Corso di
ELETTRONICA INDUSTRIALE

"Analisi del funzionamento continuo del convertitore Buck"

Argomenti trattati

- **Analisi dei circuiti non lineari con interruttori e diodi**
- **Convertitore abbassatore di tensione (Buck): Analisi del funzionamento continuo (Continuous Conduction Mode, CCM)**

Argomenti trattati

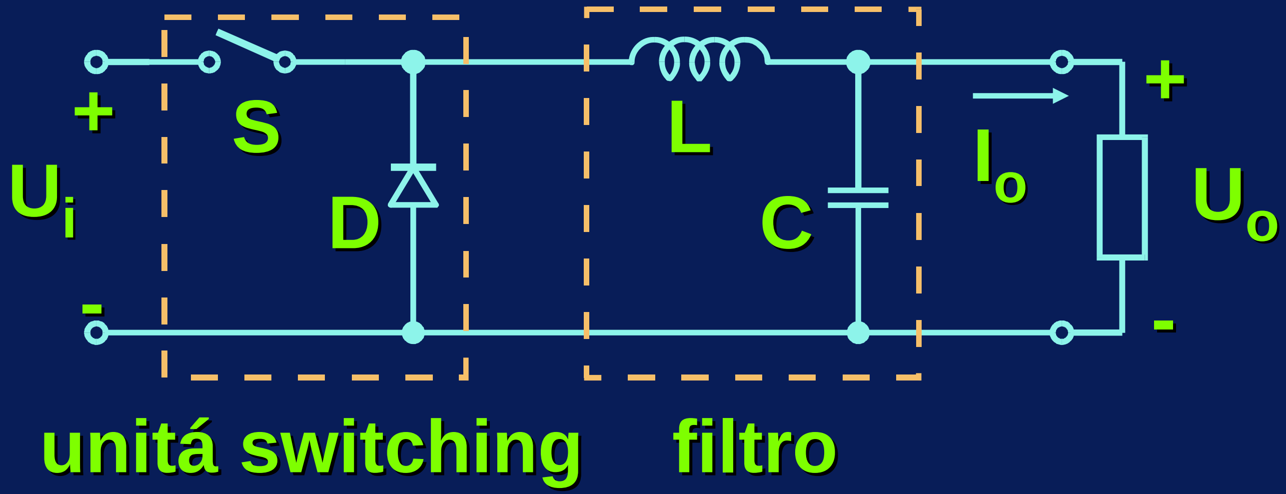
- Analisi dei circuiti non lineari con interruttori e diodi
- Convertitore abbassatore di tensione (Buck): Analisi del funzionamento continuo (Continuous Conduction Mode, CCM)
  - Fase di on (interruttore chiuso)
  - Fase di off (interruttore aperto)
  - Forme d'onda complessive
  - Caratteristica di controllo
  - Ondulazione di corrente e di tensione

Analisi dei circuiti con interruttori

Analisi dei circuiti con interruttori
Approccio lineare a tratti

- Si studia separatamente ogni modo di funzionamento (corrispondente ad uno stato di diodi ed interruttori), in cui il circuito é lineare.
- Si compongono le sequenze di modi:
  - identificando le condizioni di inizio e di fine di ciascun modo
  - determinando la successione dei modi
  - trasferendo le condizioni finali di un modo come condizioni iniziali del modo seguente

Schema del convertitore Buck



- interruttore ideale (u_{Son}=0, i_{Soff} =0, t_{swon}=t_{swoff}=0)
- diodo ideale (u_{Don}= 0, i_{Doff} = 0, t_{swon} = t_{swoff} = 0)
- L,C ideali (R_L = 0, ESR = 0, ESL = 0)
- $u_i = U_i$ = costante
- $u_o = U_o$ = costante ($\omega_r << 2\pi f_s$)
- $i_o = I_o$= costante

Forme d’onda tipiche del convertitore

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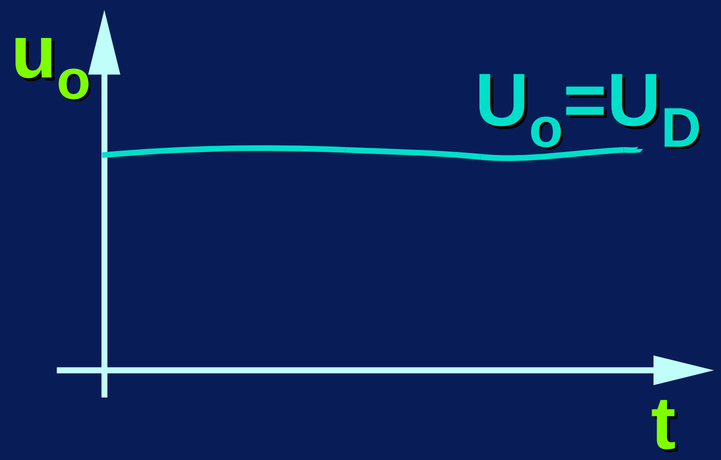

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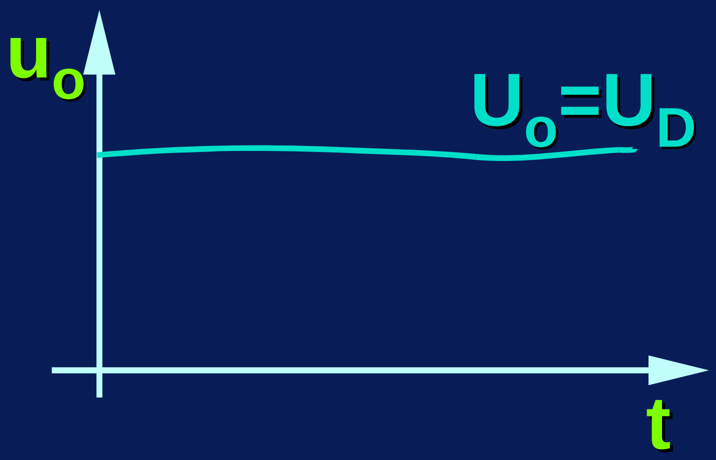
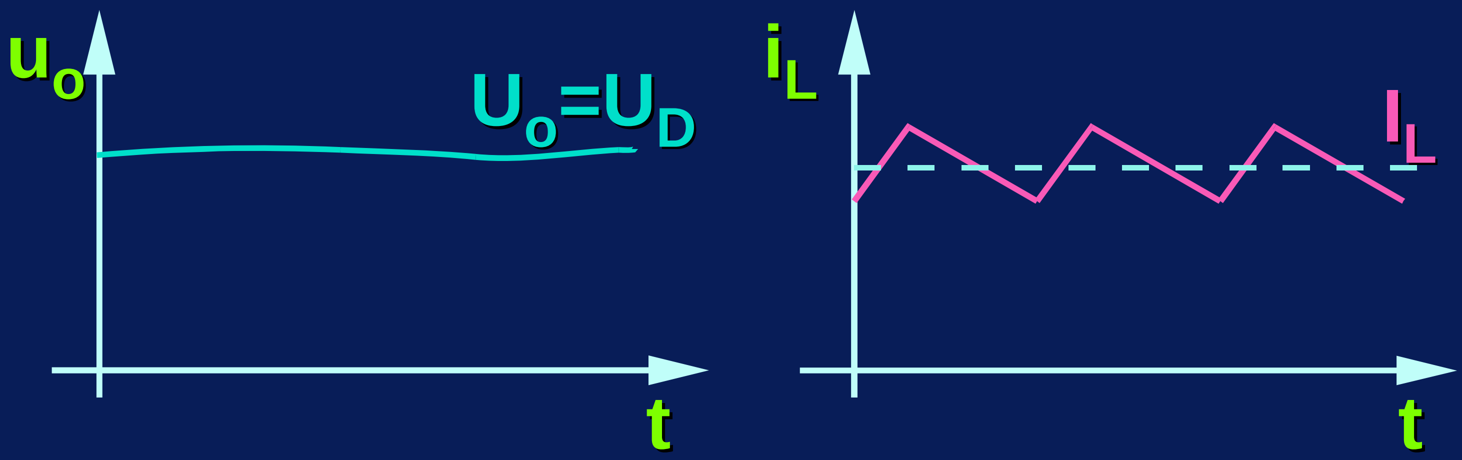


- u_o é effettivamente ben livellata ($u_o=U_o$)

Forme d'onda tipiche del convertitore



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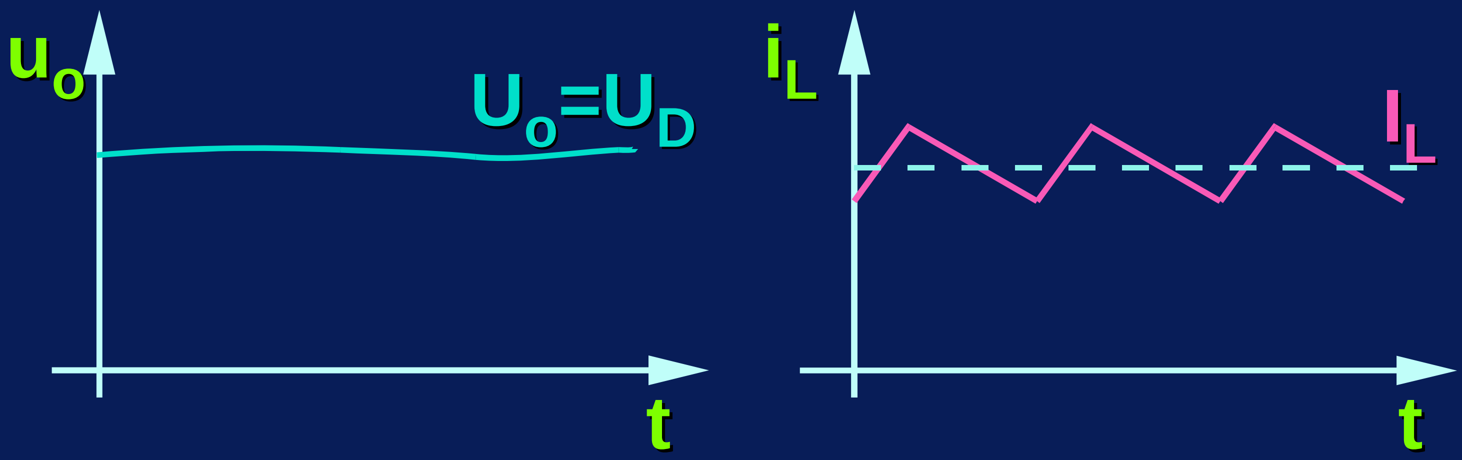

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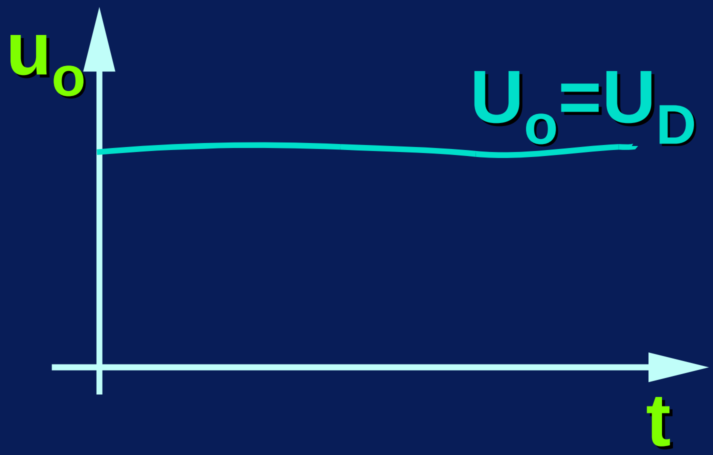
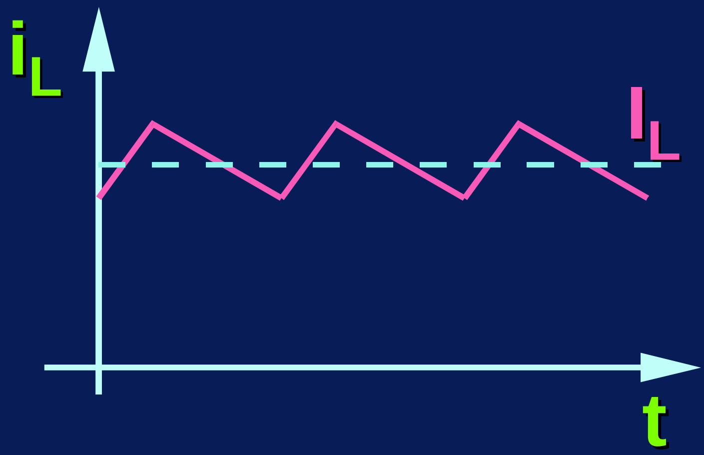
- i_L ha ondulazione (ripple), ma é sempre > 0

Forme d'onda tipiche del convertitore





- u_o é effettivamente ben livellata (u_o=U_o)
- i_L ha ondulazione (ripple), ma é sempre > 0

Questo modo di funzionamento (i_L > 0) si chiama modo continuo (CCM = Continuous Conduction Mode)

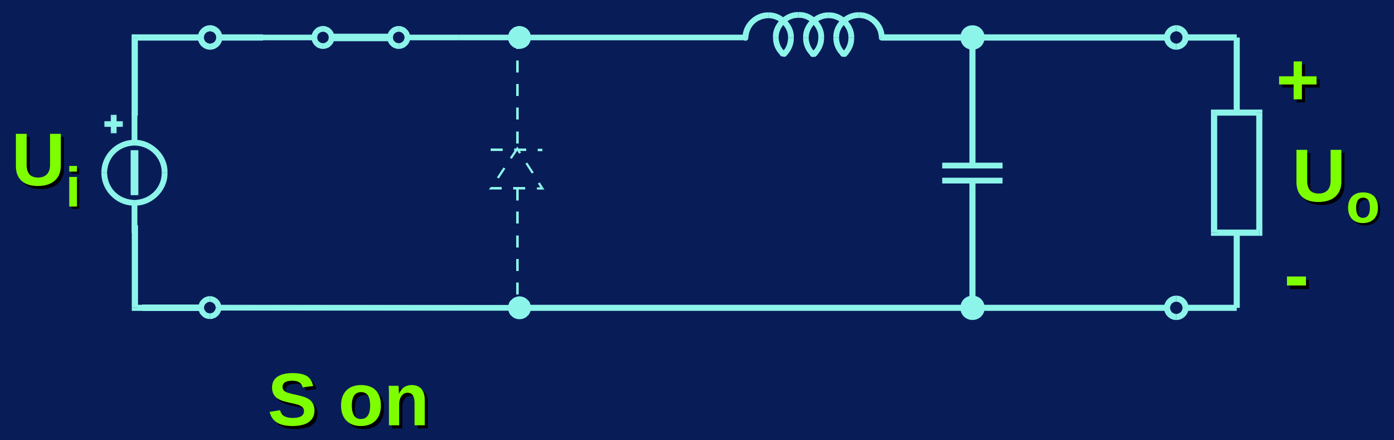
Analisi del funzionamento continuo

Analisi del funzionamento continuo

Tempo di chiusura di S (t_{on})

Analisi del funzionamento continuo

Tempo di chiusura di S (t_{on})



Analisi del funzionamento continuo

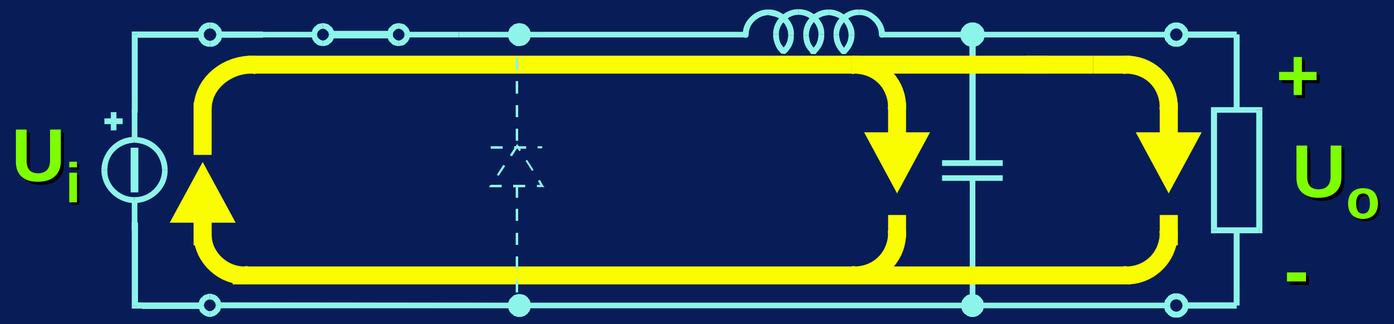
Tempo di chiusura di S (t_{on})

S on D off

- Il diodo é interdetto.

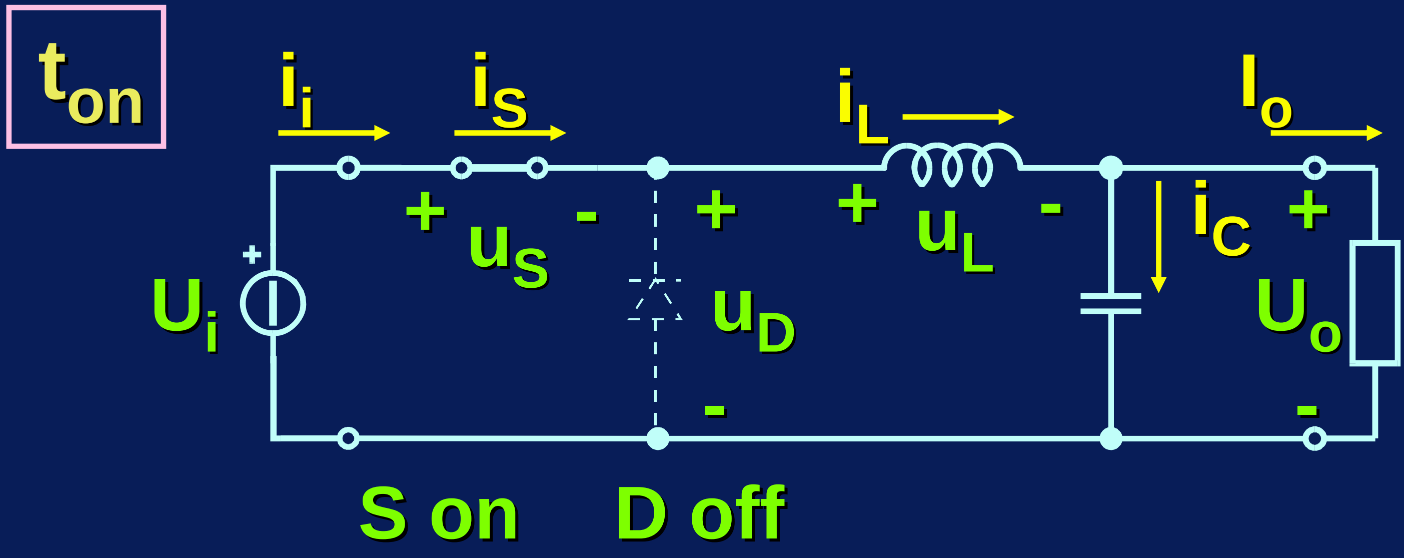
Analisi del funzionamento continuo

Tempo di chiusura di S (t_{on})



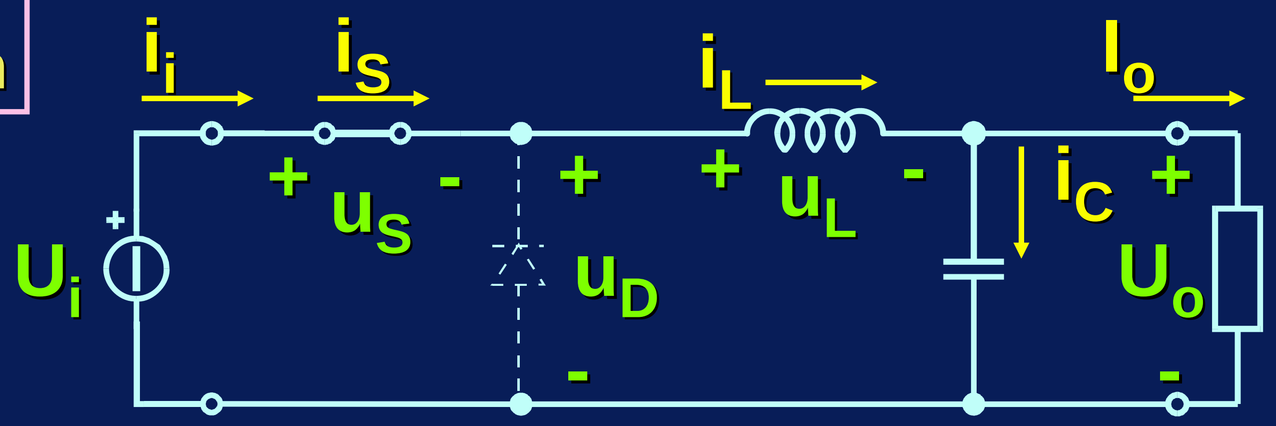
S on D off

- Il diodo é interdetto.
- Il generatore fornisce energia al filtro e al carico.



$$i_i = i_S = i_L = I_o + i_c$$

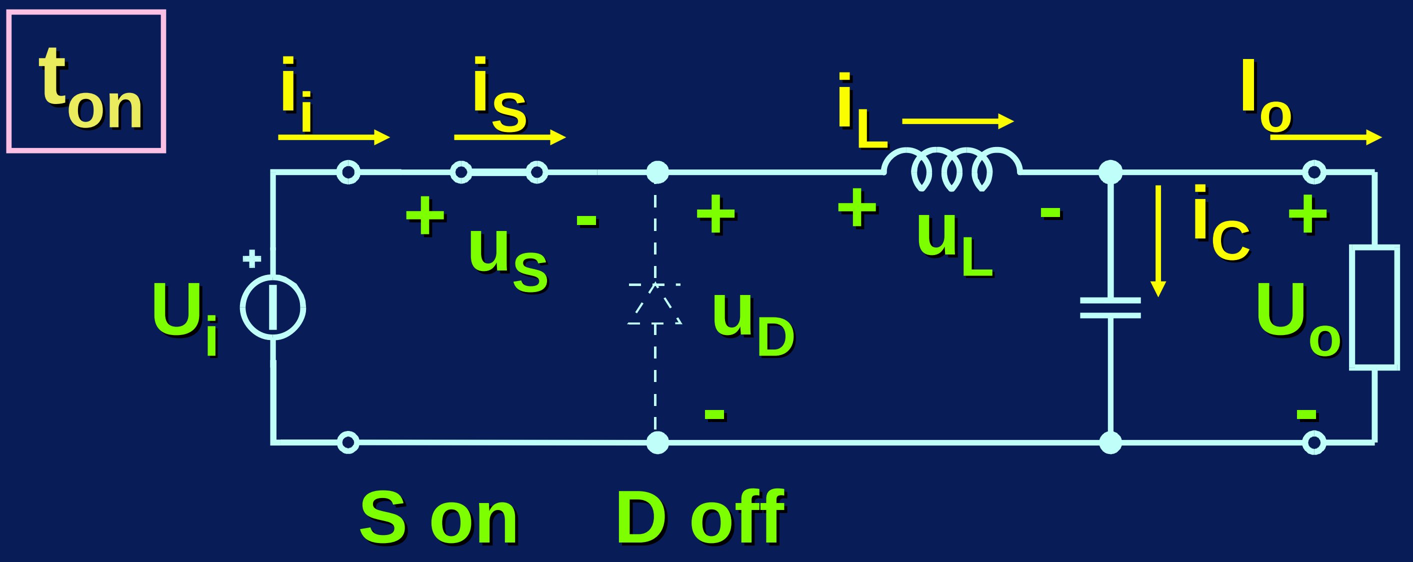
t_{on}



S on D off

$i_i = i_S = i_L = I_o + i_c$

$u_D = U_i$ (diodo contropolarizzato)

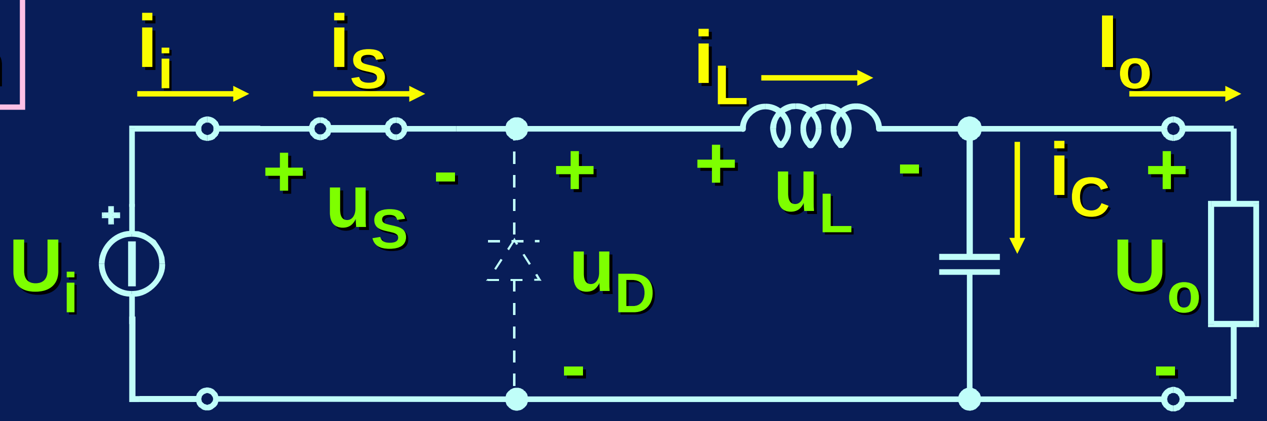


$i_i = i_S = i_L = I_o + i_c$

$u_D = U_i$ (diodo contropolarizzato)

$u_L = U_i - U_o$

t_{on}



S on D off

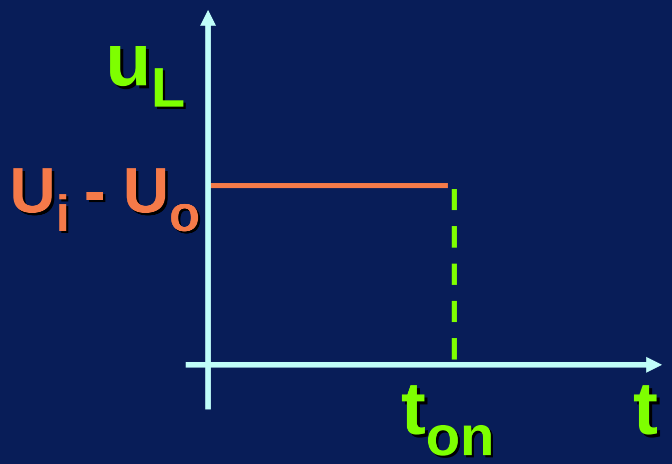
$i_i = i_S = i_L = I_o + i_c$

$u_D = U_i$ (diodo contropolarizzato)

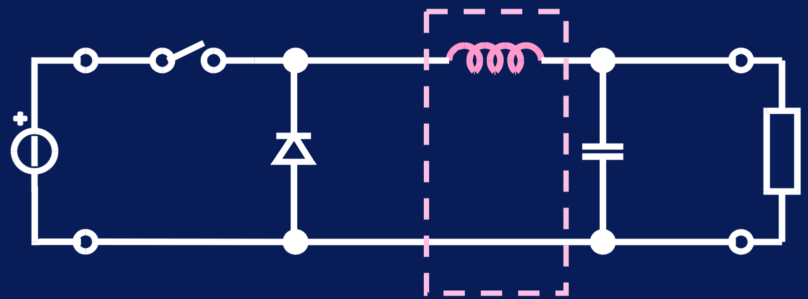
$u_L = U_i - U_o$

$$i_L(t) = i_L(0) + \frac{1}{L} \cdot \int_0^t u_L(\tau) d\tau = i_{L\,min} + \frac{U_i - U_o}{L} \cdot t$$

Tensioni e correnti durante t_{on}



$$u_L = U_i - U_o$$



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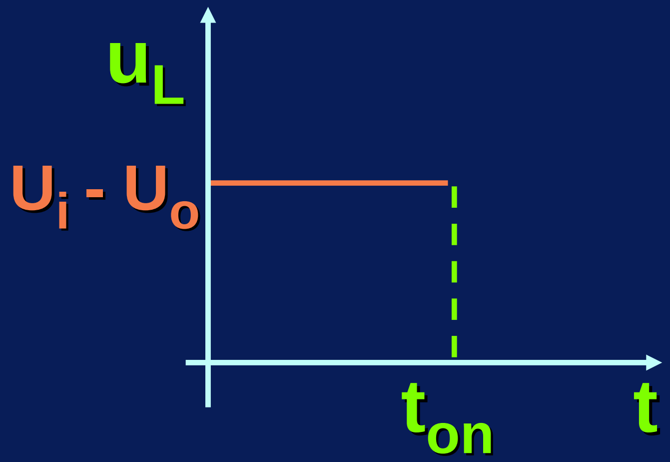

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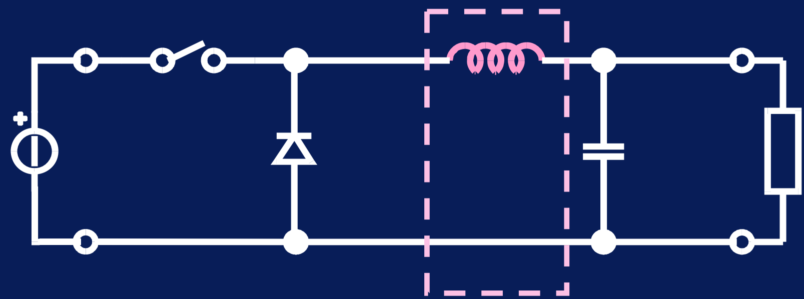
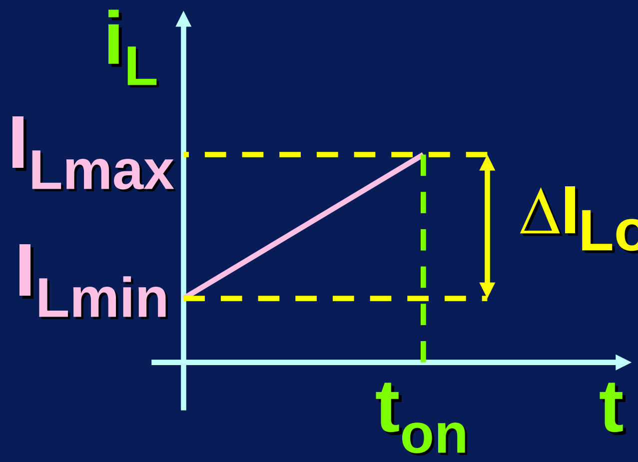
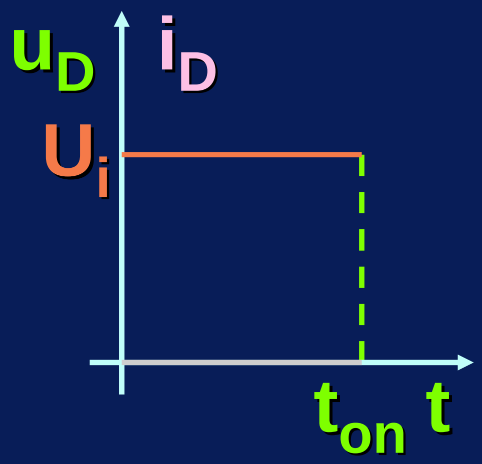




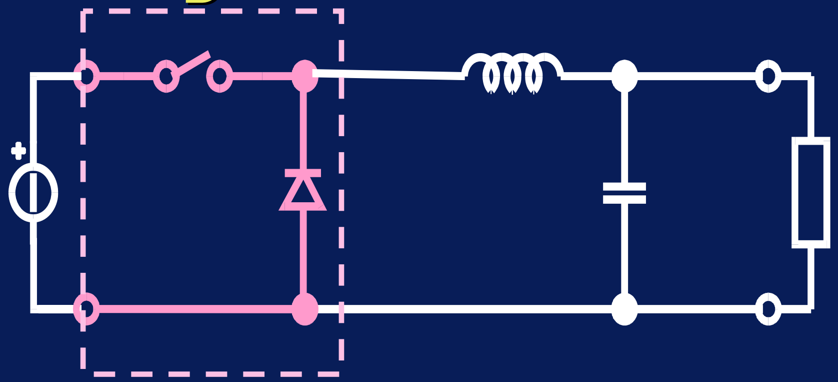
$$\Delta I_{Lon} = \frac{U_i - U_o}{L} \cdot t_{on} = \frac{U_i - U_o}{f_S \cdot L} \cdot \delta$$

Tensioni e correnti durante t_{on}

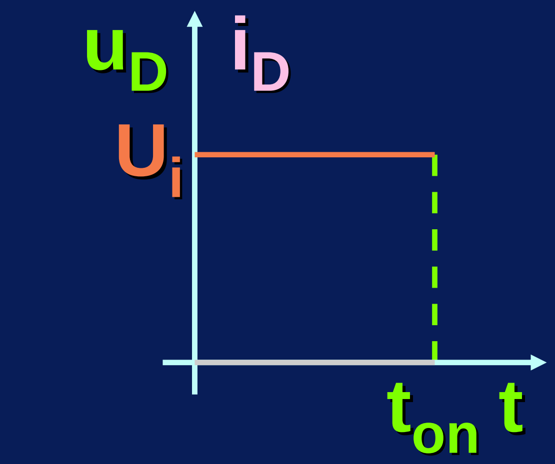


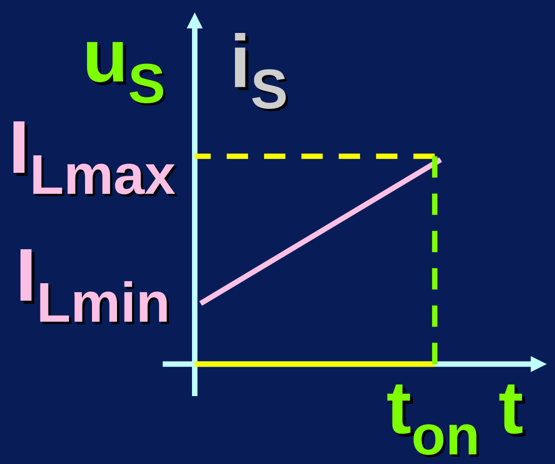
$u_D = U_i$

$i_D = 0$



Tensioni e correnti durante t_{on}





$u_D = U_i$

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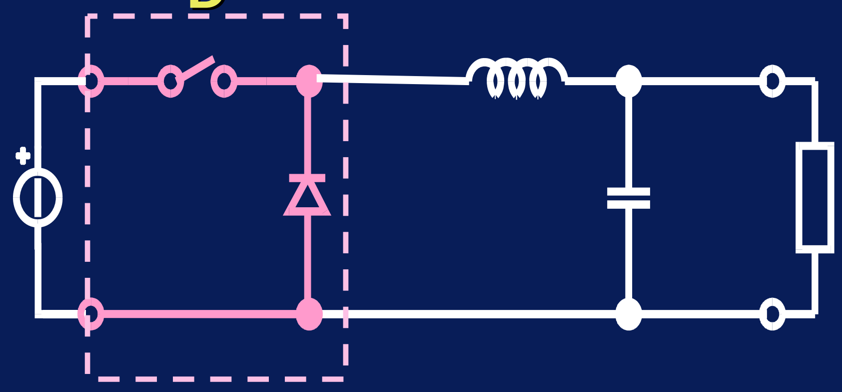
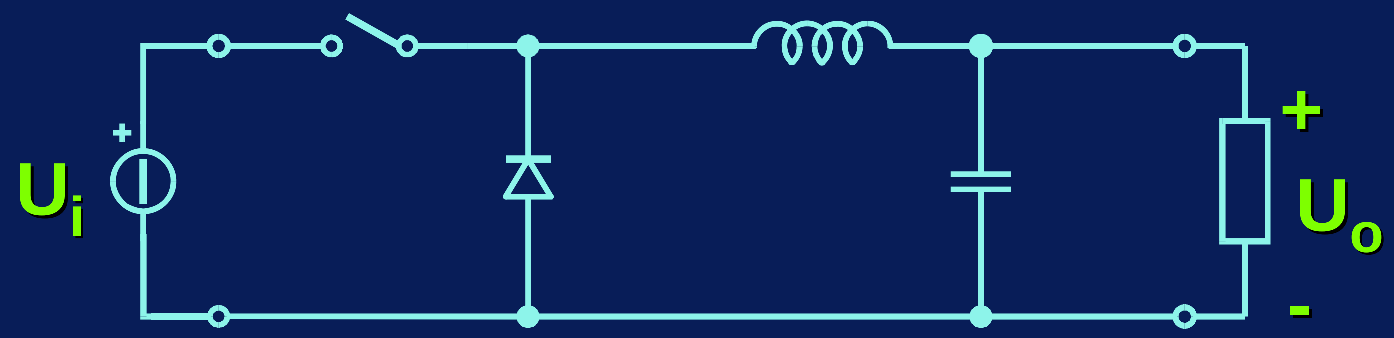


$u_S = 0$

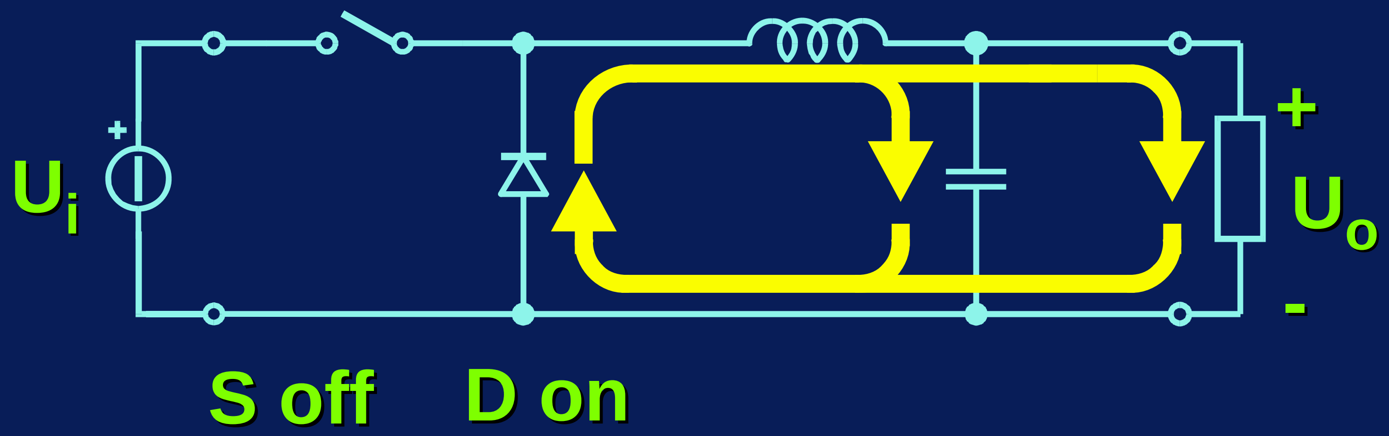
$i_S = i_L$

Tempo di apertura di S (t_{off})



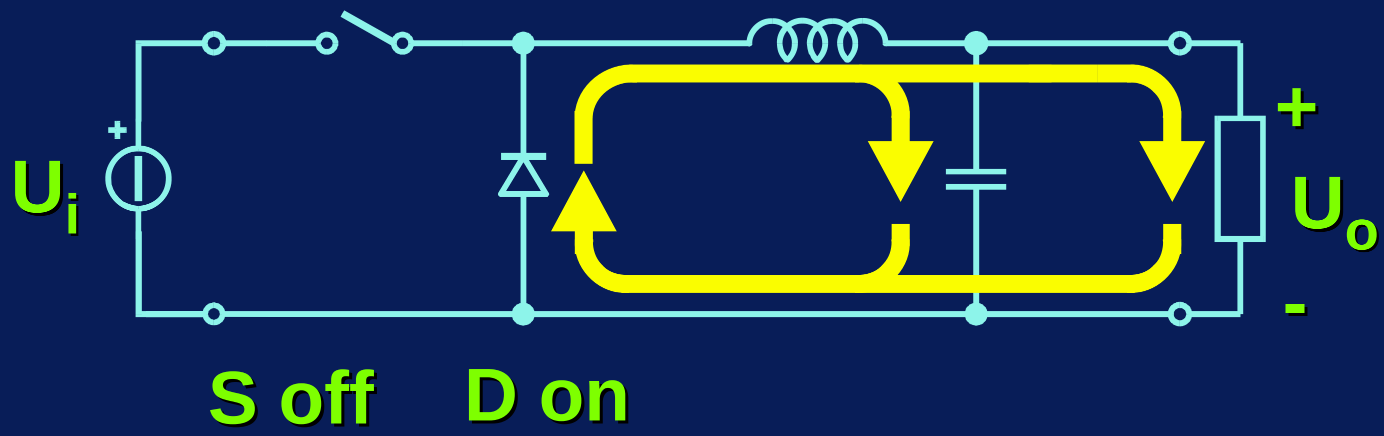
S off

Tempo di apertura di S (t_{off})



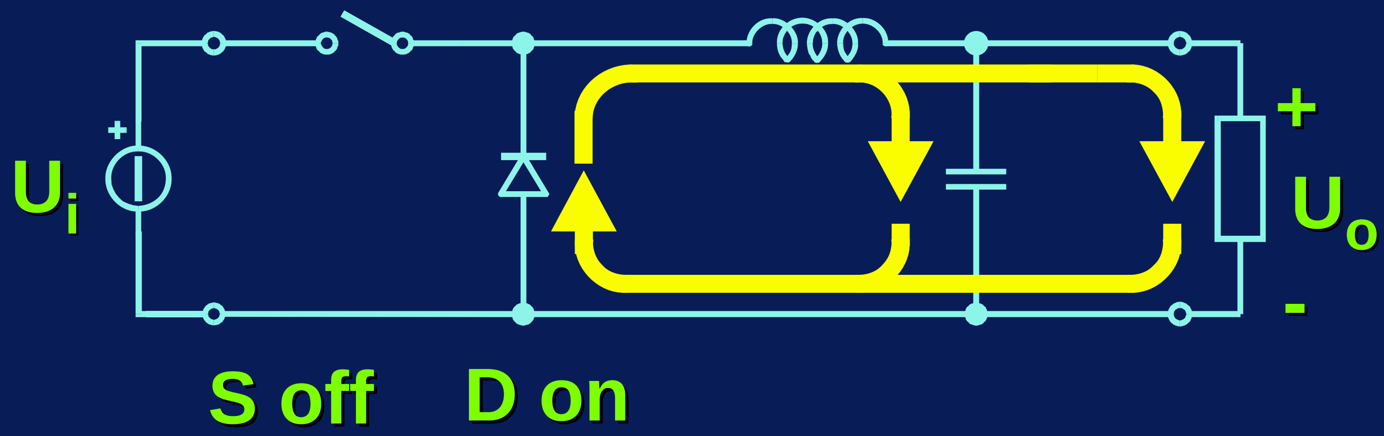
- Il diodo conduce

Tempo di apertura di S (t_{off})



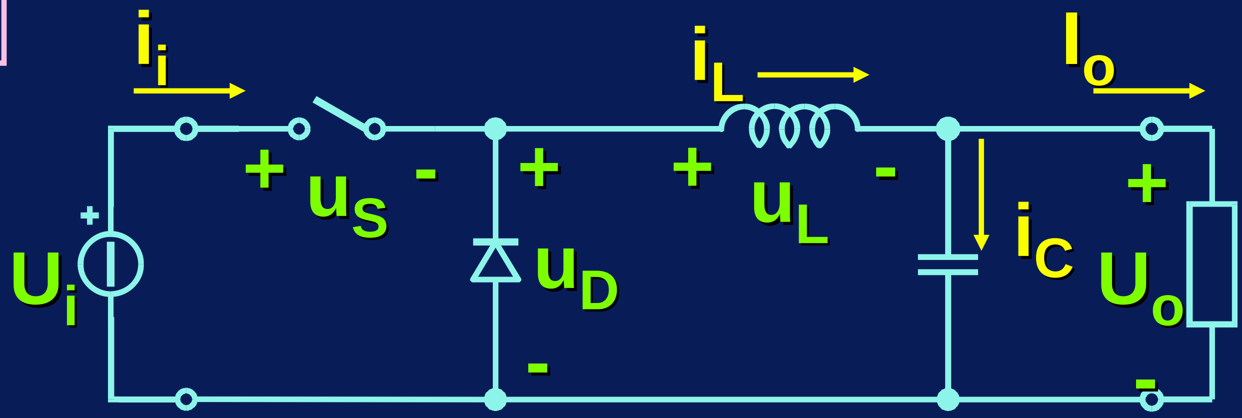
- Il diodo conduce
- L'alimentazione non fornisce energia

Tempo di apertura di S (t_{off})



- Il diodo conduce
- L’alimentazione non fornisce energia
- L’energia del carico viene fornita dal filtro

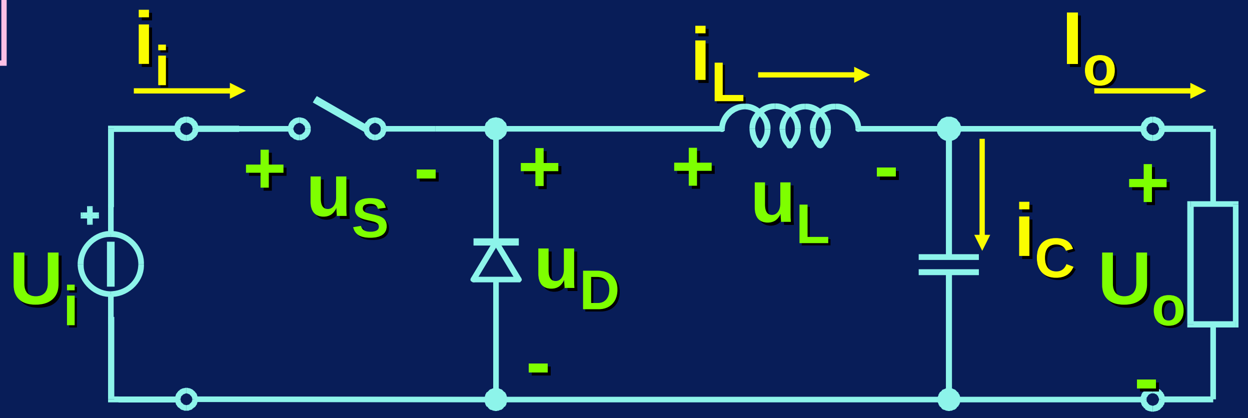
t_{off}



S off D on

$i_i = 0$ $i_L = I_o + i_c$

t_{off}



S off D on

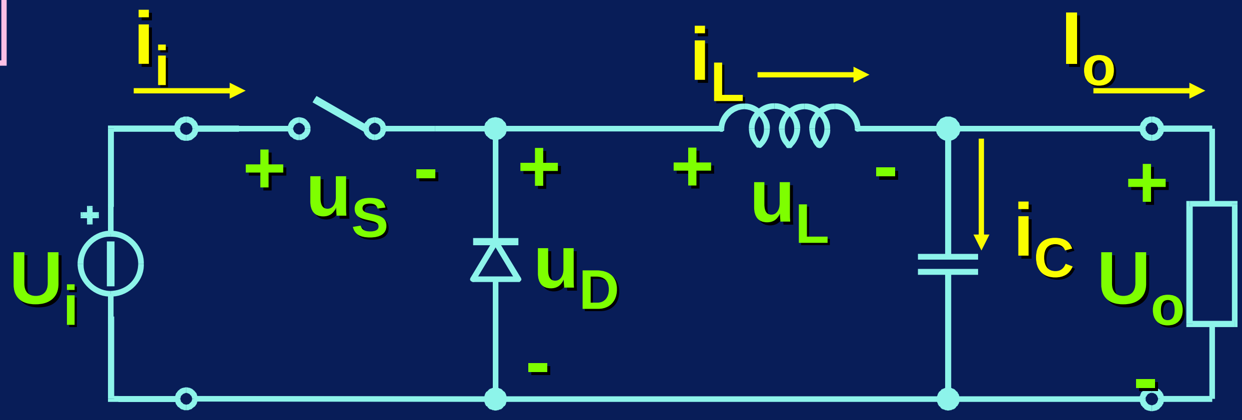
$i_i = 0$

$u_D = 0$

$i_L = I_o + i_c$

$u_S = U_i$

t_{off}



S off D on

$i_i = 0$

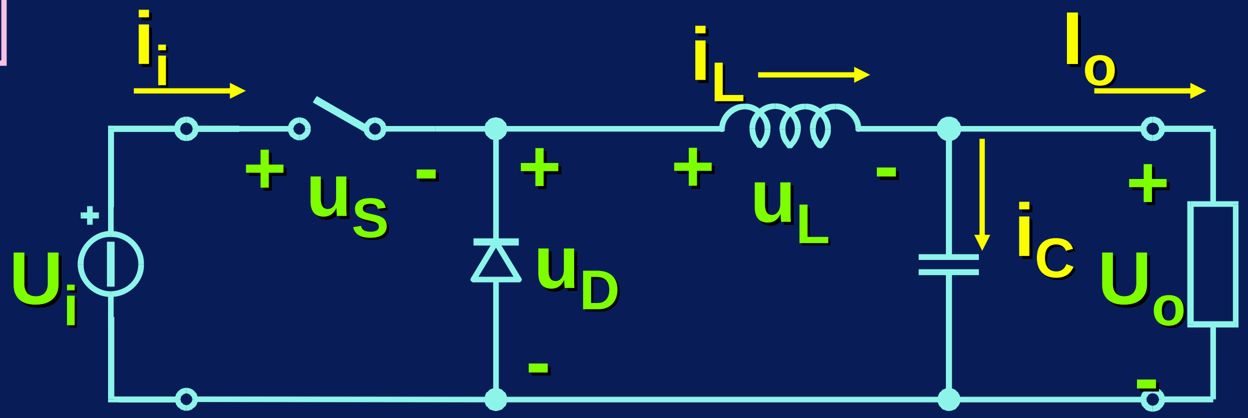
$u_D = 0$

$u_L = -U_o$

$i_L = I_o + i_c$

$u_S = U_i$

t_{off}



S off D on

$i_i = 0$

$u_D = 0$

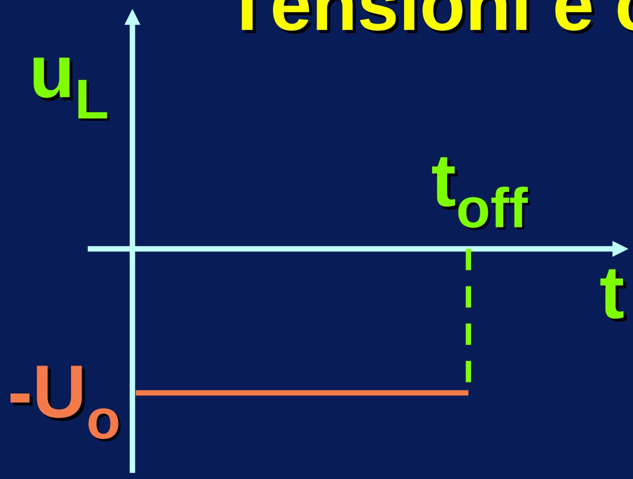
$u_L = -U_o$

$i_L = I_o + i_c$

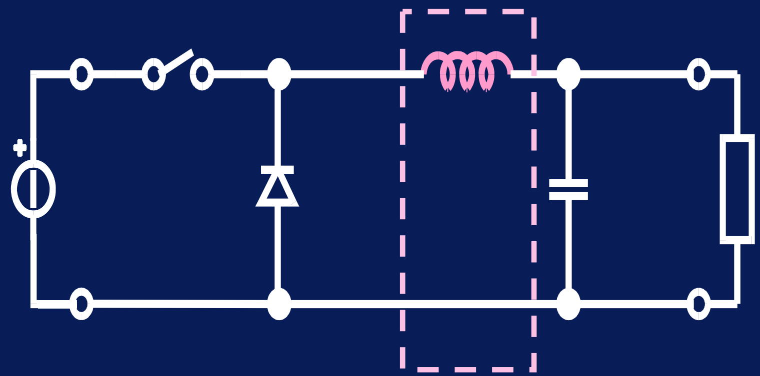
$u_S = U_i$

$$i_L(t) = i_L(0) + \frac{1}{L} \cdot \int_0^t u_L(\tau)d\tau = i_{L\,max} - \frac{U_o}{L} \cdot t$$

Tensioni e correnti durante t_{off}



$$u_L = -U_o$$



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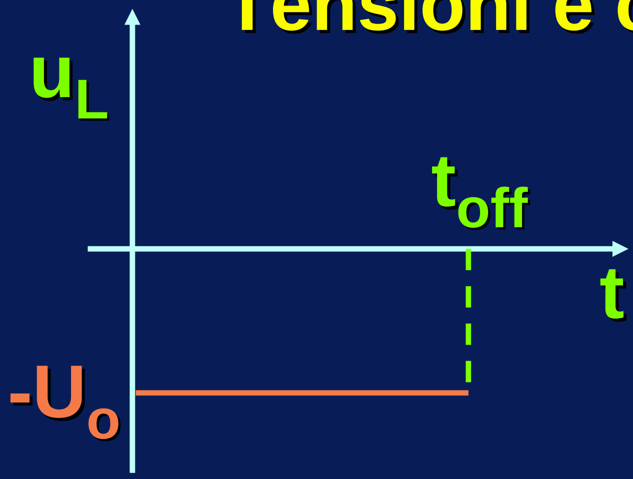

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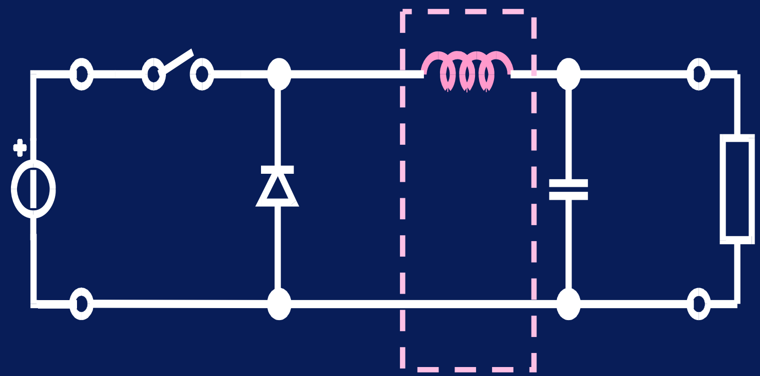
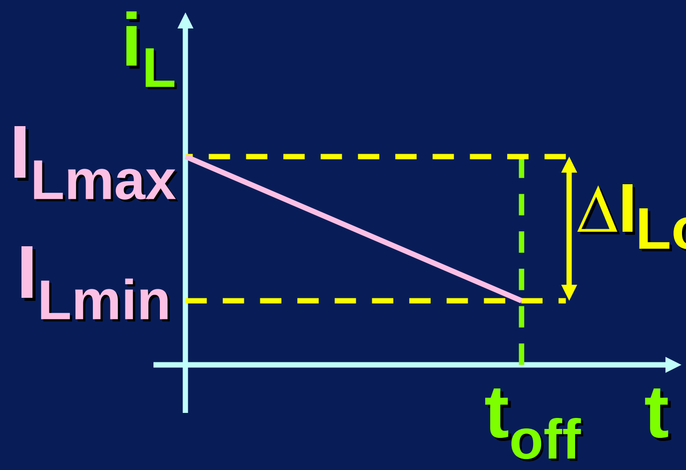
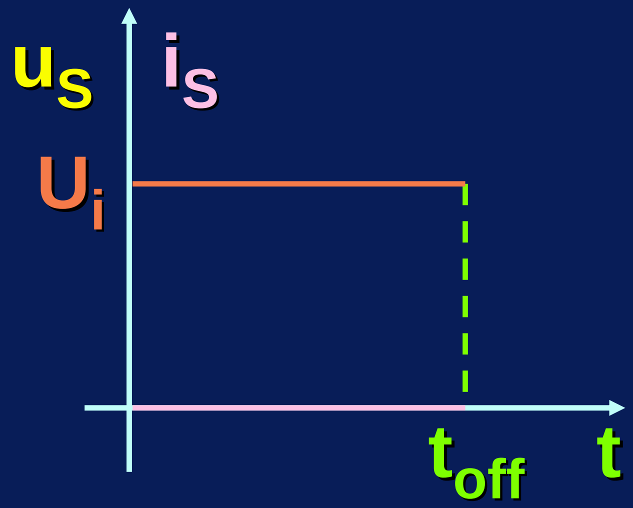




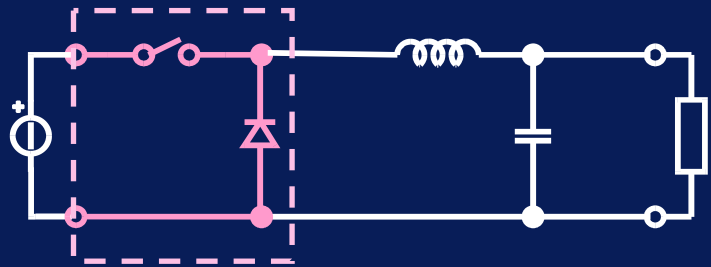
$$\Delta I_{Loff} = \frac{U_o}{L} \cdot t_{off} = \frac{U_o}{f_S \cdot L} \cdot (1 - \delta)$$

Tensioni e correnti durante t_{off}

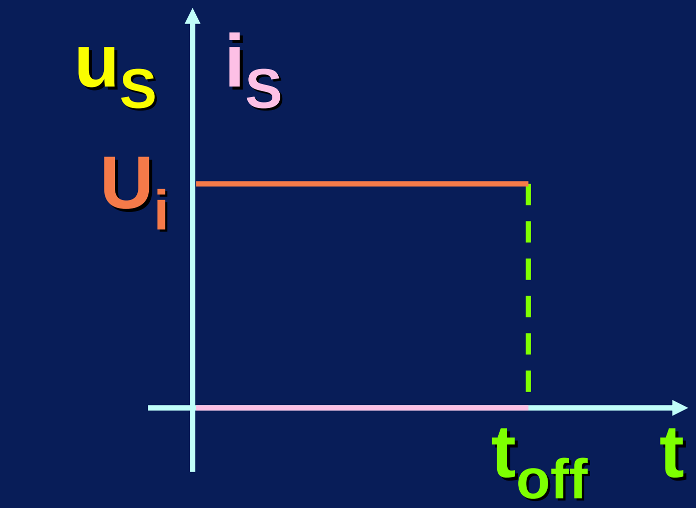


$u_S = U_i$

$i_S = 0$



Tensioni e correnti durante t_{off}



$u_S = U_i$

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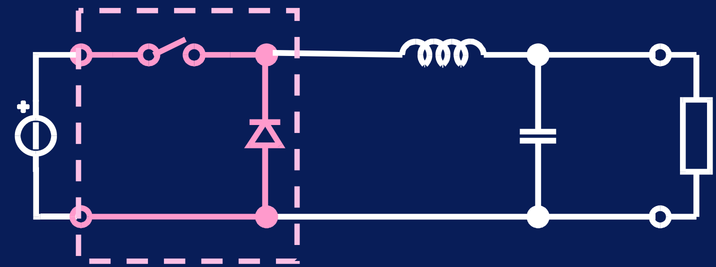
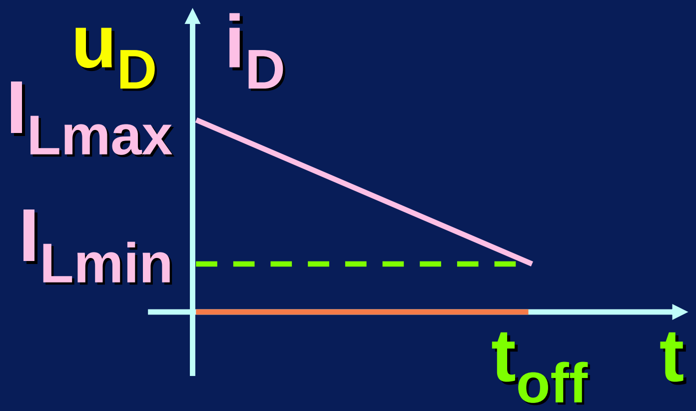
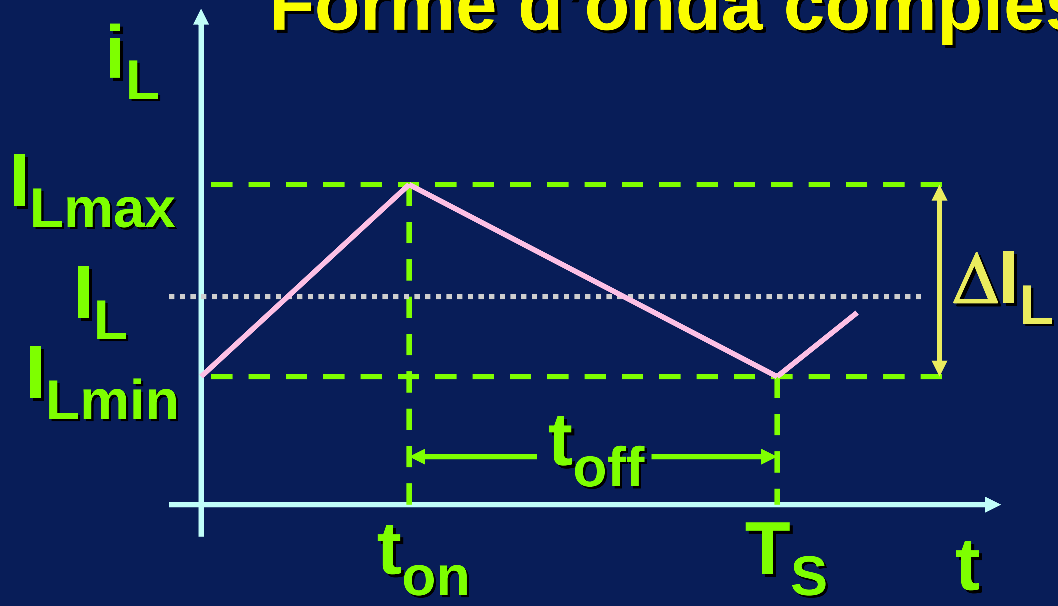


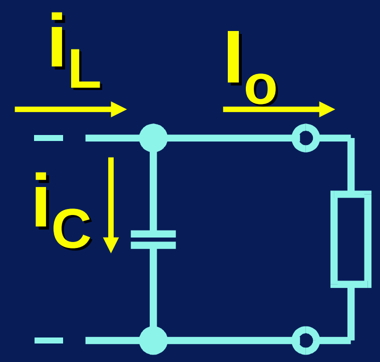


$u_D = 0$

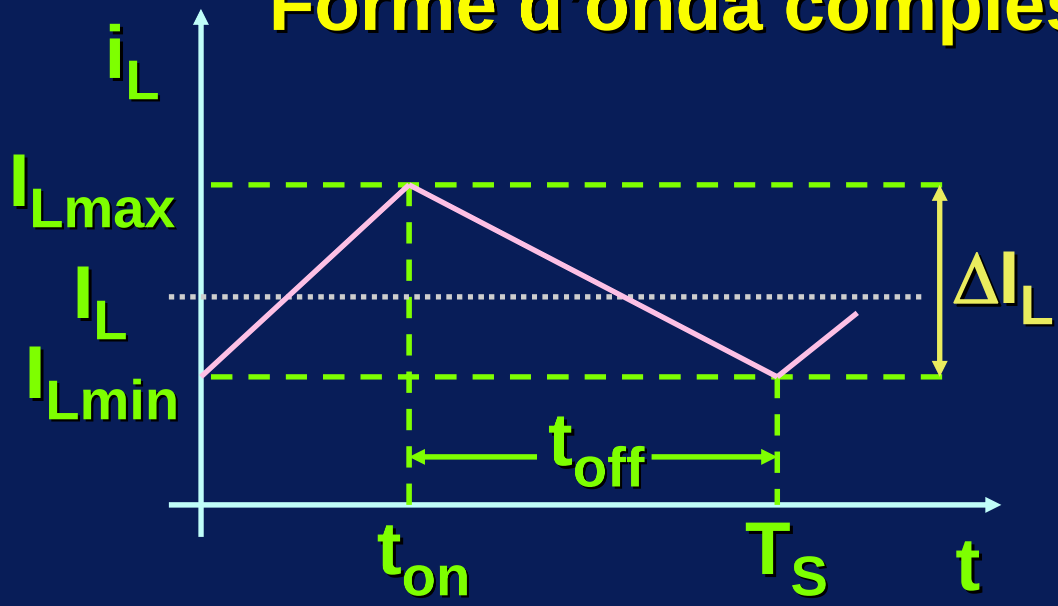
$i_D = i_L$

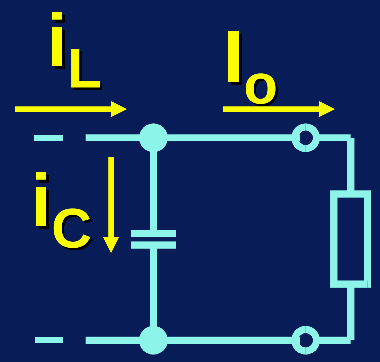
Forme d'onda complessive: i_L





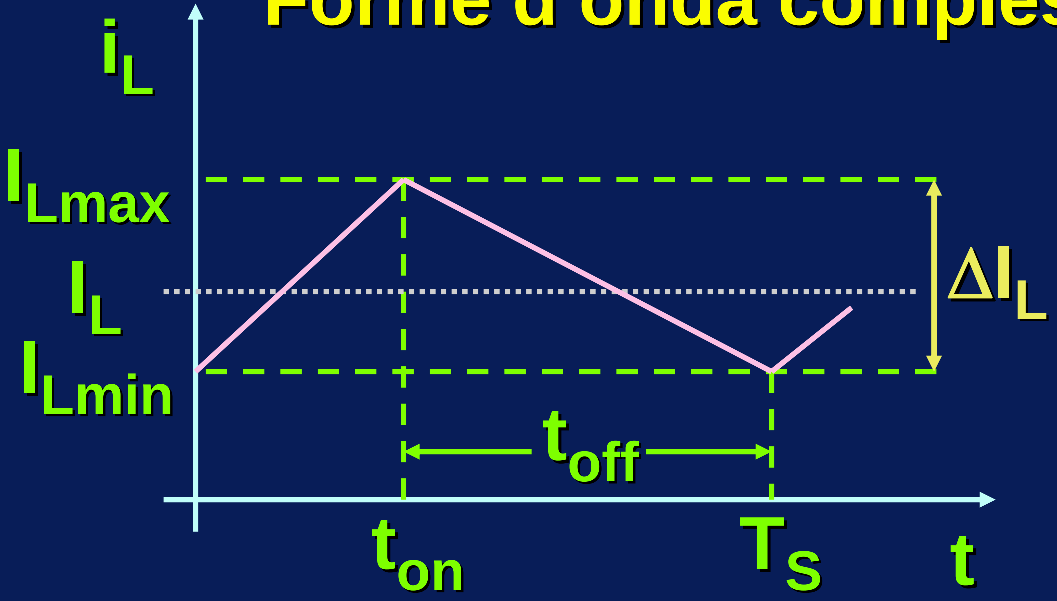
Forme d'onda complessive: i_L

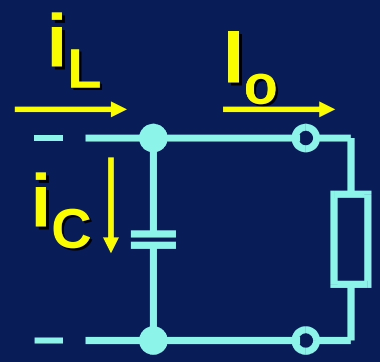




A regime: $I_C = 0 \Rightarrow I_L = I_o$

Forme d'onda complessive: i_L



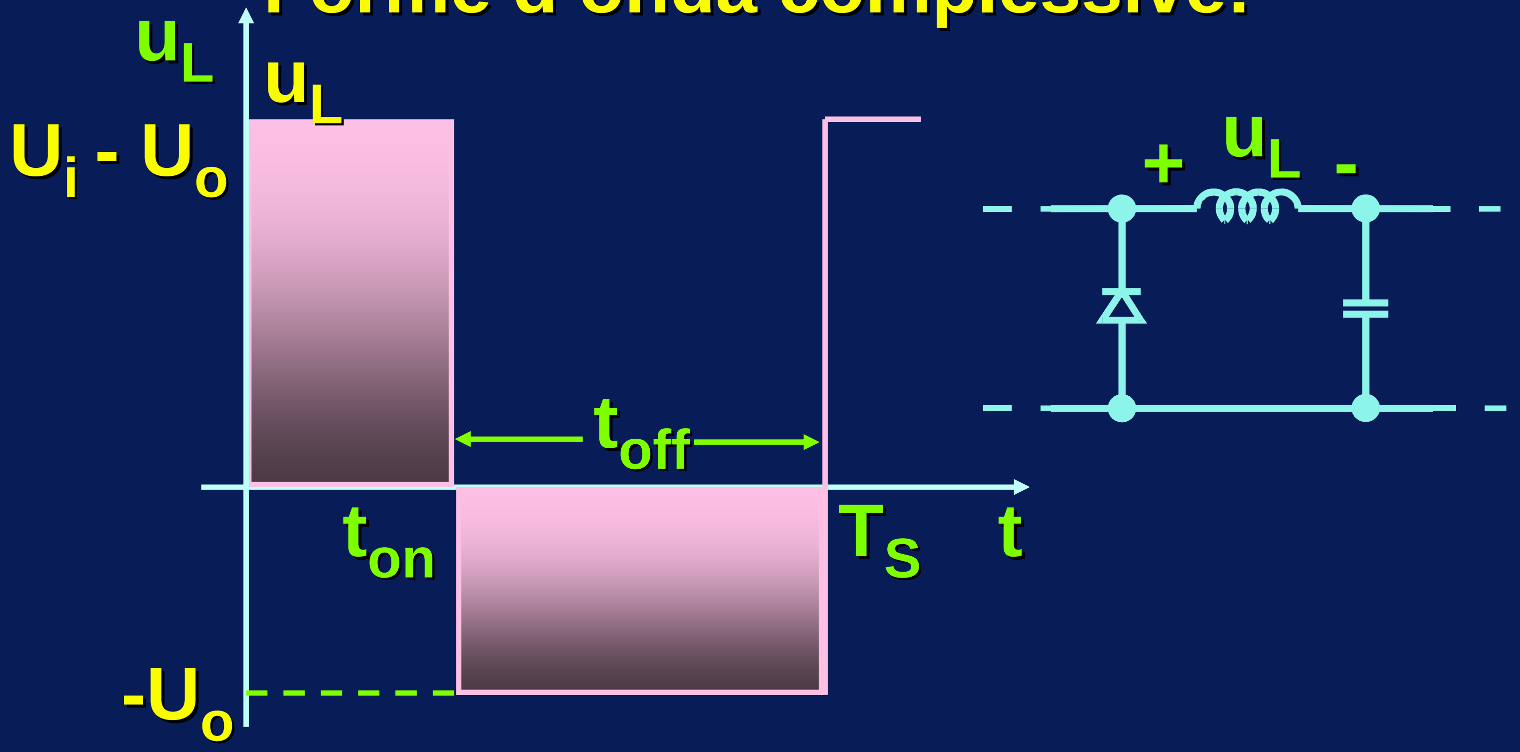


A regime: $I_C = 0 \quad \Rightarrow \quad I_L = I_o$

Ondulazione (ripple) di corrente:

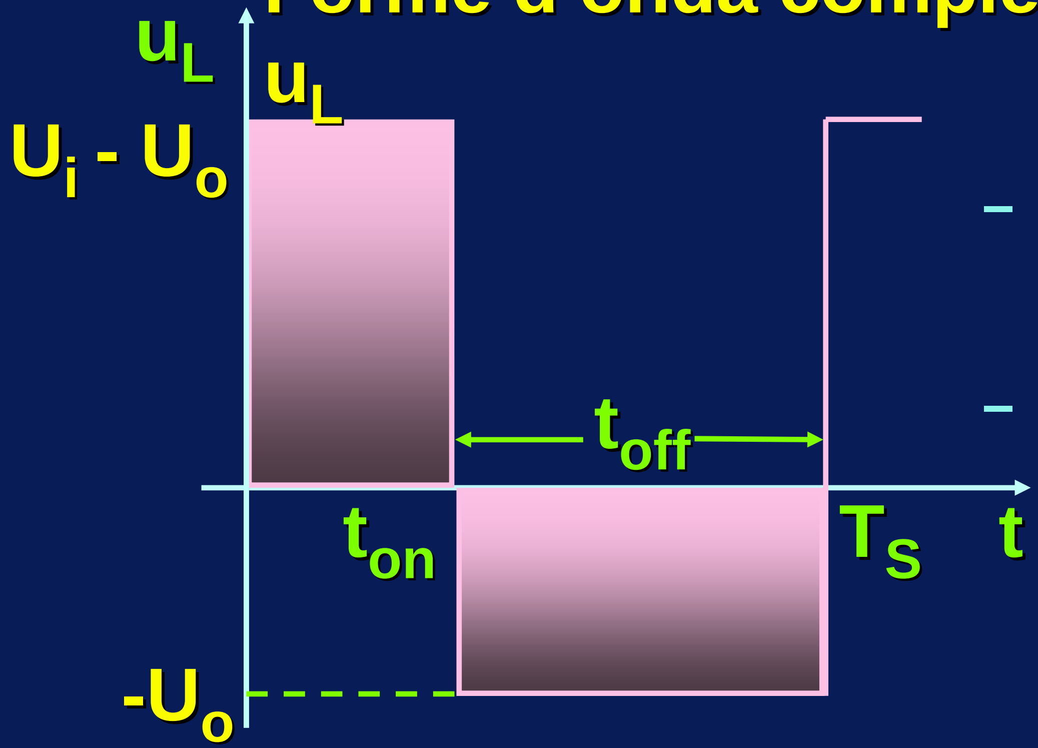
$$\Delta I_{Lon} = \Delta I_{Loff} = \Delta I_L = \frac{U_i - U_o}{L} \cdot t_{on} = \frac{U_o}{L} \cdot t_{off}$$

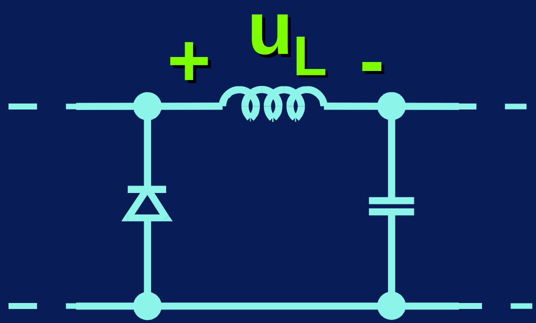
Forme d'onda complessive:



A regime: $(U_i - U_o) \cdot t_{on} = U_o \cdot t_{off}$

Forme d'onda complessive:

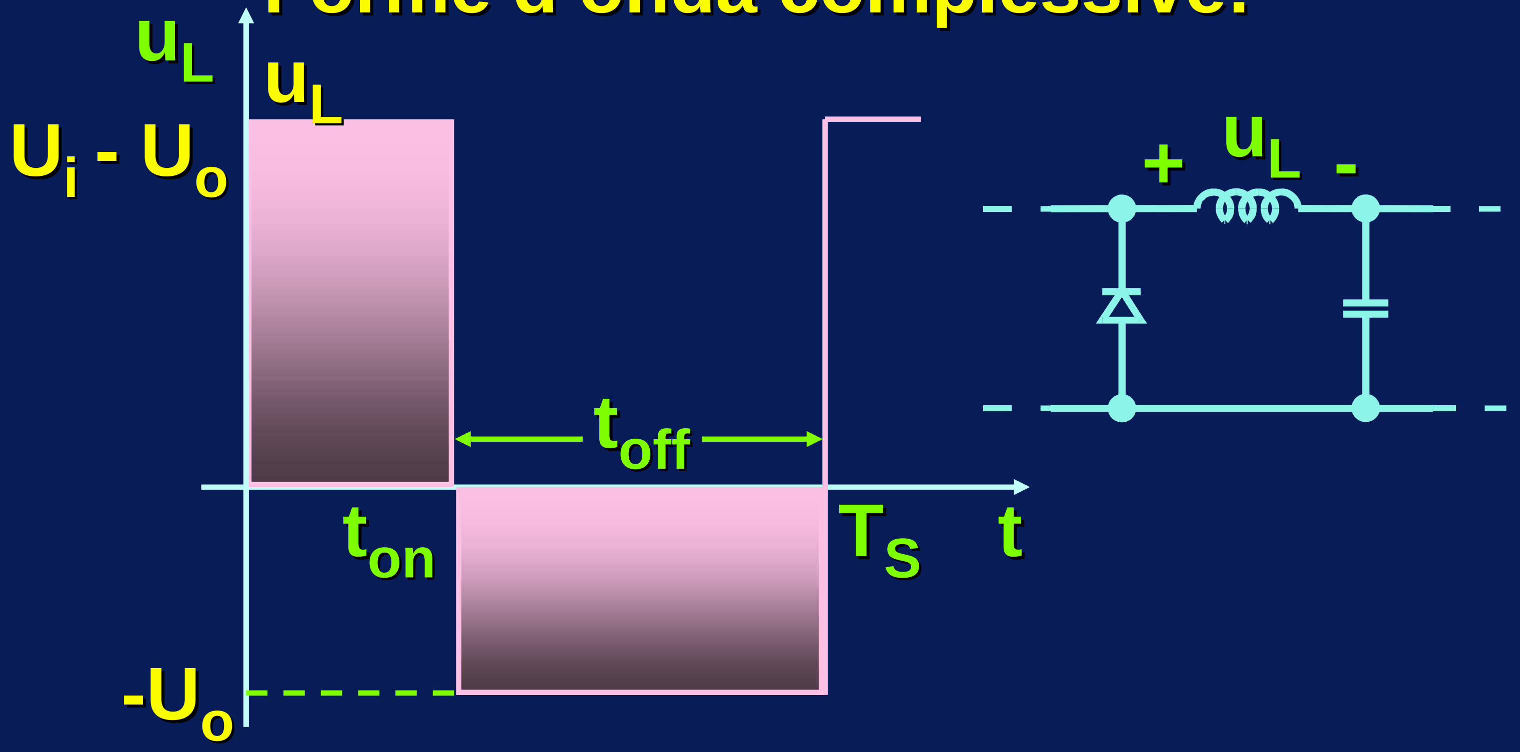




A regime: $(U_i - U_o) \cdot t_{on} = U_o \cdot t_{off}$

$$U_i \cdot t_{on} = U_o \cdot (t_{on} + t_{off})$$

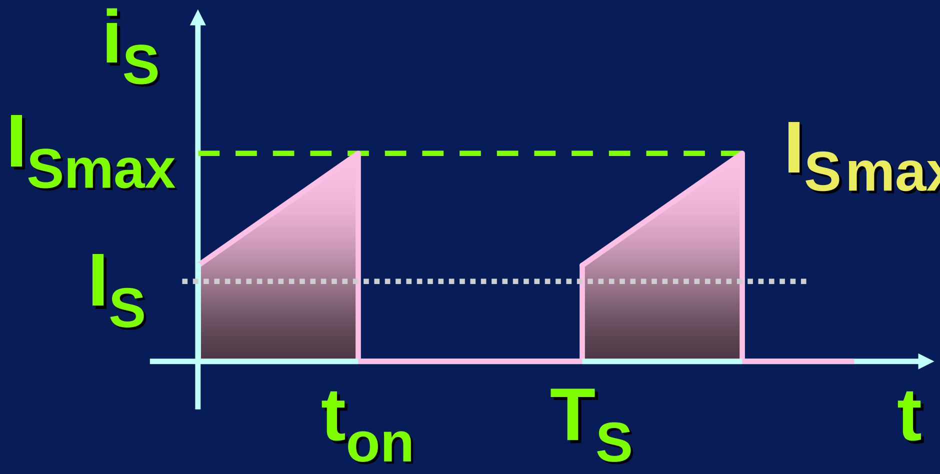
Forme d'onda complessive:



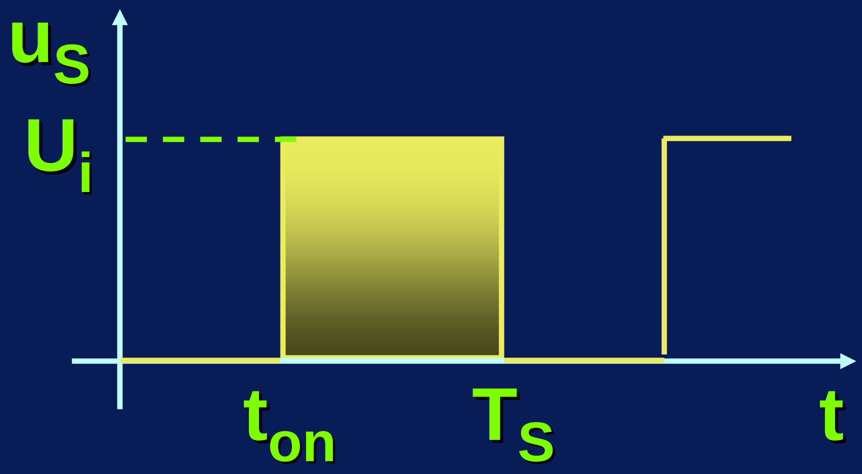
A regime: $$\left(U_i - U_o\right) \cdot t_{on} = U_o \cdot t_{off}$$

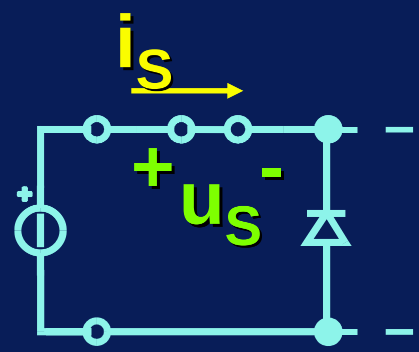
$$U_i \cdot t_{on} = U_o \cdot \left(t_{on} + t_{off}\right) \Rightarrow U_o = \frac{t_{on}}{T_S} \cdot U_i = \delta \cdot U_i$$

Forme d'onda complessive: u_S, i_S

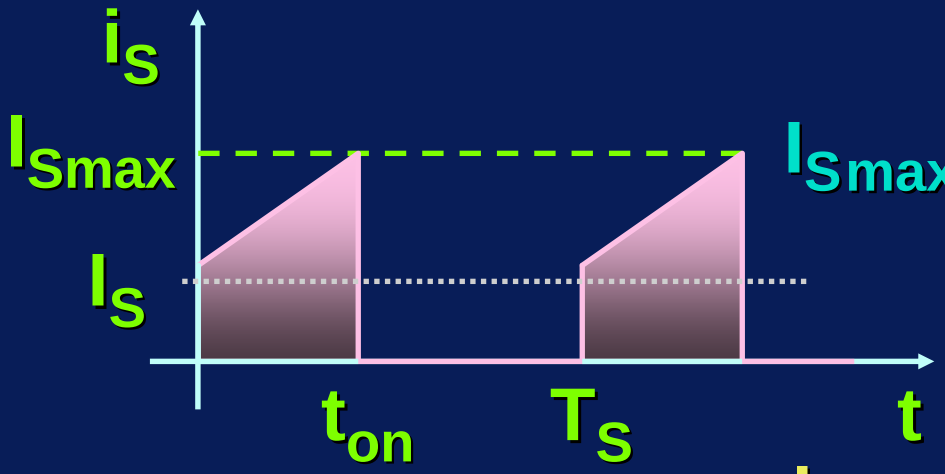


$$I_{Smax} = I_{L\,max} = I_L + \frac{\Delta I_L}{2}$$



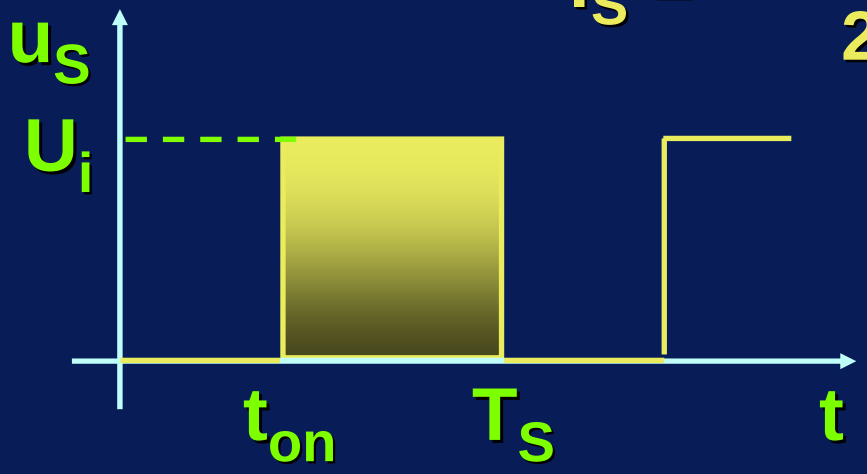


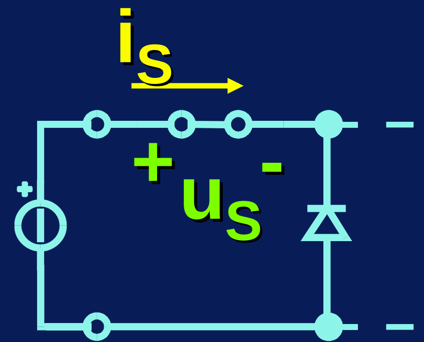
Forme d'onda complessive: u_S, i_S



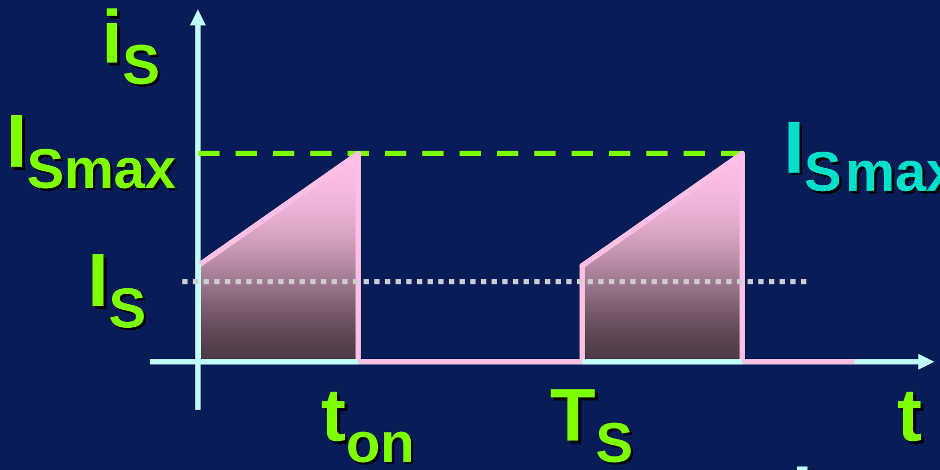
$$I_{Smax} = I_{Lmax} = I_L + \frac{\Delta I_L}{2}$$

$$I_S = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{on} = I_L \cdot \delta$$



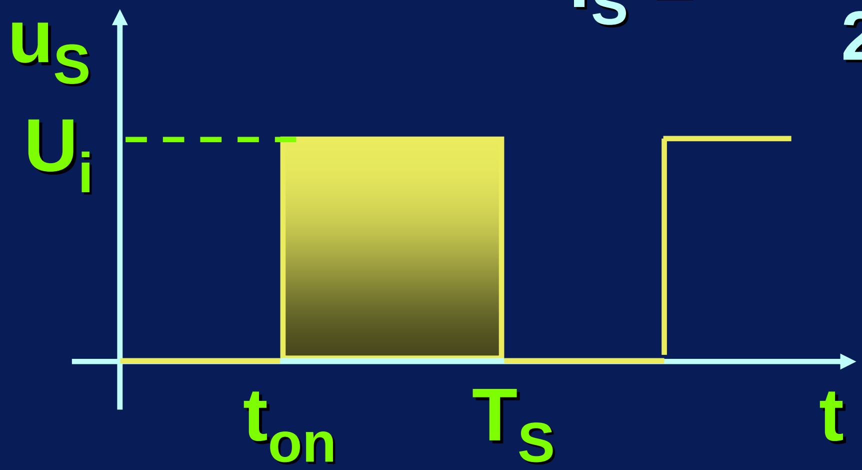


Forme d'onda complessive: u_S, i_S



$$I_{Smax} = I_{Lmax} = I_L + \frac{\Delta I_L}{2}$$

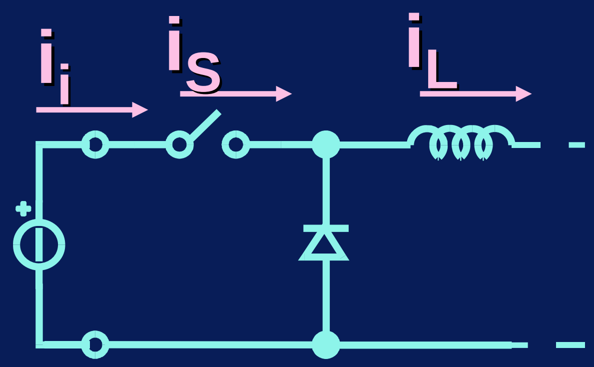
$$I_S = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{on} = I_L \cdot \delta$$



$$U_{Smax} = U_i$$

Nota:

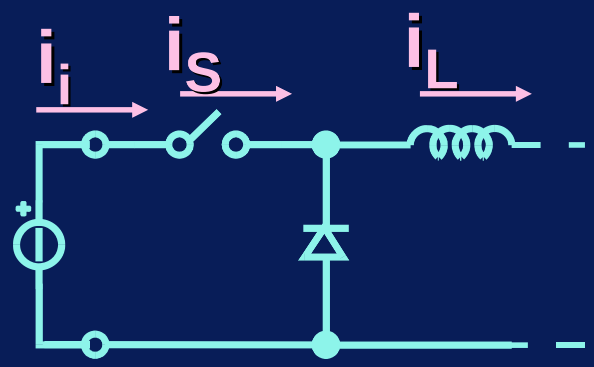
$$I_i = I_S = I_L \cdot \delta = I_o \cdot \delta$$



Nota:

$$I_i = I_S = I_L \cdot \delta = I_o \cdot \delta$$

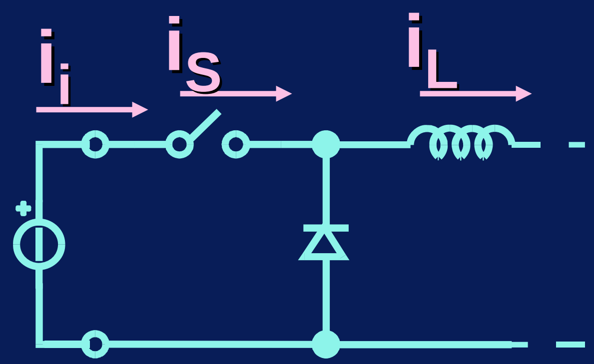
$$P_i = U_i \cdot I_i = U_i \cdot I_o \cdot \delta$$



Nota:

$$I_i = I_S = I_L \cdot \delta = I_o \cdot \delta$$

$$P_i = U_i \cdot I_i = U_i \cdot I_o \cdot \delta$$



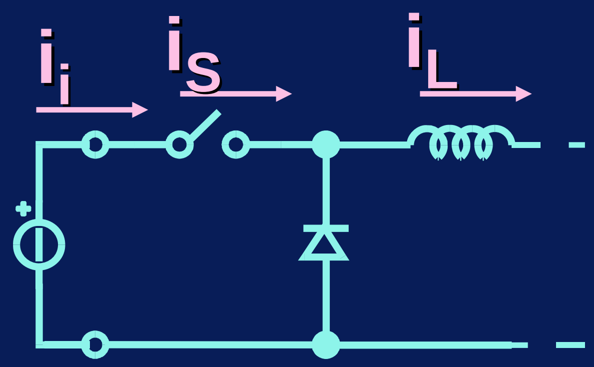
Ciò è coerente con la conservazione della potenza:

$$P_i = P_o \quad \Rightarrow \quad U_i \cdot I_i = U_o \cdot I_o$$

Nota:

$$I_i = I_S = I_L \cdot \delta = I_o \cdot \delta$$

$$P_i = U_i \cdot I_i = U_i \cdot I_o \cdot \delta$$

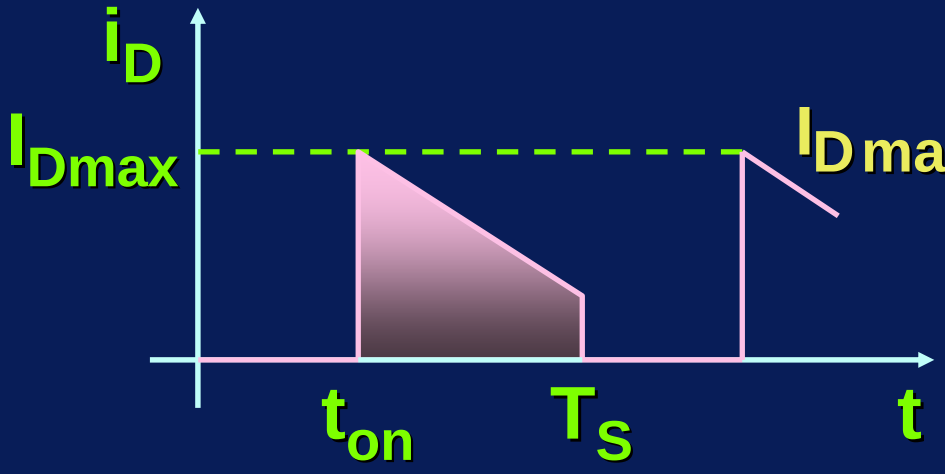


Ciò è coerente con la conservazione della potenza:

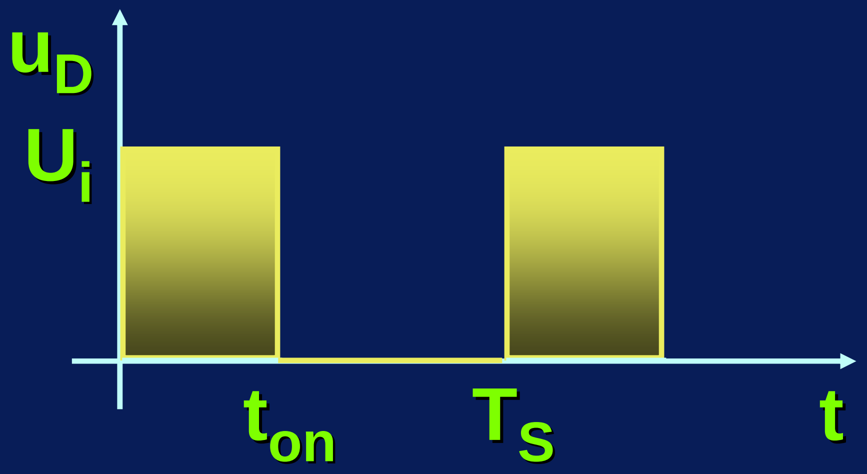
$$P_i = P_o \qquad \Rightarrow \qquad U_i \cdot I_i = U_o \cdot I_o$$

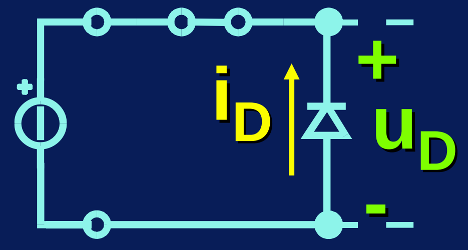
da cui: $$\frac{I_i}{I_o} = \frac{U_o}{U_i} = \delta$$

Forme d'onda complessive: u_D, i_D

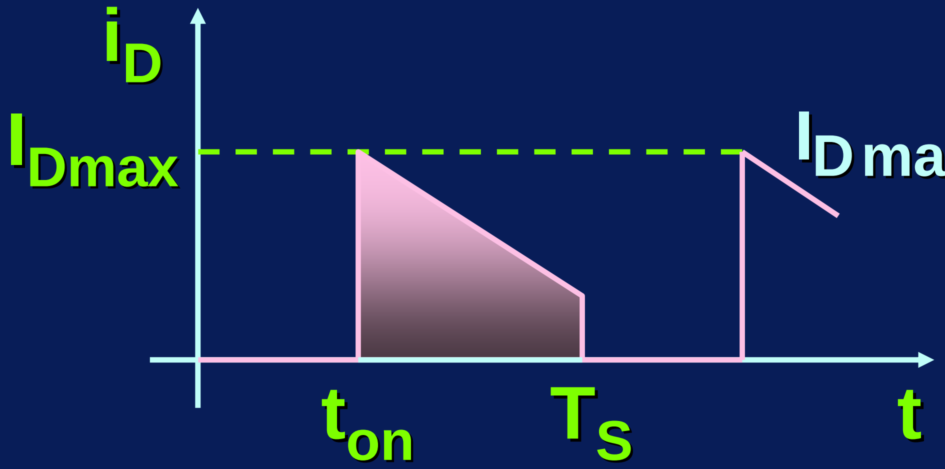


$$I_{D\,max} = I_{L\,max} = I_L + \frac{\Delta I_L}{2}$$



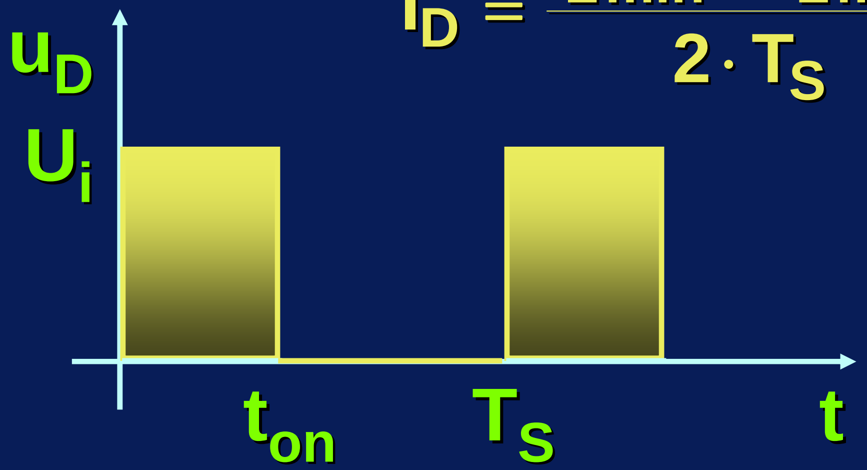


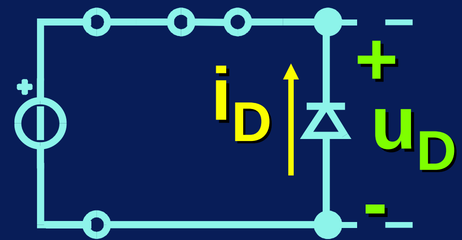
Forme d’onda complessive: u_D, i_D



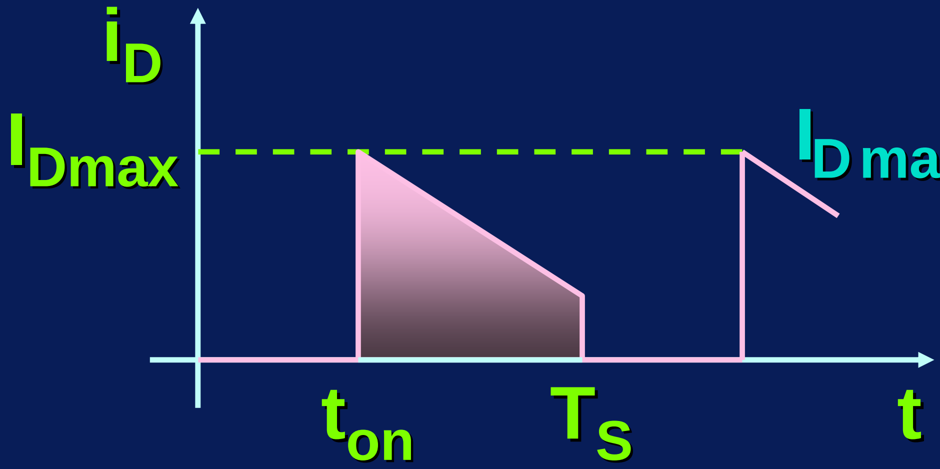
$$I_{D\,max} = I_{L\,max} = I_L + \frac{\Delta I_L}{2}$$

$$I_D = \frac{I_{L\,min} + I_{L\,max}}{2 \cdot T_S} \cdot t_{off} = I_L \cdot (1 - \delta)$$



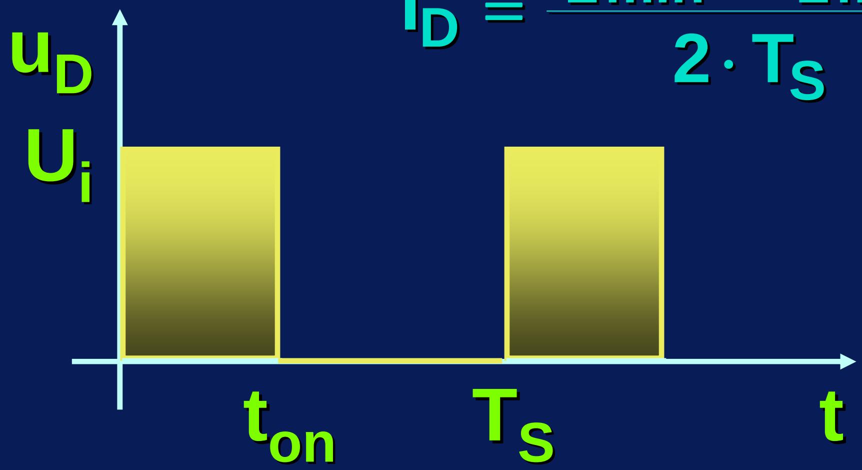


Forme d'onda complessive: u_D, i_D



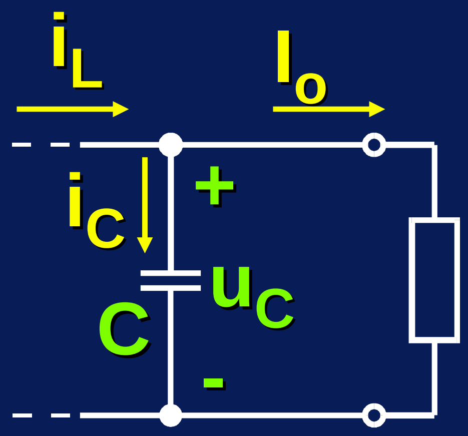
$$I_{D\,max} = I_{L\,max} = I_L + \frac{\Delta I_L}{2}$$

$$I_D = \frac{I_{L\,min} + I_{L\,max}}{2 \cdot T_S} \cdot t_{off} = I_L \cdot (1 - \delta)$$

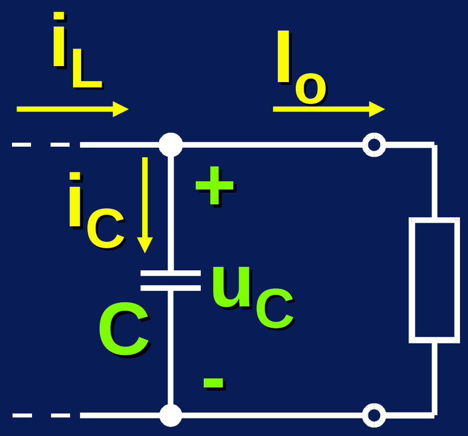


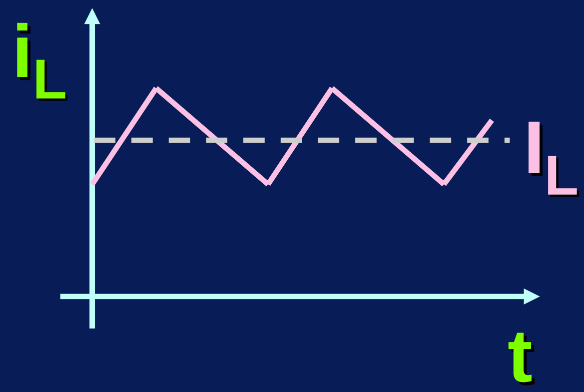
$$U_{Dmax} = U_i$$

Forme d'onda complessive: i_C

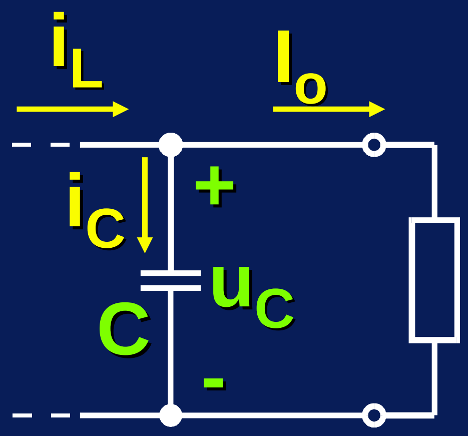


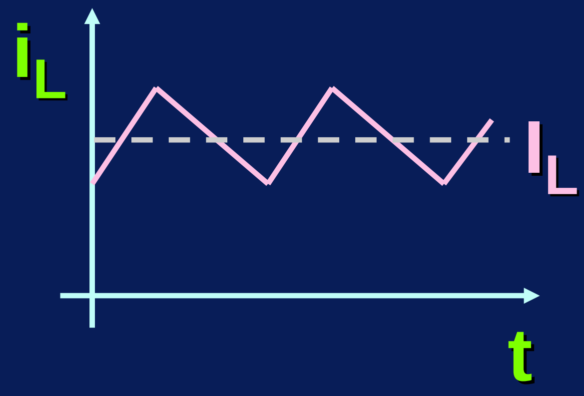
Forme d'onda complessive: i_C





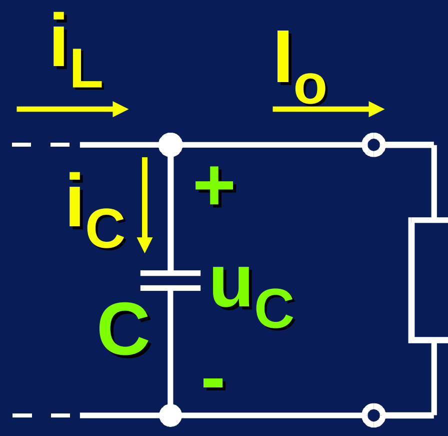
Forme d'onda complessive: i_C

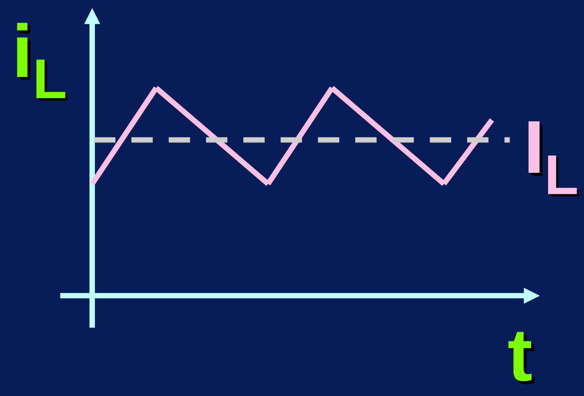




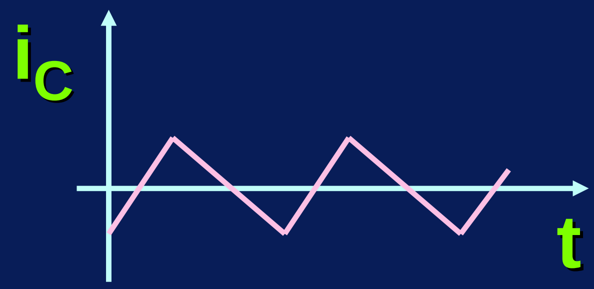
A regime: $I_L = I_o \quad \Rightarrow \quad i_C = i_L - I_o$

Forme d'onda complessive: i_C

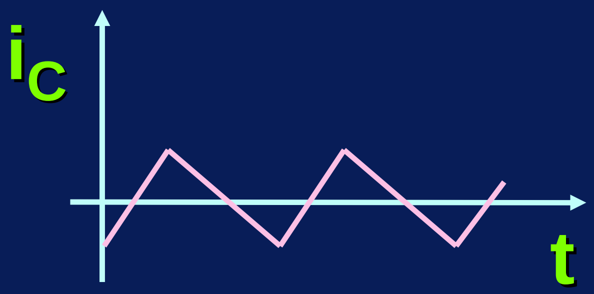


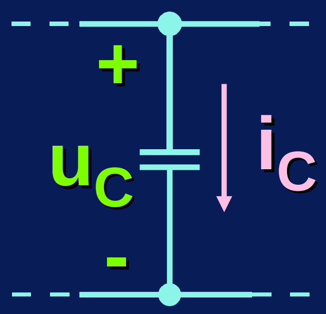


A regime: $I_L = I_o$ $\Rightarrow$ $i_C = i_L - I_o$

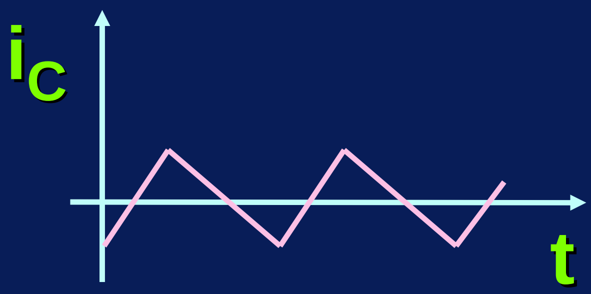


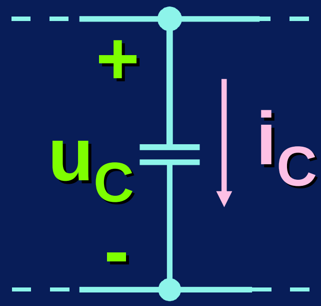
Forme d'onda complessive: u_C





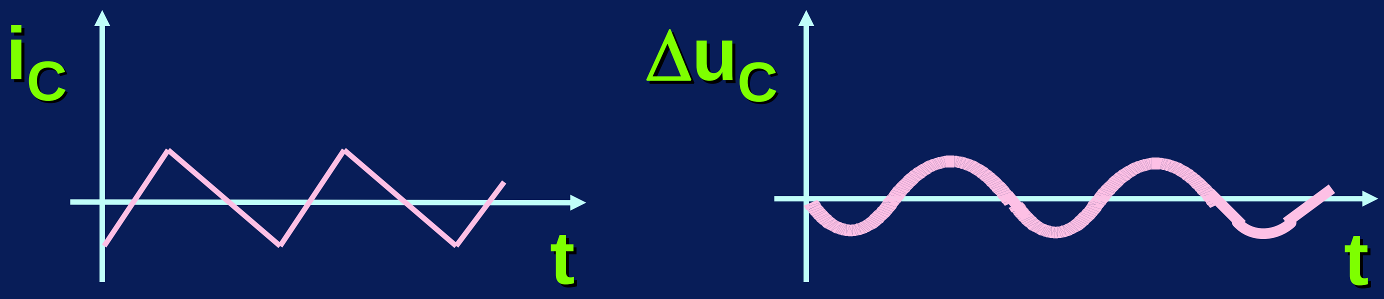
Forme d'onda complessive: u_C





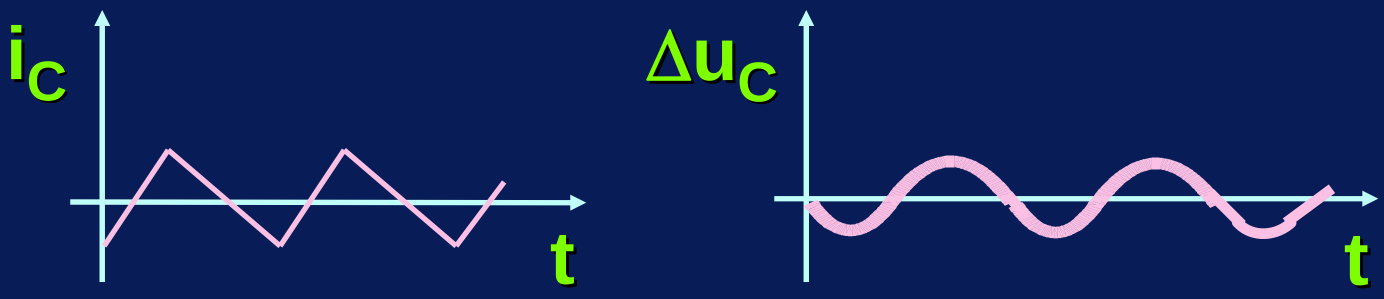
$$\Delta u_C = u_C - U_o = \frac{1}{C} \cdot \int i_C dt$$

Forme d'onda complessive: u_C



$$\Delta u_C = u_C - U_o = \frac{1}{C} \cdot \int i_C dt$$

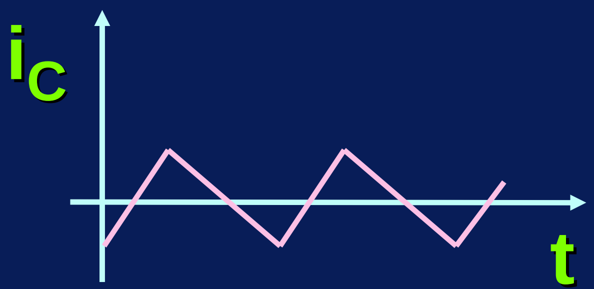
Forme d'onda complessive: u_C

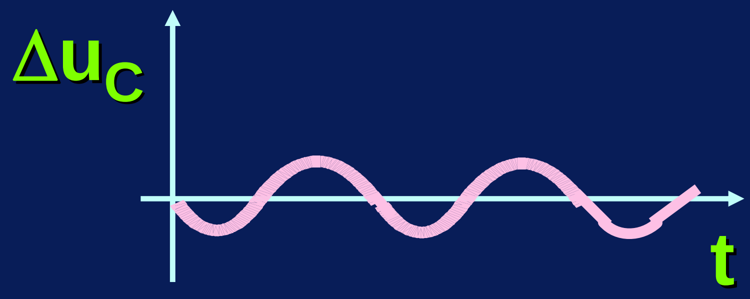


$$\Delta u_C = u_C - U_o = \frac{1}{C} \cdot \int i_C dt$$

$$\Delta u_C = \frac{1}{2 \cdot C} \cdot \left(I_{C max} \cdot \frac{t_{on} + t_{off}}{2} \right)$$

Forme d'onda complessive: u_C





$$\Delta u_C = u_C - U_o = \frac{1}{C} \cdot \int i_C dt$$

$$\Delta u_C = \frac{1}{2 \cdot C} \cdot \left(I_{C\,max} \cdot \frac{t_{on} + t_{off}}{2} \right)$$

$$= \frac{1}{2 \cdot C} \cdot \frac{\Delta I_L}{2} \cdot \frac{T_S}{2} = \frac{\Delta I_L}{8 \cdot f_S \cdot C}$$

Esempio di dimensionamento

$U_i = 24V \pm 20\%$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 1\% U_o$

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

U_o= 12V

I_o=0 ÷ 2A

$\Delta U_o \leq$ 120mV

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

U_o= 12V

I_o=0 ÷ 2A

$\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i}$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $U_o = 12V$

$I_o = 0 \div 2A$ $\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i} = \frac{12}{U_{i\,max}} \div \frac{12}{U_{i\,min}}$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $U_o = 12V$

$I_o = 0 \div 2A$ $\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i} = \frac{12}{U_{i\,max}} \div \frac{12}{U_{i\,min}} = 0.416 \div 0.625$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i} = \frac{12}{U_{i\,max}} \div \frac{12}{U_{i\,min}} = 0.416 \div 0.625$$

$$\Delta I_L = \frac{U_i - U_o}{L} \cdot t_{on} = \frac{U_o}{L} \cdot t_{off}$$

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V U_o= 12V

I_o=0 ÷ 2A $\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i} = \frac{12}{U_{i\,max}} \div \frac{12}{U_{i\,min}} = 0.416 \div 0.625$$

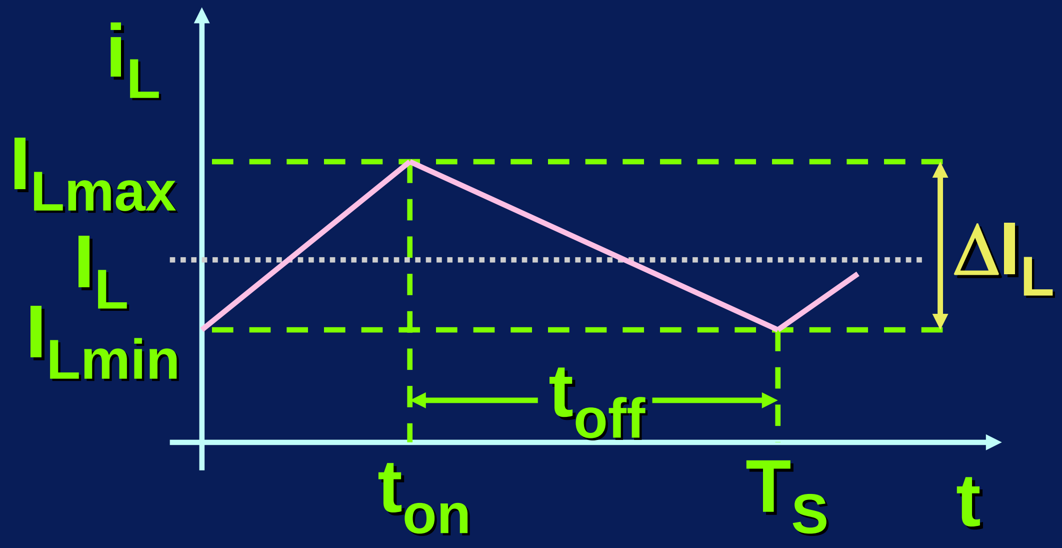
$$\Delta I_L = \frac{U_i - U_o}{L} \cdot t_{on} = \frac{U_o}{L} \cdot t_{off} = \frac{U_o}{f_s L} \cdot (1 - \delta)$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $\quad$ $U_o = 12V$

$I_o = 0 \div 2A$ $\quad$ $\Delta U_o \leq 120mV$

$$\delta = \frac{U_o}{U_i} = \frac{12}{U_{i\,max}} \div \frac{12}{U_{i\,min}} = 0.416 \div 0.625$$



Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

U_o= 12V

I_o=0 ÷ 2A

$\Delta U_o \leq$ 120mV

ΔI_L è massimo quando δ è minimo (se U_o è costante)

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $U_o = 12V$

$I_o = 0 \div 2A$ $\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}} \right)$$

Posto: $\Delta I_{Lmax} = 0.2\, I_{on}$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $U_o = 12V$

$I_o = 0 \div 2A$ $\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Posto: $\Delta I_{Lmax} = 0.2\, I_{On}$ (CCM per $I_O > 0.1 I_{On}$)

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $\quad$ $U_o = 12V$

$I_o = 0 \div 2A$ $\quad$ $\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Posto: $\Delta I_{Lmax} = 0.2\, I_O$ e $f_s = 100kHz$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$ $U_o = 12V$

$I_o = 0 \div 2A$ $\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Posto: $\Delta I_{Lmax} = 0.2\, I_O$ e $f_s = 100kHz$

$$L = \frac{U_o}{f_s \Delta I_{Lmax}} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$$\Delta I_L = \frac{U_o}{f_s L} \cdot \left(1 - \frac{U_o}{U_{imax}}\right)$$

Posto: $\Delta I_{Lmax} = 0.2\, I_O$ e $f_s = 100kHz$

$$L = \frac{U_o}{f_s \Delta I_{Lmax}} \cdot \left(1 - \frac{U_o}{U_{imax}}\right) = 175\mu H$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$$\Delta U_{C\,max} = \frac{\Delta I_{L\,max}}{8 f_s C}$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$$\Delta U_{Cmax} = \frac{\Delta I_{Lmax}}{8 f_s C} \Rightarrow C = \frac{\Delta I_{Lmax}}{8 f_s \Delta U_{Cmax}}$$

Esempio di dimensionamento

$U_i = 19.6V \div 28.8V$

$U_o = 12V$

$I_o = 0 \div 2A$

$\Delta U_o \leq 120mV$

$C = 4.16\ \mu F$

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

I_o=0 ÷ 2A

U_o= 12V

$\Delta U_o \leq$ 120mV

C = 4.16 μF ⇨ C = 4.7 μF

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

U_o= 12V

I_o=0 ÷ 2A

$\Delta U_o \leq$ 120mV

C = 4.16 μF → C = 4.7 μF

Pulsazione di risonanza:

Esempio di dimensionamento

U_i = 19.6V ÷ 28.8V

U_o = 12V

I_o=0 ÷ 2A

$\Delta U_o \leq 120mV$

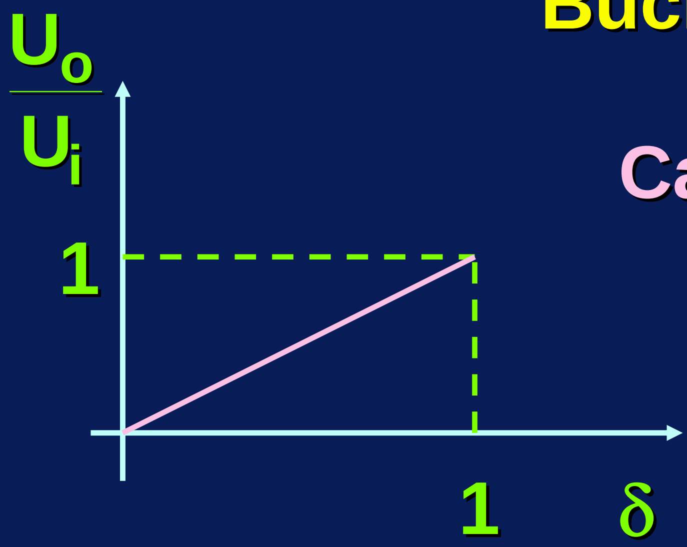
C = 4.16 μF ⇒ C = 4.7 μF

Pulsazione di risonanza:

$$\omega_r = \frac{1}{\sqrt{LC}} \cong 35\,krad/s$$

Caratteristiche statiche del convertitore Buck in CCM

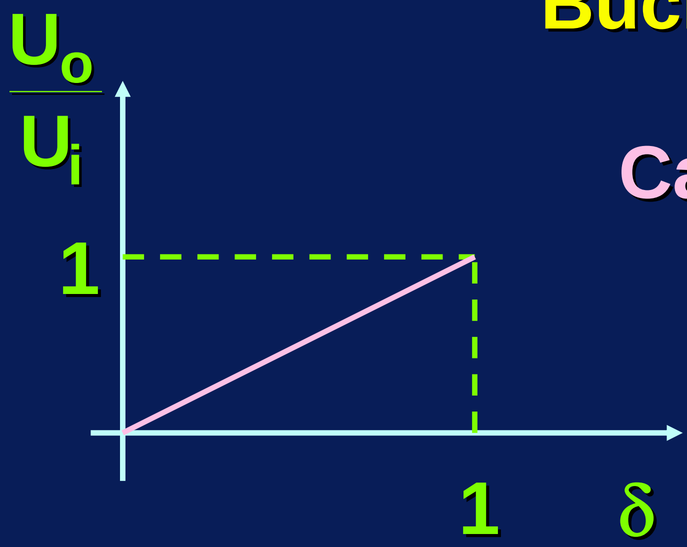
Caratteristiche statiche del convertitore Buck in CCM



Caratteristica di controllo

$$U_o = \delta U_i$$

Caratteristiche statiche del convertitore Buck in CCM



Caratteristica di controllo

$$U_o = \delta U_i$$

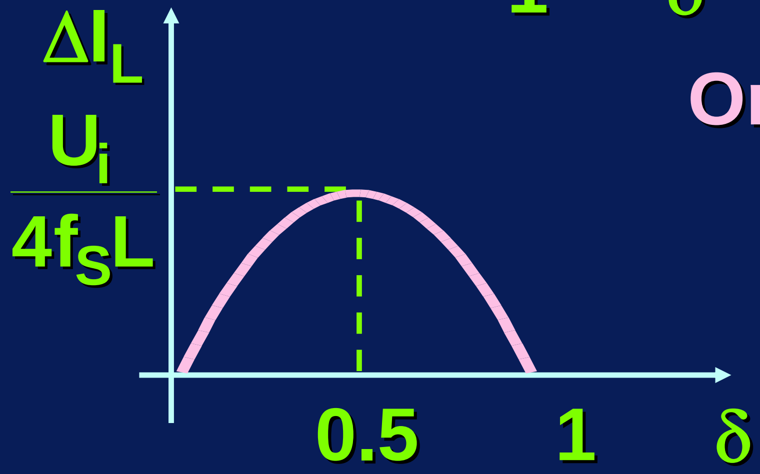
Controllo lineare

Caratteristiche statiche del convertitore Buck in CCM

Caratteristica di controllo

$$U_o = \delta U_i$$

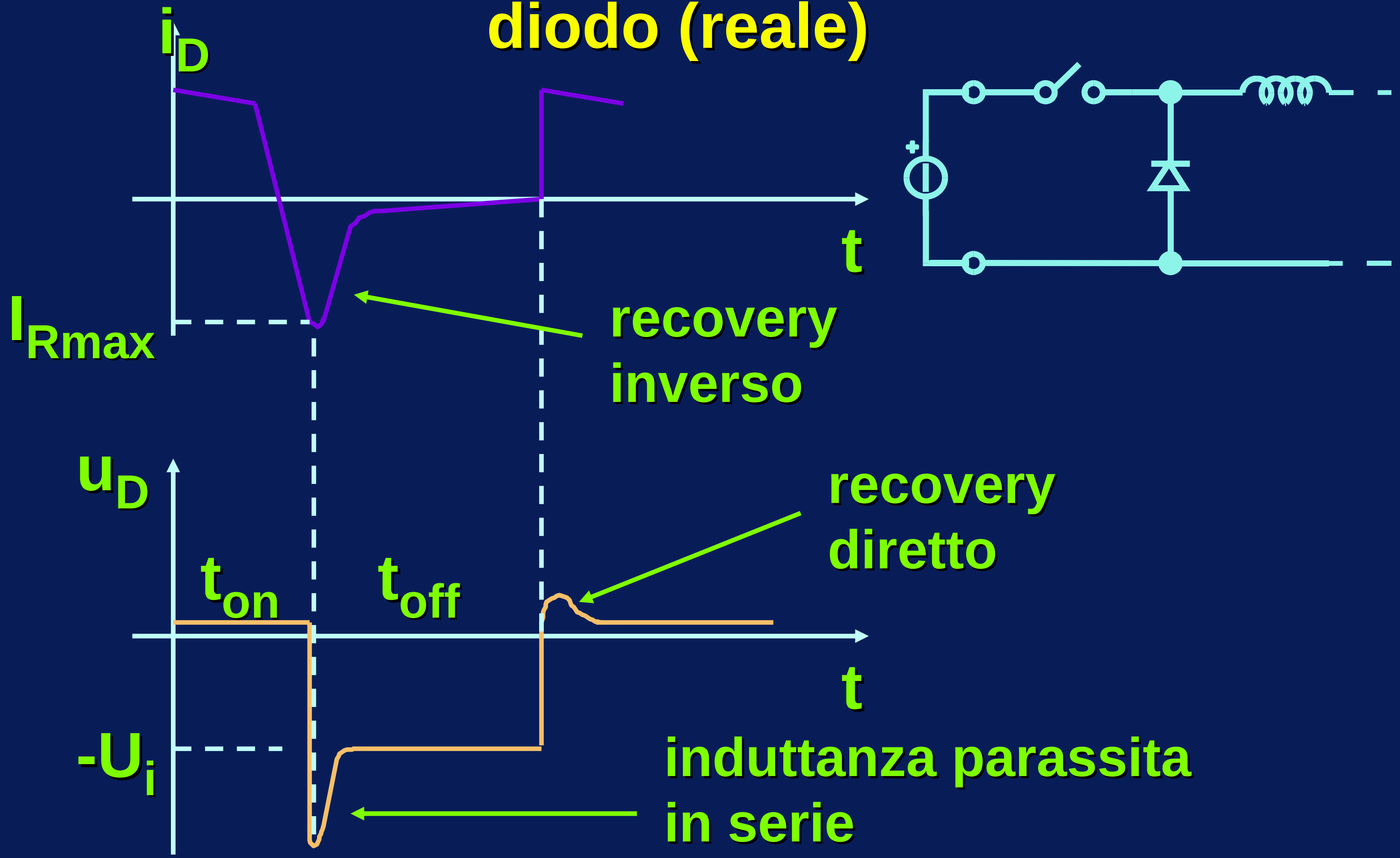
Controllo lineare



Ondulazione di corrente

$$\Delta I_L = \frac{U_i \cdot \delta \cdot (1-\delta)}{f_S \cdot L}$$

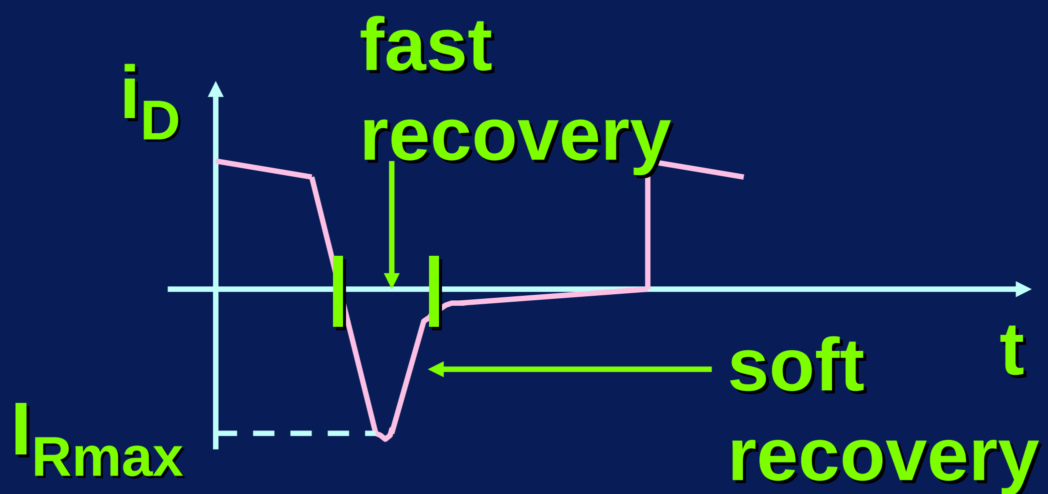
Andamenti di corrente e tensione del diodo (reale)



Osservazioni

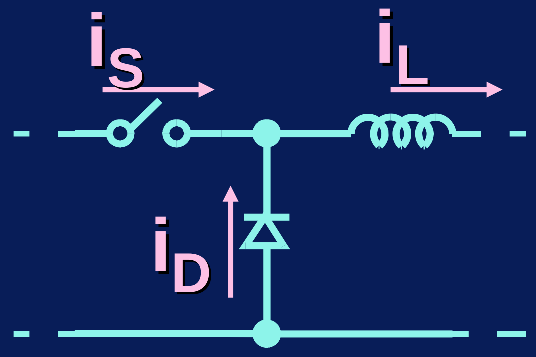
- **La corrente di recovery inverso puó avere lo stesso ordine di grandezza della corrente diretta**
- **Al recovery inverso sono associate perdite**
- **Il recovery diretto é normalmente ininfluente**
- **I diodi vanno scelti soft-recovery (per ridurre la sovratensione) e fast-recovery (per ridurre I_{Rmax} e le perdite)**

Osservazioni



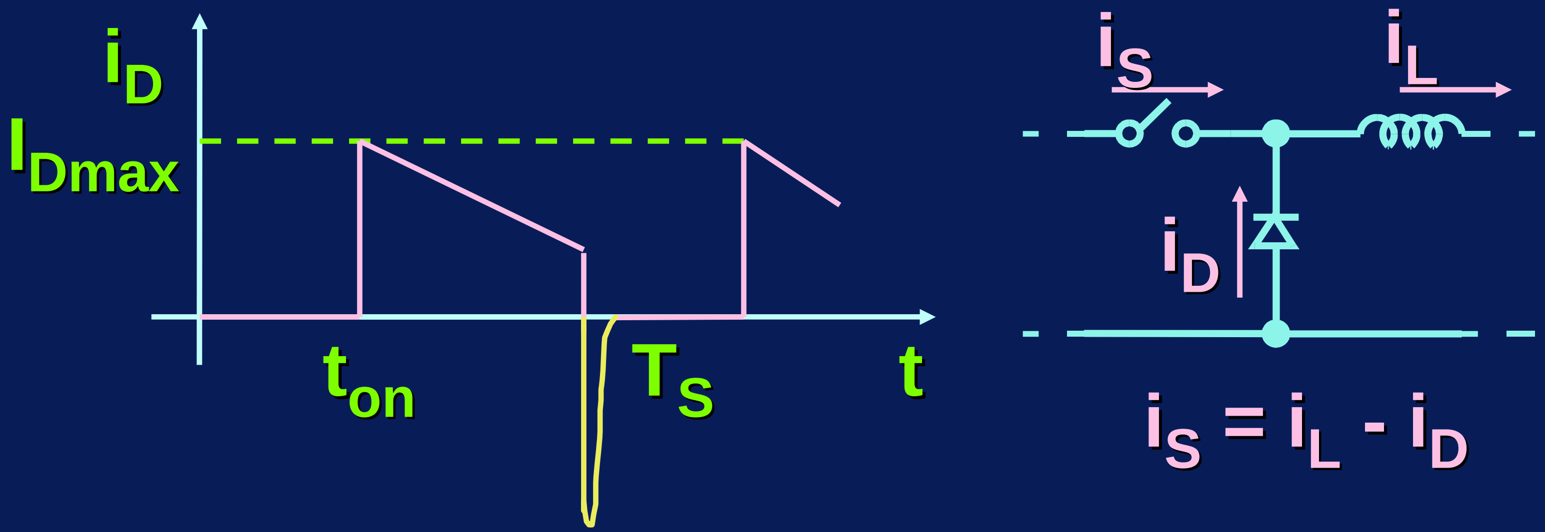
- I diodi vanno scelti soft-recovery (per ridurre la sovratensione) e fast-recovery (per ridurre I_{Rmax} e le perdite)

Andamenti reali della corrente in S e D



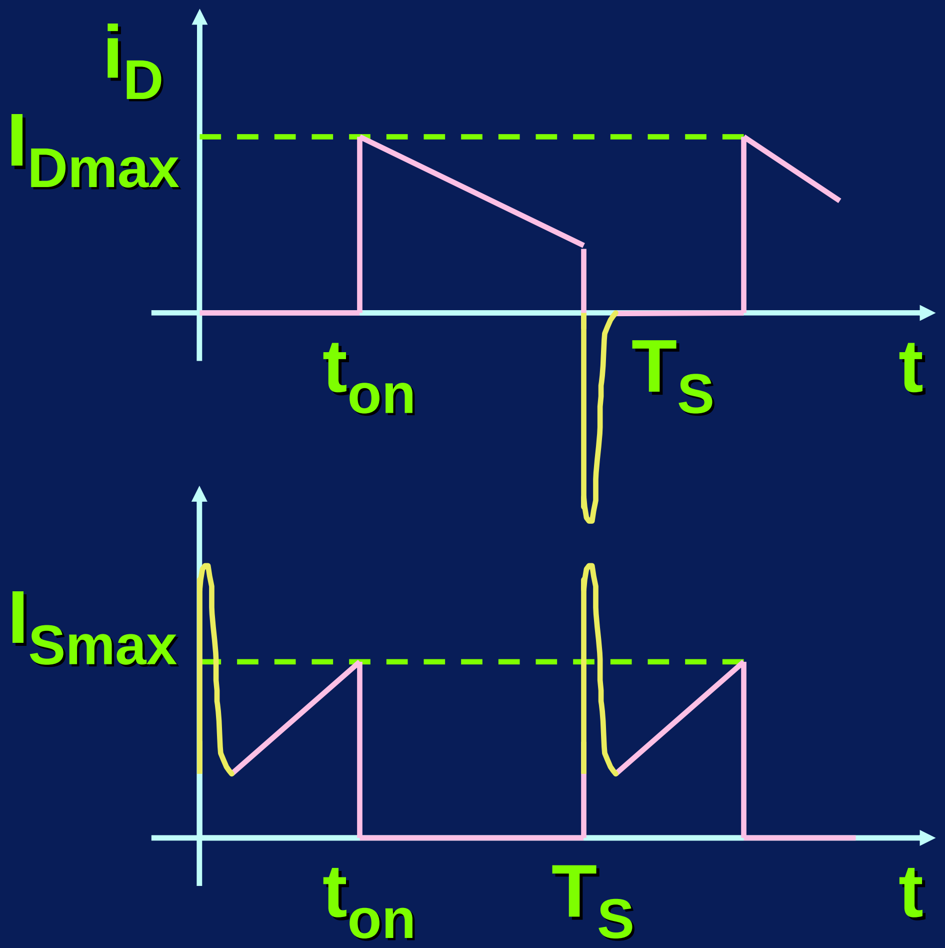
$$i_S = i_L - i_D$$

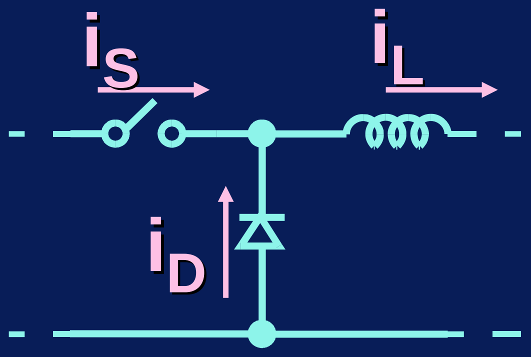
Andamenti reali della corrente in S e D



Il recovery inverso del diodo causa sovracorrenti nell'interruttore

Andamenti reali della corrente in S e D





$$i_S = i_L - i_D$$

Conclusioni

- Si è analizzato il funzionamento continuo (CCM) del convertitore abbassatore di tensione (buck)
- Il convertitore ha una caratteristica di controllo lineare
- I parametri del filtro vengono scelti per limitare l'ondulazione della tensione d'uscita e della corrente nell'induttanza
- Il filtro risulta tanto più piccolo quanto più elevata è la frequenza di commutazione
- Le sollecitazioni in tensione e corrente sono influenzate dal recovery inverso del diodo