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Energy Conversion I

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Desk D216

Layout

- Non isolated choppers
  - Introduction
  - Direct conversion
    - Buck
    - Boost
  - Reversible choppers
    - Half bridge
    - H – bridge
  - Inverter
  - Energy storage based chopper
    - Buck-boost
    - Cuck
    - SEPIC
- Isolated power supplies
- Power components

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Progress

- **Lesson : 8 x 2h**
- **Tutorials : 9 x 2h**
- **Labs : 4 x 4h**
  - **Buck chopper**
  - **Reversible chopper for DC motor**
  - **Switch mode power supply Flyback**
  - **Switch mode power supply Forward**
- **Marks : Final exam - Labs**

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Prerequisites

- **Kirchhoff's circuit laws**
- **Average value of a signal, integral calculus, RMS value**
- **AC and DC real power, power factor, complex representation, phasor**
- **Transformers (magnetic field, flux)**
- **Linear control (Laplace transform, Bode diagram, gain/phase margin, PI controller)**

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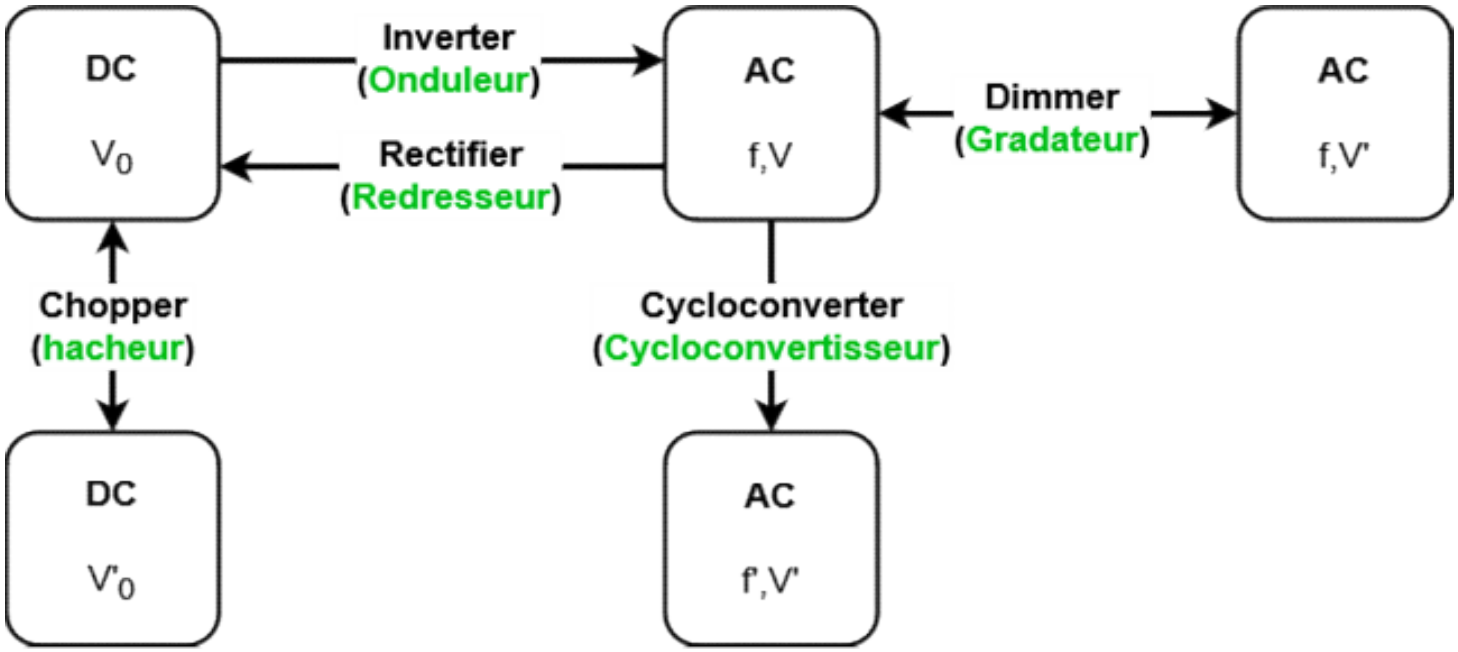
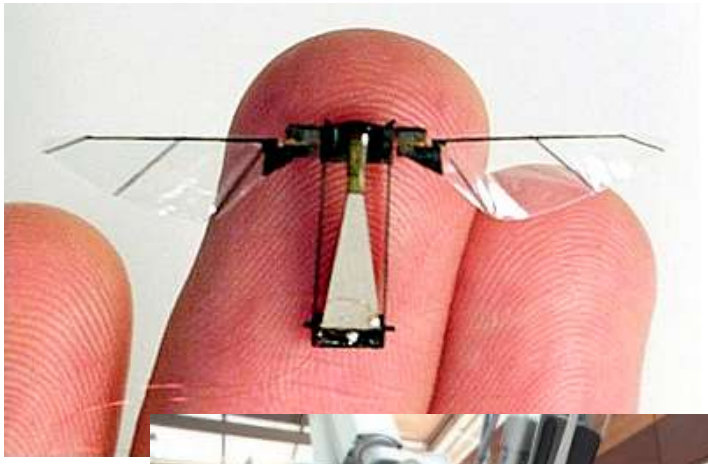
Introduction

Energy conversion: principles



Micro-mechanisms



1-100 W

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Use : automatisms

0,1 à 10 kW

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Use : rail traction

100 kW

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High speed rail traction

500 kW

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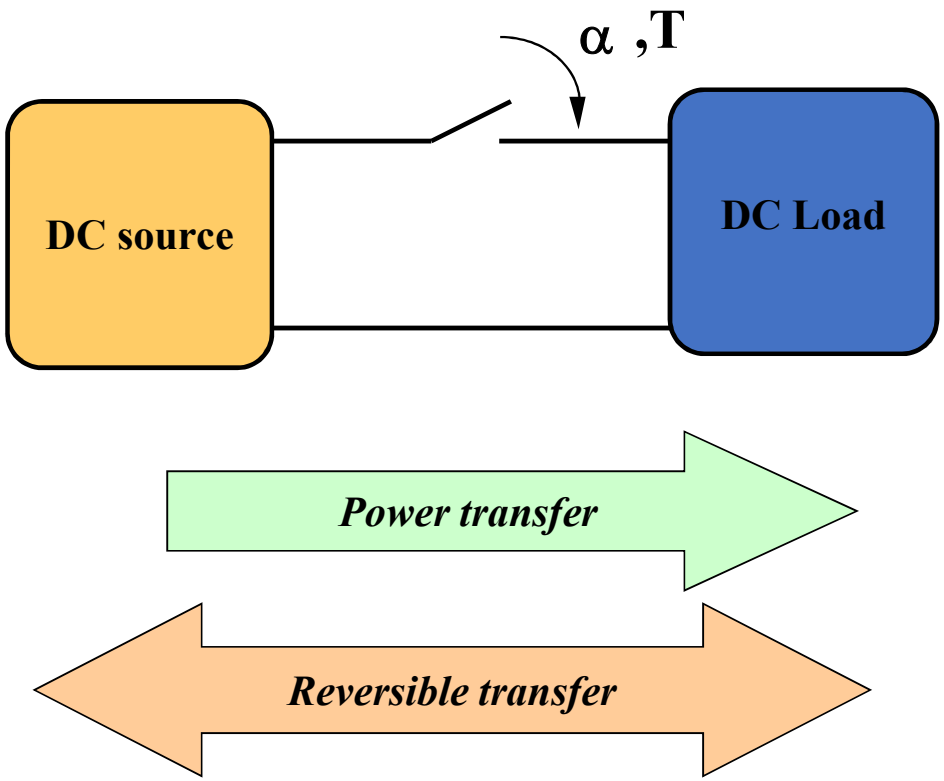
Photovoltaic plant

300 MWc

«Chopper » function : a switching electronic



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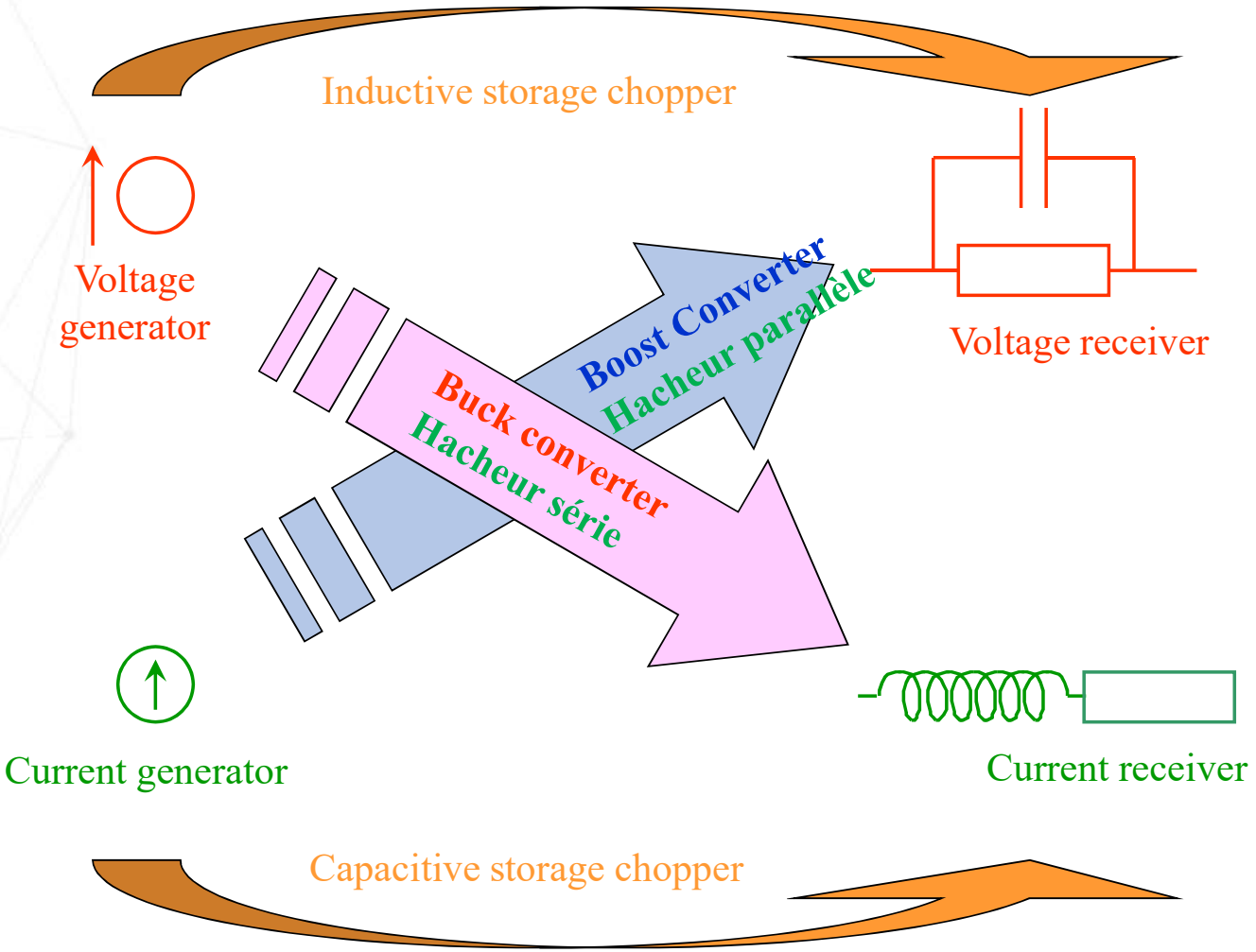
Link power sources

Voltage Source — *Active* *(Energy generator)*

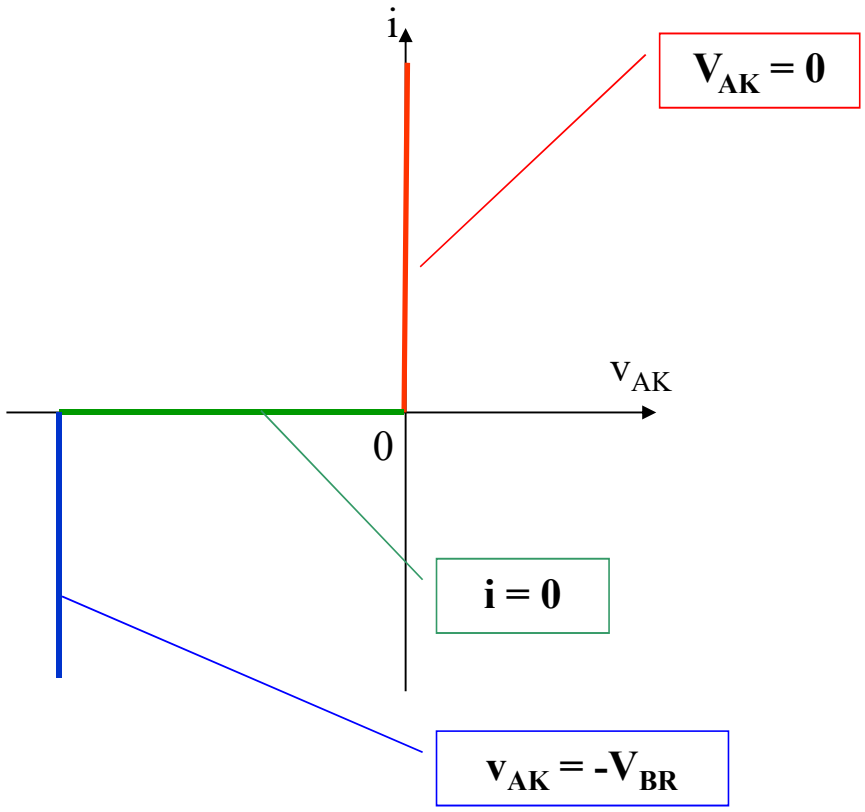
Current Source — *Passive* *(Energy receiver)*

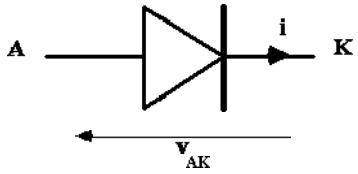
Theorem
Only two sources with different category can be directly connected.

Non reversible chopper



« Perfect » diode





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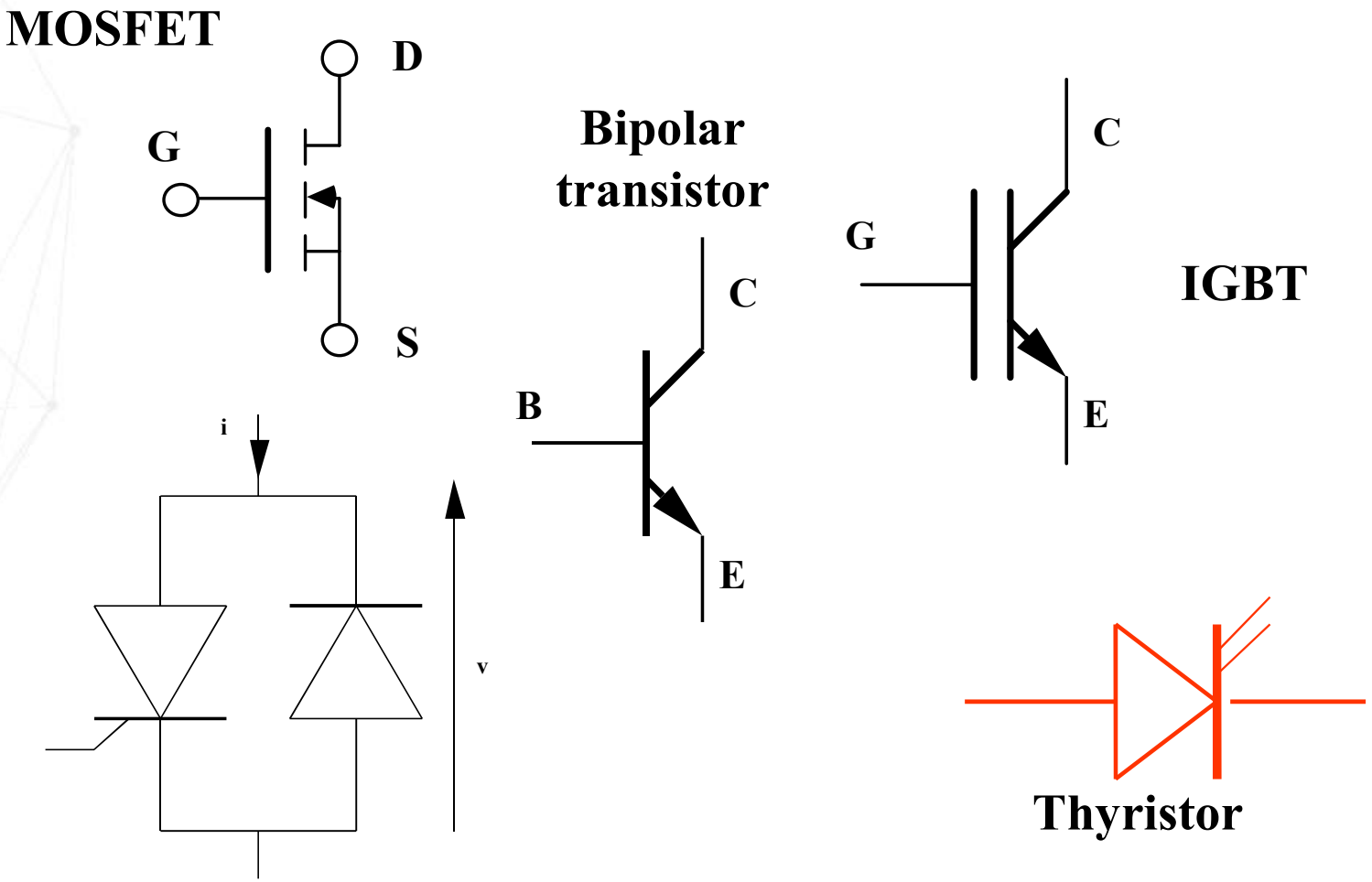
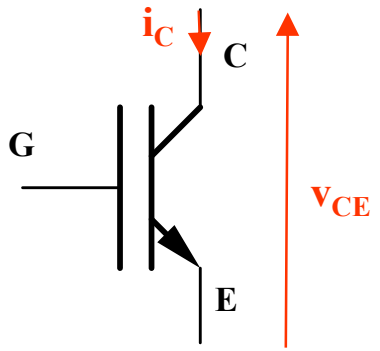
Controlled switch

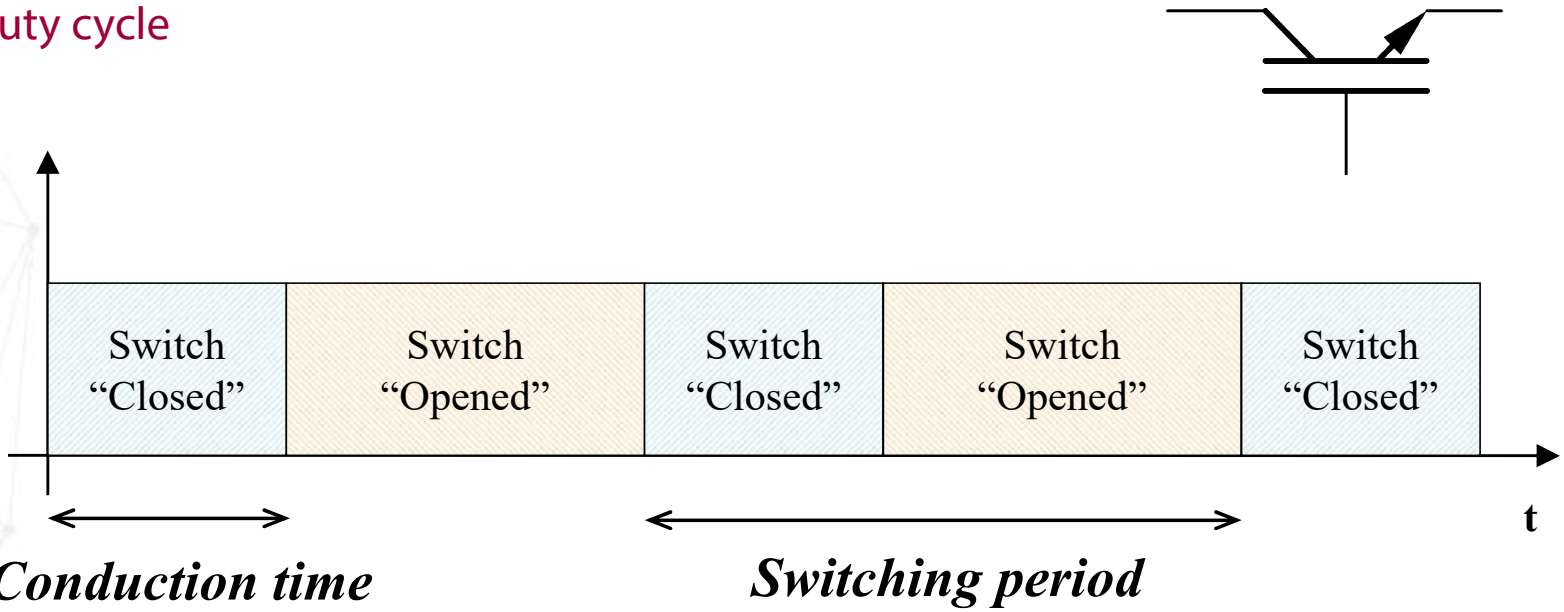


« Perfect » controlled switch ex : IGBT



- On state: « short circuit »
  - $v_{CE} = 0$, i_C fixed by circuit
- Off state: « open circuit »
  - $i_C = 0$, v_{CE} fixed by circuit

Duty cycle



$$\alpha = \frac{Conduction\ time}{Switching\ period}$$

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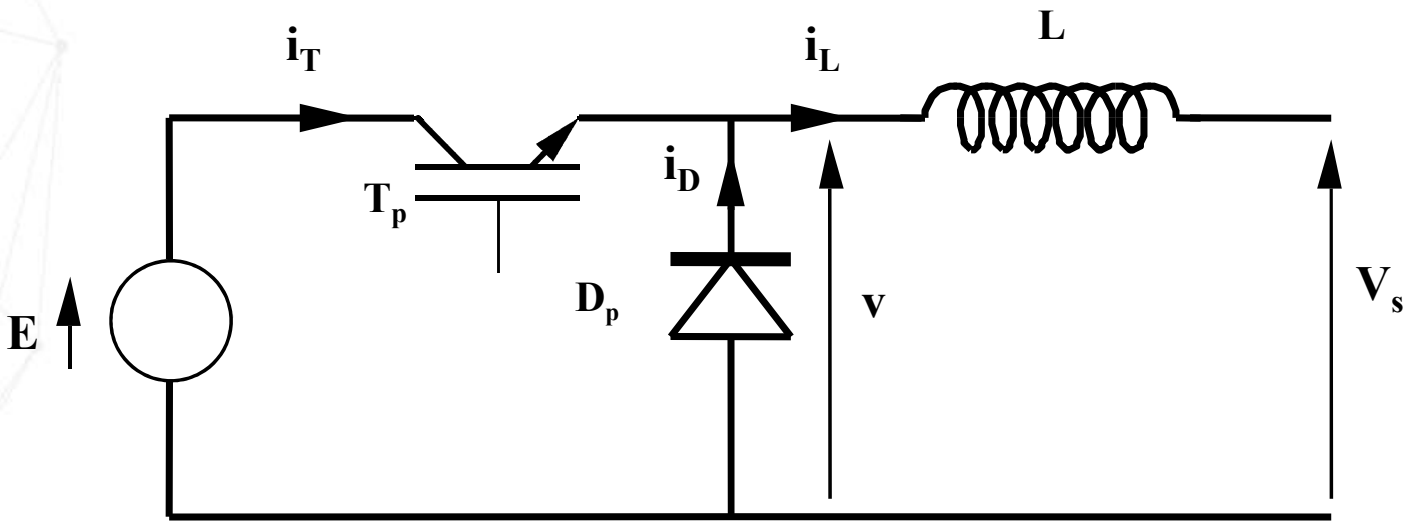
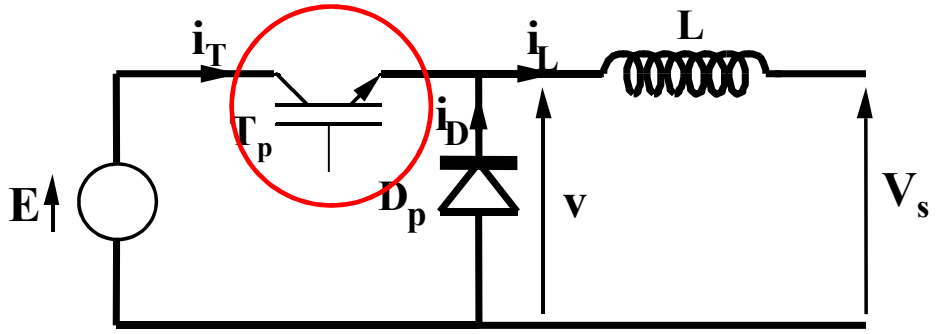
Buck Chopper

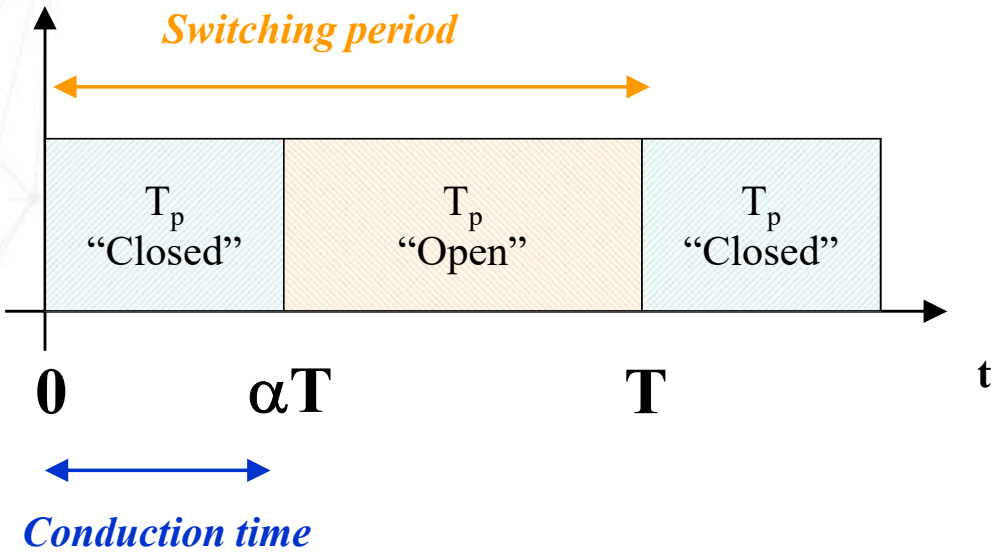
Buck chopper : principle



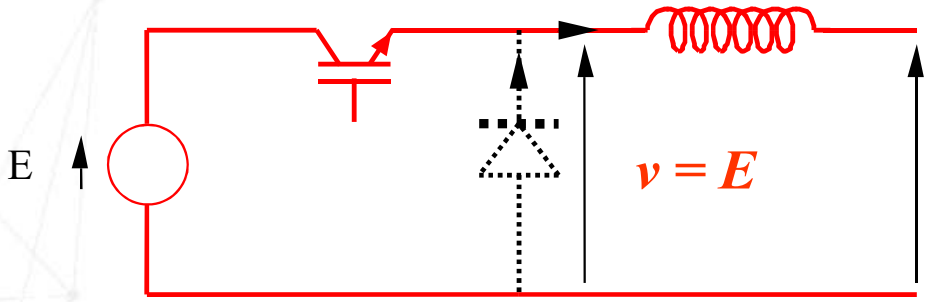
***Hypothesis* : V_s = constant**

Control

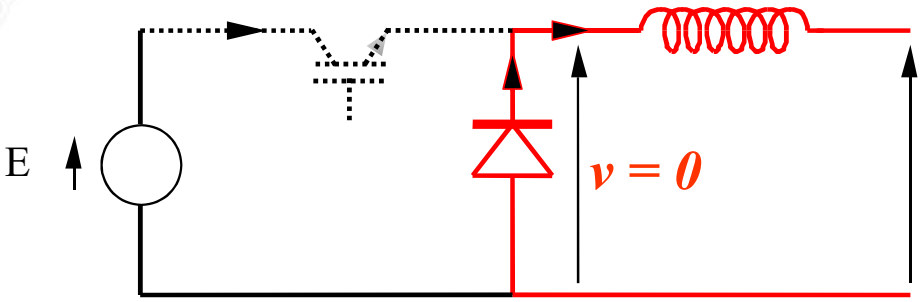




Operation



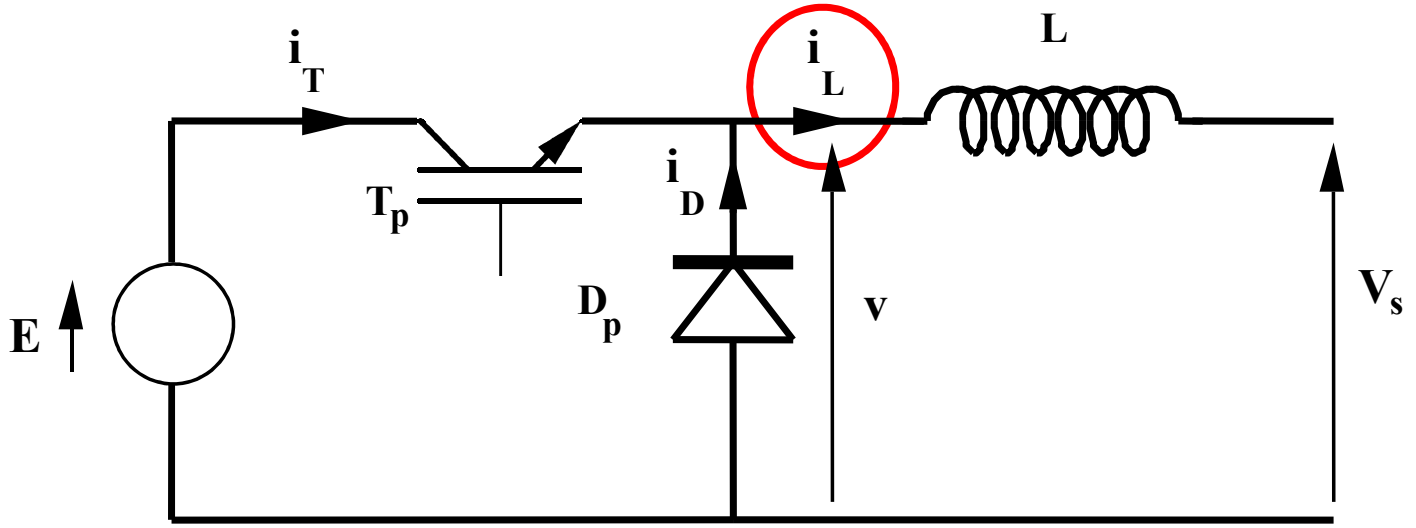
$0 < t < \alpha T$



$\alpha T < t < T$

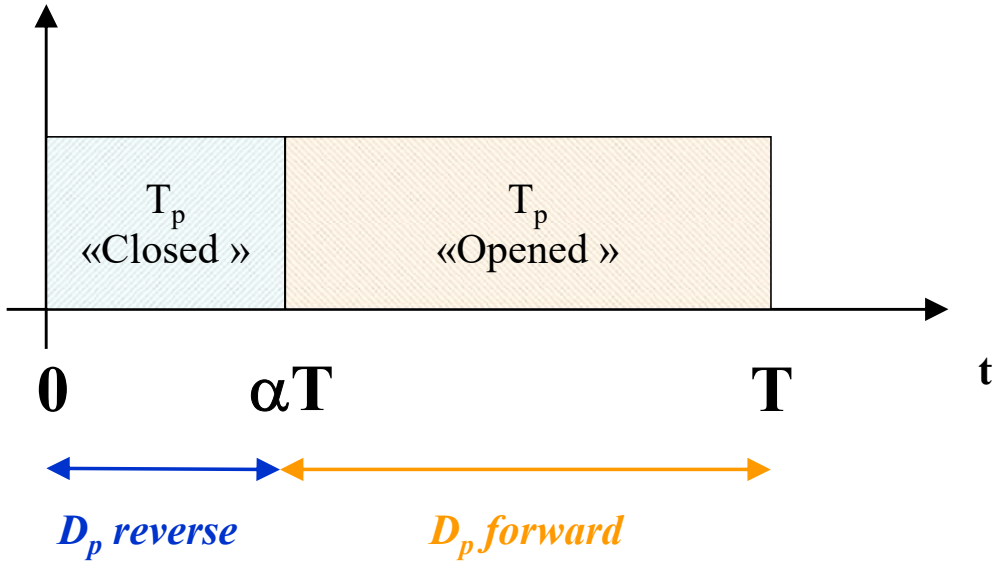
Modes

- ***Continuous conduction mode: $i_L > 0$***



- ***Discontinuous conduction mode: $i_L(t_0) = 0$; $t_0 < T$***

Continuous mode



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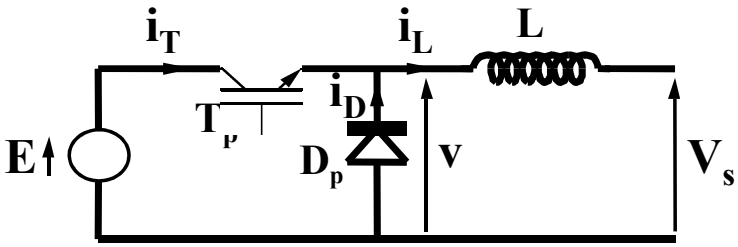
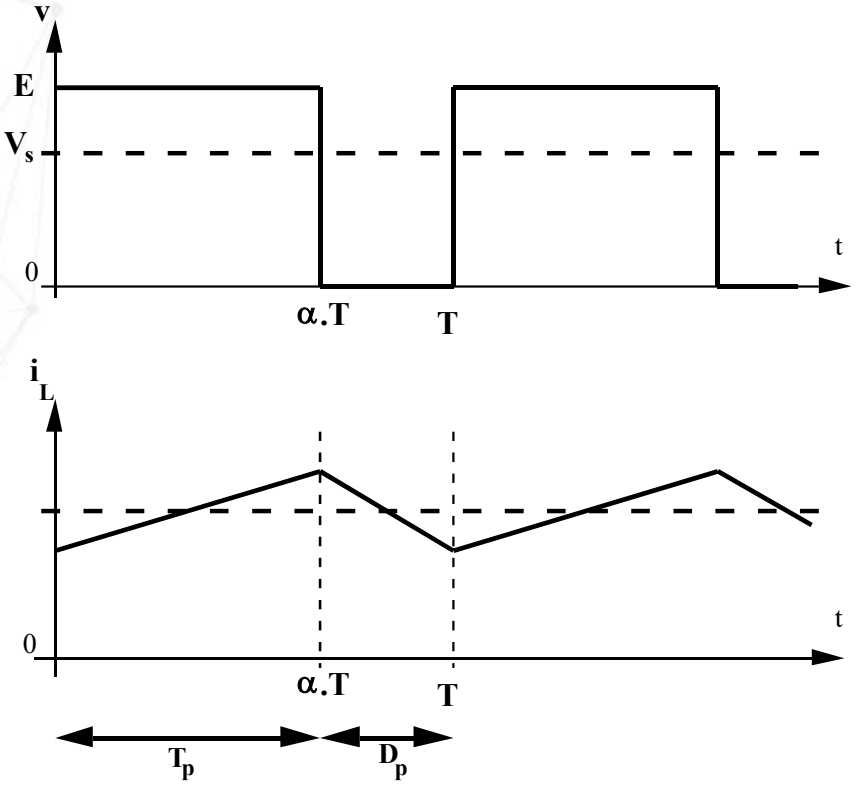
Continuous mode: Chronograms





- $0 < t < \alpha T$

$$\frac{di}{dt} = \frac{E - V_s}{L}$$

- $\alpha T < t < T$

$$\frac{di}{dt} = -\frac{V_s}{L}$$

$$E > V_S$$

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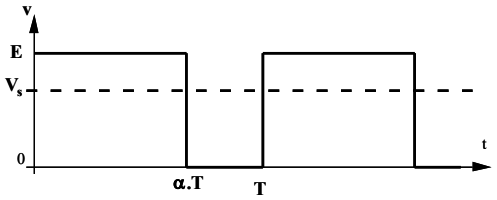
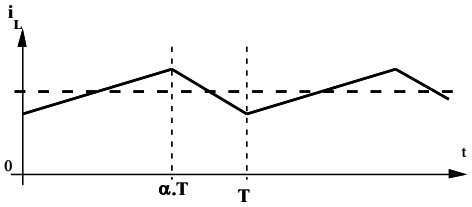
Continuous mode (Calculation)

Output voltage



$$\langle v \rangle = \alpha.E = V_s$$

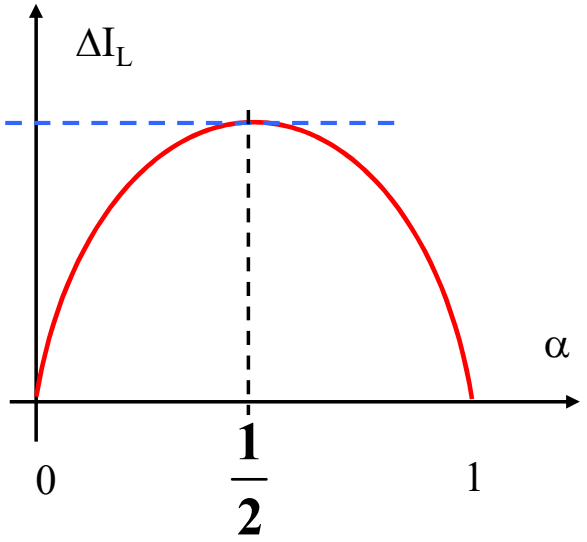
Current ripple i_L



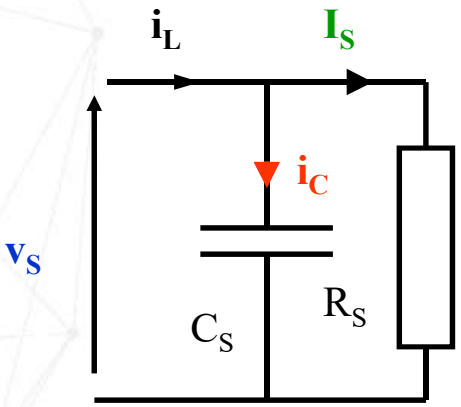
$$\Delta I_L = \alpha.(1-\alpha).\frac{E.T}{L}$$

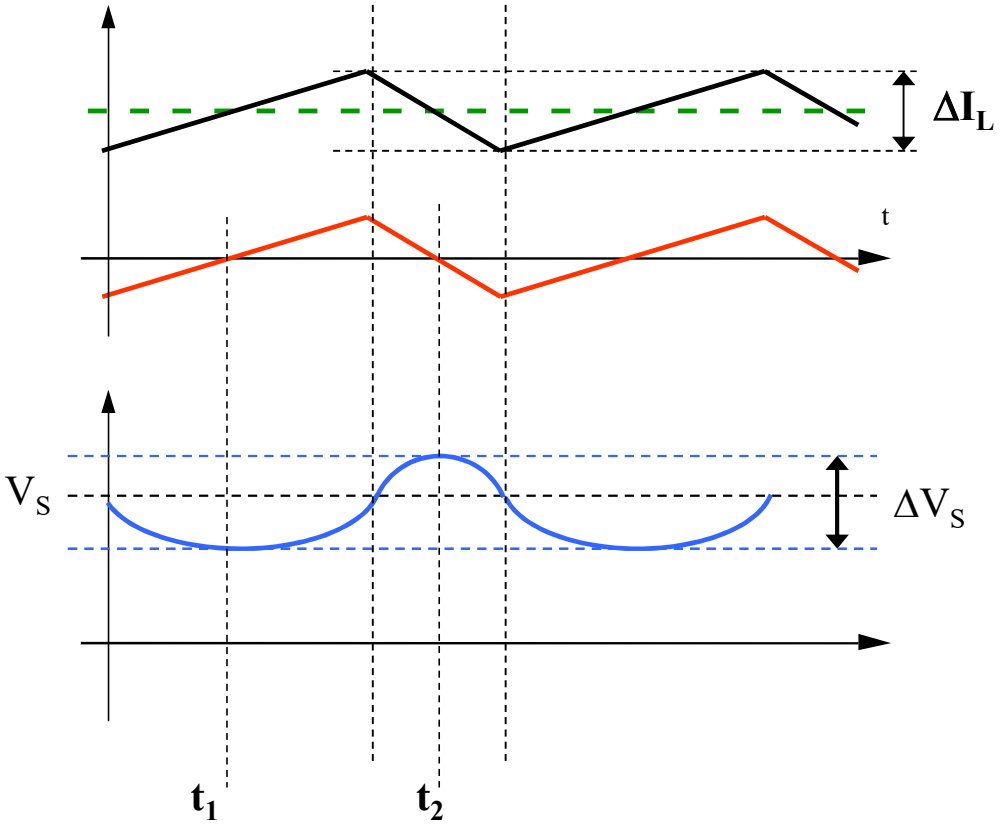
Maximum ripple

$$\Delta I_{L\,max} = \frac{E.T}{4\,L}$$



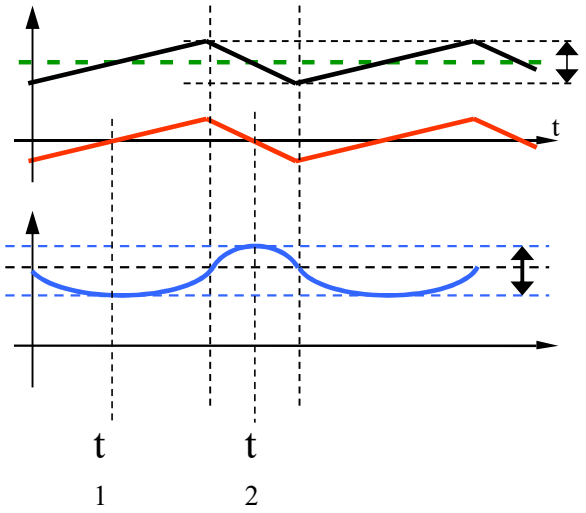
Continuous mode: Output filtering principle





$$i_C = C_S . \frac{dv_S}{dt}$$

Continuous mode: Output filtering calculation



$$t_1 = \alpha\frac{T}{2} \qquad t_2 = \frac{(1+\alpha).T}{2}$$

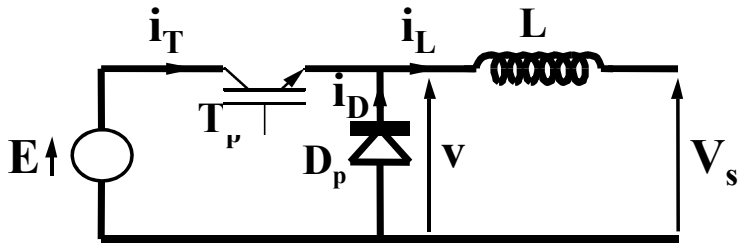
$$\Delta I_L = \alpha.(1-\alpha).\frac{E.T}{L}$$

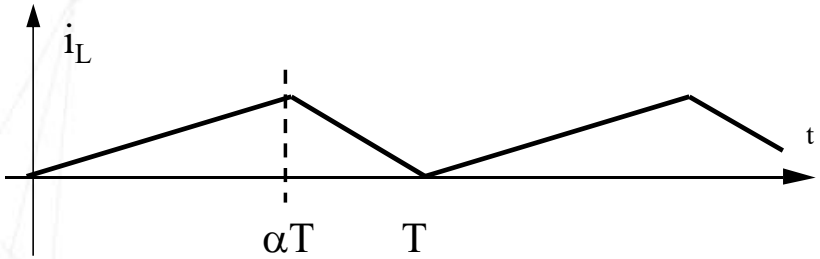
$$\Delta V_S = \frac{1}{C_S}.\int_{t_1}^{t_2} i_C(t).dt = \frac{1}{C_S}.\frac{1}{2}.\frac{\Delta I_L}{2}.(t_2 - t_1) = \frac{\Delta I_L.T}{8.C_S}$$

$$C_S = \frac{\alpha(1-\alpha).E.T^2}{8.L.\Delta V_S}$$

C_S

Boundary mode





$$i_L(T) = 0$$

$$< I_L > = \frac{1}{2}.\left(\frac{E-V_S}{L}.\alpha T\right) = \frac{1}{2}.\frac{\alpha(1-\alpha).E.T}{L} \qquad V_S = \alpha.E$$

$$< I_L >= \frac{T}{2L}.V_S\left(1-\frac{V_S}{E}\right)$$

Curve of mode separation (Vs,Is)

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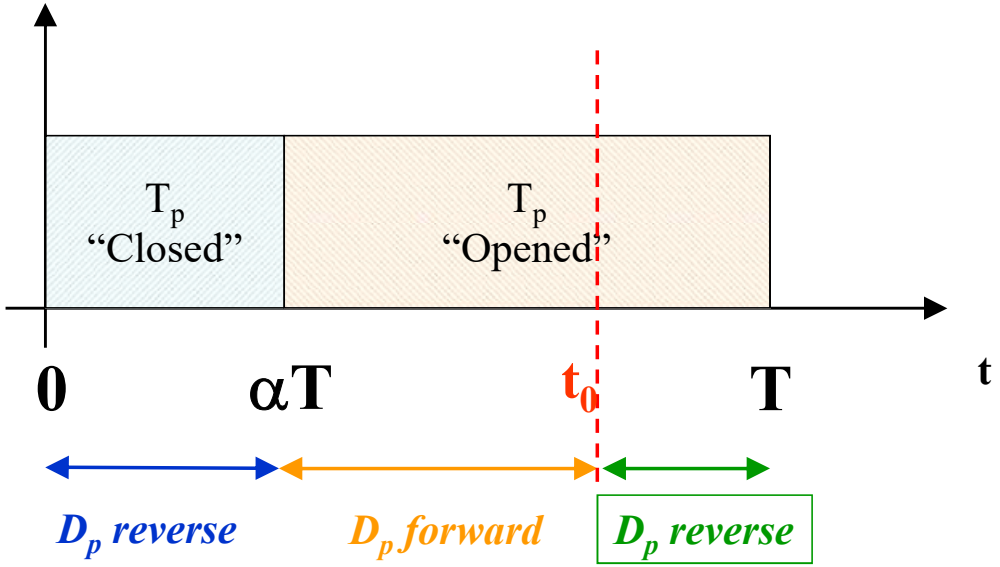
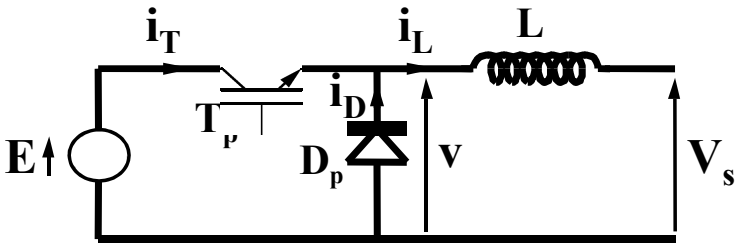
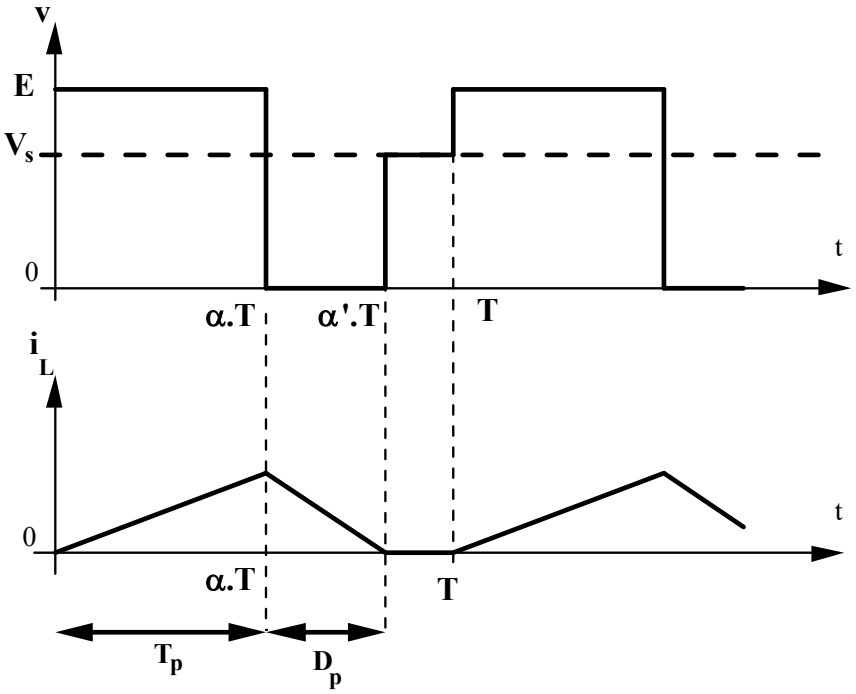
Discontinuous mode



At $t_0 = a\,'.T$: diode switches to reverse mode

Discontinuous mode: Chronograms





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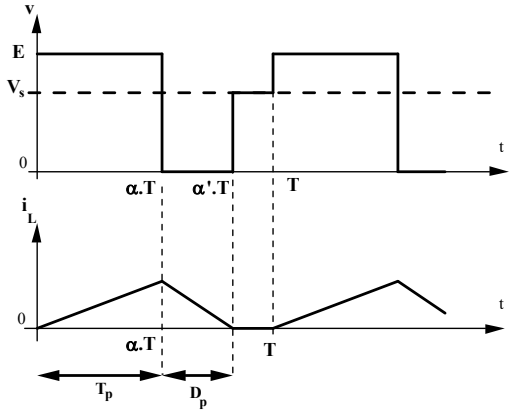
Discontinuous mode: calculation



$$I_{max} = \frac{E - V_S}{L}.\alpha T = \frac{V_S}{L}.(\alpha' T - \alpha T) \quad \Rightarrow \quad \frac{\alpha}{\alpha'} = \frac{V_S}{E}$$

$$< I_L > = \frac{1}{2}.I_{max}.\alpha' = \frac{E - V_S}{2L}.\alpha.\alpha'.T = \frac{\alpha.E.T}{2L}(\alpha' - \alpha)$$

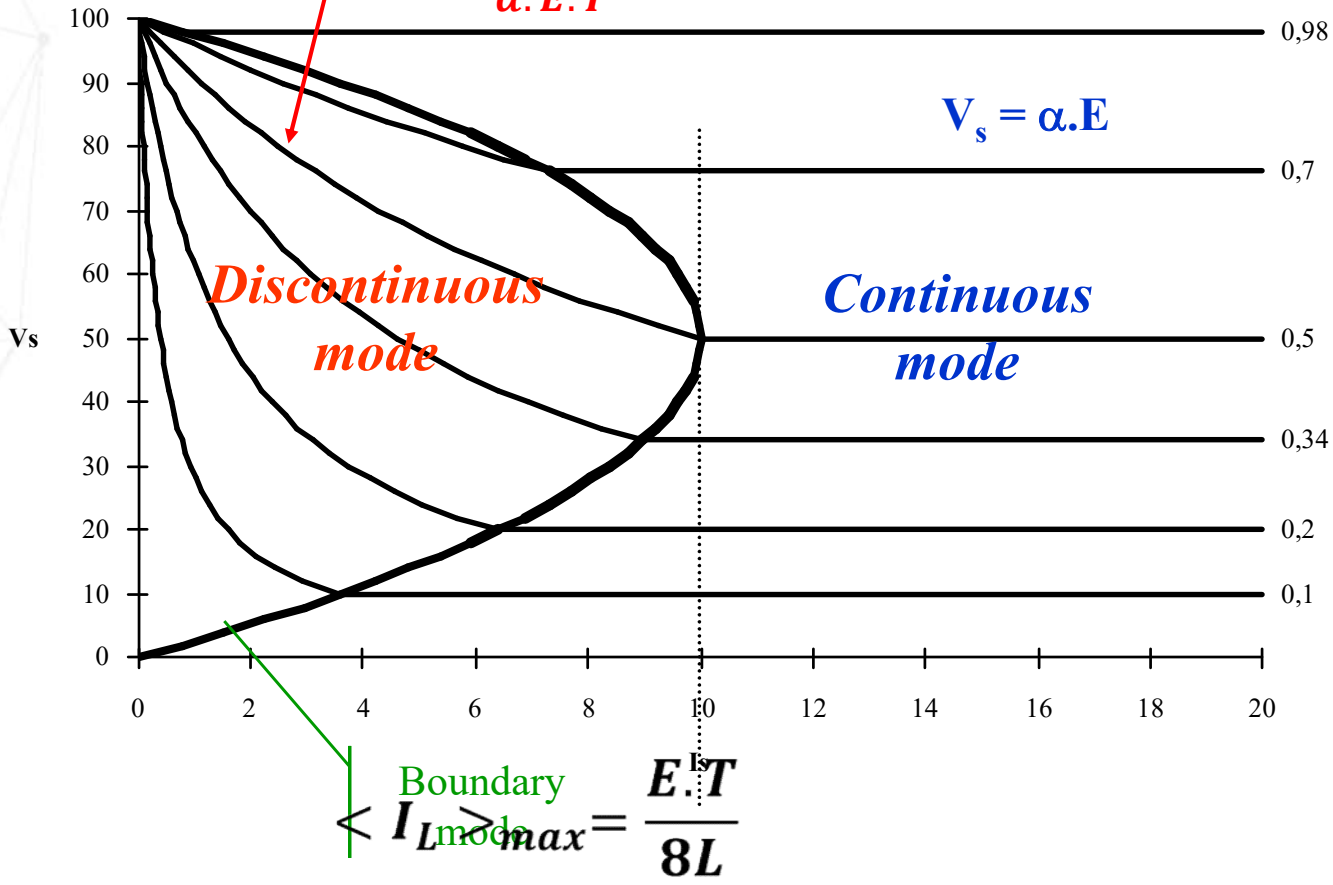
$$\Rightarrow \quad \alpha' = \alpha + \frac{2L.< I_L >}{\alpha.E.T}$$

$$\Rightarrow \quad V_S = \frac{\alpha.E}{\alpha + \frac{2L.< I_L >}{\alpha.E.T}}$$

Output current: $< I_L > = I_S$

Output characteristics

$$V_S = \frac{\alpha . E}{\alpha + \frac{2L. < I_L >}{\alpha . E . T}}$$



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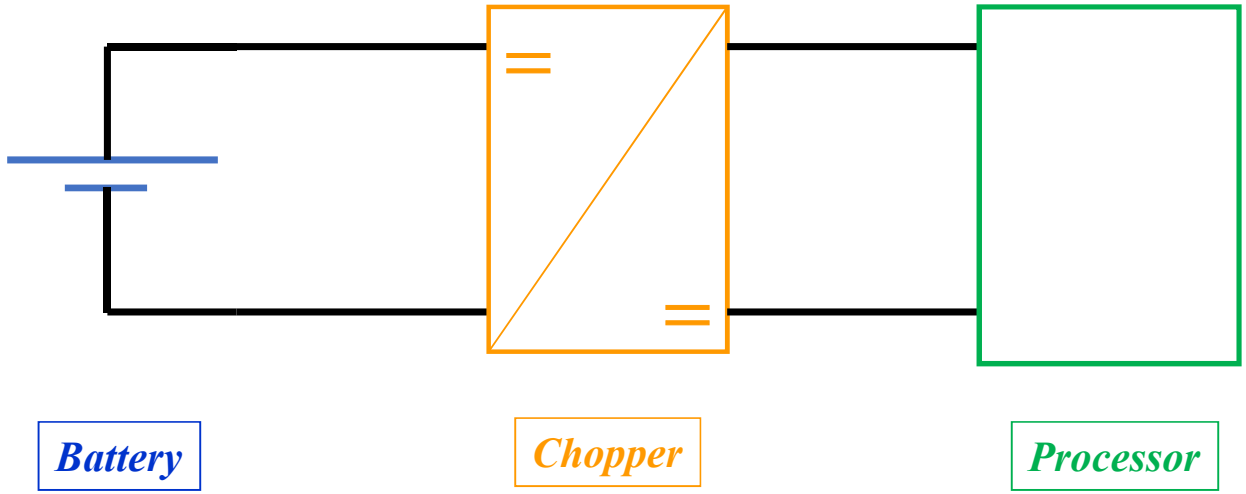
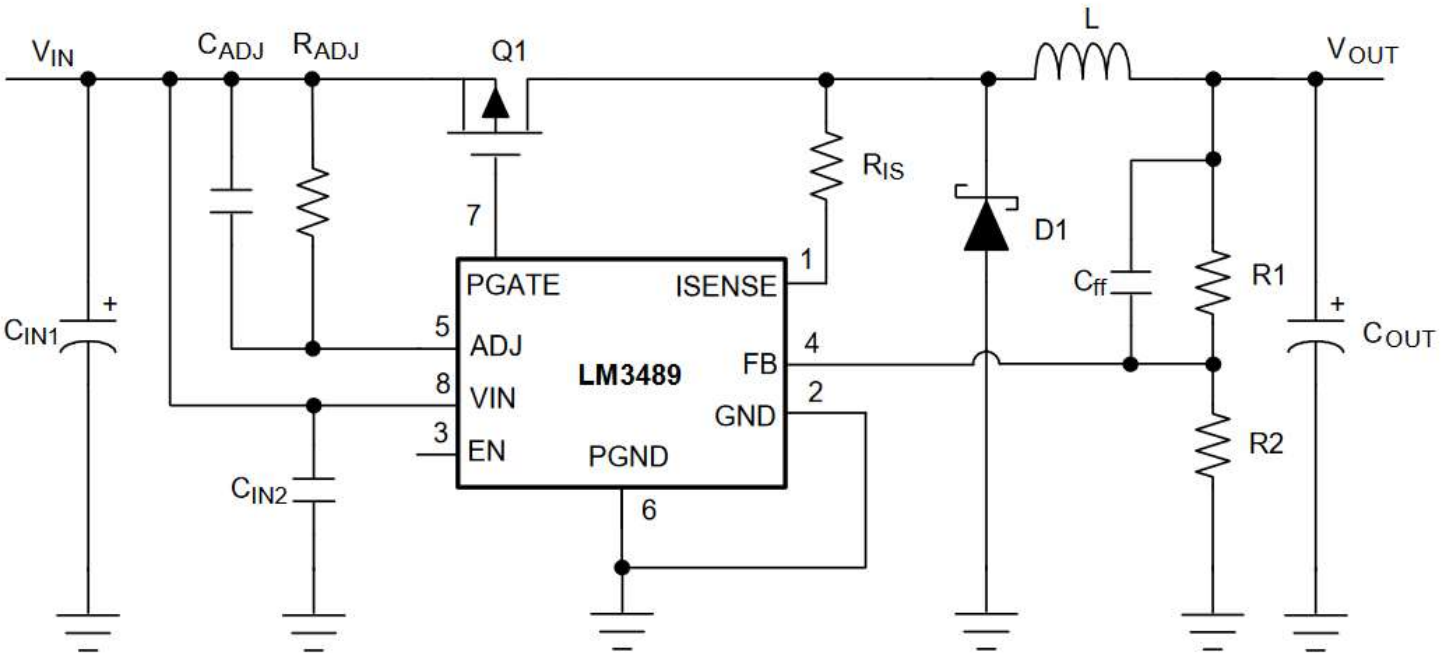
Example



=> DC supply from battery

Example : LM3489



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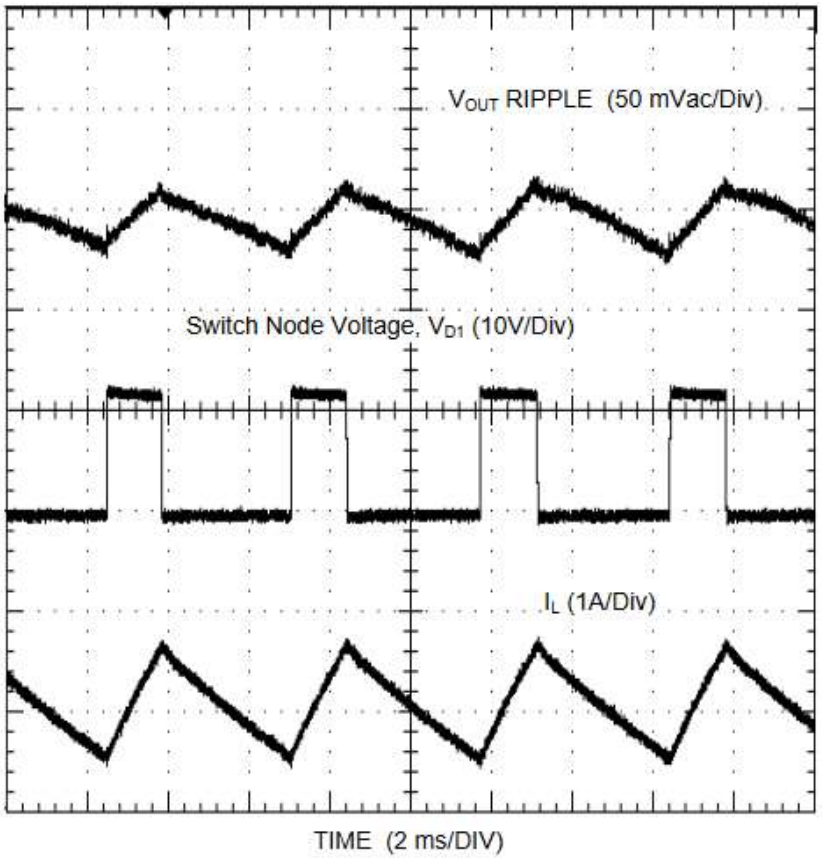
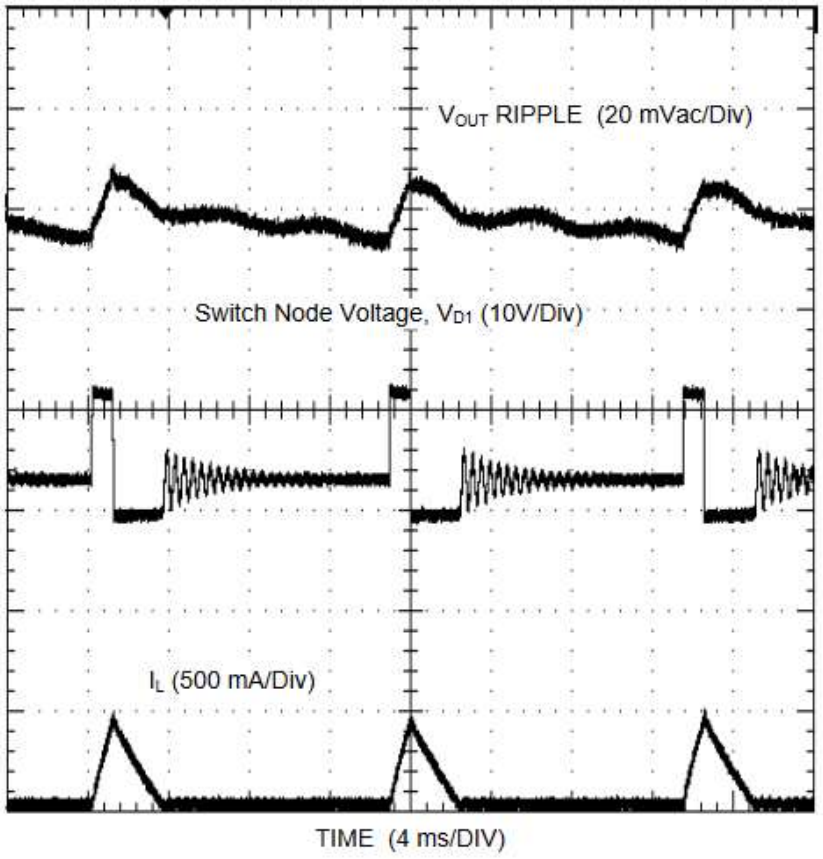
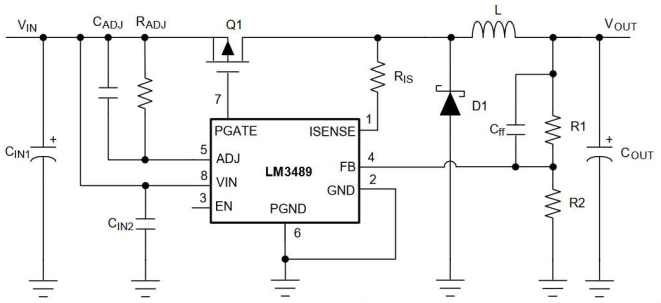
Example : LM3489

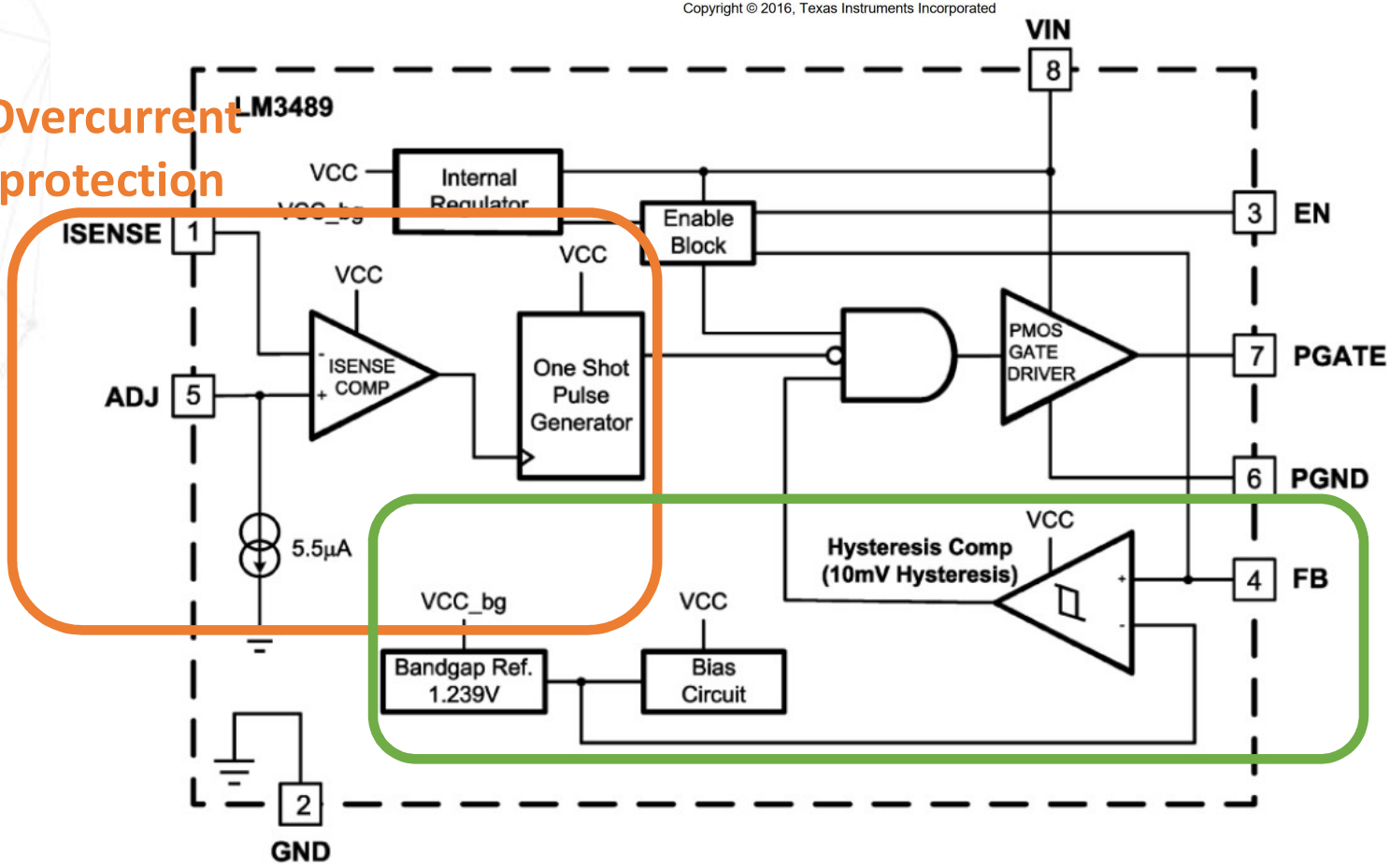




Example : LM3489

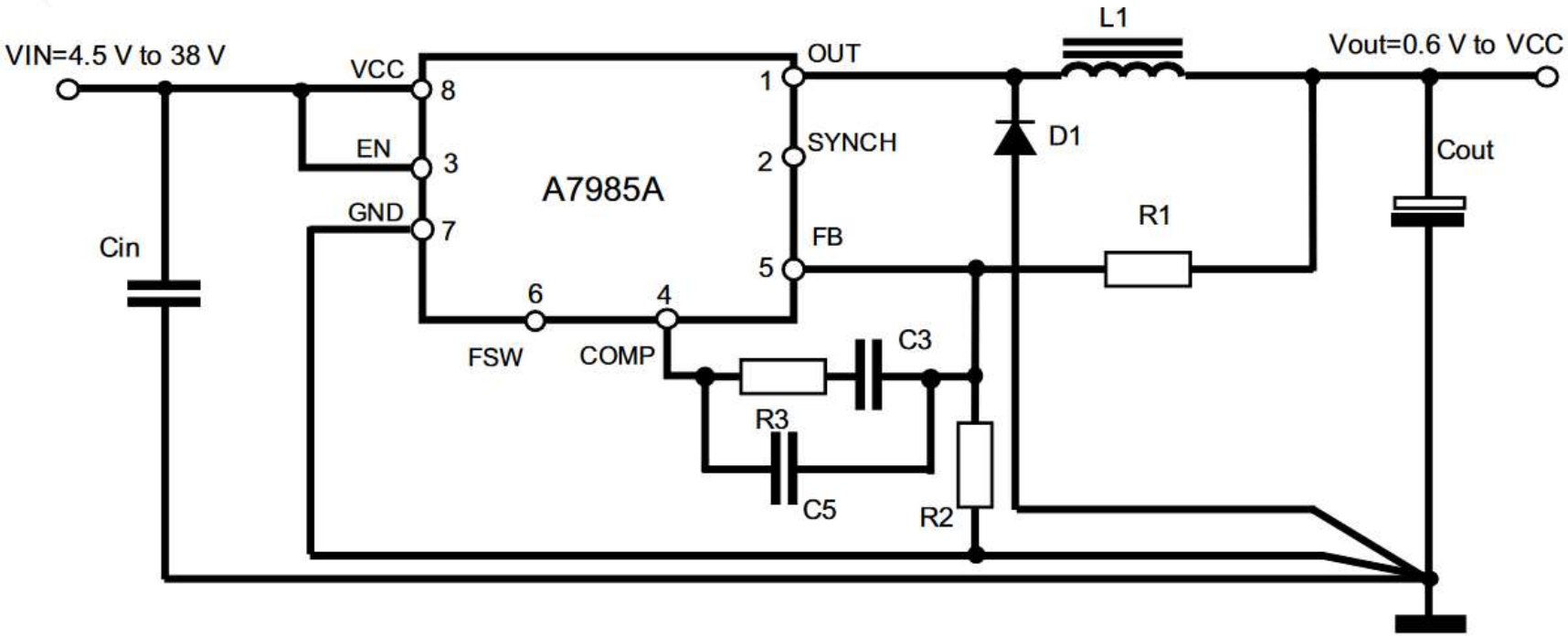


Overcurrent protection



Voltage hysteresis control

Example : A7985A



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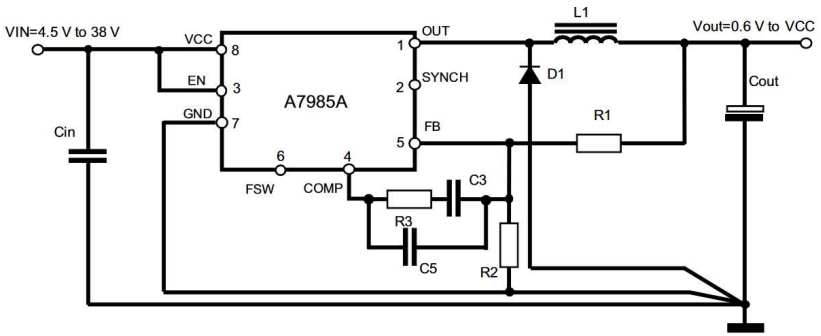
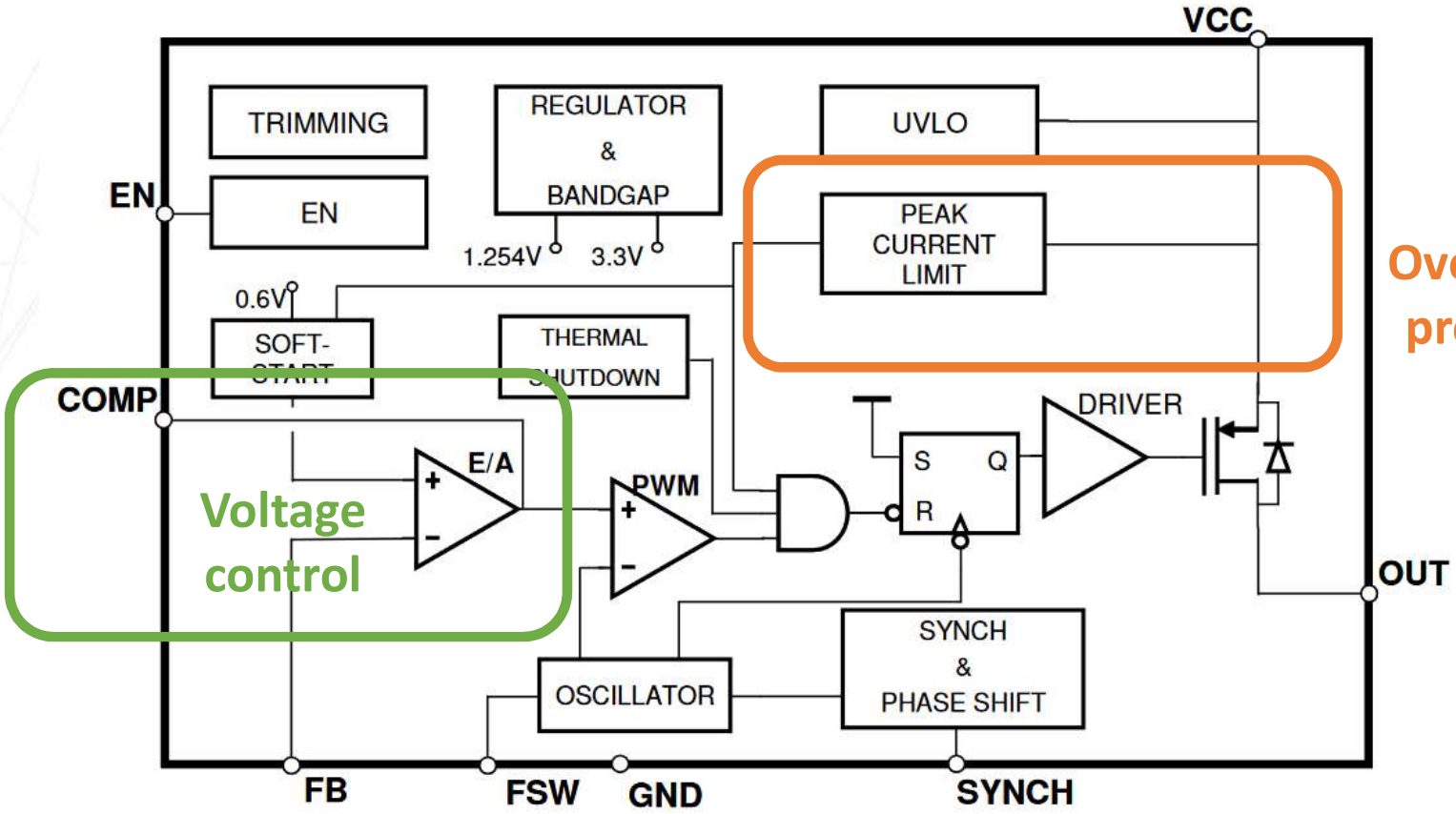
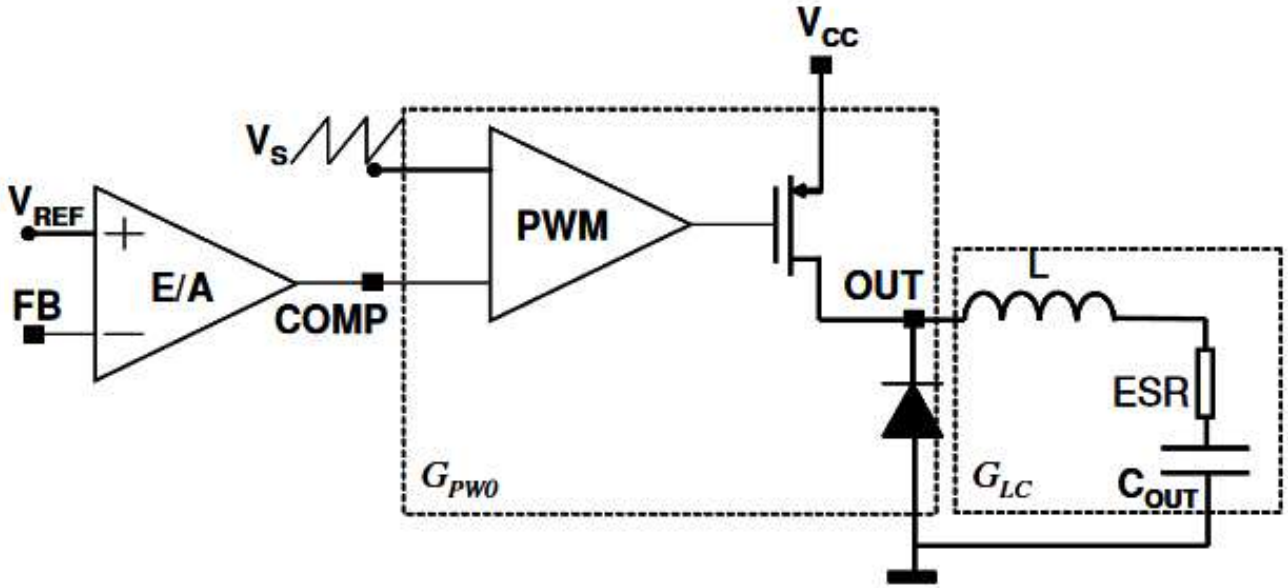
Example : A7985A





Overcurrent protection

Example : A7985A



$$G_{LC}(s) = \frac{1 + \frac{s}{2\pi \cdot f_{zESR}}}{1 + \frac{s}{2\pi \cdot Q \cdot f_{LC}} + \left(\frac{s}{2\pi \cdot f_{LC}}\right)^2}$$

$$f_{LC} = \frac{1}{2\pi \cdot \sqrt{L \cdot C_{OUT}} \cdot \sqrt{1 + \frac{ESR}{R_{OUT}}}}, \quad f_{zESR} = \frac{1}{2\pi \cdot ESR \cdot C_{OUT}}$$

$$Q = \frac{\sqrt{R_{OUT} \cdot L \cdot C_{OUT} \cdot (R_{OUT} + ESR)}}{L + C_{OUT} \cdot R_{OUT} \cdot ESR}$$

Usually : $f_{LC} < f_{zESR}$

→ Slightly depends on the load

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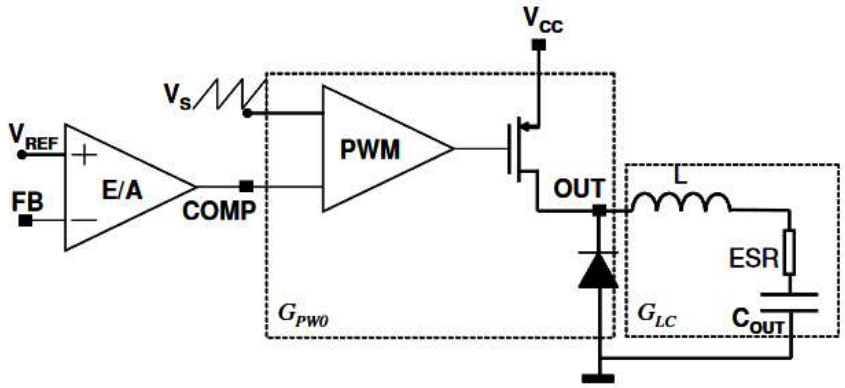
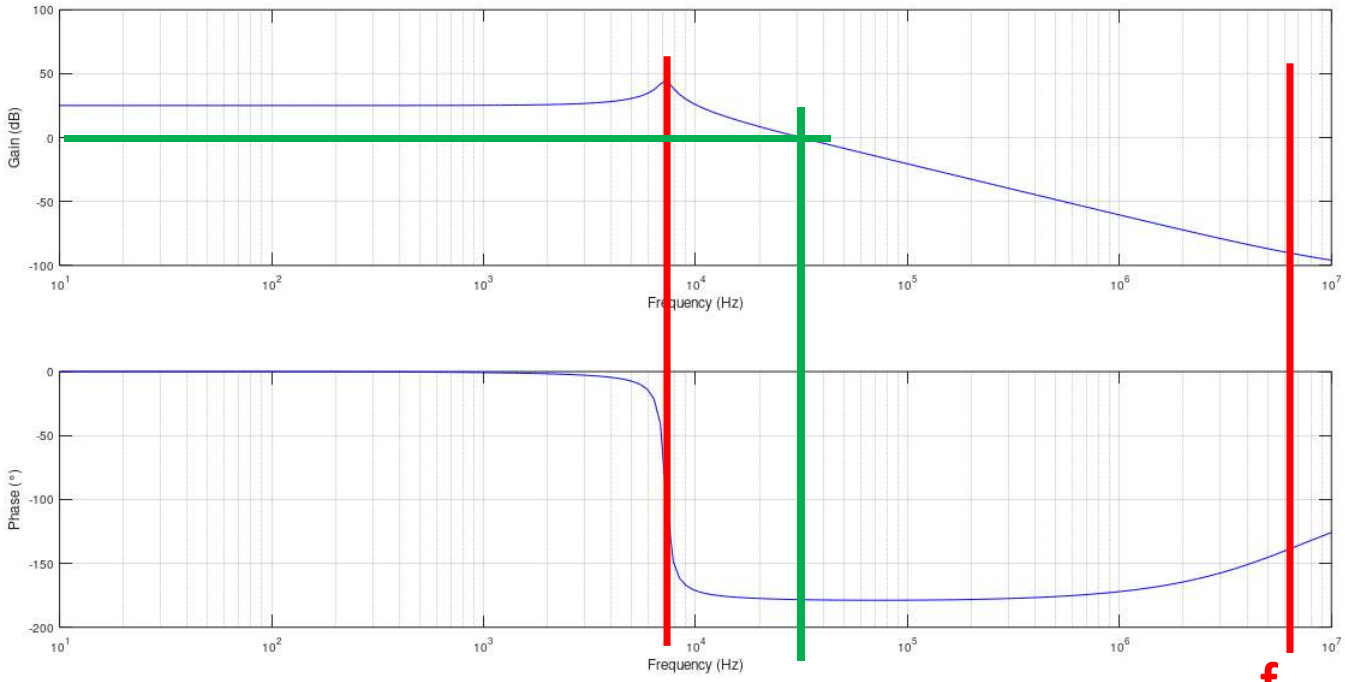
Example : A7985A





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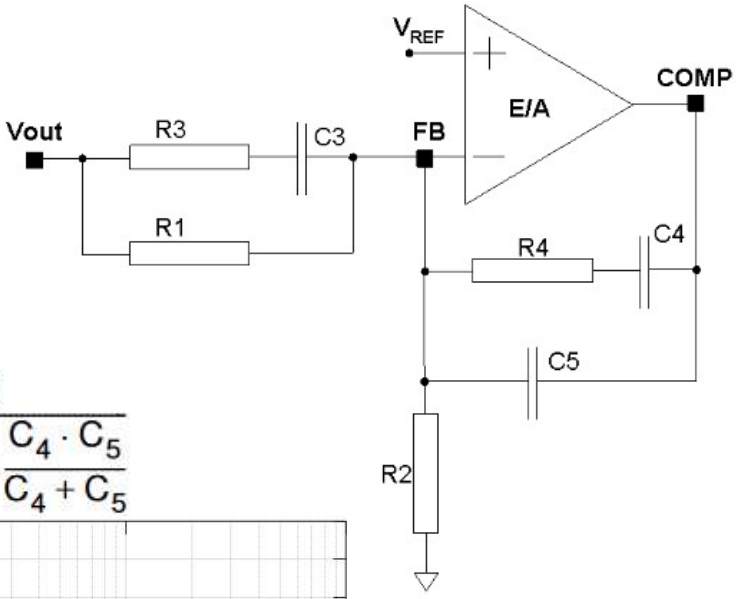
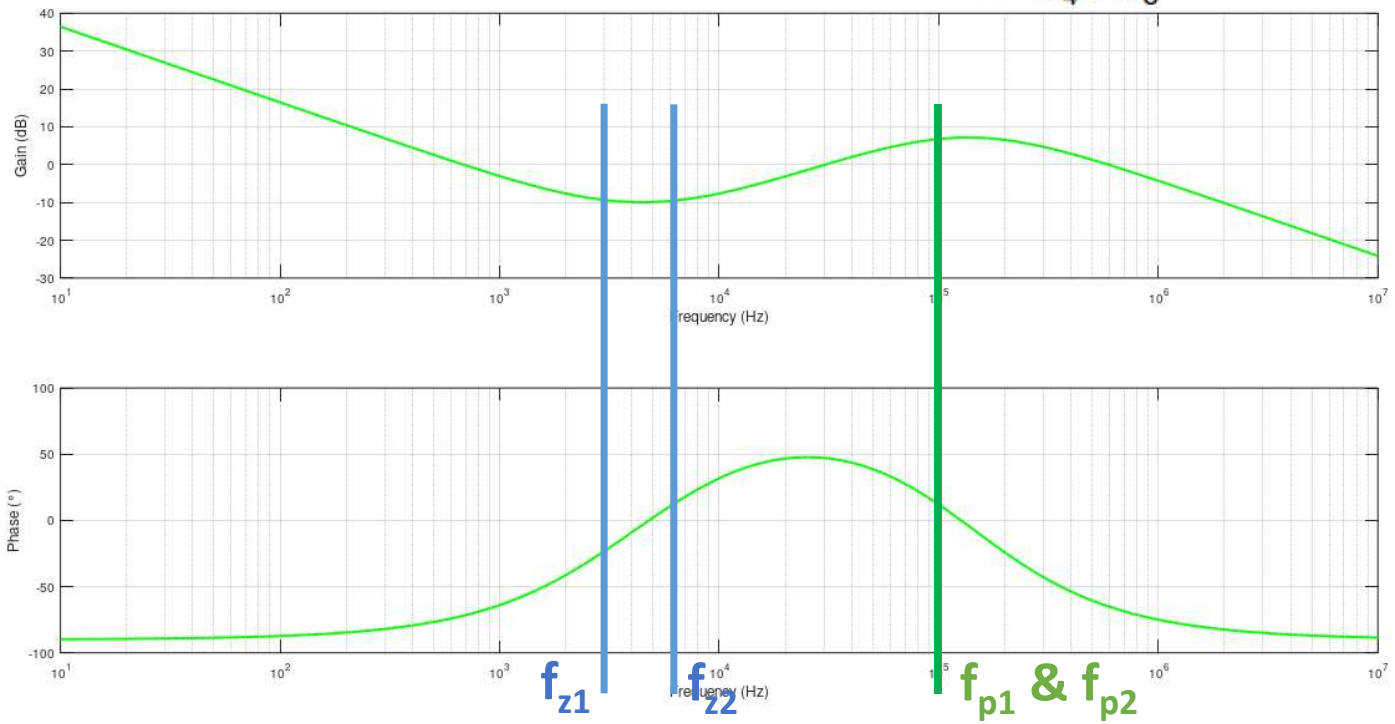
Example : A7985A

If $f_{zESR} \gg BW\ (desired)$
(ESR < 1mΩ)



Zeroes : $f_{Z1} = \frac{1}{2\pi \cdot C_3 \cdot (R_1 + R_3)}$, $f_{Z2} = \frac{1}{2\pi \cdot R_4 \cdot C_4}$

Poles : $f_{P0} = 0$, $f_{P1} = \frac{1}{2\pi \cdot R_3 \cdot C_3}$, $f_{P2} = \frac{1}{2\pi \cdot R_4 \cdot \frac{C_4 \cdot C_5}{C_4 + C_5}}$



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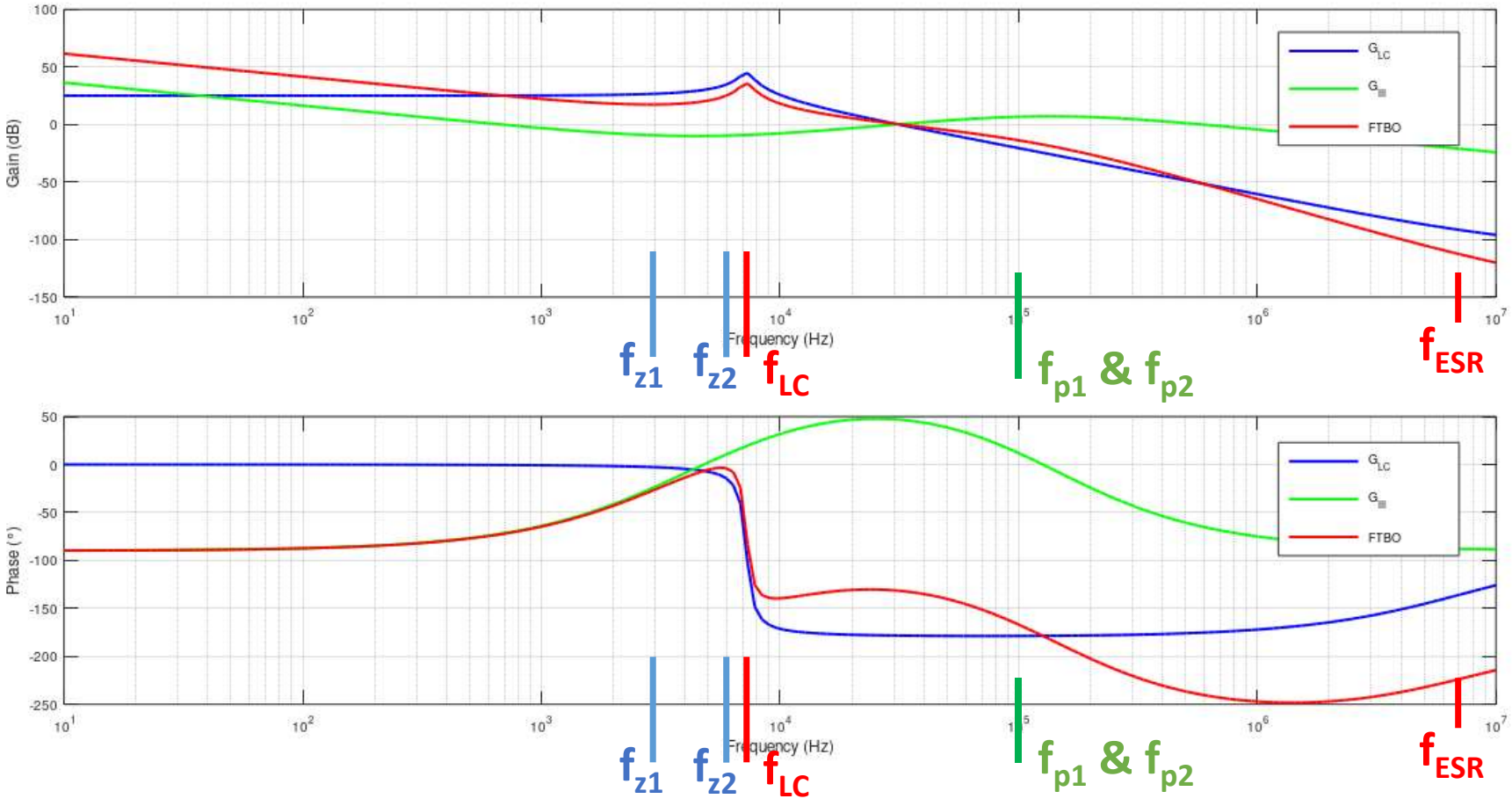
Example : A7985A



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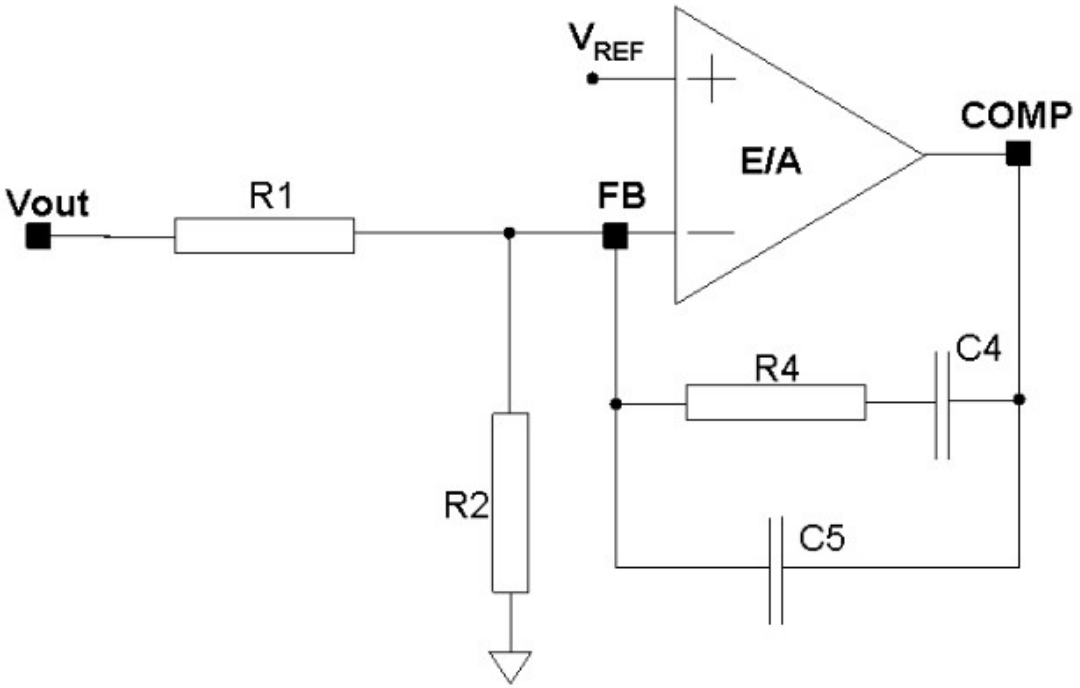
Example : A7985A

If $f_{zESR} \approx BW\ (desired)$
ESR > 30 mΩ

→ Use of the zero of ESR to stabilize the loop



Zero : $f_{Z1} = \frac{1}{2\pi \cdot R_4 \cdot C_4}$,

Poles : $f_{P0} = 0$,

$$f_{P1} = \frac{1}{2\pi \cdot R_4 \cdot \frac{C_4 \cdot C_5}{C_4 + C_5}}$$

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Boost Chopper

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Boost chopper

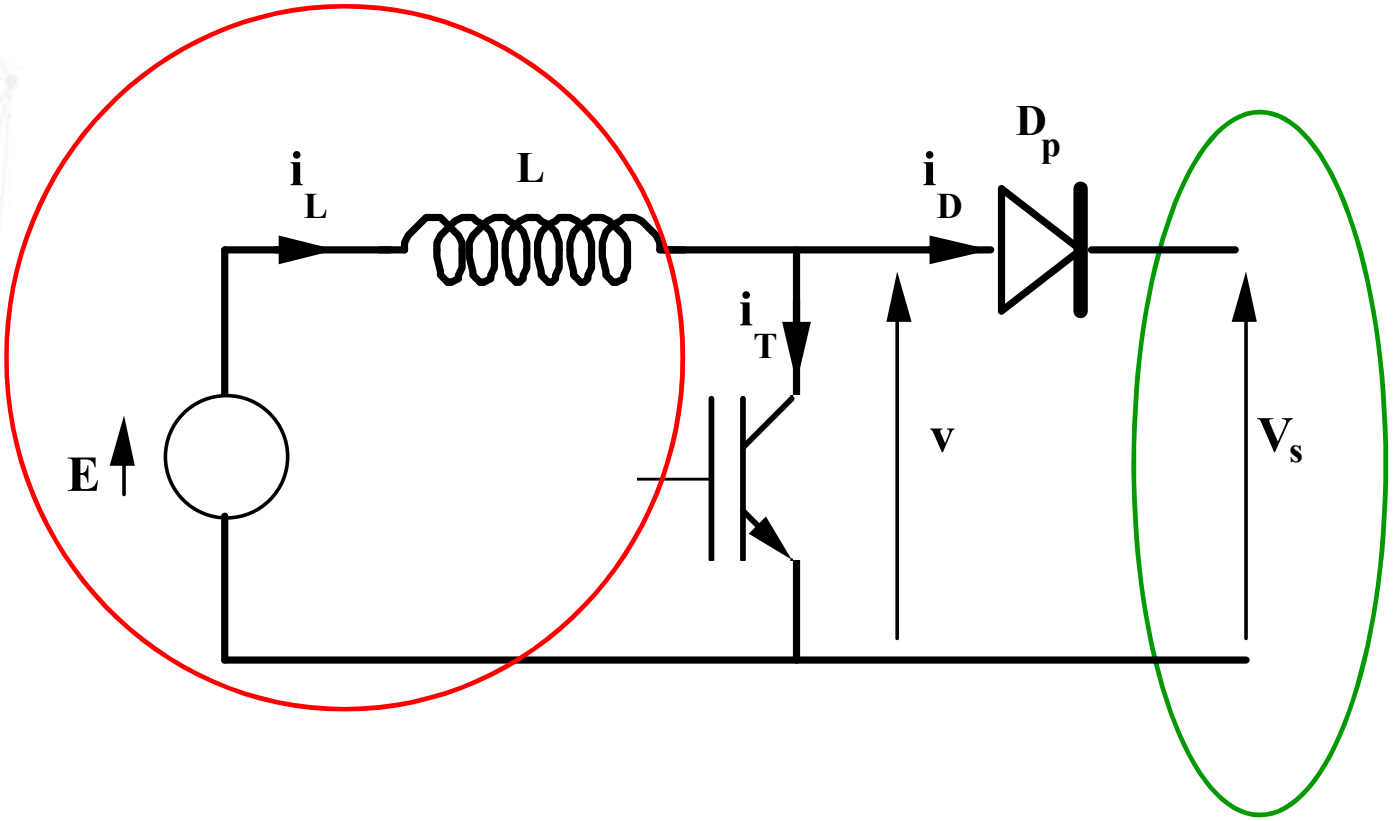
Buck chopper : Voltage source → **Current receiver**

Boost chopper : Current source → **Voltage receiver**

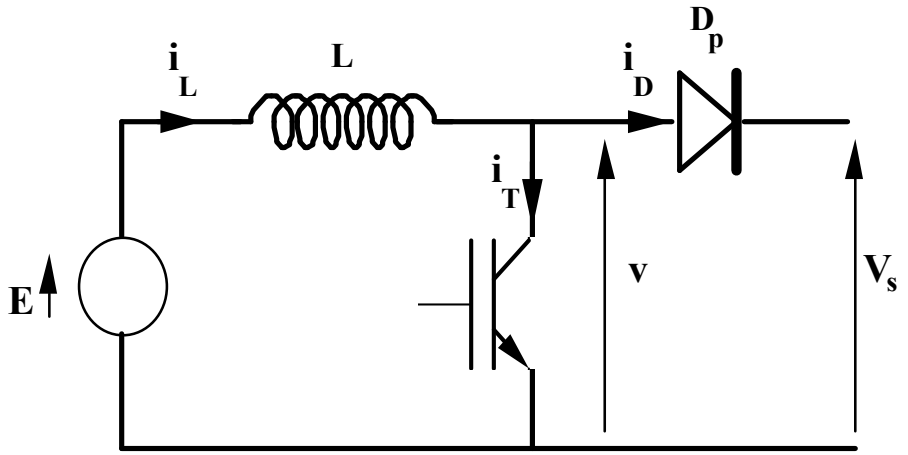
Current source⇔ Voltage source + inductor

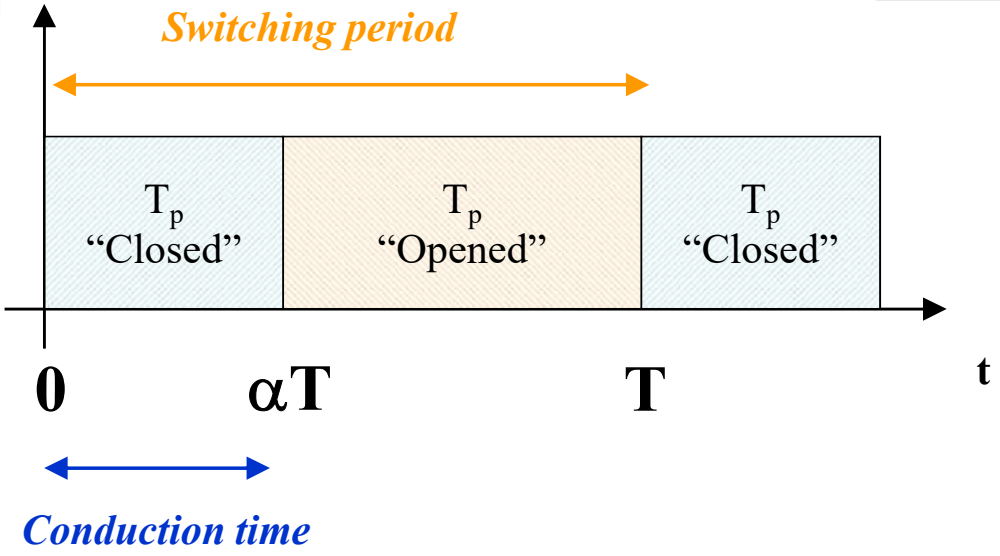
→ **Voltage receiver⇔ Battery or capacitive receiver**

Boost chopper: principle



Control





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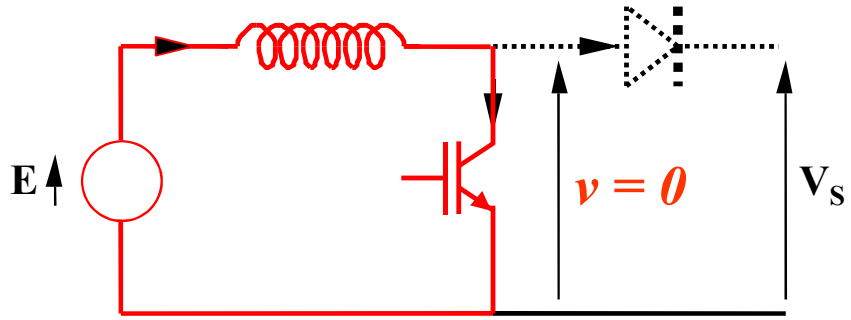
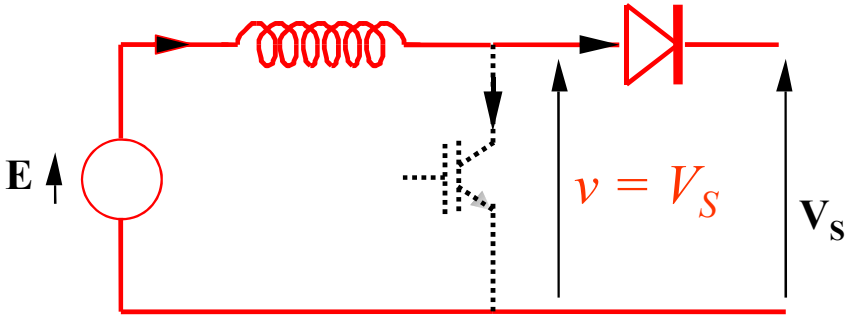
Principle



$0 < t < \alpha T$



$\alpha T < t < T$

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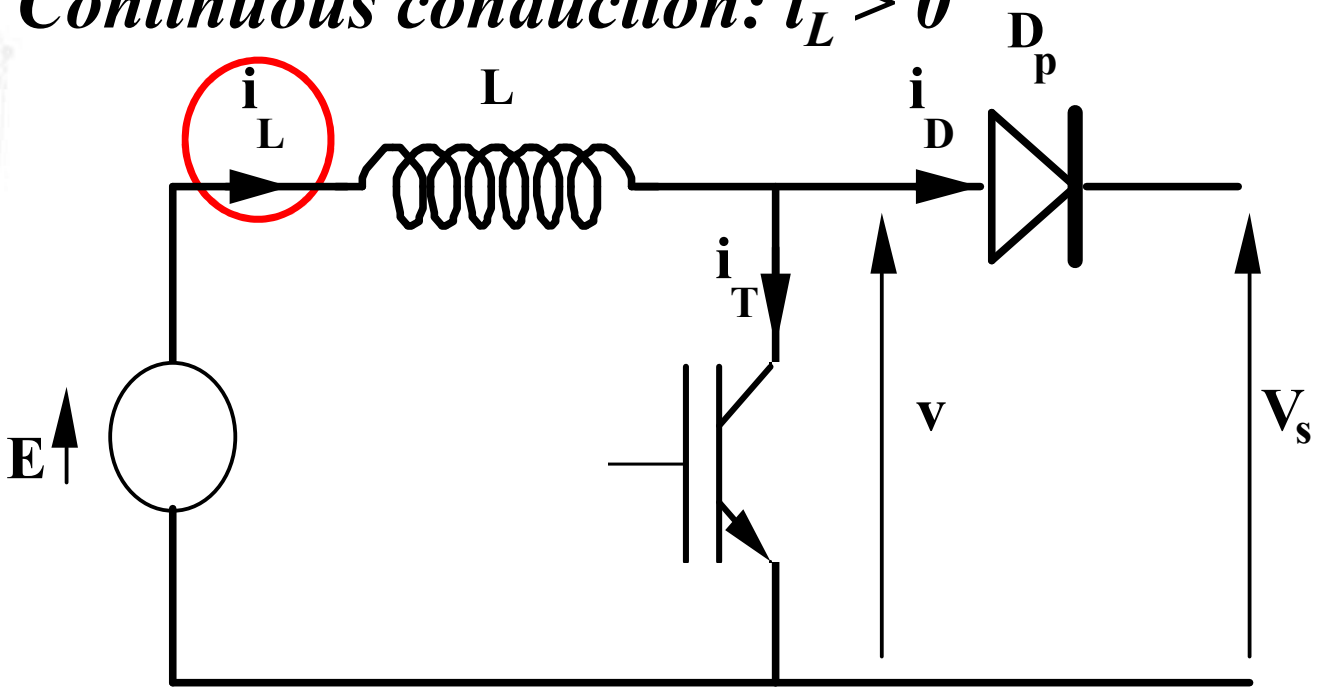
Modes

- ***Continuous conduction: $i_L > 0$***



- ***Discontinuous conduction: $i_L(t_0) = 0$; $t_0 < T$***

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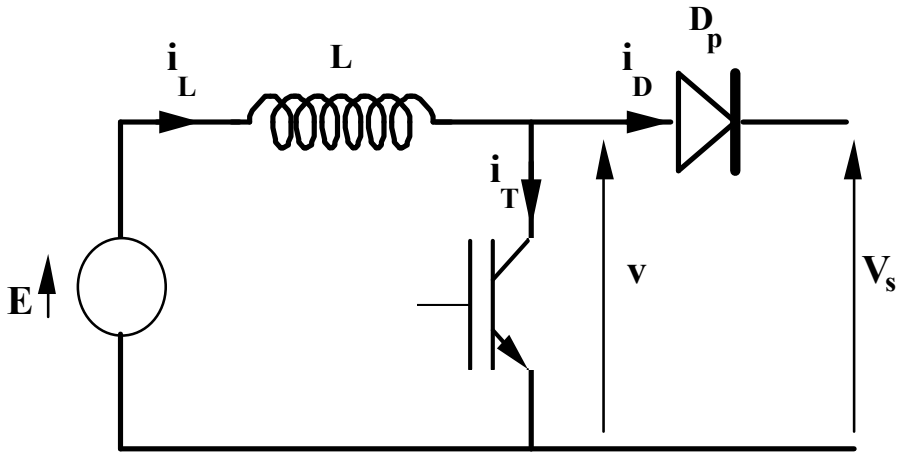
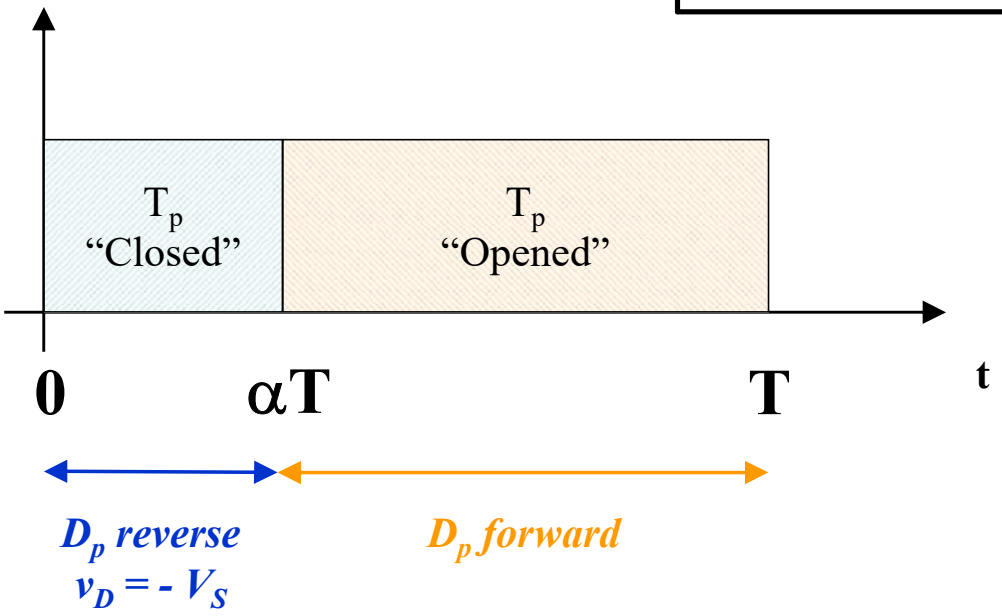
Continuous mode





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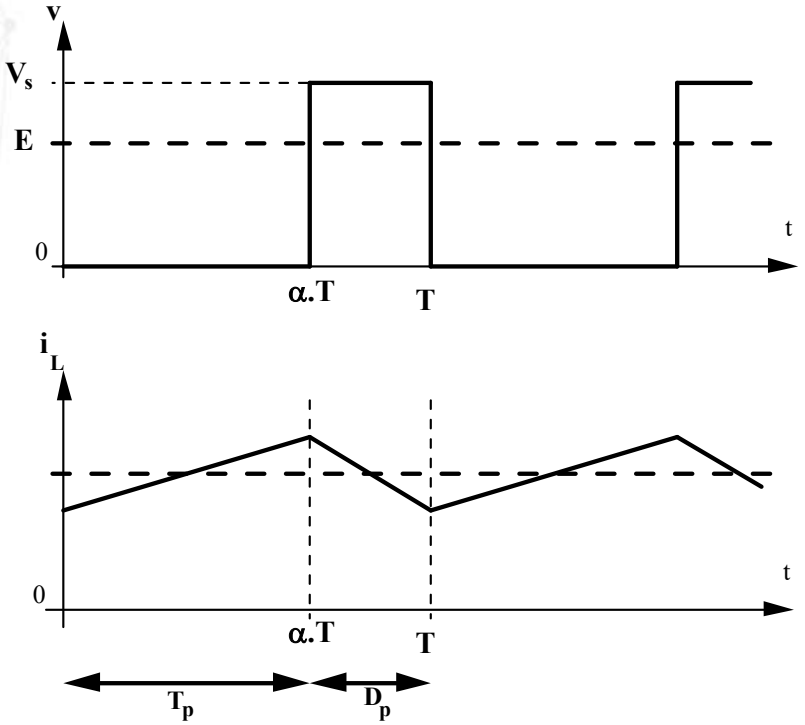
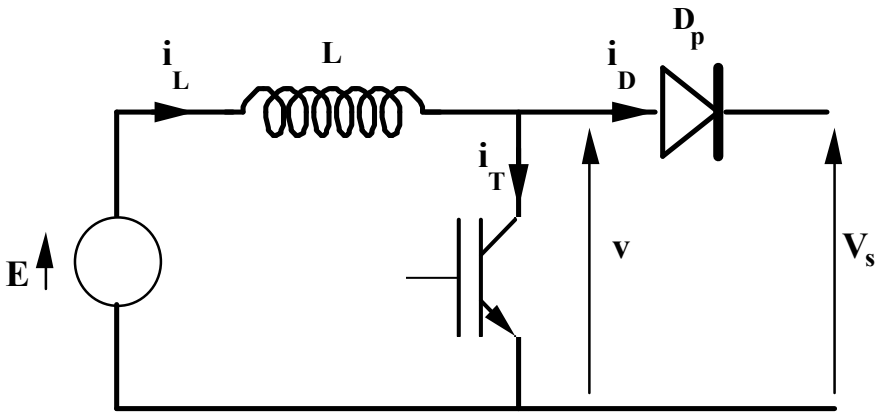
Continuous mode: Chronograms





- $0 < t < \alpha T$

$$\frac{di}{dt} = \frac{E}{L}$$

- $\alpha T < t < T$

$$\frac{di}{dt} = \frac{E - V_s}{L}$$

$E < V_S$

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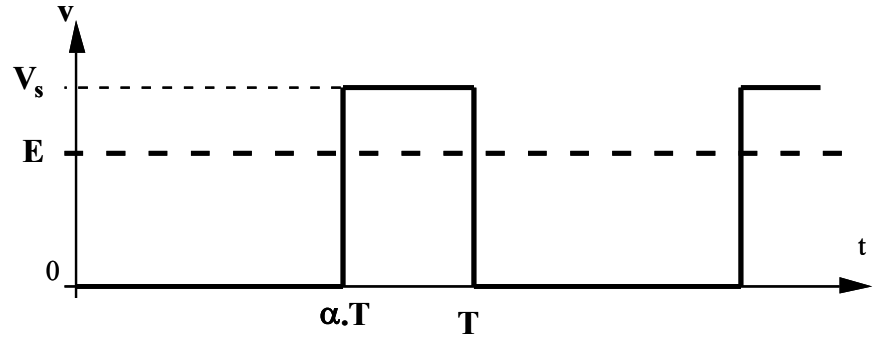
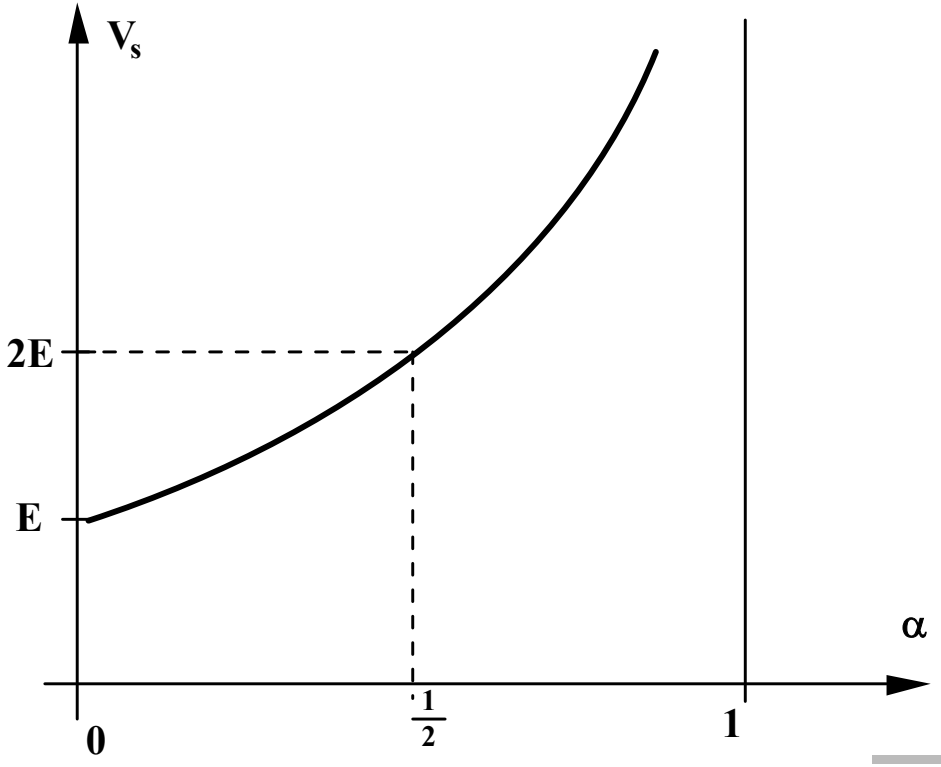
Continuous mode: Output voltage calculation

$$V_S = \frac{E}{1-\alpha}$$





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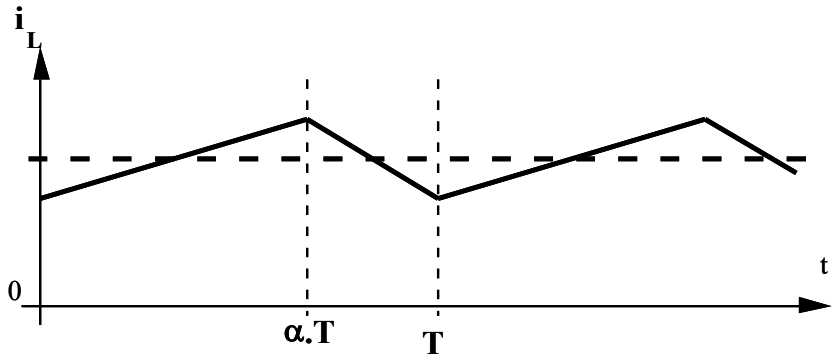
Continuous mode: Current ripple calculation



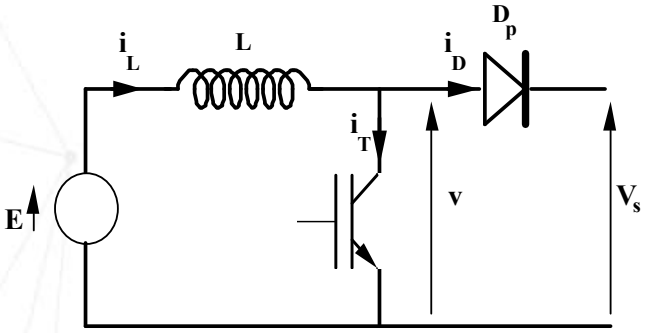
Current ripple i_L

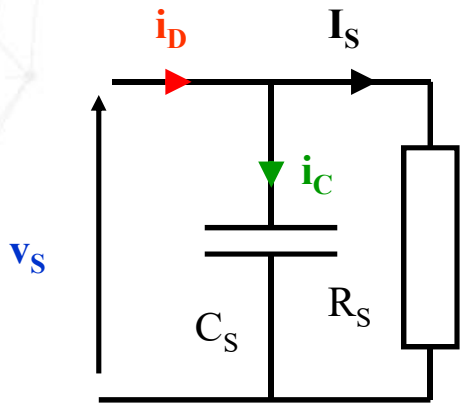
$$\Delta I_L = \alpha . \frac{E.T}{L}$$

Maximum ripple ($\alpha = 1$)

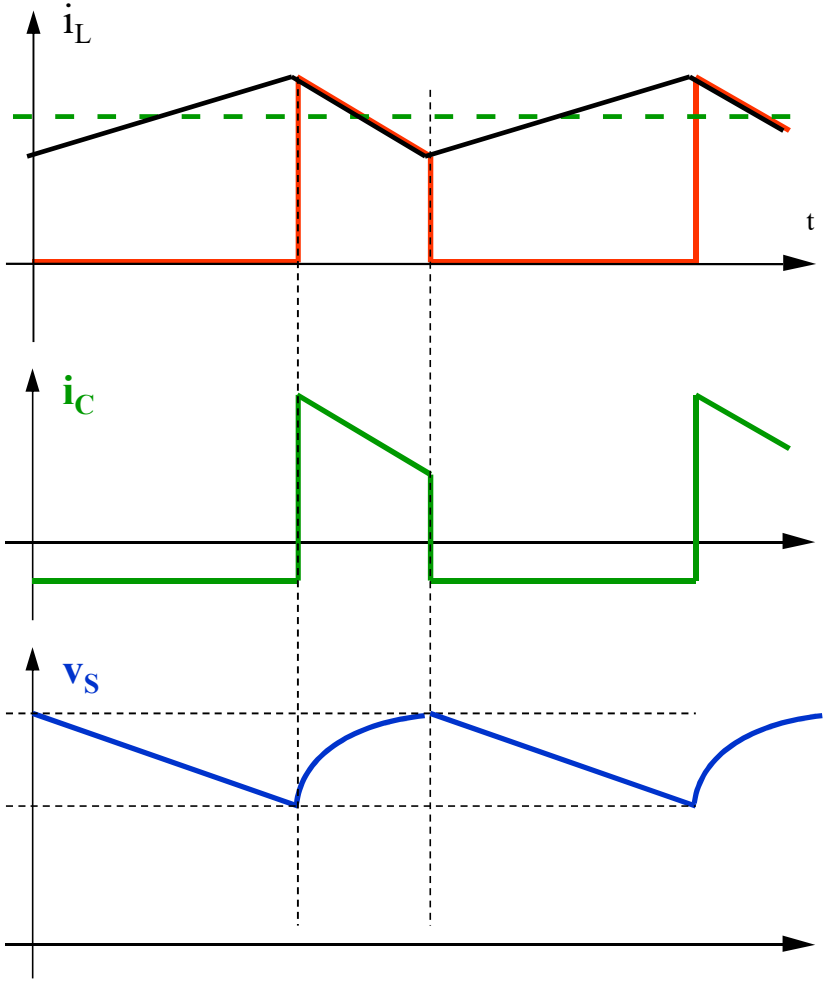
$$\boxed{\Delta I_{L\,max} = \frac{E.T}{L}}$$

Continuous mode: Output filtering





$$i_C = C_S . \frac{dv_S}{dt}$$



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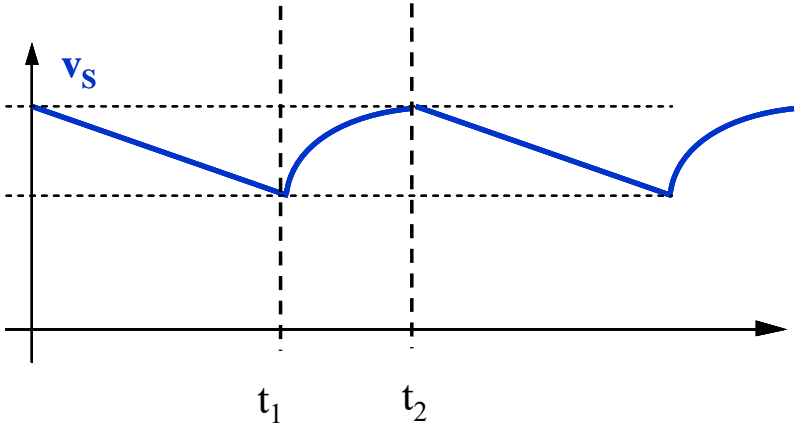
Continuous mode: Output filtering

$$\Delta V_S = \frac{1}{C_S}.\int_{t_1}^{t_2} i_C(t).dt = \frac{I_S.\alpha T}{C_S}$$

$$or\ I_S = \frac{V_S}{R_S} = \frac{E}{(1-\alpha)R_S}$$



$$\Delta V_S = \frac{ET}{R_S C_S}.\frac{\alpha}{1-\alpha}$$

C_S

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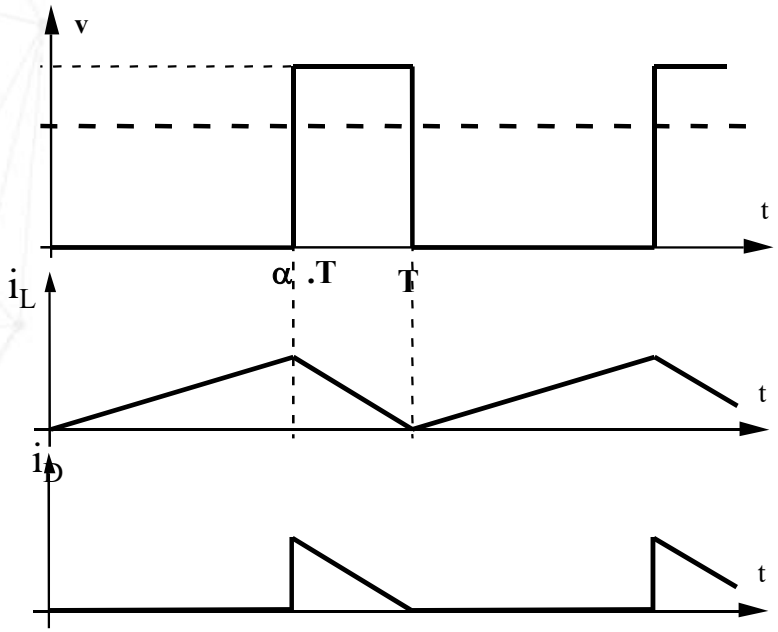
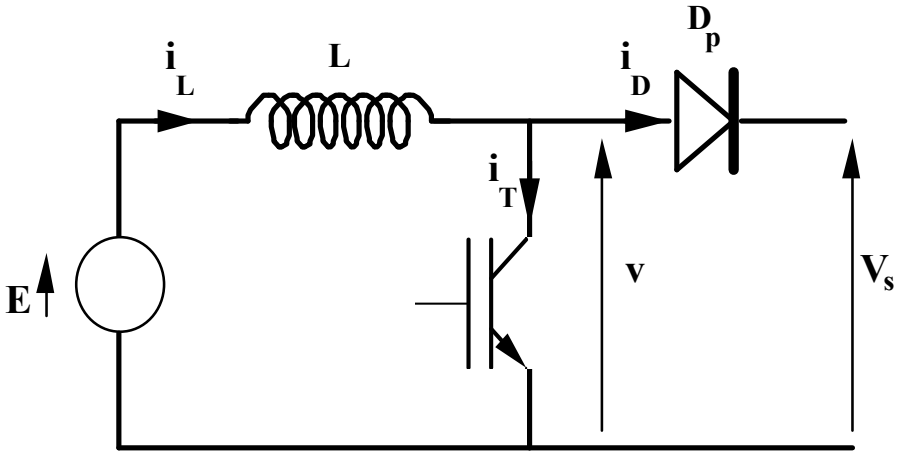
Boundary mode: $i_L(T)=0$





$$I_S = < i_D > = \frac{1}{2} . I_{L\max} . (1-\alpha) = \frac{ET}{2L} . \alpha (1-\alpha)$$

$$V_S = \frac{E}{1-\alpha}$$

$$I_S = \frac{ET}{2L} \cdot \frac{E}{V_S} \cdot \left(1 - \frac{E}{V_S} \right)$$

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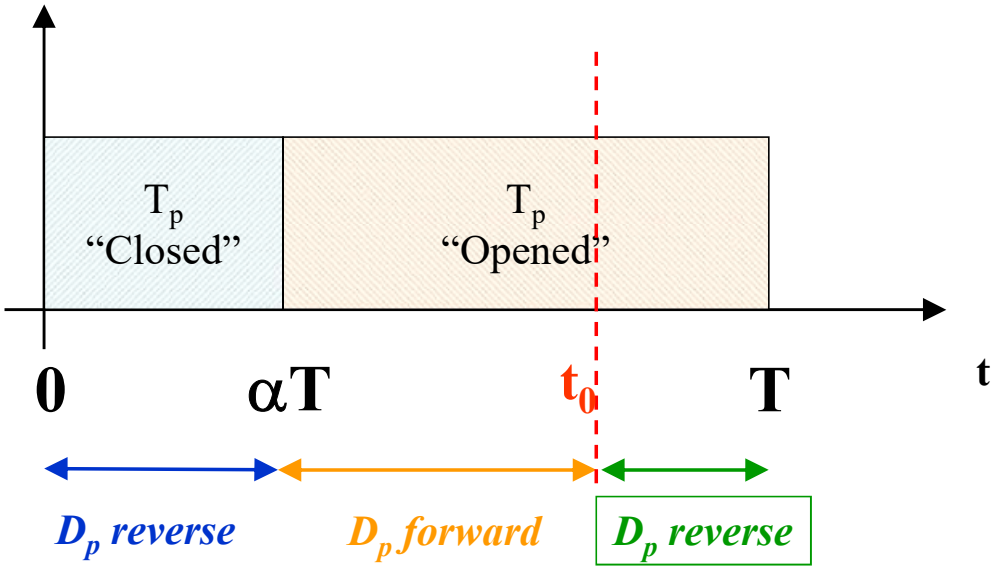
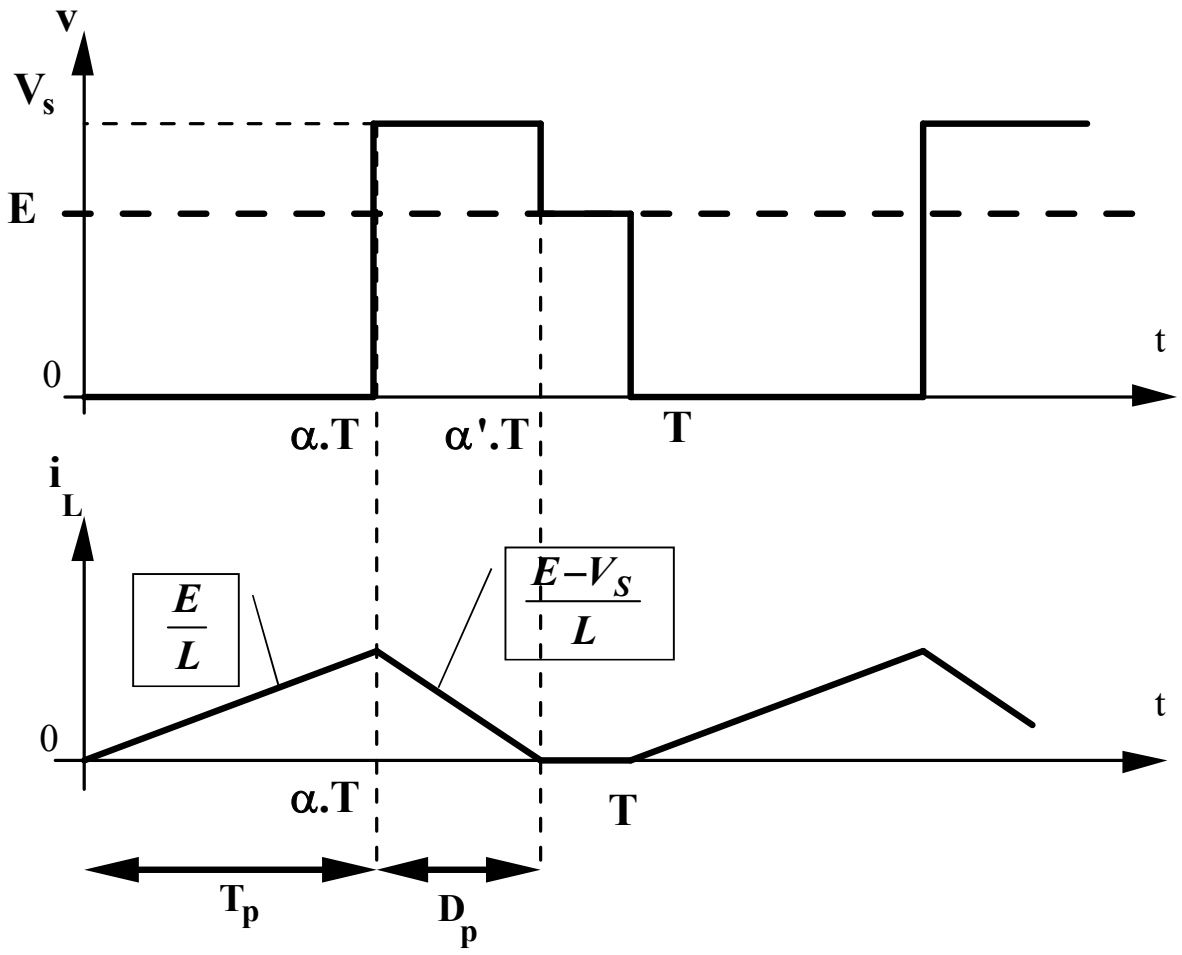
Discontinuous mode



At $t_0 = \alpha'.T$: diode switches to reverse mode

Discontinuous mode: Chronograms



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Discontinuous mode: calculation

$$\frac{E}{L}\alpha T=\frac{V_S-E}{L}(\alpha'-\alpha)T \quad \Rightarrow \quad V_S=\frac{\alpha'}{\alpha'-\alpha}E$$

$$I_S=<i_D>=\frac{1}{2}.I_{L\max}.(\alpha'-\alpha)=\frac{ET}{2L}.\alpha(\alpha'-\alpha)$$

$$\Rightarrow \quad V_S=E+\frac{\alpha^2E^2T}{2LI_S}$$

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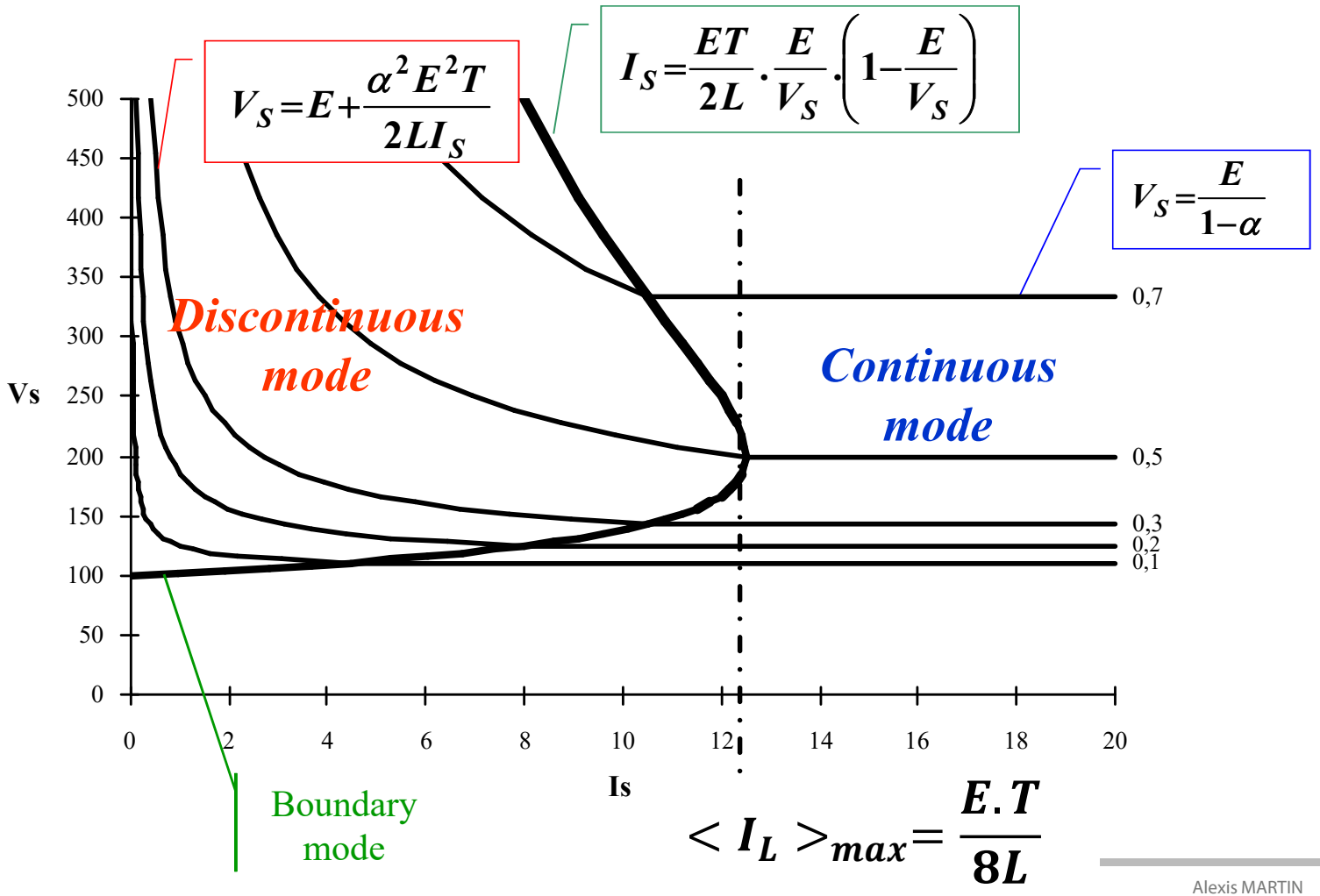
Discontinuous mode: output characteristics



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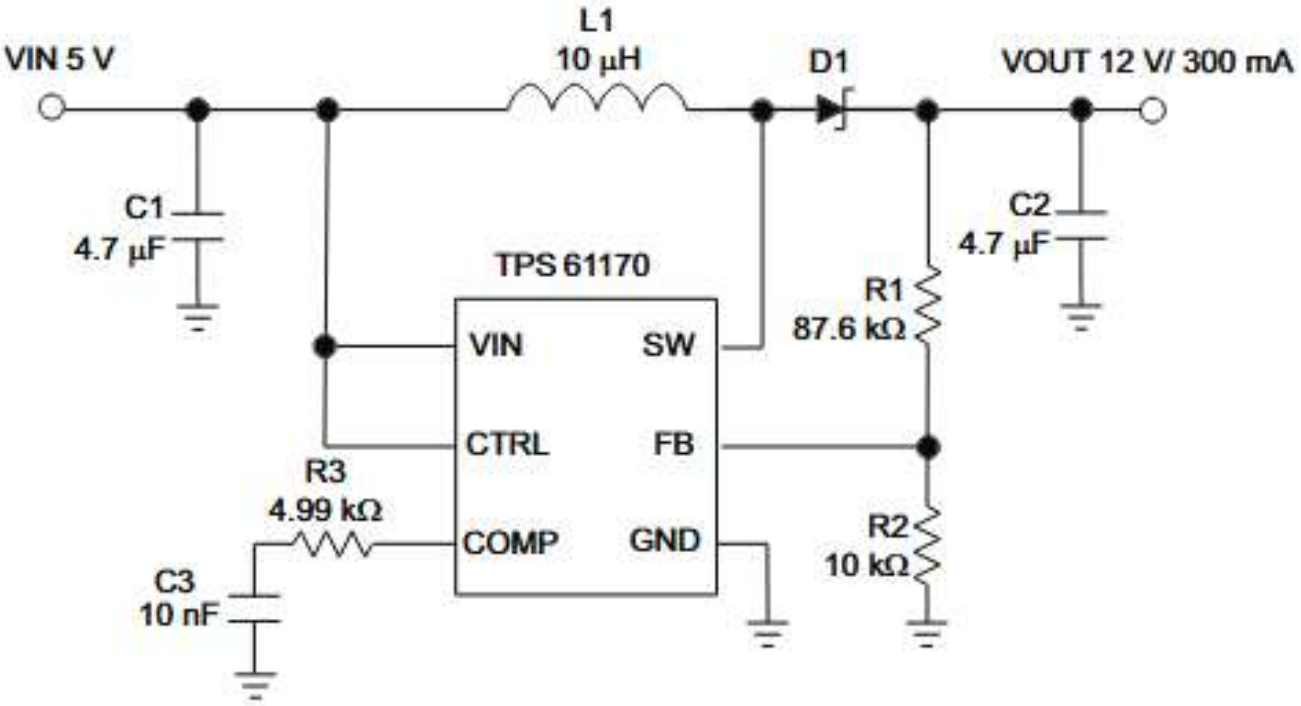
Example : TPS61170



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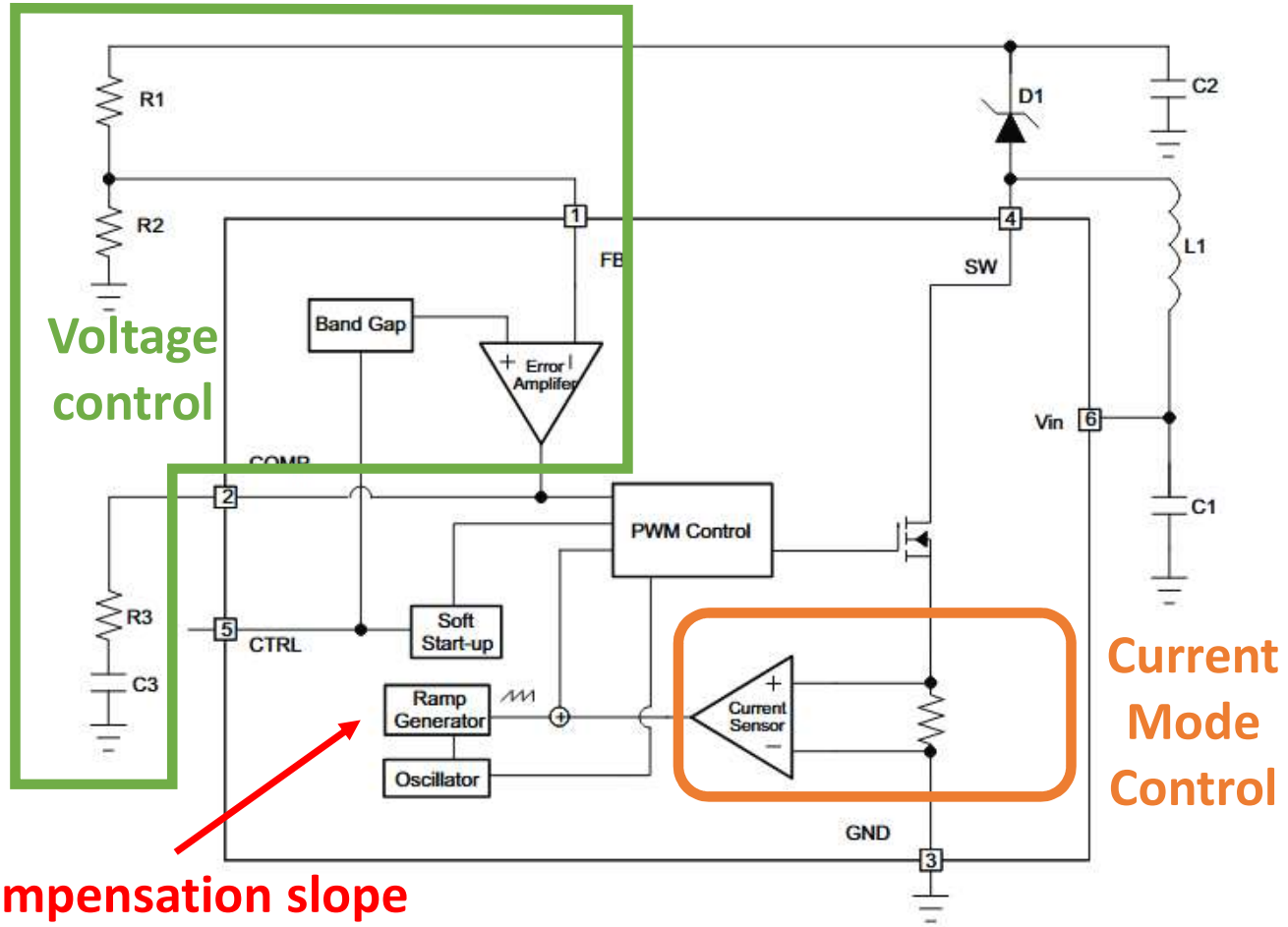
Example : TPS61170



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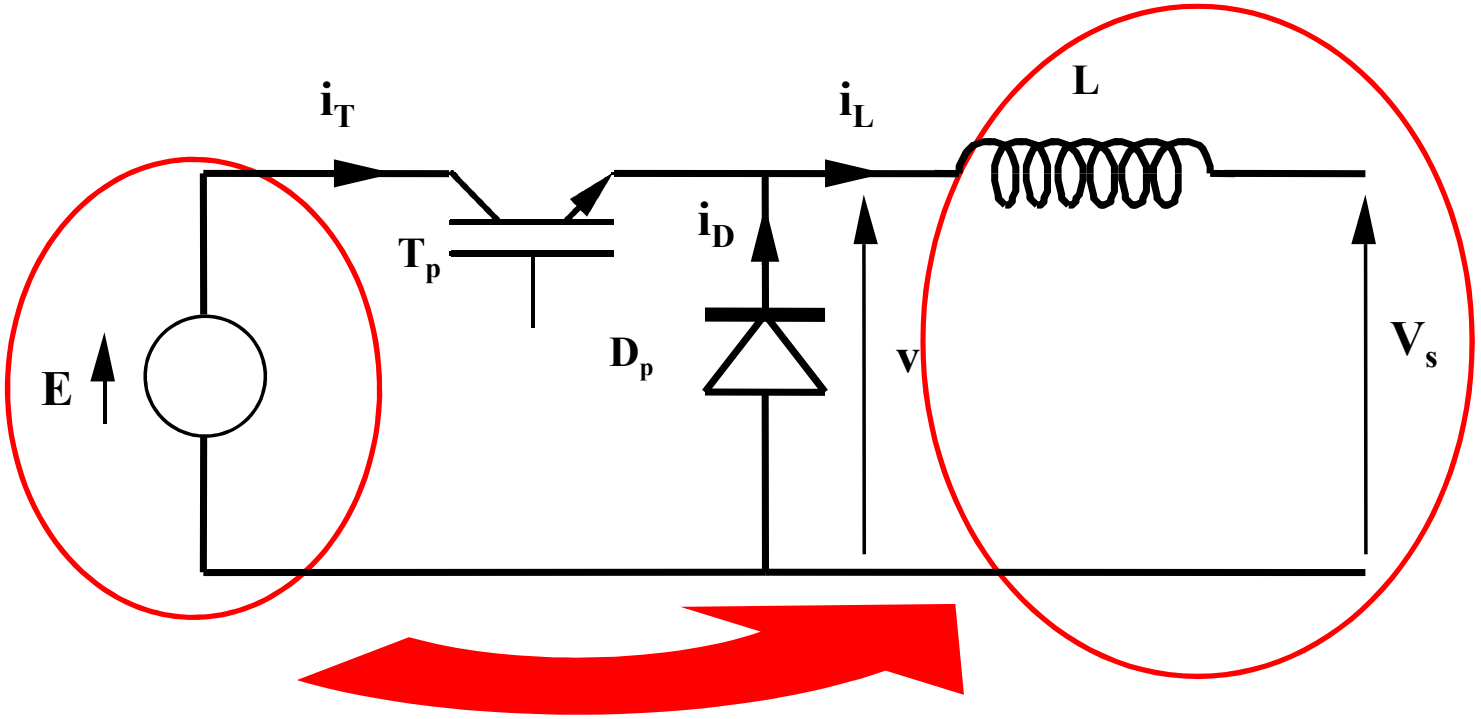
Reminder : buck chopper



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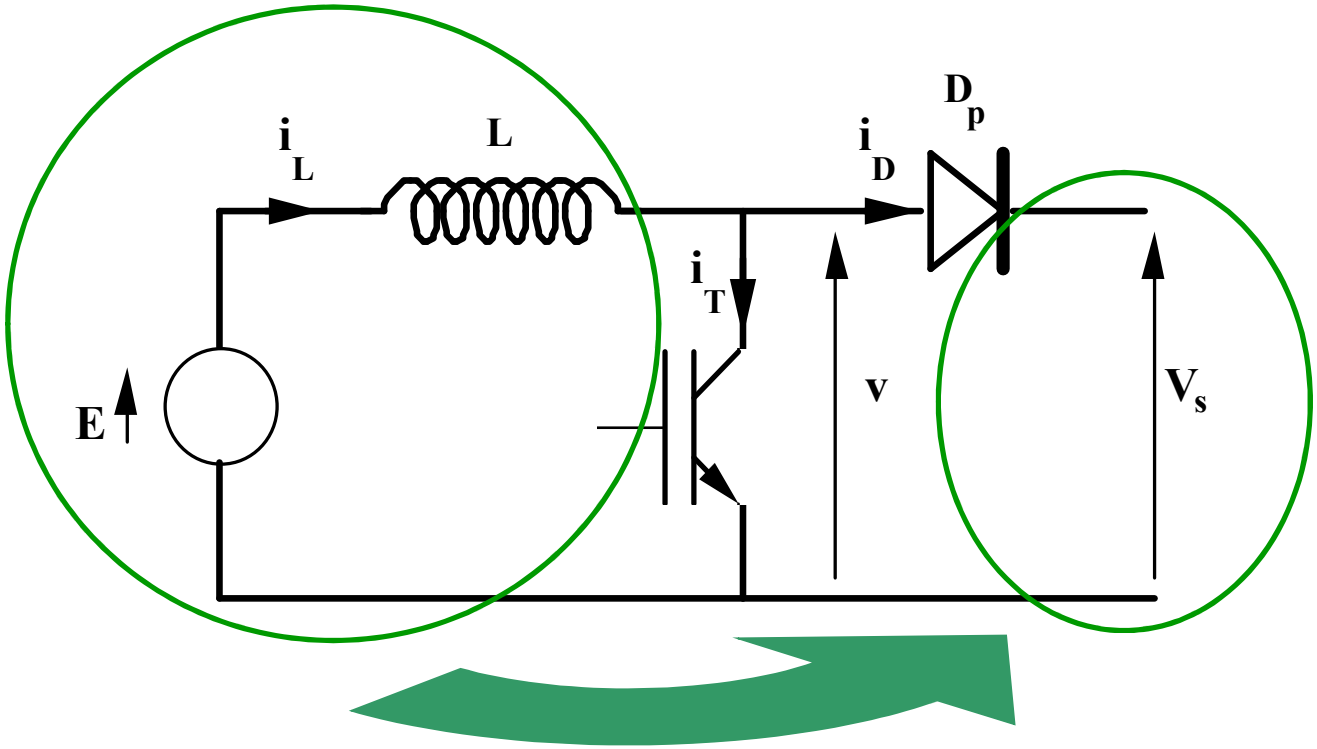
Reminder : boost chopper



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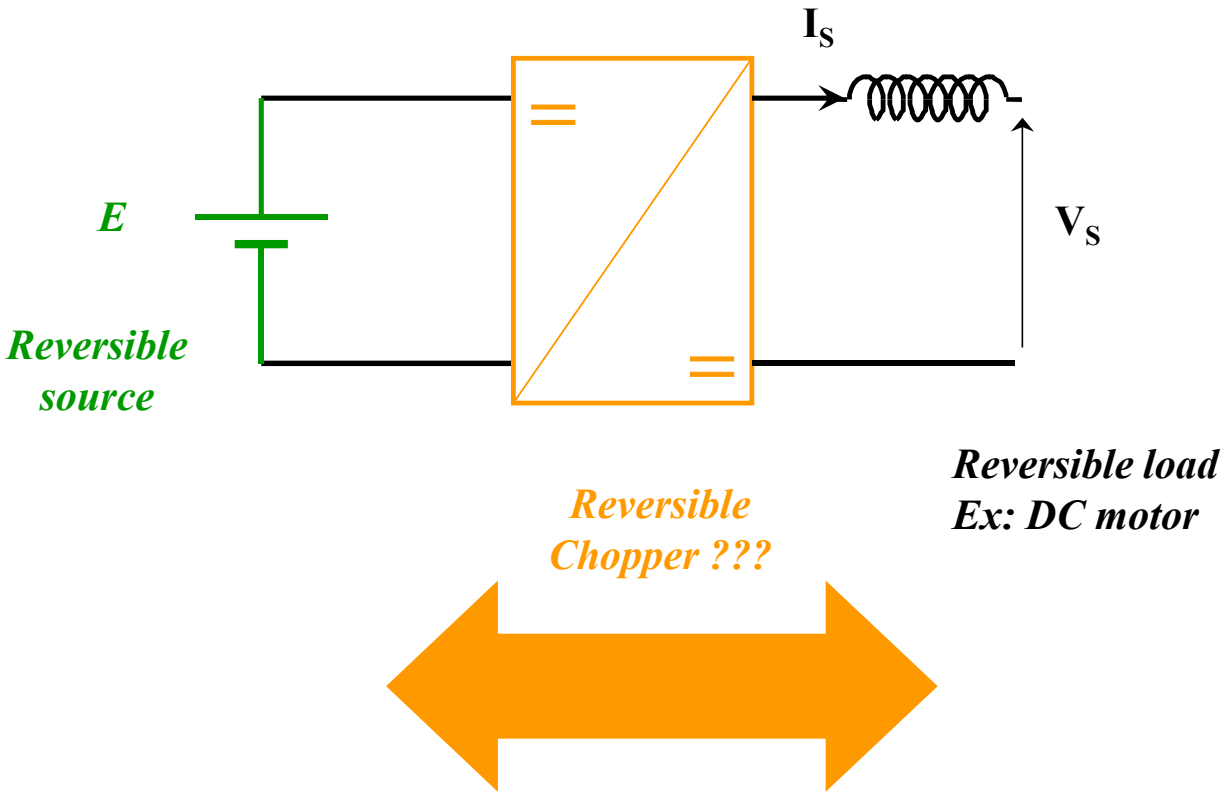
Linked sources



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Reversible Chopper

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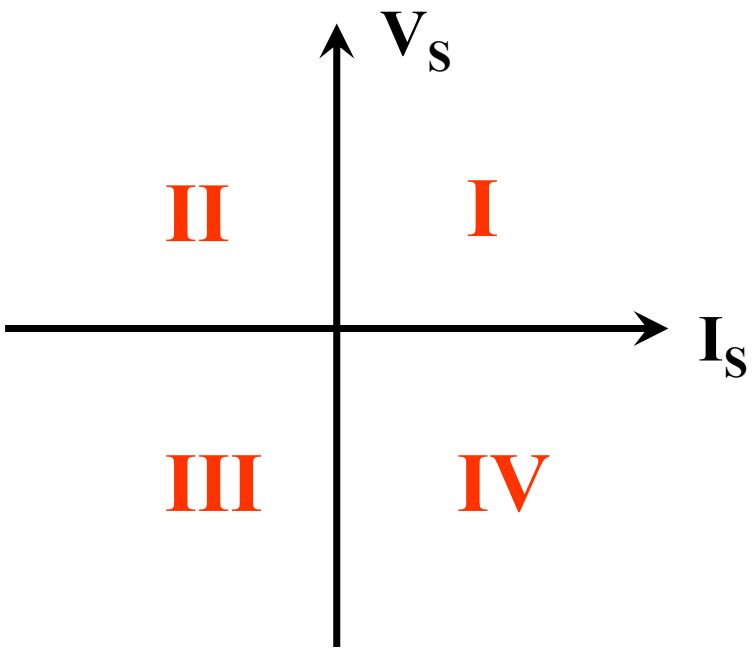
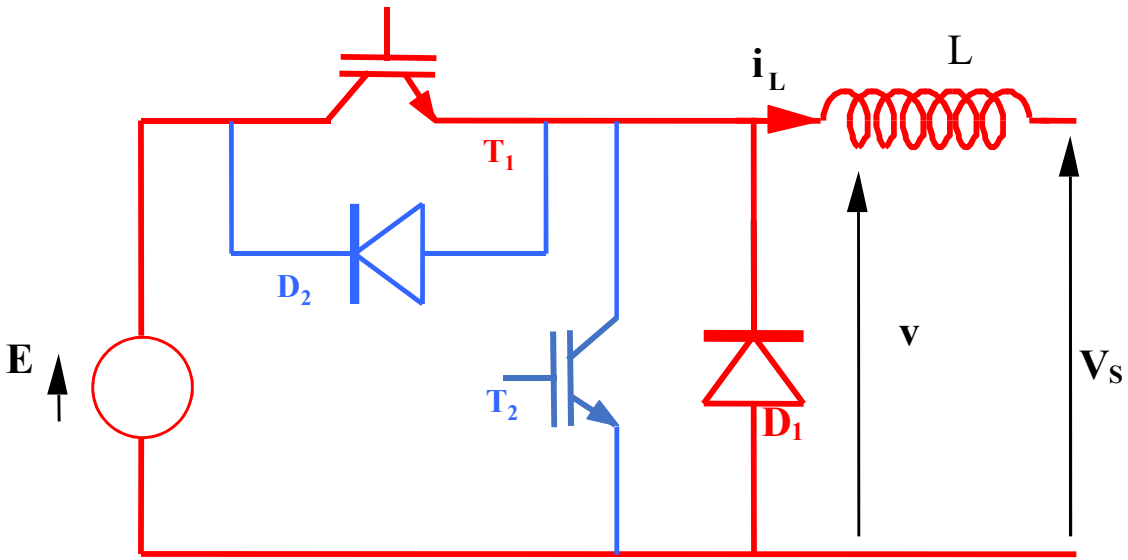
Reversible choppers: quadrants



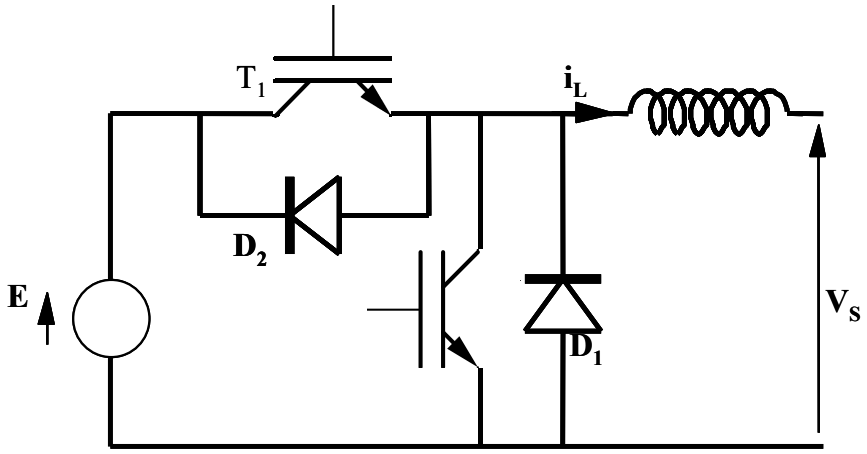
Two quadrants reversible chopper



Buck chopper

Boost chopper

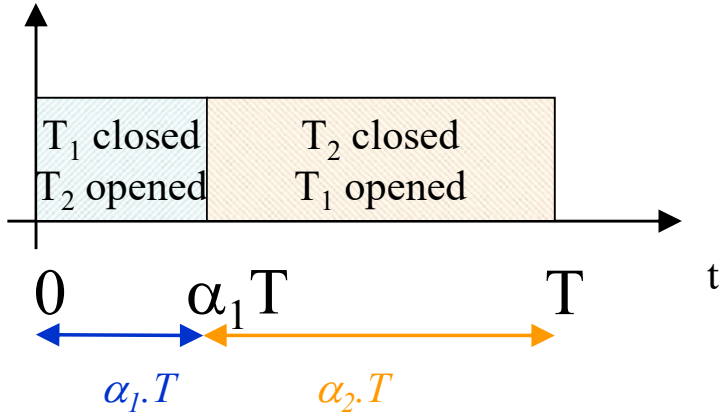
Two quadrants chopper: control



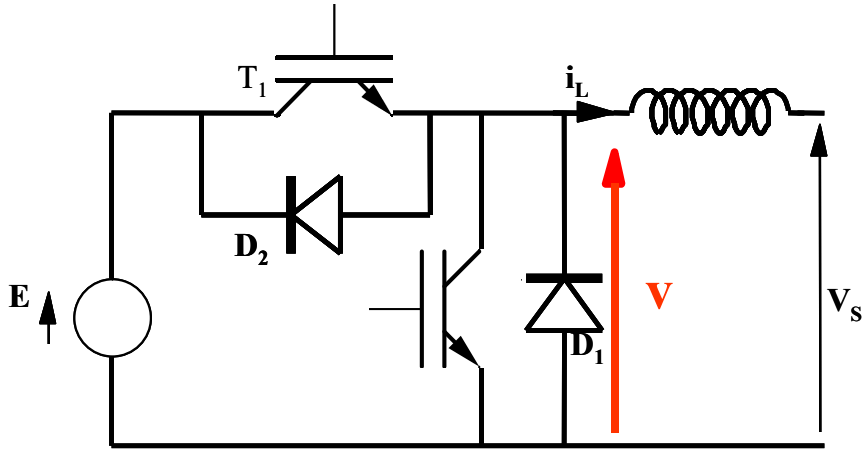
2 switches => 2 duty cycles

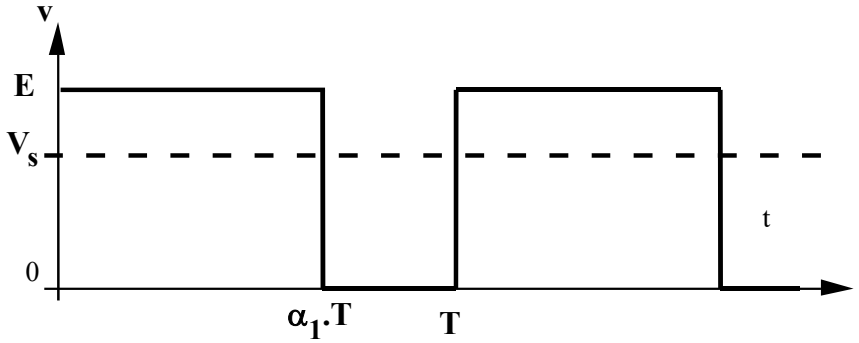
Complementary control

$\alpha_1 + \alpha_2 = 1$



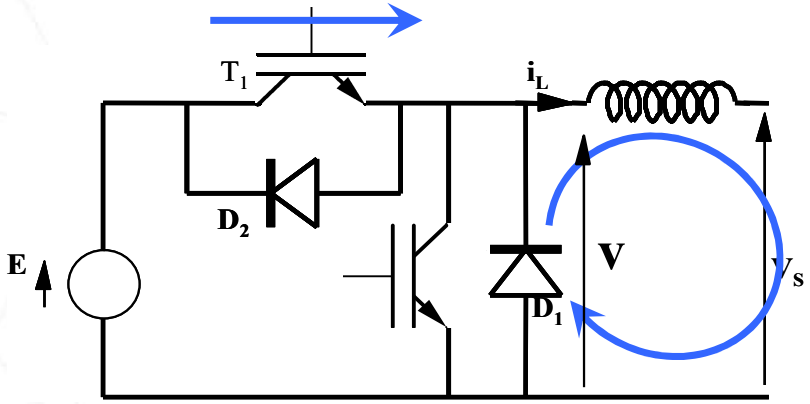
Two quadrants chopper: output voltage

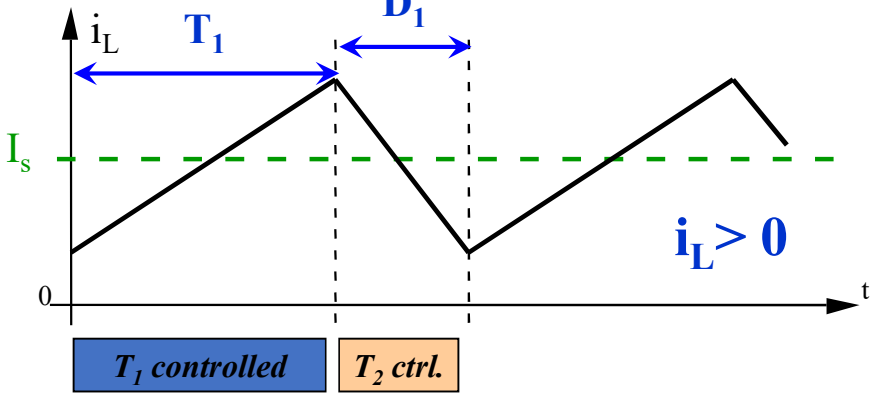


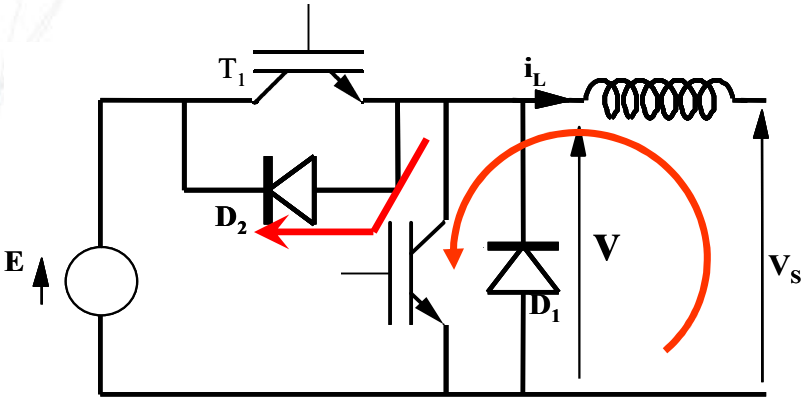


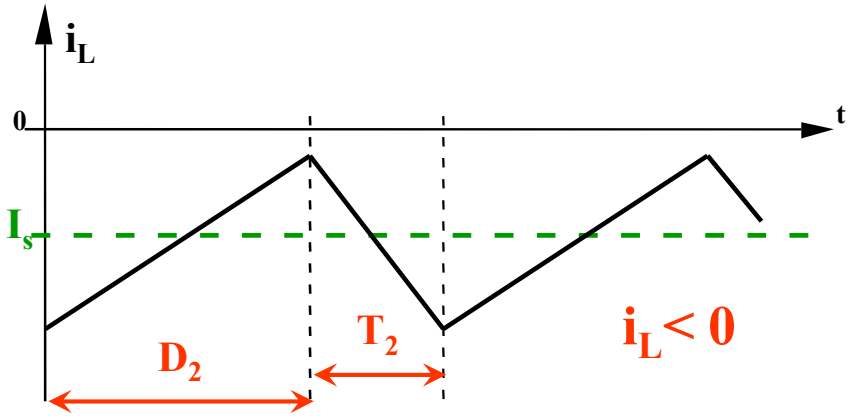
$$V_S = \alpha_1 . E$$

Two quadrants chopper: output current









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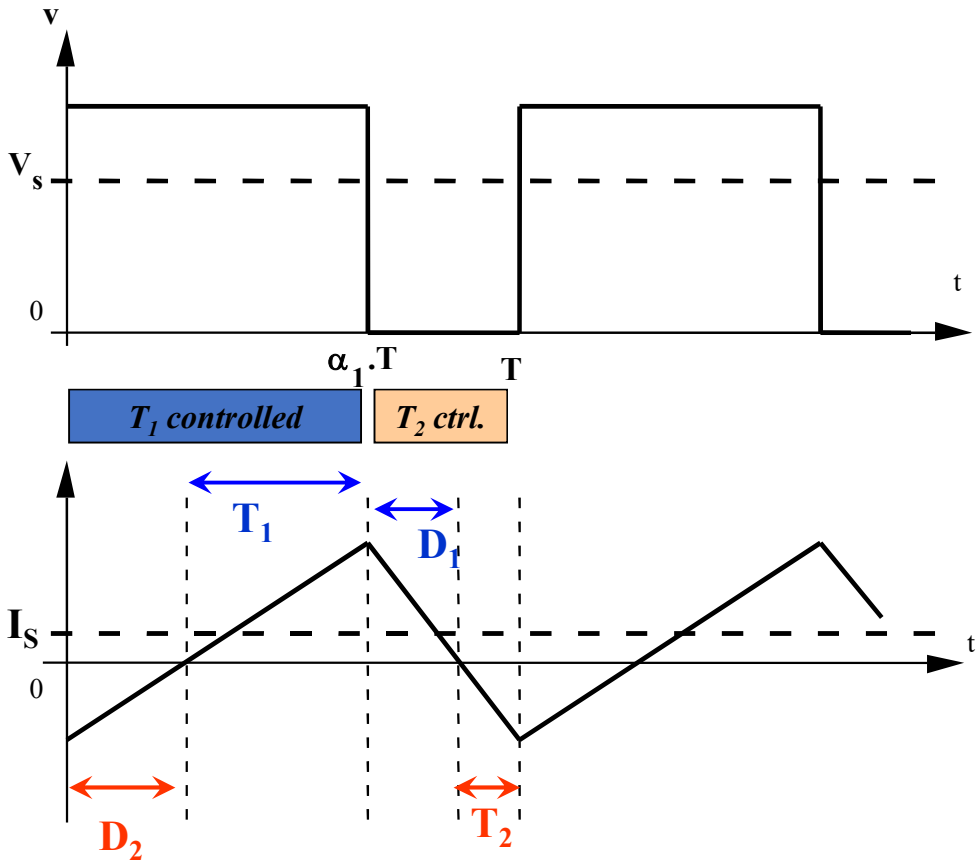
Two quadrants chopper: Arbitrary output current



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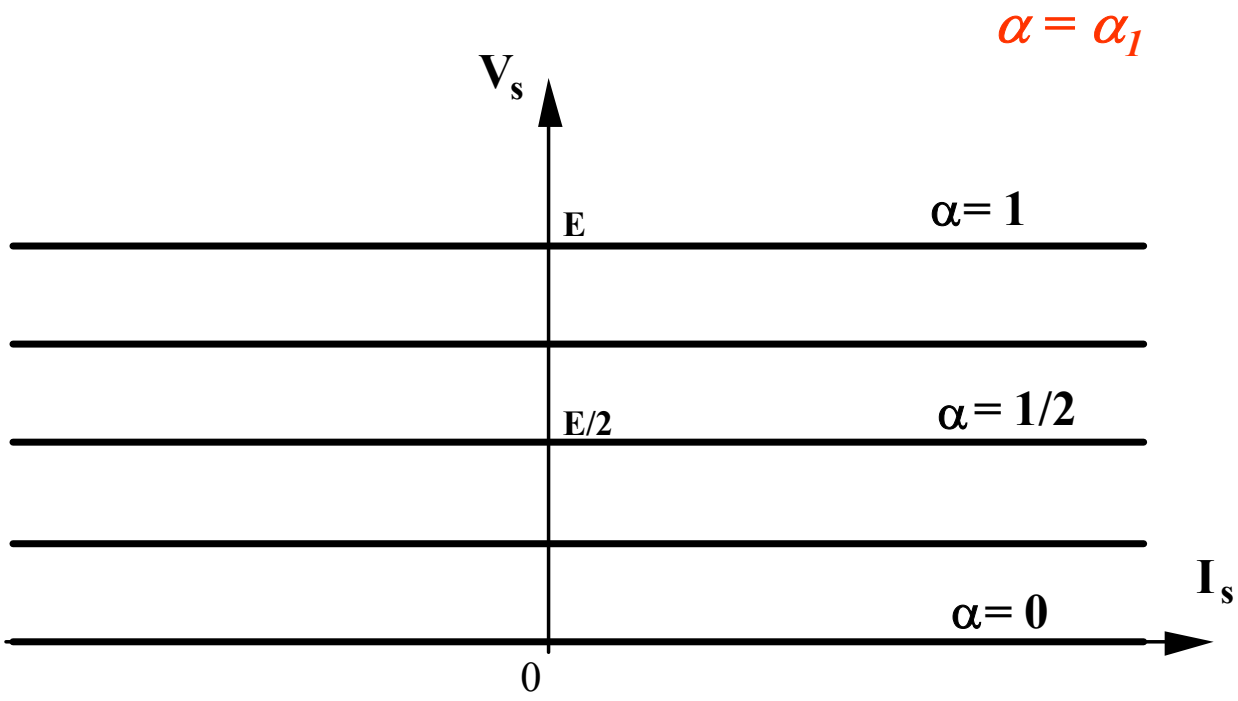
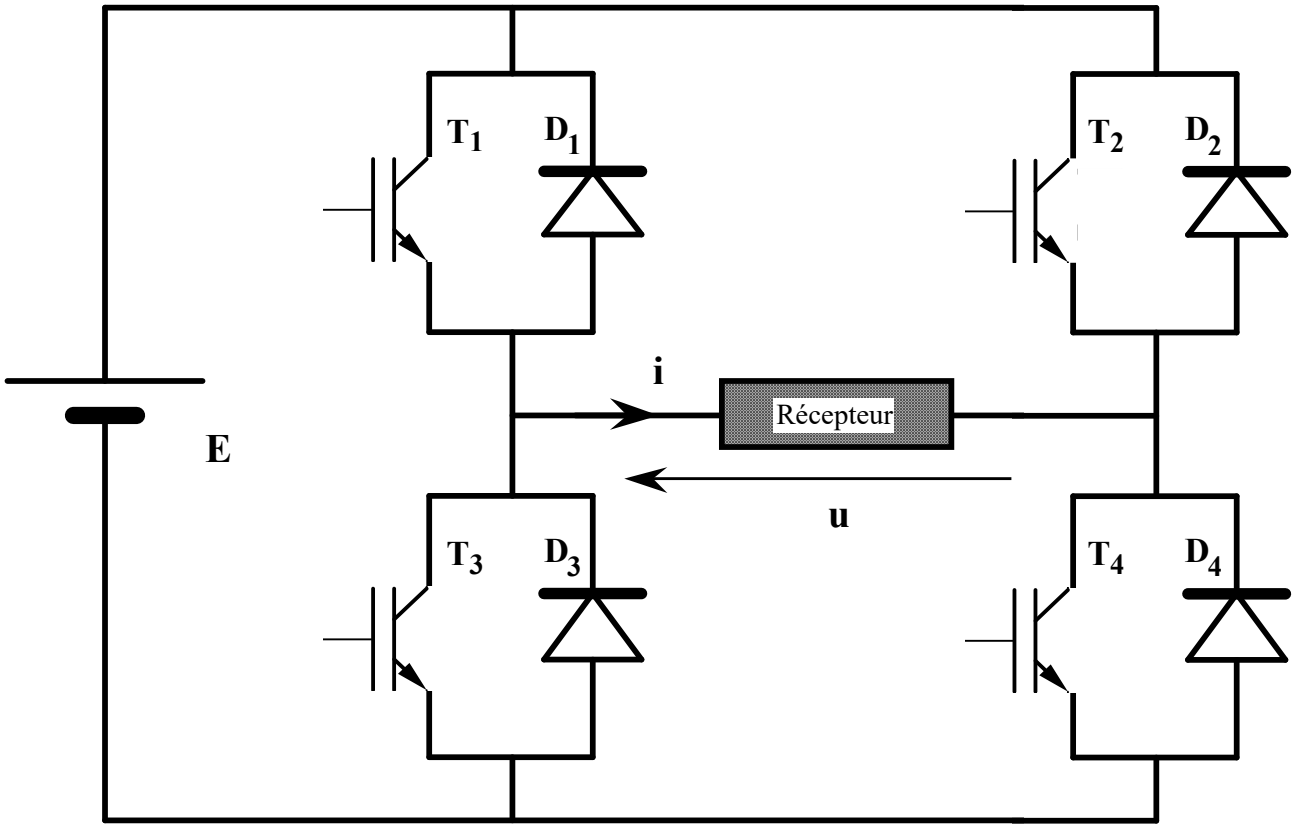
Two quadrants chopper: Output characteristics grid



4 quadrants chopper



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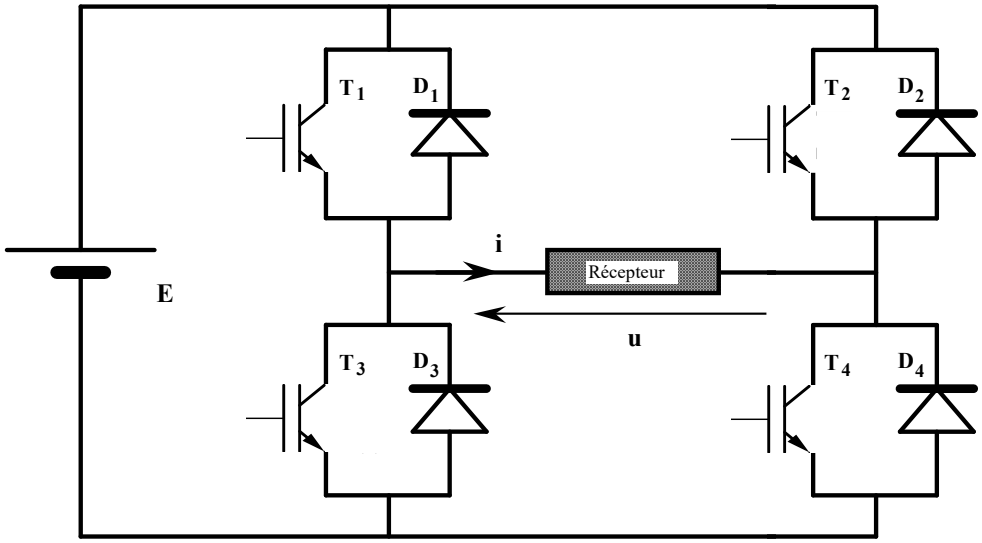
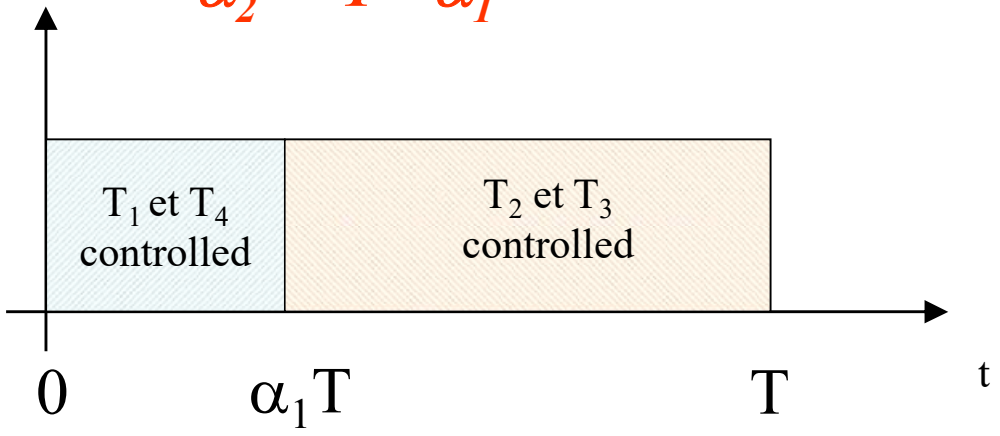
4 quadrants chopper: Synchronous complementary control



$$\alpha_1 = \alpha_4 \quad et \quad \alpha_2 = \alpha_3$$

$$\alpha_2 = 1 - \alpha_1$$



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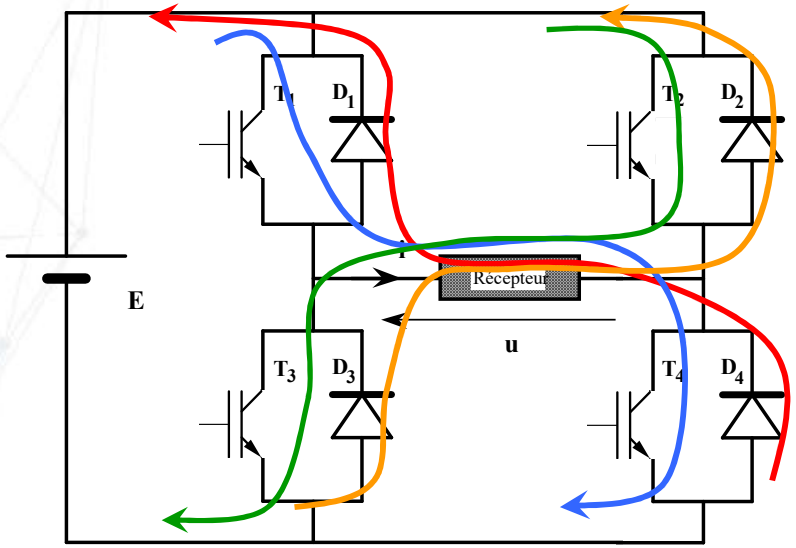
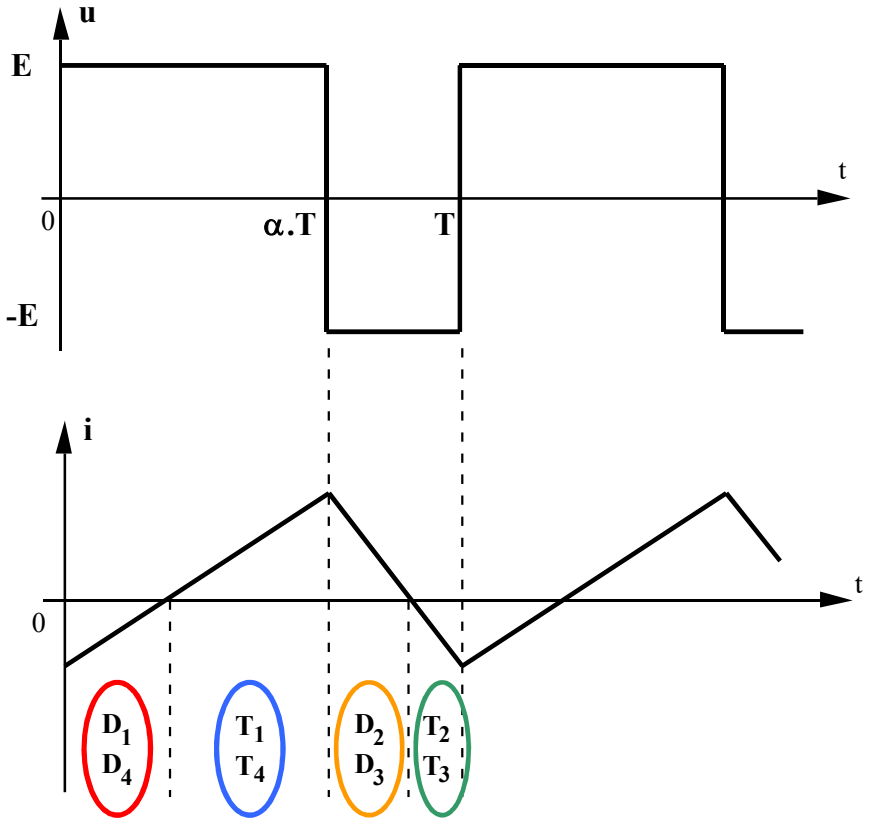
4 quadrants chopper:
Synchronous complementary control (chronograms)





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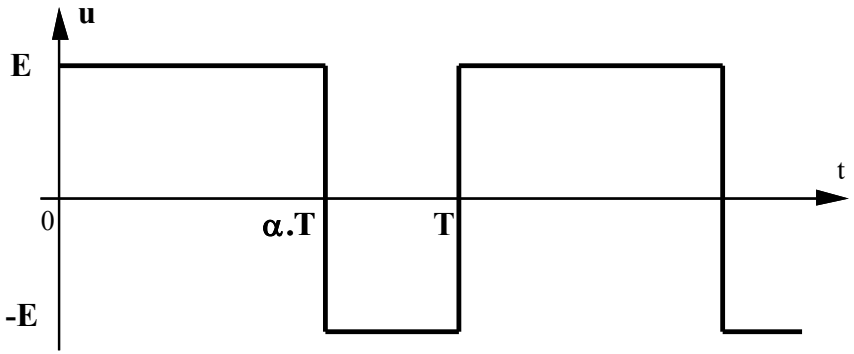
4 quadrants chopper:
Synchronous complementary control (Average output voltage)



$$< u > = (2\alpha - 1).E$$

High voltage ripple: 2.E
Low switching frequency

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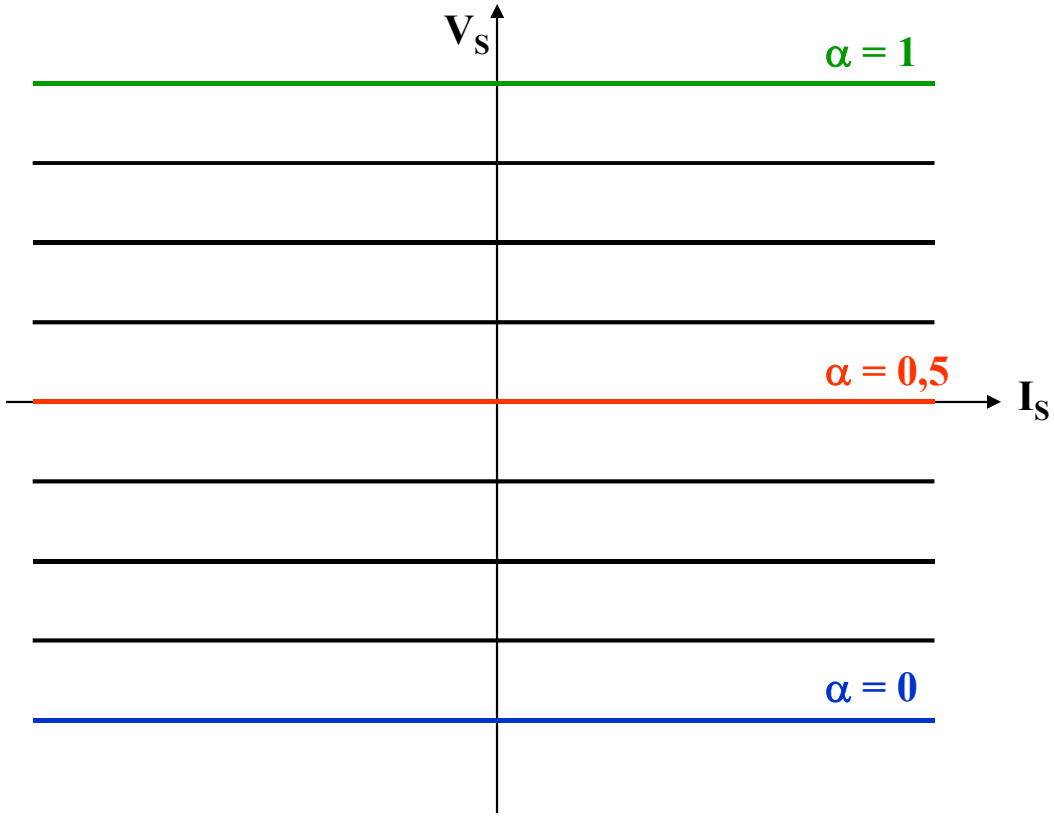
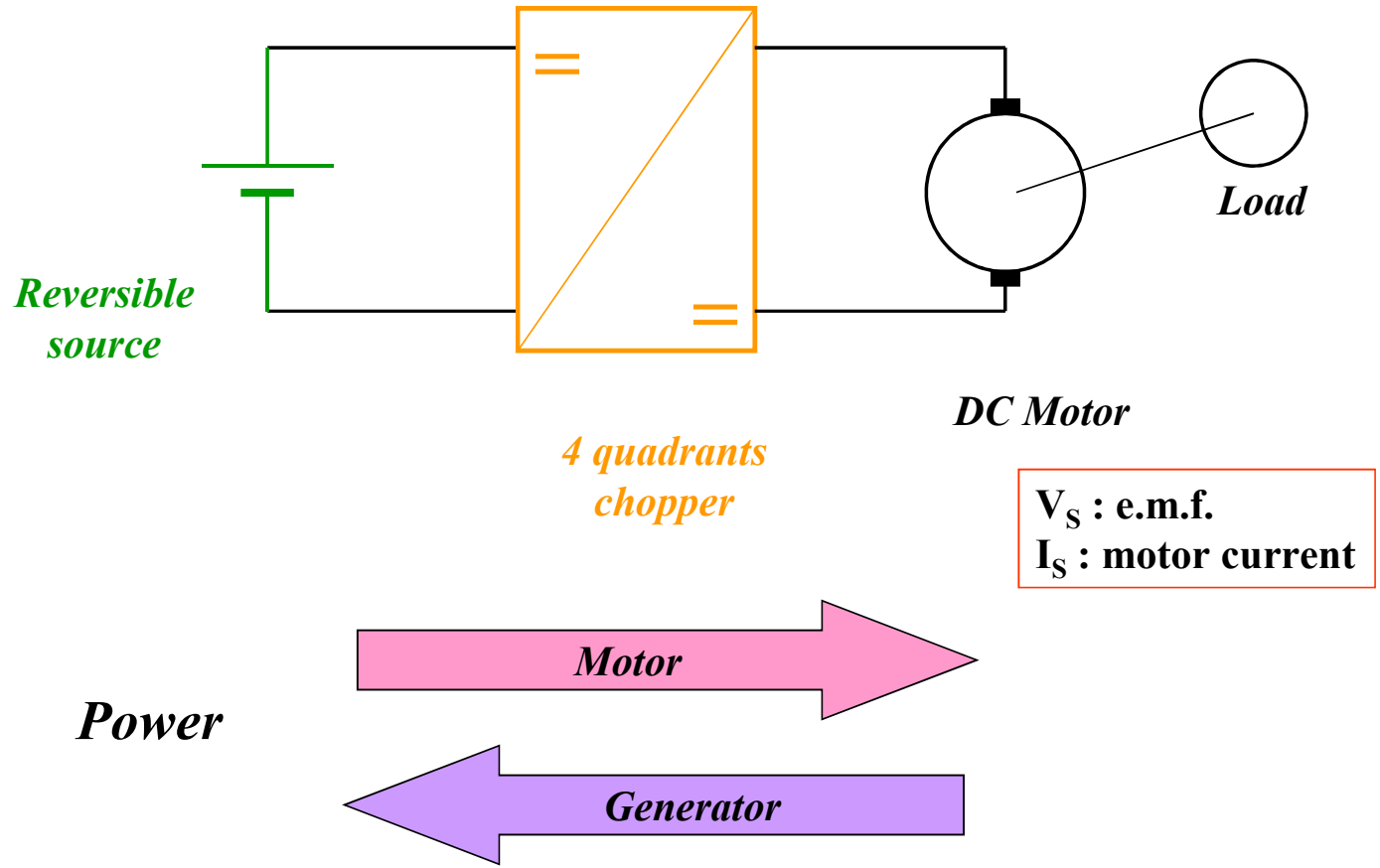
4 quadrants chopper: Output characteristics



4 quadrants chopper: control of a DC motor



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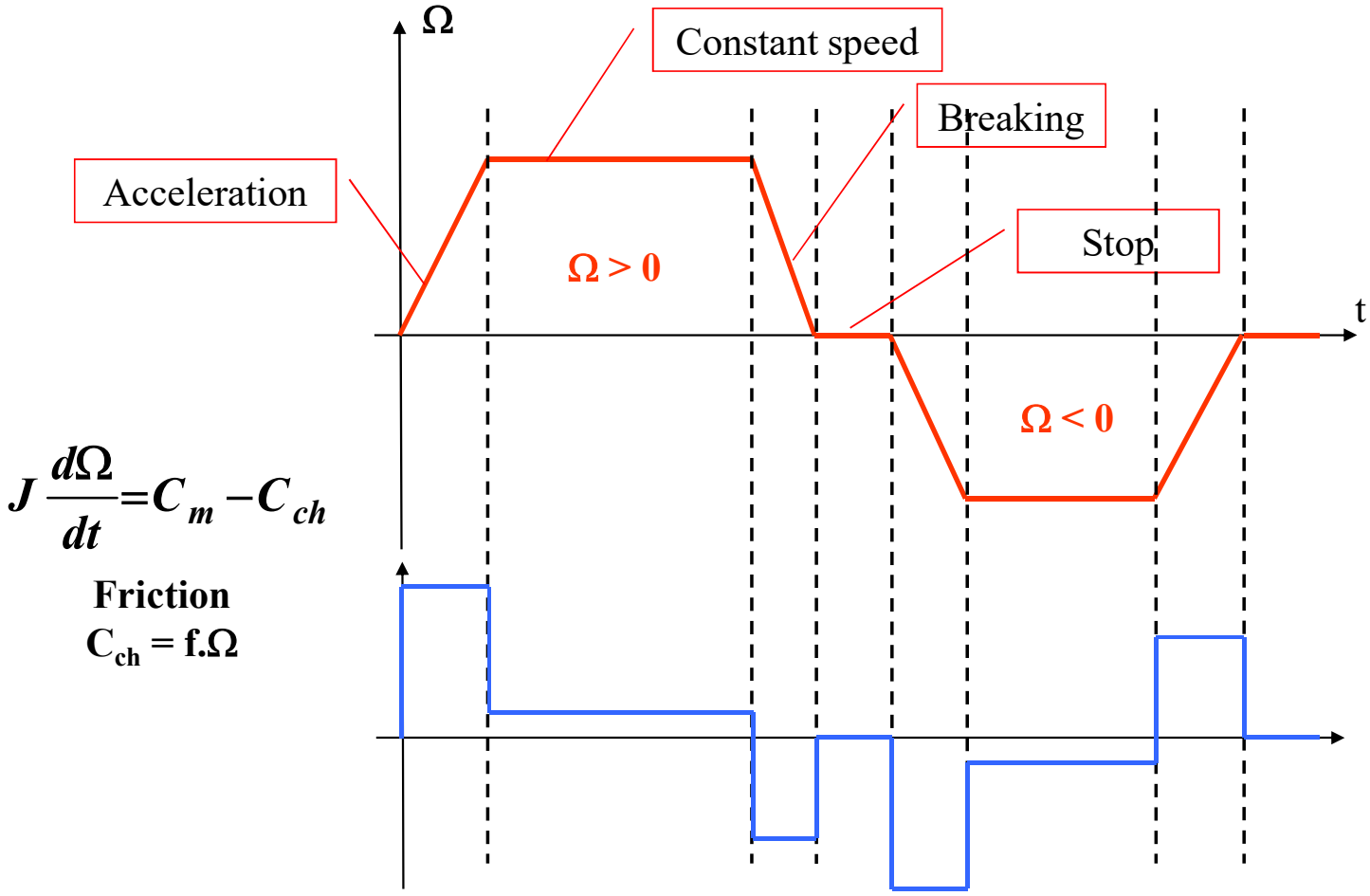
4 quadrants chopper: working cycle



$$J\frac{d\Omega}{dt}=C_m-C_{ch}$$

Friction

$C_{ch} = f.\Omega$

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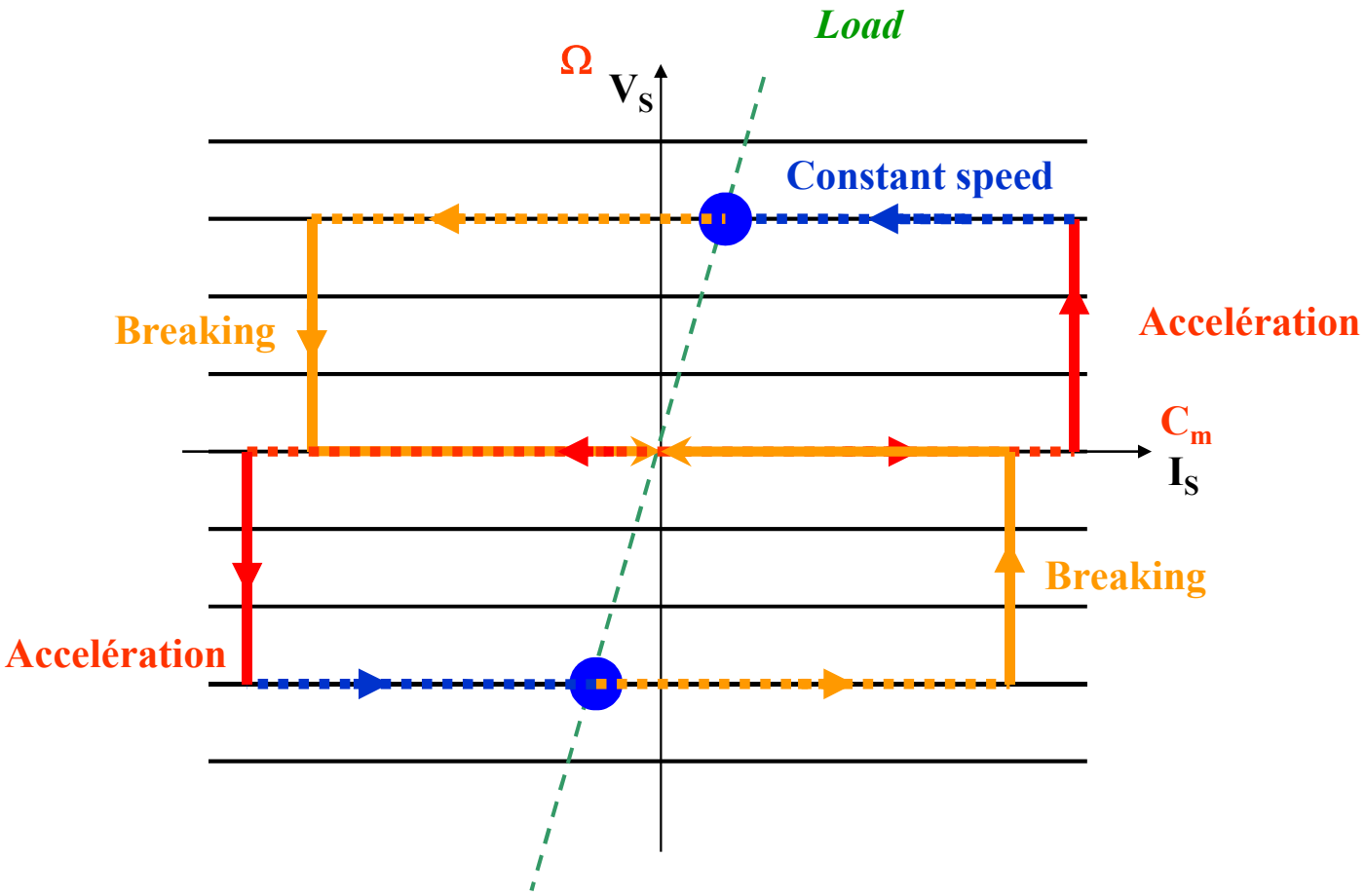
4 quadrants chopper: Operating point



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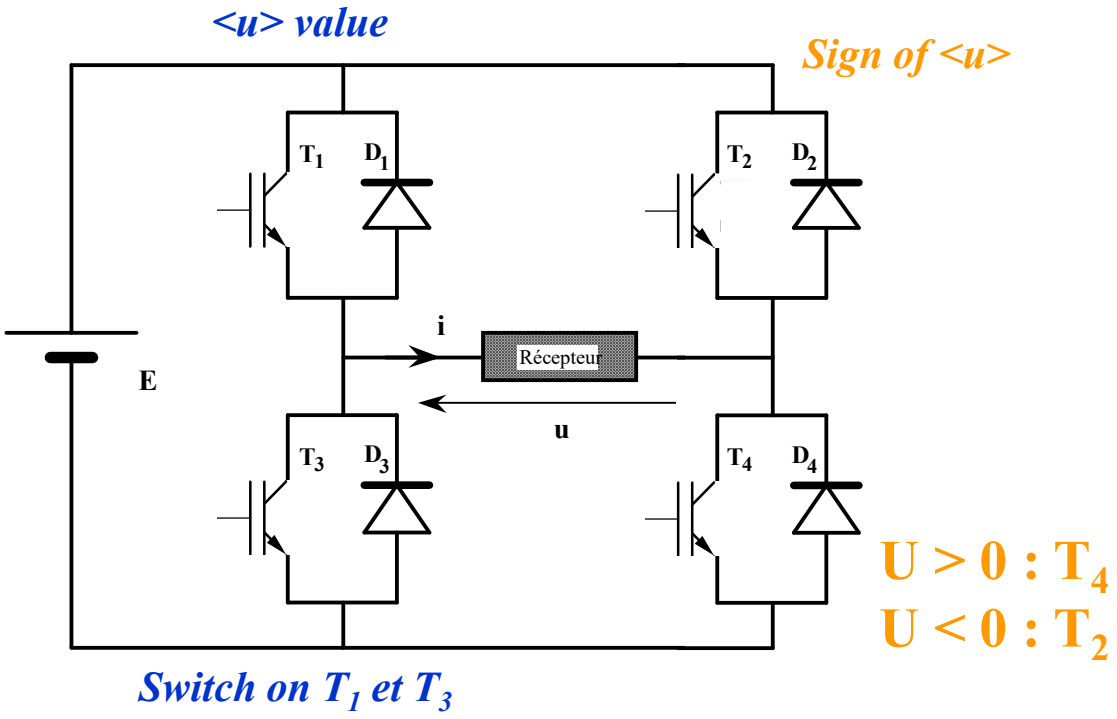
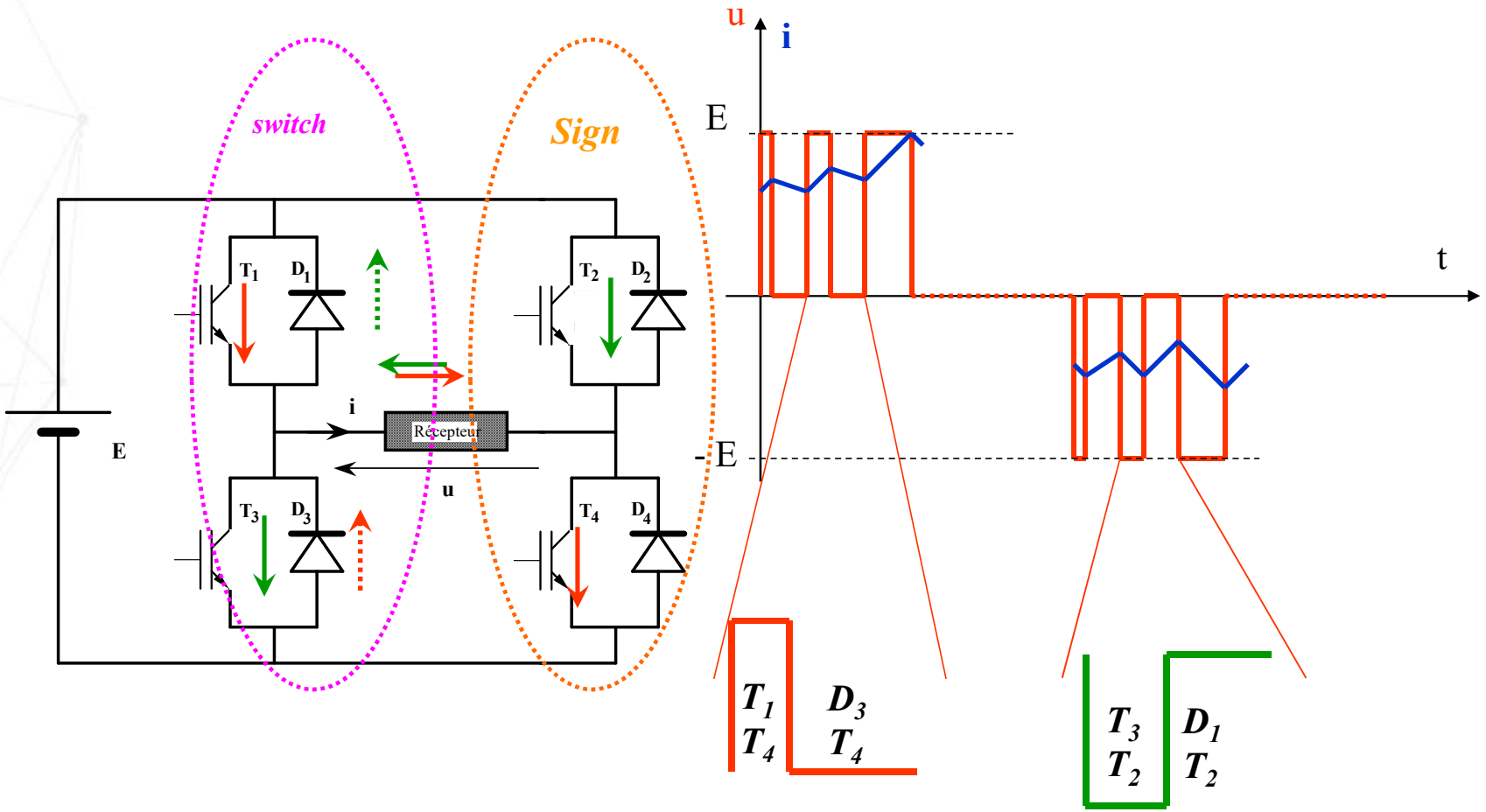
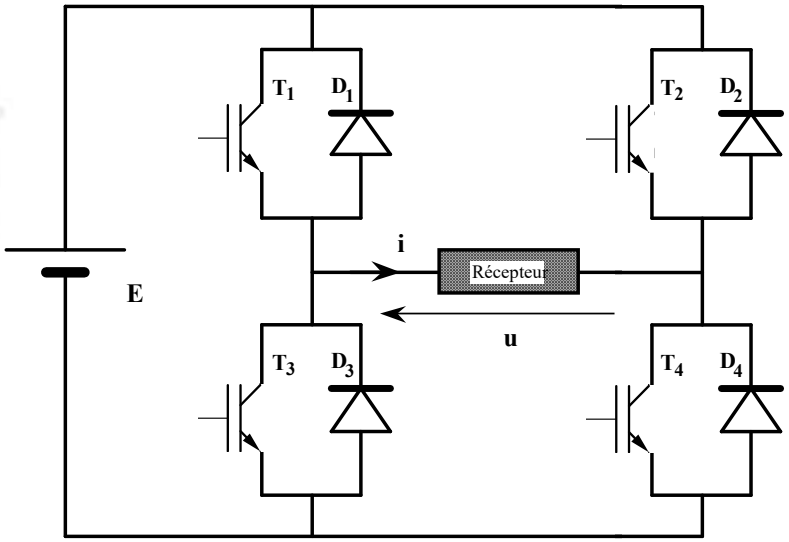
4 quadrants chopper: additional control



4 quadrants chopper: additional control



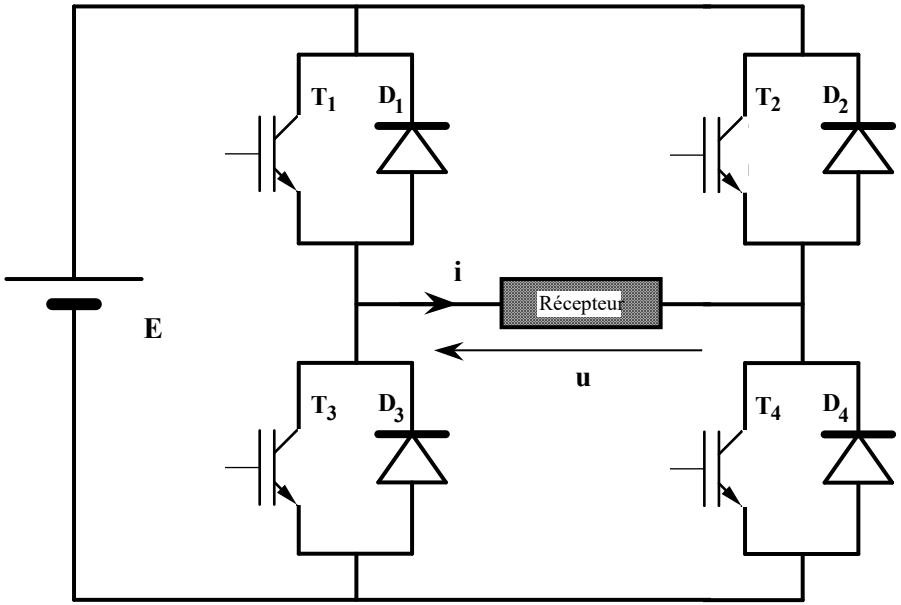
4 quadrants chopper: additional control



U = +/- α.E
Average value during a switching time T_d

Voltage ripple reduced: E
Switching only on T_1/T_3 : losses reduced
Instabilities around 0V ! !

4 quadrants chopper: Shifted complementary control



$\alpha_1 = \alpha_4$

$\alpha_2 = \alpha_3$

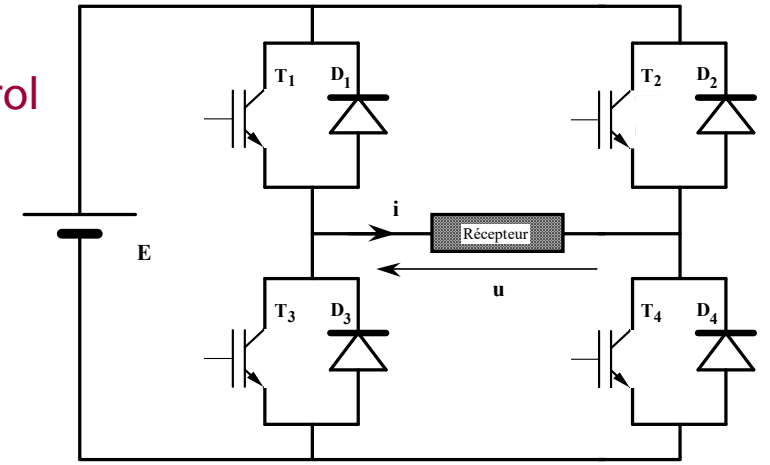
$\alpha_3 = 1 - \alpha_1$

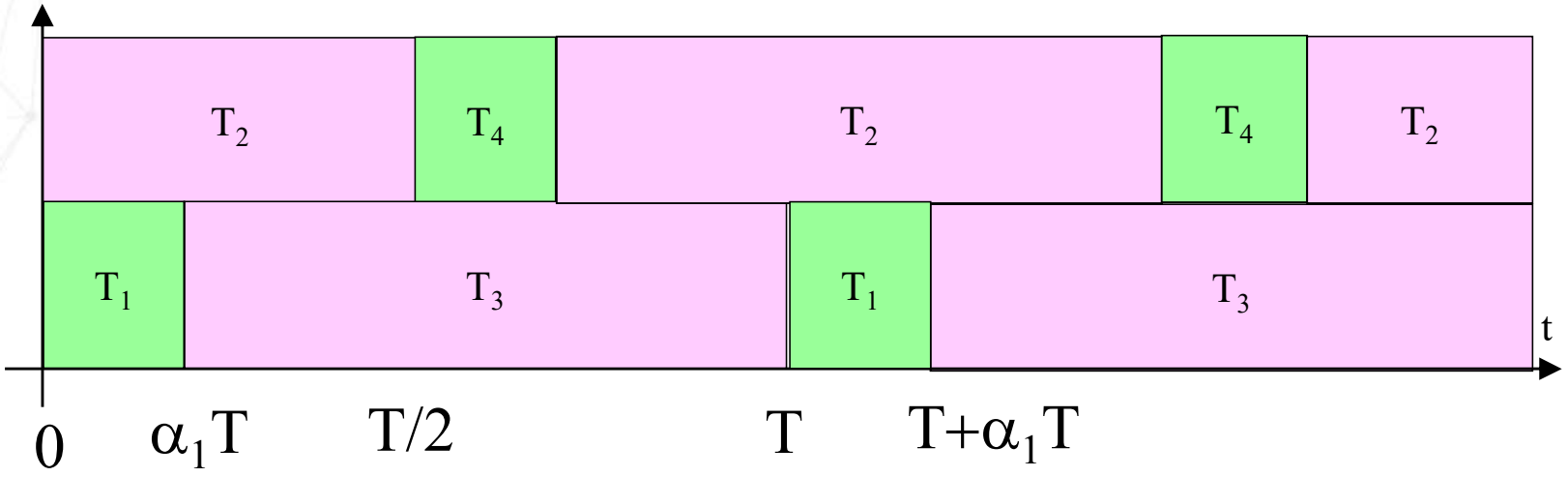
$\alpha_4 = 1 - \alpha_2$

Switching on T_1 and T_3 at $t = 0$

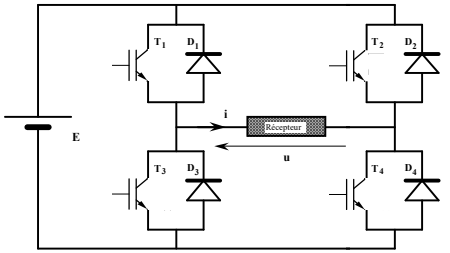
Switching on T_2 and T_4 at $t = T/2$

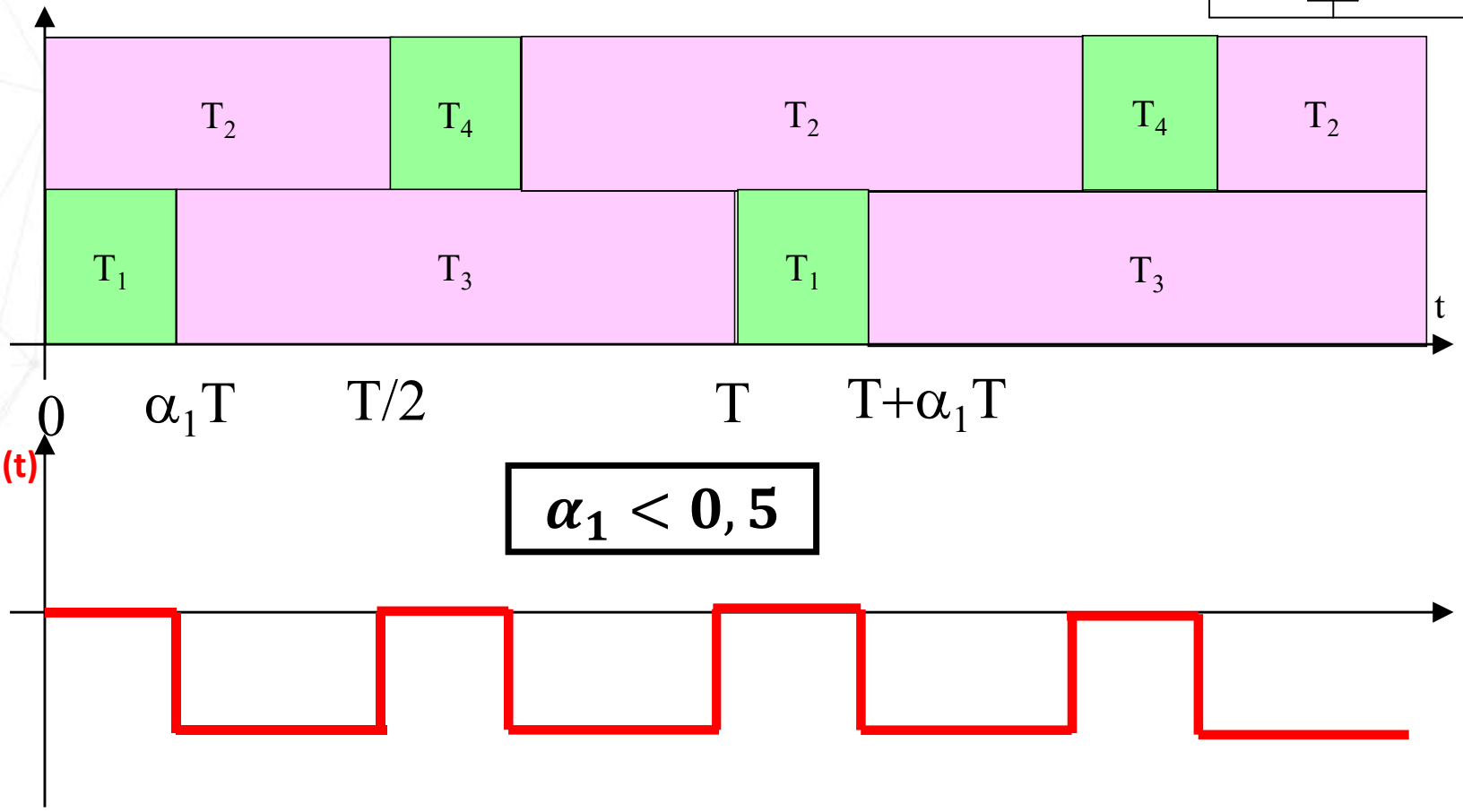
4 quadrants chopper: Shifted complementary control





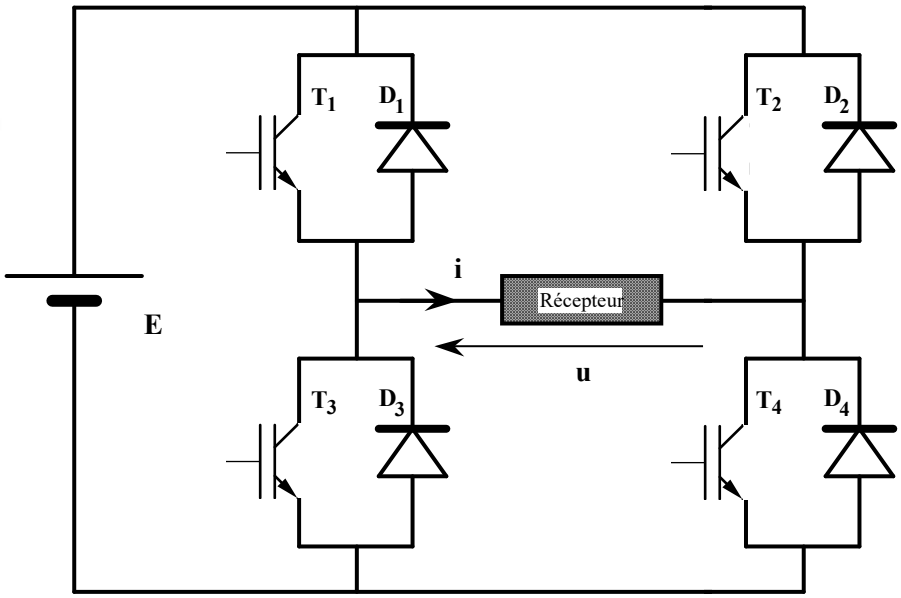
4 quadrants chopper: Shifted complementary control





$$\alpha_1 < 0,5$$

4 quadrants chopper: Shifted complementary control



$$U = (2\alpha - 1).E$$

Voltage ripple reduced: E
High switching frequency
=> PWM

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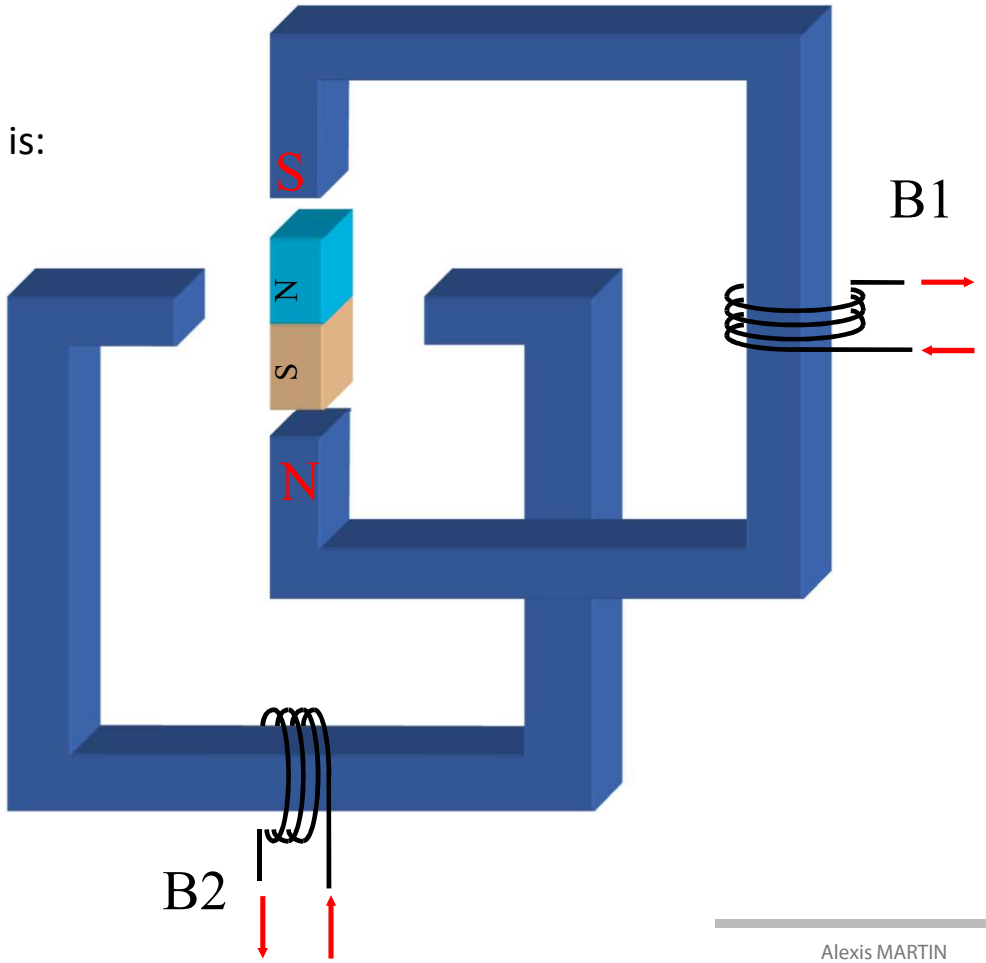
4 quadrants chopper: Stepper motor control

Operation principle: full step

For a clockwise rotation, the sequence is:

B1	B2
+I	0
0	+I
-I	0
0	-I



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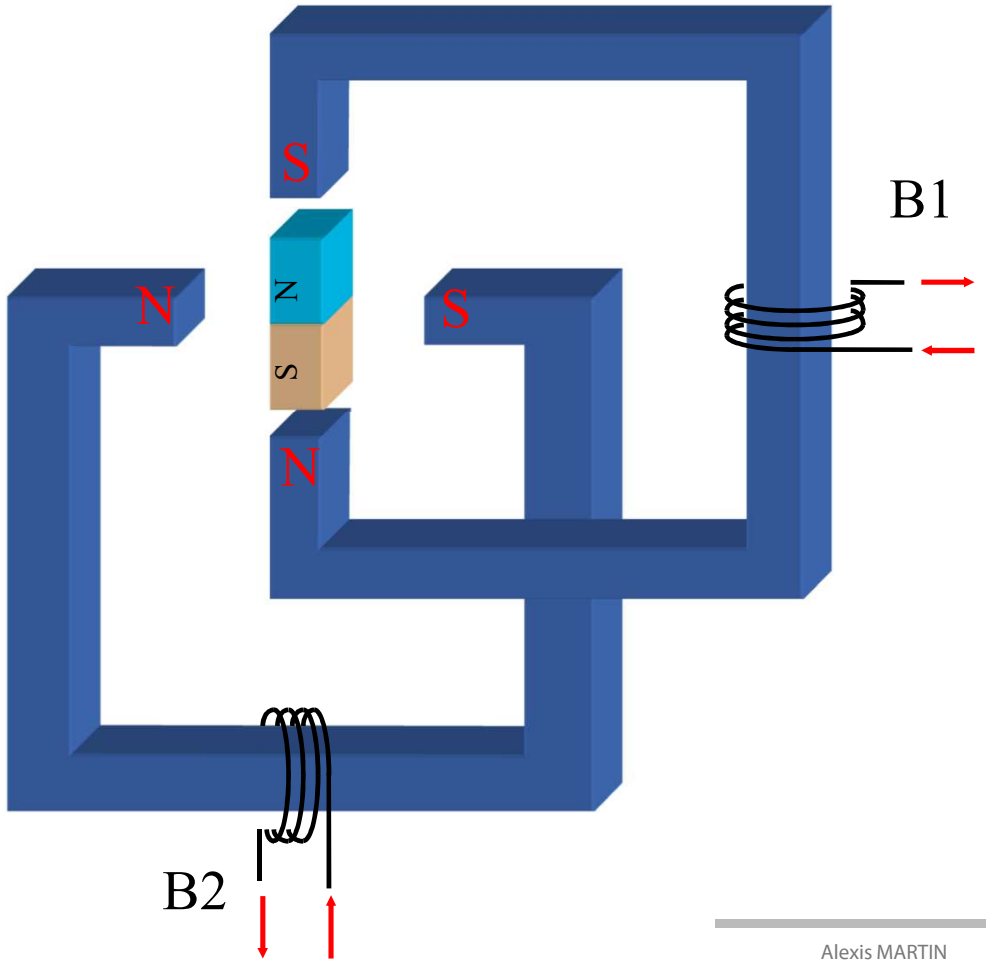
4 quadrants chopper: Stepper motor control

Operation principle: half step

For a clockwise rotation:

B1	B2
I+	0
I+	I+
0	I+
I-	I+
I-	0
I-	I-
0	I-
I+	I-



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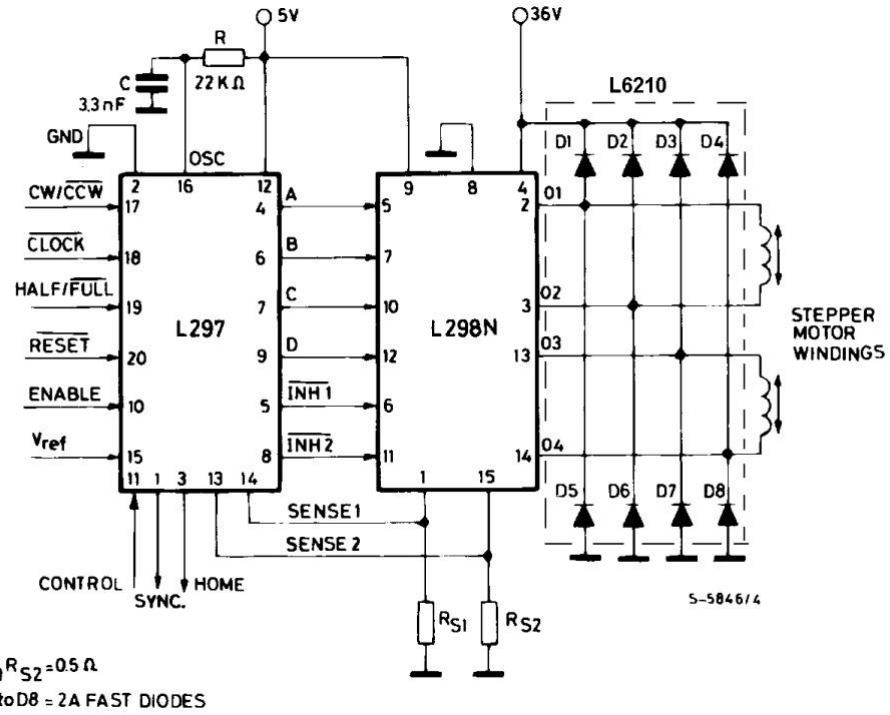
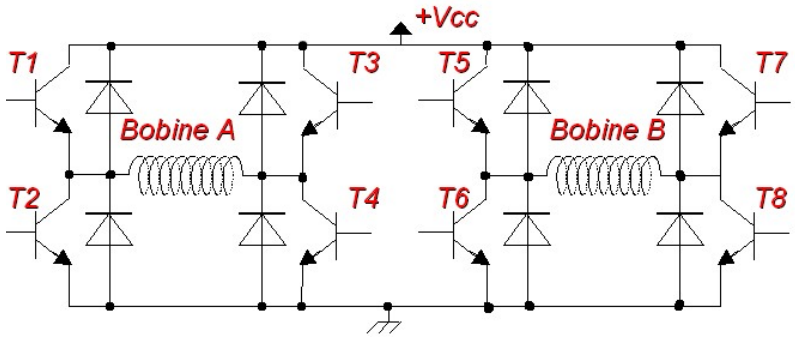
4 quadrants chopper: Stepper motor control





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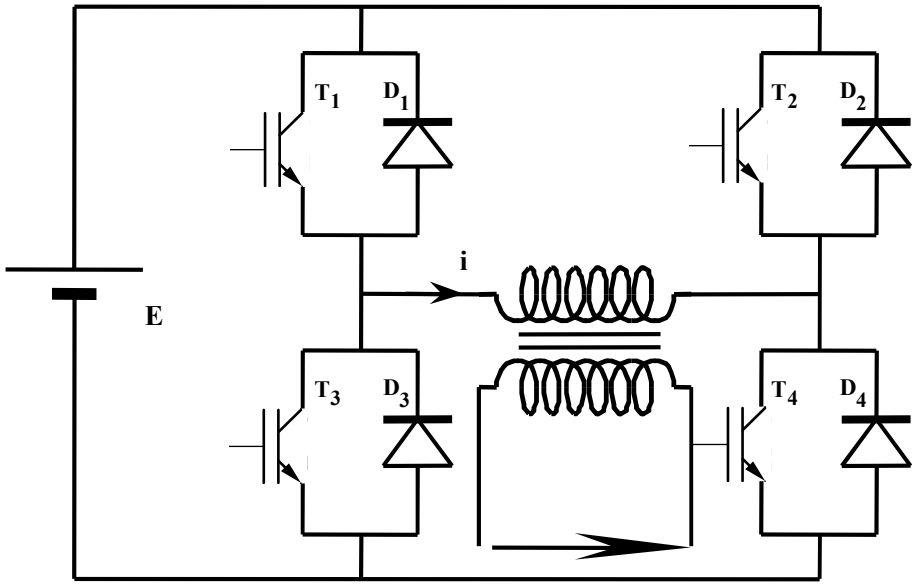
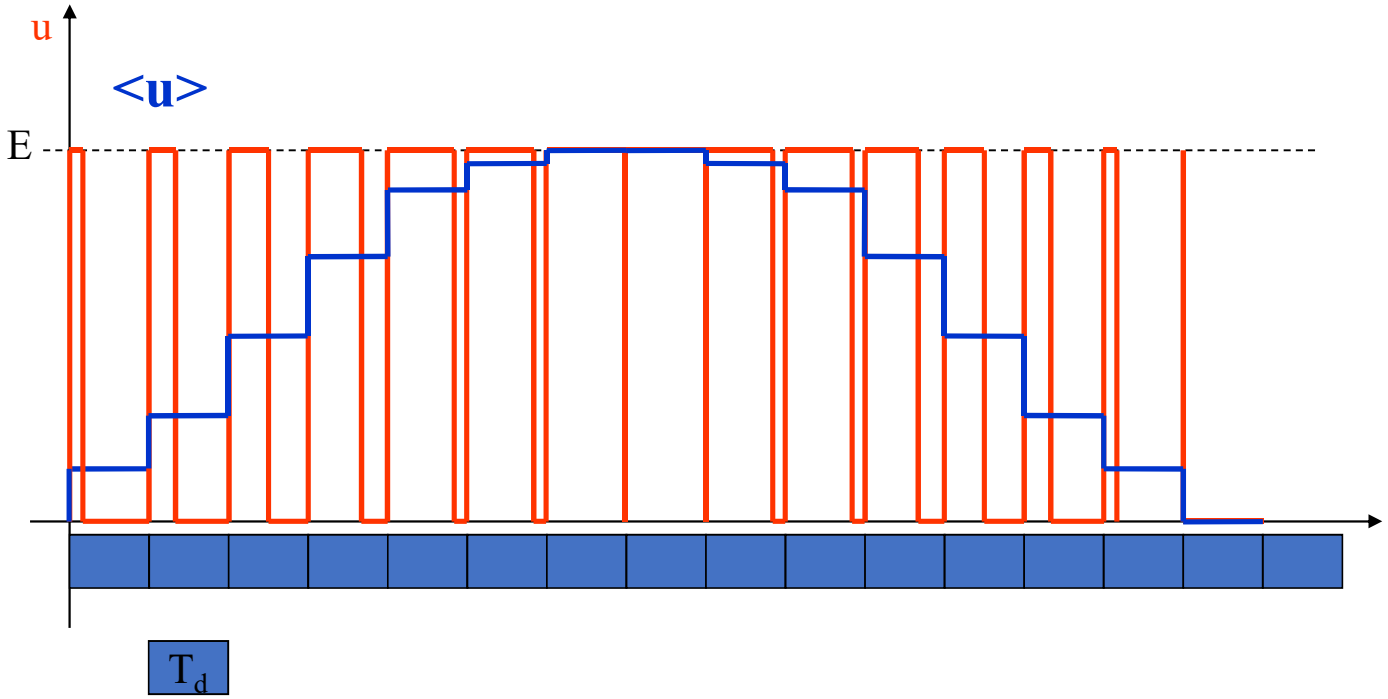
Inverter

Single phase inverter



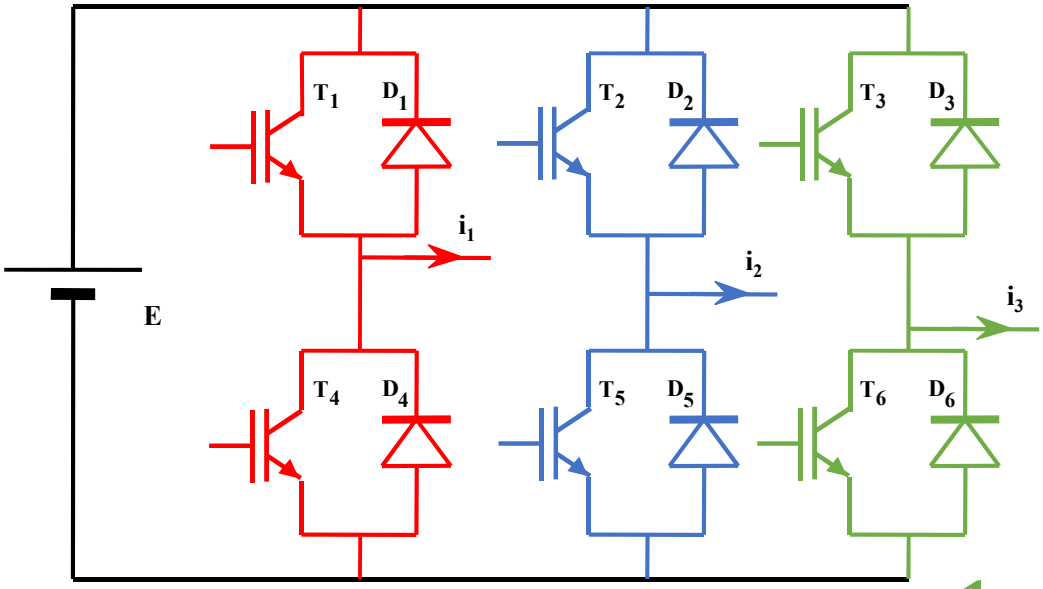
$$\alpha = \frac{1}{2} + \delta_\alpha \sin(\omega t)$$

Single phase inverter: PWM control



Three phase inverter

$$\alpha_2 = \frac{1}{2} + \delta_\alpha \sin(\omega t - \frac{2\pi}{3})$$



$$\alpha_1 = \frac{1}{2} + \delta_\alpha \sin(\omega t)$$

$$\alpha_3 = \frac{1}{2} + \delta_\alpha \sin(\omega t + \frac{2\pi}{3})$$

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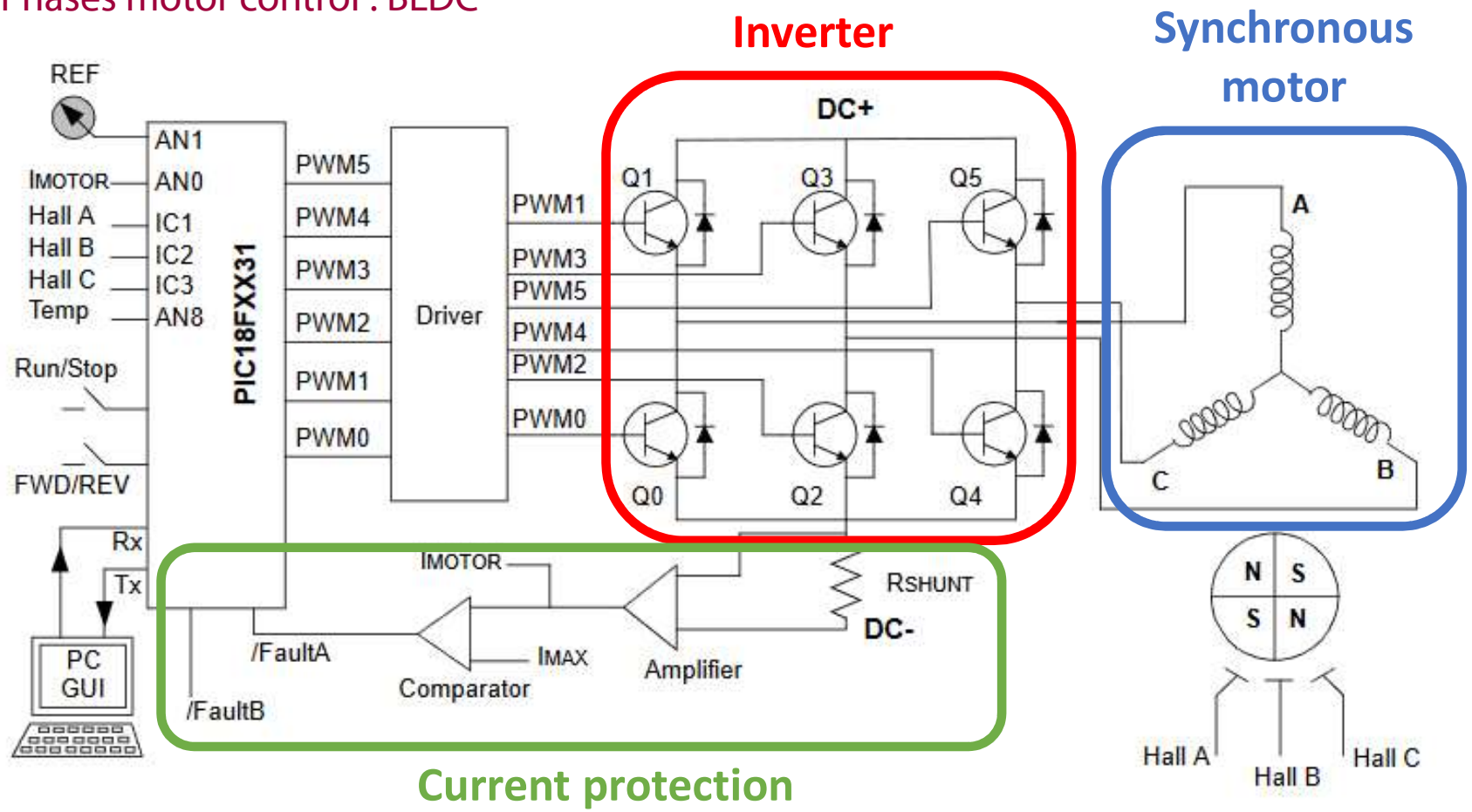
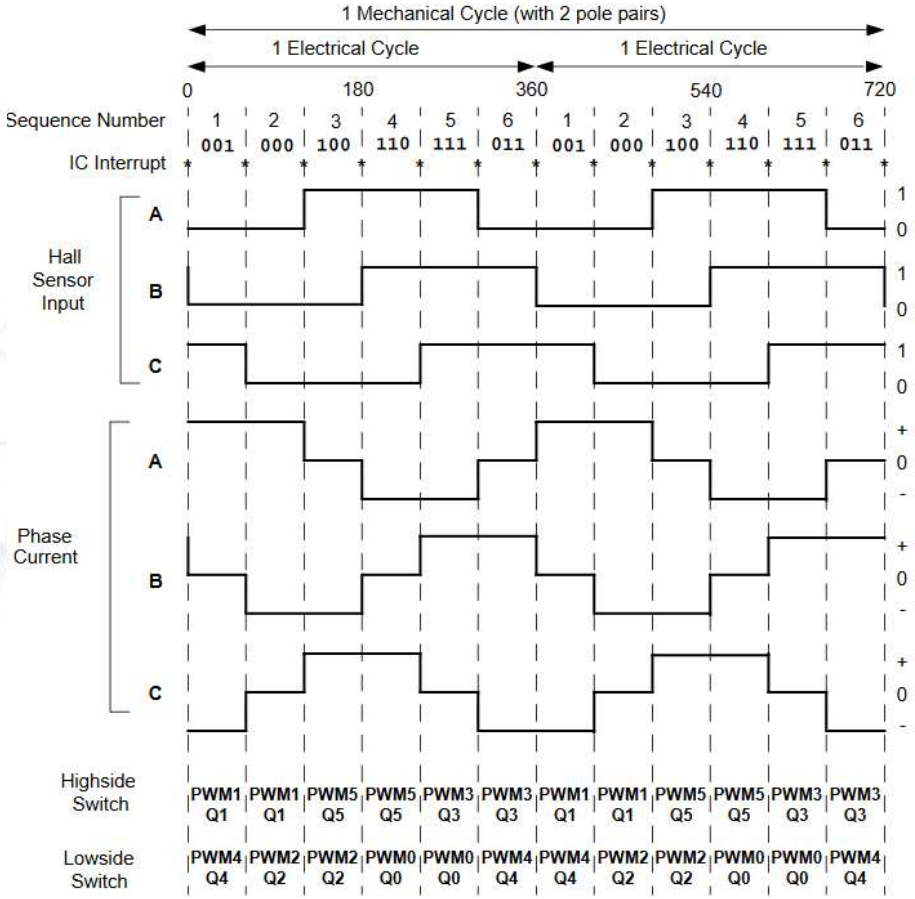
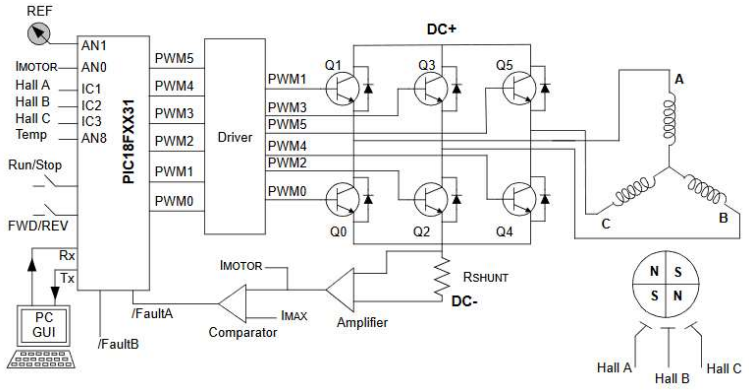
3 Phases motor control : BLDC



AN899 (Microchip) : Brushless DC Motor Control Using PIC18FXX31 MCUs

3 Phases motor control : BLDC





Sequence Number	Hall Sensor Input			Active PWMs		Phase Current		
	A	B	C			A	B	C
1	0	0	1	PWM1(Q1)	PWM4(Q4)	DC+	Off	DC-
2	0	0	0	PWM1(Q1)	PWM2(Q2)	DC+	DC-	Off
3	1	0	0	PWM5(Q5)	PWM2(Q2)	Off	DC-	DC+
4	1	1	0	PWM5(Q5)	PWM0(Q0)	DC-	Off	DC+
5	1	1	1	PWM3(Q3)	PWM0(Q0)	DC-	DC+	Off
6	0	1	1	PWM3(Q3)	PWM4(Q4)	Off	DC+	DC-

AN899 (Microchip) : Brushless DC Motor Control Using PIC18FXX31 MCUs

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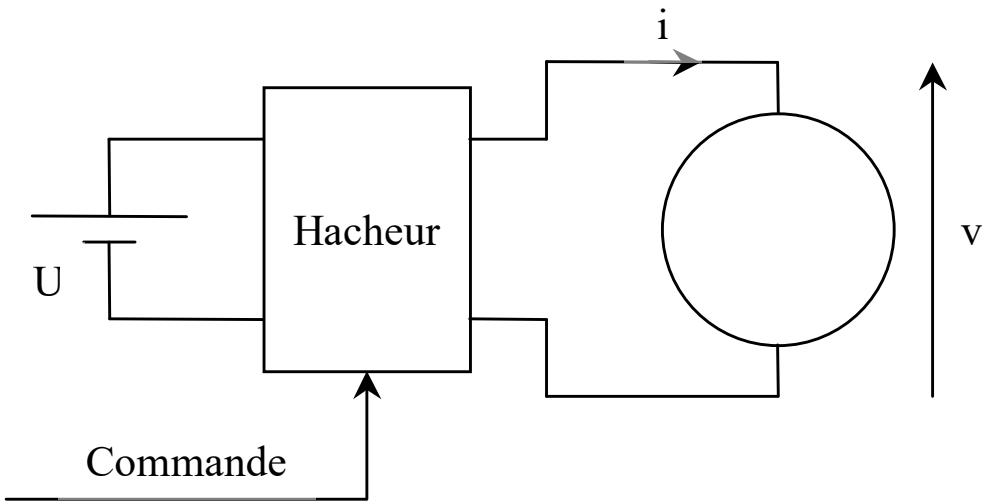
Closed loop chopper control

Closed loop chopper control



Possible control : speed / torque

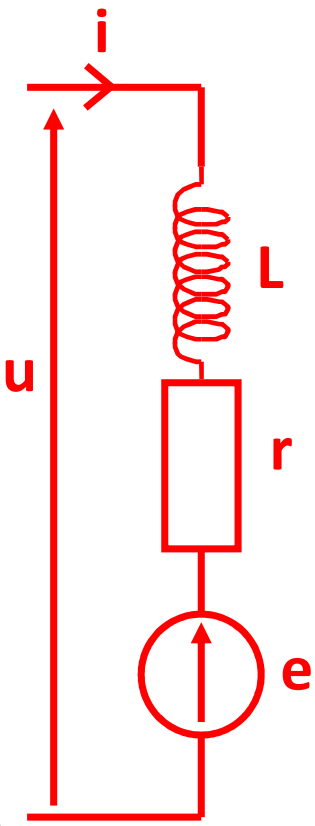
Voltage / current

DC motor model

Electrical equation : $u = e + r.i + L.\frac{di}{dt}$

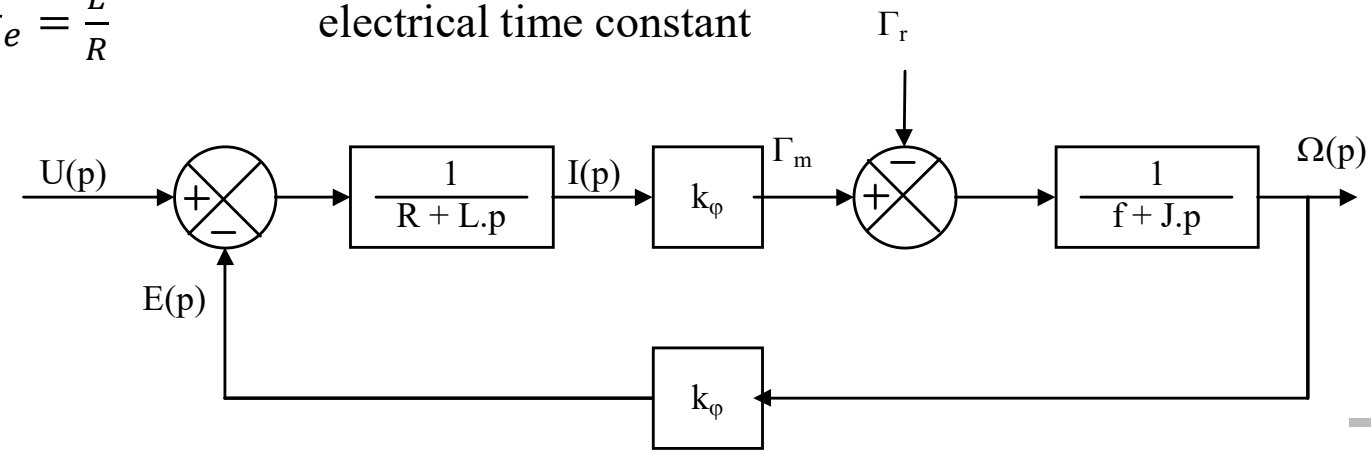
Mechanical equation : $J\frac{d\Omega}{dt} + f\Omega = \gamma_m - \gamma_r$

Coupling equations : $e = k_\phi.\Omega$ $\gamma_m = k_\phi.i$

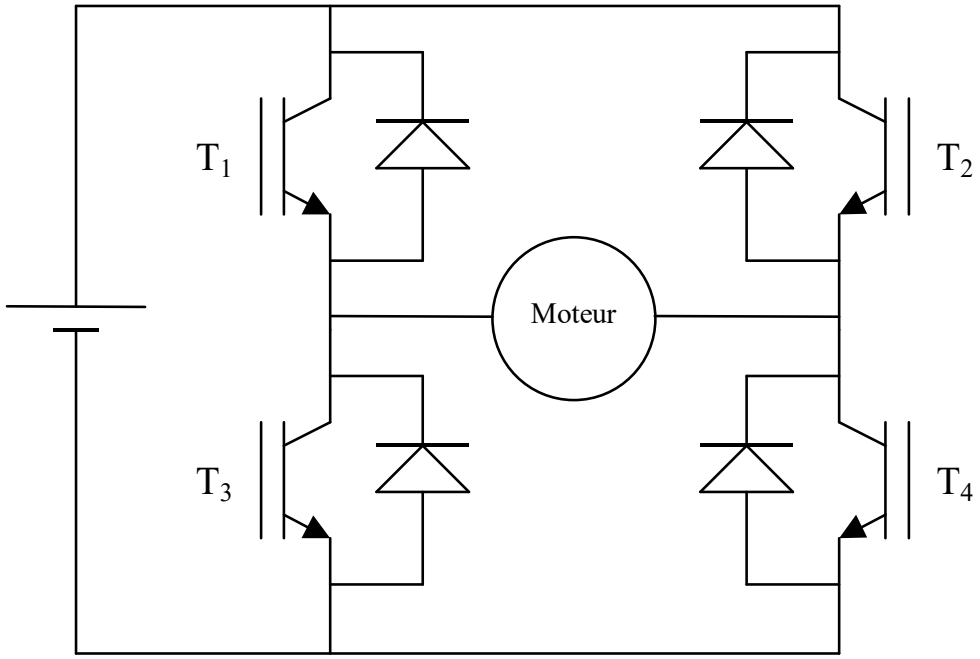


$\tau_{em} = \frac{J.R}{k_\phi^2 + R.f}$ electromechanical time constant

$\tau_e = \frac{L}{R}$ electrical time constant



Reversible structure



Chopper model

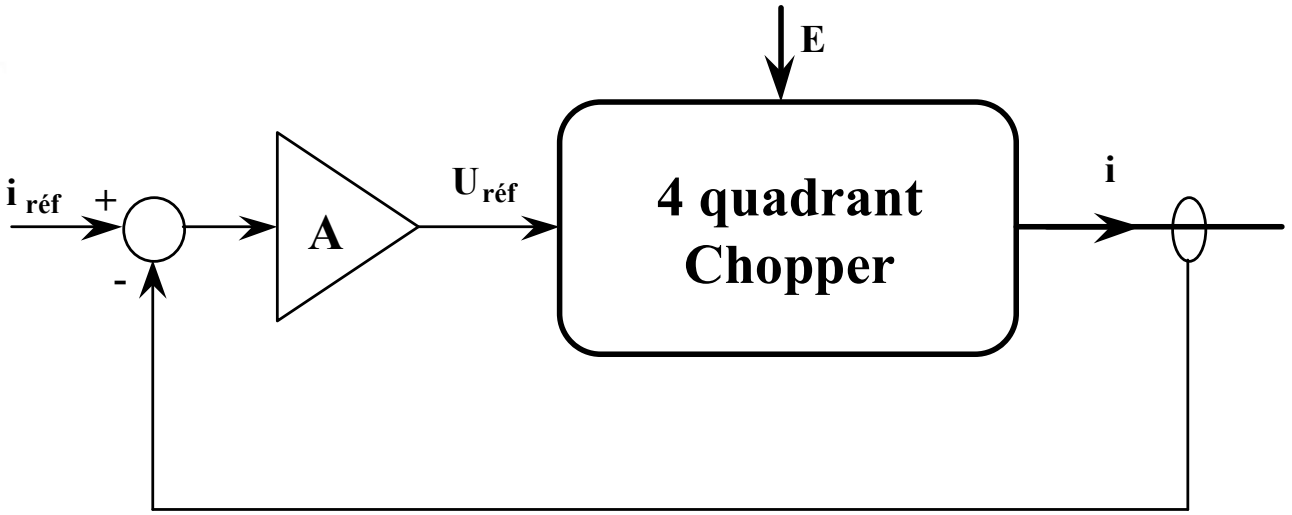
$$G_h(p) = \frac{U}{V_{dc}} . e^{-\frac{T_d}{2}.p}$$

(Average delay T_d /2)

$$G_h(p) \approx \frac{G_0}{1+\tau_h.p} \quad \text{with} \quad \tau_h = \frac{T_d}{2} \quad \text{and} \quad G_0 = \frac{U}{V_{dc}}$$

(linearization)

Current control



Torque control of a motor

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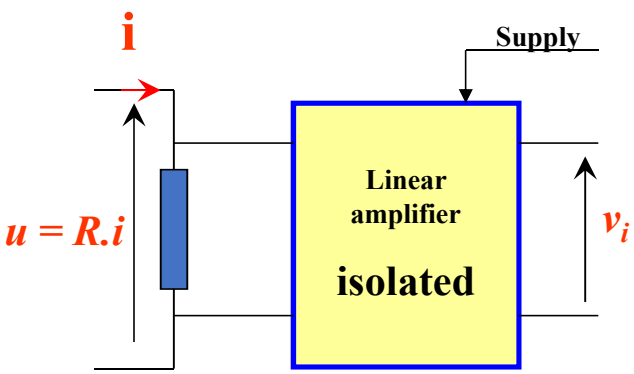
Current loop

Armature current regulation

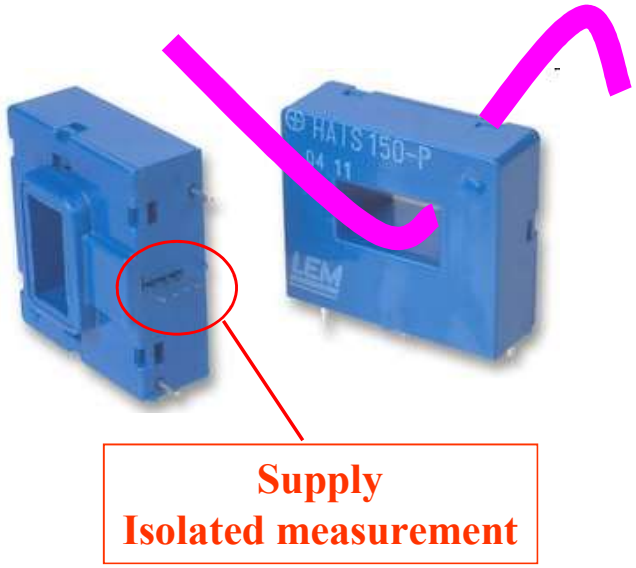
- *Current regulation*
- *Torque control ($G = k_{\varphi}.I$)*
- *Better transient response*
- *Need a high performance sensor*
- *Simple Regulation (P.I.)*

Current loop: Current sensor

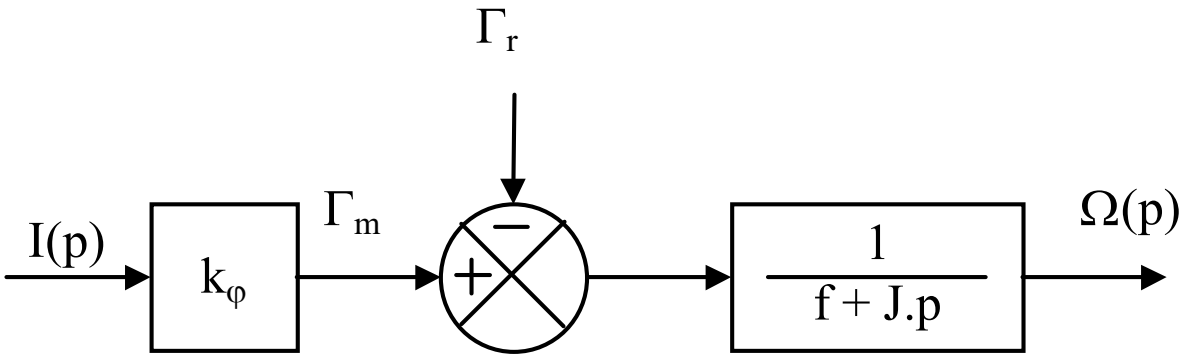
Resistor = shunt



Hall effect sensor

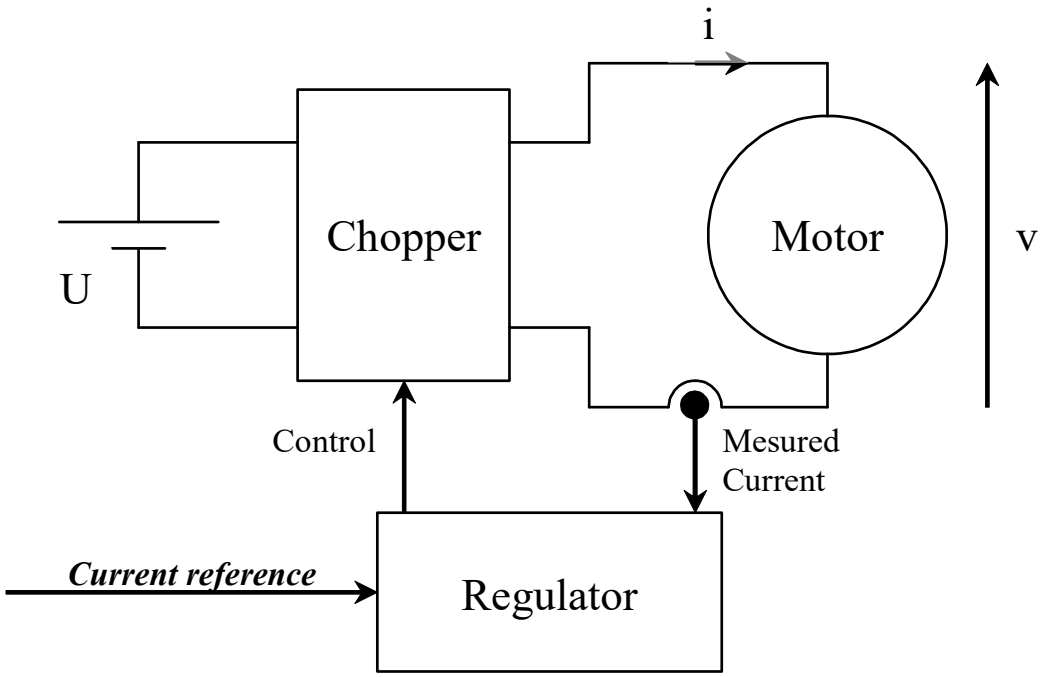


DC motor: Current control



$$G_i(p) = \frac{\Omega(p)}{I(p)} = \frac{k_\varphi}{f + J.p}$$

Current loop



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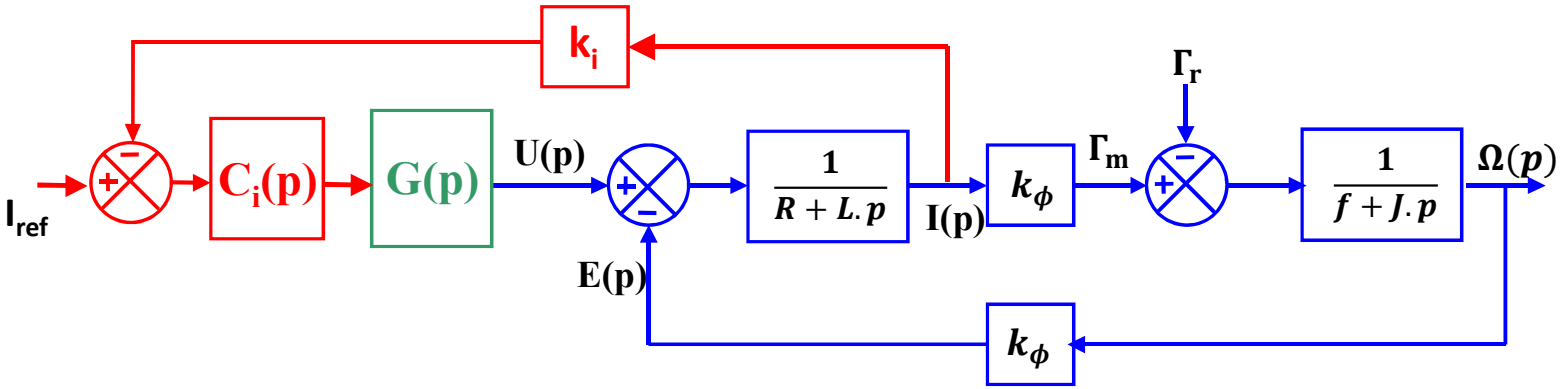
Control criteria

Accuracy : no static error

Speed : time response enhancement

Unconditional stability (high margin)

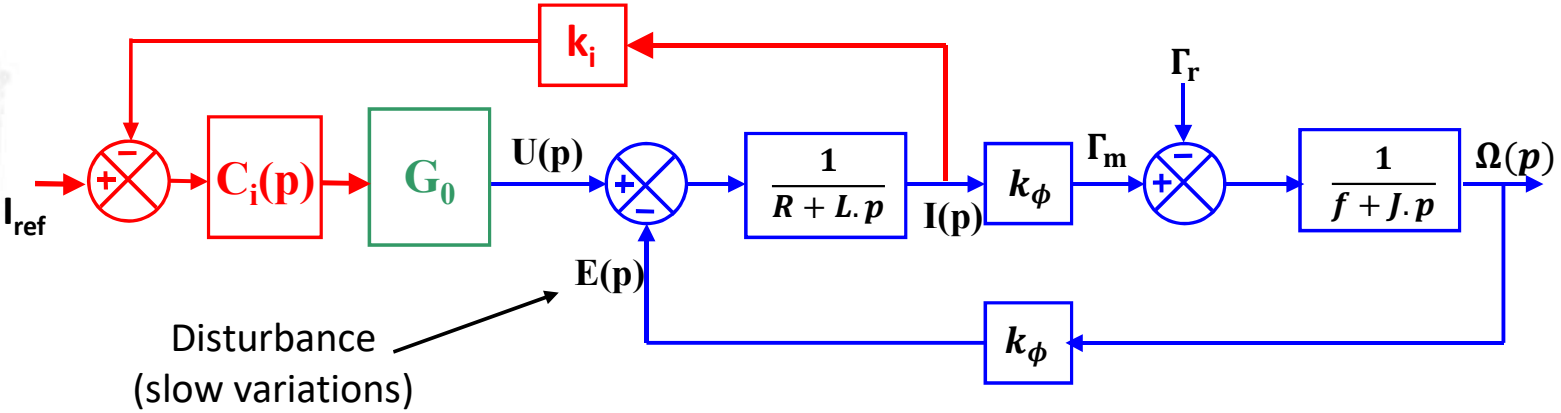
Current Control



Controller **Chopper** **DC motor**

$=>$ *Controller choice: Ci(p)*

P.I. control: simplified chopper



$$C_i(p) = k_i . \frac{1+\tau_i p}{\tau_i p} \qquad H_{NCOL}(p) = \frac{G_0 / R}{1+\tau_e p}$$

$$H_{OL}(p) = \frac{k_i.(1+\tau_i p) G_0 / R}{\tau_i p (1+\tau_e p)}$$

$$\Rightarrow \quad \tau_i = \tau_e$$

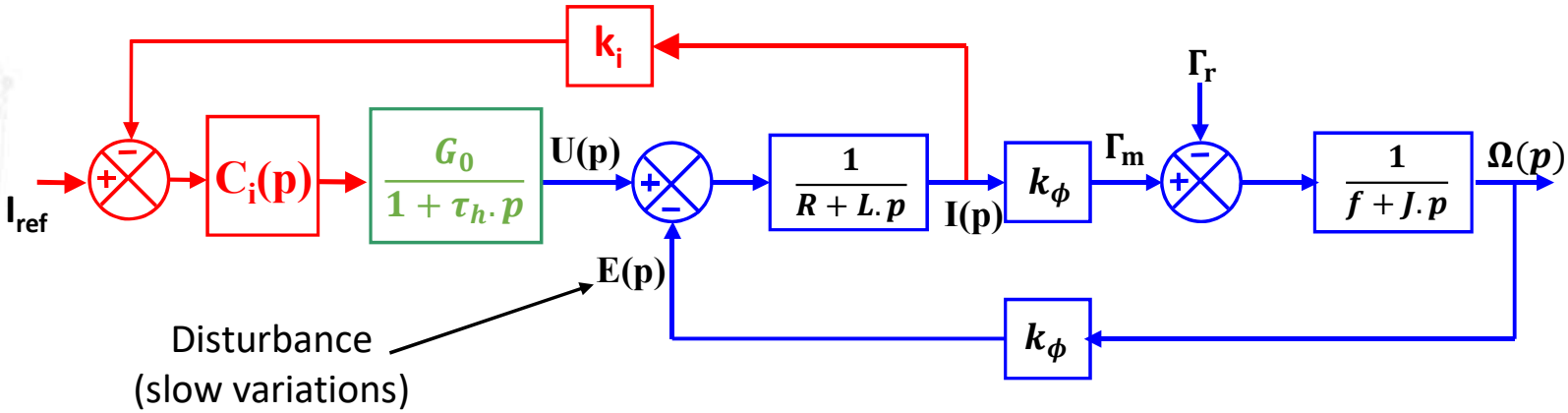
P.I. control: simplified chopper

$$H_{CL}(p) = \frac{k_i.G_0 / R}{k_i.G_0 / R + \tau_e p} = \frac{1}{1 + \tau_{BF} p}$$

$$\tau_{BF} = \frac{\tau_e}{\frac{k_i G_0}{R}}$$

1st order without error, faster

P.I. control: first order chopper



$$C_i(p) = k_i \cdot \frac{1+\tau_i p}{\tau_i p} \qquad H_{OL}(p) = \frac{G_0 / R}{(1+\tau_h p).(1+\tau_e p)}$$

$$H_{OL}(p) = \frac{k_i.(1+\tau_i p) G_0 / R}{\tau_i p (1+\tau_h p).(1+\tau_e p)}$$

$$\Rightarrow \ \tau_i = \max(\tau_h, \tau_e)$$

Closed loop

$$H_{OL}(p) = \frac{k_i G_0 / R}{\tau_{he} p (1 + \tau_{he})}$$

$$\boldsymbol{H_{CL}(p) = \frac{1}{1 + 2m\frac{p}{\omega_0} + \frac{p^2}{\omega_0^2}}}$$

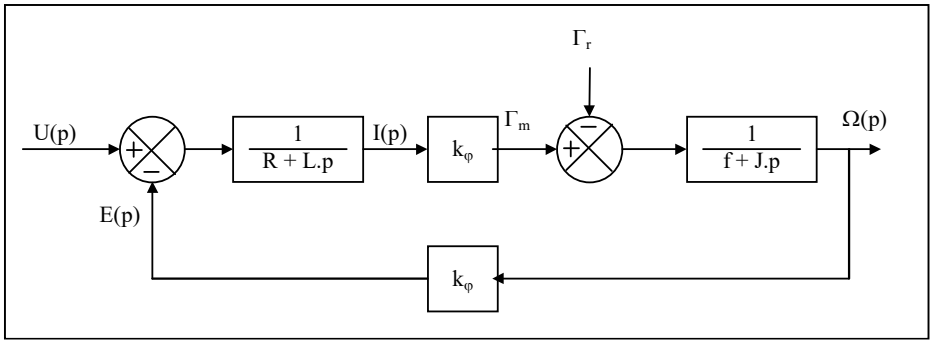
Second ordre without error

Choose of m : damping [0,7 .. 1]

Choose of ω_0 : bandwidth

DC motor: Speed / voltage transfer function

$$G'_u(p) = \frac{\Omega(p)}{U(p)} = \frac{k_\varphi}{k_\varphi^2 + (R + L.p).(f + J.p)}$$

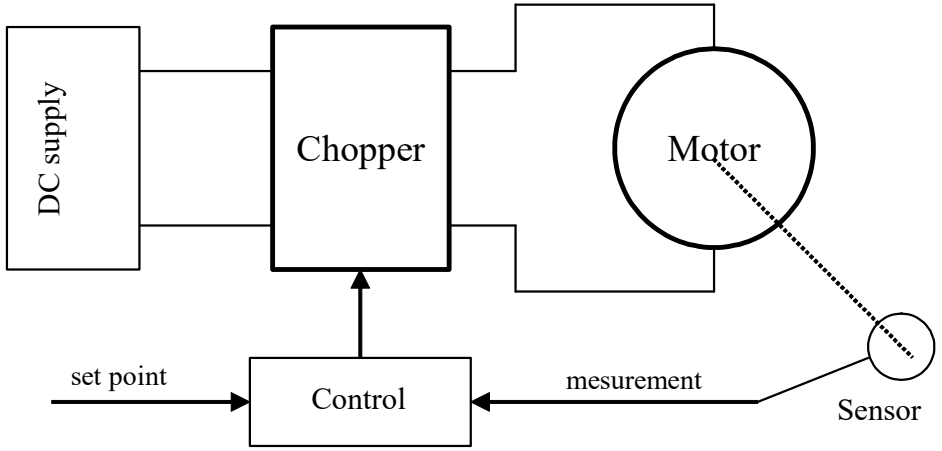


$$G_u(p) = \frac{\Omega(p)}{U(p)} = \frac{k_\varphi}{k_\varphi^2 + Rf} \cdot \frac{1}{(1 + \tau_e p).(1 + \tau_{em} p)}$$

$\tau_{em} = \frac{J.R}{k_\phi^2 + R.f}$ electromechanical time constant

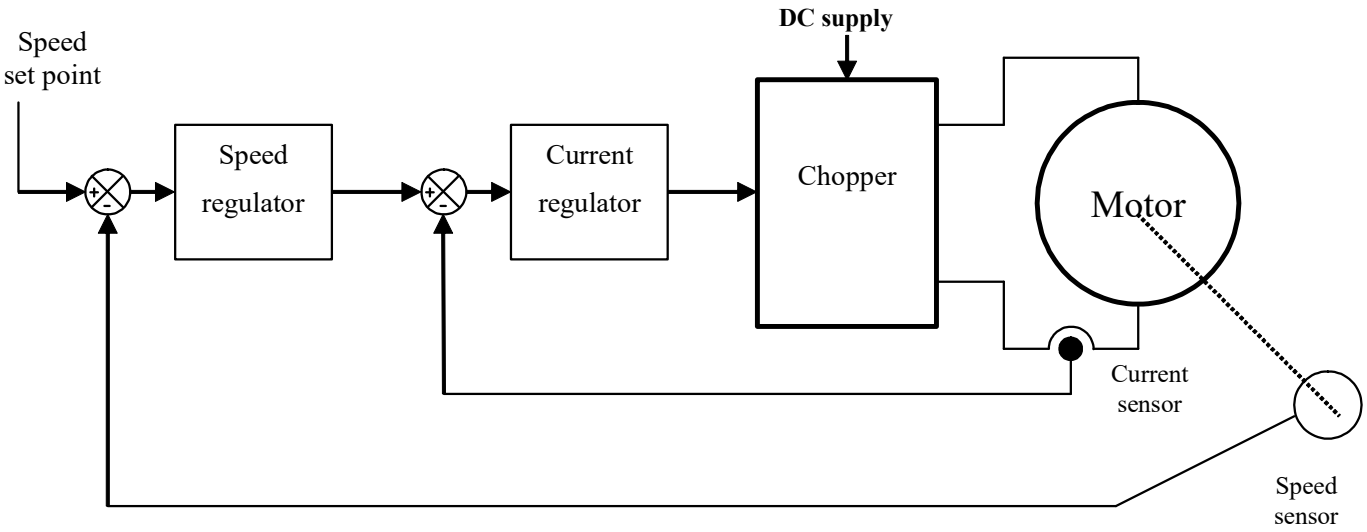
$\tau_e = \frac{L}{R}$ electrical time constant

Speed loop



$$G_{hv}(p) = \frac{V_{\Omega mes}(p)}{V_{\Omega ref}(p)} = \frac{G_{0\Omega}}{1 + 2m\frac{p}{\omega_0} + \frac{p^2}{\omega_0^2}}$$

Nested loop



Internal loop faster than external loop

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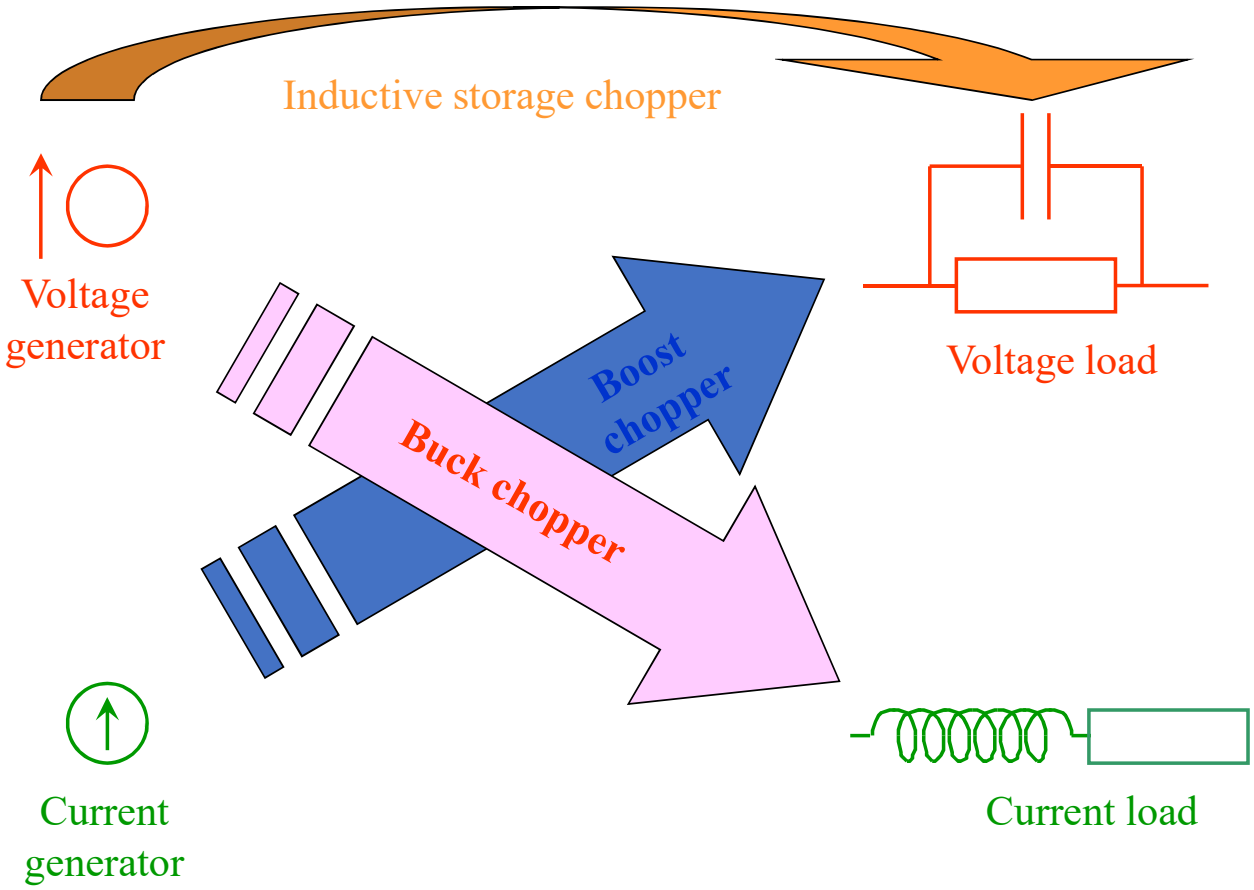
Indirect Choppers

Indirect chopper: principle



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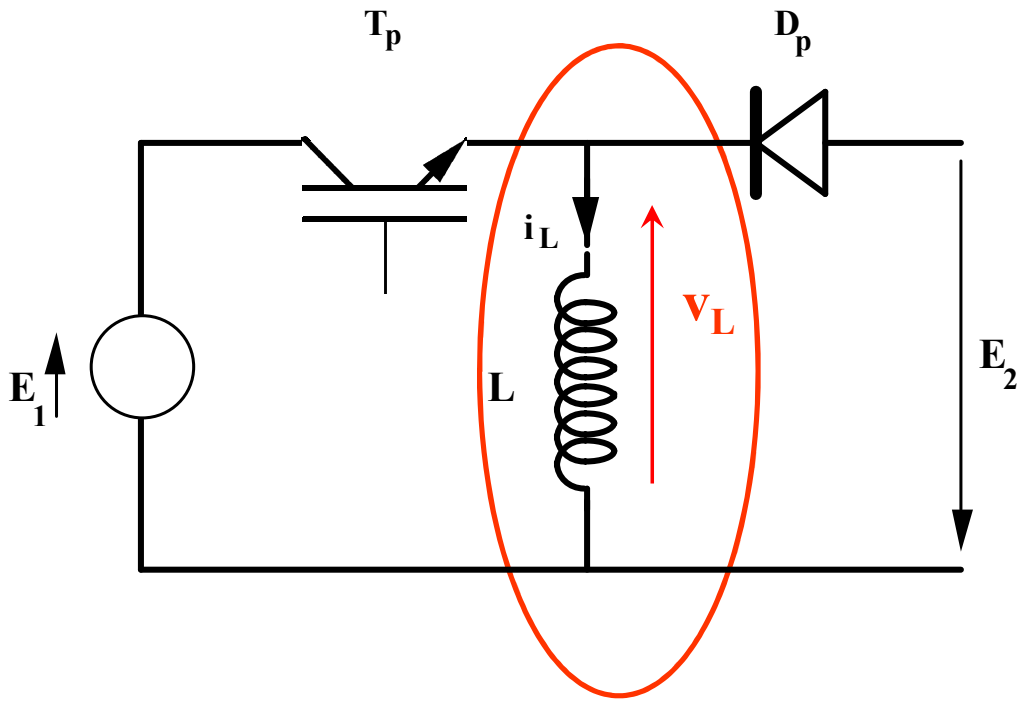
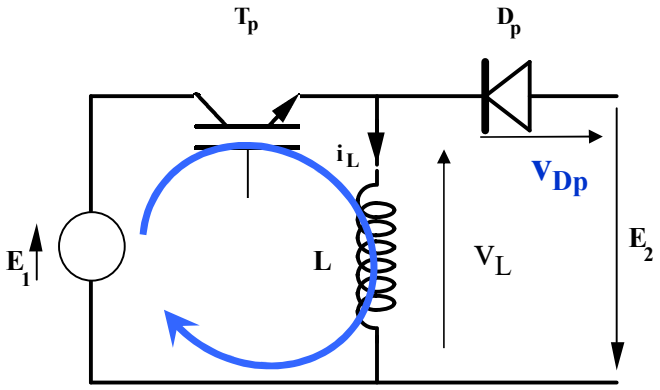
Buck-Boost structure



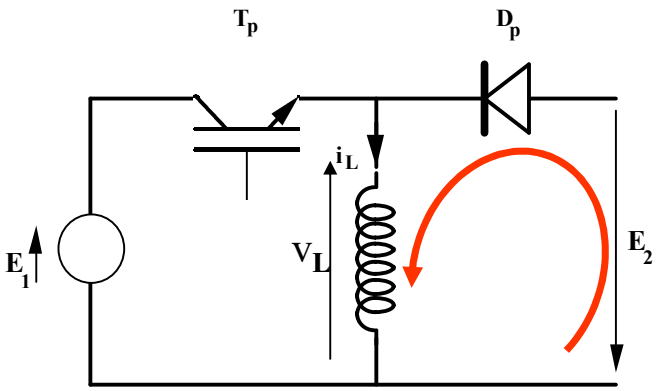
Buck-boost: Continuous mode ($i_L > 0$)



0 < t < αT : T_p closed

$v_{Dp} = -E_1 - E_2$ => D_p reverse

$v_L = E_1 = L.di_L/dt$ => i_L increasing > 0



αT < t < T: T_p opened

$i_L > 0$ => D_p forward

$v_L = -E_2 = L.di_L/dt$ => i_L decreasing

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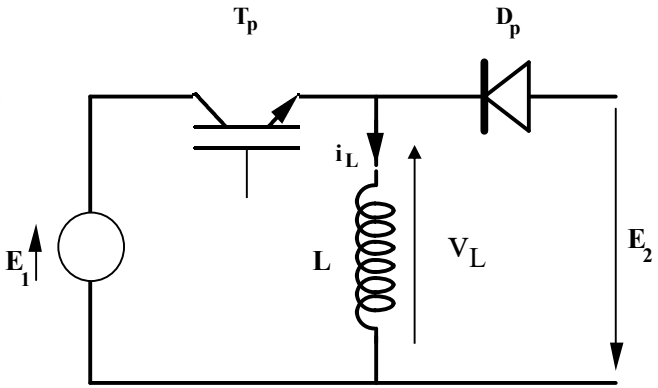
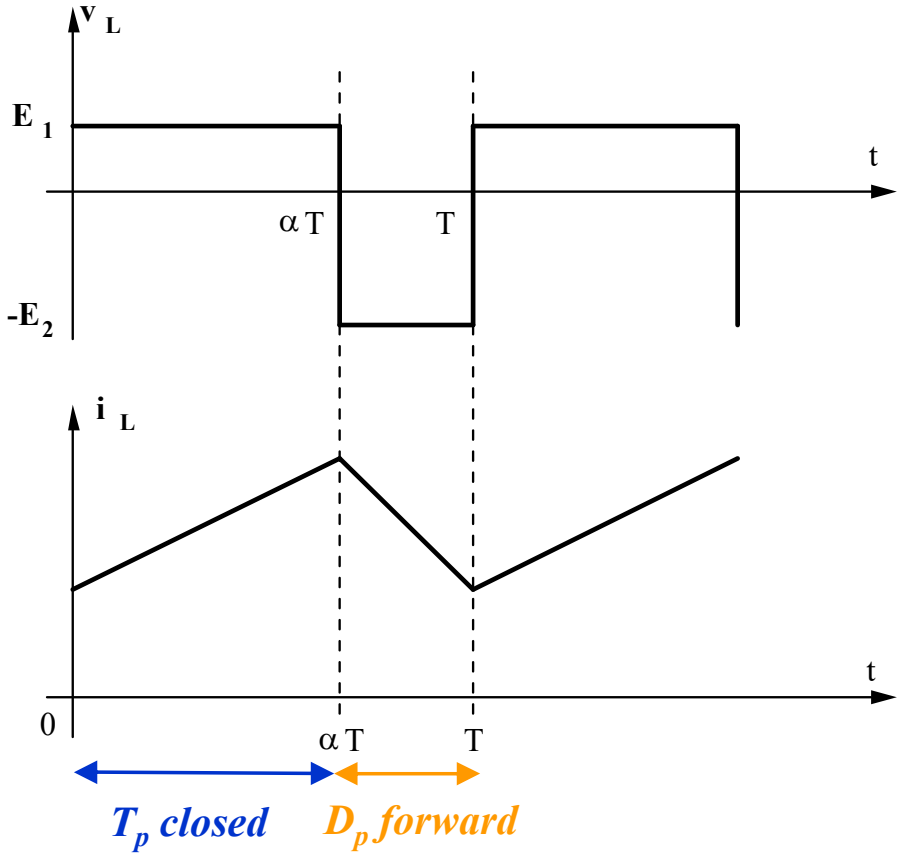
Buck-boost: Continuous mode (chronograms)

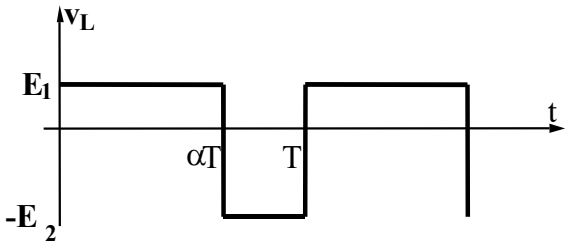


$$\langle v_L \rangle = 0$$

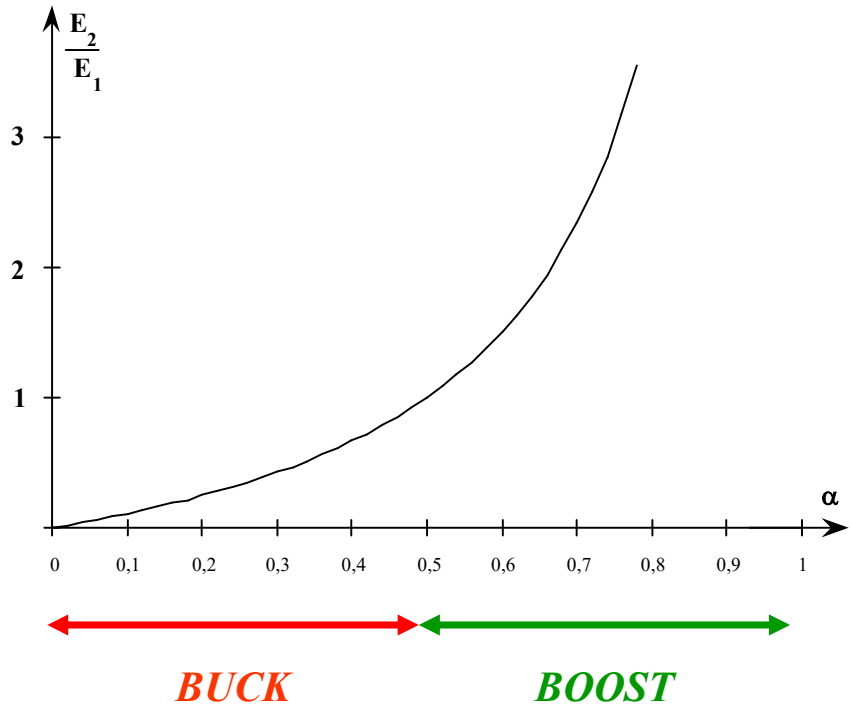
Inductive storage chopper



Buck-boost: Continuous mode (Transfer characteristics)



$$\langle v_L \rangle = 0$$



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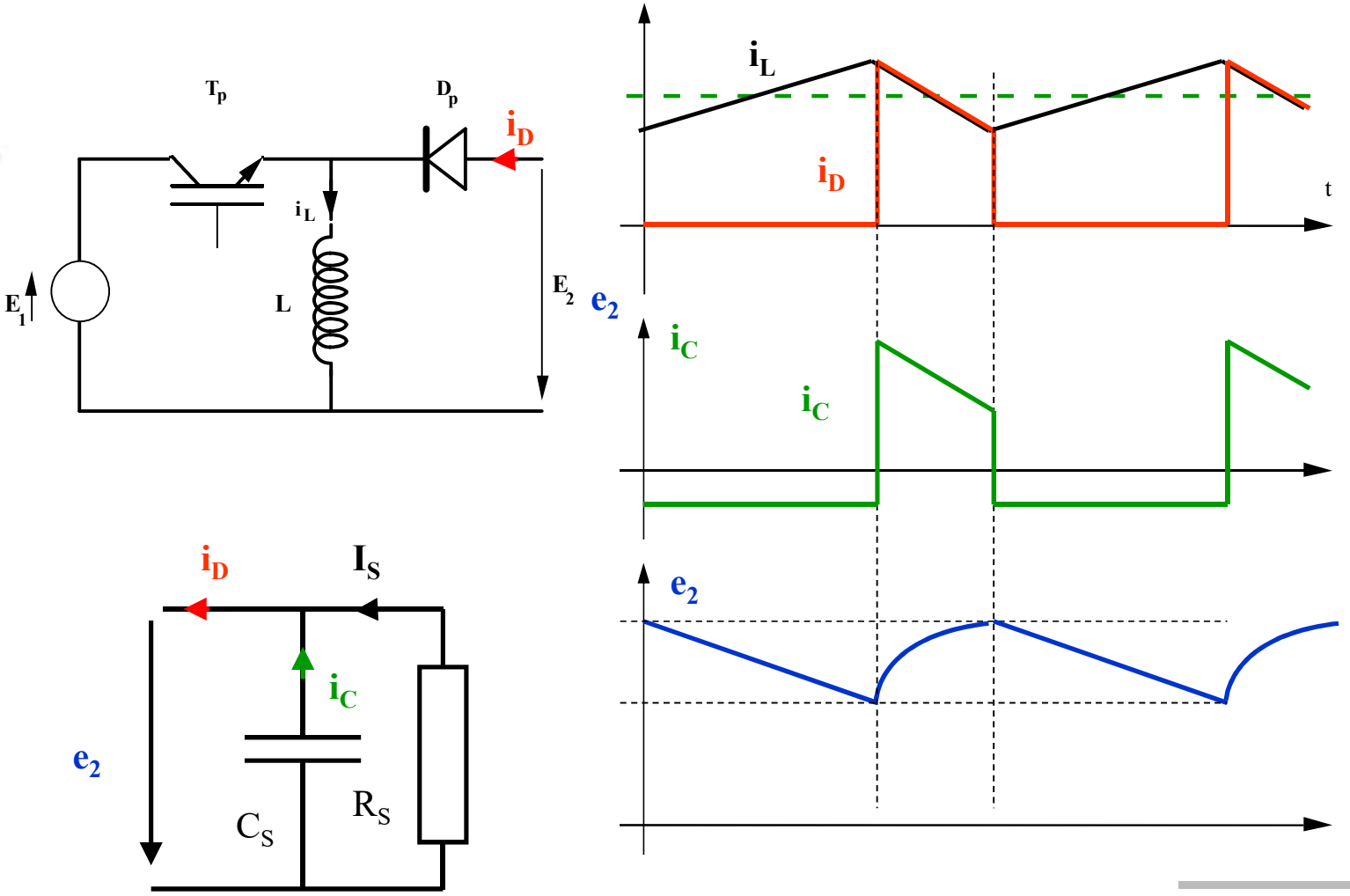
Buck-boost: Continuous mode (output filtering)



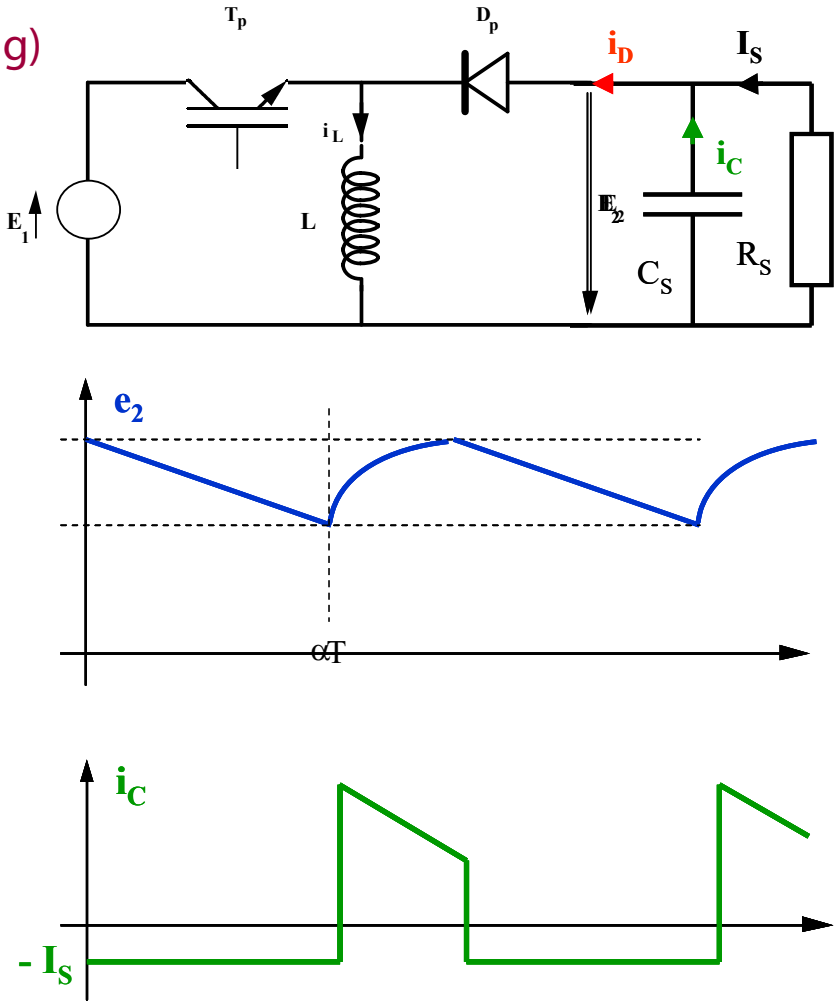
Buck-boost: Continuous mode (Output filtering)

$$\Delta e_2 = \frac{1}{C_S}.\int_0^{\alpha T} i_C(t).dt = \frac{I_S.\alpha T}{C_S}$$

$$or\ I_S = \frac{E_2}{R_S} = \frac{\alpha.E_1}{(1-\alpha)R_S}$$

$$\Delta e_2 = \frac{E_1 T}{R_S C_S}.\frac{\alpha^2}{1-\alpha}$$

$\Rightarrow$ C_S



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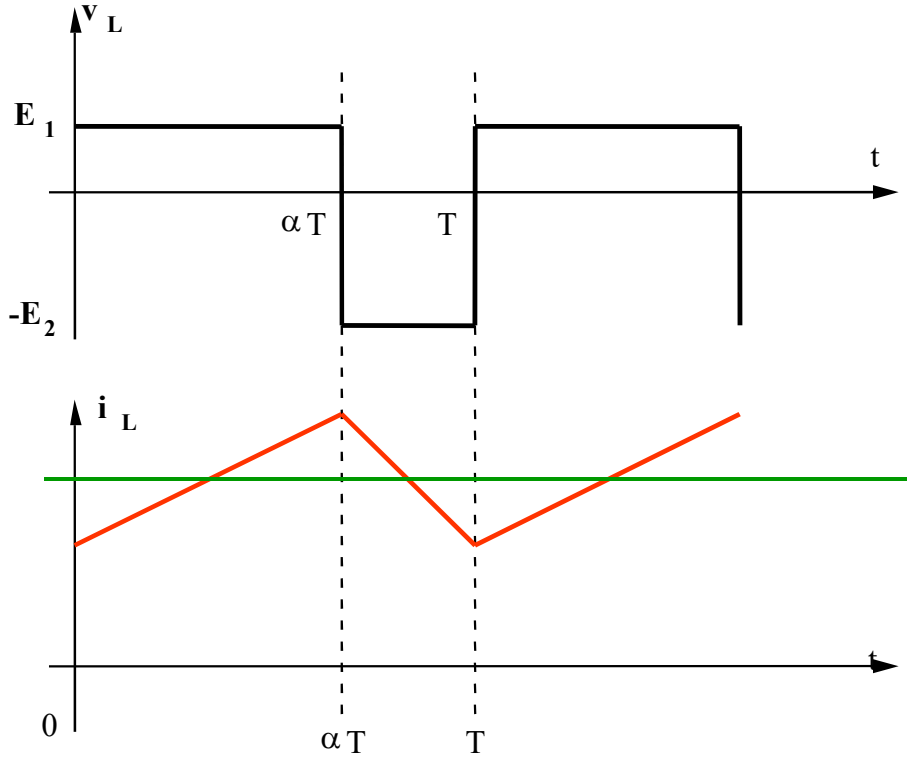
Buck-boost: "decreasing" load



=> Boundary mode

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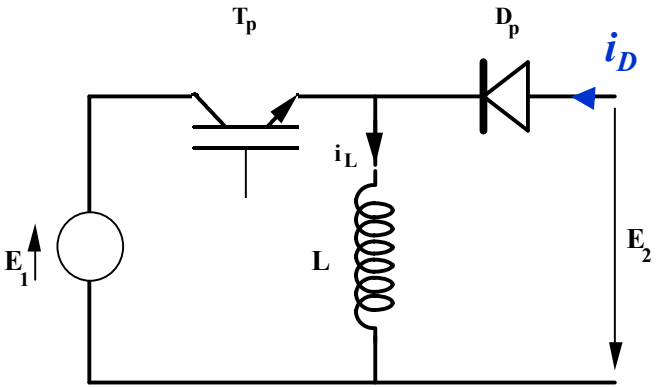
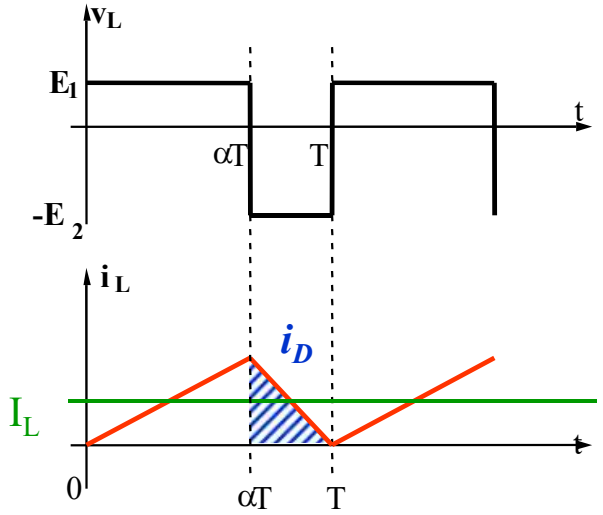
Buck-boost: Boundary mode





$$E_2 = E_1 . \frac{\alpha}{1-\alpha} \Rightarrow \alpha = \frac{E_2}{E_1 + E_2}$$

$$I_{Lc} = \frac{E_1}{L} \frac{\alpha T}{2} = \frac{E_1 . E_2}{E_1 + E_2} . \frac{T}{2L} = \frac{I_{L\max}}{2}$$

Average boundary mode $I_S = \langle i_D \rangle$

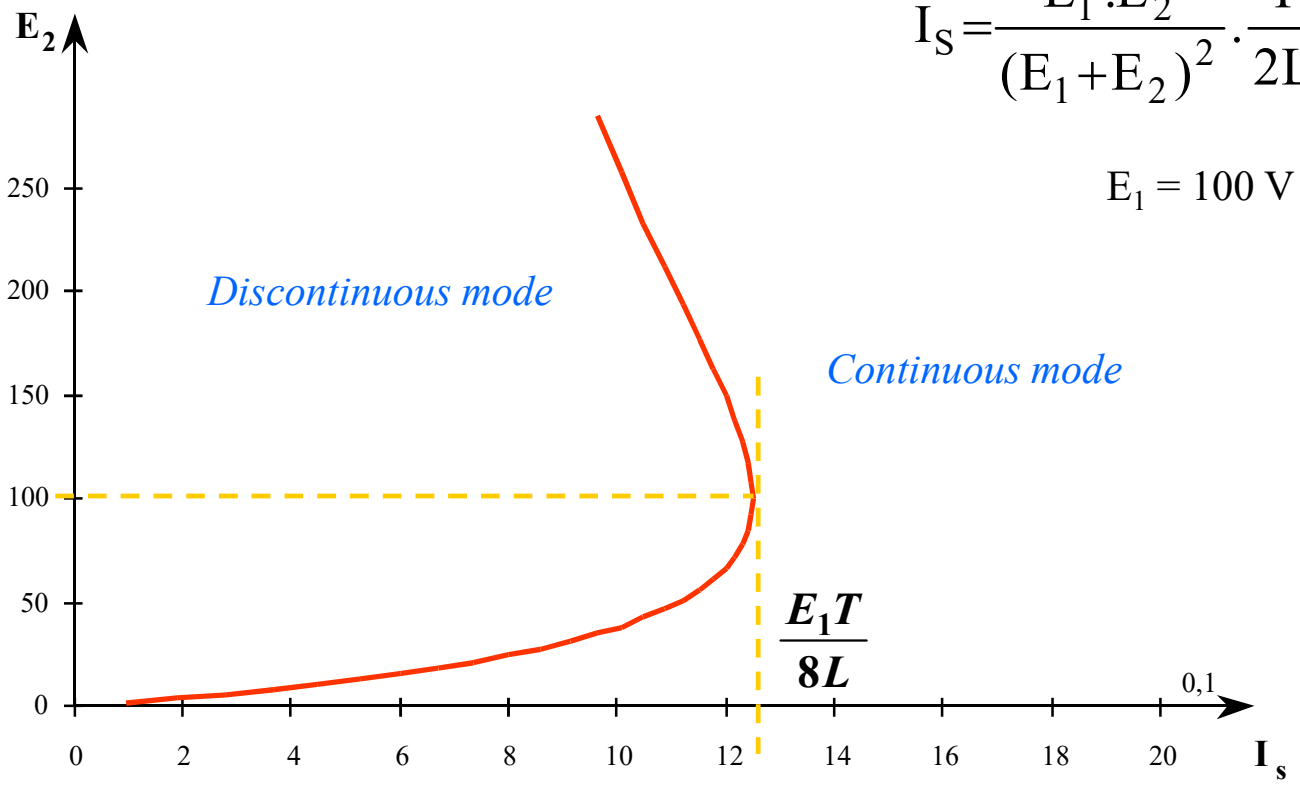
$$I_S = \frac{I_{L\max}}{2} . (1-\alpha) = \frac{E_1^2 . E_2}{(E_1 + E_2)^2} . \frac{T}{2L} .$$

$$E_2 = f(I_S)$$

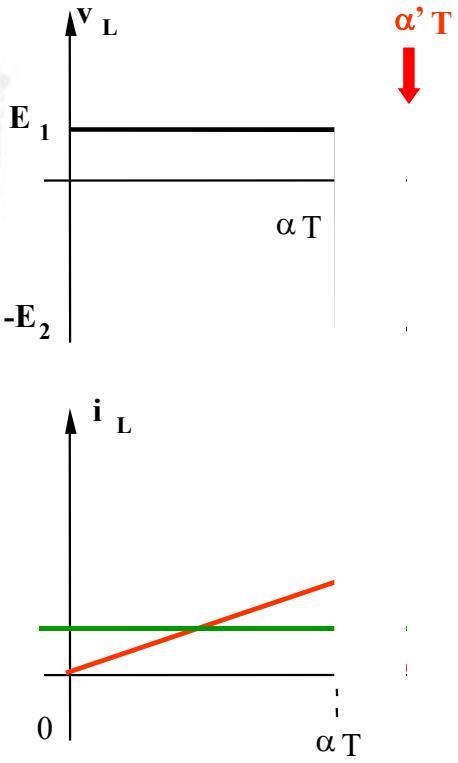
Buck-boost: Boundary mode (characteristics)

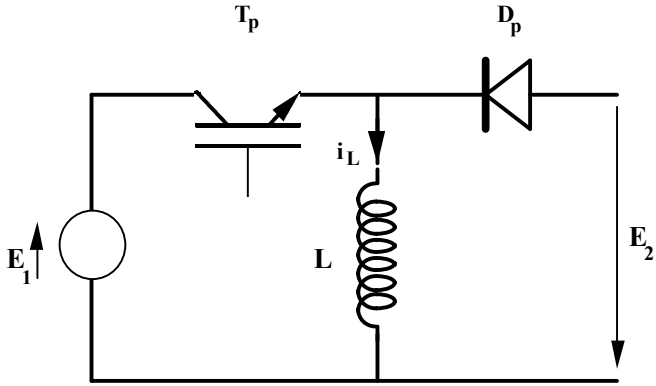
$$I_S = \frac{E_1^2 . E_2}{(E_1 + E_2)^2} . \frac{T}{2L} .$$

$E_1 = 100$ V



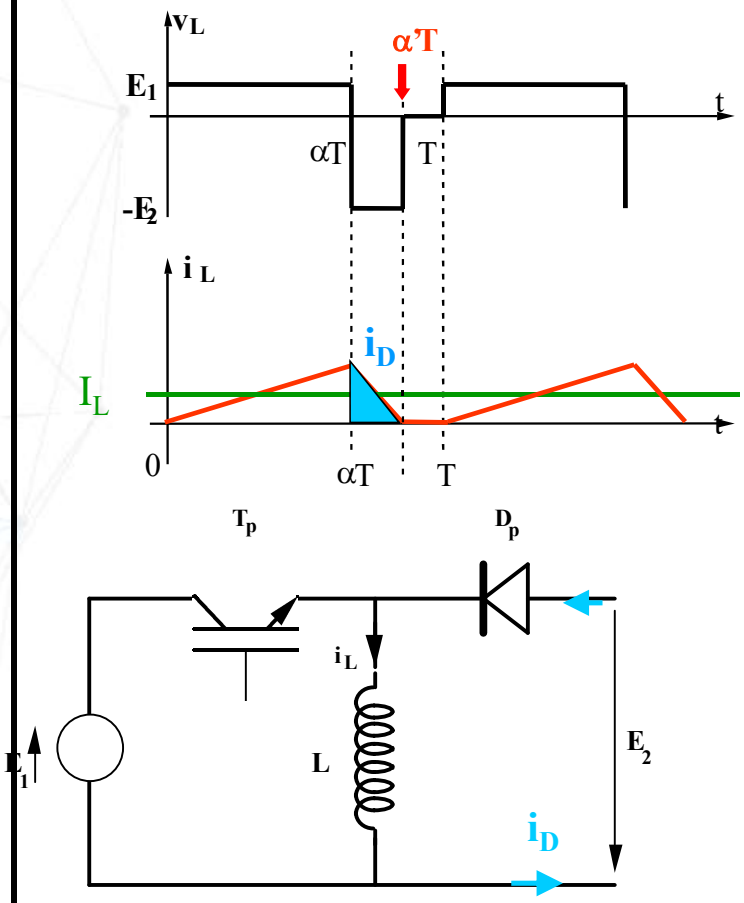
Buck-boost: Discontinuous mode





Full study: Switched-mode power supply

Buck-boost: Discontinuous mode



$$< v_L >=0=\alpha.E_1-(\alpha'-\alpha).E_2 \quad => \quad \alpha'=\alpha\frac{E_1+E_2}{E_2}$$

$$I_S=< i_D >=(\alpha'-\alpha).\frac{I_{L\max}}{2}=(\alpha'-\alpha).\left(\alpha\frac{E_1 T}{2L}\right)$$

$$I_S=\frac{\alpha^2.E_1^2.T}{2L.E_2}$$

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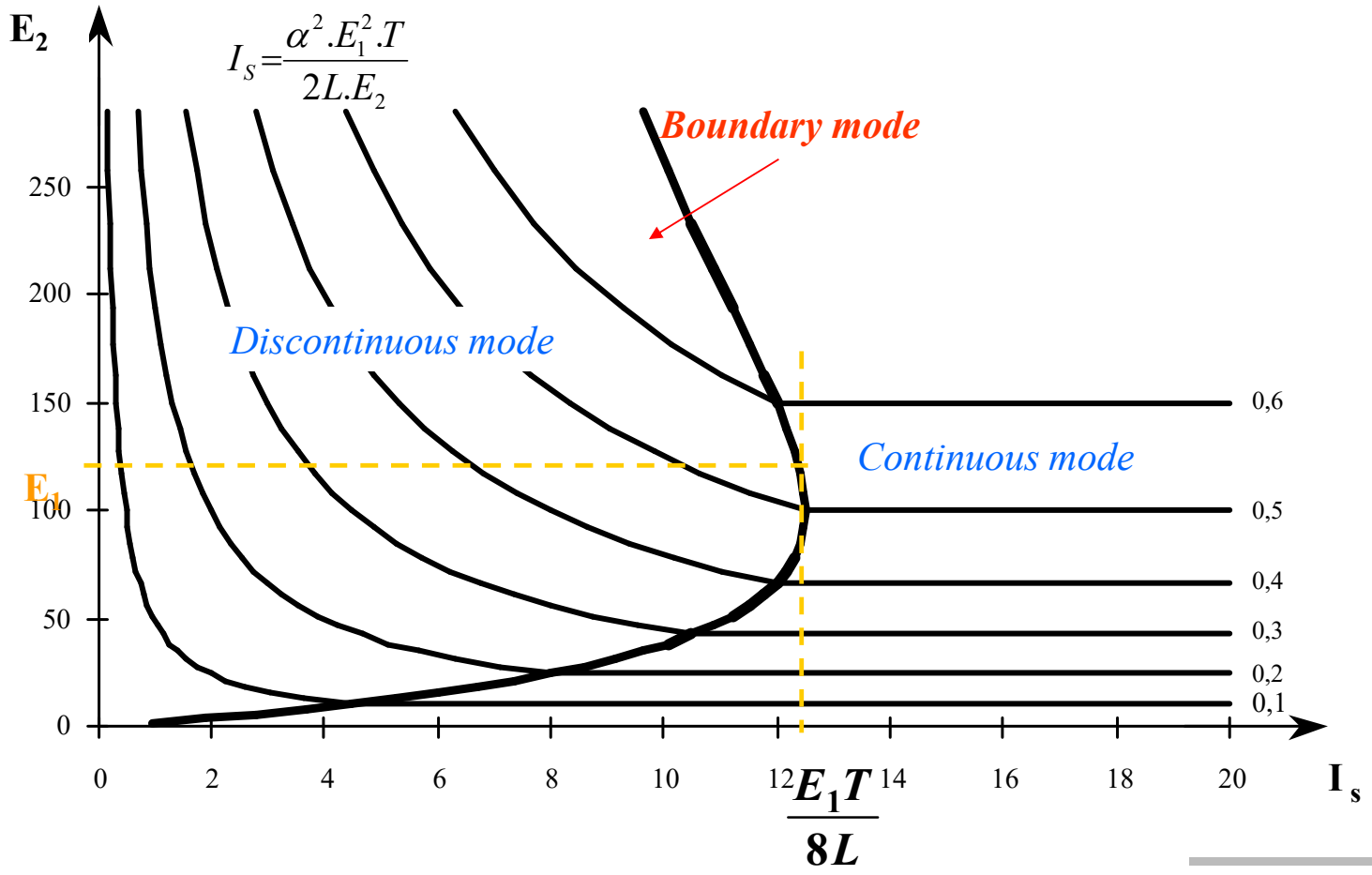
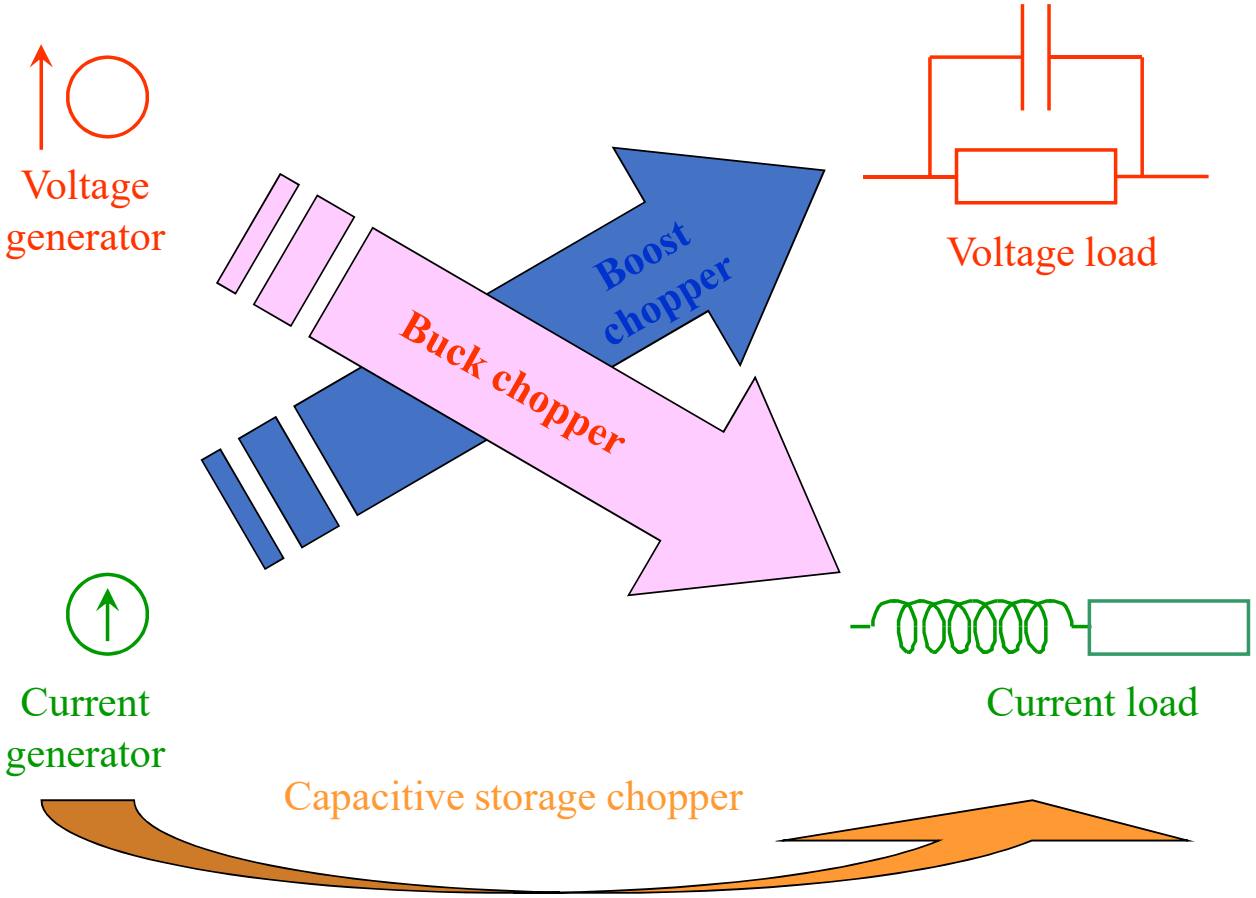
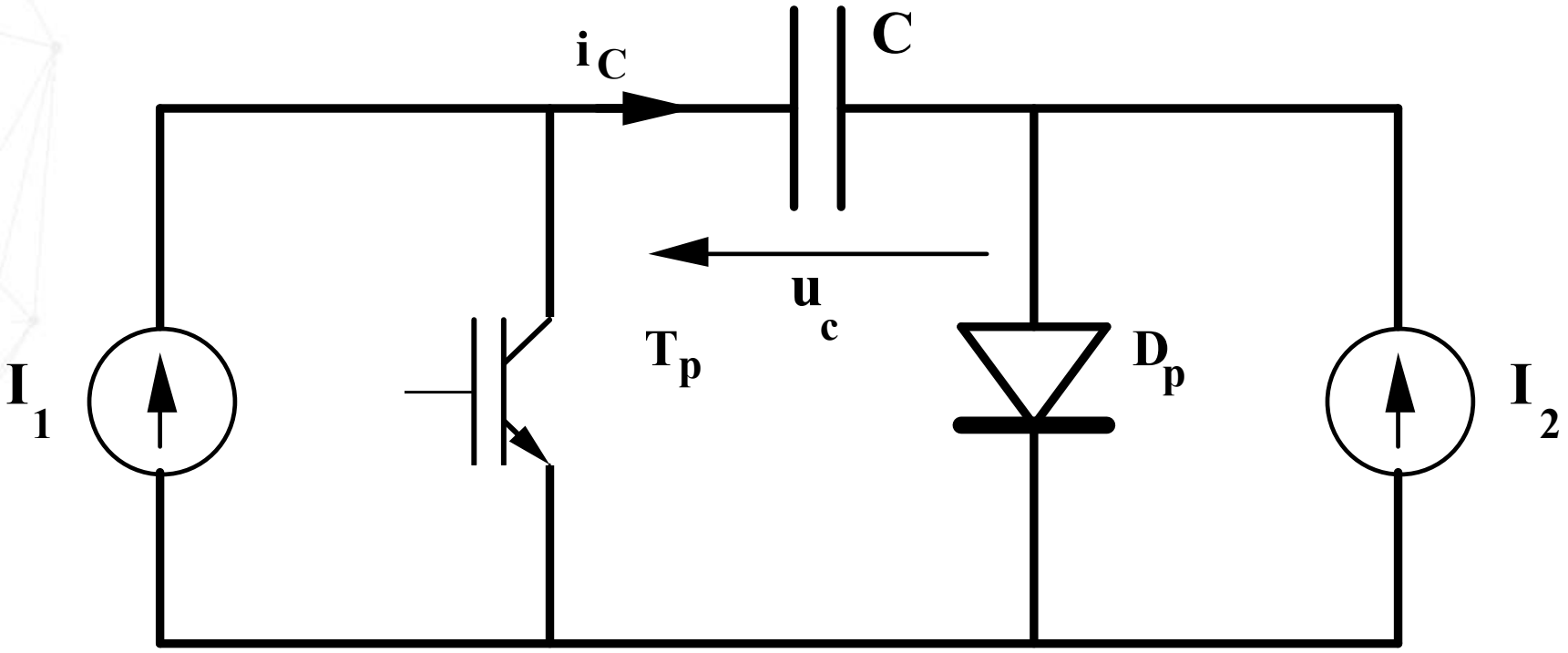
Buck-boost: Output characteristics



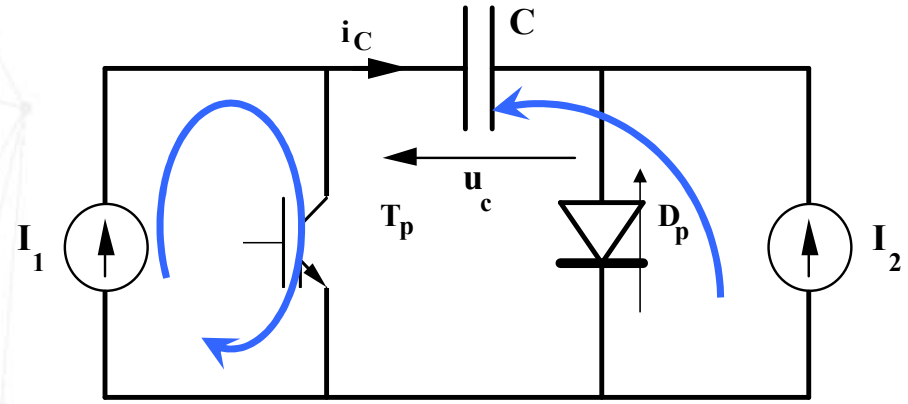
Capacitive storage chopper



CUK structure



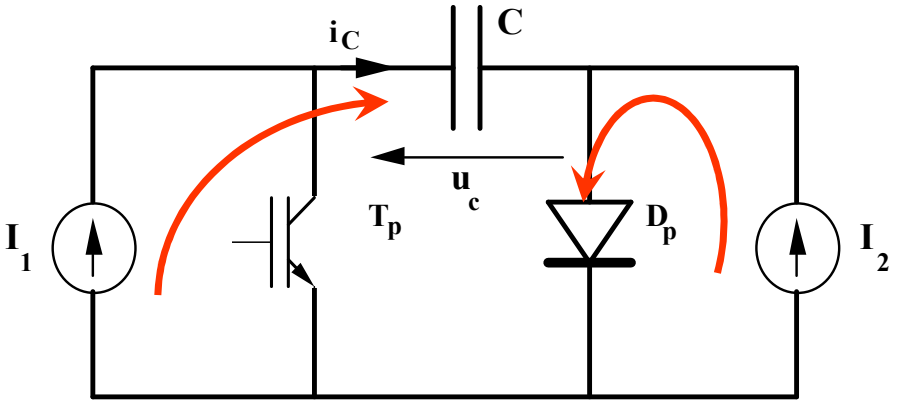
CUK structure: continuous mode (u_C>0)



0 < t < αT : T_p closed

$v_{Dp} = -u_c$ => D_p reverse

$i_c = -I_2 = C.du_c/dt$ => u_c decreases



αT < t < T : T_p opened

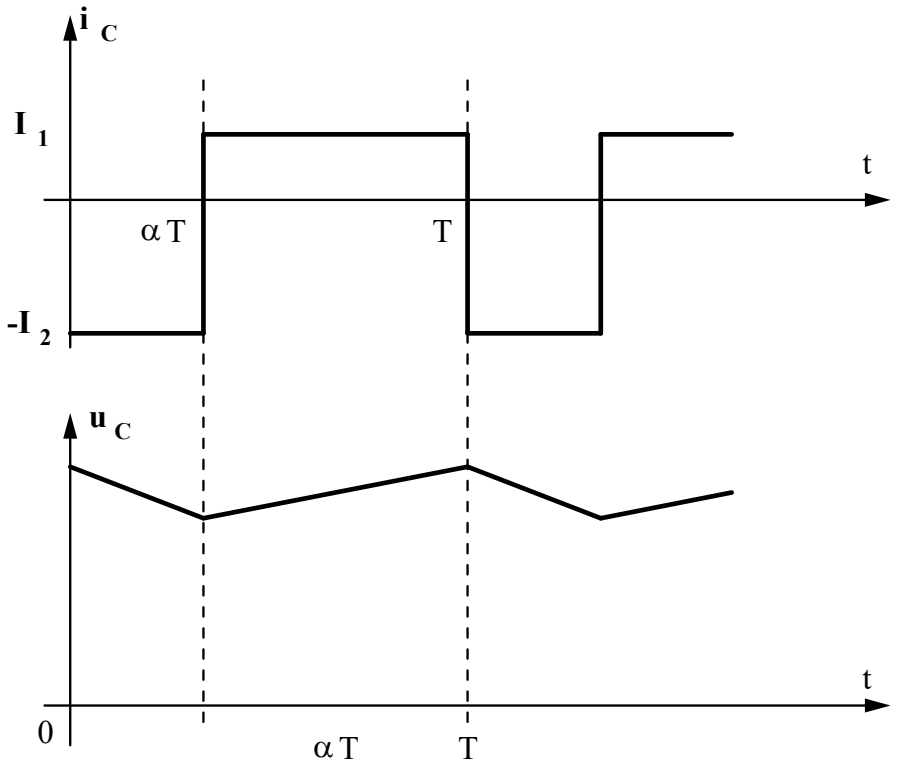
$i_c = I_1 = C.du_c/dt$ => u_c increases

$i_D = I_1 + I_2$ => Dp forward

CUK structure: Chronograms

$$\langle i_C \rangle = 0$$

$$I_2 = I_1 . \frac{1-\alpha}{\alpha}$$



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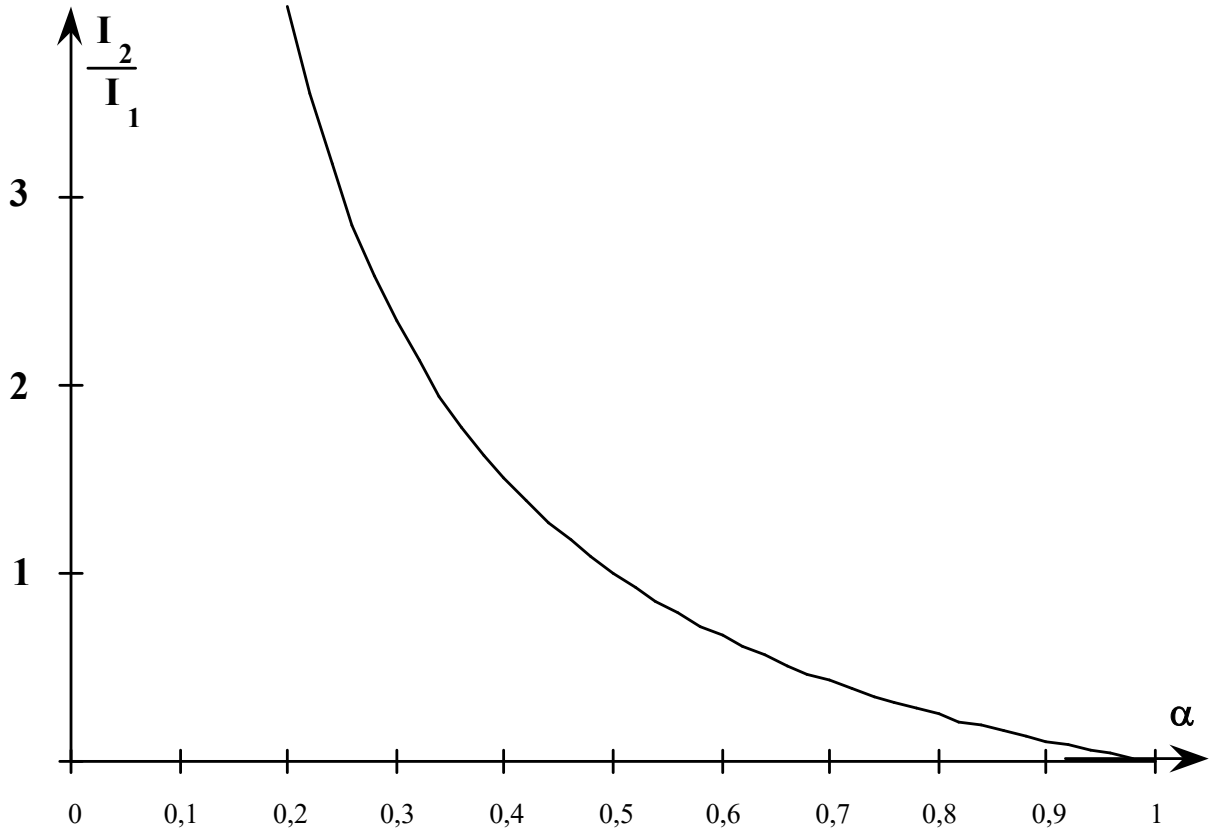
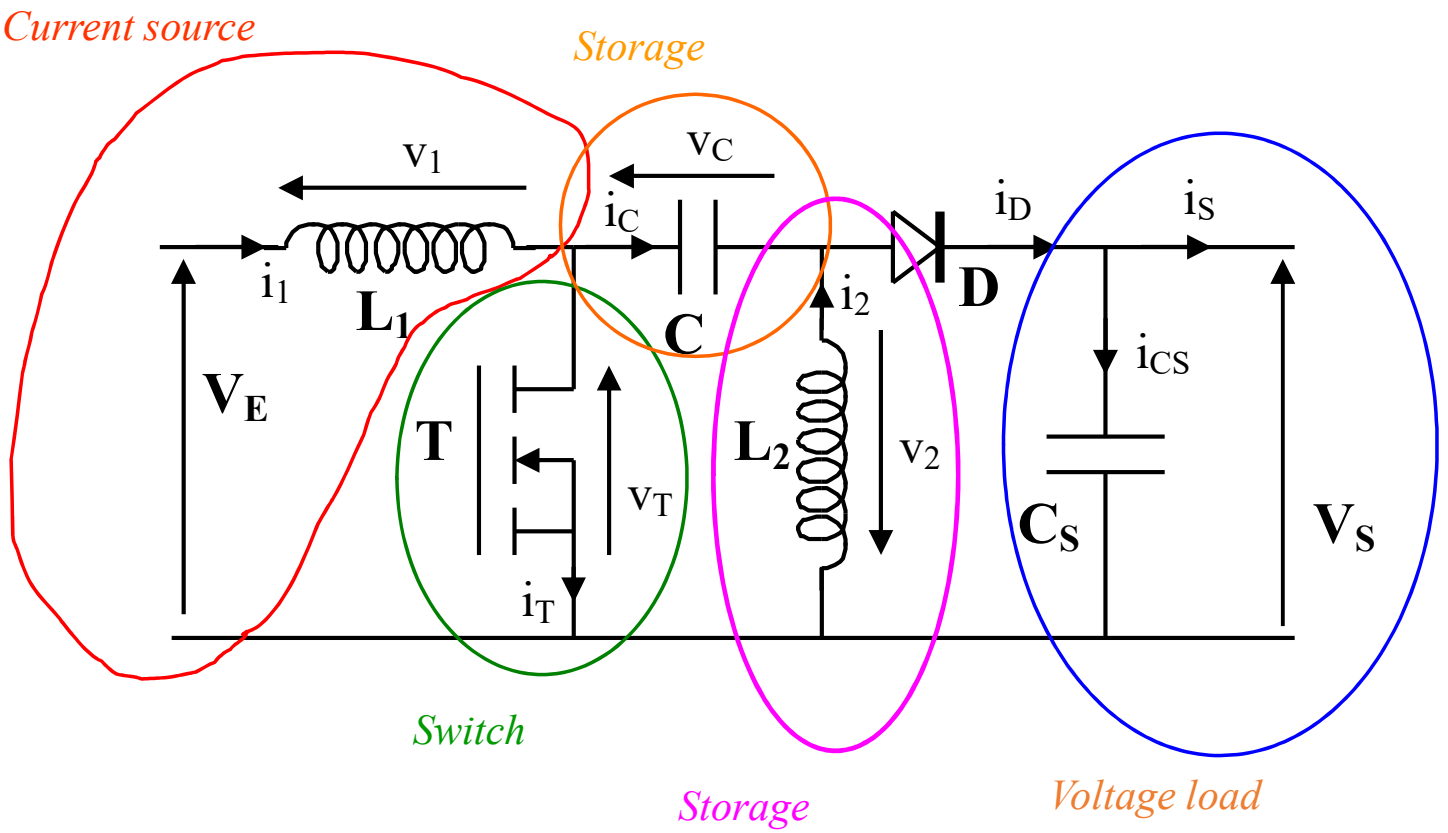
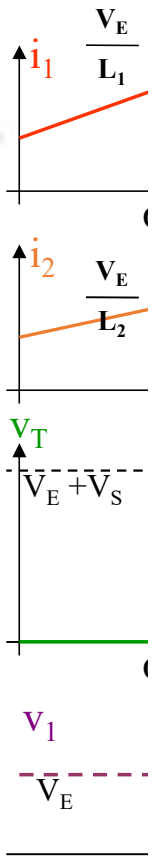
CUK structure: Transfer characteristic

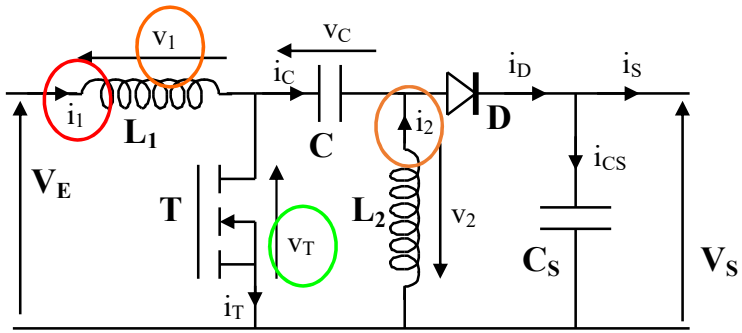


SEPIC: Single Ended Primary Inductor Convertor



SEPIC: Continuous mode (voltage transfer)





$\langle v_1 \rangle = 0$ et $\langle v_2 \rangle = 0 \Rightarrow \langle v_C \rangle = V_E$ = **Constant**

$$V_S = V_E \cdot \frac{\alpha}{1-\alpha}$$

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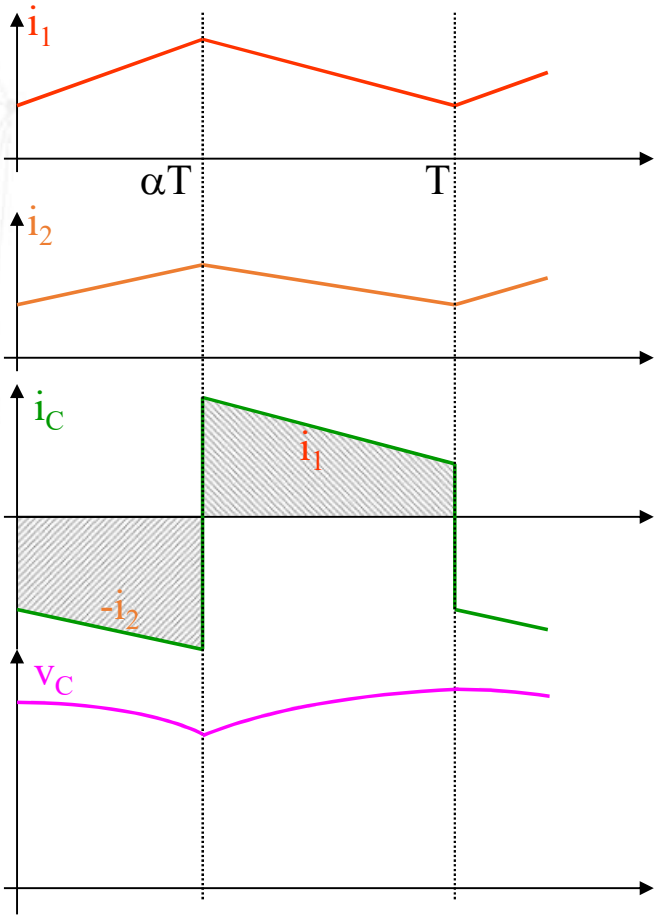
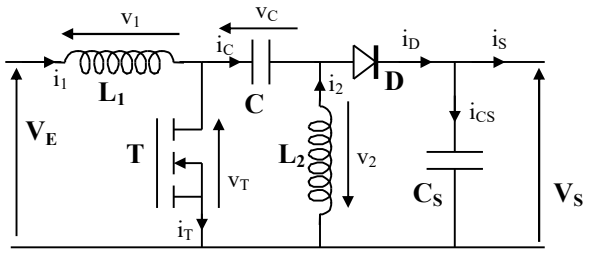
SEPIC: Continuous mode (coupling capacitor)



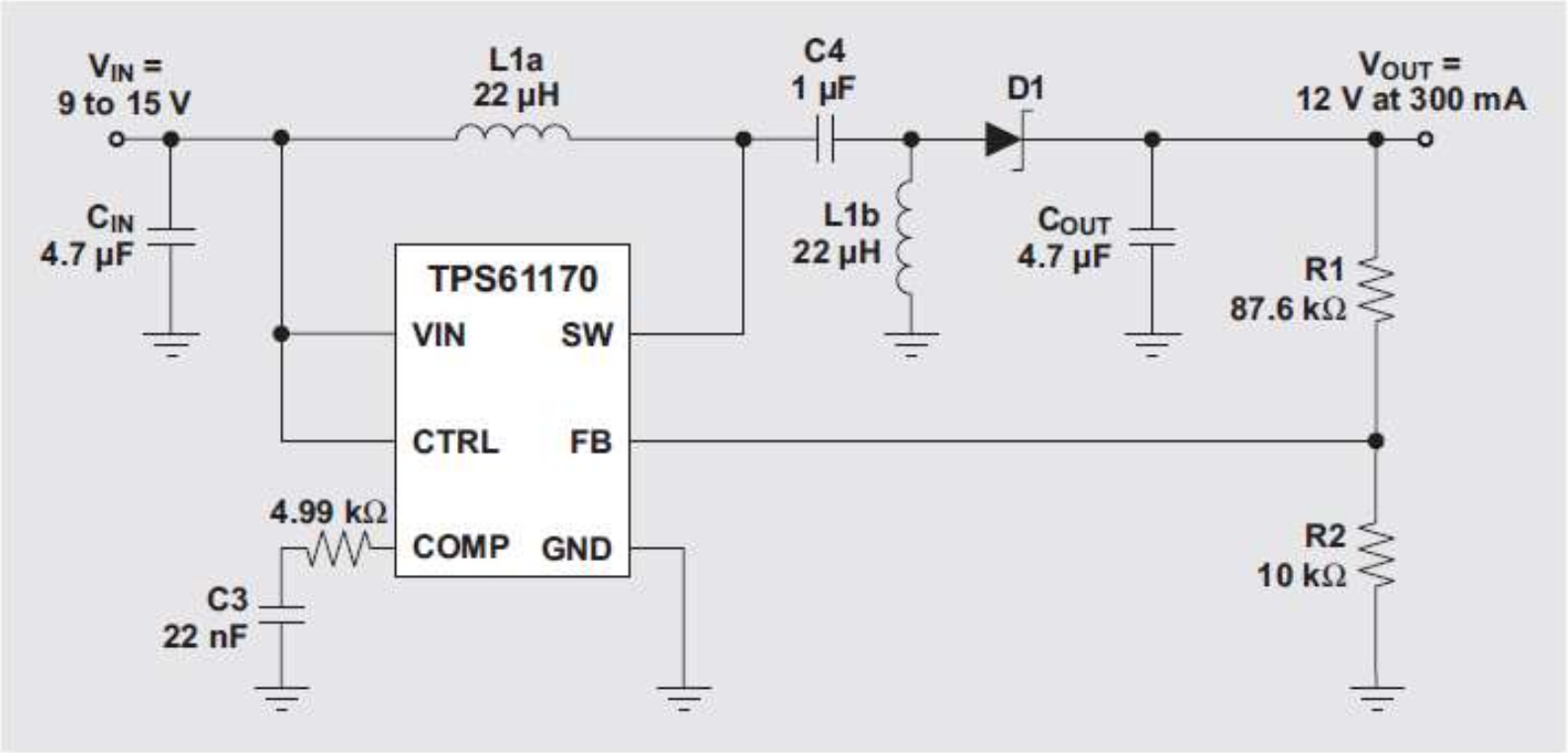


$$I_2 = I_S \qquad I_S = I_E \cdot \frac{1-\alpha}{\alpha}$$

$$\Delta V_C = \frac{\alpha . I_S}{C . f}$$

$$I_{Ceff} = I_S \cdot \sqrt{\frac{\alpha}{1-\alpha}}$$

SEPIC: circuit example
TPS 61170 – Texas Instrument



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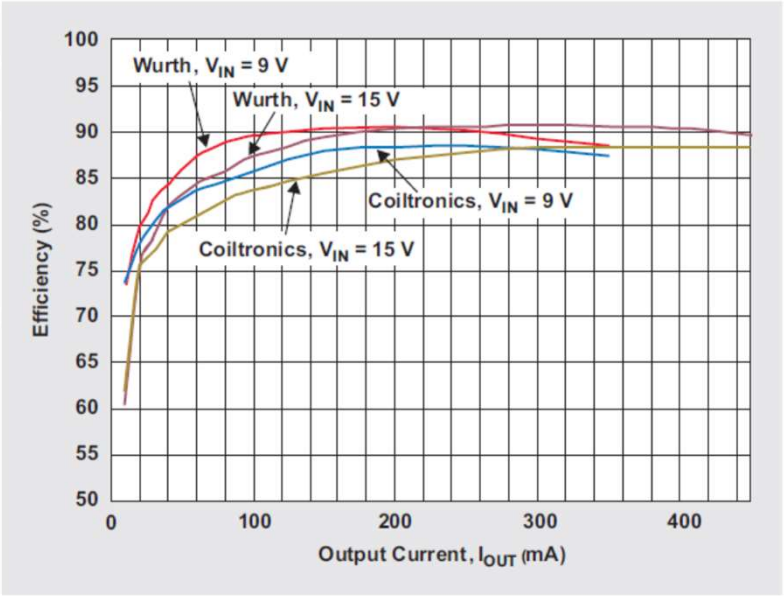
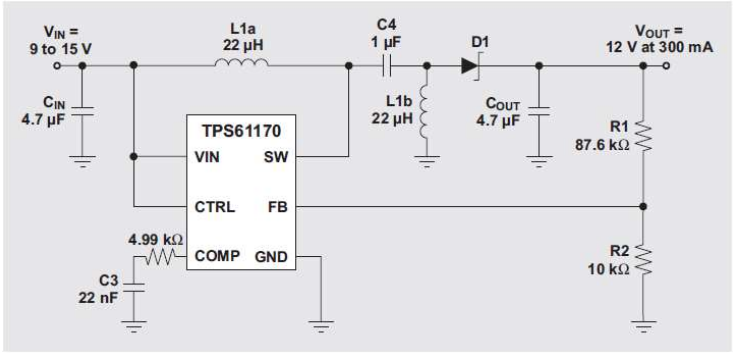
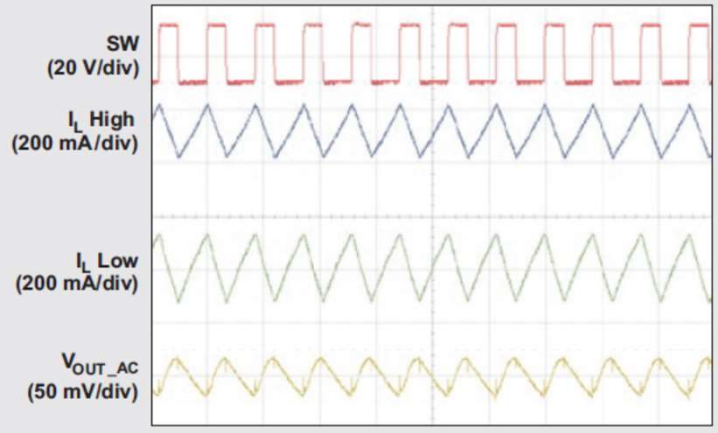
SEPIC: circuit example
TPS 61170 – Texas Instrument







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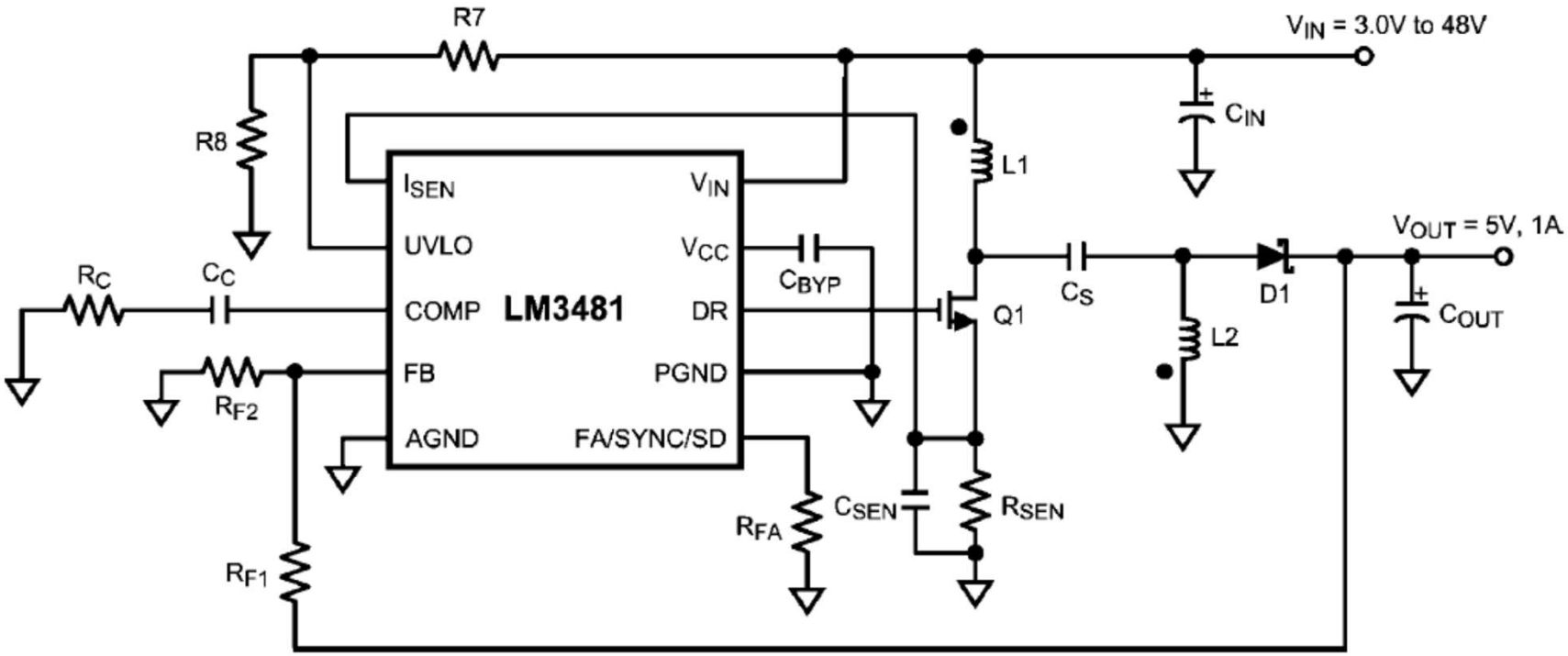

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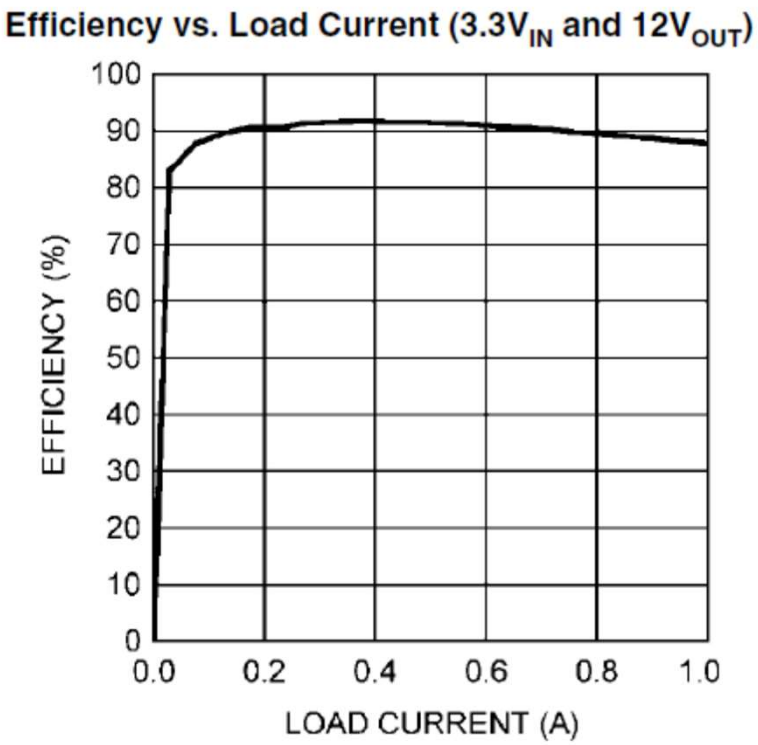

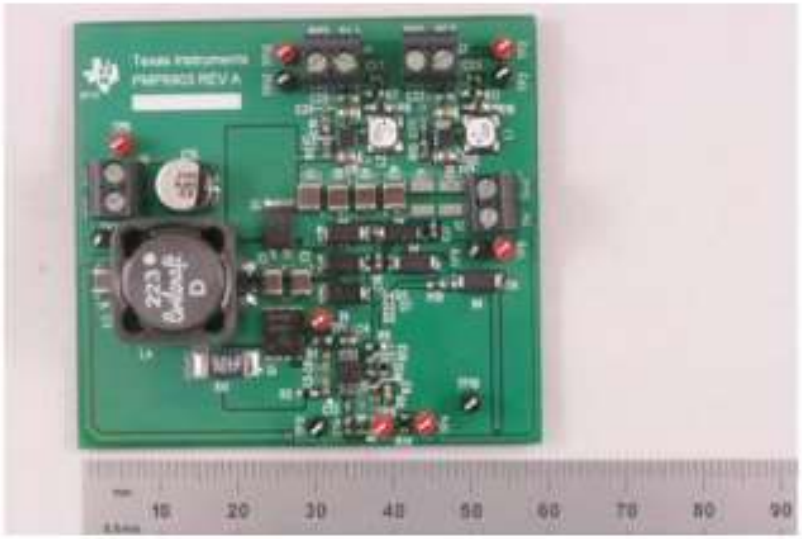

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LM3481: internal schematic