Corso di
ELETTRONICA INDUSTRIALE

“Convertitore Buck-Boost”

Convertitore innalzatore/abbassatore
(Buck / Boost)

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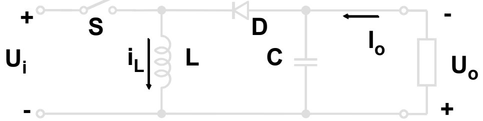
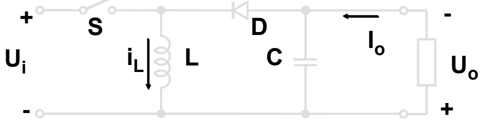
(Buck / Boost)



Convertitore innalzatore/abbassatore
(Buck / Boost)



Ipotesi per lo studio:

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

Analisi del funzionamento continuo (CCM)

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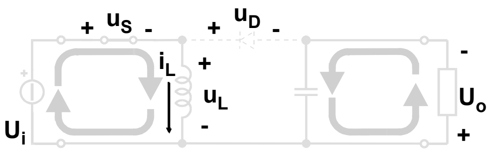
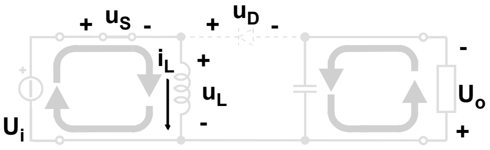
Tempo di chiusura di S (t_{on})   S on - D off



$u_L = U_i$ $\qquad$ $u_D = U_o + U_i$

Analisi del funzionamento continuo (CCM)

Tempo di chiusura di S (t_{on})   S on - D off



+ u_S -
+ u_D -
i_L
+
u_L
-
-
U_o
+
U_i

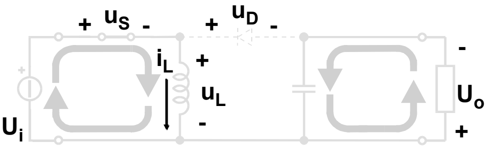
$u_L = U_i$

$u_D = U_o + U_i$

Nota:
La tensione di carico ha polarità negativa

Analisi del funzionamento continuo (CCM)

Tempo di chiusura di S (t_{on})   S on - D off



+ u_S -
+ u_D -
i_L
+
u_L
-
-
U_o
+
U_i

$u_L = U_i$

$u_D = U_o + U_i$

Durante questa fase viene trasferita energia dall'alimentazione all'induttanza

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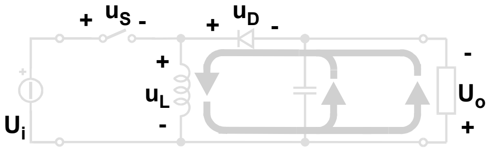
Analisi del funzionamento continuo (CCM)

Tempo di apertura di S (t_{off})   S off - D on



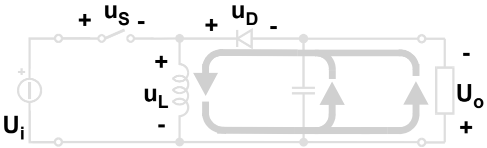
+ u_S -
+ u_D -
+
u_L
-
-
U_o
+
U_i

$u_L = - U_o$

$u_S = U_o + U_i$

Analisi del funzionamento continuo (CCM)

Tempo di apertura di S (t_{off})   S off - D on



+ u_S -
+ u_D -
+
u_L
-
-
U_o
+
U_i

$u_L = - U_o$

$u_S = U_o + U_i$

Durante questa fase la sola induttanza fornisce energia allo stadio di uscita

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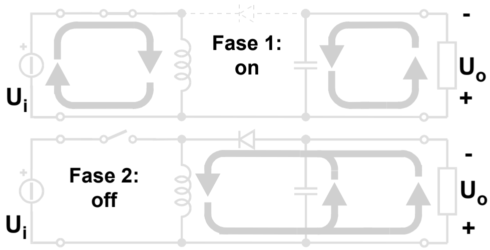
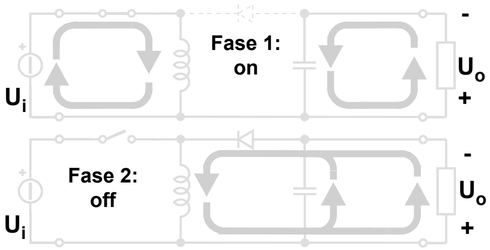
Analisi del funzionamento continuo (CCM)



Fase 1: on
-
U_o
+
U_i
Fase 2: off
-
U_o
+
U_i

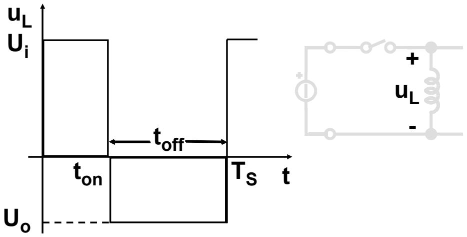
Analisi del funzionamento continuo (CCM)



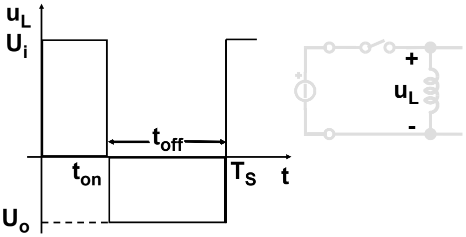
Fase 1: on
-
U_o
+
U_i
Fase 2: off
-
U_o
+
U_i

Il meccanismo di trasferimento di energia in due fasi (sorgente -> induttanza -> carico) consente di alimentare il carico a qualunque tensione

Buck/Boost - Forme d’onda in CCM: u_L

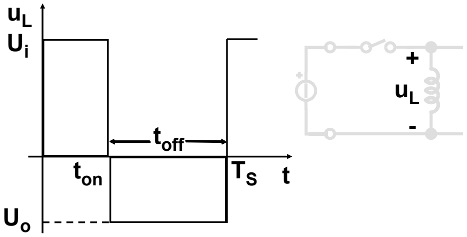

u_L
U_i
t_{off}
t_{on}
T_S
t
U_o
+
u_L
-

Buck/Boost - Forme d’onda in CCM: u_L


u_L
U_i
t_{off}
t_{on}
T_S
t
U_o
+
u_L
-

$U_i \cdot t_{on} = U_o \cdot t_{off}$

Buck/Boost - Forme d’onda in CCM: u_L

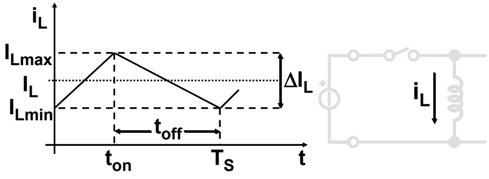

u_L
U_i
t_{off}
t_{on}
T_S
t
U_o
+
u_L
-

$U_i \cdot t_{on} = U_o \cdot t_{off}$

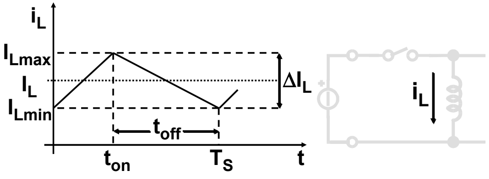
$$M = \frac{U_o}{U_i} = \frac{t_{on}}{t_{off}} = \frac{\delta}{1-\delta}$$

Buck/Boost - Forme d’onda in CCM: i_L

Buck/Boost - Forme d’onda in CCM: i_L

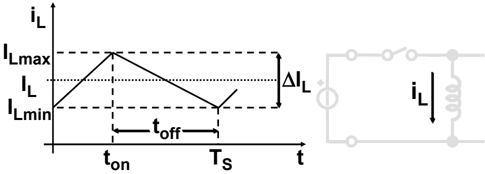

i_L
I_{Lmax}
I_L
I_{Lmin}
ΔI_L
t_{off}
t_{on}
T_S
t
i_L

Buck/Boost - Forme d’onda in CCM: i_L


i_L
I_{Lmax}
I_L
I_{Lmin}
ΔI_L
t_{off}
t_{on}
T_S
t
i_L

A regime:

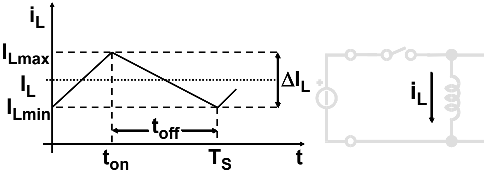
Buck/Boost - Forme d'onda in CCM: i_L


i_L
I_{Lmax}
I_L
I_{Lmin}
ΔI_L
t_{off}
t_{on}
T_S
t
i_L

A regime:

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

Buck/Boost - Forme d'onda in CCM: i_L


i_L
I_{Lmax}
I_L
I_{Lmin}
ΔI_L
t_{off}
t_{on}
T_S
t
i_L

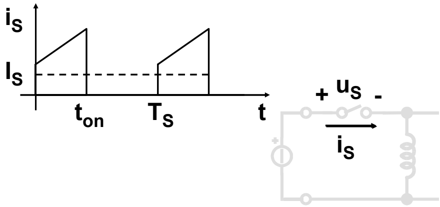
A regime:

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

$$M = \frac{U_o}{U_i} = \frac{t_{on}}{t_{off}} = \frac{\delta}{1-\delta}$$

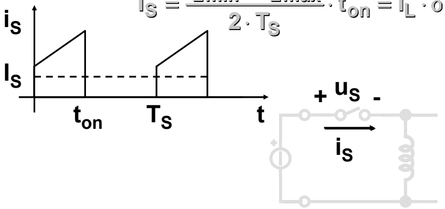
Buck/Boost - Forme d'onda in CCM: i_S,u_S

Buck/Boost - Forme d'onda in CCM: i_S,u_S


i_S
I_S
t_{on}
T_S
t
+ u_S -
i_S

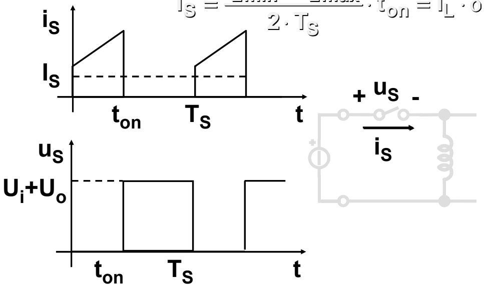
Buck/Boost - Forme d'onda in CCM: i_S,u_S

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


i_S
I_S
t_{on}
T_S
t
+ u_S -
i_S

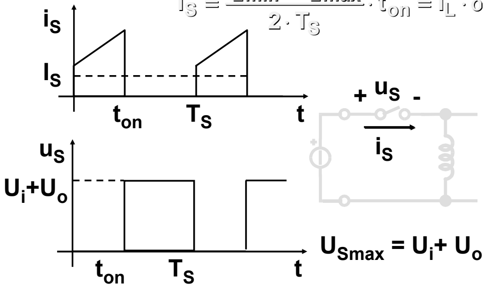
Buck/Boost - Forme d'onda in CCM: i_S,u_S

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


i_S
I_S
t_{on}
T_S
t
+ u_S -
i_S
u_S
U_i+U_o
t_{on}
T_S
t

Buck/Boost - Forme d'onda in CCM: i_S,u_S

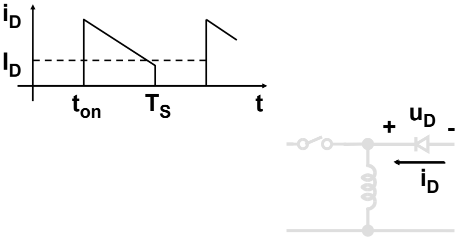
$$I_S = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{on} = I_L \cdot \delta$$


i_S
I_S
t_{on}
T_S
t
u_S
U_i+U_o
t_{on}
T_S
t
+ u_S -
i_S

U_{Smax} = U_i+ U_o

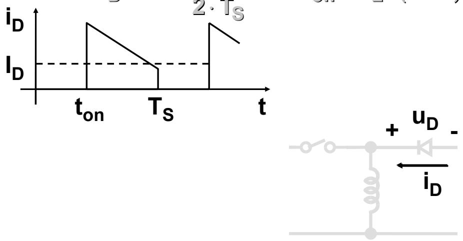
Buck/Boost - Forme d'onda in CCM: i_D,u_D

Buck/Boost - Forme d'onda in CCM: i_D,u_D


i_D
I_D
t_{on}
T_S
t
+ u_D -
i_D

Buck/Boost - Forme d'onda in CCM: i_D,u_D

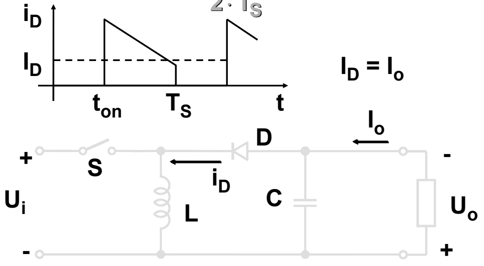
$$I_D = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{off} = I_L \cdot (1-\delta)$$


i_D
I_D
t_{on}
T_S
t
+ u_D -
i_D

Buck/Boost - Forme d'onda in CCM: i_D,u_D

$$I_D = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{off} = I_L \cdot (1-\delta)$$

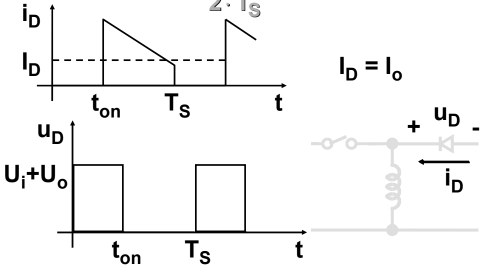
I_D = I_o


i_D
I_D
t_{on}
T_S
t
I_o
+
S
D
-
i_D
U_i
L
C
U_o
-
+

Buck/Boost - Forme d'onda in CCM: i_D,u_D

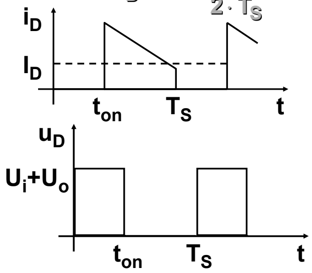
$$I_D = \frac{I_{Lmin} + I_{Lmax}}{2 \cdot T_S} \cdot t_{off} = I_L \cdot (1-\delta)$$

I_D = I_o


i_D
I_D
t_{on}
T_S
t
u_D
U_i+U_o
t_{on}
T_S
t
+ u_D -
i_D

Buck/Boost - Forme d'onda in CCM: i_D,u_D

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



I_D = I_o

U_{Dmax} = U_i+U_o

Nota

$$U_{Smax} = U_{Dmax} = U_o + U_i$$

Le maggiori capacitá di regolazione di questo convertitore si associano a maggiori sollecitazioni in tensione dei componenti

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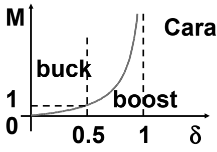
Convertitore Buck/Boost in CCM

Convertitore Buck/Boost in CCM

Caratteristica di controllo

$$M = \frac{U_o}{U_i} = \frac{\delta}{1-\delta}$$

Convertitore Buck/Boost in CCM



Caratteristica di controllo

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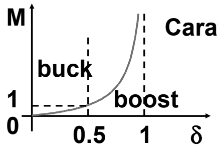
Convertitore Buck/Boost in CCM



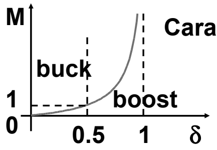
Caratteristica di controllo

$$M = \frac{U_o}{U_i} = \frac{\delta}{1-\delta}$$

Ondulazione di corrente

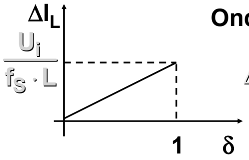
$$\Delta I_L = \frac{U_i}{L} \cdot t_{on} = \frac{U_i \cdot \delta}{f_S \cdot L}$$

Convertitore Buck/Boost in CCM



Caratteristica di controllo

$$M = \frac{U_o}{U_i} = \frac{\delta}{1-\delta}$$



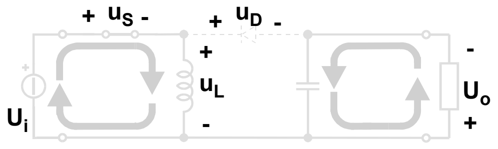
Ondulazione di corrente

$$\Delta I_L = \frac{U_i}{L} \cdot t_{on} = \frac{U_i \cdot \delta}{f_S \cdot L}$$

Analisi del funzionamento discontinuo (DCM)

Analisi del funzionamento discontinuo (DCM)

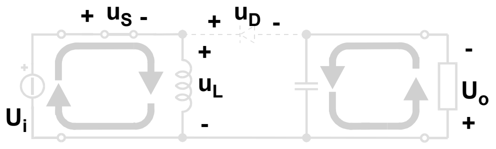
Tempo di chiusura di S (t_{on})   S on - D off



$u_L = U_i$ $u_D = U_o + U_i$

Analisi del funzionamento discontinuo (DCM)

Tempo di chiusura di S (t_{on})   S on - D off

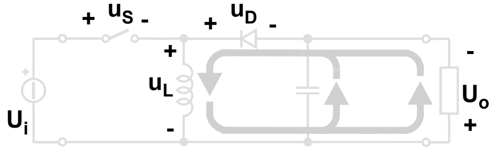


$u_L = U_i$ $u_D = U_o + U_i$

A differenza del funzionamento CCM, la corrente i_L inizia con valore nullo.

Analisi del funzionamento discontinuo (DCM)

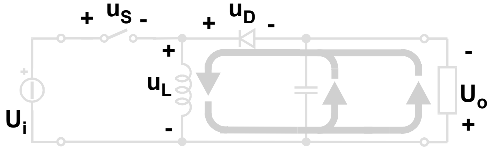
Tempo di apertura di S (t'_{off})   S off - D on



$u_L = - U_o$ $u_S = U_o + U_i$

Analisi del funzionamento discontinuo (DCM)

Tempo di apertura di S (t'_{off})   S off - D on

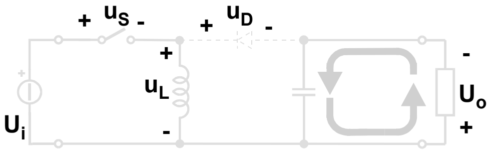


$u_L = - U_o$ $u_S = U_o + U_i$

Alla fine di questa fase la corrente dell'induttanza si annulla

Analisi del funzionamento discontinuo (DCM)

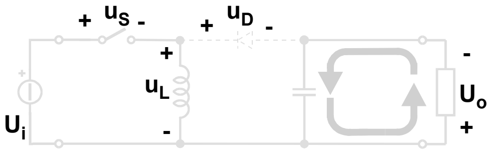
Tempo di apertura di S (t''_{off}) S off - D off



$u_D = U_o$ $u_S = U_i$

Analisi del funzionamento discontinuo (DCM)

Tempo di apertura di S (t''_{off}) S off - D off



$u_D = U_o$ $u_S = U_i$

Durante questa fase il solo condensatore fornisce energia al carico

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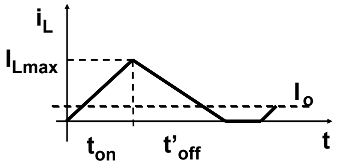
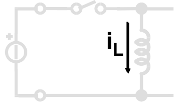
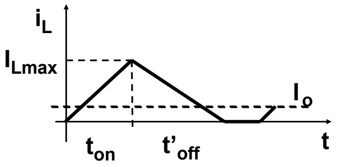
Buck/Boost: Forme d'onda in DCM: i_L

Buck/Boost: Forme d'onda in DCM: i_L

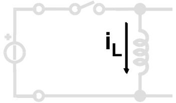




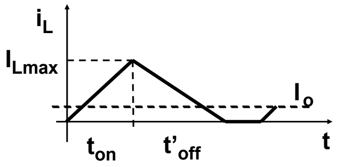
Buck/Boost: Forme d'onda in DCM: i_L



$$I_{L\,max} = \frac{U_i}{L} \cdot t_{on}$$

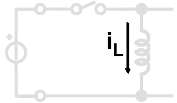


Buck/Boost: Forme d'onda in DCM: i_L



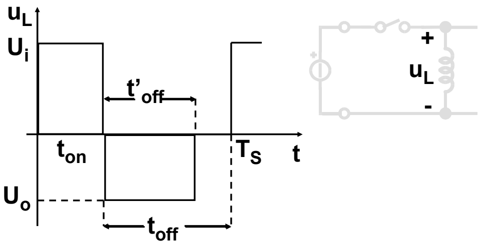
$$I_{L\,max} = \frac{U_i}{L} \cdot t_{on}$$

$$I_o = \frac{I_{L\,max} \cdot t'_{off}}{2 \cdot T_S}$$

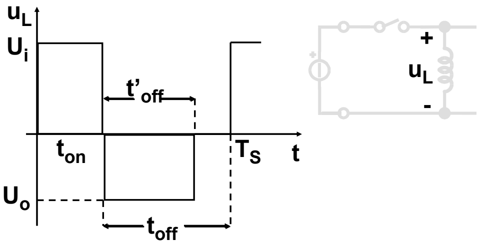


Buck/Boost: Forme d’onda in DCM: u_L

Buck/Boost: Forme d’onda in DCM: u_L



Buck/Boost: Forme d’onda in DCM: u_L



$$U_i \cdot t_{on} = U_o \cdot t'_{off}$$

Caratteristica di controllo in DCM

Caratteristica di controllo in DCM

$$I_o = \frac{I_{L\max} \cdot t'_{off}}{2 \cdot T_S}; \qquad I_{L\max} = \frac{U_i}{L} \cdot t_{on};$$

$$t'_{off} = \frac{U_i}{U_o} \cdot t_{on}$$

Caratteristica di controllo in DCM

$$I_o = \frac{I_{L\max} \cdot t'_{off}}{2 \cdot T_S}; \qquad I_{L\max} = \frac{U_i}{L} \cdot t_{on};$$

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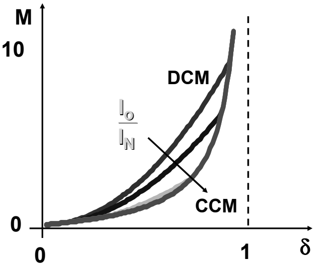
$$\Downarrow$$

$$M = \frac{U_o}{U_i} = \delta^2 \cdot \frac{U_i}{2 \cdot f_S \cdot L \cdot I_o} = \delta^2 \cdot \frac{I_N}{I_o}$$

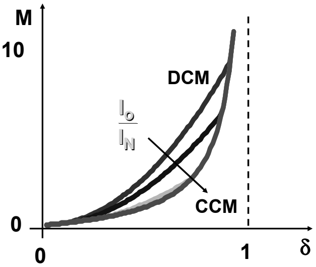
dove: $I_N = \frac{U_i}{2 \cdot f_S \cdot L}$

Caratteristiche di controllo totali

Caratteristiche di controllo totali



Caratteristiche di controllo totali



Anche in questo caso valgono le curve che danno la tensione d'uscita più elevata

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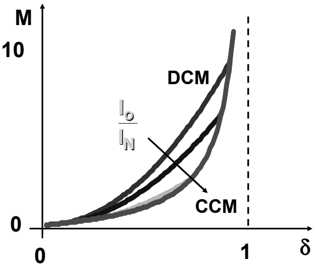
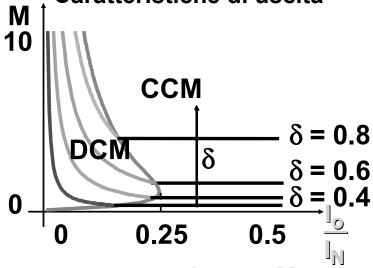
Caratteristiche di controllo totali



Il funzionamento intermittente può manifestarsi per valori centrali di δ

Caratteristiche di uscita

Caratteristiche di uscita



Curva limite: $\frac{I_o}{I_N} = \frac{M}{(1+M)^2}$

Caratteristica di controllo in DCM per carico resistivo

Caratteristica di controllo in DCM per carico resistivo

$$M = \frac{\delta}{\sqrt{k}}$$

dove: $k = \frac{2 \cdot f_S \cdot L}{R_o}$

Nota: Correnti nei filtri capacitivi

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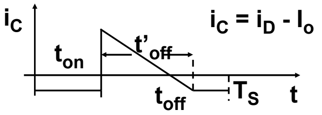
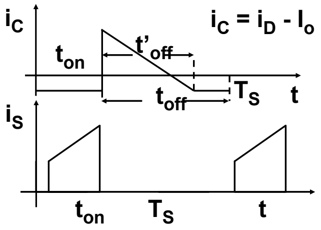


$i_C = i_D - I_o$

Note:
i_C presenta fronti ripidi

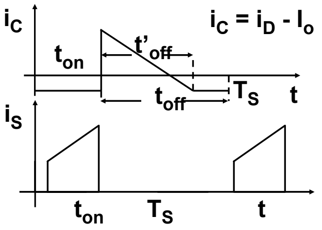
Nota: Correnti nei filtri capacitivi



$i_C = i_D - I_o$

Note:
i_C presenta fronti ripidi
$i_i = i_S$ presenta anch’essa fronti ripidi

Nota: Correnti nei filtri capacitivi



$i_C = i_D - I_o$

Sia il condensatore di filtro d’ingresso che quello di uscita devono avere bassa ESL

Note

- Le tecniche di controllo sono le stesse del convertitore Buck
- La risposta dinamica è però difficile da dominare in CCM (caratteristica statica nonlineare, modello ai piccoli segnali a parametri variabili e zero a parte reale positiva). In DCM invece si ha solo un polo con costante di tempo $R_0C/2$.
- Lo schema buck-boost a trasformatore (flyback) è molto usato per piccole potenze

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Conclusioni

- I convertitori boost e buck-boost consentono di estendere il campo di regolazione del regolatore buck
- Ciò viene pagato con maggiori sollecitazioni in tensione dei componenti e con una maggiore difficoltà di controllo
- Il regolatore boost ha il vantaggio di filtrare la corrente d’ingresso
- Il regolatore buck-boost ha una semplice configurazione a trasformatore (flyback)