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Energy Conversion I

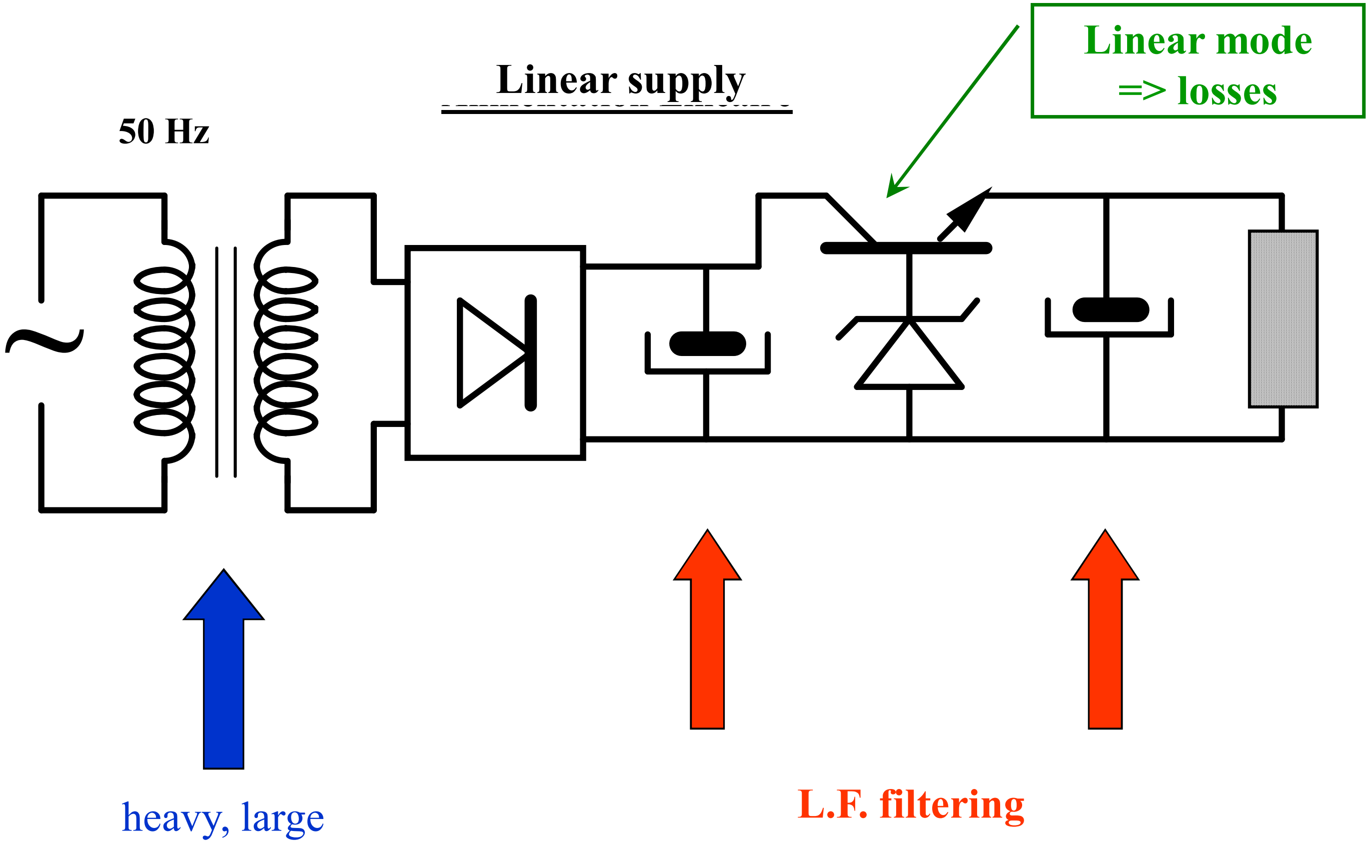
alexis.martin@ensea.fr
Desk D216

Layout

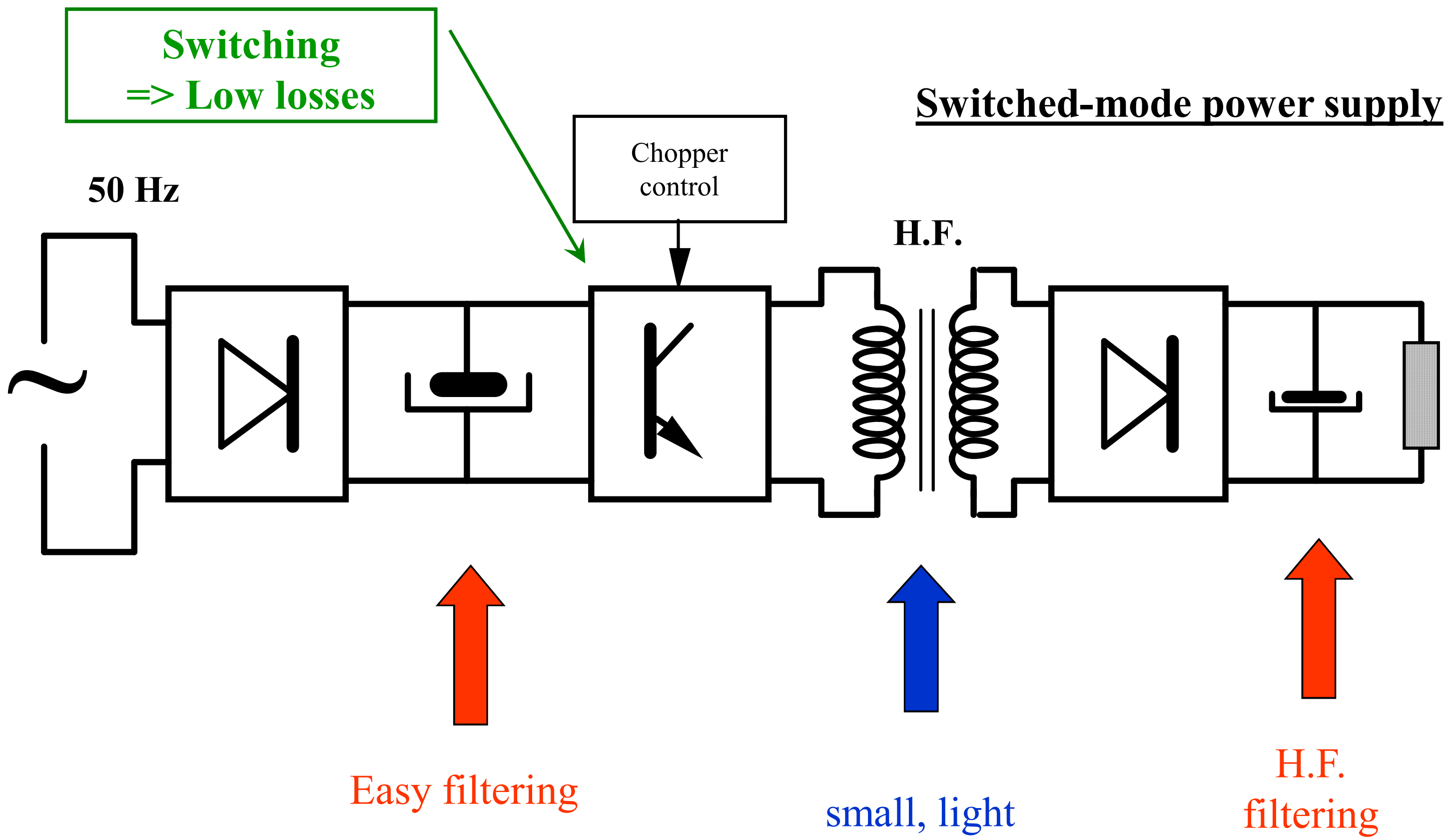
- Non isolated choppers
- **Switch mode power supplies**
  - Introduction
  - Flyback
  - Forward
  - Push-Pull
- Power components

Introduction

Linear isolated power supply principle



Isolated switched-mode power supply principle



Comparison

Element	LINEAR	Switching
Transformer	Large (50 Hz)	Small (H.F.)
Transistor	Linear (losses)	Switching
Output filter	Large (50 Hz)	Simple (H.F.)
Command	autonomous, simple	control, complex
Efficiency	40 % < < 50 %	70 % < < 90 %
Control	0,1 %	0,5 %

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Switched-mode power supply nomenclature

- ***Flyback*** ***: energy storage converter***
- ***Forward*** ***: direct converter***
- ***Push-Pull*** ***: symmetric converter (full bridge or half bridge)***

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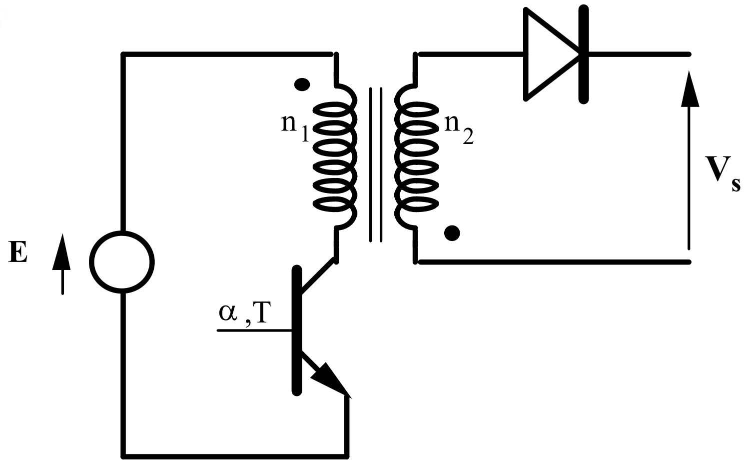
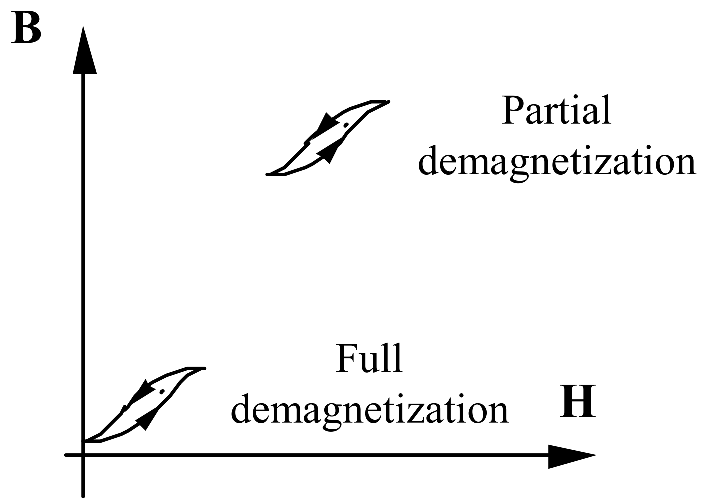
Flyback principle





Easiness, low power, few components

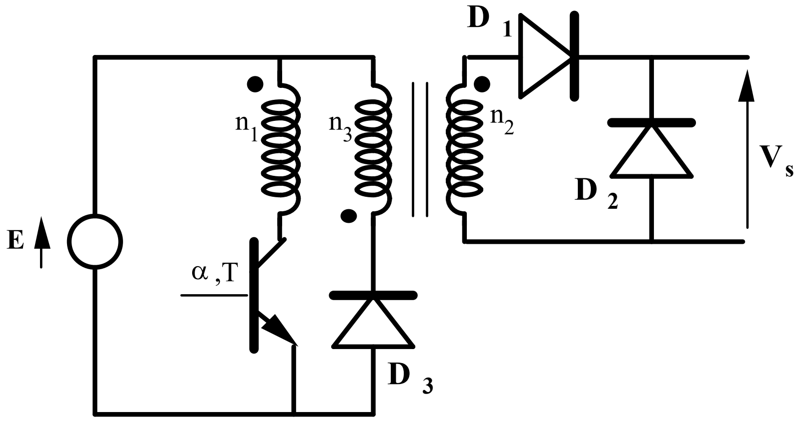
Introduction

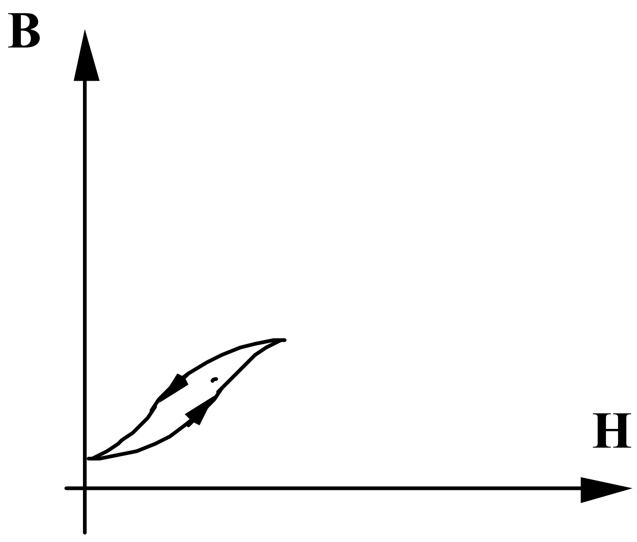
Flyback

Forward

Push-Pull

Forward principle





Magnetic component optimized, more components

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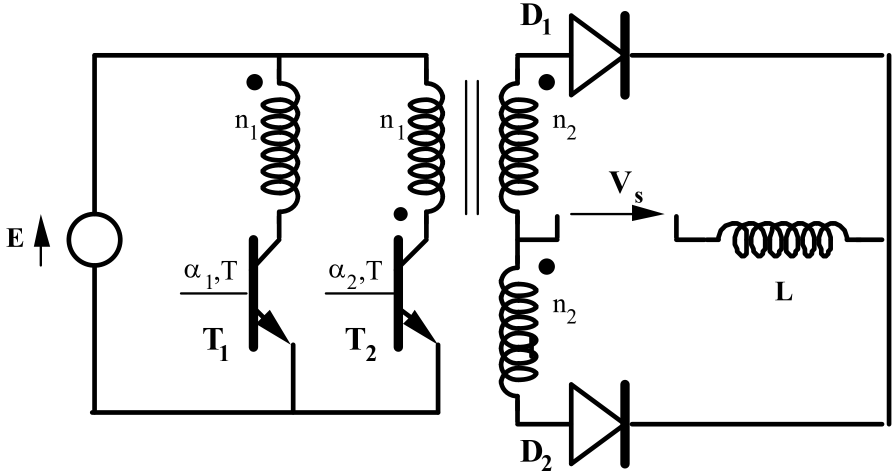
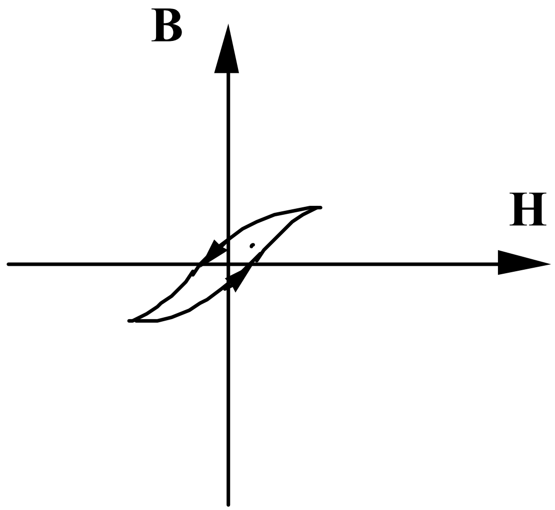
Symmetric converter





High power, 2 transistors or more

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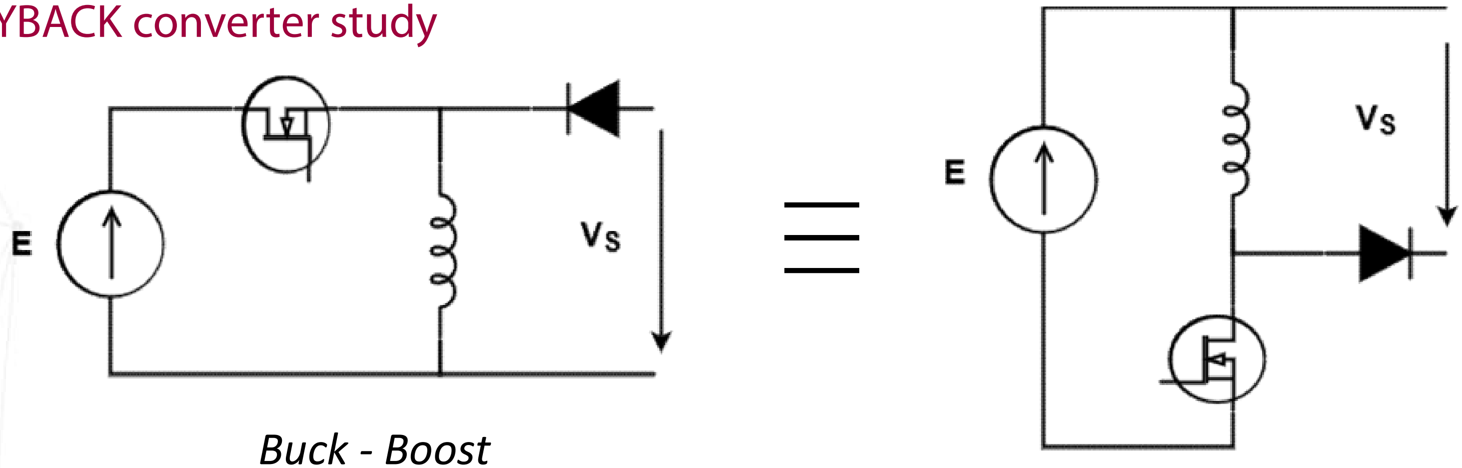
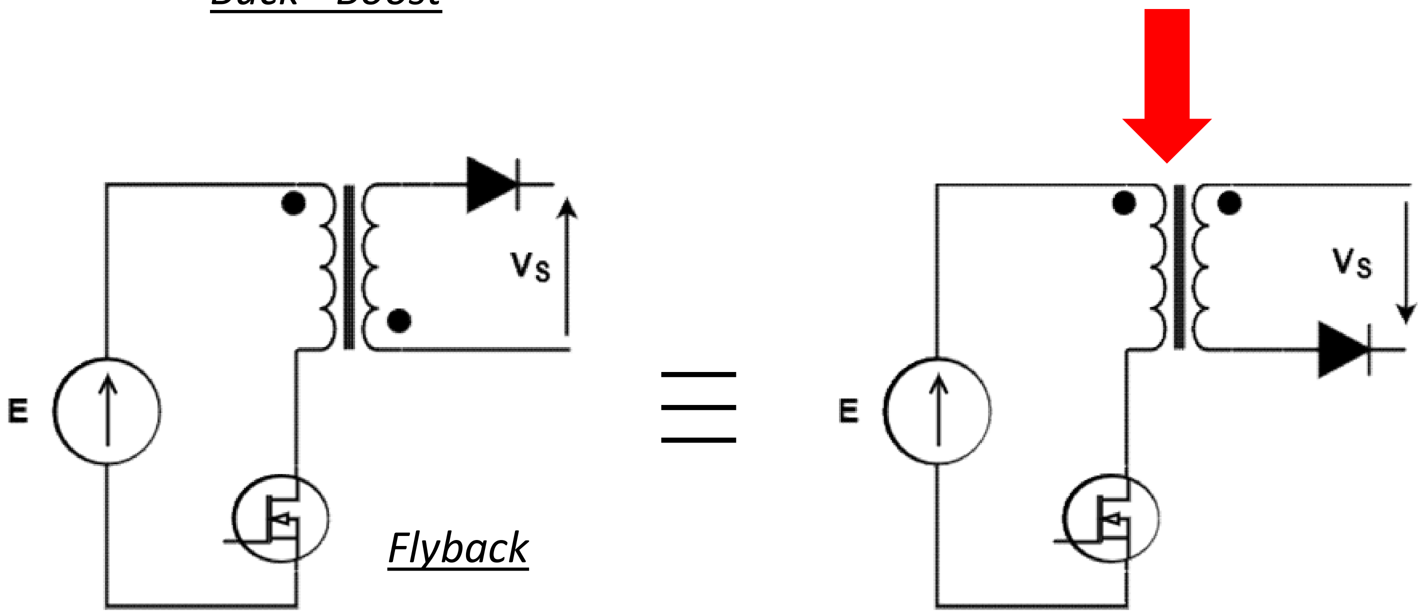
Flyback

FLYBACK converter study

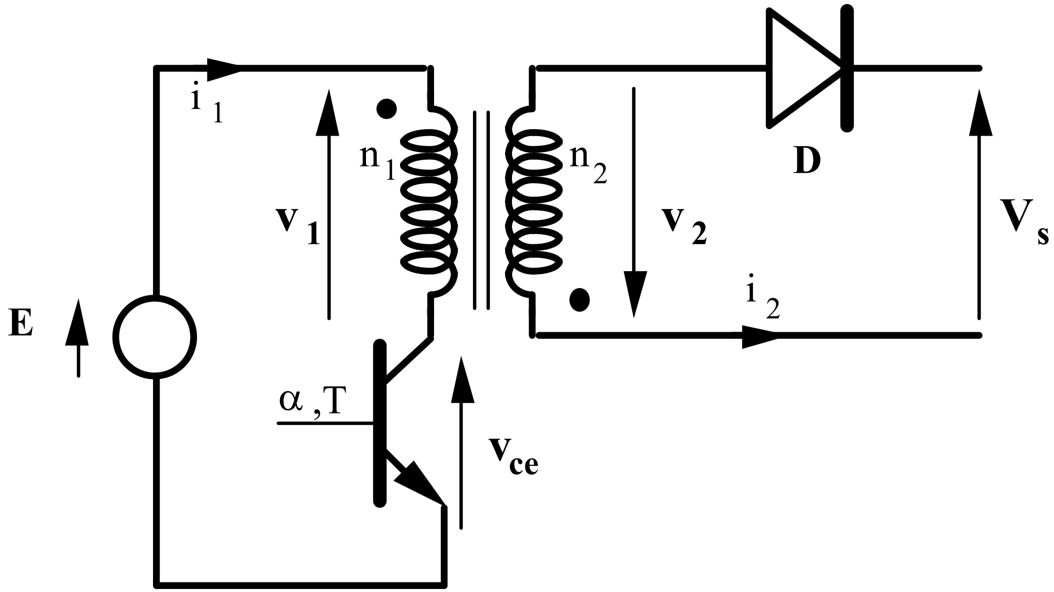


Buck - Boost



Flyback

FLYBACK converter study



Hypothesis **: *E constant, V_s constant, perfect semi-conductors***

2 magnetic modes
Partial demagnetization (continuous mode)
Full demagnetization (discontinuous mode)

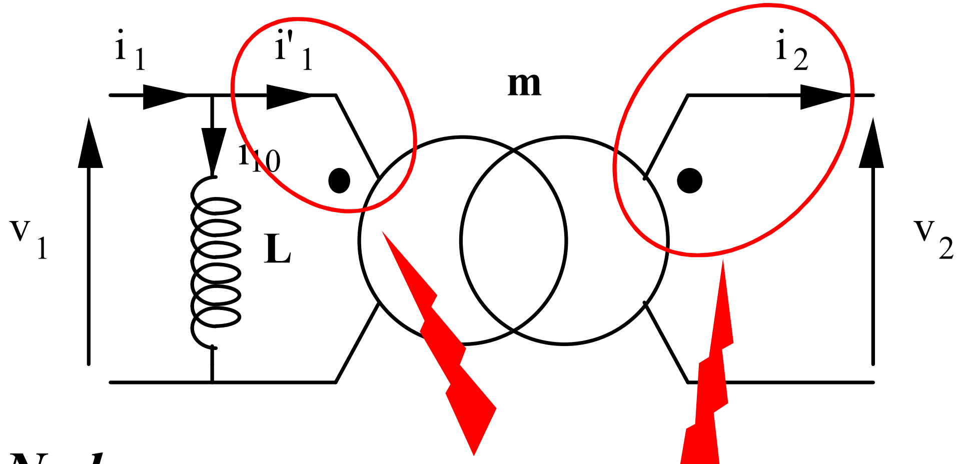
Introduction

Flyback
Transformer
Continuous mode
Discontinuous mode
Sizing

Forward

Push-Pull

Transformer model: convention !



No losses

L : magnetizing inductance (at the primary)
R: Reluctance of the magnetic circuit

$$m = \frac{n_2}{n_1} = \frac{v_2}{v_1} = \frac{i_1'}{i_2}$$

$$\boxed{\oint H.dl = R.\varphi = N_1.i_1 - N_2.i_2 = N_1.i_{10}}$$

Hopkinson's law

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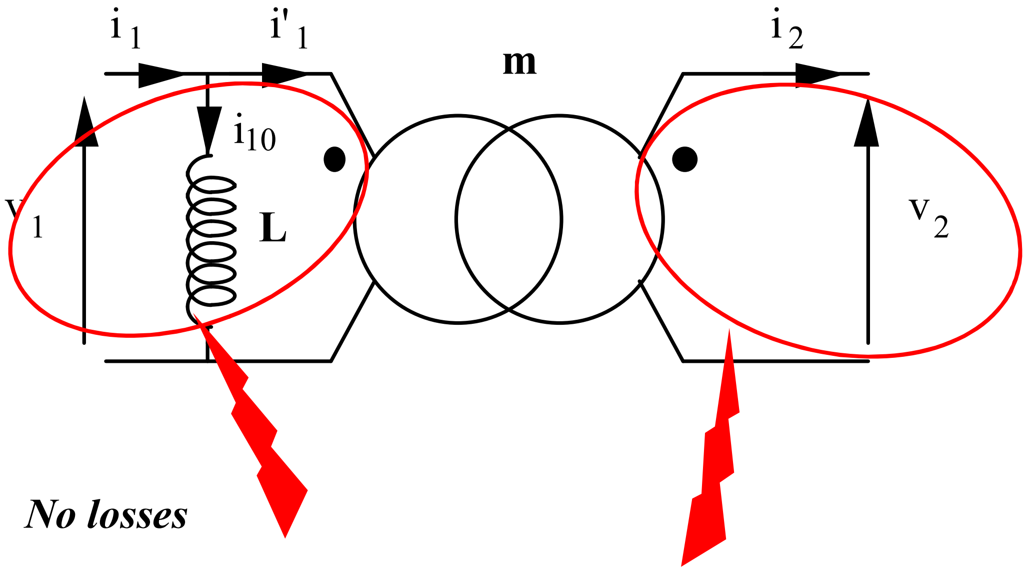
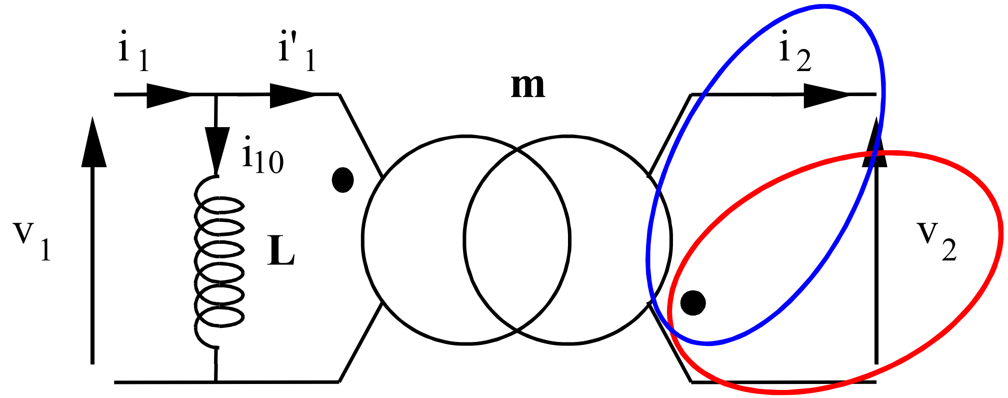
Transformer model: convention !



$$\boxed{v_1 = +n_1 \frac{d\varphi}{dt} \qquad v_2 = +n_2 \frac{d\varphi}{dt}}$$

FLYBACK transformer model

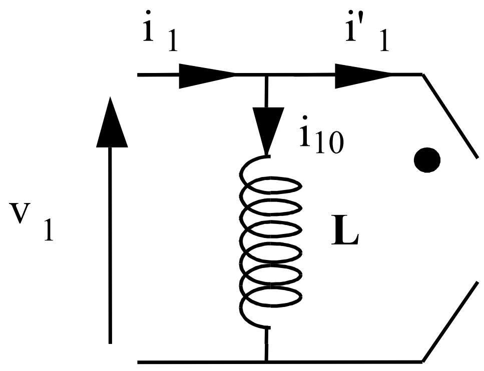


$$m = \frac{N_2}{N_1} = -\frac{v_2}{v_1} = -\frac{i'_1}{i_2}$$

$$v_2 = -n_2 \frac{d\varphi}{dt}$$

$$\oint H.dl = R.\varphi = N_1.i_1 + N_2.i_2 = N_1.i_{10}$$

Magnetizing current



$$i_1 = i_{10} + i'_1$$

$$R.\varphi = N_1 . i_{10}$$

$$L_1 = \frac{N_1^2}{R}$$

Magnetizing current ⇔ flux in the magnetic circuit

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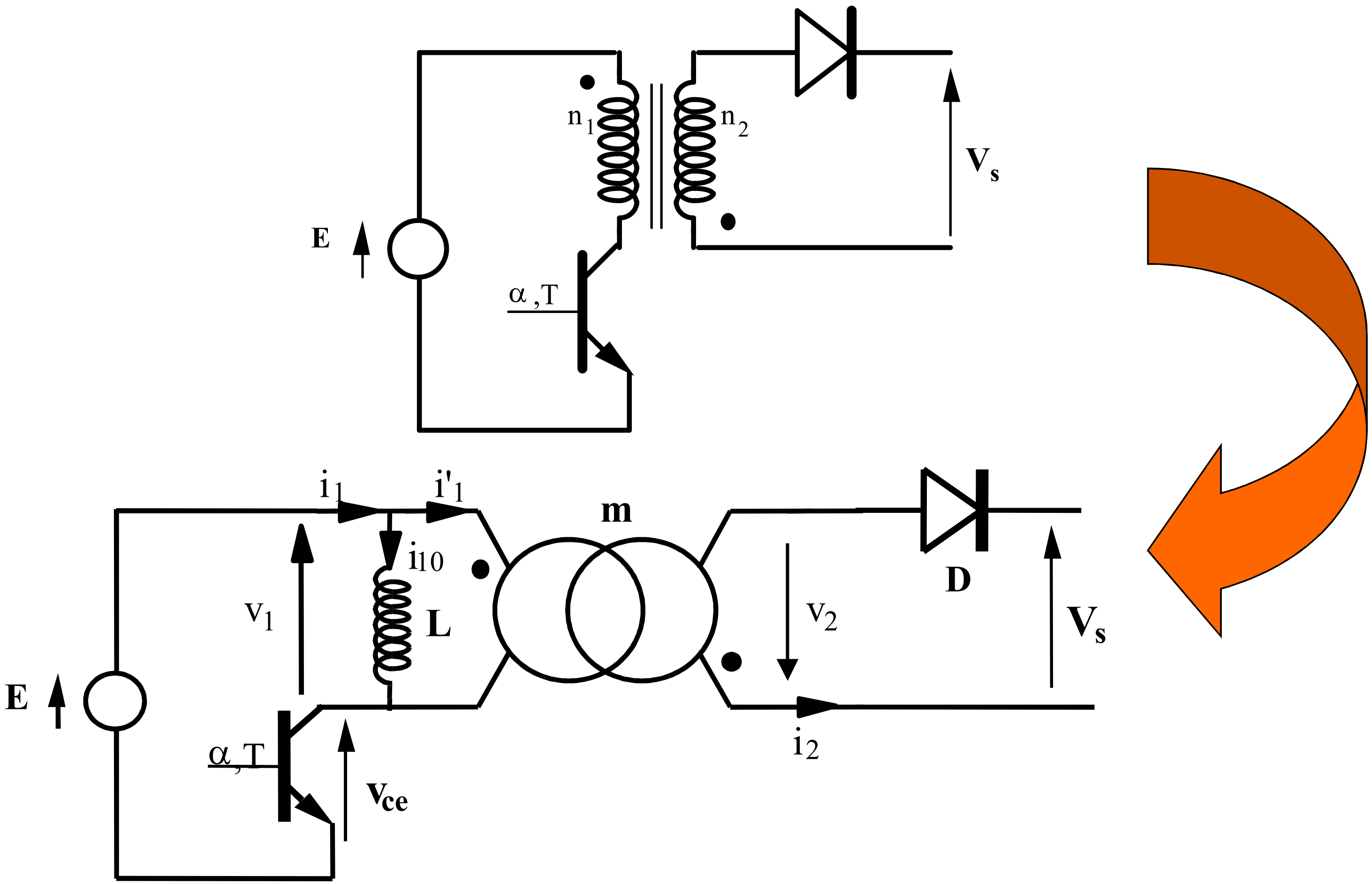
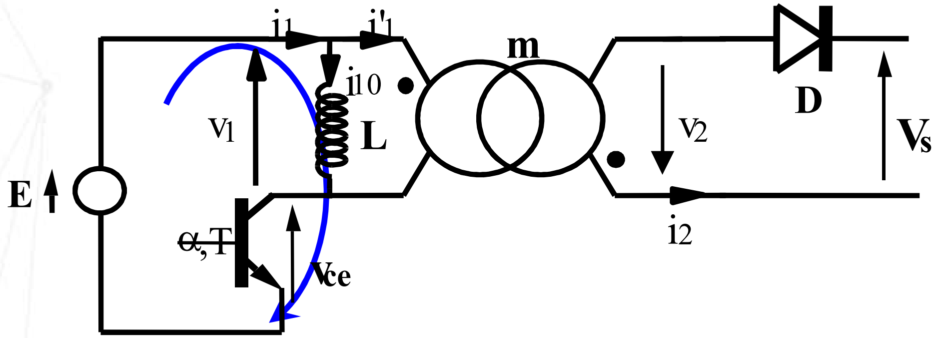
FLYBACK equivalent scheme

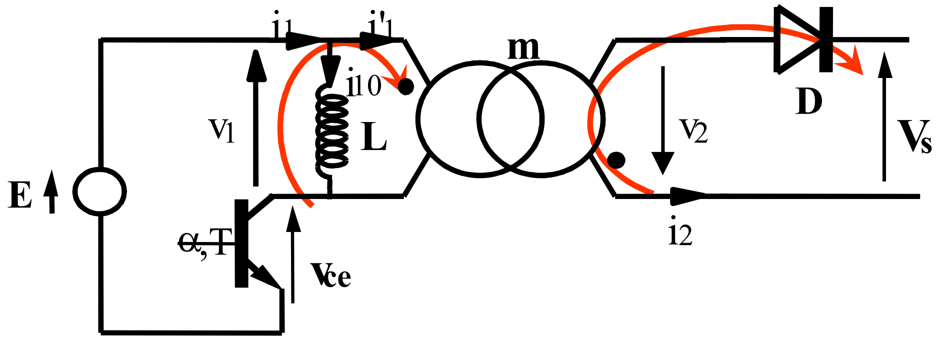


Partial demagnetization mode: continuous conduction



$0 < t < \alpha T$: T_p closed
$\Rightarrow v_1 = E \Rightarrow v_2 = m.E$
$v_D = -mE - V_s < 0 \Rightarrow$ *D reverse*

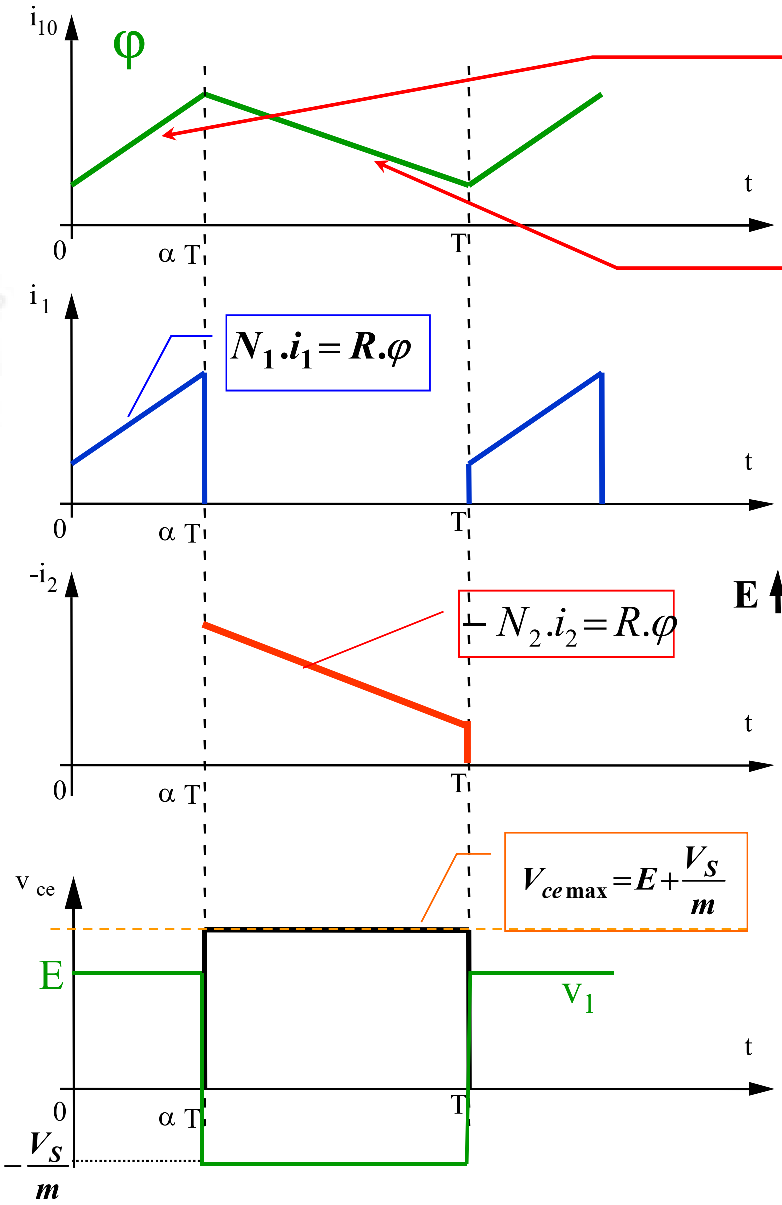
$i_2 = 0 \Rightarrow i'_1 = 0 \Rightarrow i_1 = i_{10}$
Energy storing



$\alpha T < t < T$: T_p opened
$\Rightarrow i_1 = 0 \Rightarrow i'_1 = -i_{10} < 0$
$\Rightarrow i_2 < 0 \Rightarrow$ *D forward*

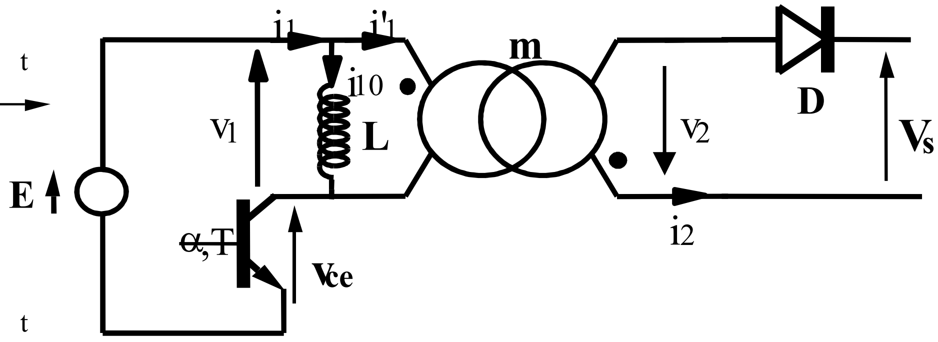
$v_2 = -V_S \Rightarrow v_1 = -V_S/m \Rightarrow \varphi$ decreases
Energy restitution

$$\boxed{\oint H.dl = R.\varphi = N_1.i_1 - N_2.i_2 = N_1.i_{10}}$$



$$v_1 = L_1.\frac{di_{10}}{dt} = N_1.\frac{d\varphi}{dt} \qquad \frac{d\varphi}{dt} = \frac{E}{N_1}$$

$$v_2 = N_2.\frac{d\varphi}{dt} \qquad \frac{d\varphi}{dt} = -\frac{V_S}{N_2}$$

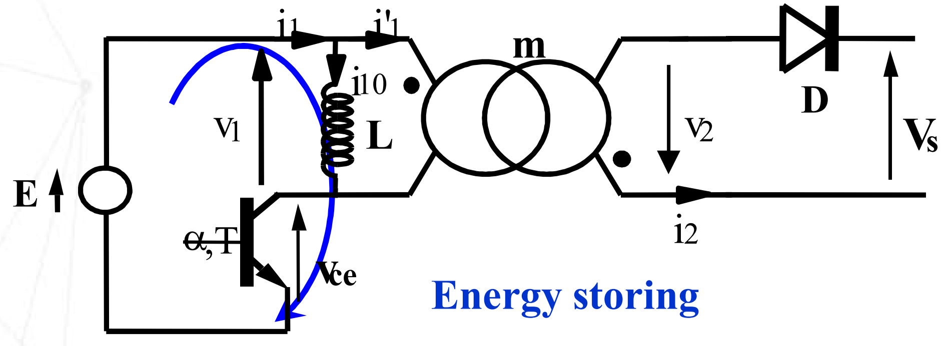


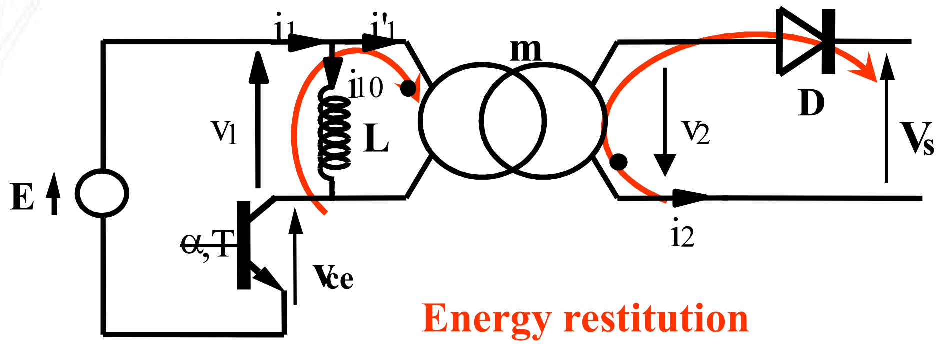
Output voltage calculation

$$< v_1 > = 0 \qquad < v_1 > = \frac{1}{T}.\left[E.\alpha T + \left(-\frac{V_S}{m}\right).(T - \alpha.T)\right]$$

$$\boxed{V_S = \frac{\alpha}{1-\alpha}.mE}$$

Demagnetization issue





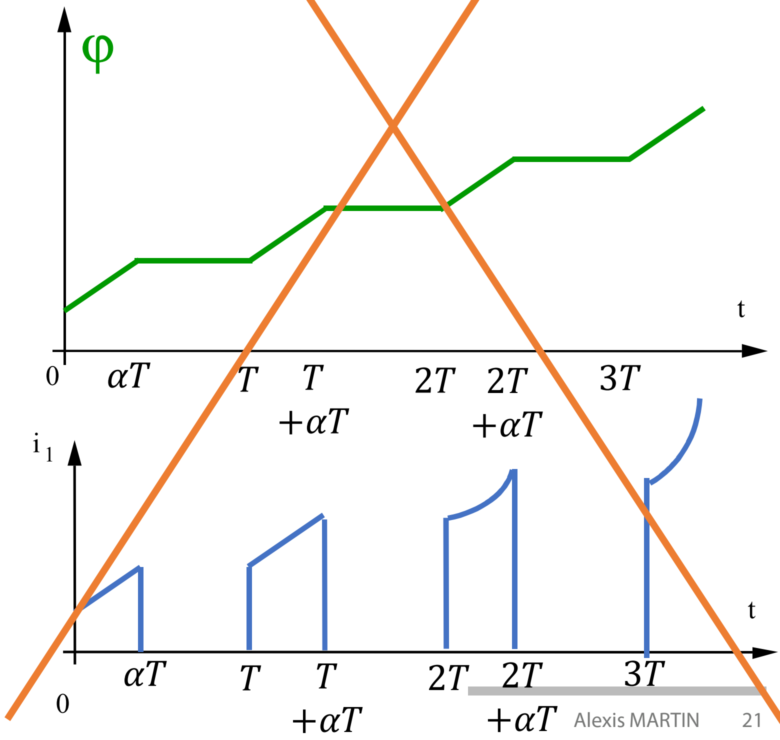
Charge infinie du condensateur de sortie

~~**Warning:**~~

~~If no load connected: $i_2=0$~~

~~-> No demagnetization~~

~~**-> Issue**~~



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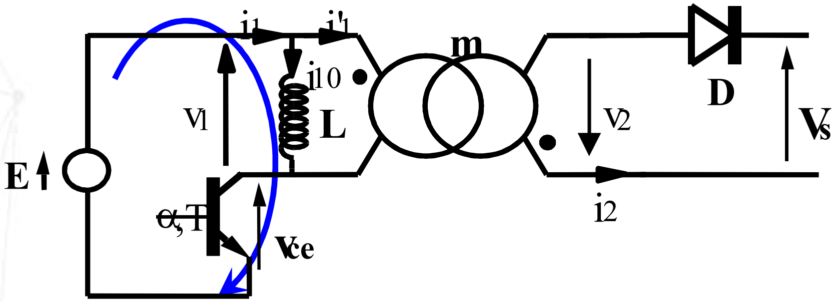
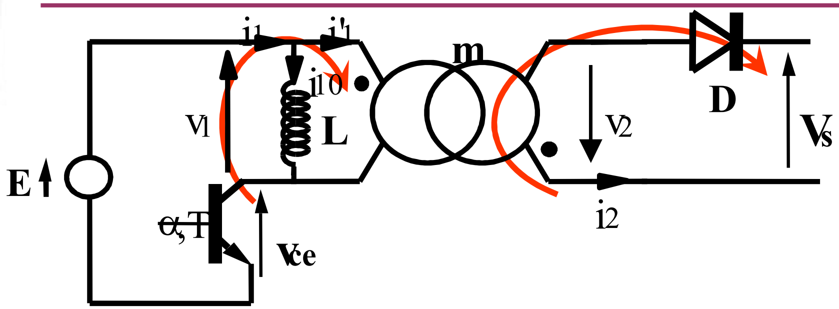
Discontinuous mode: behavior

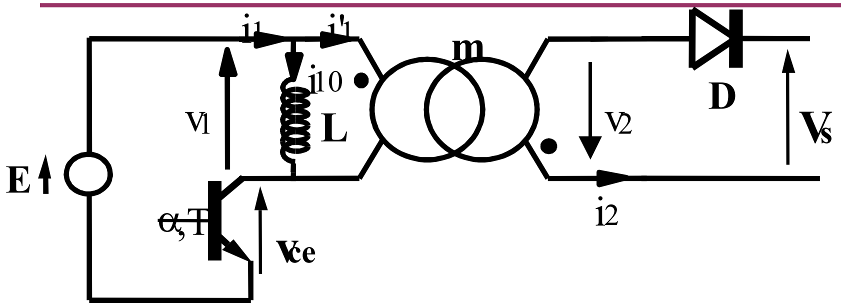


$0 < t < \alpha T$: T_p closed
=> $v_1 = E$ => $v_2 = m.E$
$v_D < 0$ => *D reverse*
$i_2 = 0$ => $i'_1 = 0$ => $i_1 = i_{10}$
Energy stoking
Unchanged mode



$\alpha T < t < \alpha' T$: T_p opened
=> $i_1 = 0$ => $i'_1 = - i_{10} < 0$
=> $i_2 < 0$ => *D forward*
and then reverse naturally

$v_2 = -V_S$ => $v_1 = - V_S/m$ => φ decreases
Energy restitution



$\alpha' T < t < T$: T and D both reverse
All currents are zero
=> $v_1 = 0$; $v_2 = 0$ => $\varphi = 0$

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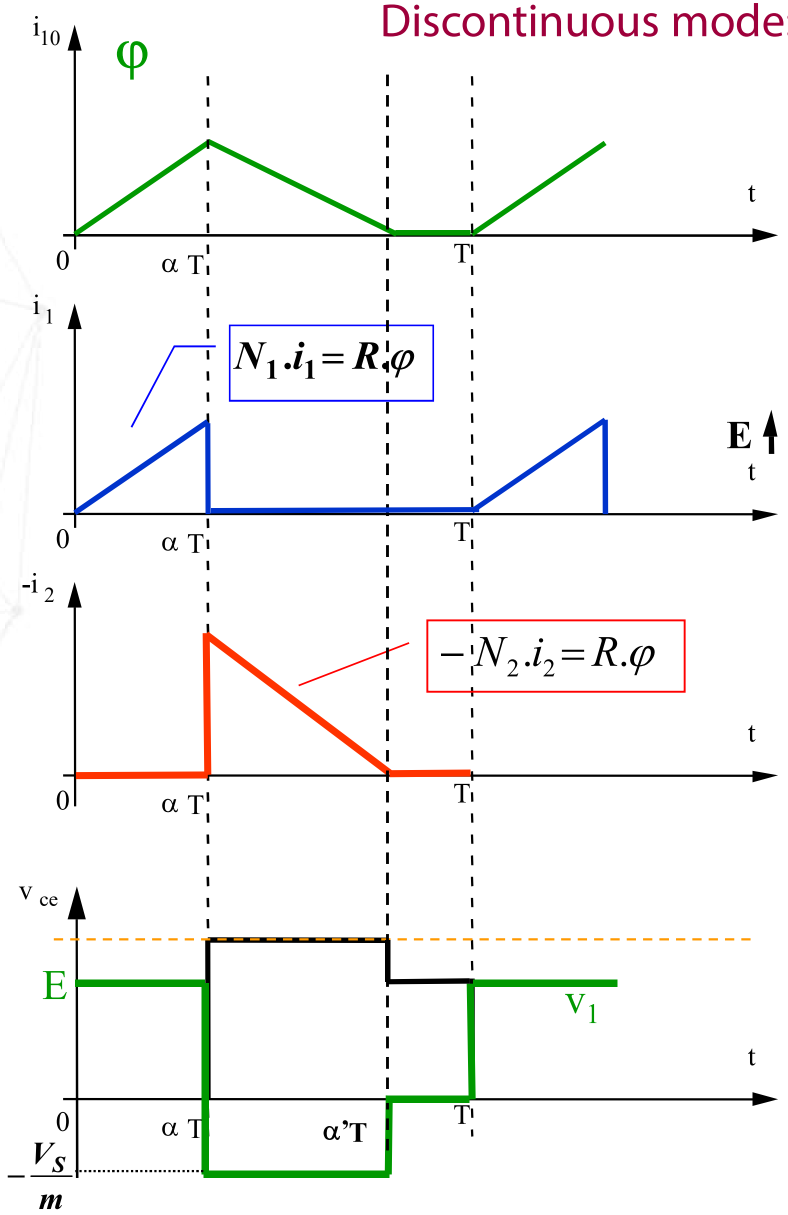
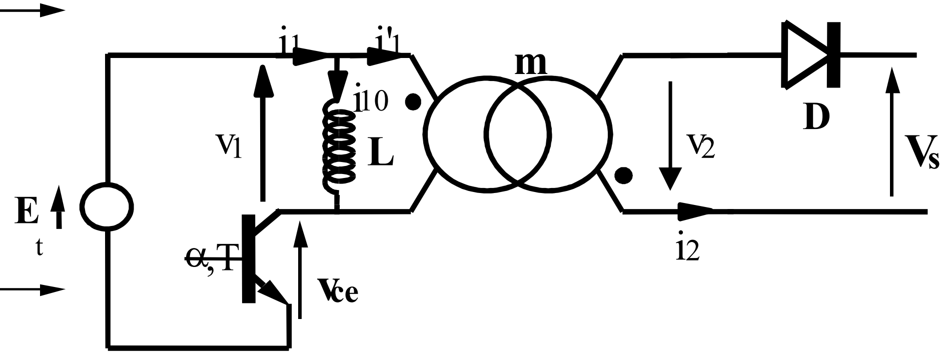
Discontinuous mode: chronograms





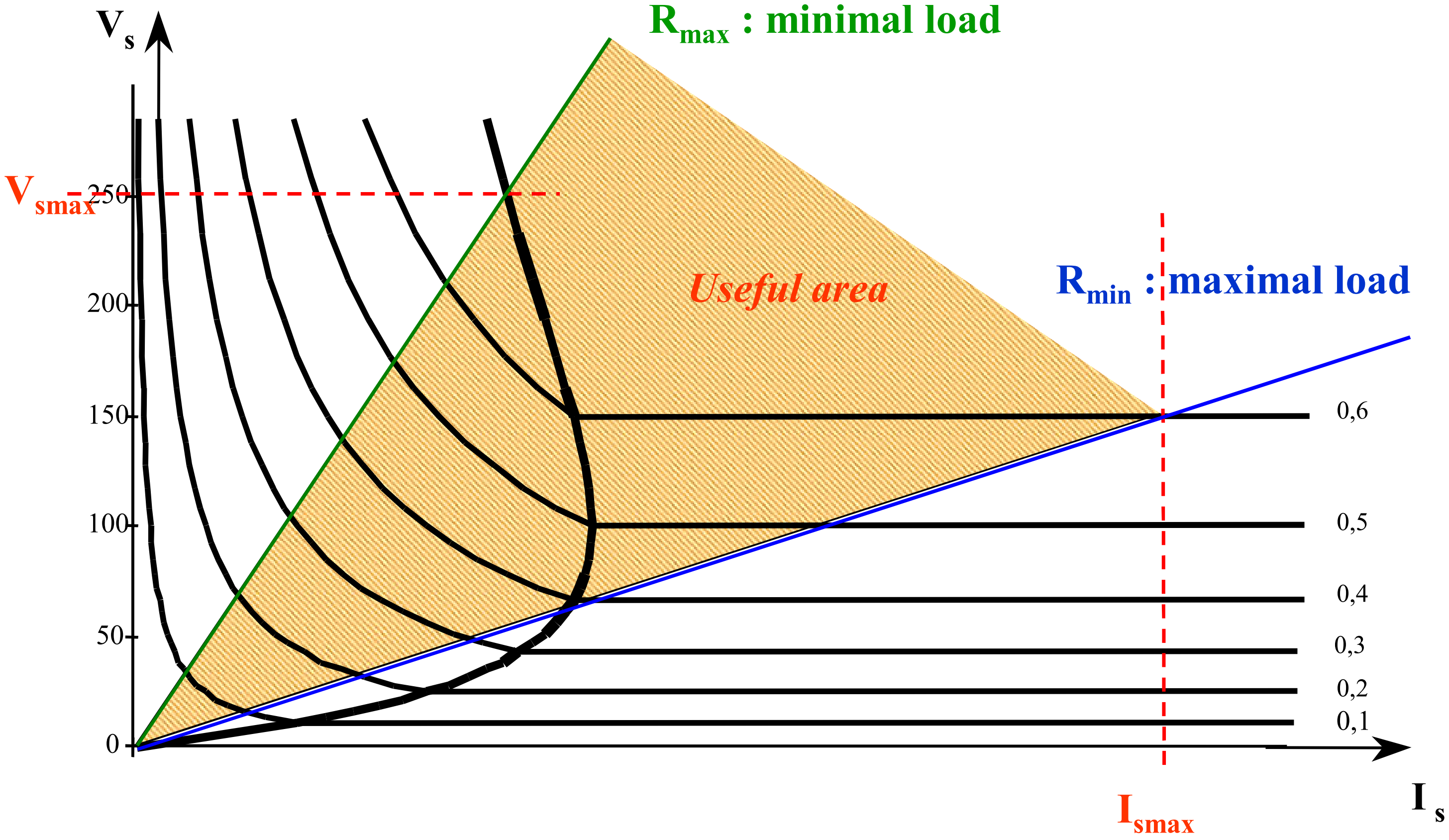
Output voltage calculation: Transferred energy

$$W_L = \frac{1}{2}.L.I_{1\max}^2 = \frac{1}{2}.L.\left(\frac{\alpha.E.T}{L}\right)^2$$

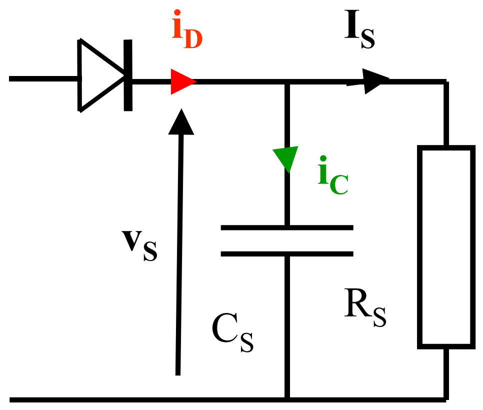
$$P_S = V_S.I_S = f.W_L$$

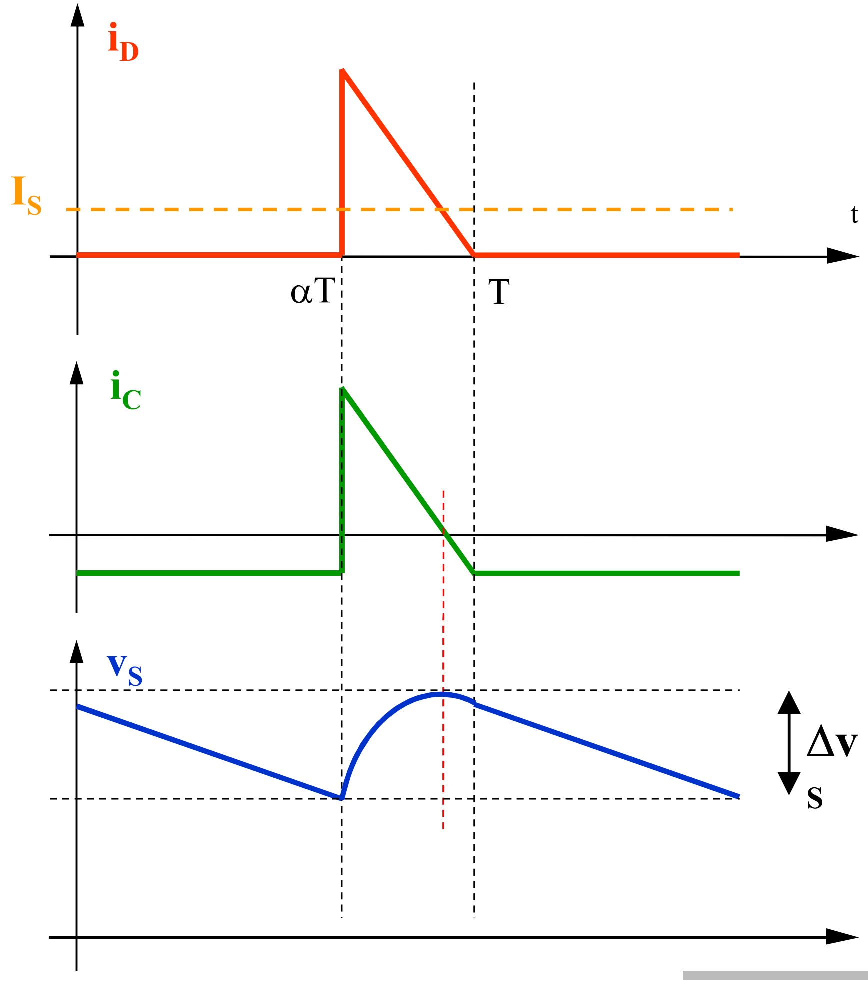
$$\boxed{V_S = \frac{\alpha^2.E^2.T}{2.L.I_S}}$$

Discontinuous mode: output characteristics

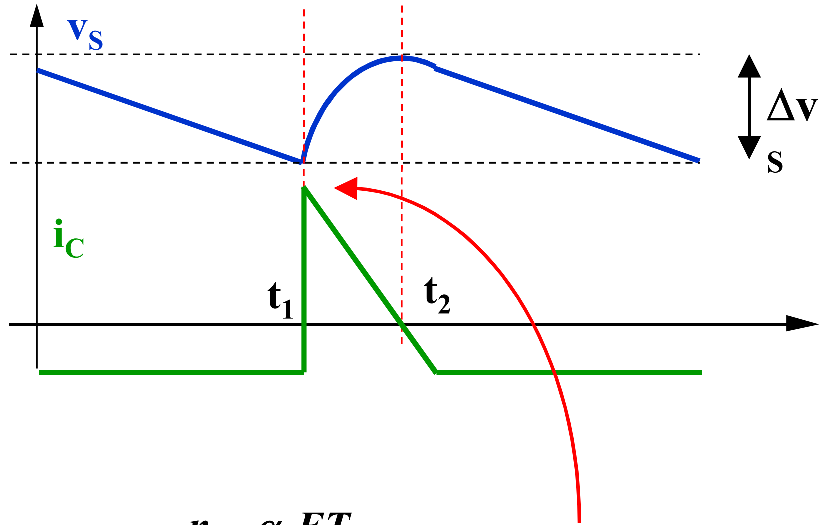


Boundary mode: Output filtering





Boundary mode: capacitor calculation



$$\Delta v_S = \frac{1}{C_S}\int_{t_1}^{t_2} i_C(t)\,dt = k_v . V_S$$

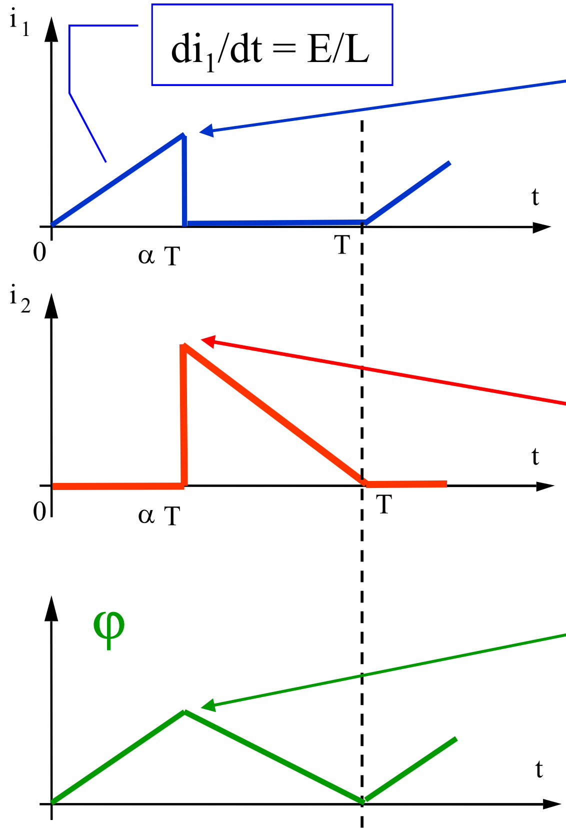
$$t_1 = \alpha T$$

$$I_{D\max} = \frac{n_1}{n_2} . \frac{\alpha . ET}{L}$$

$$I_{D\max} = \frac{n_1}{n_2} . \frac{\alpha . ET}{L} \qquad I_{C\max} = I_{D\max} - I_S \qquad i_C(t_2) = 0$$

C_S calculation

Boundary mode: sizing components



$$I_{1\max} = \frac{\alpha.E.T}{L} \qquad I_{1moy} = \frac{\alpha^2.E.T}{2L}$$

$$I_{1eff}^2 = \frac{1}{T}.\int_0^T i_1^2(t).dt = \frac{1}{T}.\left(\frac{E}{L}\right)^2.\frac{\alpha^3 T^3}{3} = \frac{\alpha}{3}.I_{1\max}^2$$

$$\Rightarrow \boxed{I_{1eff} = \sqrt{\frac{\alpha}{3}}.I_{1\max}}$$

$$I_{2\max} = \frac{N_1}{N_2}.I_{1\max} \qquad \boxed{I_{2eff} = \sqrt{\frac{1-\alpha}{3}}.I_{2\max}}$$

$$\varphi_{\max} = \frac{N_1 I_{1\max}}{R} \qquad \textit{Non-saturation}: \varphi_{max} = A_e B_{sat}$$

$$\Rightarrow \boxed{I_{1\max} < \frac{R.B_{sat}.A_e}{N_1}}$$

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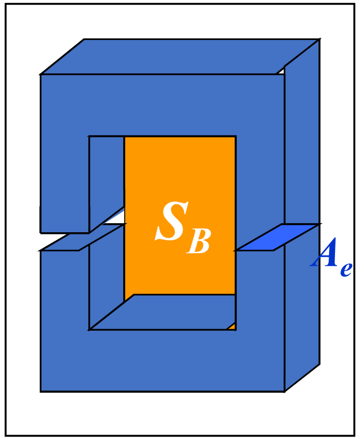
Boundary mode: transformer sizing



$$\delta = \frac{I_{1eff}}{s_{sp1}} = \frac{I_{2eff}}{s_{sp2}} \quad < \text{max current density: } \delta_{max}$$

$$S_{Tcu} = N_1.s_{sp1} + N_2.s_{sp2} \quad < k_B.\ \text{Window area } S_B$$

$$k_B = winding\ coefficient$$

$$k_B.S_B > N_1.\frac{I_{1eff}}{\delta_{max}} + N_2.\frac{I_{2eff}}{\delta_{max}}$$

$$I_{1eff} = \sqrt{\frac{\alpha}{3}}.I_{1\max}$$

$$I_{2eff} = \sqrt{\frac{1-\alpha}{3}}.I_{2\max}$$

$$I_{2\max} = \frac{N_1}{N_2}.I_{1\max}$$

$$\boxed{I_{1\max} < \frac{k_B.S_B.\delta_{\max}}{N_1}.\frac{\sqrt{3}}{\sqrt{\alpha}+\sqrt{1-\alpha}}}$$

Introduction

Flyback
Transformer
Continuous mode
Discontinuous mode
Sizing

Forward

Push-Pull

Boundary mode: transformer sizing

$$P_S = f.W_L = f.\frac{1}{2}.L.I_{1\max}^2$$

$$I_{1\max} < \frac{R.B_{sat}.A_e}{N_1}$$

$$I_{1\max} < \frac{k_B.S_B.\delta_{\max}}{N_1}.\frac{\sqrt{3}}{\sqrt{\alpha}+\sqrt{1-\alpha}}$$

$$P_S < f.\frac{L}{2}.\frac{R.B_{sat}.A_e}{N_1}.\frac{k_B.S_B.\delta_{\max}}{N_1}.\frac{\sqrt{3}}{\sqrt{\alpha}+\sqrt{1-\alpha}}$$

$$A_e.S_B > \boxed{2.\frac{\sqrt{\alpha}+\sqrt{1-\alpha}}{\sqrt{3}}.\frac{P_S}{f.k_B.B_{sat}.\delta_{\max}}}$$

With P_S

With f

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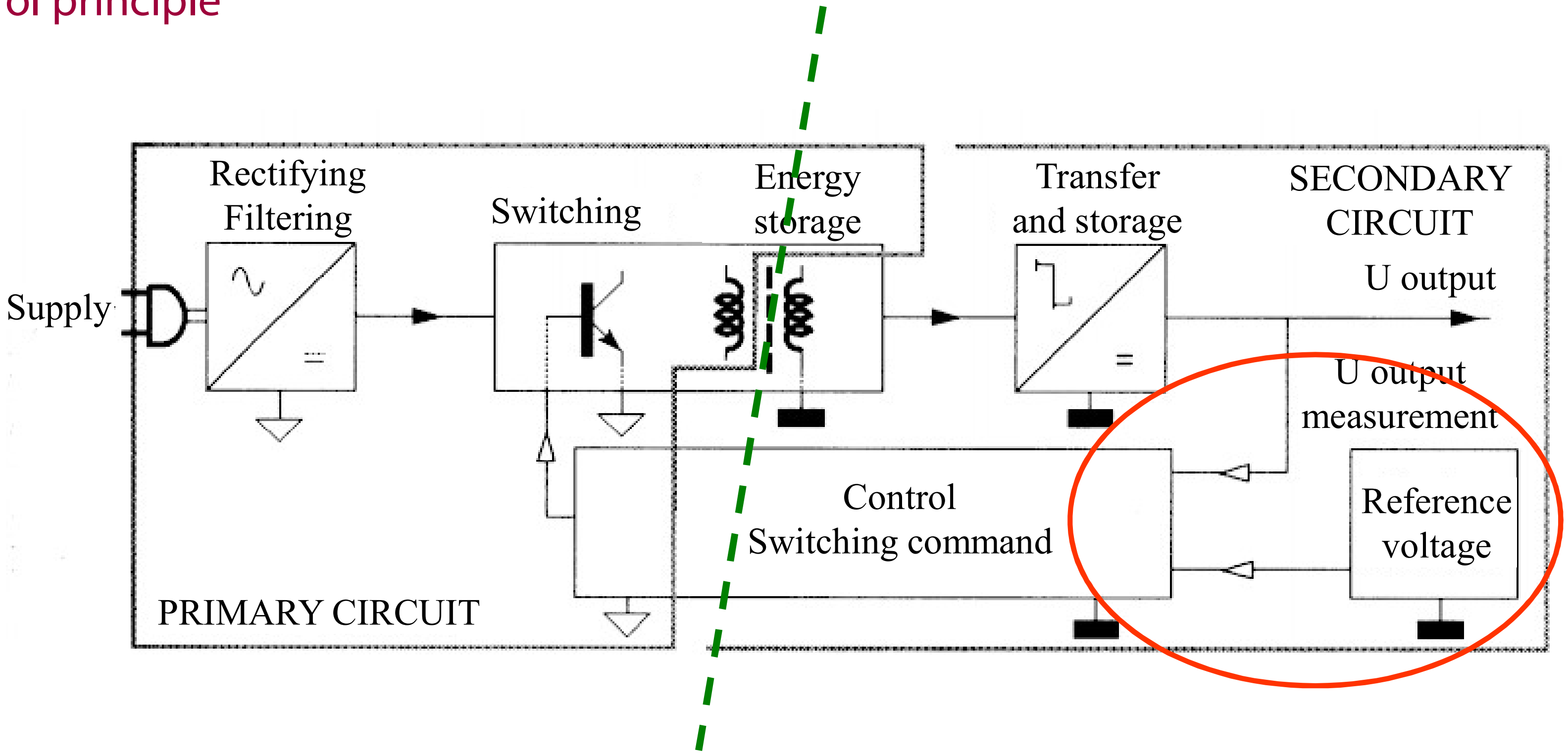
Control principle



Output voltage control

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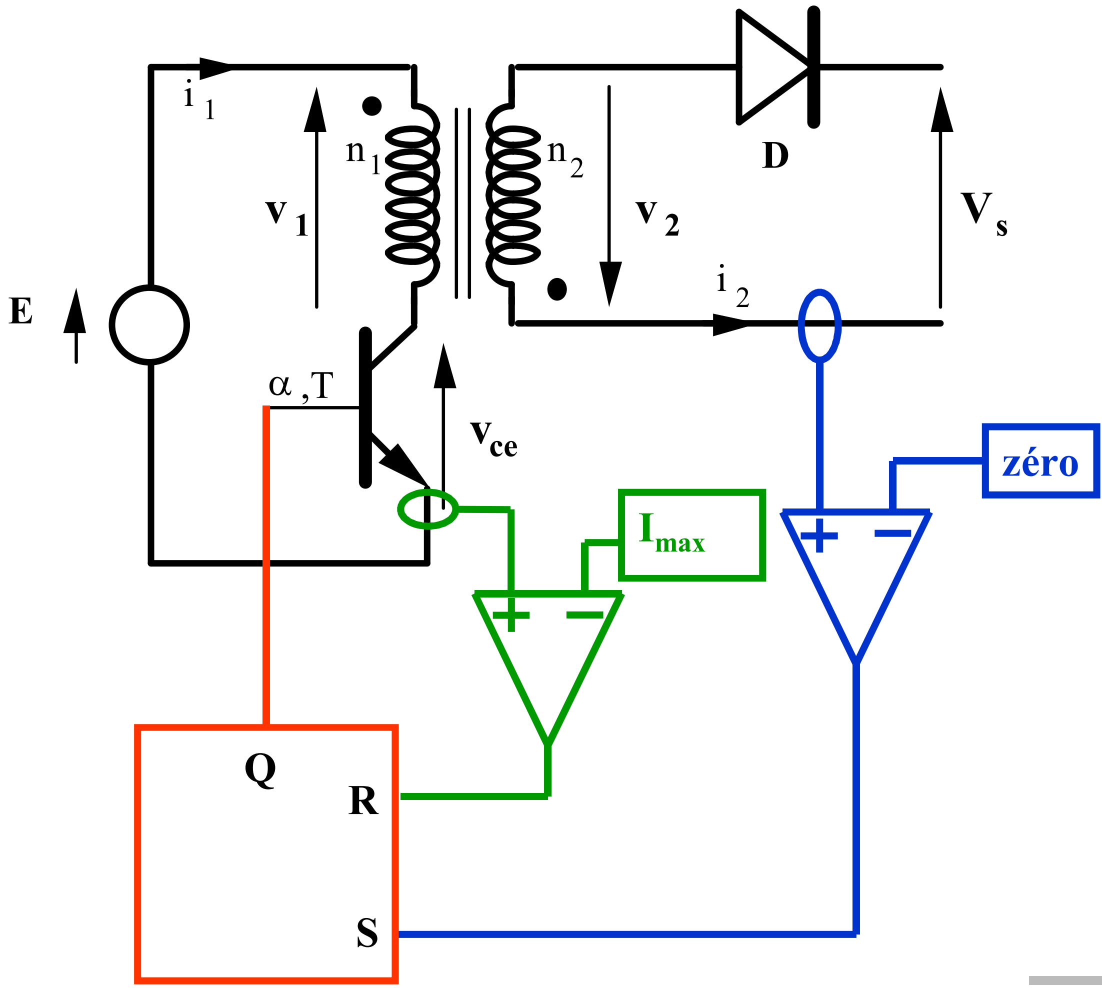
Boundary mode holding



Introduction

Flyback

Transformer

Continuous mode

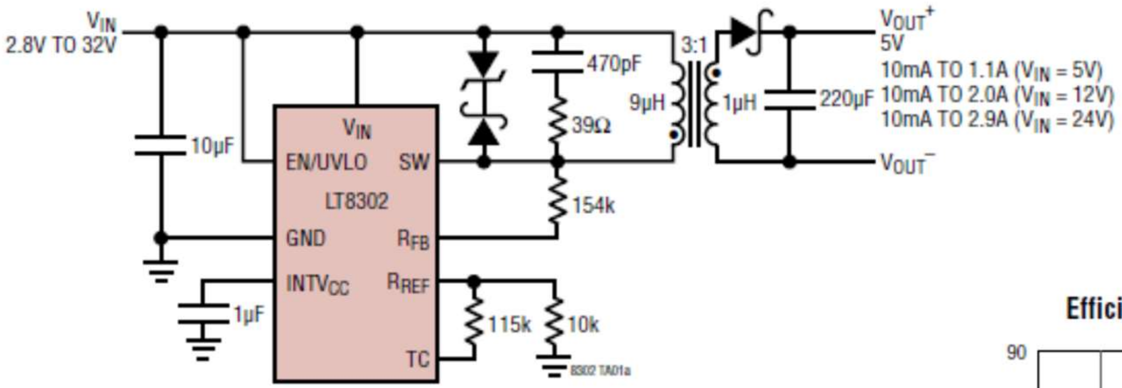
Discontinuous mode

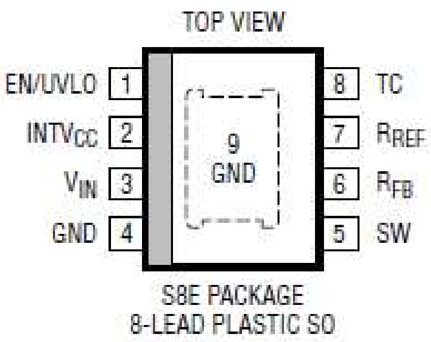
Sizing

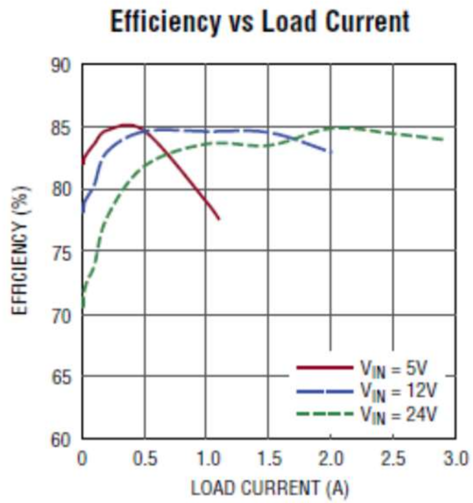
Forward

Push-Pull

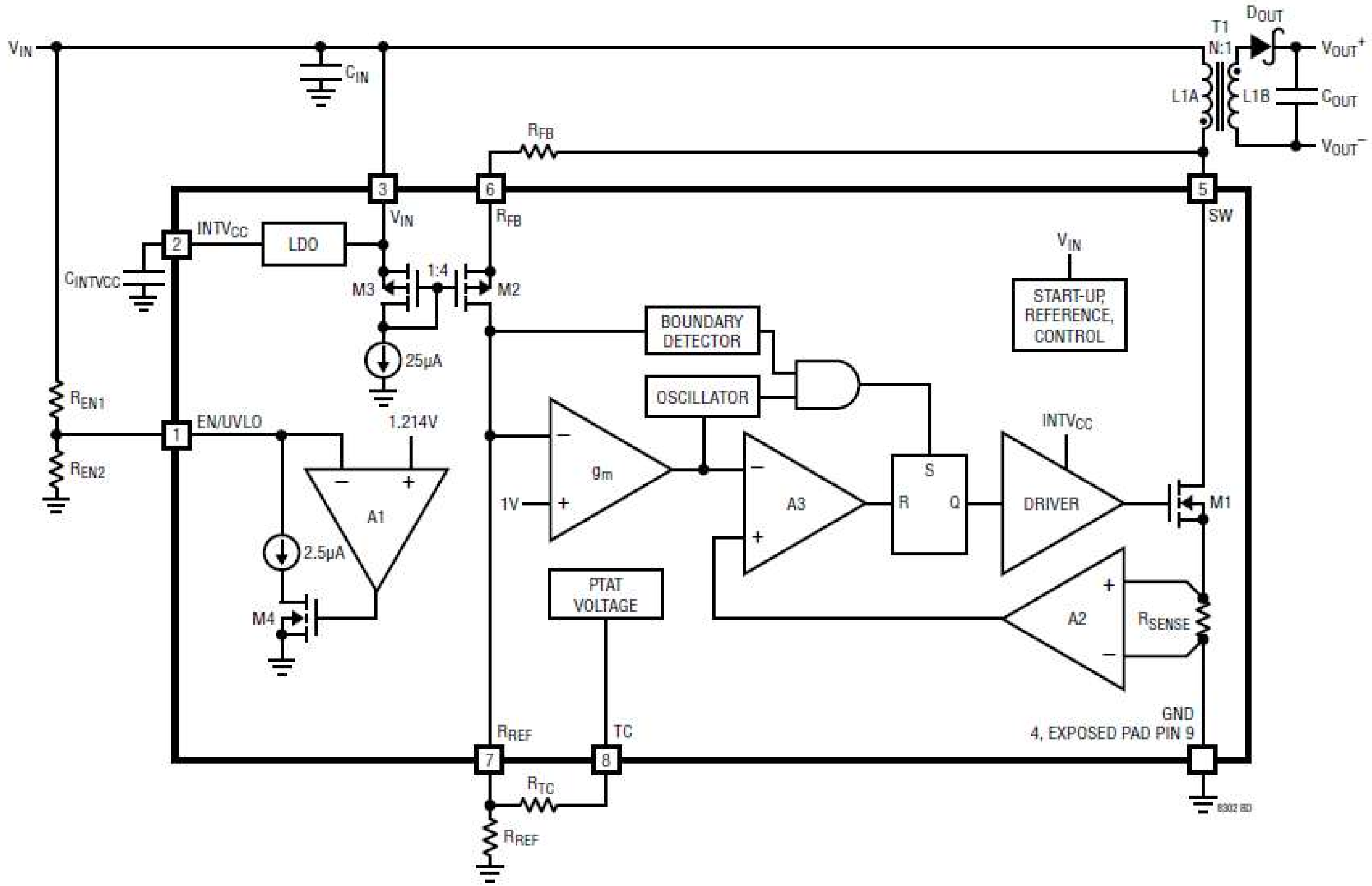
Example: LT8302



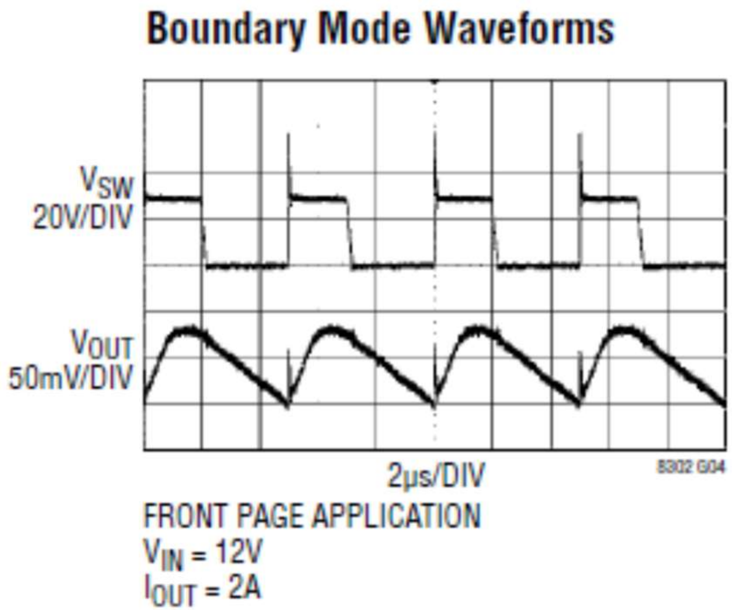


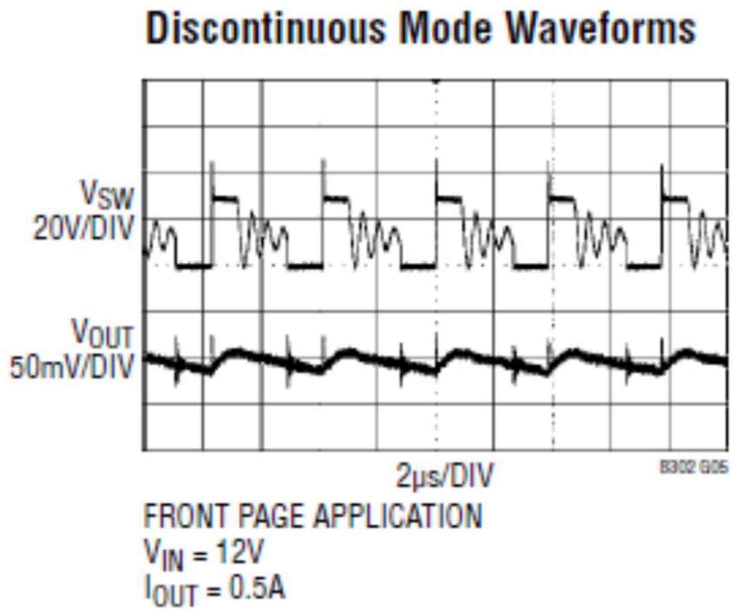


Example: LT8302 (internal scheme)

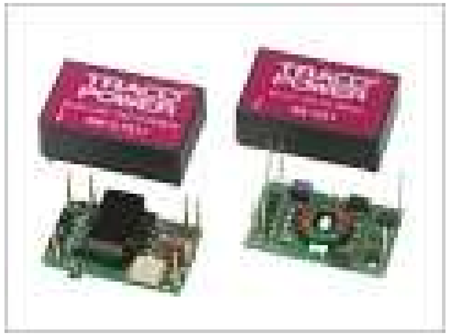


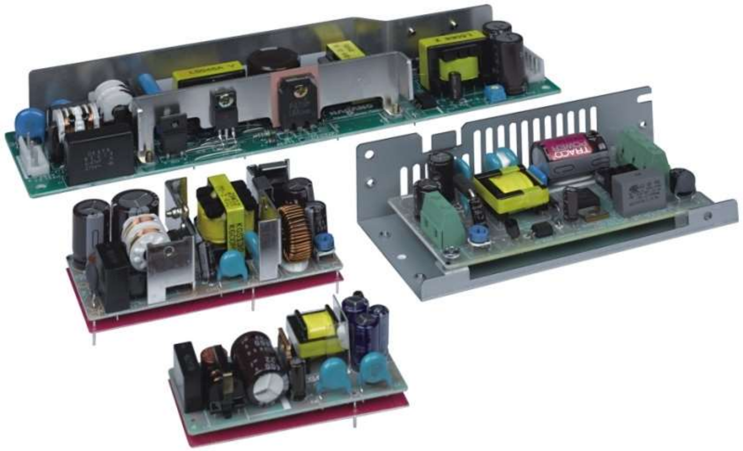
Example: LT8302





Flyback examples





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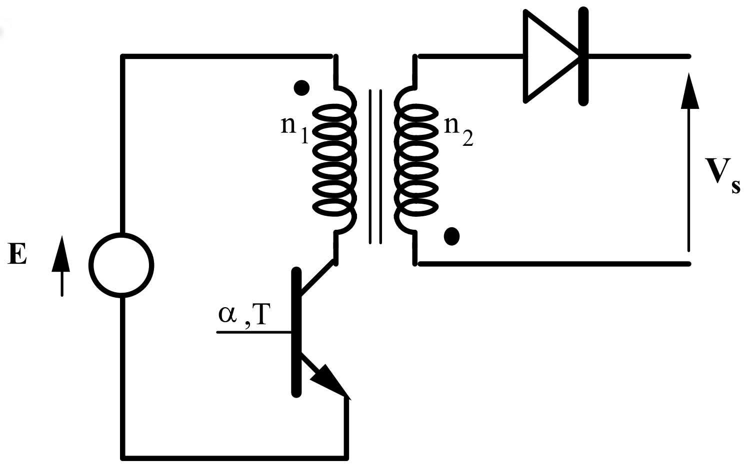
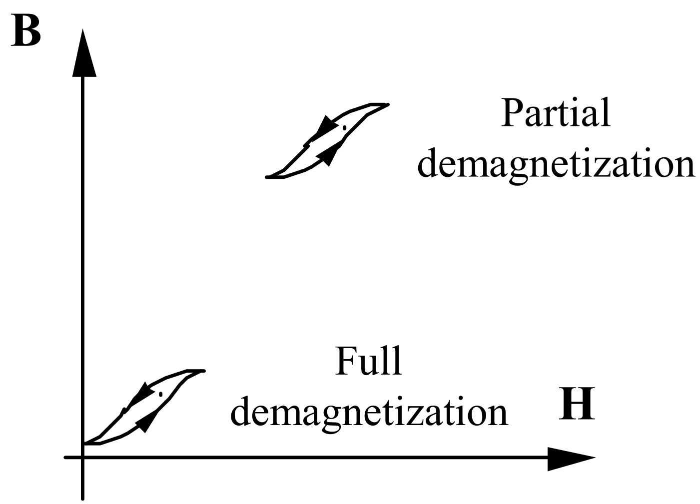
Forward

Flyback principle





Easiness, low power, few components

Limited for high power due to energy storage limitations

Introduction

Flyback

Forward

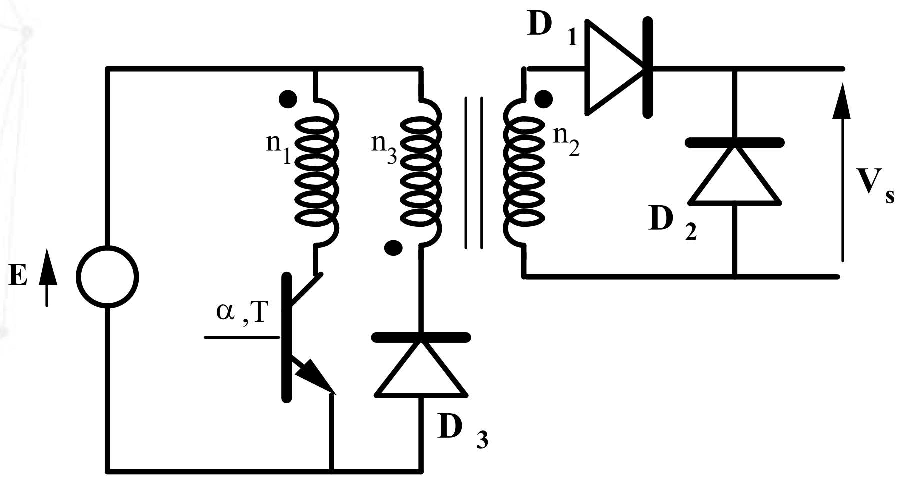
Principle

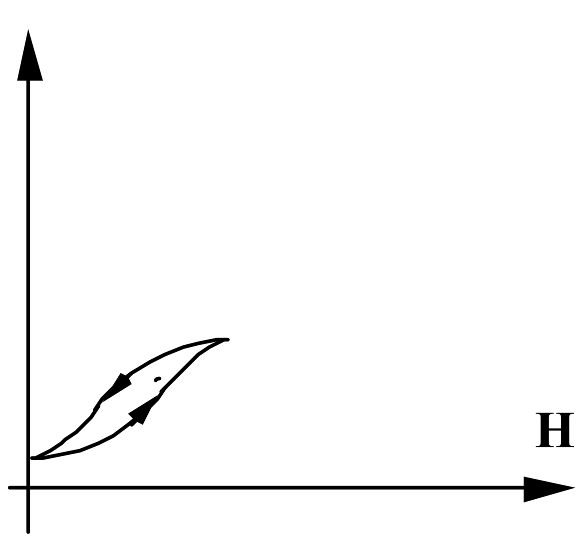
Continuous mode

Sizing

Push-Pull

Forward principle





Magnetic component optimized, more components

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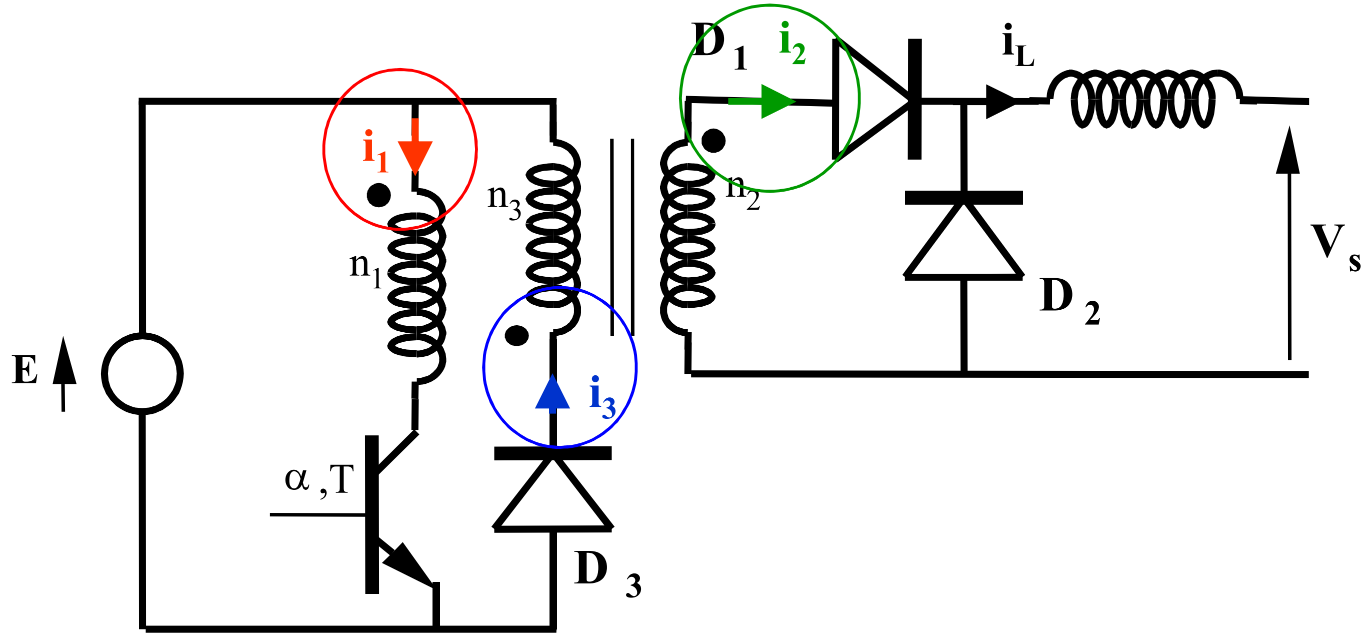
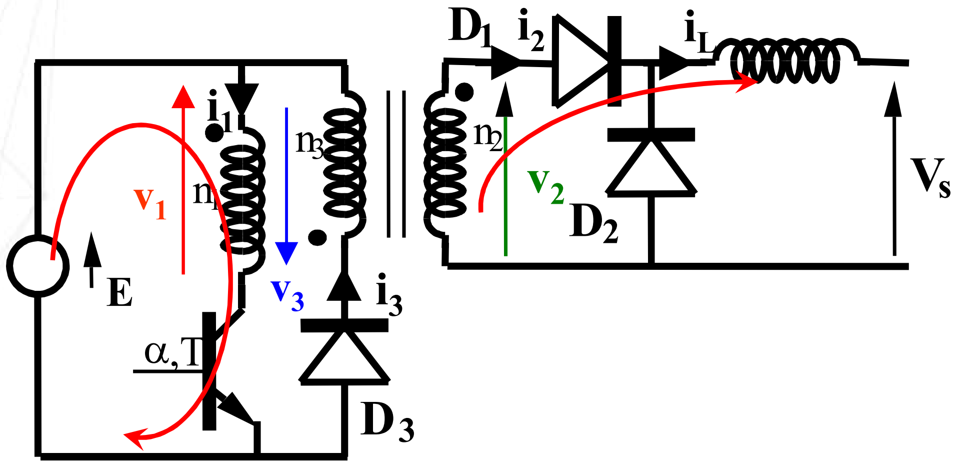
Hopkinson's law



$$\boxed{\oint H.dl = R.\varphi = n_1.i_1 + n_3.i_3 - n_2.i_2}$$

Continuous mode study: $i_L > 0$

At least one of the two diodes D_1 and D_2 forwards.



$$v_1 = E = n_1 . \frac{d\varphi}{dt}$$ *magnetization*

$$v_2 = n_2 . \frac{d\varphi}{dt} \qquad v_3 = n_3 . \frac{d\varphi}{dt}$$

$0 < t < \alpha T$

T_p forward.

$$v_1 = E \quad => \quad v_2 = \frac{n_2}{n_1} . E$$

D_1 forward, D_2 reverse
$i_2 = i_L > 0$

$$v_1 = E \quad => \quad v_3 = \frac{n_3}{n_1} . E$$

D_3 reverse

$$n_1 . i_1 - n_2 . i_2 = R . \varphi$$

Introduction

Flyback

Forward

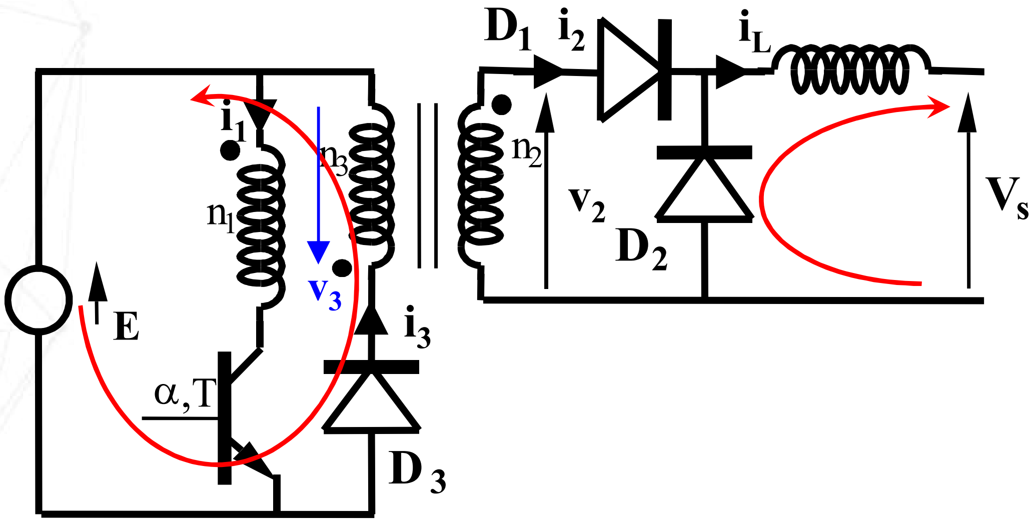
Principle

Continuous mode

Sizing

Push-Pull

Continuous mode study



T_p *opened* => $i_1 = 0$

$$n_3.i_3 - n_2.i_2 = R.\varphi > 0$$

$i_3 > 0$ => D_3 *forward*

$v_3 = -E = n_3.\dfrac{d\varphi}{dt}$ ***demagnetization***

$v_2 = -\dfrac{n_2}{n_3}E$ *D_1 reverse, D_2 forward* => $i_2 = 0$

$L.\dfrac{di_L}{dt} = -V_S$

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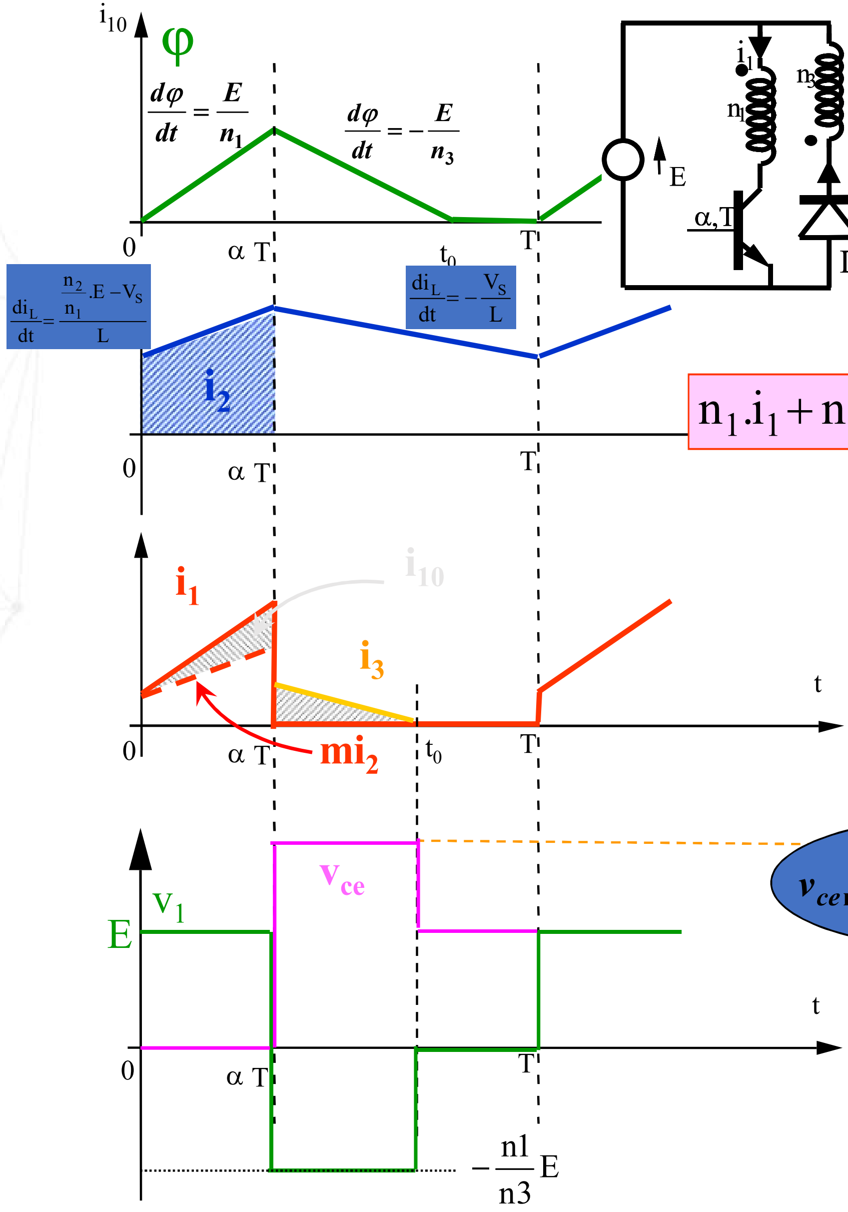

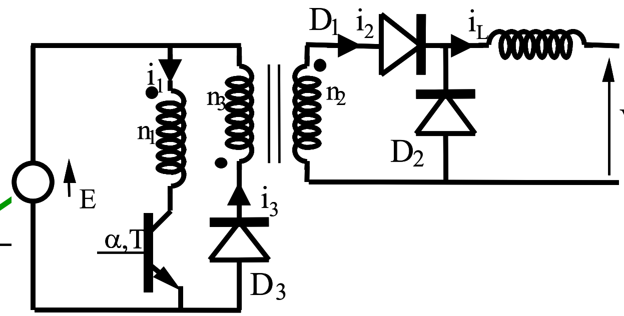

$$n_1.i_1 + n_3.i_3 - n_2.i_2 = R.\varphi$$

$$i_{10} = \frac{R\varphi}{n_1} \qquad i_3 = \frac{R\varphi}{n_3}$$

$$i_3 = \frac{n_1}{n_3}.\frac{\alpha.ET}{L_1} - \frac{E}{L_3}t$$

$$L_1 = \frac{n_1^2}{R} \quad et \quad L_3 = \frac{n_3^2}{R}$$

Full demagnetization if: $t_0 < T$

$$v_{ce\max} = E\left(1+\frac{n_3}{n_1}\right)$$

$$\boxed{\alpha.\left(1+\frac{n_3}{n_1}\right)<1}$$

$$v_{ce\max} = 2.E \quad => \quad n_1 = n_3 \quad => \quad \alpha < \frac{1}{2}$$

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Beyond Engineering

Introduction

Flyback

Forward

Principle

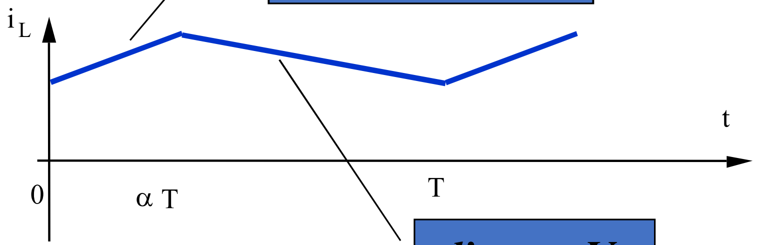
Continuous mode

Sizing

Push-Pull

Continuous mode study: voltage transfer

$$\frac{di_L}{dt}=\frac{mE-V_S}{L}$$



$$\frac{di_L}{dt}=-\frac{V_S}{L}$$

$$<v_L>=0$$

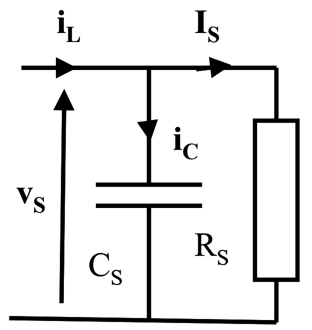
$$\Delta i_L=\frac{mE-V_S}{L}.\alpha T=\frac{V_S}{L}(1-\alpha)T$$

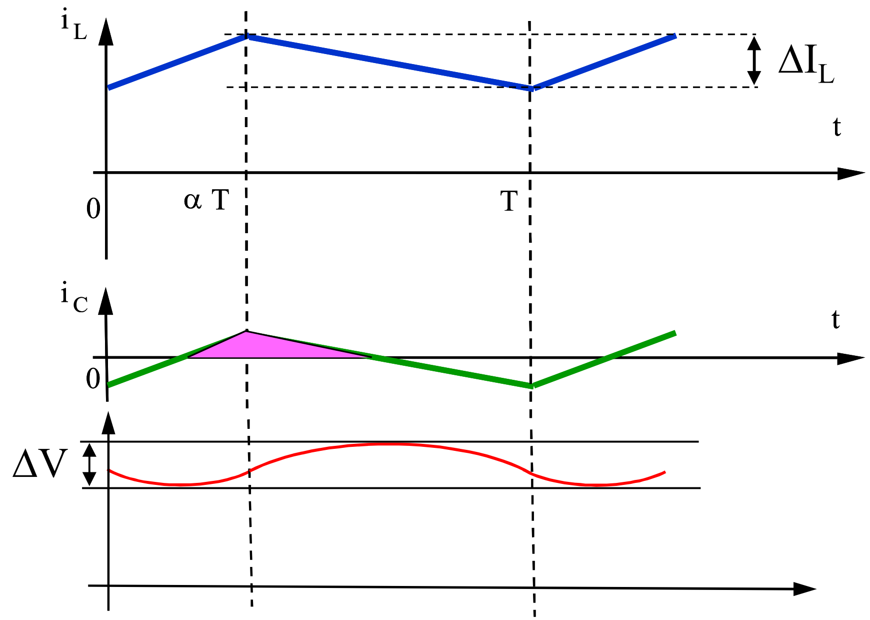
$$\boxed{V_S=\alpha.m.E}$$

Continuous mode study: Components sizing

- ***Filtering capacitor: C_S***
- ***Transformer => Ae.SB***
- ***Output inductance => Ae.SB***

Continuous mode study: Filtering capacitor





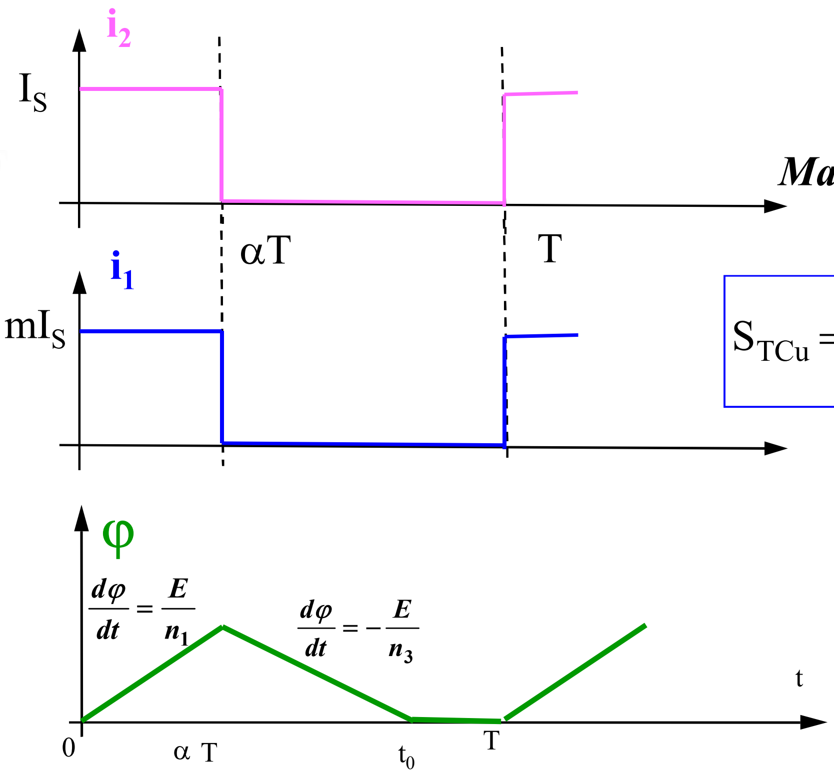
$$\Delta V = \frac{1}{C_S}\cdot\int_{\frac{\alpha T}{2}}^{\frac{T+\alpha T}{2}} i_C(t)dt = \frac{1}{C_S}\cdot\frac{1}{2}\cdot i_{C\max}\cdot\frac{T}{2}$$

$$i_{C\max} = \frac{\Delta I_L}{2} = \frac{1}{2}\cdot\frac{V_S}{L}(1-\alpha).T$$

Max ripple for α = 0.5

$$\boxed{C_S = \frac{m.E.T^2}{32.L.\Delta V}}$$

Continuous mode study: transformer sizing



Magnetising current neglected

$$I_{2eff} = \sqrt{\alpha}.I_S$$

$$I_{1eff} = m.\sqrt{\alpha}.I_S$$

$$\boxed{S_{TCu} = n_1.\frac{I_{1eff}}{\delta_{max}} + n_2.\frac{I_{2eff}}{\delta_{max}} = 2.\sqrt{\alpha}.n_2.\frac{I_S}{\delta_{max}} < k_B.S_B}$$

$$\boxed{\varphi_{max} = \frac{E}{n_1}.\alpha.T < A_e.B_{sat}}$$

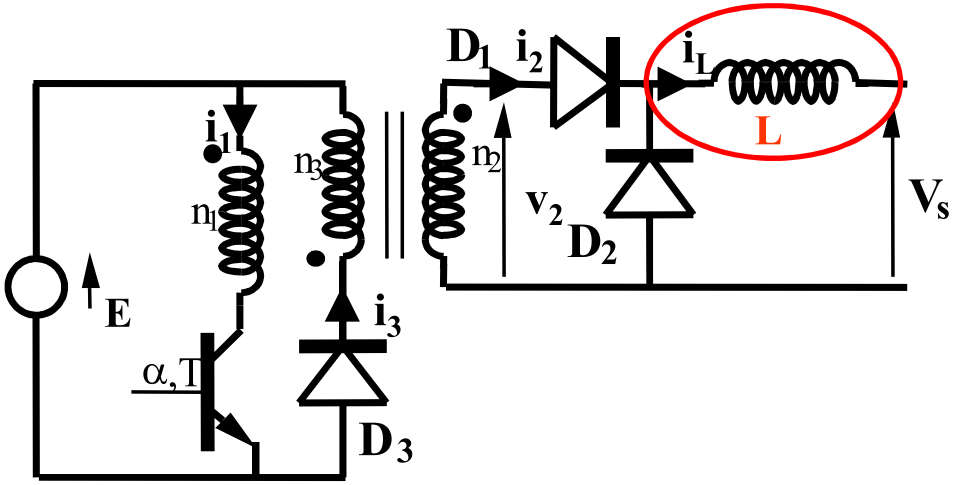
$$k_B.S_B.A_e.B_{sat} > \frac{2.\sqrt{\alpha}.n_2.I_S.\alpha.E.T}{\delta_{max}.n_1}$$

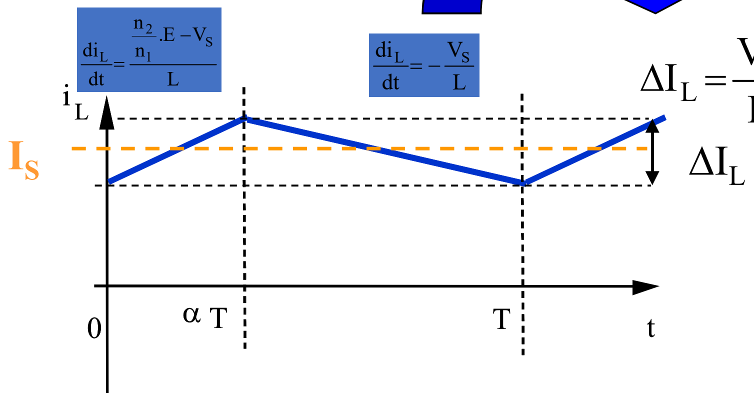
With P_S

With f

$$\boxed{A_e.S_B > \frac{2.\sqrt{\alpha}.P_S}{f.k_B.B_{sat}.\delta_{max}}}$$

Continuous mode study: inductor sizing





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

Hold the continuous mode

$$I_S > \frac{\Delta I_L}{2}$$

$$\boxed{L > \frac{\alpha.V_S}{2I_S.f}}$$

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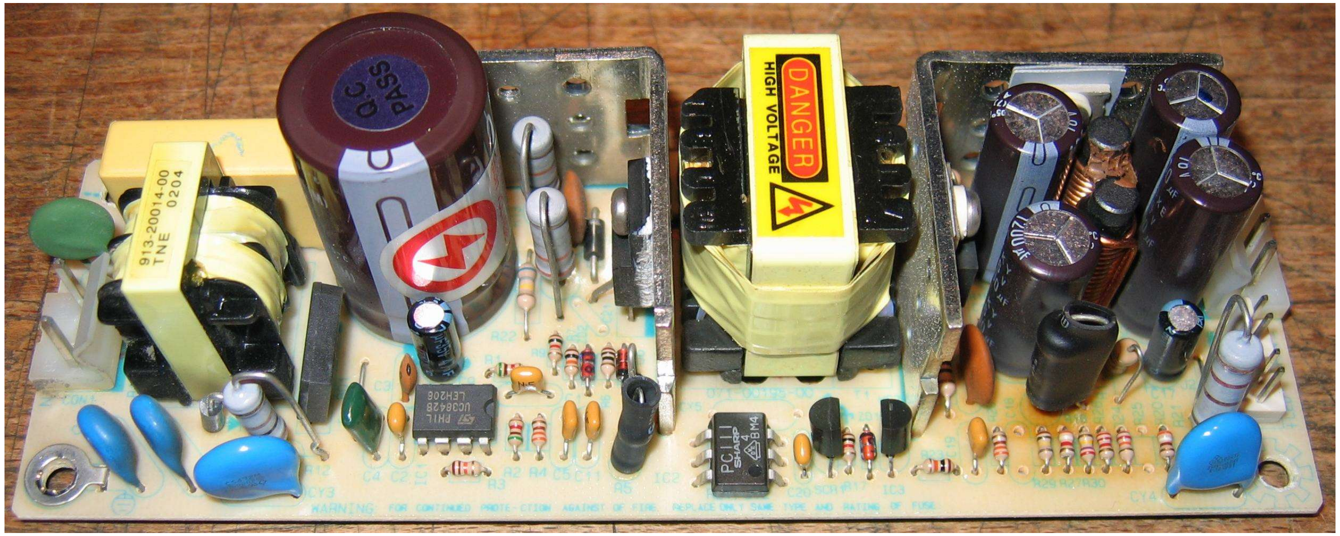
Example



Manufacturer reference: CI Design Y0-2040AA

Input : 100 à 240 Vac

Output : 12 Vdc (2 A) 5 Vdc (3 A)

Introduction

Flyback

Forward

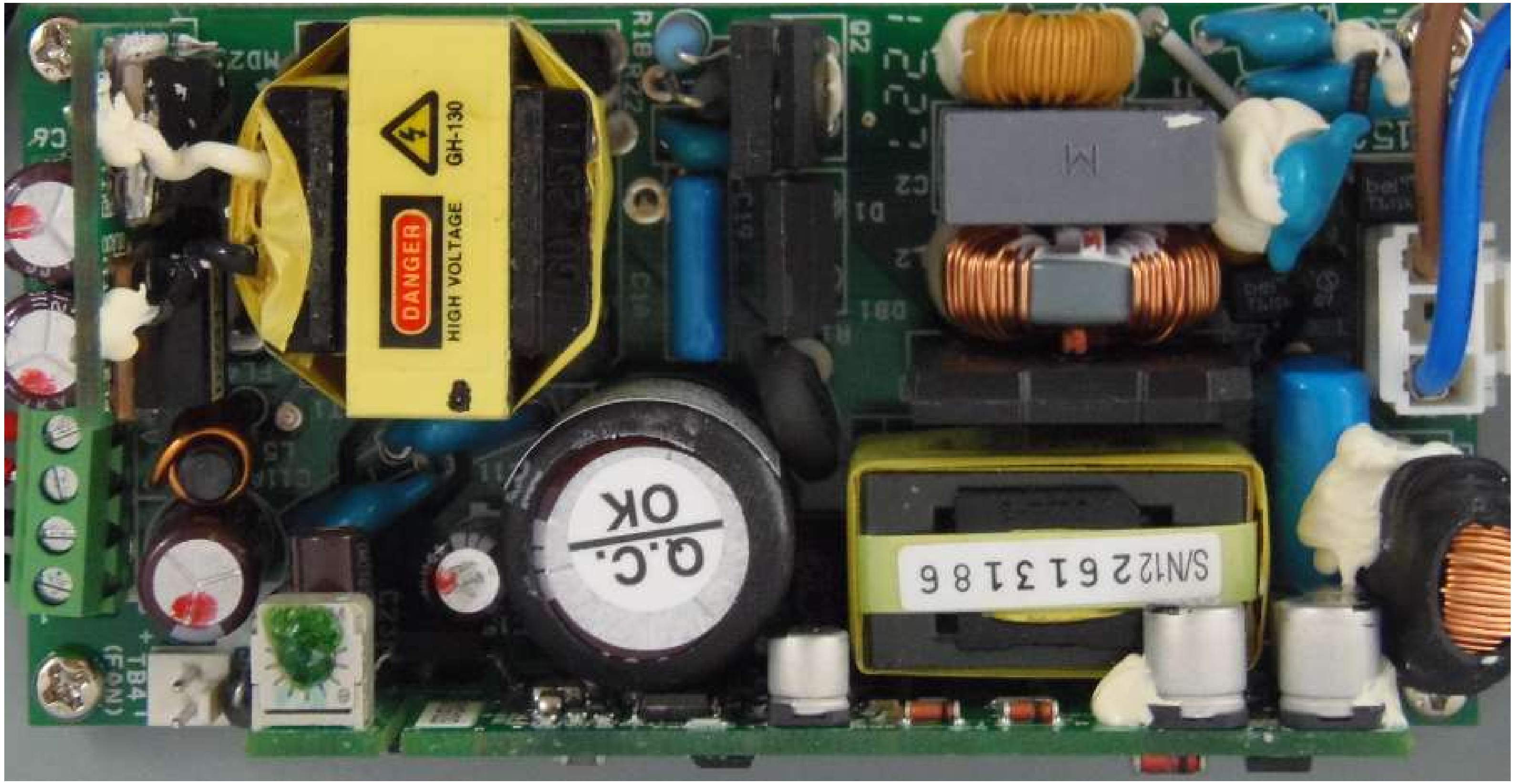
Principle

Continuous mode

Sizing

Push-Pull

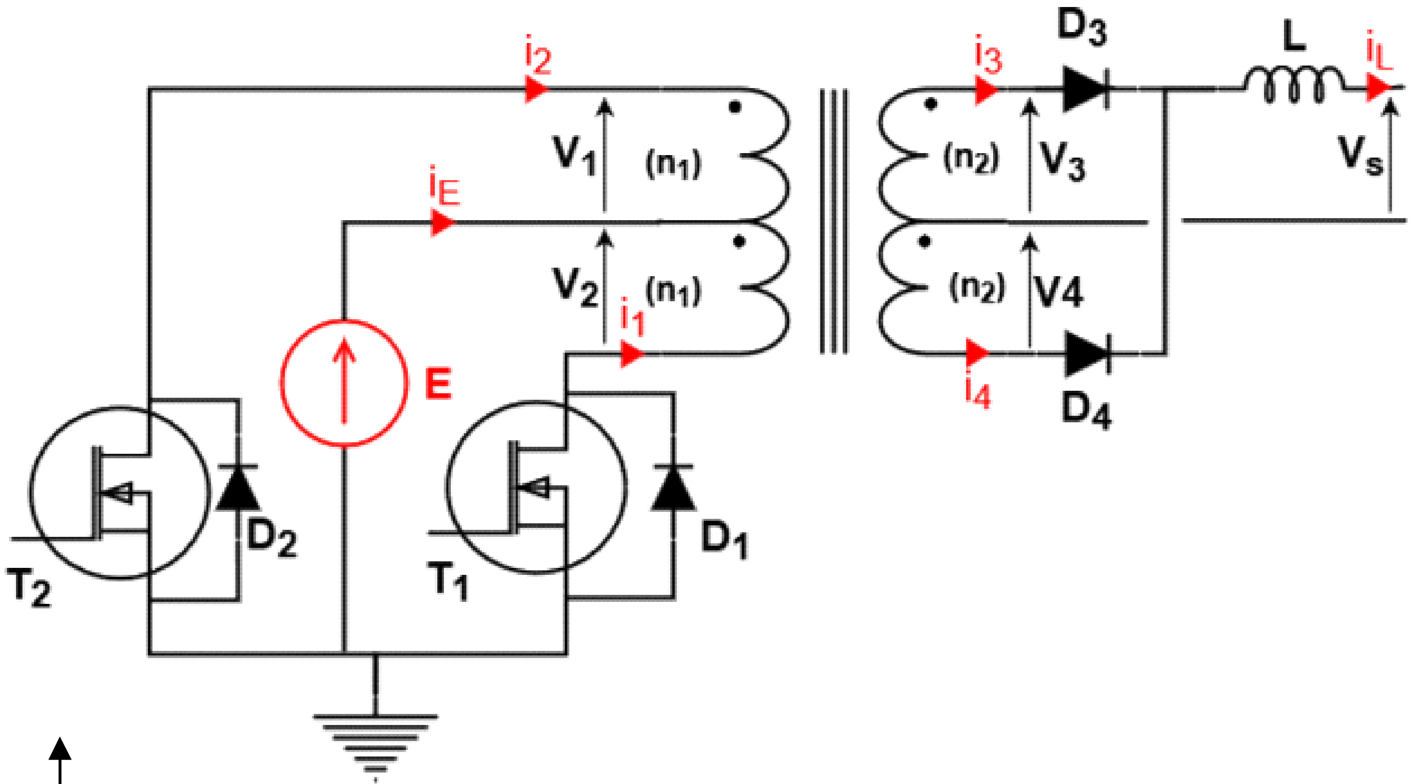
Example

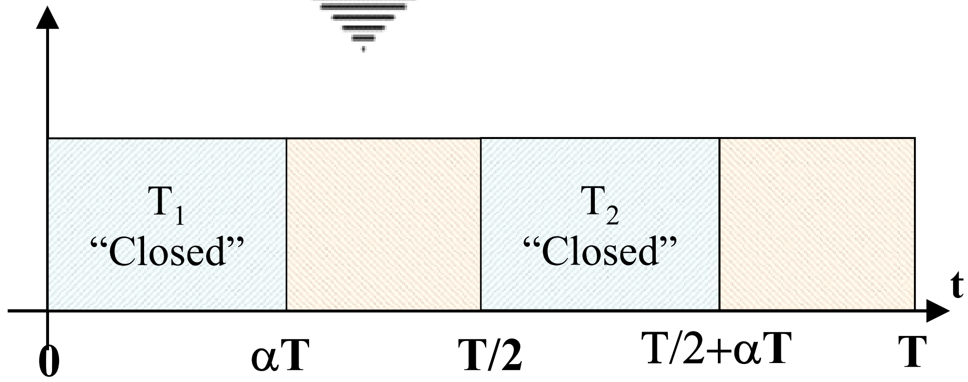


NuForce

Push-Pull

Push-Pull


i2
iE
V1
(n1)
V2
i1
(n1)
E
i3
D3
L
iL
(n2)
V3
Vs
(n2)
V4
i4
D4
T2
D2
T1
D1


T1
"Closed"
T2
"Closed"
t
0
αT
T/2
T/2+αT
T

No load study : $i_L = 0$

0 < t < αT: T_1 "closed", T2 "open"

- $v_2 = n_1 . \frac{d\varphi}{dt} = E > 0$

Magnetization

- $v_1 = v_2 = E > 0$

D_2 « reverse »

$$-n_1 . i_1 = \mathcal{R} . \varphi$$

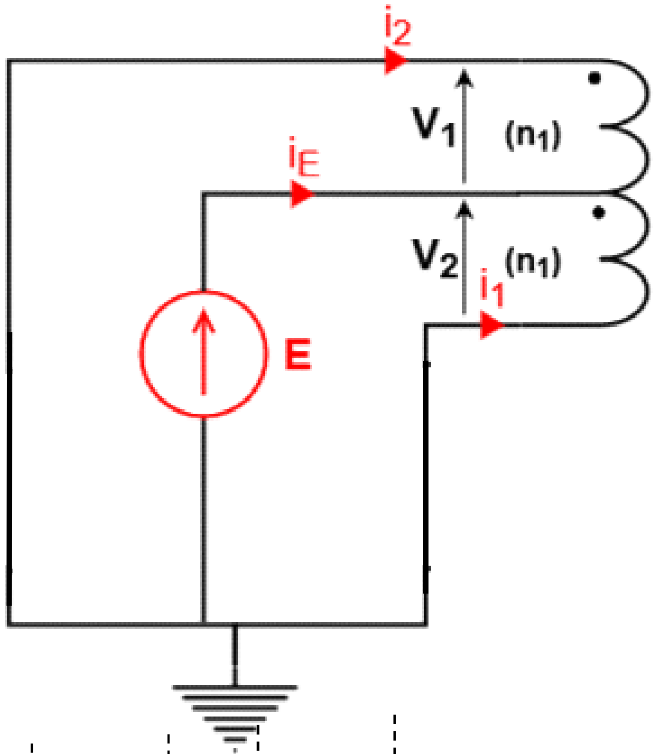
αT < t < T/2: T_1 &T_2 "open"

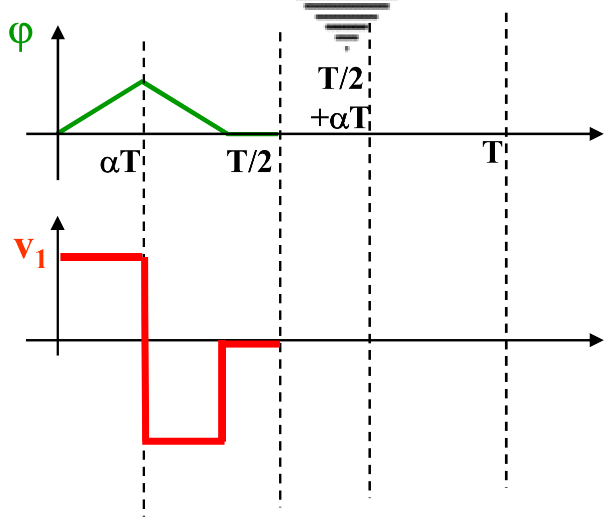
- $\mathcal{R} . \varphi = -n_1 . i_1 + n_1 . i_2 > 0$

D_2 « forward », D_1 « reverse »

- $\mathcal{R} . \varphi = n_1 . i_2 > 0$
- $v_1 = n_1 . \frac{d\varphi}{dt} = -E < 0$

Demagnetization





No load study : $i_L = 0$

T/2 < t < T/2+αT: T_1 “open”, T2 “closed”

- $v_1 = n_1.\frac{d\varphi}{dt} = -E < 0$

Magnetization

- $v_1 = v_2 = -E < 0$

⇒ **D_1 « reverse »**

$$n_1.i_2 = \mathcal{R}.\varphi$$

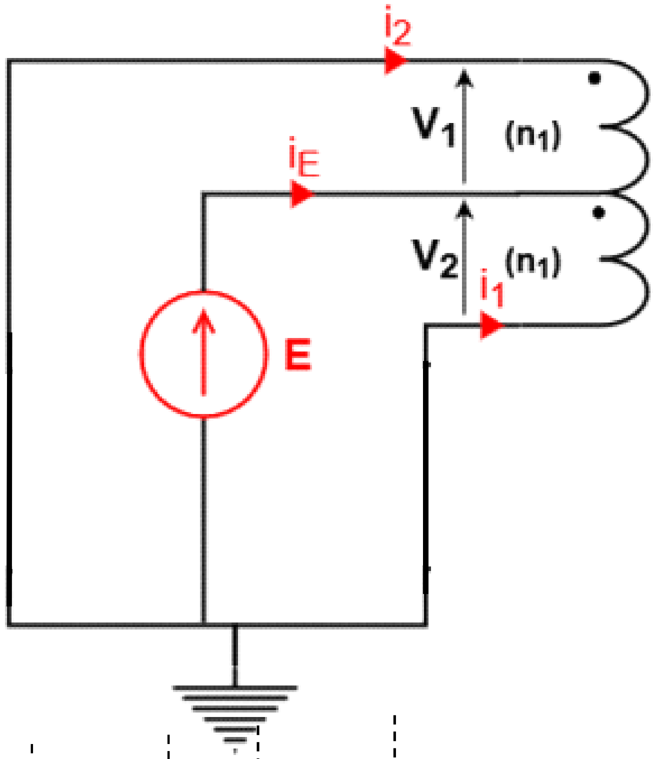
T/2+αT < t < T: T_1 &T_2 “open”

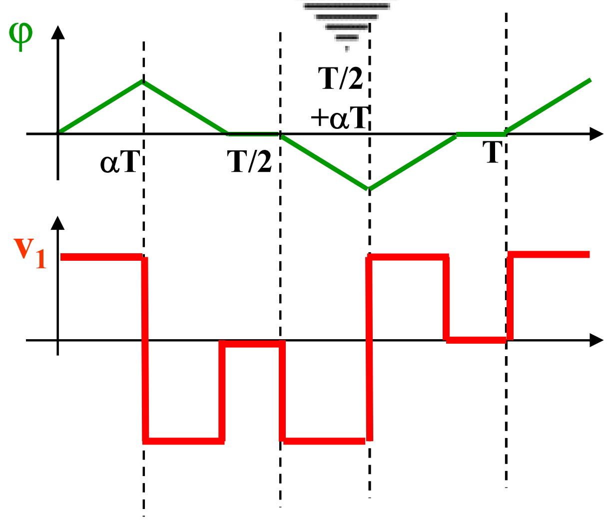
- $\mathcal{R}.\varphi = -n_1.i_1 + n_1.i_2 < 0$

⇒ **D_1 « forward », D_2 « reverse »**

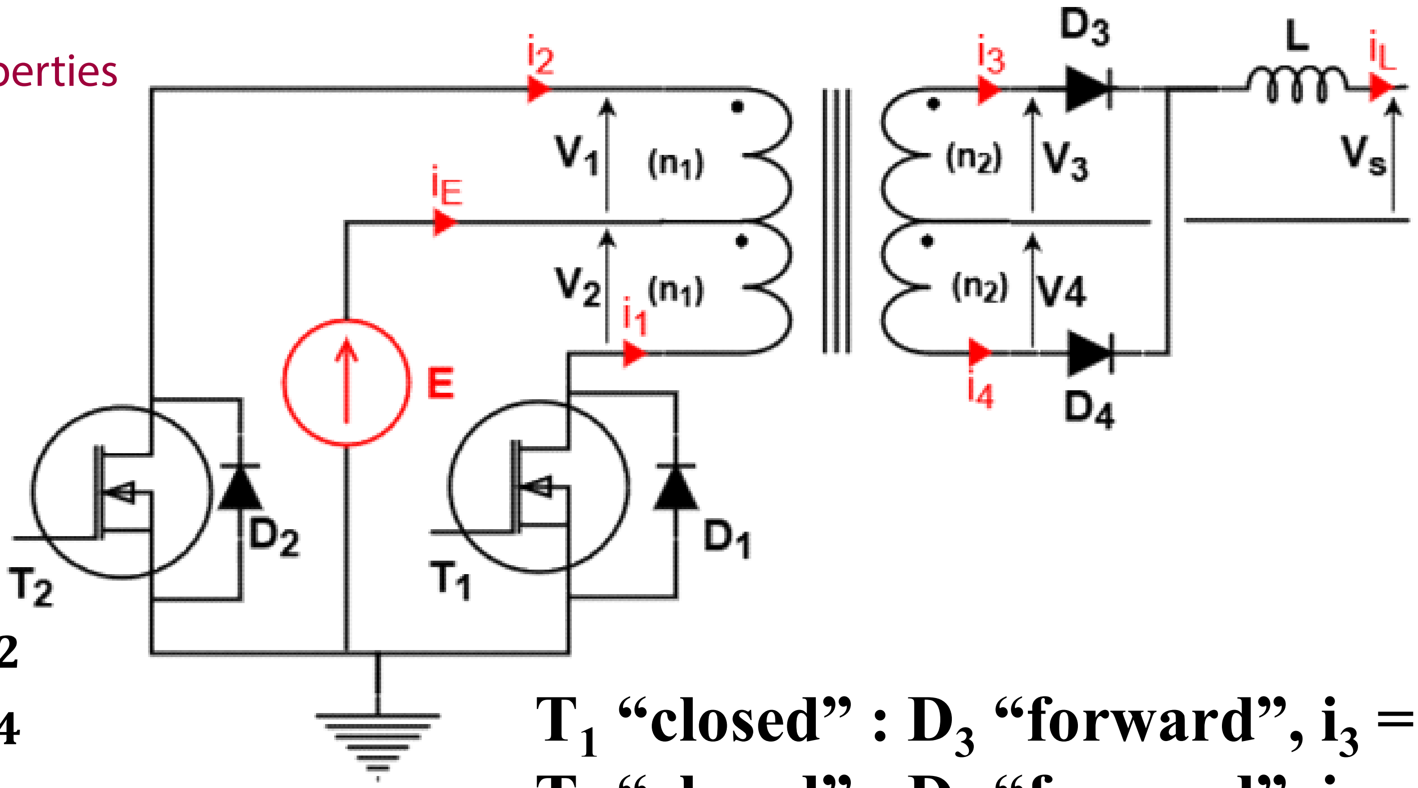
- $\mathcal{R}.\varphi = -n_1.i_1 < 0$
- $v_2 = n_1.\frac{d\varphi}{dt} = E > 0$

Demagnetization





General properties



$$v_1 = v_2$$

$$v_3 = v_4$$

$$v_3 = \frac{n_2}{n_1} v_1$$

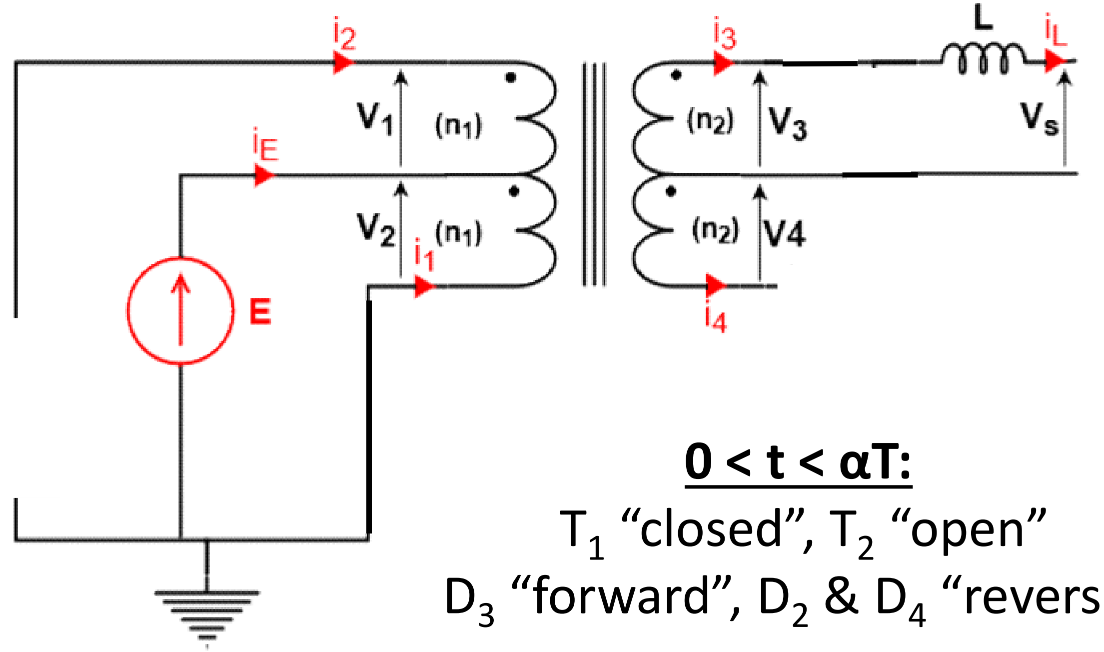
T_1 "closed" : D_3 "forward", $i_3 = i_L$

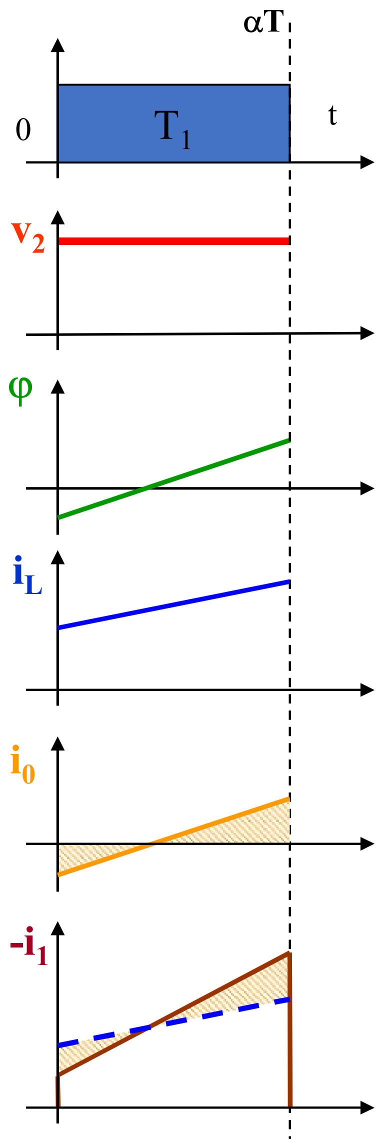
T_2 "closed" : D_4 "forward", $i_4 = i_L$

Hopkinson's law

$$\boxed{\oint H.dl = \mathcal{R}.\varphi = -n_1.i_1 + n_1.i_2 - n_2.i_3 + n_2.i_4}$$

Continuous mode study: magnetization





<u>0 < t < αT:</u>

T_1 "closed", T_2 "open"

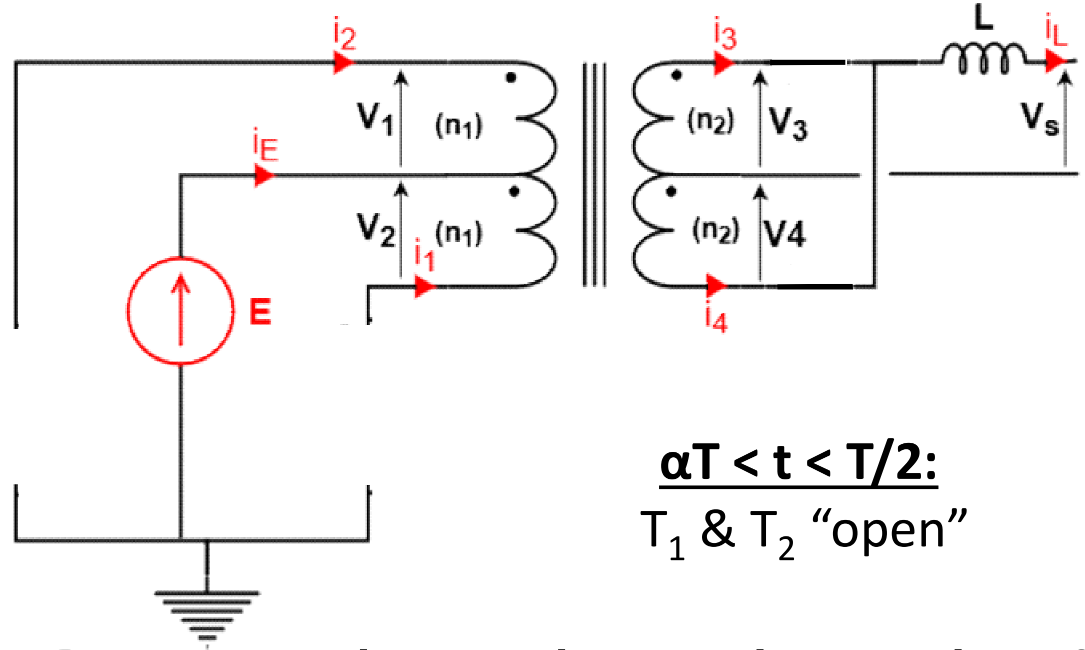
D_3 "forward", D_2 & D_4 "reverse"

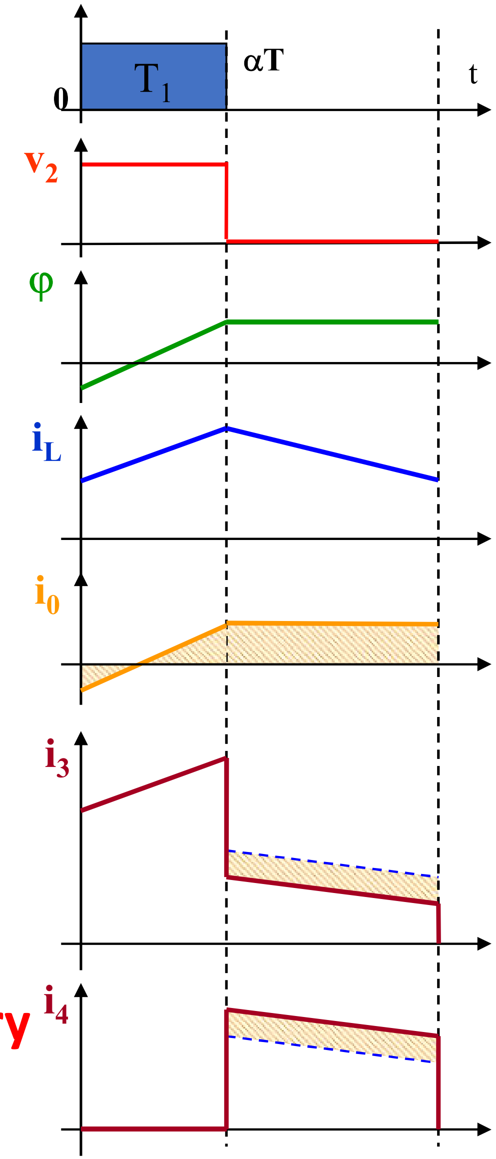
- $v_2 = n_1 . \frac{d\varphi}{dt} = E > 0$ Magnetization

$$-\boldsymbol{n_1 . i_1 - n_2 . i_3 = \mathcal{R} . \varphi}$$

$$\Rightarrow \quad \boldsymbol{i_1 = -\frac{\mathcal{R}}{n_1} . \varphi - \frac{n_2}{n_1} . i_3 = -i_0 - \frac{n_2}{n_1} . i_L}$$

Continuous mode study: second phase





$\alpha T < t < T/2$:

T_1 & T_2 "open"

$$\mathcal{R}.\varphi = -n_1.i_1 + n_1.i_2 - n_2.i_3 + n_2.i_4 > 0$$

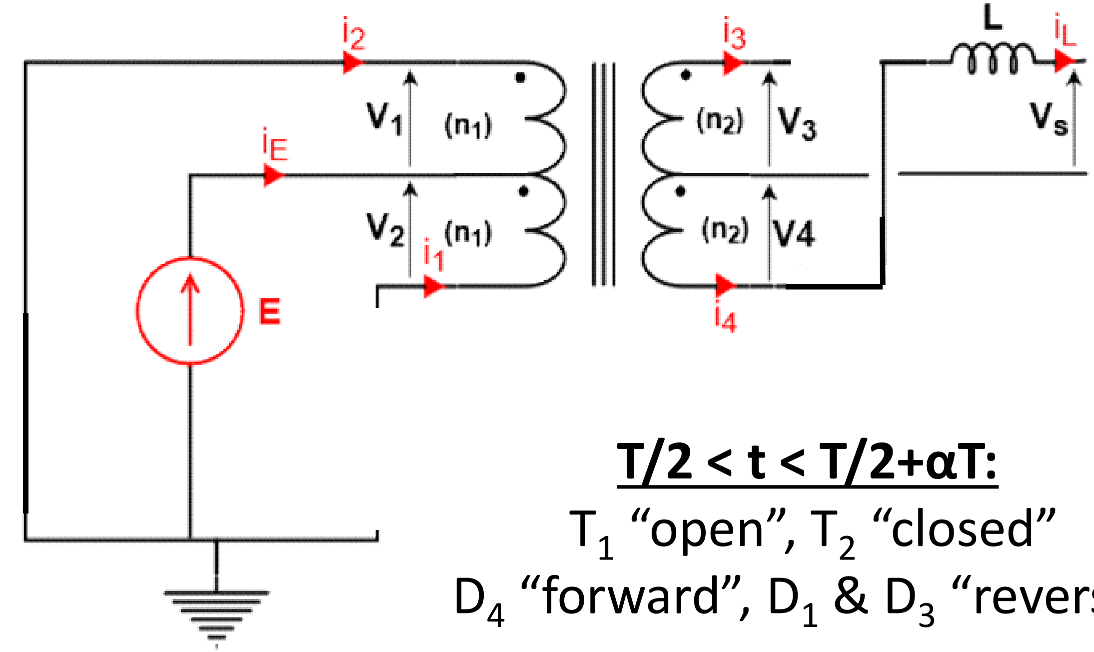
- If D_2 « forward » ⇒ **D_2 "reverse",**

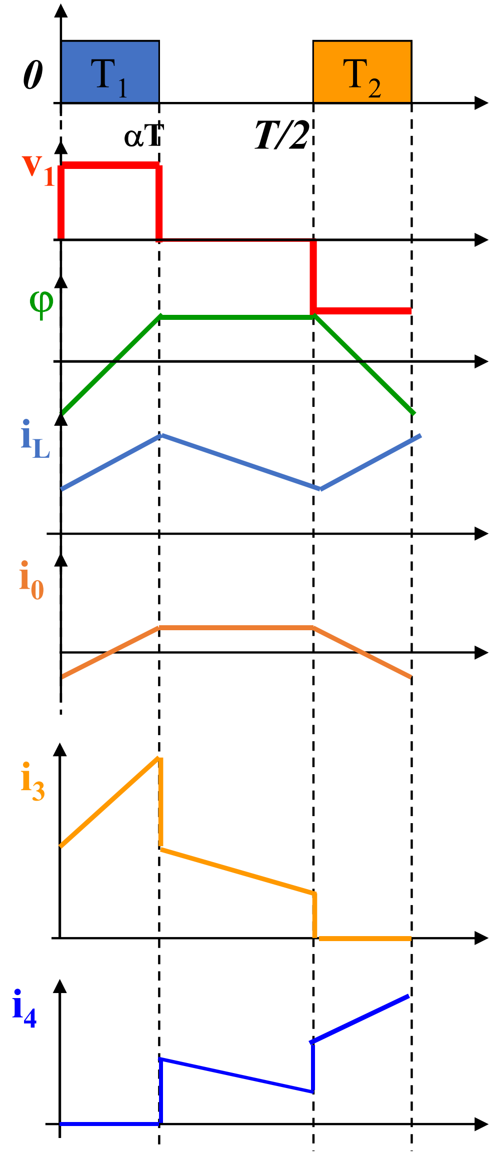
$$\mathcal{R}.\varphi = n_1.i_2 + n_2.i_L$$ **Demagnetization with secondary**

$$\mathcal{R}.\varphi = -n_2.i_3 + n_2.i_4 > 0$$ ⇒ **D_3 & D_4 "forward"**

$$v_2 = v_3 = v_4 = 0$$ ⇒ $$\varphi = cst$$

Continuous mode study: demagnetization





<u>T/2 < t < T/2+αT:</u>

T_1 "open", T_2 "closed"

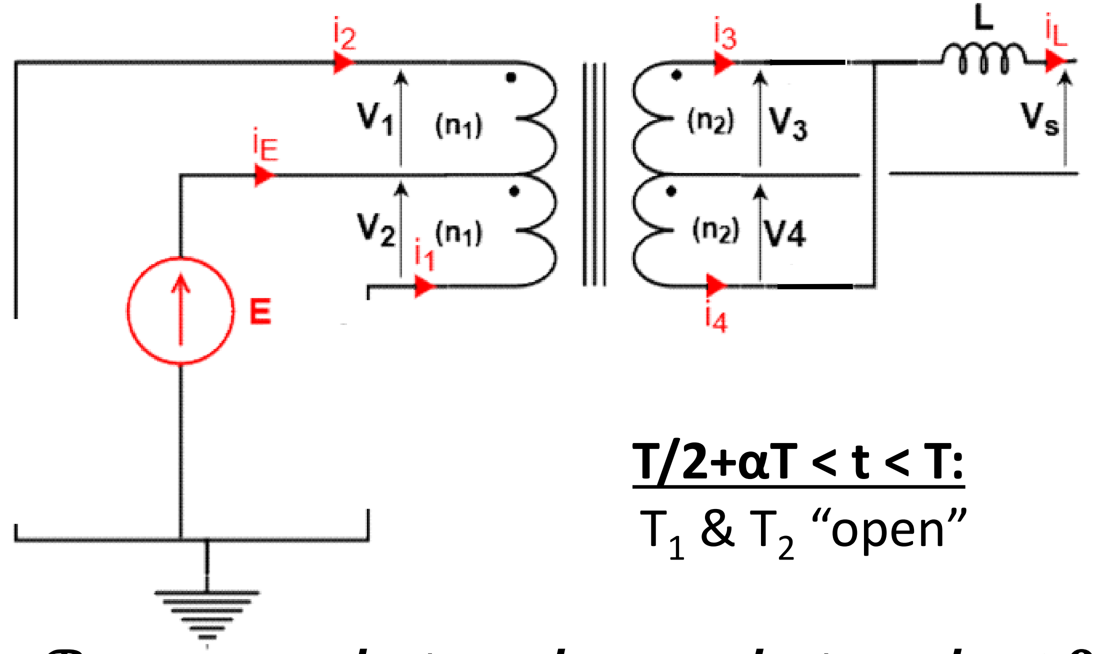
D_4 "forward", D_1 & D_3 "reverse"

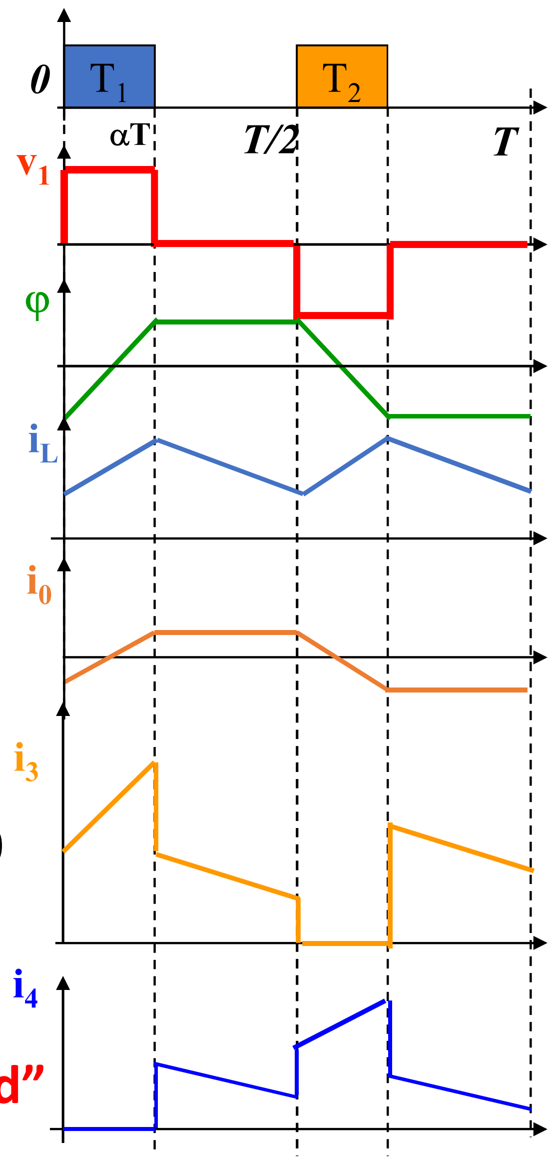
- $v_1 = n_1 . \frac{d\varphi}{dt} = -E < 0$ Demagnetization

$$\boldsymbol{n_1 . i_2 - n_2 . i_4 = \mathcal{R} . \varphi}$$

$$\boldsymbol{i_2 = \frac{\mathcal{R}}{n_1} . \varphi + \frac{n_2}{n_1} . i_4 = i_0 - \frac{n_2}{n_1} . i_L}$$

Continuous mode study: fourth phase





T/2+αT < t < T:

T_1 & T_2 “open”

$$\mathcal{R}.\varphi = -n_1.i_1 + n_1.i_2 - n_2.i_3 + n_2.i_4 < 0$$

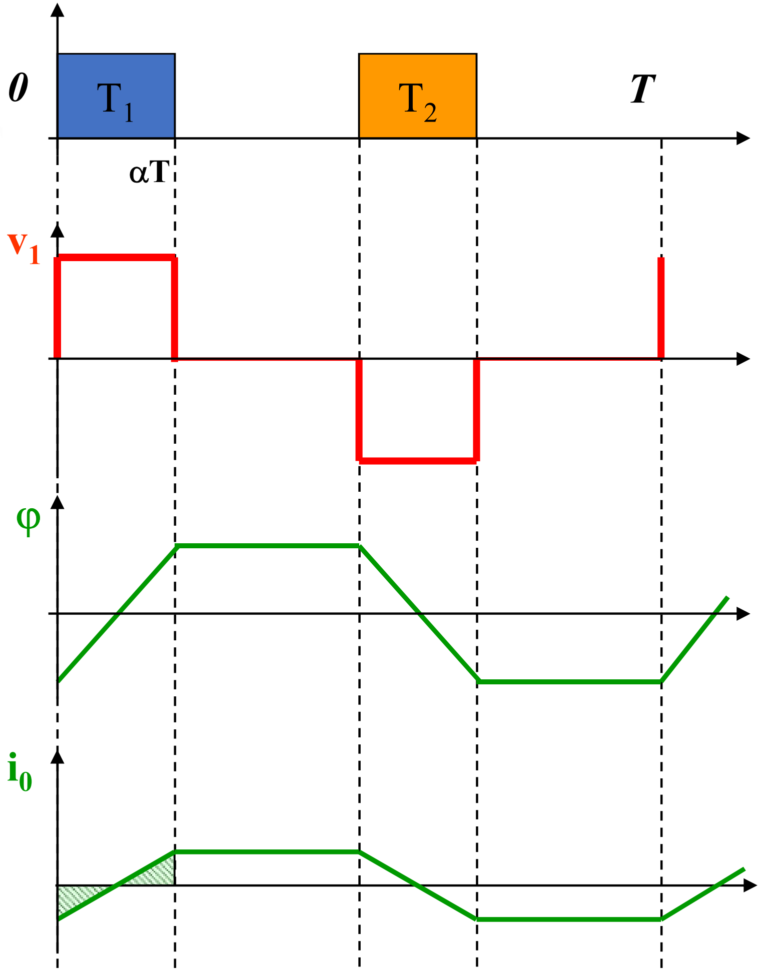
- If D_1 « forward »

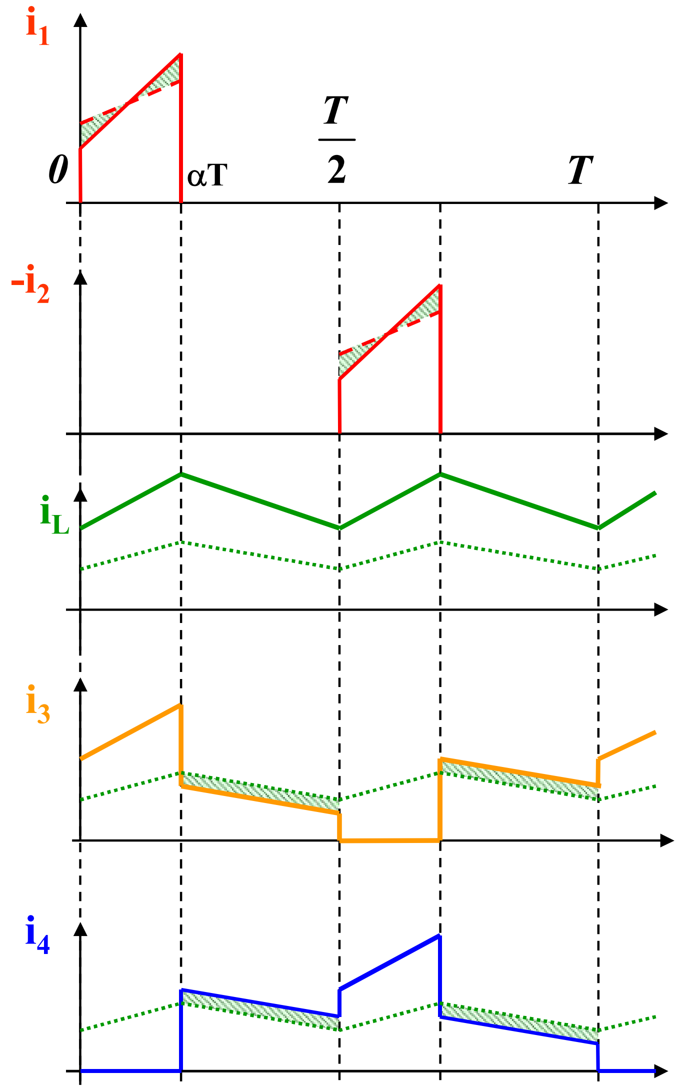
$$\mathcal{R}.\varphi = -n_1.i_1 - n_2.i_L$$ ⇒ **D_1 “reverse”**

$$\mathcal{R}.\varphi = -n_2.i_3 + n_2.i_4 < 0$$ ⇒ **D_3 & D_4 “forward”**

$$v_2 = v_3 = v_4 = 0$$ ⇒ $\varphi = cst$

Continuous mode study: chronograms





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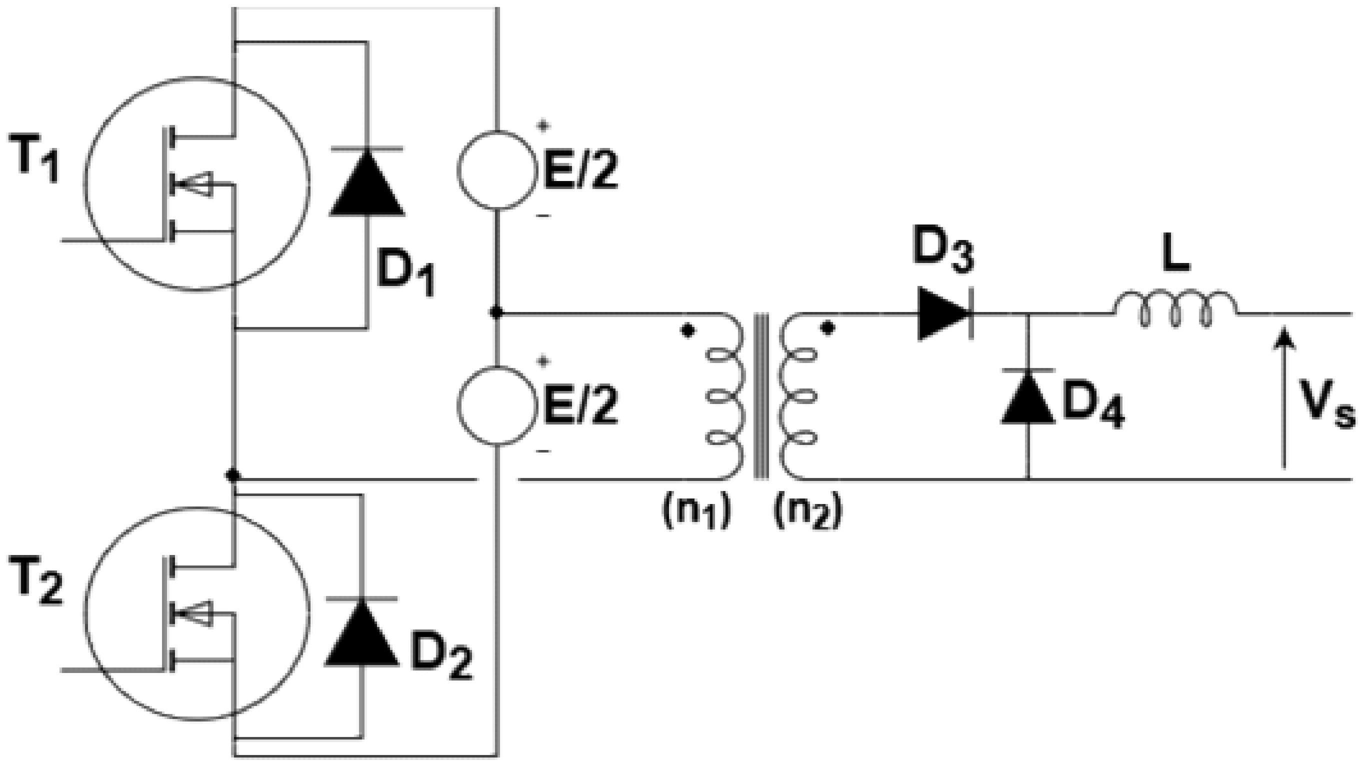
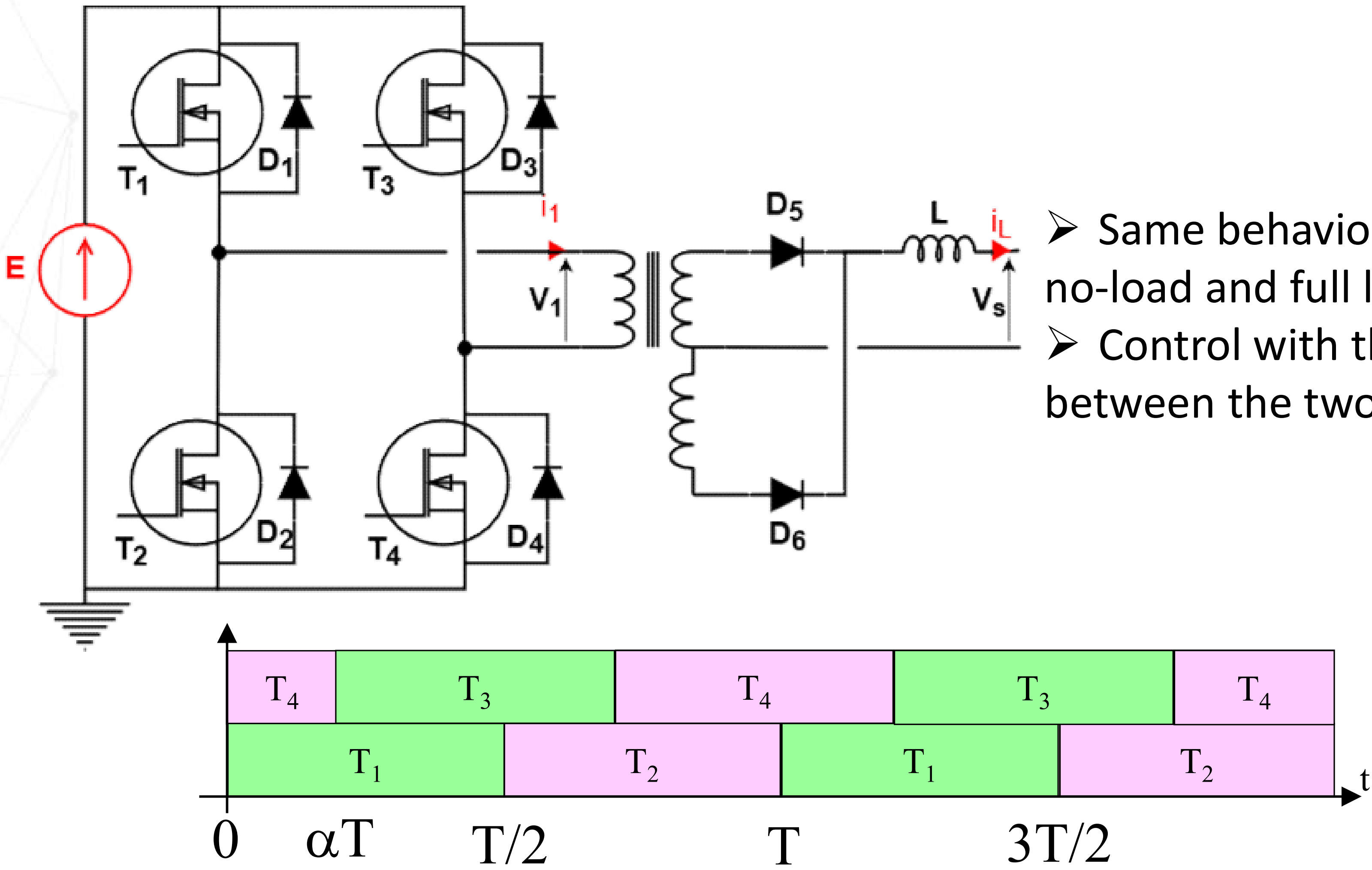
Other symmetrical structures : Half Bridge Forward



- ➢ Same behavior as Push-Pull
- ➢ Only on primary and secondary winding
- ➢ Transformer simpler (so cheaper)

Other symmetrical structures: Full Bridge Forward



- ➢ Same behavior with no-load and full load
- ➢ Control with the shift between the two arms