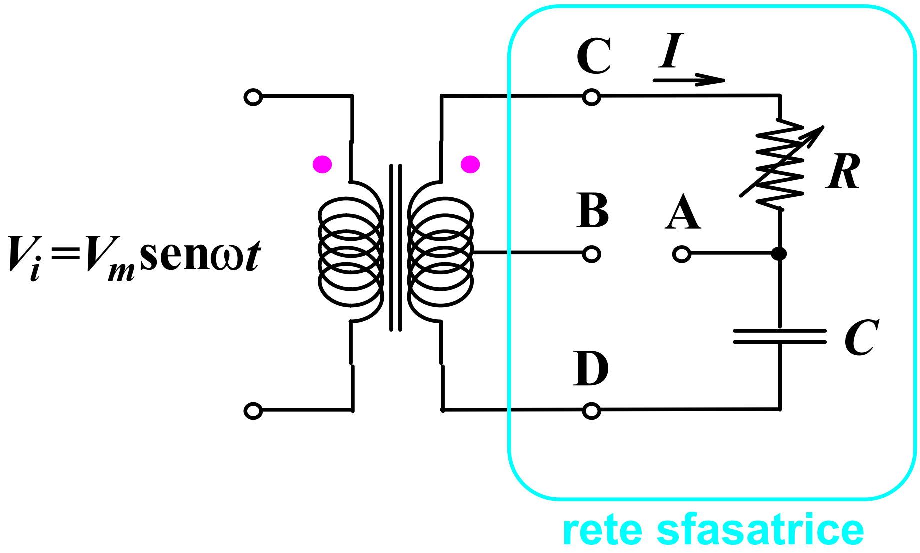


$$V_{CD} = \left(R + \frac{1}{j\omega C}\right) I$$

$$I = \frac{2V_{CB}}{R + \frac{1}{j\omega C}}$$

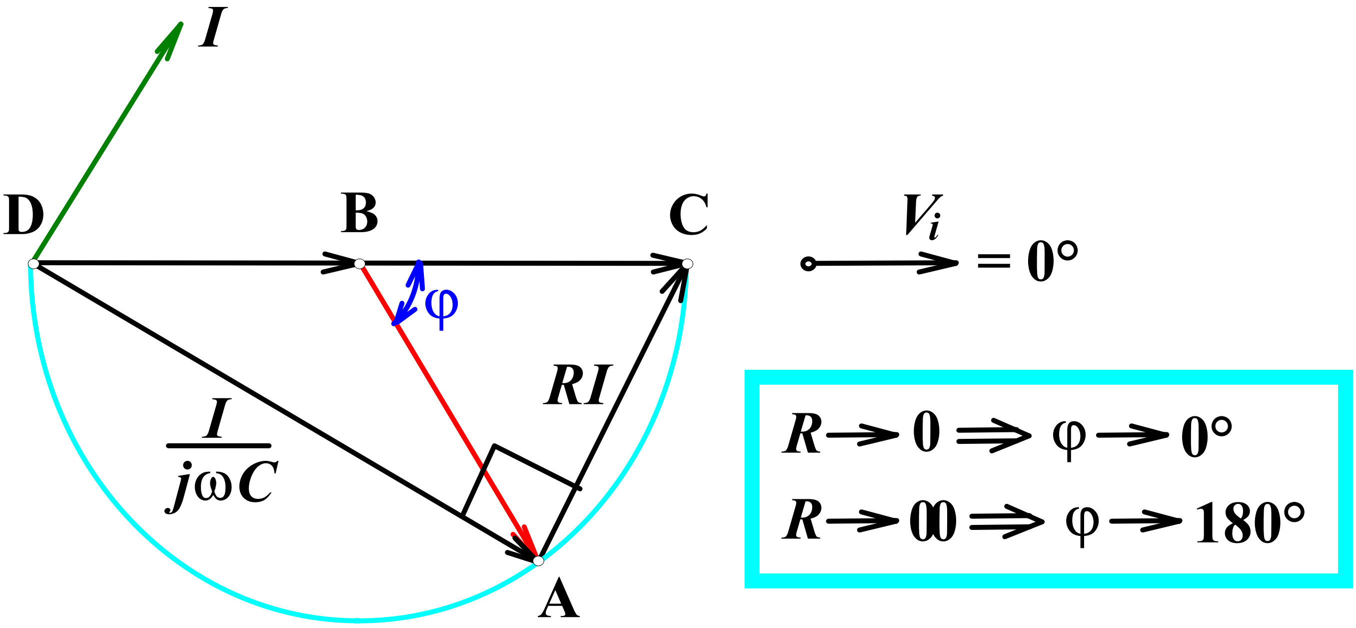
$$V_{CD} = 2V_{CB}$$

$$V_{AB} = V_{CB} - R\,I$$

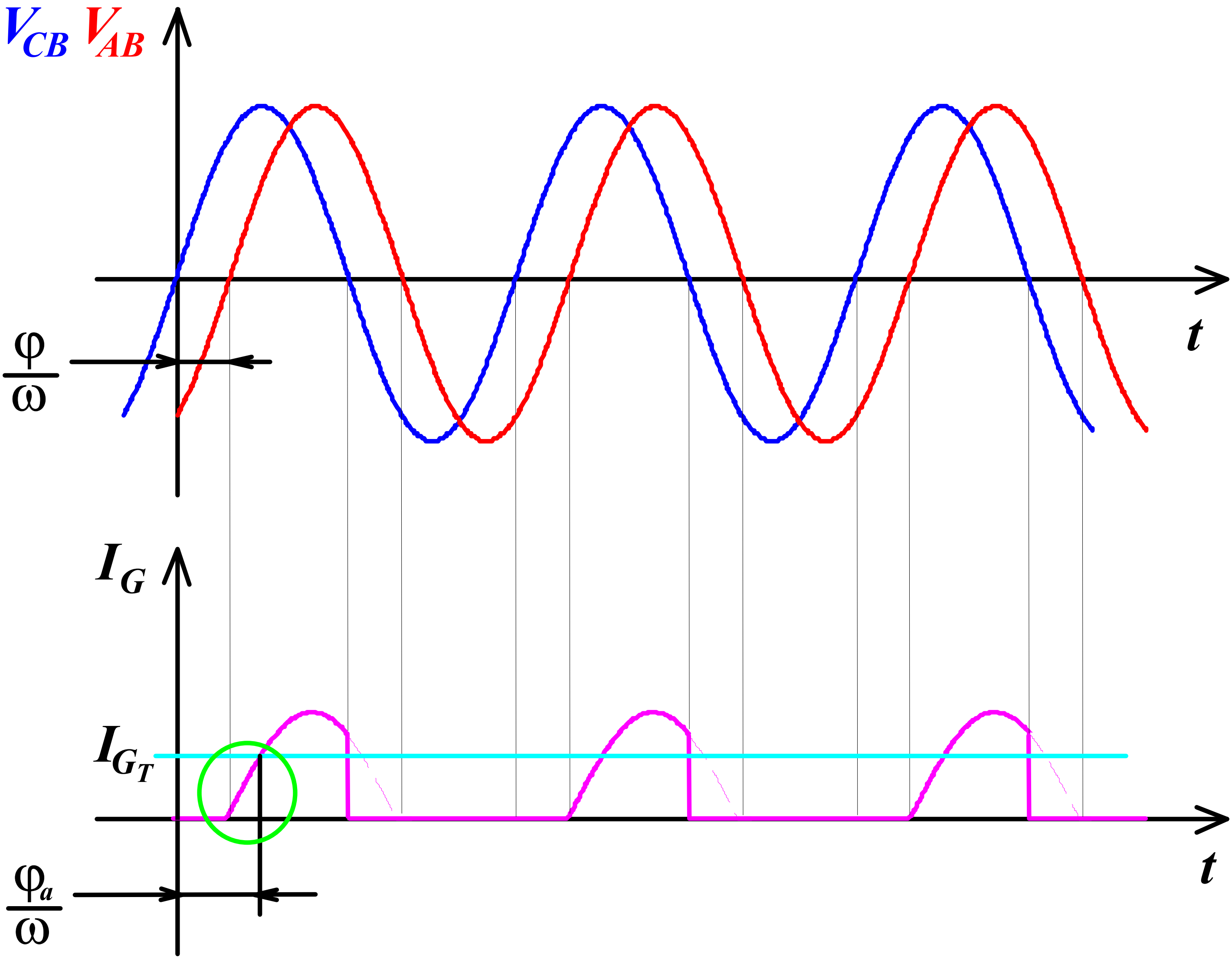


$$V_{AB} = V_{CB}\left(1 - \frac{2R}{R + \frac{1}{j\omega C}}\right) = V_{CB}\left(\frac{1 - j\omega RC}{1 + j\omega RC}\right) \Rightarrow |V_{AB}| = |V_{CB}|$$

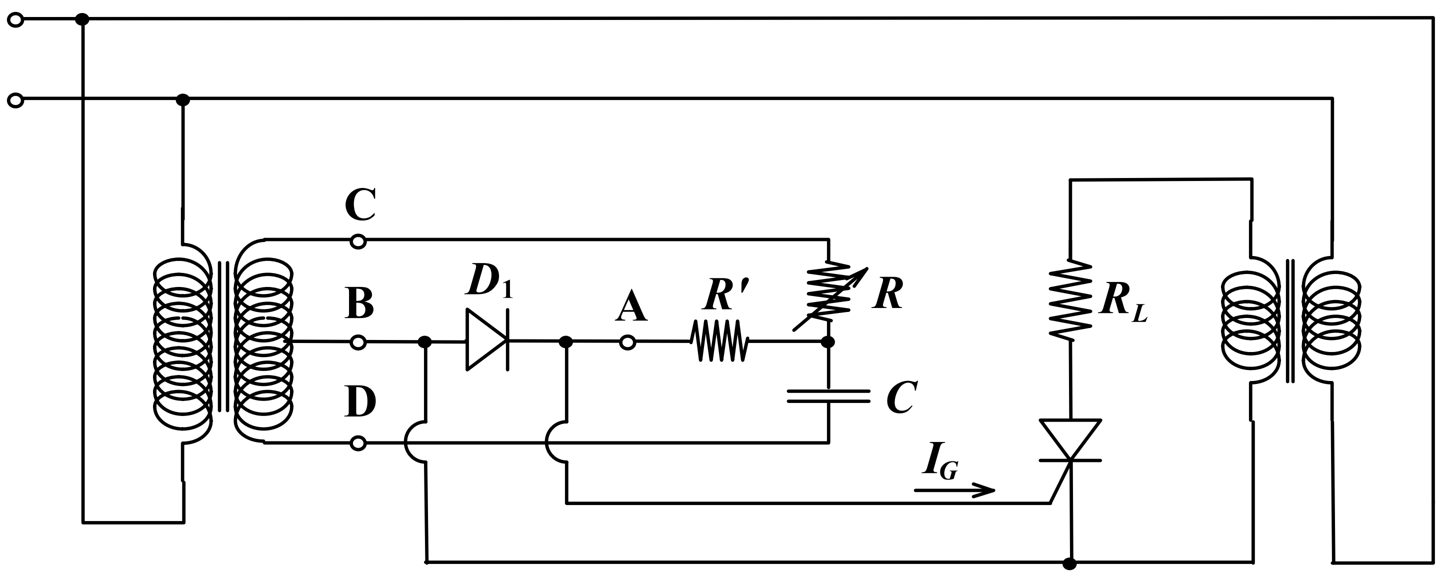
$$\boxed{V_{AB} = |V_{CB}|\, e^{j\varphi}} \qquad \textit{con}\ .\ \varphi = -2\,\mathrm{arctg}\,\omega RC$$

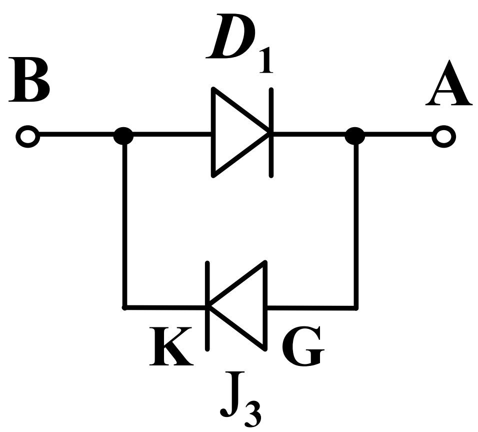


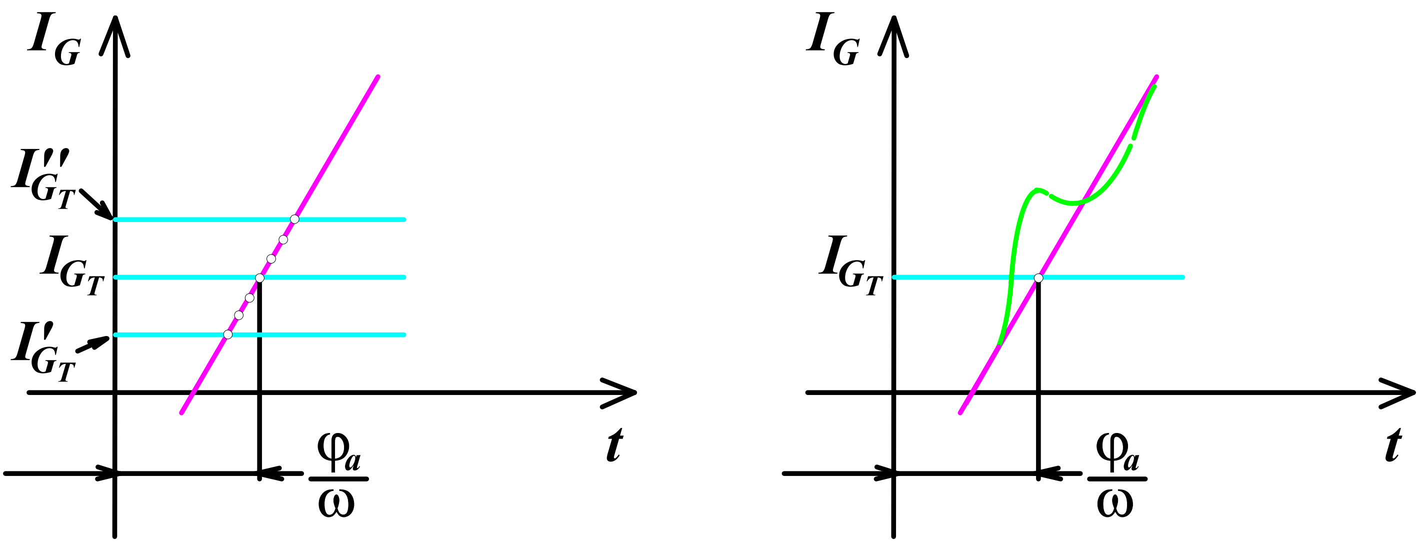
I
D
B
C
φ
RI
I / jωC
A
Vi = 0°
R → 0 ⇒ φ → 0°
R → ∞ ⇒ φ → 180°



VCB VAB
t
φ / ω
IG
IGT
t
φa / ω

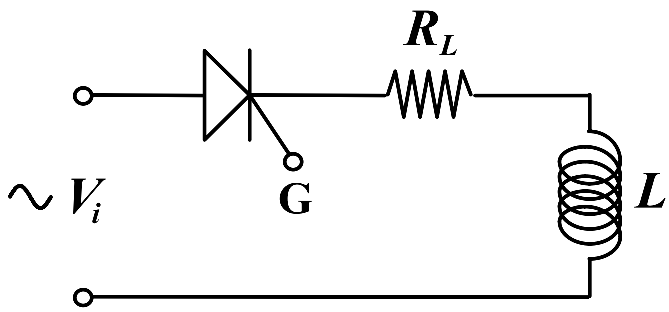

C
B
D
D_1
A
R'
R
C
R_L
I_G

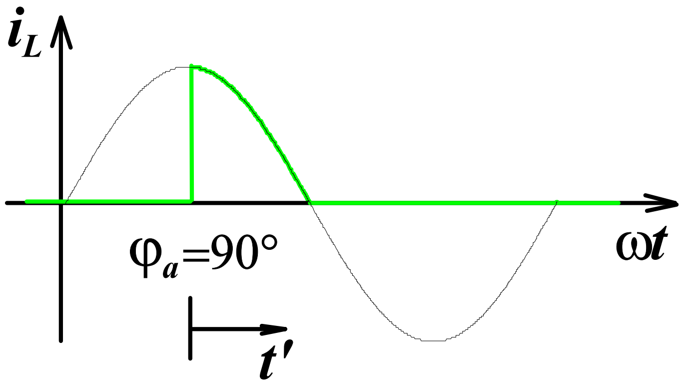

B
D_1
A
K
G
J_3

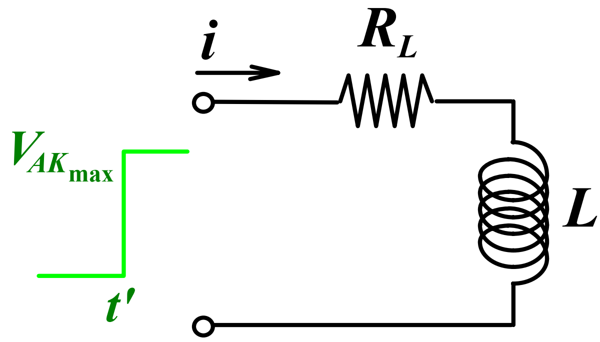

I_G
I''_{G_T}
I_{G_T}
I'_{G_T}
t
$\frac{\varphi_a}{\omega}$
I_G
I_{G_T}
t
$\frac{\varphi_a}{\omega}$

Utilizzo di una rete smorzatrice (snubber)

Problema: $\dfrac{di}{dt} \qquad \dfrac{dv_{AK}}{dt}$







$$i(t') = \mathrm{A} + \mathrm{B}e^{-\frac{t'}{\tau}} \quad \text{con} \quad \tau = \frac{L}{R_L}$$

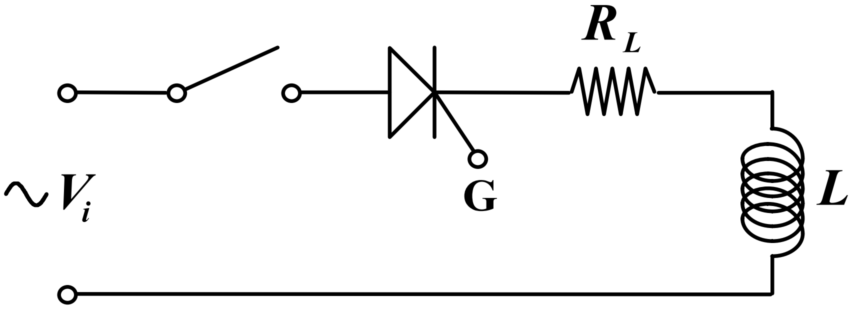
$$i(0) = 0 \quad \Rightarrow \quad \mathrm{A} = -\mathrm{B}$$

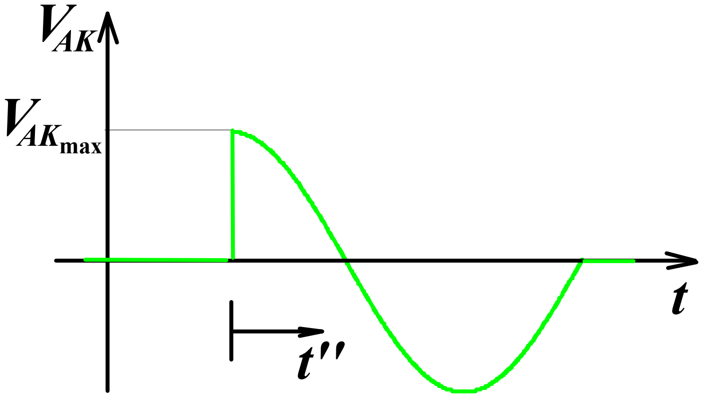
$$i_{t\to\infty} = \frac{V_{AK\,\max}}{R_L} = \mathrm{A} \quad \Rightarrow \quad i(t') = \frac{V_{AK\,\max}}{R_L}\left(1 - e^{-\frac{t'}{\tau}}\right)$$

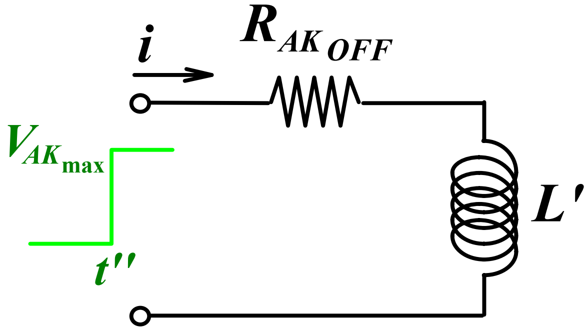
$$\frac{di}{dt'} = \frac{V_{AK\,\max}}{R_L \cdot \frac{L}{R_L}}\, e^{-\frac{t'}{\tau}} \quad \Rightarrow \quad \boxed{\left.\frac{di}{dt'}\right|_{\max} = \frac{V_{AK\,\max}}{L}}$$

$$\text{Hp:}\quad \left.\frac{di}{dt'}\right|_{\max} = \frac{100\text{ A}}{\mu\text{s}} \quad\Rightarrow\quad L = \frac{V_{AK\,\max}}{\left.\frac{di}{dt'}\right|_{\max}} = \frac{300\text{ V}}{\frac{100\text{ A}}{\mu\text{s}}} \cong \mathbf{3\cdot 10^{-6}\ H}$$

$$\left.\frac{dv_{AK}}{dt}\right|_{\max} = ?$$







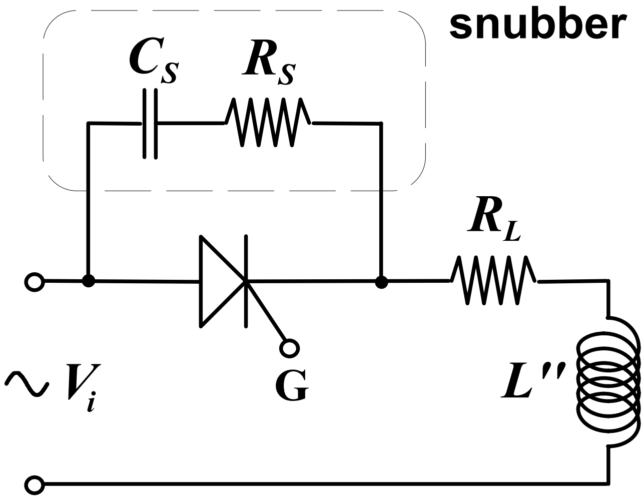
$$\text{Hp: } I_{OFF} = 10\text{mA} \quad\Rightarrow\quad R_{AK\,OFF} = \frac{300}{10^{-2}\text{A}} = 30\text{k}\Omega >> R_L$$

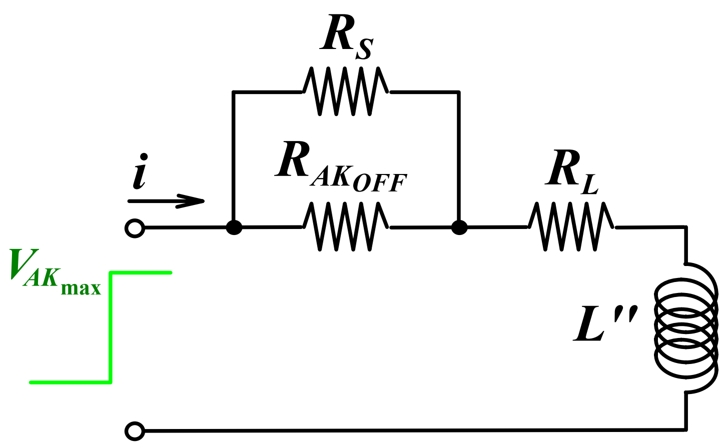
$$i(t'') = \frac{V_{AK\,\max}}{R_{AK\,OFF}}\left(1 - e^{-\frac{t''}{\tau'}}\right) \quad \text{con} \quad \tau' = \frac{L}{R_{AK\,OFF}}$$

$$v_{AK}(t) = R_{AK\,OFF}\cdot i = V_{AK\,\max}\left(1 - e^{-\frac{t''}{\tau'}}\right)$$

$$\frac{dv_{AK}}{dt''} = \frac{V_{AK\,\max}}{\tau'}\, e^{-\frac{t''}{\tau'}} \quad\Rightarrow\quad \boxed{\left.\frac{dv_{AK}}{dt''}\right|_{\max} = \frac{R_{AK\,OFF}\,V_{AK\,\max}}{L}}$$

$$\text{Hp: } \frac{dv_{AK}}{dt''} = \frac{300\text{V}}{\mu\text{s}} \Rightarrow L' = \frac{R_{AK_{OFF}} V_{AK_{\max}}}{\left.\frac{dv_{AK}}{dt}\right|_{\max}} = \frac{30 \cdot 10^3 \Omega \cdot 300 \text{ V}}{300 \cdot 10^6 \frac{\text{V}}{\text{s}}} = \mathbf{30 \text{ mH } (?!)}$$





$$\left.\frac{dv_{AK}}{dt''}\right|_{\max} = \frac{V_{AK_{\max}}}{L''} R_S$$

$$\Downarrow$$

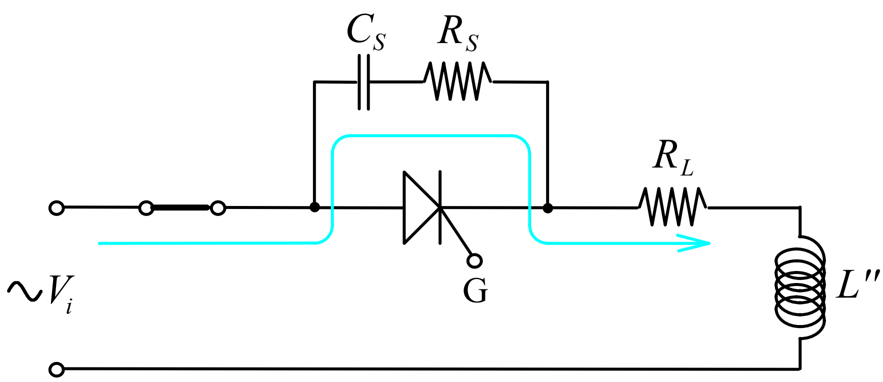
$$\text{Hp}: R_S = \frac{1}{1000} R_{AK_{OFF}}$$

$$\Downarrow$$

$$L'' = \frac{L'}{1000} = 30\mu\text{H}$$

Tipicamente $R_S = 10 \div 15 \ \Omega \, (>> R_L)$ $\quad C_S = 100 \text{ nF}$

$\cancel{C_S \uparrow}$ $\quad$ $\cancel{R_S \downarrow}$



Alimentatori

a dissipazione	***a commutazione***
(< 50W)	***(fino a 2kW)***

Rendimento di un alimentatore

$$\eta = \frac{P_{CARICO}}{P_{RETE}} = \frac{\text{Potenza ceduta al carico}}{\text{Potenza assorbita dalla sorgente primaria}}$$

Problemi connessi: consumo, riscaldamento ⇒ smaltimento calore

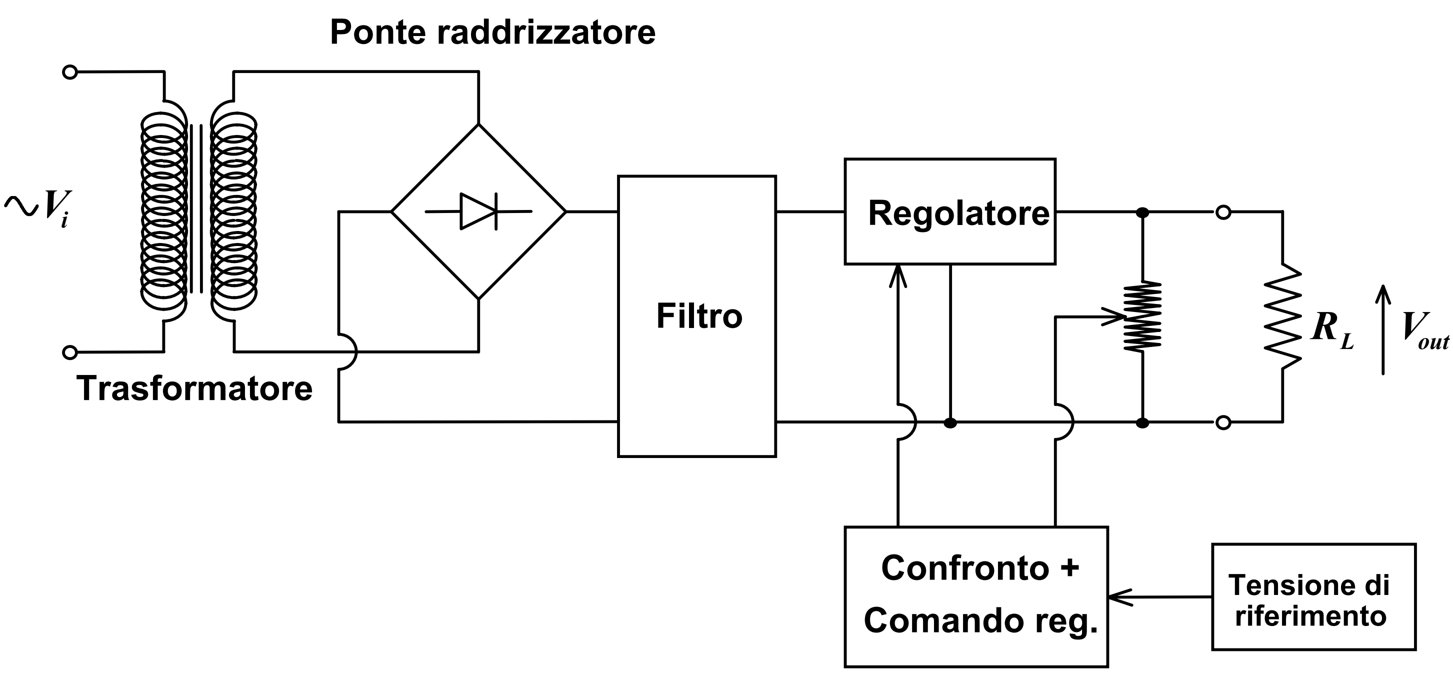
Raffronto tra le caratteristiche degli alimentatori

	Alimentatori a dissipazione	***Alimentatori a commutazione***
Rendimento (η)	**25÷50%**	**75÷90%**
Peso	**5kg/100W**	**2kg/100W**
Ingombro	**$10dm^3$/100W**	**$2dm^3$/100W**
Generazione di disturbi	**NO**	**SI**
Sensibilità ai disturbi	**NULLA**	**SI**

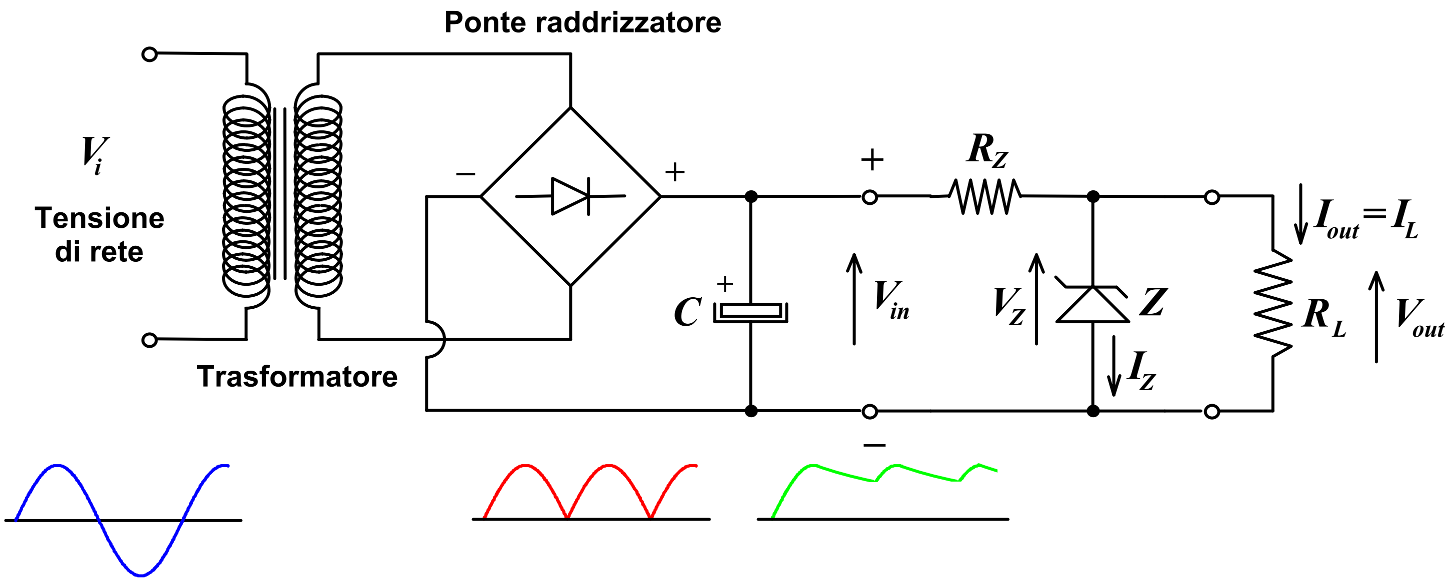
VANTAGGI

SVANTAGGI

Alimentatori a dissipazione

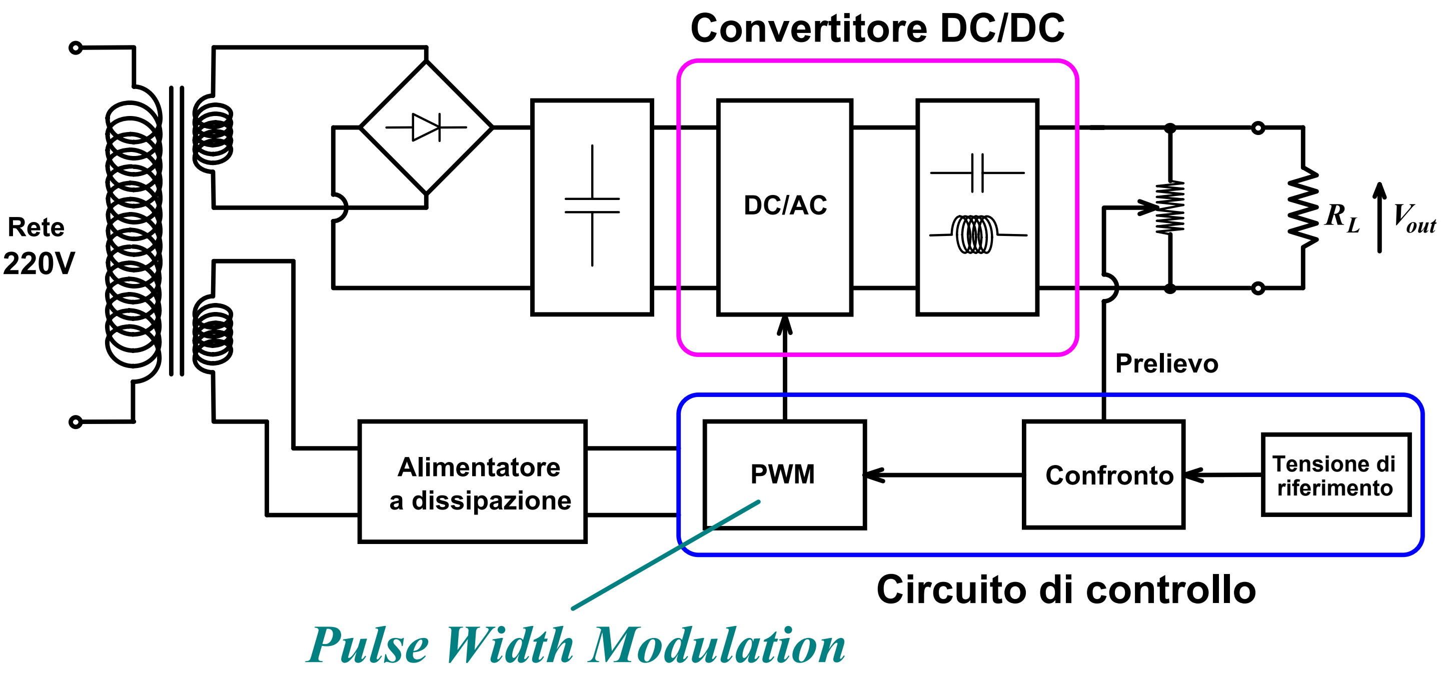


Esempio: alimentatore stabilizzato a diodo Zener



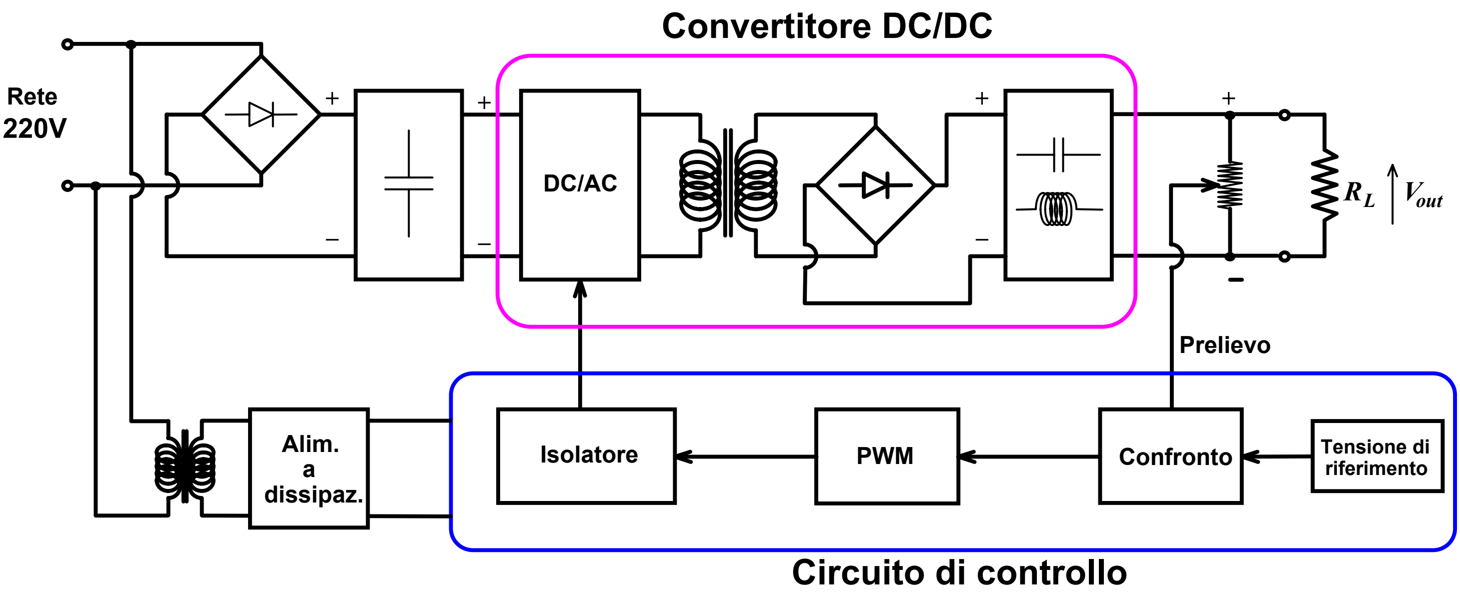
Alimentatori a commutazione
(SMPS=Switched Mode Power Supply)

Schema a secondario

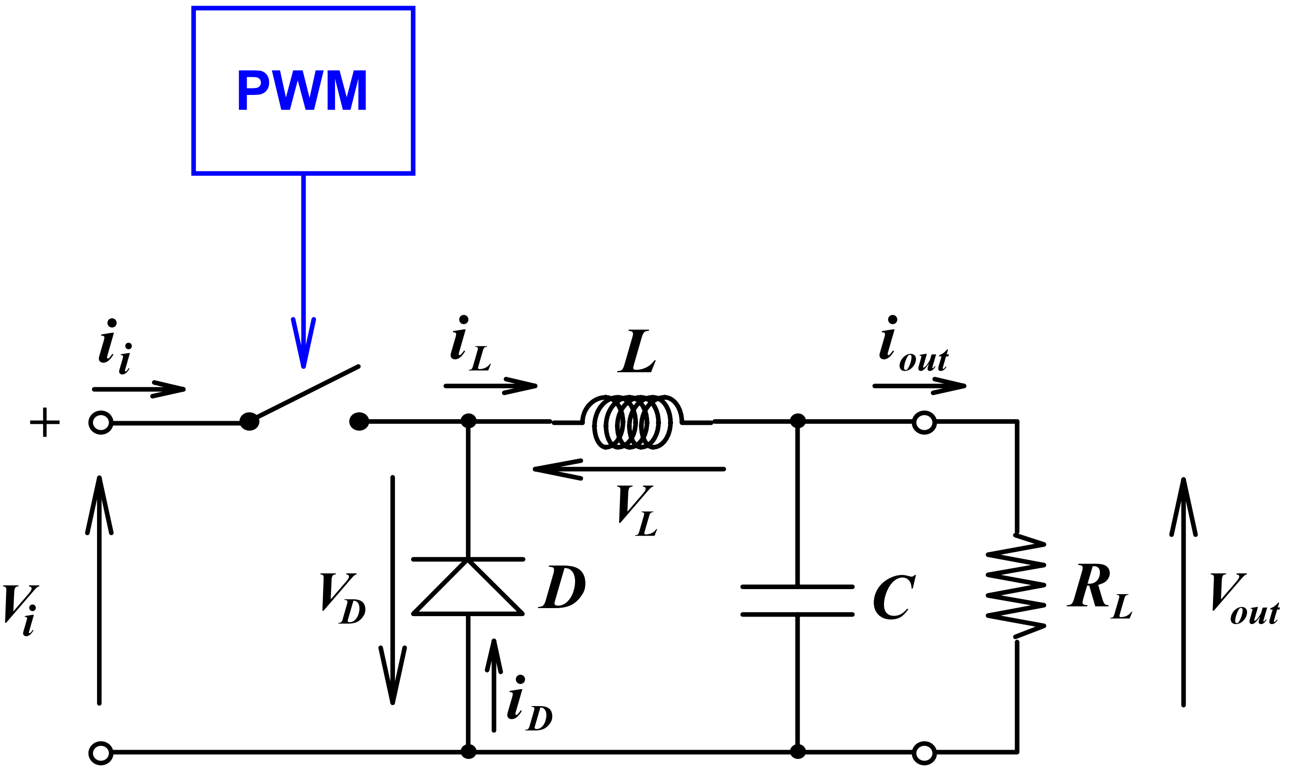


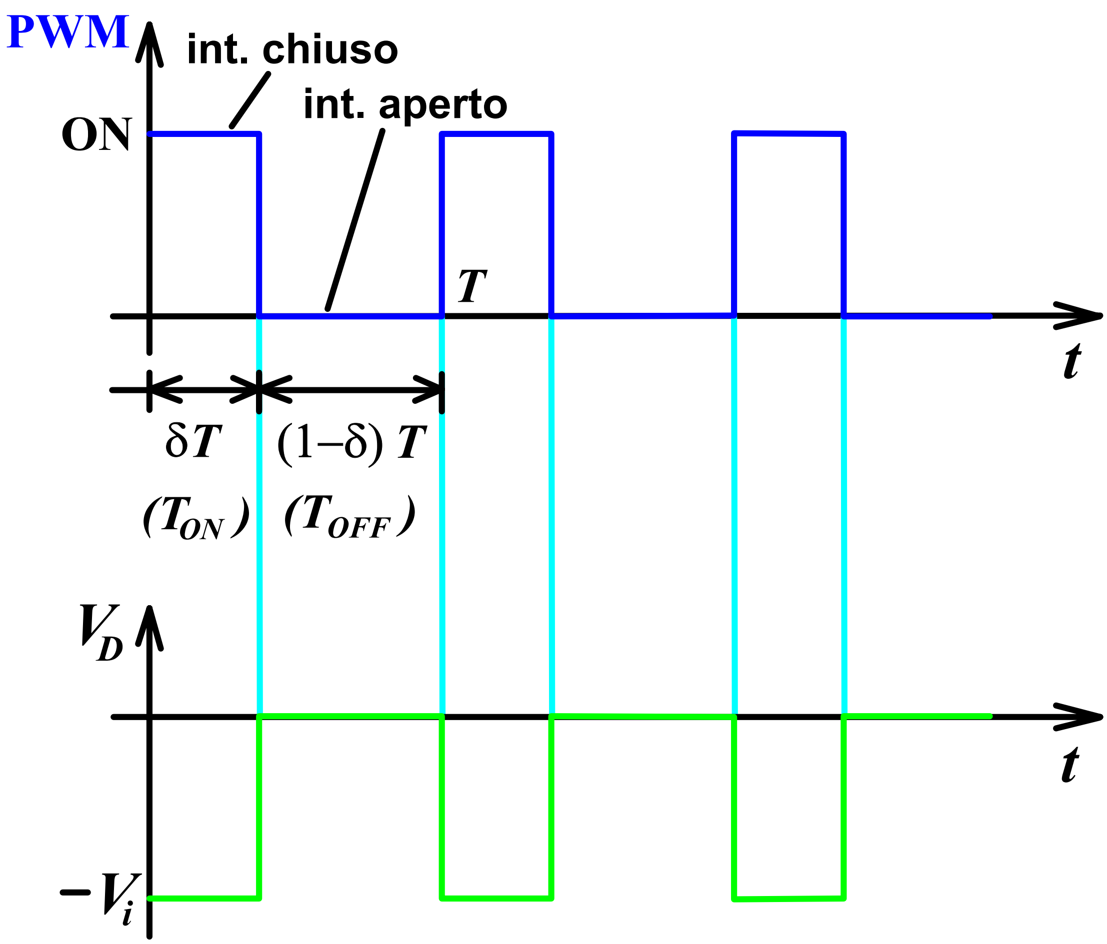
Schema a primario

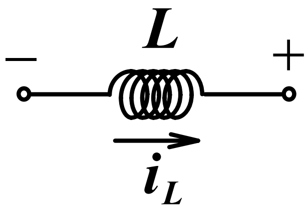
(Vantaggi: ridotte dimensioni del trasformatore e degli elementi reattivi dei filtri)



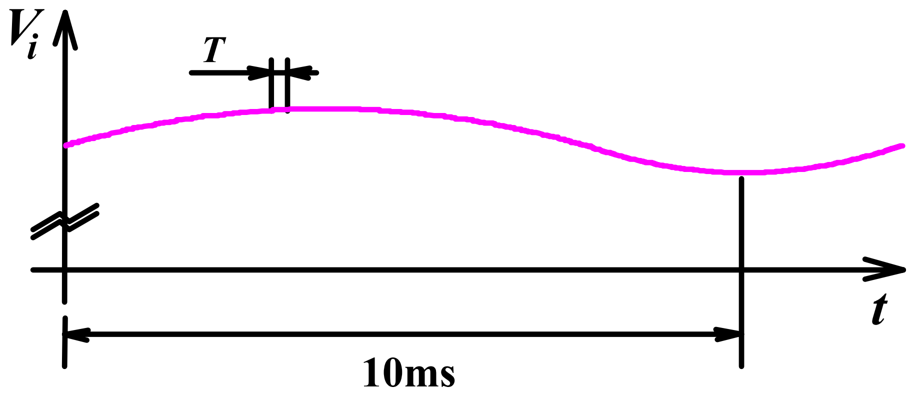
Convertitore DC/DC buck (step-down)





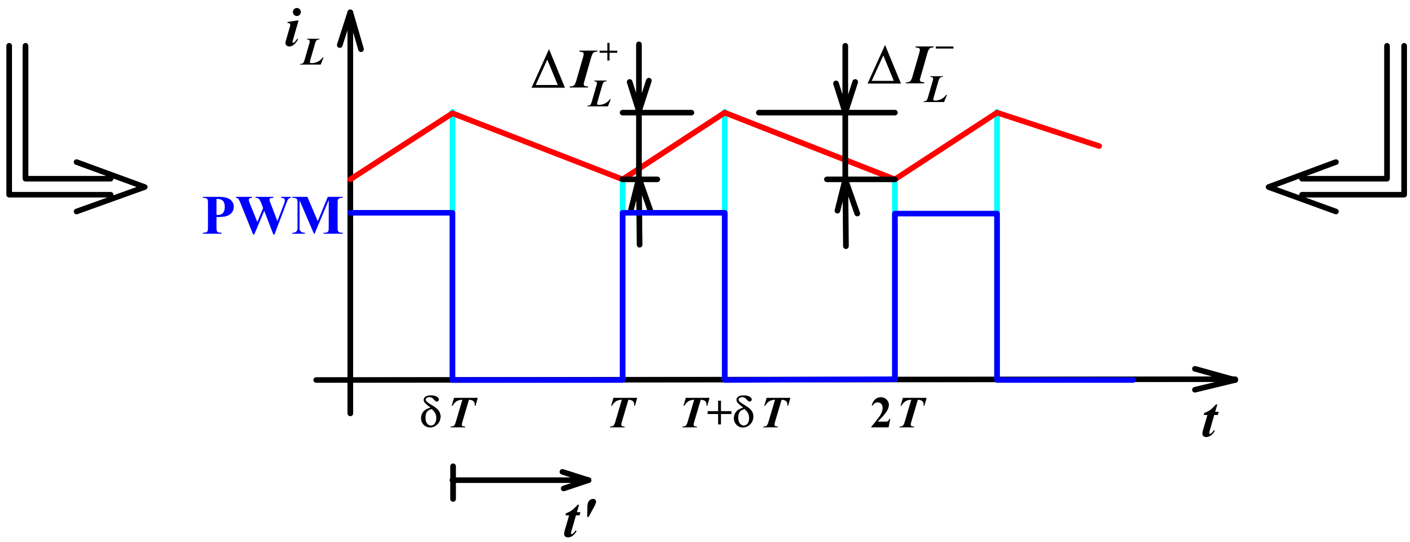


$$v_L = L\,\frac{di_L}{dt}$$



frequenza di commutazione: ***20÷200 kHz***

Intervallo $T_{ON} = \delta T$	***Intervallo*** $T_{OFF} = (1-\delta)\,T$
$i_L = \frac{1}{L}\int_0^t (V_i - V_{out})dt + I(0)$ ($I(0)$= ***valore di*** i_L ***per*** t=0) $\Downarrow$ $i_L = \frac{V_i - V_{out}}{L}\,t + I(0)$	$V_L = -V_\gamma - V_{out} \cong -V_{out}$ $t' = t - \delta T$ ($I'(0)$= ***valore di*** i_L ***per*** t'=0) $\Downarrow$ $i_L = \frac{1}{L}(-V_{out})\,t' + I'(0)$



$$\Delta I_L^+ = \frac{V_i - V_{out}}{L}\delta T \quad \Delta I_L^- = \frac{V_{out}}{L}(1-\delta)T$$

$$\Downarrow$$

$$\Delta I_L^+ = \Delta I_L^-$$

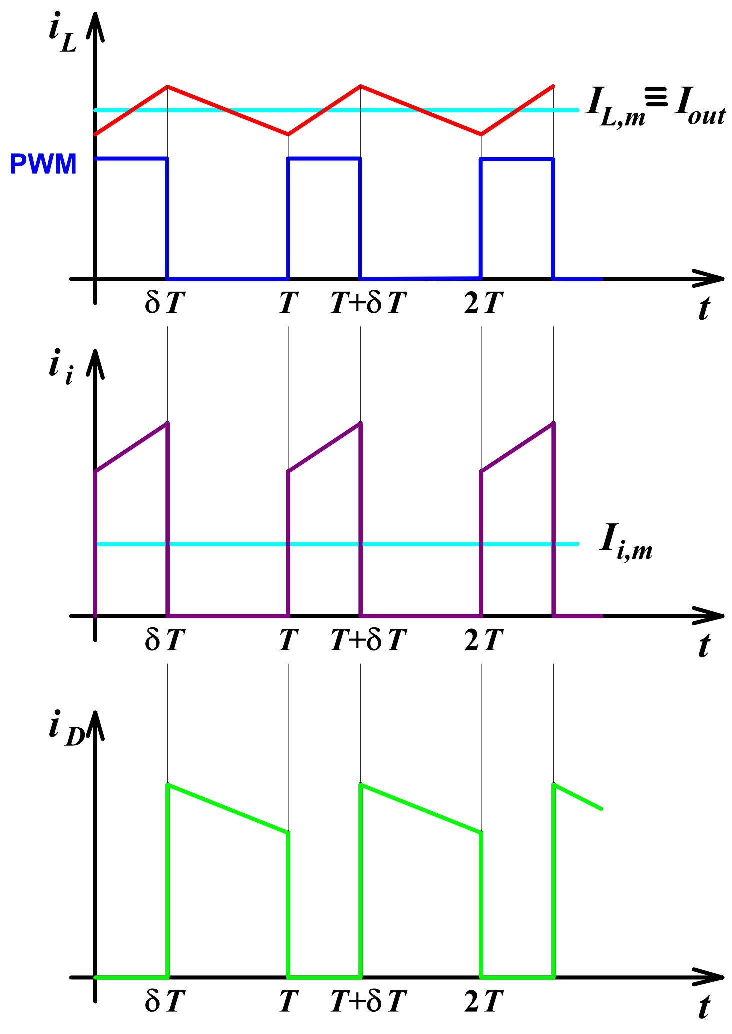
$$\Downarrow$$

$$\frac{V_i - V_{out}}{L}\delta T = \frac{V_{out}}{L}(1-\delta)T \Rightarrow V_i\delta T - V_{out}\delta T = V_{out} - V_{out}\delta T$$

$$\Downarrow$$

$$\boxed{V_{out} = \delta V_i}$$

Buck, Step-down, Forward



$$I_{i,m} \cdot T = I_{L,m} \cdot \delta T = I_{out} \cdot \delta T$$

$$\Downarrow$$

$$\boxed{I_{out} = \frac{I_{i,m}}{\delta}}$$

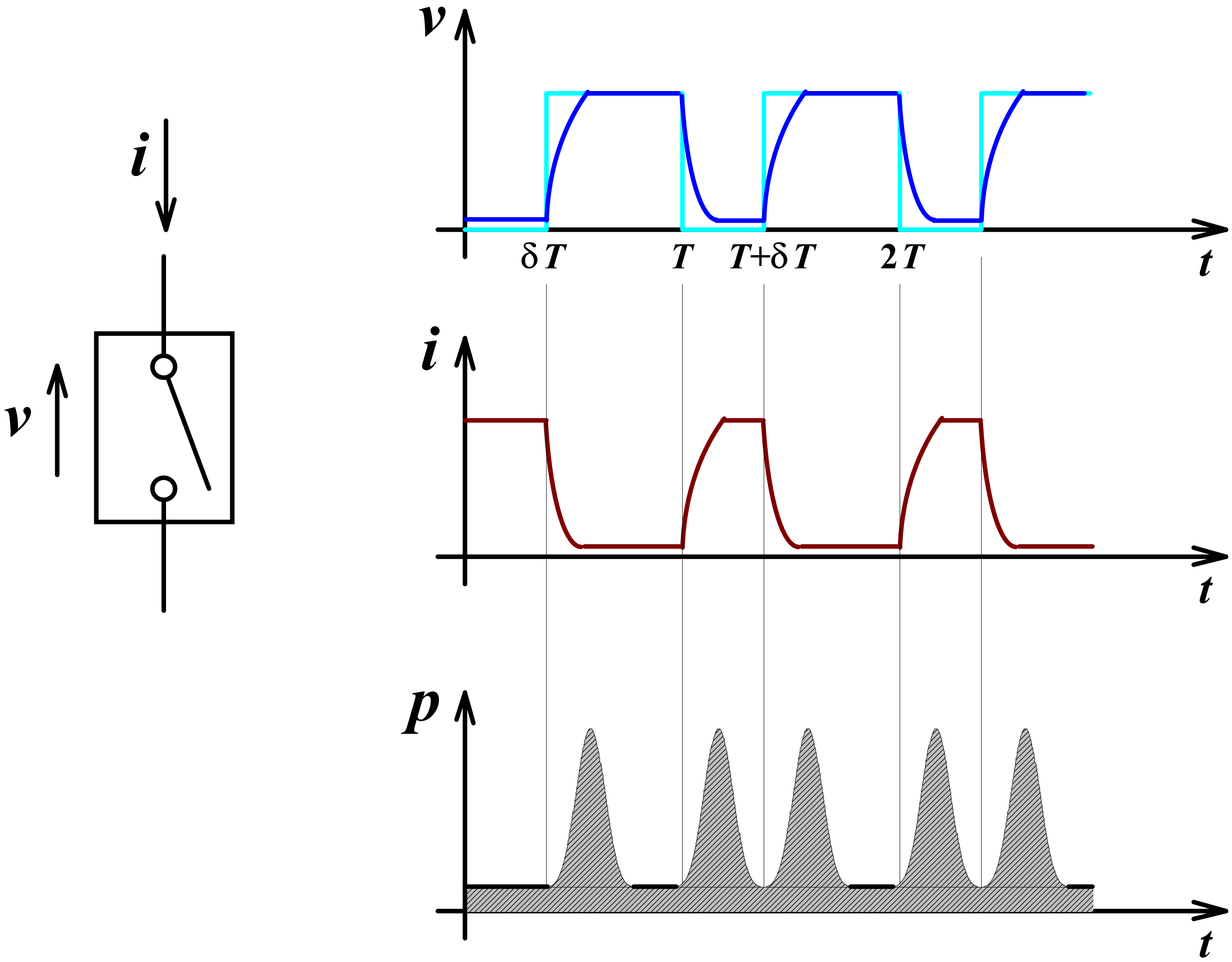
$$\Downarrow$$

$$\boxed{V_{out} I_{out} = I_{i,m} V_i}$$

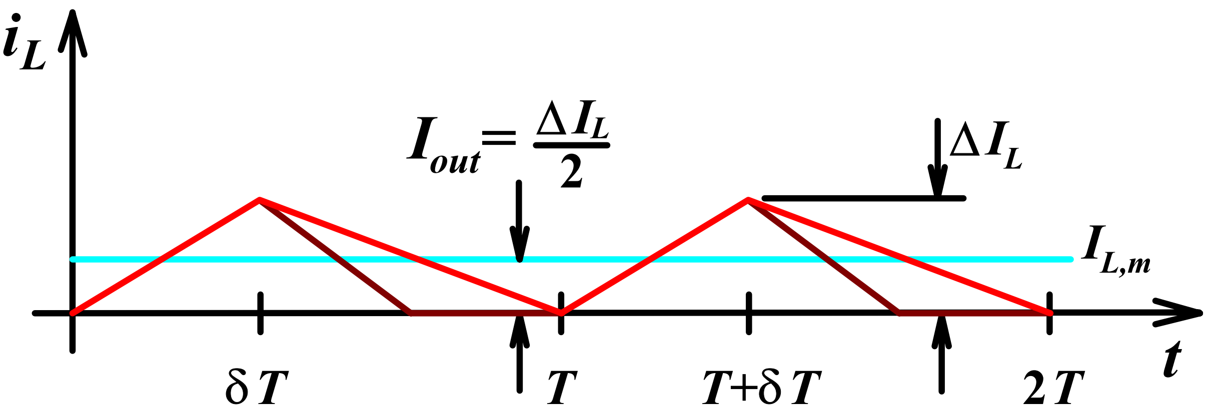
«TRASFORMATORE IN CONTINUA»

CONVERTITORE DC/DC

Perdite di potenza dovute al commutatore

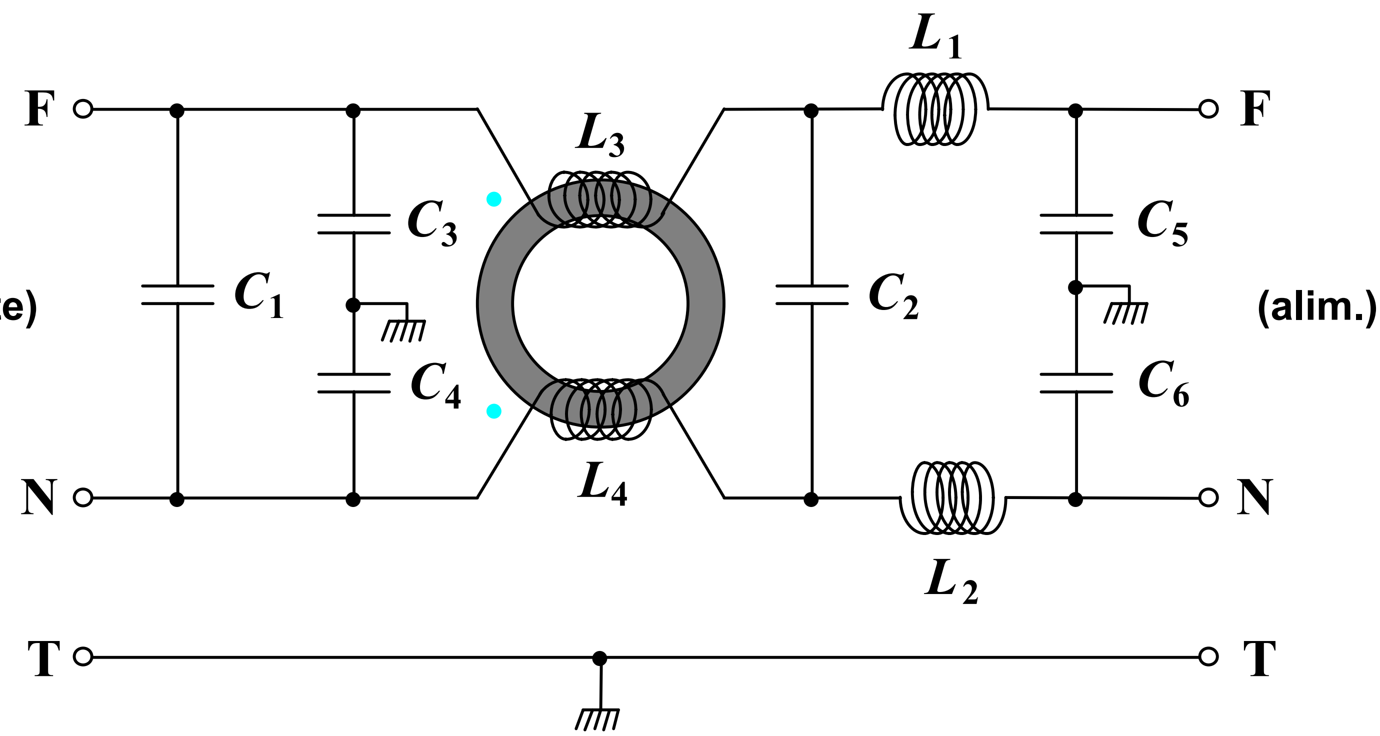


Funzionamento discontinuo ⇒ generazione di disturbi



$$L = L_{\min} = \frac{(V_i - V_{out})\,\delta T}{2\, I_{out,\min}} \quad \Rightarrow \quad \Delta I_L$$

Filtro di rete



Dimensionamento di L

$$\Delta I_L^+ = \frac{V_i - V_{out}}{L}\delta T \quad \delta = \frac{V_{out}}{V_i}$$

$$\Downarrow$$

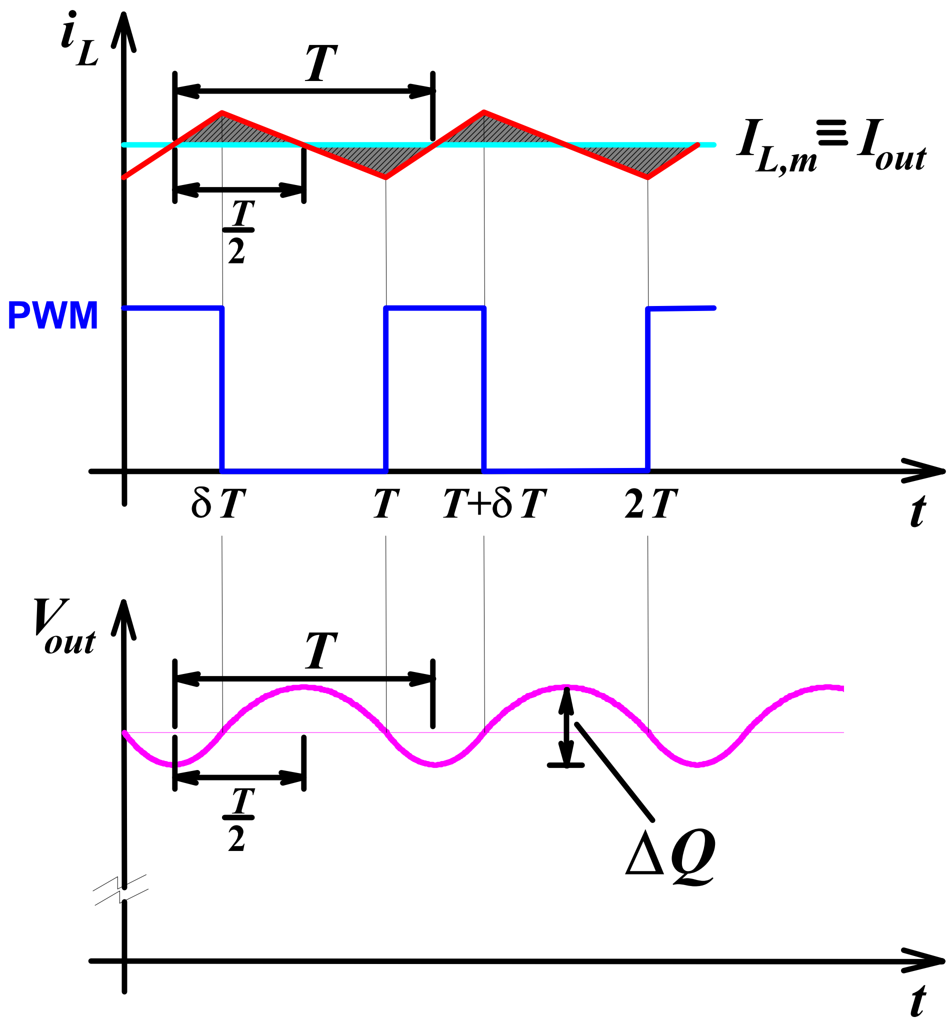
$$L = \frac{(V_i - V_{out})\delta T}{\Delta I_L^+} = \frac{(V_i - V_{out})\dfrac{V_{out}}{V_i}T}{\Delta I_L^+}$$

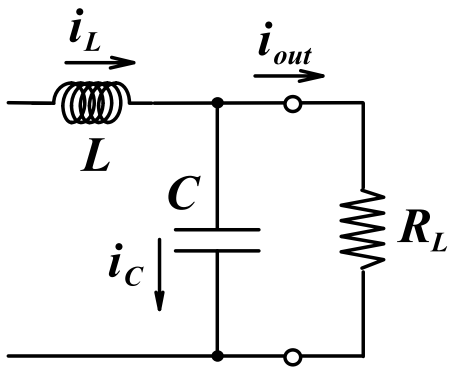
$$\Downarrow$$

$$\Delta I_L^+ = kI_{L,m} = kI_{out} \Rightarrow L = \frac{(V_i - V_{out})}{kI_{out}} \cdot \frac{V_{out}}{V_i} \cdot \frac{1}{f}$$

(tipicamente si sceglie** $k = 0,4$**)

Dimensionamento di C





$$i_C = C\frac{dV_C}{dt}$$

$$v_C = \frac{1}{C}\int i\,dt$$

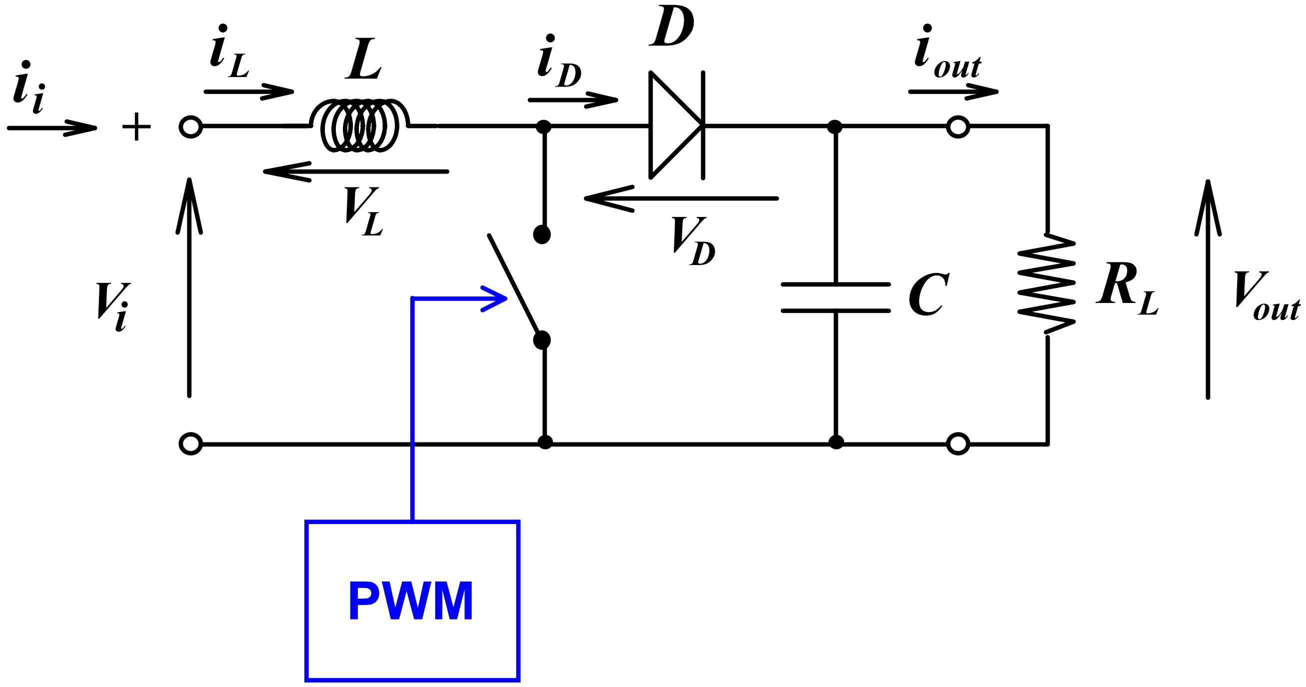
$$\Delta Q = C\Delta V_{out}$$

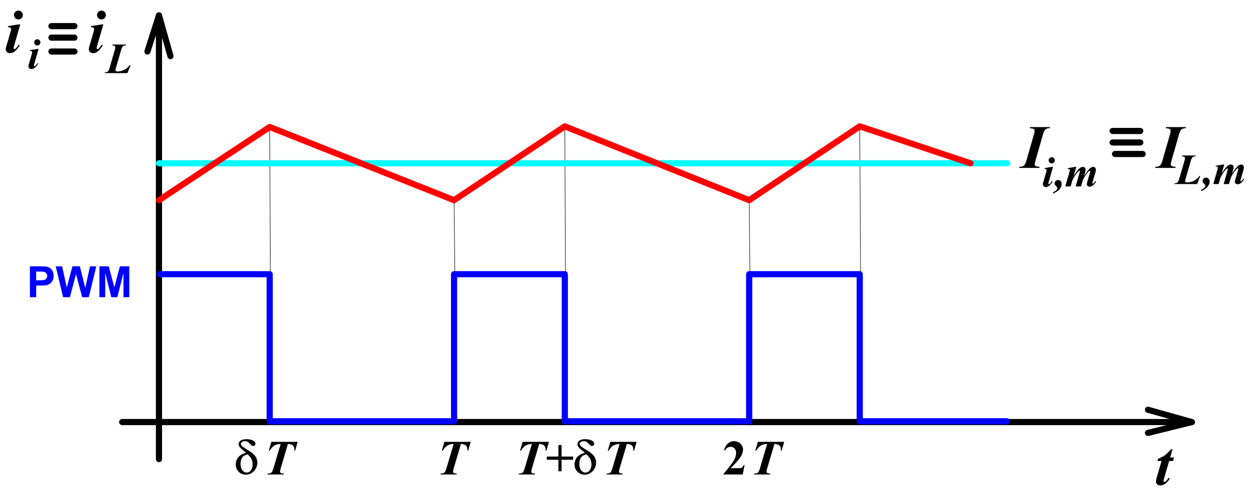
$$\Delta Q = \frac{T}{2}\,\frac{\Delta I_L^+}{2}\,\frac{1}{2} = \frac{T}{8}\,\Delta I_L^+$$

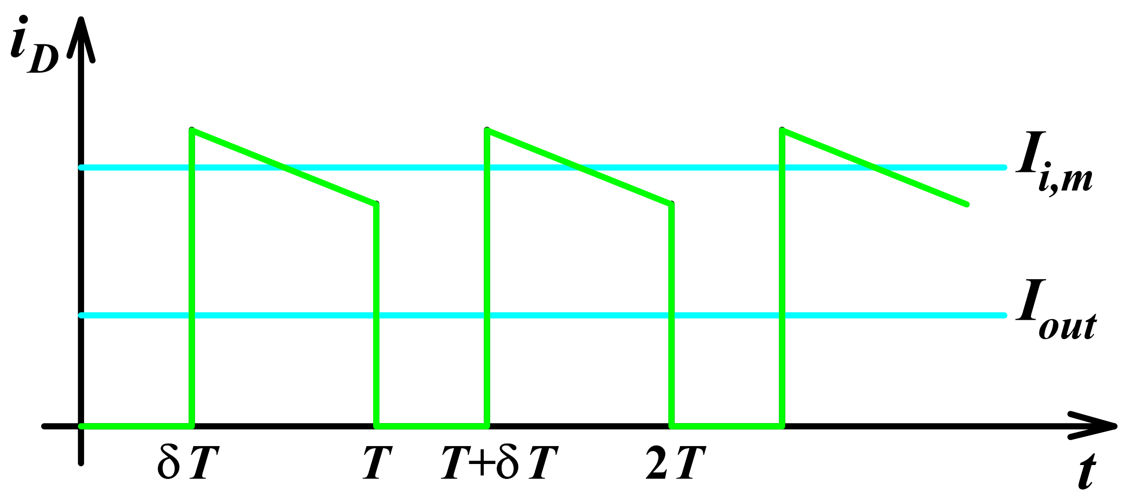
$$\Delta V_{out} = \frac{\Delta Q}{C} \quad \Rightarrow \quad \Delta V_{out} = \frac{T\,\Delta I_L^+}{8\,C}$$

$$C = \frac{\Delta Q}{\Delta V_{out}} = \frac{1}{\Delta V_{out}} \cdot \frac{T\,\Delta I_L}{8} = \frac{k\,I_{out}}{8f\,\Delta V_{out}} = \frac{V_{out}\,(V_i - V_{out})}{8f^2\,L\,V_i\,\Delta V_{out}}$$

Convertitore DC/DC boost (step-up)







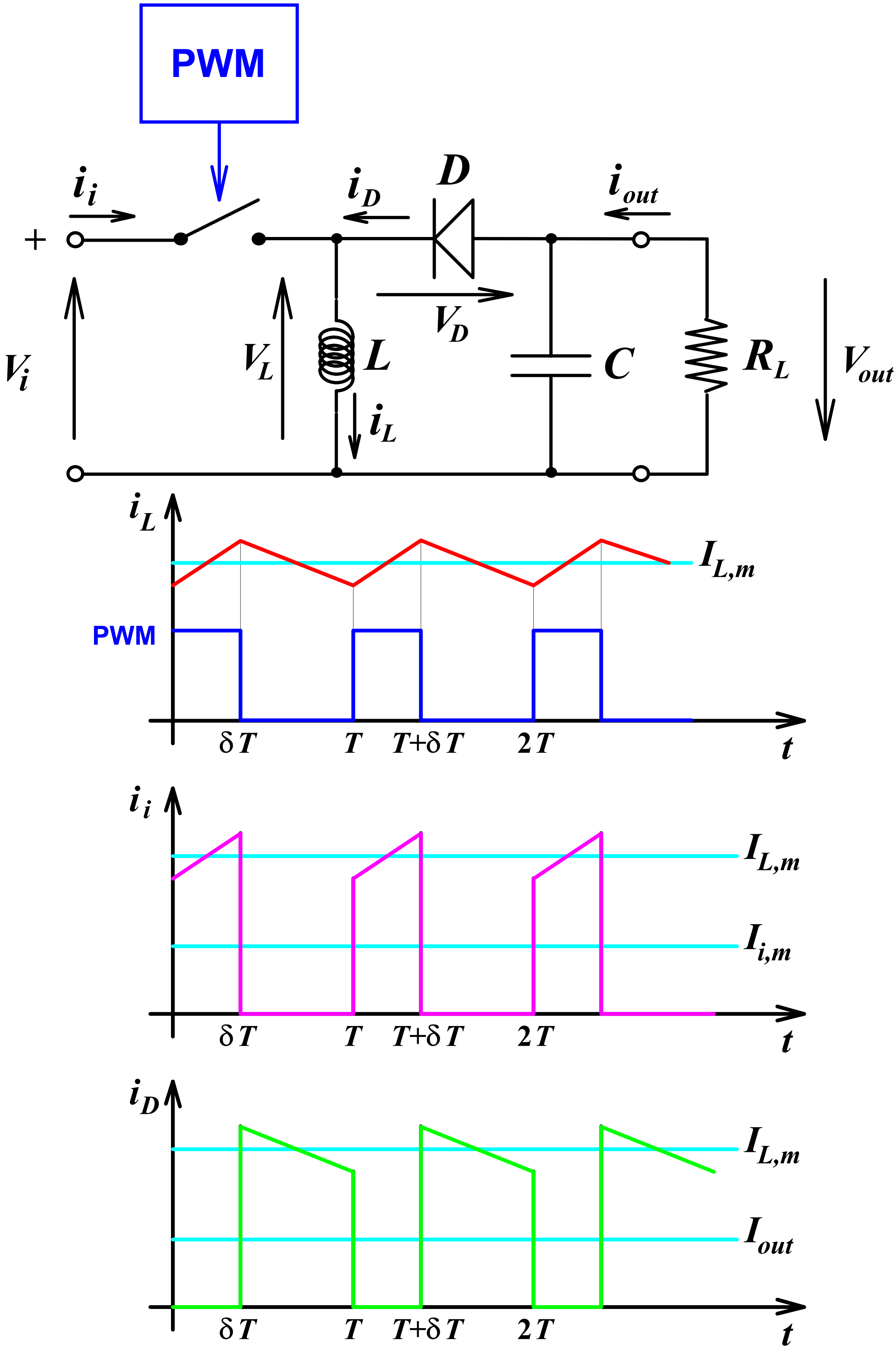
$$\Delta I_L^+ = \frac{V_i}{L}\delta T \qquad \Delta I_L^- = \frac{V_{out} - V_i}{L}(1-\delta)T$$

$$\delta V_i = (V_{out} - V_i)(1-\delta) \quad \Rightarrow \quad \boxed{V_{out} = \frac{V_i}{1-\delta}}$$

$$I_{i,m}(1-\delta)T = I_{out}T \quad \Rightarrow \quad \boxed{I_{out} = (1-\delta)I_{i,m}}$$

Dimensionamento di L	***Dimensionamento di C***
$\Delta I_L = \frac{(V_{out} - V_i)V_i}{fLV_{out}}$ $\Downarrow$ $L = \frac{(V_{out} - V_i)V_i}{f\Delta I_L V_{out}}$ $I_{L,m} = I_{i,m} = \frac{I_{out}V_{out}}{V_i}$ $\Downarrow$ $L = \frac{V_i^2(V_{out} - V_i)}{fkI_{out}V_{out}^2}$ ***con*** $\Delta I_L = kI_{L,m}$	***In prima approssimazione*** $\Delta V_{out} = \frac{I_{out}\delta T}{C}$ $\Delta V_{out} = \frac{I_{out}}{C}\left(T - \frac{V_i}{V_{out}}T\right)$ $= \frac{I_{out}(V_{out} - V_i)}{fCV_{out}}$ $C = \frac{I_{out}(V_{out} - V_i)}{fV_{out}\Delta V_{out}}$

Convertitore DC/DC invertente



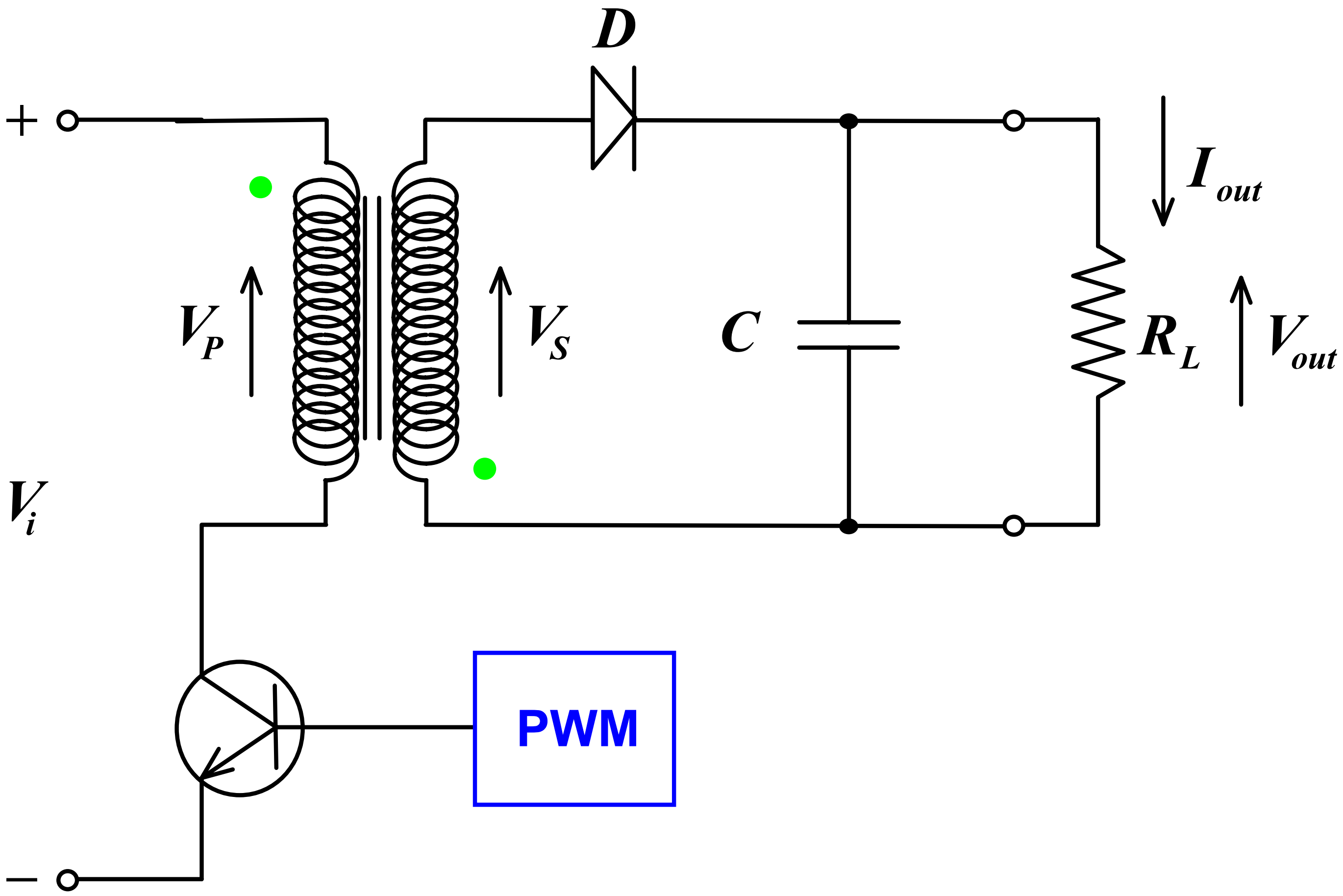
$$\Delta I_L^+ = \frac{V_i}{L}\,\delta T \qquad\qquad \Delta I_L^- = \frac{V_{out}}{L}\,(1-\delta)\,T$$

$$\frac{V_i}{L}\,\delta T = \frac{V_{out}}{L}\,(1-\delta)\,T \quad \Rightarrow \quad \boxed{V_{out} = V_i\,\frac{\delta}{1-\delta}}$$

$$\left.\begin{aligned} I_{i,m}\cdot T &= I_{L,m}\cdot \delta T \\ I_{out}\cdot T &= I_{L,m}\cdot(1-\delta)\,T \end{aligned}\right. \quad \Rightarrow \quad \boxed{I_{out} = I_{i,m}\,\frac{1-\delta}{\delta}}$$

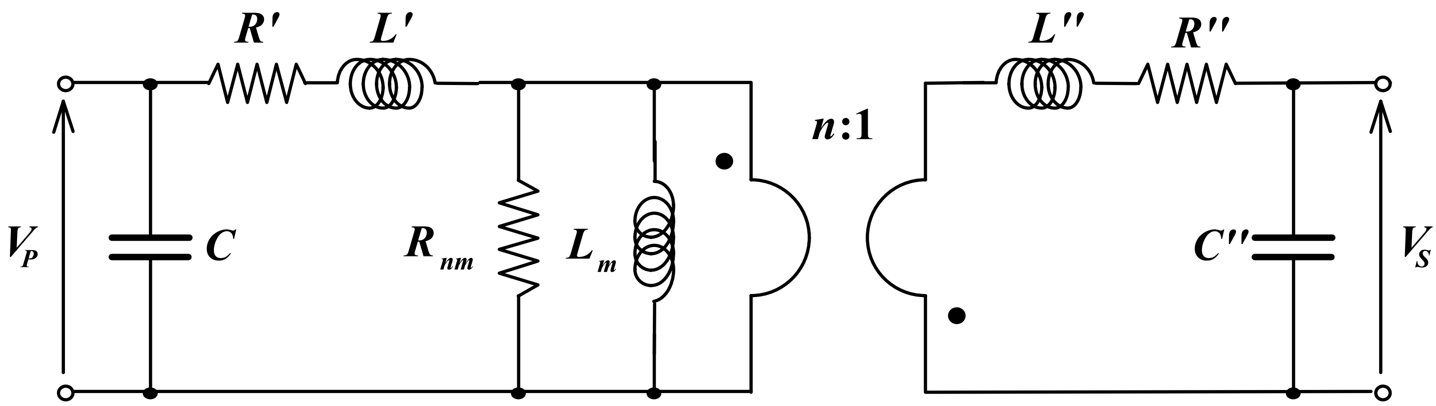
Dimensionamento di L	***Dimensionamento di C***
$\Delta I_L = \dfrac{V_i V_{out}}{f L (V_i + V_{out})}$ $\Downarrow$ $L = \dfrac{V_i V_{out}}{f \Delta I_L (V_i + V_{out})}$ $I_{L,m} = \dfrac{I_{out}(V_i + V_{out})}{V_i}$ $\Downarrow$ $L = \dfrac{V_i^2 V_{out}}{f k I_{out} (V_i + V_{out})^2}$ *con* $\Delta I_L = k I_{L,m}$	***In prima approssimazione*** $\Delta V_{out} = \dfrac{I_{out}\delta T}{C}$ $\Delta V_{out} = \dfrac{I_{out}}{C}\left(\dfrac{V_{out}}{V_i + V_{out}} T\right)$ $= \dfrac{I_{out} V_{out}}{f C (V_i + V_{out})}$ $C = \dfrac{I_{out} V_{out}}{f \Delta V_{out} (V_i + V_{out})}$

Convertitore DC/DC flyback (ad interdizione)

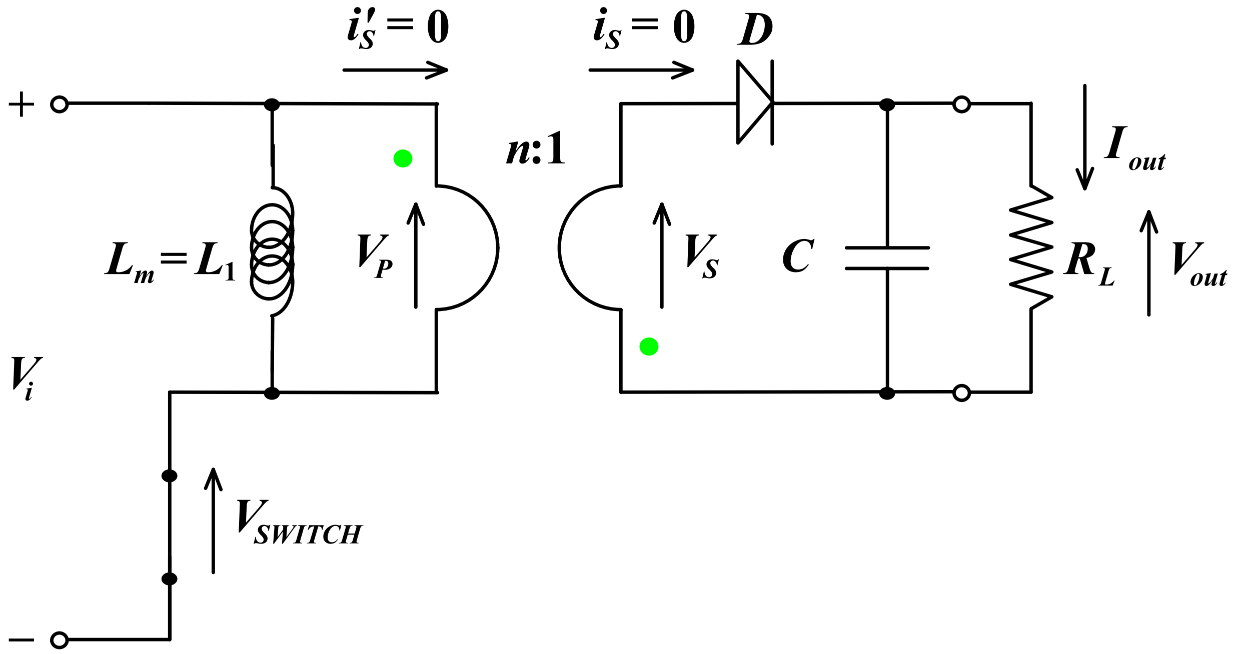


$$\frac{V_P}{V_S} = \frac{n_1}{n_2} = n = \frac{i_S}{i_P}$$

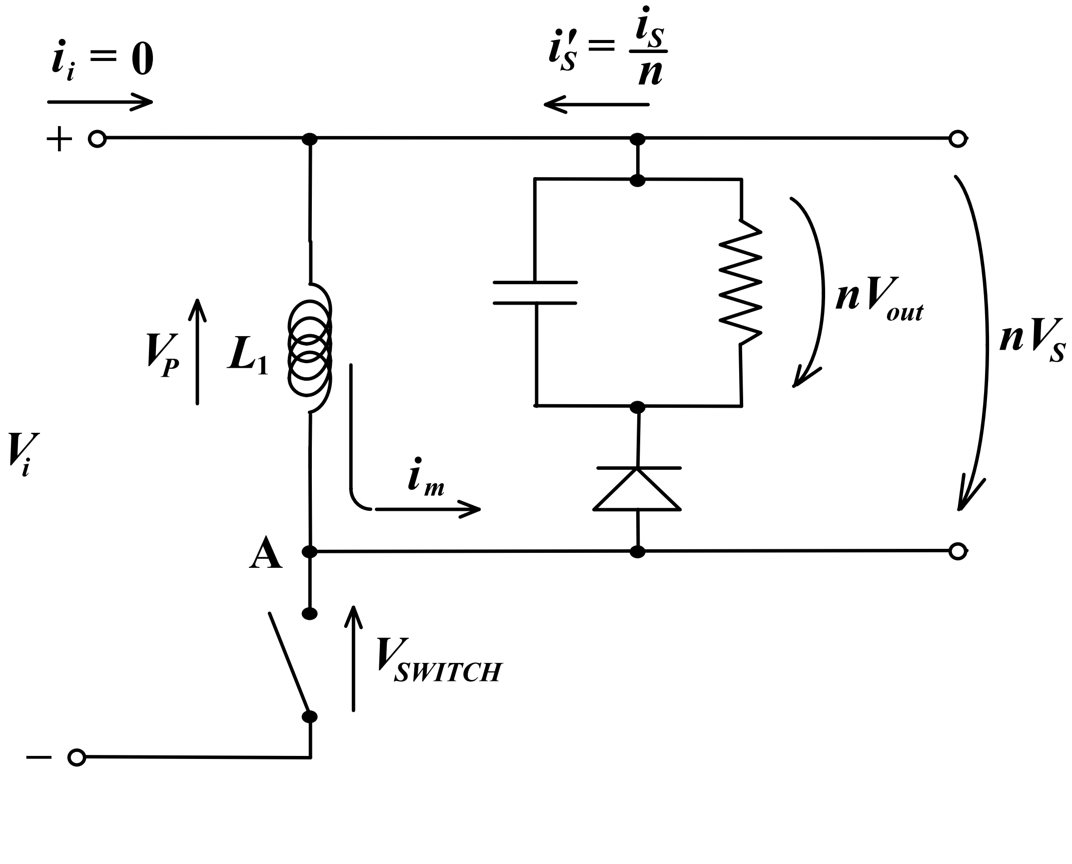
Modello equivalente del trasformatore



Fase ON



Fase OFF



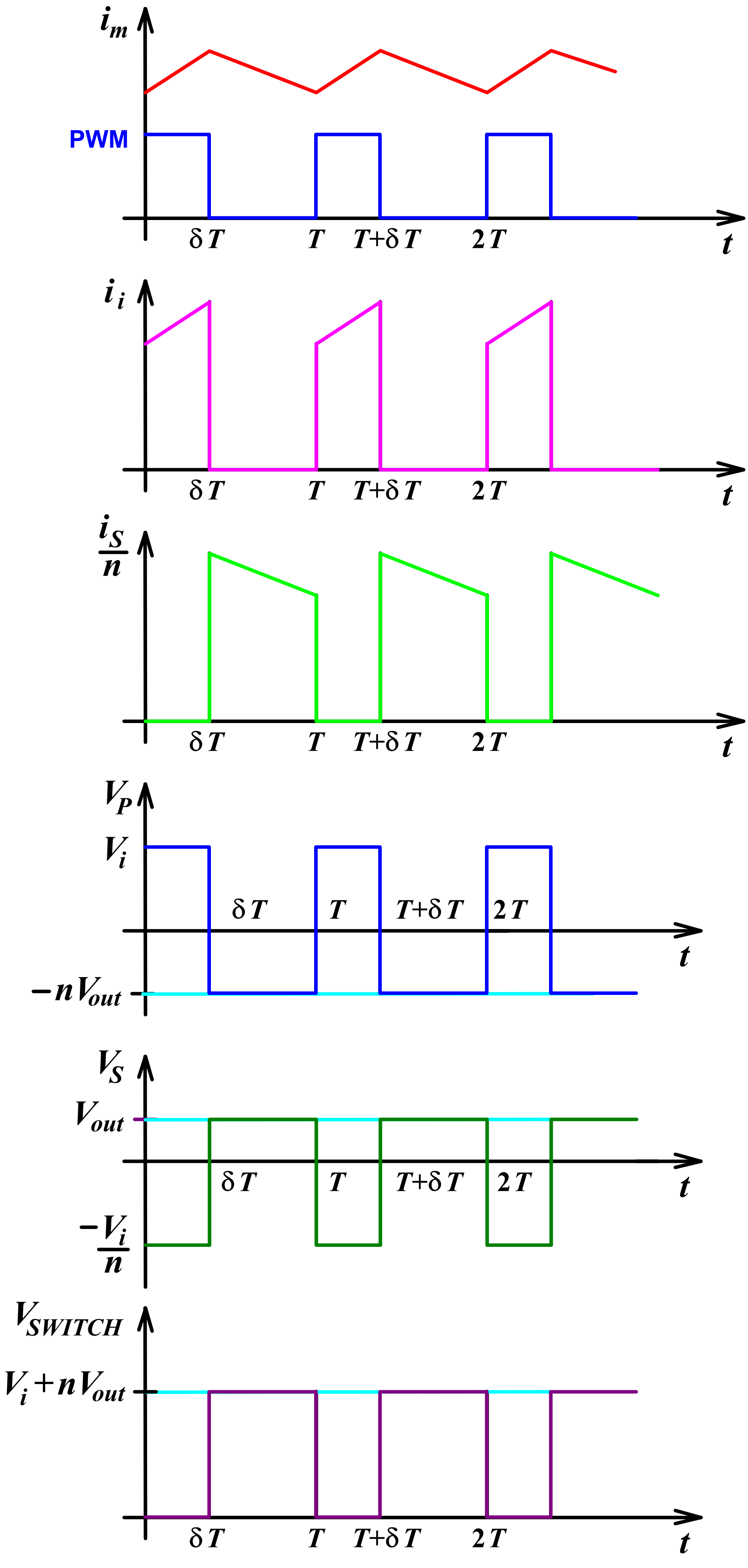
$$\textit{Fase ON}\ \ \Delta I_m^+ = \frac{V_i}{L_1}\,\delta\,T$$

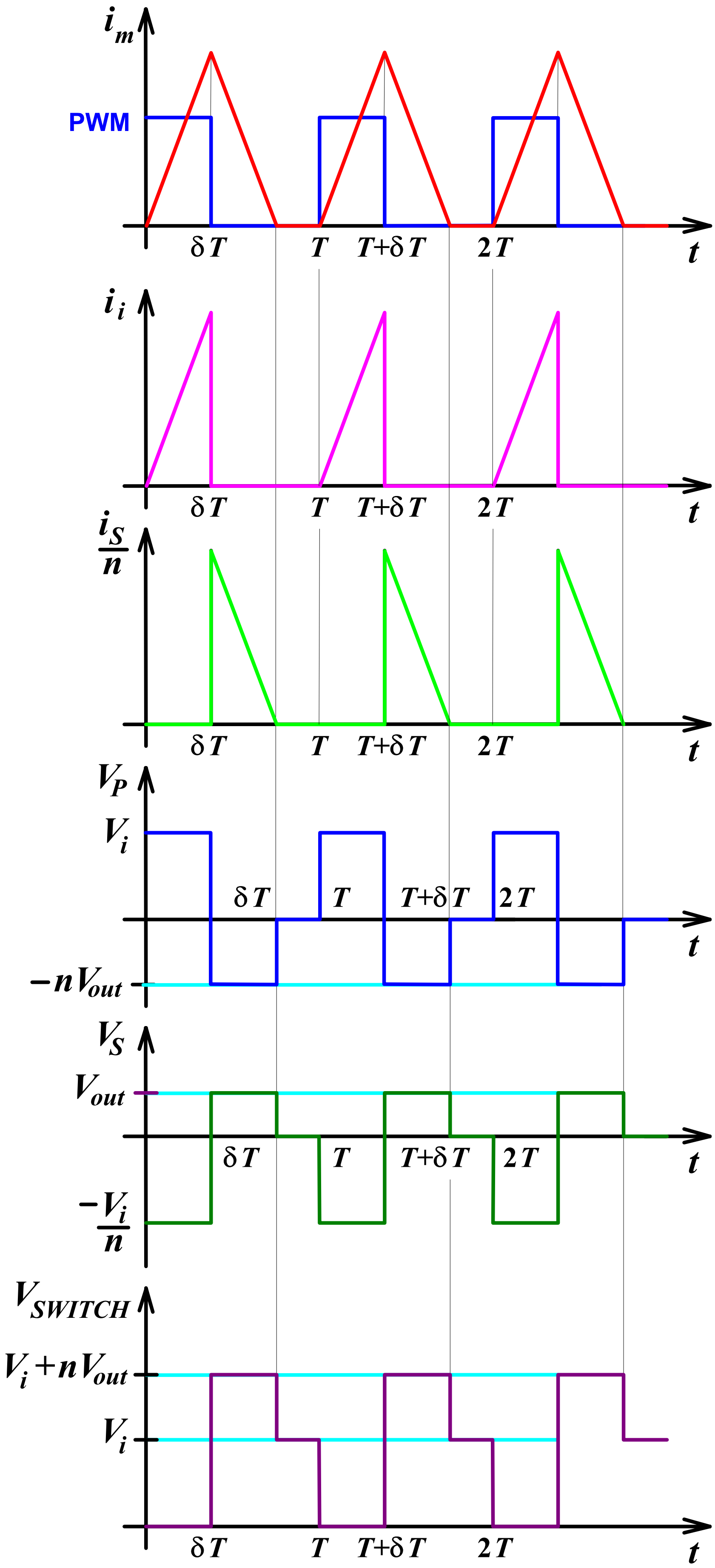
$$\textit{Fase OFF}\ \ \Delta I_m^- = \frac{nV_{out}}{L_1}\,(1-\delta)\,T$$

$$\xRightarrow{\Delta I_m^+ = \Delta I_m^-}$$

$$\boxed{V_{out} = \frac{V_i}{n}\,\frac{\delta}{1-\delta}}$$

Funzionamento continuo (onda trapezoidale)





Funzionamento discontinuo (onda triangolare)

$$\frac{V_{out}}{V_i} = ?$$

$$E = \frac{1}{2} L_1 I_m^2$$

$$I_m = \frac{V_i}{L_1} \delta T$$

$$P = \frac{1}{2} L_1 \left(\frac{\delta V_i}{L_1}\right)^2 \frac{T^2}{T}$$

(SORGENTE PRIMARIA)

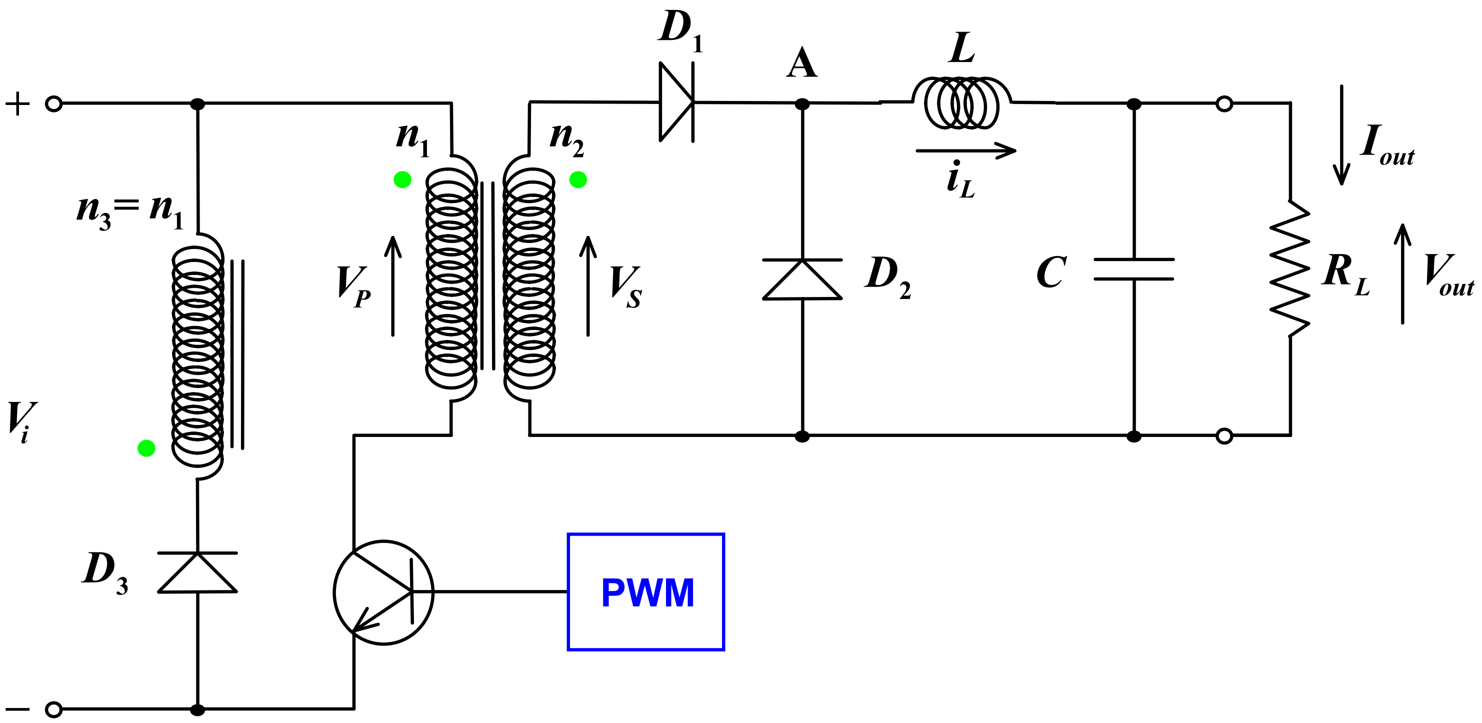
$$P_L = \frac{V_{out}^2}{R_L}$$

(AL CARICO)

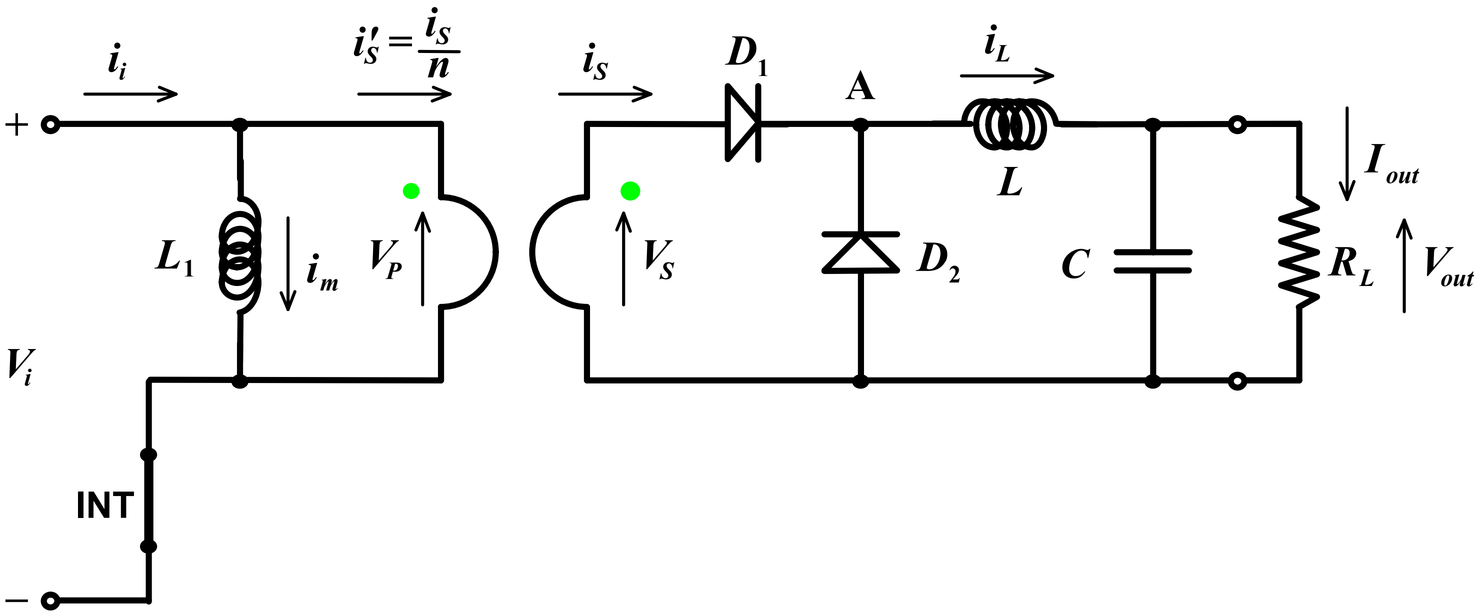
$$\boxed{V_{out} = \delta V_i \sqrt{\frac{R_L}{2 L_1} T}}$$

$$V_{SW\max} = V_i + n V_{out}$$

Convertitore DC/DC forward (a conduzione)



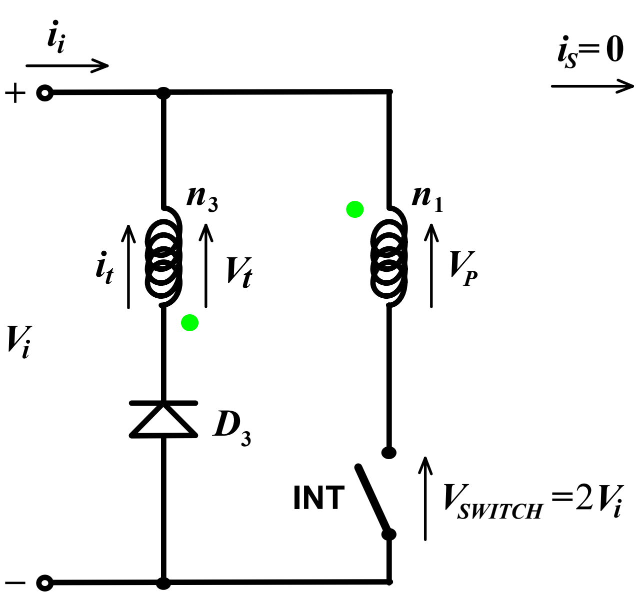
Fase ON



$$i_S = i_L \quad i_i = i_m + \frac{i_S}{n} = i_i = \frac{V_i}{L_1} t + \frac{1}{n}\left(\frac{V_i}{n} - V_{out}\right)\frac{1}{L} t + I_i(0)$$

$$\Delta I_L^+ = \left(\frac{V_i}{n} - V_{out}\right)\frac{1}{L}\delta T$$

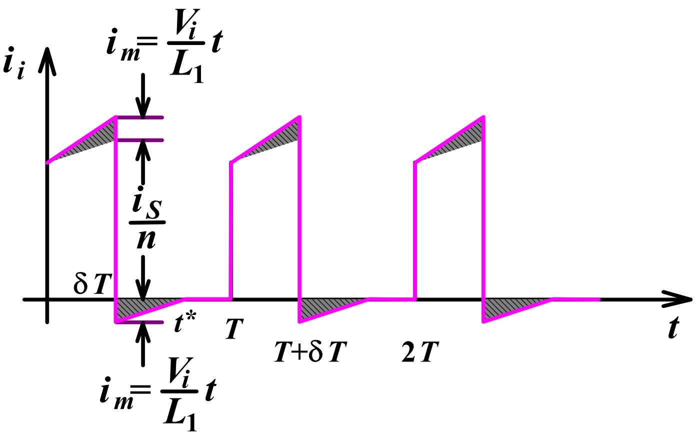
Fase OFF

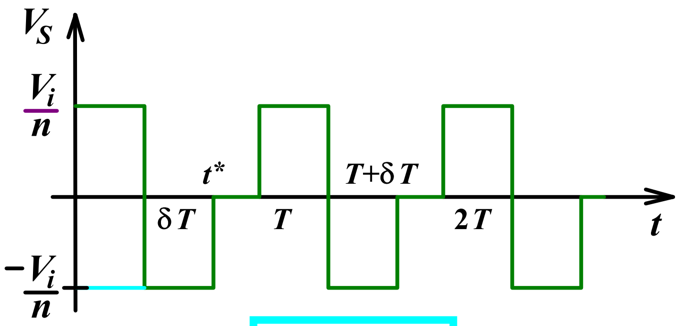


$$i_m = i_t$$

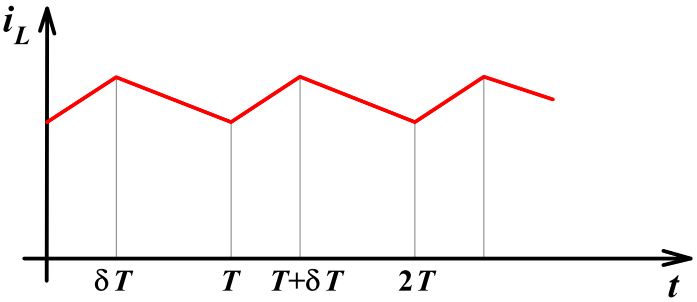
$$V_t = V_\gamma + V_i \cong V_i \qquad V_P = -V_t = -V_i \qquad V_S = -\frac{V_i}{n}$$

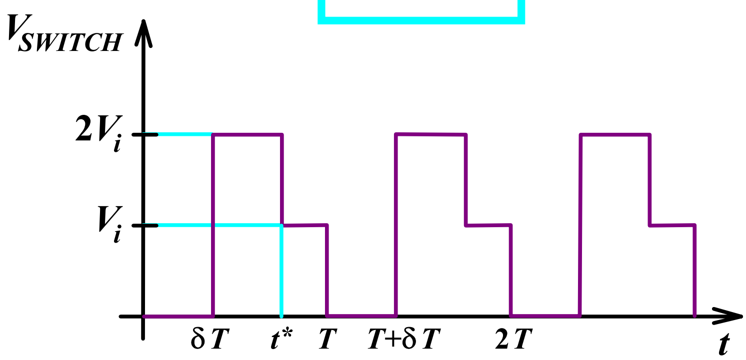
$$\Delta I_L^- = \frac{V_{out}}{L}(1-\delta)\,T \quad \Rightarrow \quad \Delta I_L^+ = \Delta I_L^- \quad \Rightarrow \quad \boxed{V_{out} = \frac{\delta}{n} V_i}$$



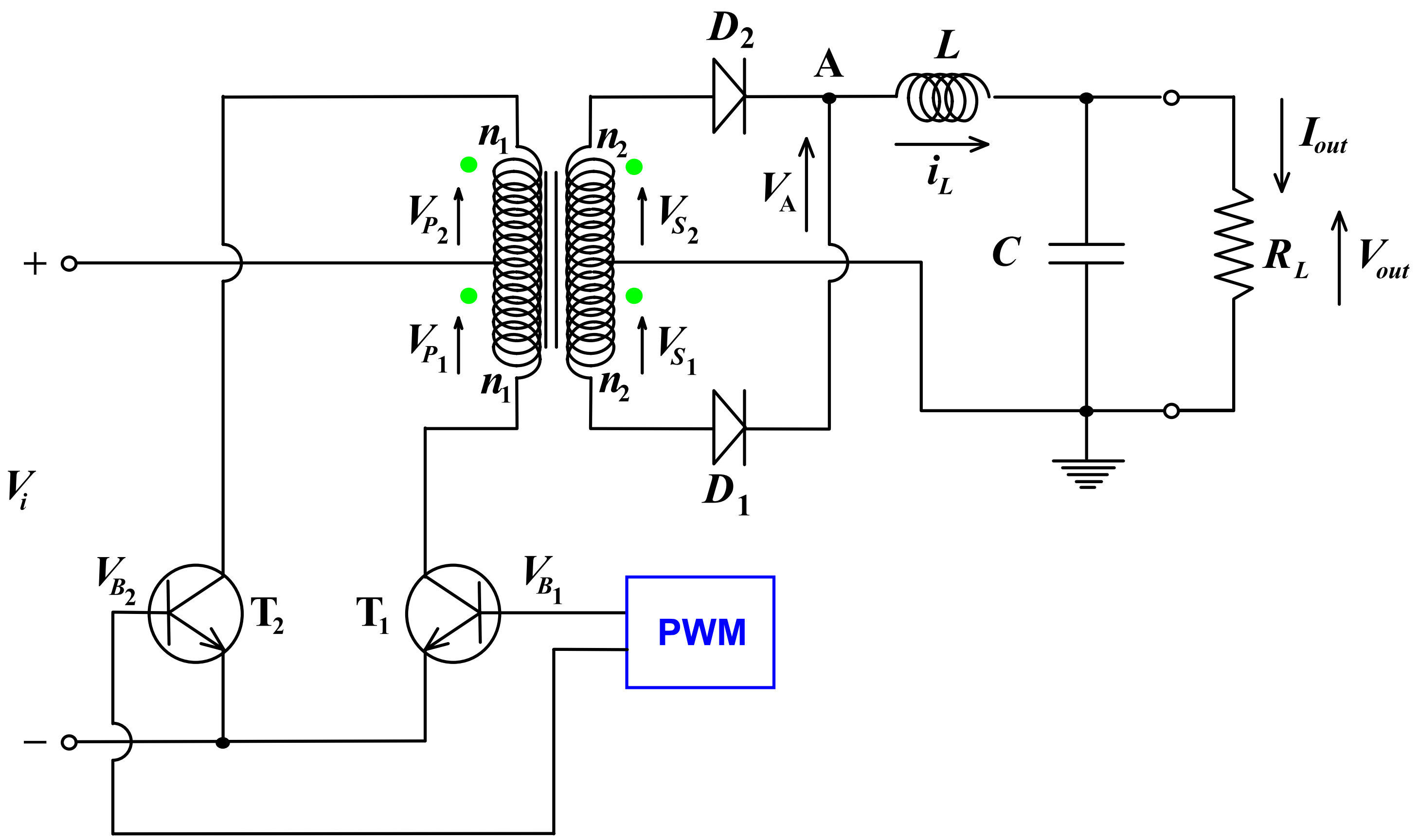


$\boxed{\delta < 50\%}$





Convertitore push-pull (in controfase) [500W]



Fasi 1,3

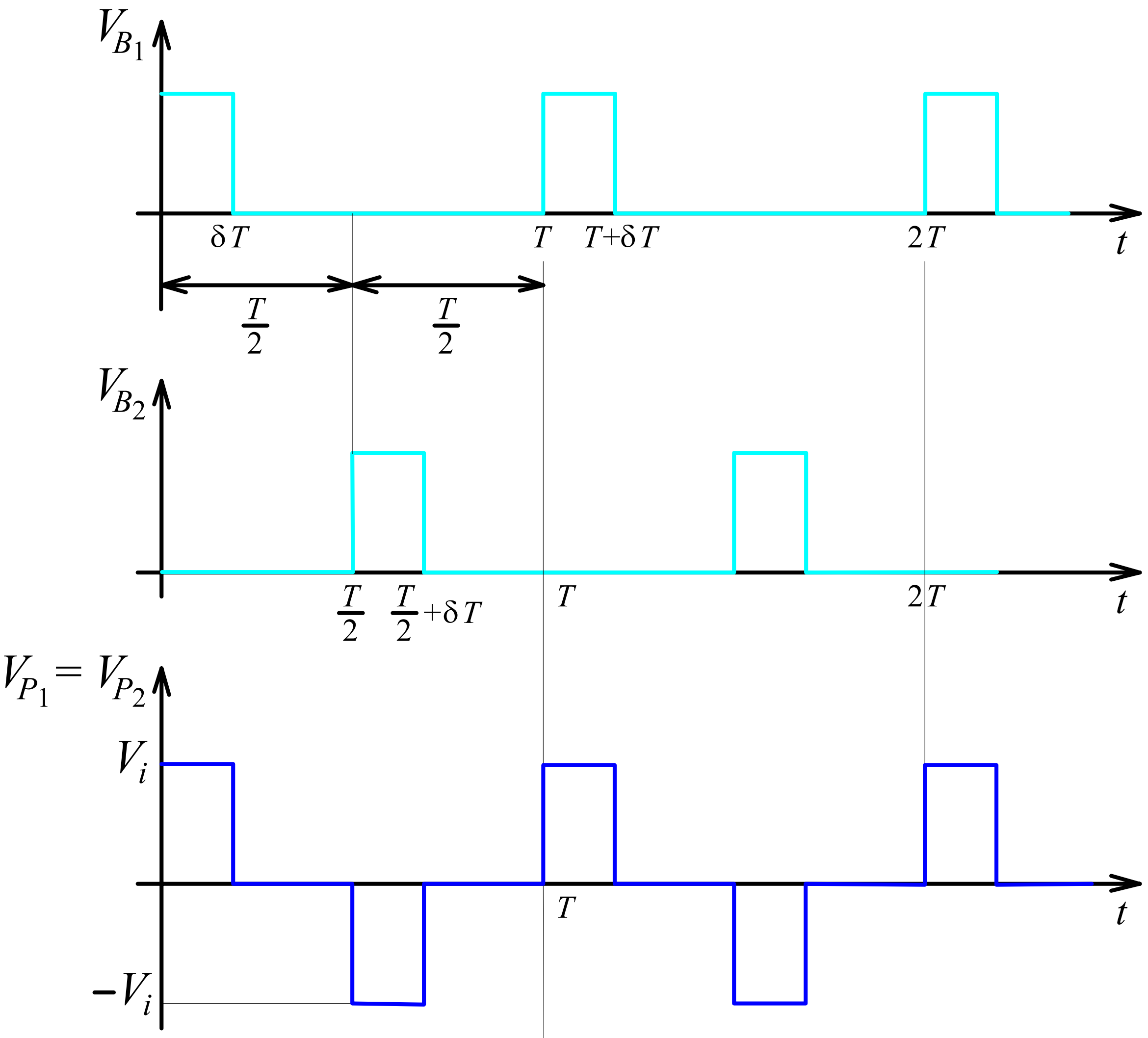
$$i_L = \left(\frac{V_i}{n} - V_{out}\right)t + I_L(0) \Rightarrow \Delta I_L^+ = \left(\frac{V_i}{n} - V_{out}\right)\delta T$$

Fasi 2,4 $$i_L = \frac{V_{out}}{L}t' + I'_L(0) \Rightarrow \Delta I_L^- = \frac{V_{out}}{L}\left(\frac{T}{2} - \delta T\right)$$

$$\Delta I_L^+ = \Delta I_L^- \Rightarrow \frac{V_i}{n}\delta - \delta V_{out} = \frac{V_{out}}{2} - \delta V_{out}$$

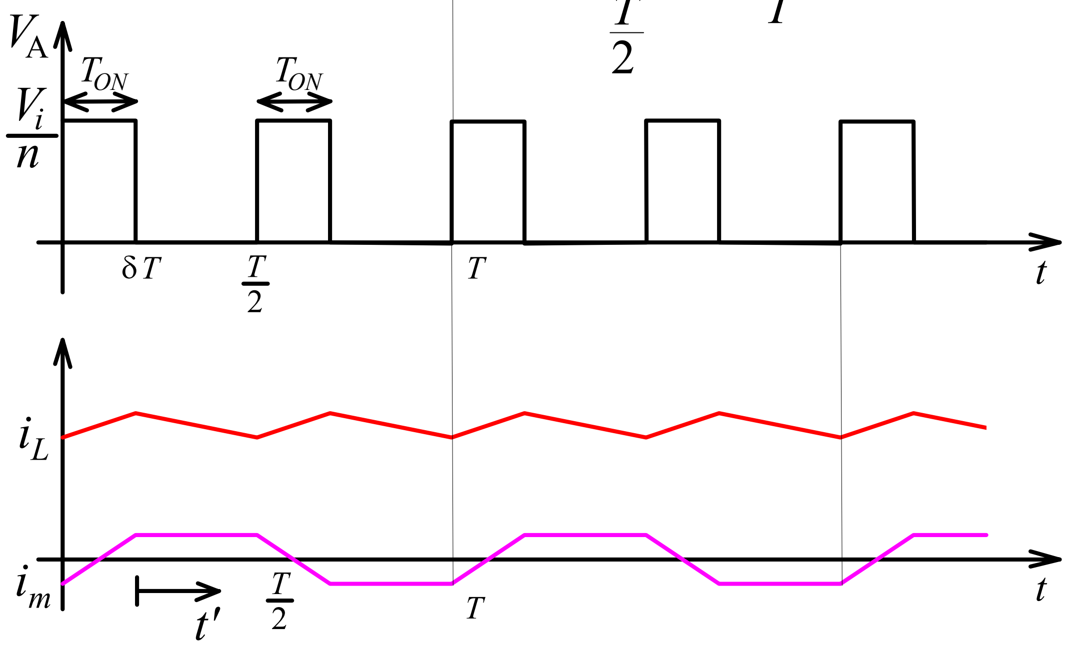
$$\Downarrow$$

$$\boxed{V_{out} = \frac{2}{n}\delta V_i}$$

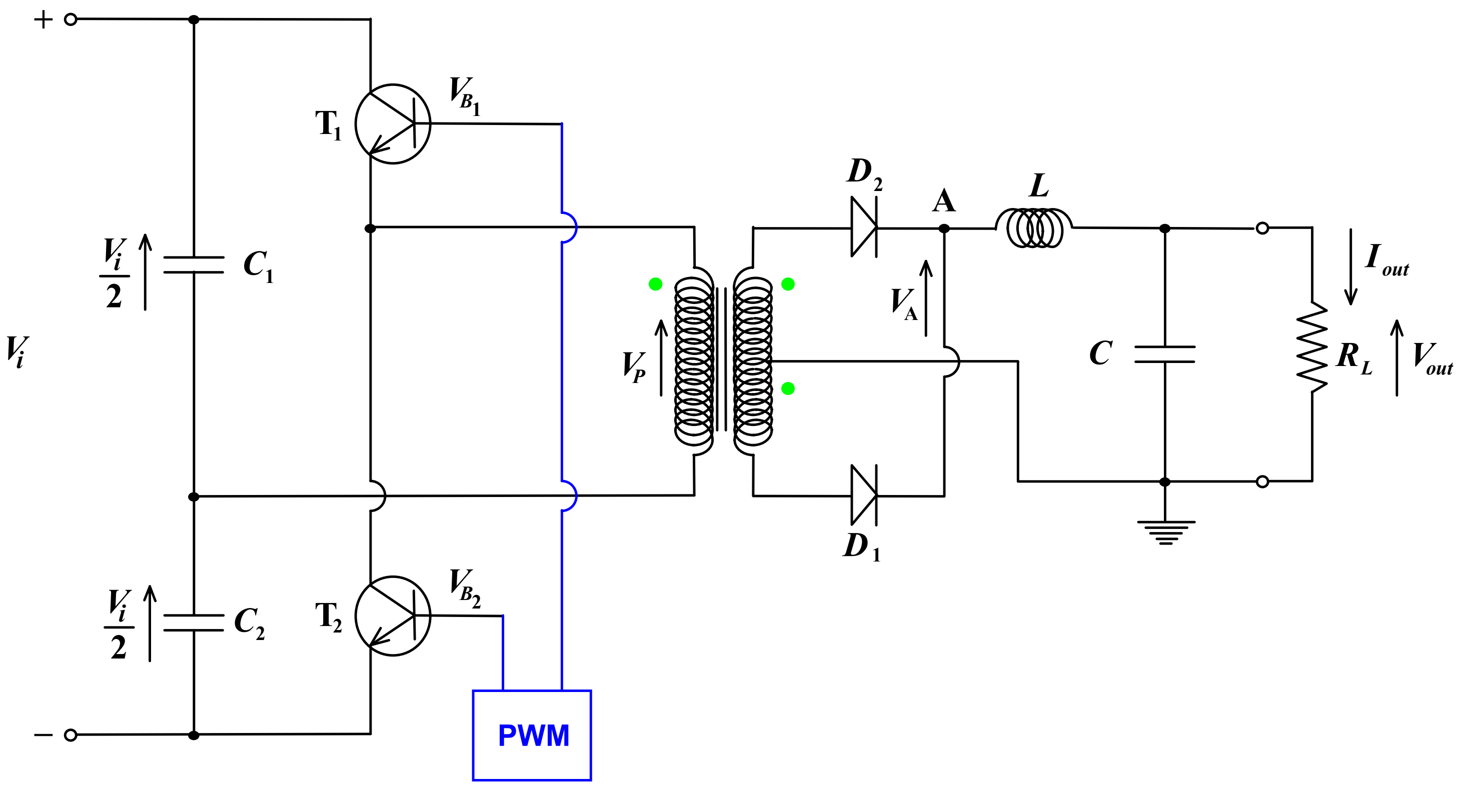


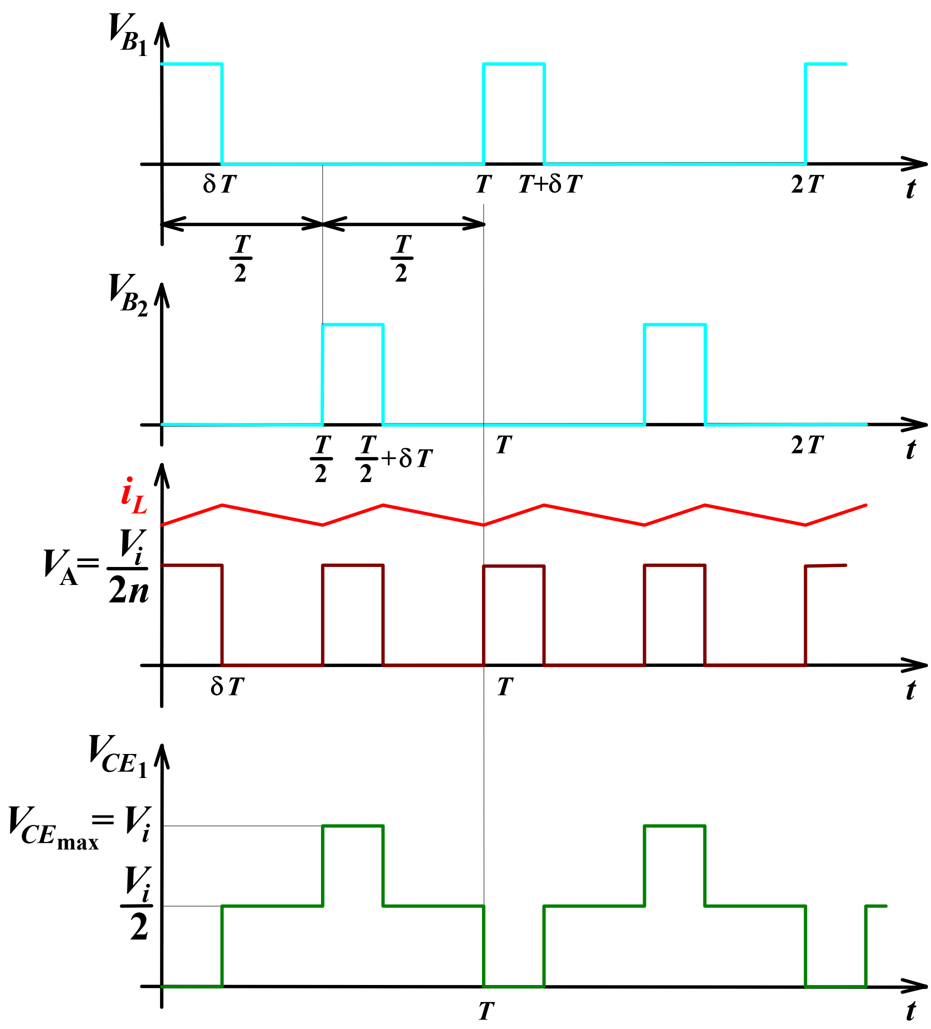
T_1	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF
T_2	OFF	OFF	ON	OFF	OFF	OFF	ON	OFF	OFF	OFF

$$\delta' = \frac{T_{ON}}{\frac{T}{2}} = 2\,\frac{T_{ON}}{T} = 2\delta$$



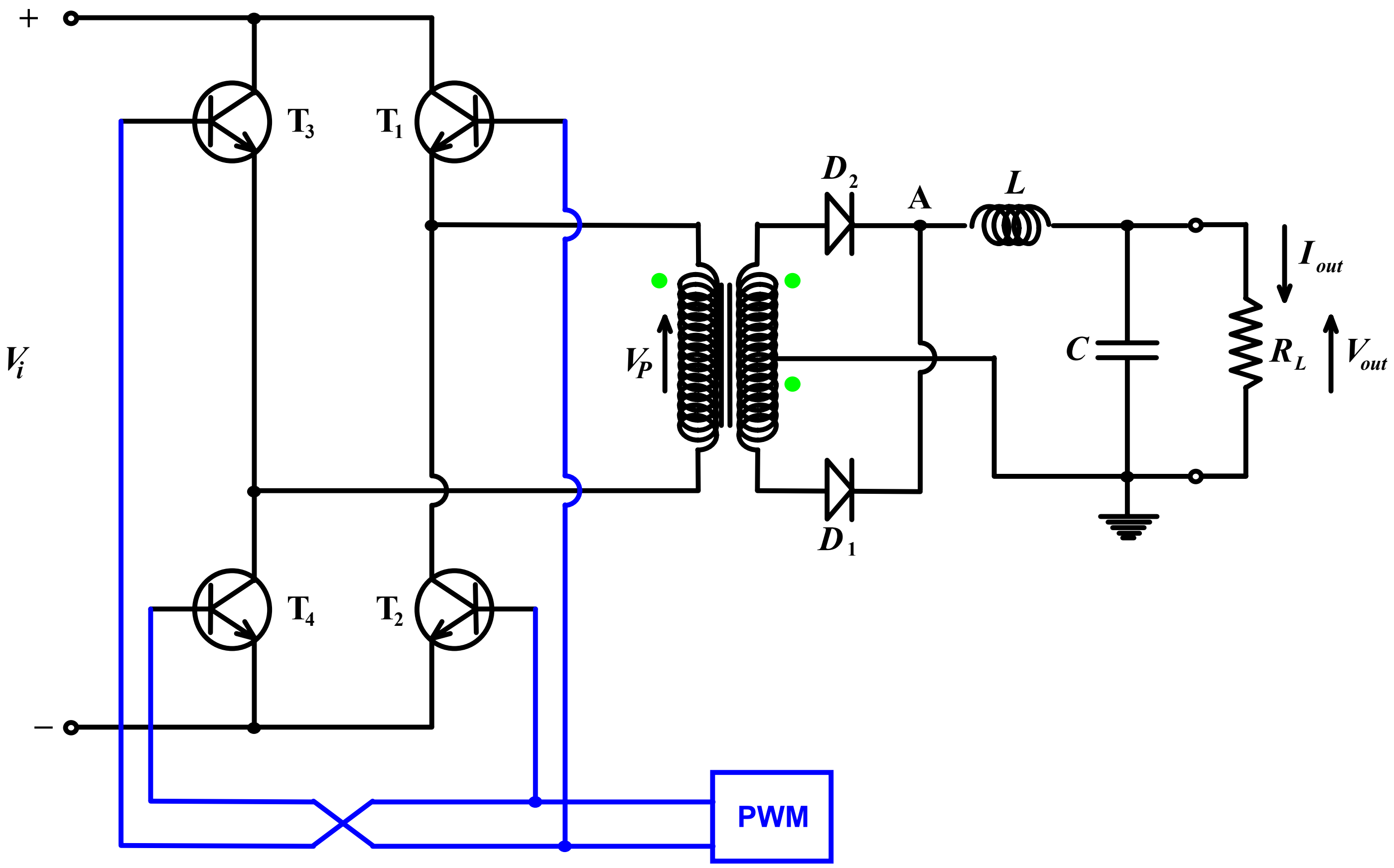
Convertitore a semiponte [> 500W]





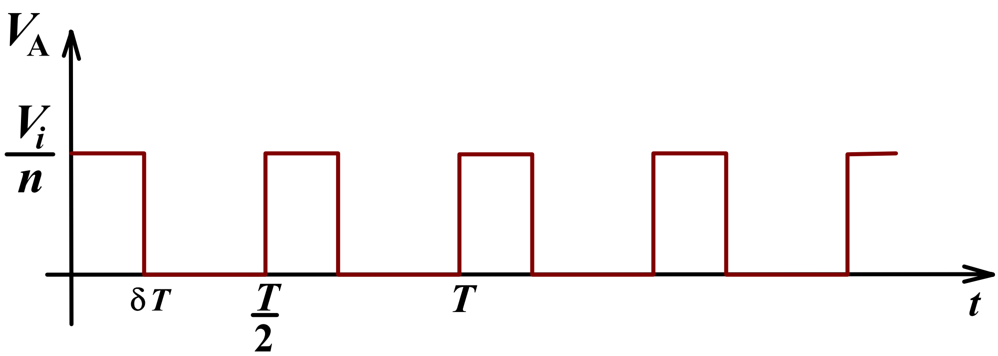
$$\boxed{V_{out} = \frac{V_i}{n}\,\delta}$$

Convertitore a ponte intero [≤ 2kW]

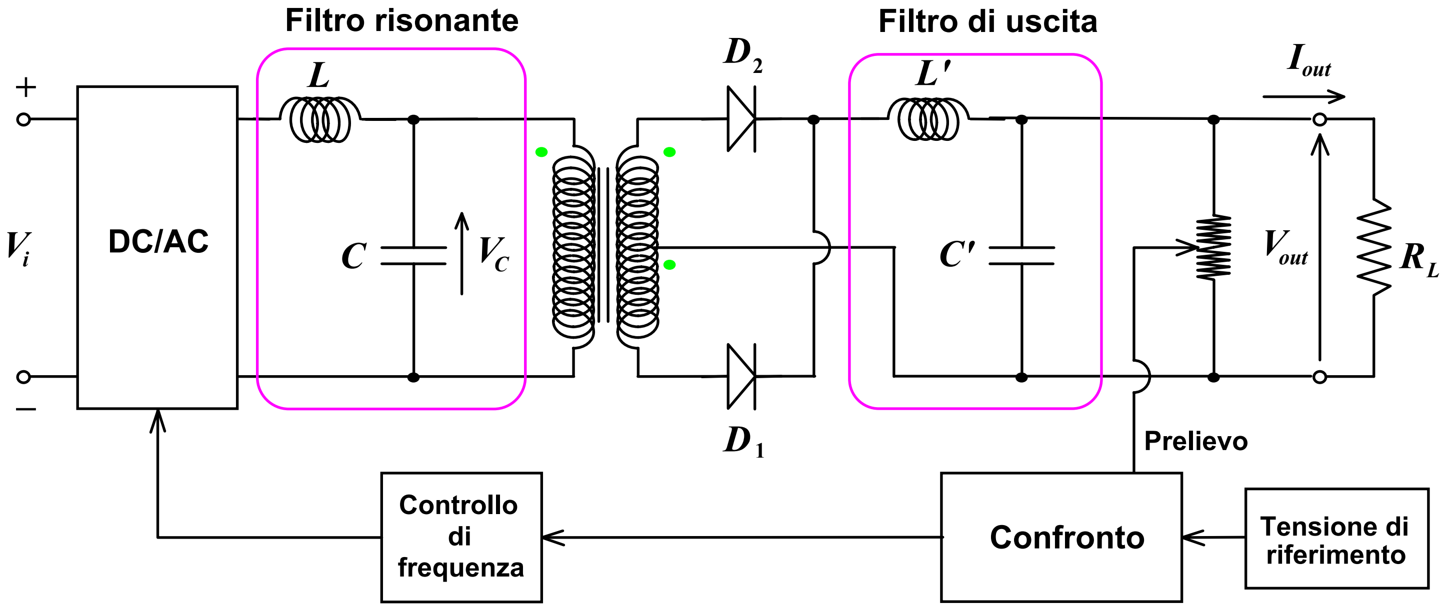


Fase	*Transistore 1*	*Transistore 2*	*Transistore 3*	*Transistore 4*
1	ON	OFF	OFF	ON
2	OFF	OFF	OFF	OFF
3	OFF	ON	ON	OFF
4	OFF	OFF	OFF	OFF

$$\boxed{V_{out} = \frac{2}{n}\,\delta\,V_i}$$

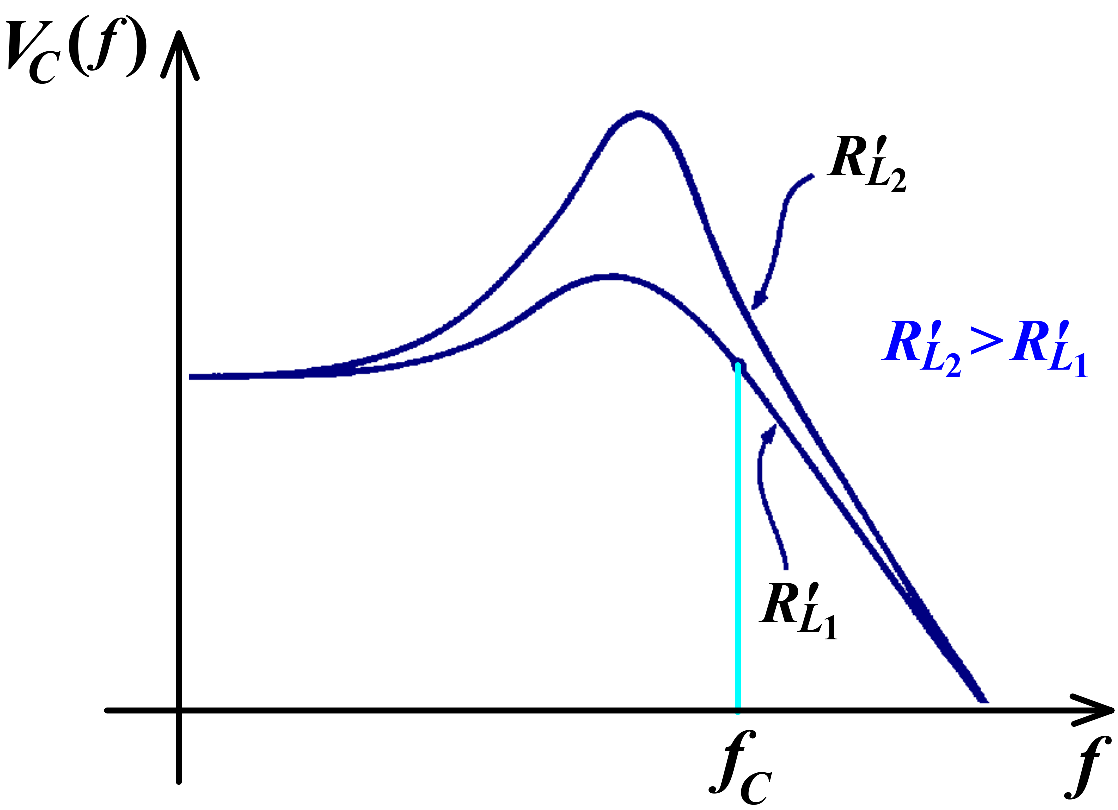


Alimentatore a risonanza

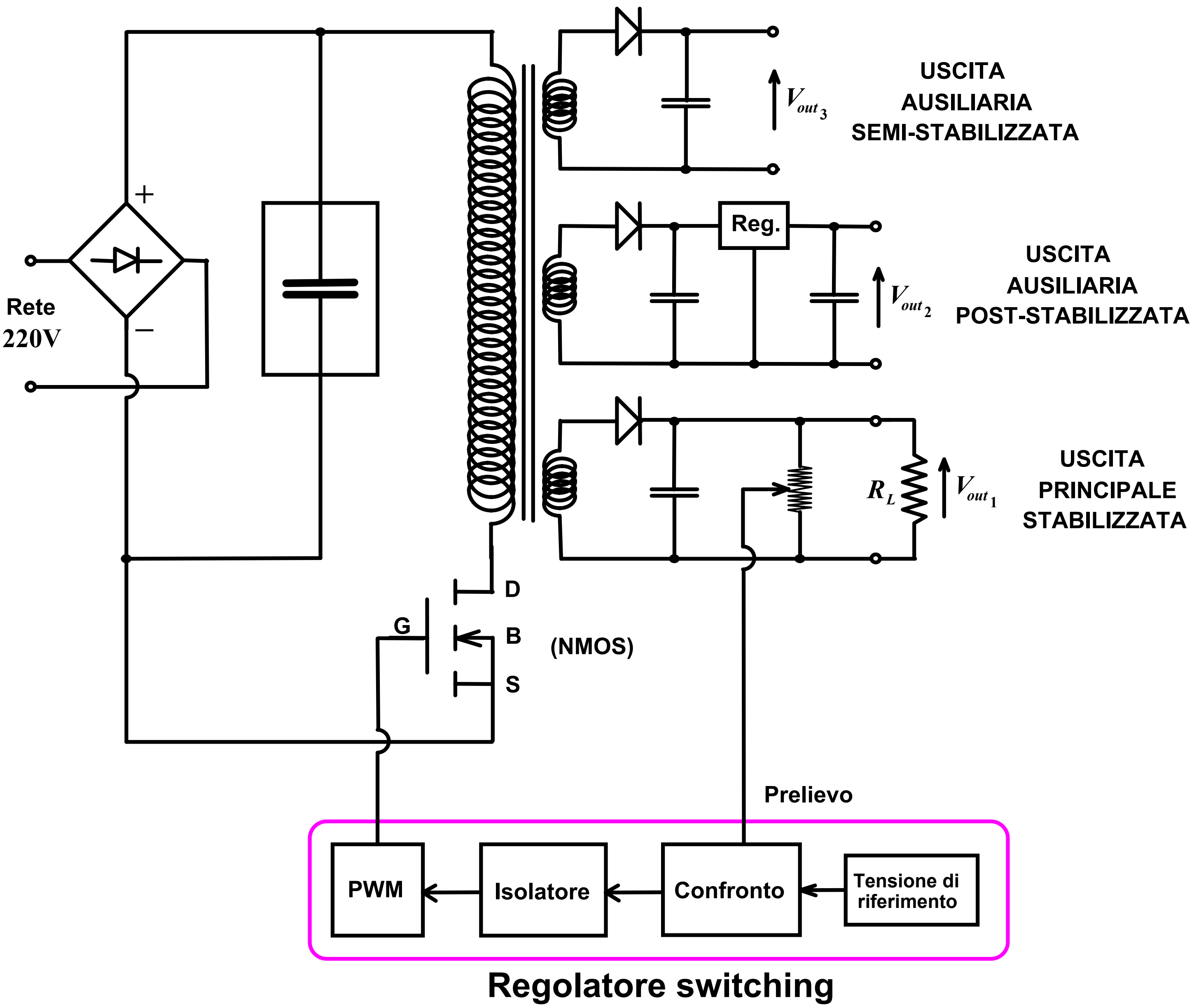


L, C filtro risonante

L', C' filtro di uscita



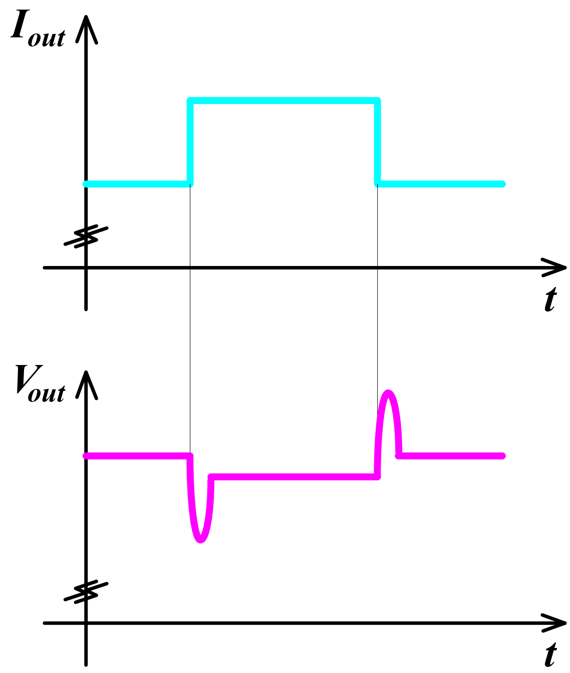
SMPS con uscite multiple



Caratteristiche principali:

- ***buona regolazione nei confronti delle variazioni della tensione di rete;***
  - ***variazioni della tensione sulle uscite ausiliarie a seguito di variazioni di carico sull'uscita principale (effetto della cross-regulation).***

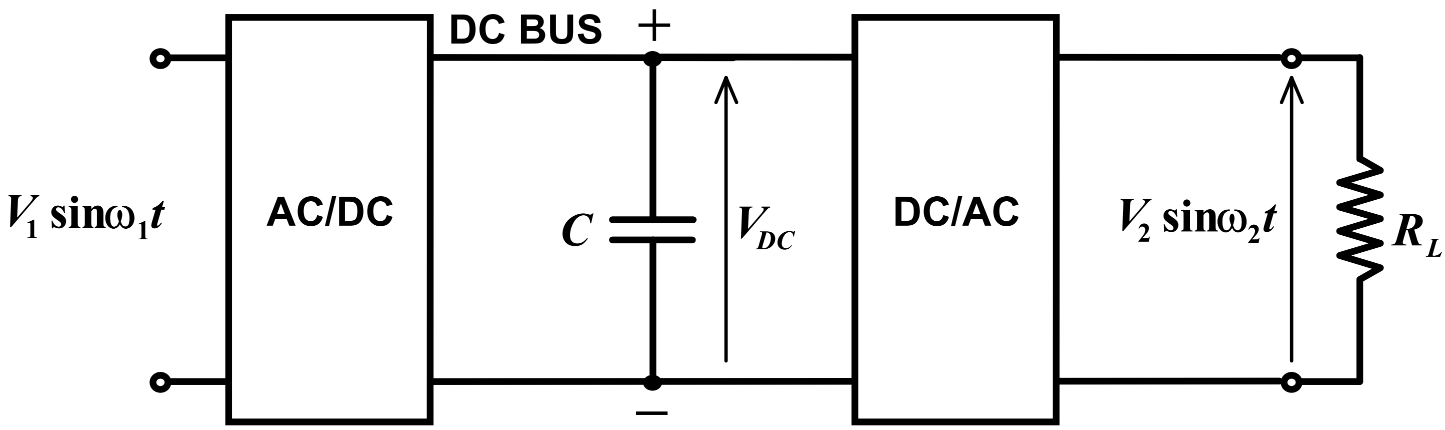
Risposta ai transitori



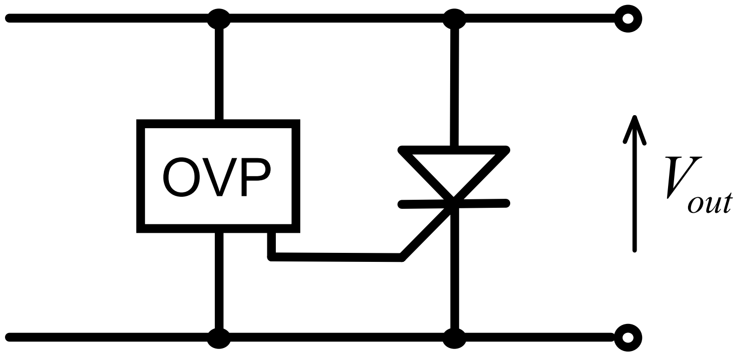
Tecniche utilizzate

- ***Feedforward***
- ***Current mode***
- ***Soft start***

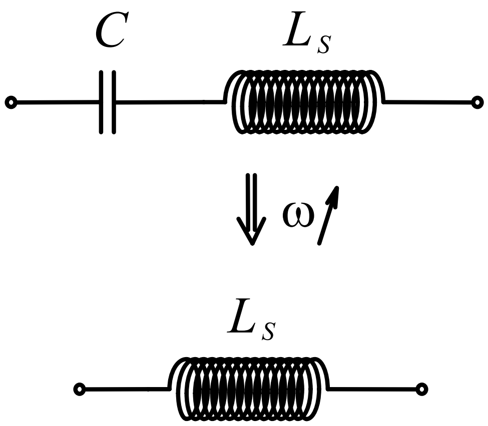
UPS (Uninterruptible Power Supply)

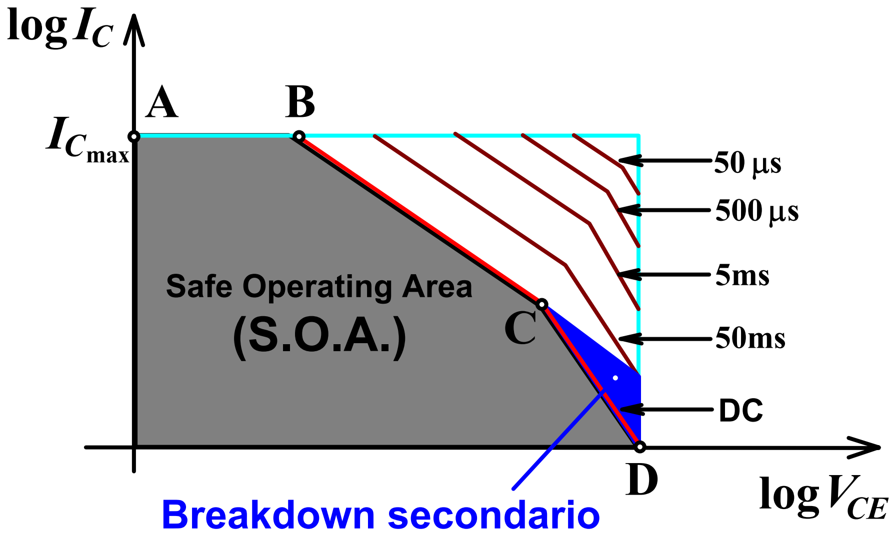


OVP
(Over Voltage Protection)



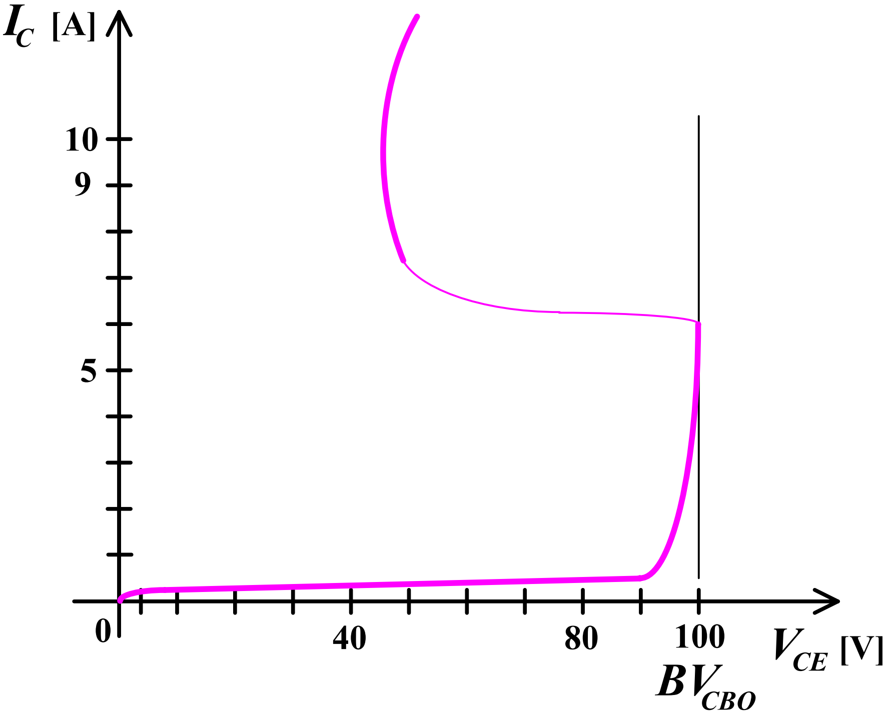
Scelta dei dispositivi passivi ed attivi

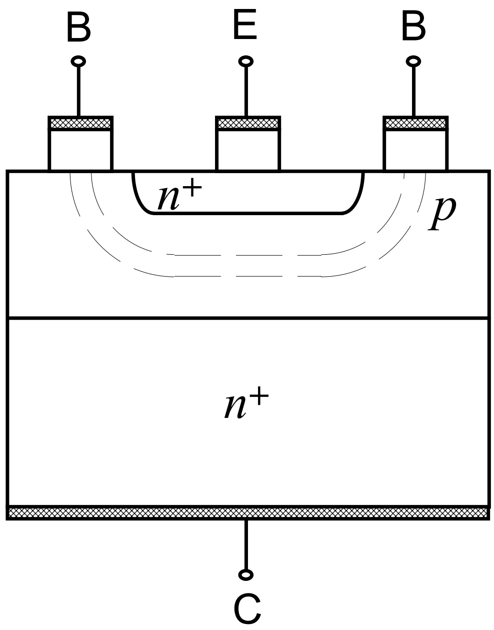




Parametri di interesse:
ESR=Equivalent Series Resistance
ESL=Equivalent Series Inductance

Breakdown secondario

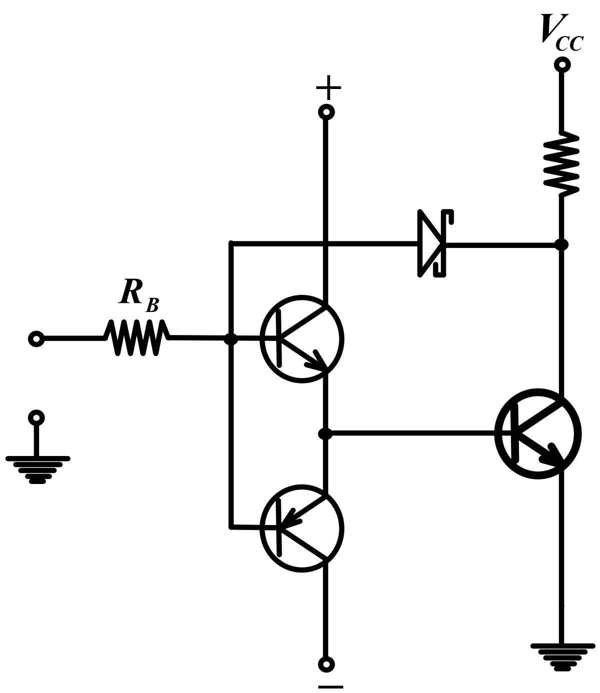




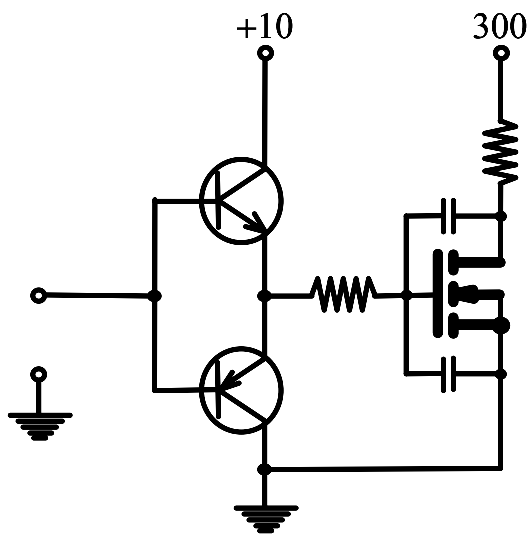
Per evitare l'effetto di focalizzazione della corrente le connessioni interne della base e dell'emettitore sono fatte a pettine interdigitale.

Circuiti di pilotaggio

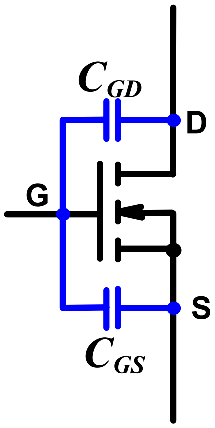
pilotaggio di BJT



pilotaggio di MOSFET



Esempio numerico



C_{GD} =50pF

C_{GS}=500pF

$$\Delta Q = C_{GS}\,\Delta V_{GS} + C_{GD}\,\Delta V_{DG}$$
$$= 500\cdot 10^{-12}\cdot 10 + 50\cdot 10^{-12}\cdot 290 \cong$$
$$\cong 20\cdot 10^{-9} = 20\ \text{nC}$$
$$I = \frac{\Delta Q}{\Delta t} = \frac{20\cdot 10^{-9}}{100\cdot 10^{-9}} = \mathbf{200\ mA}$$

IGBT (Insulated Gate Bipolar Transistor)

Caratteristiche principali: ***V_{CE} bassa, pilotaggio di MOS, lento ON→ OFF***