Switched Mode Converters (1 Quadrant)

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Summary

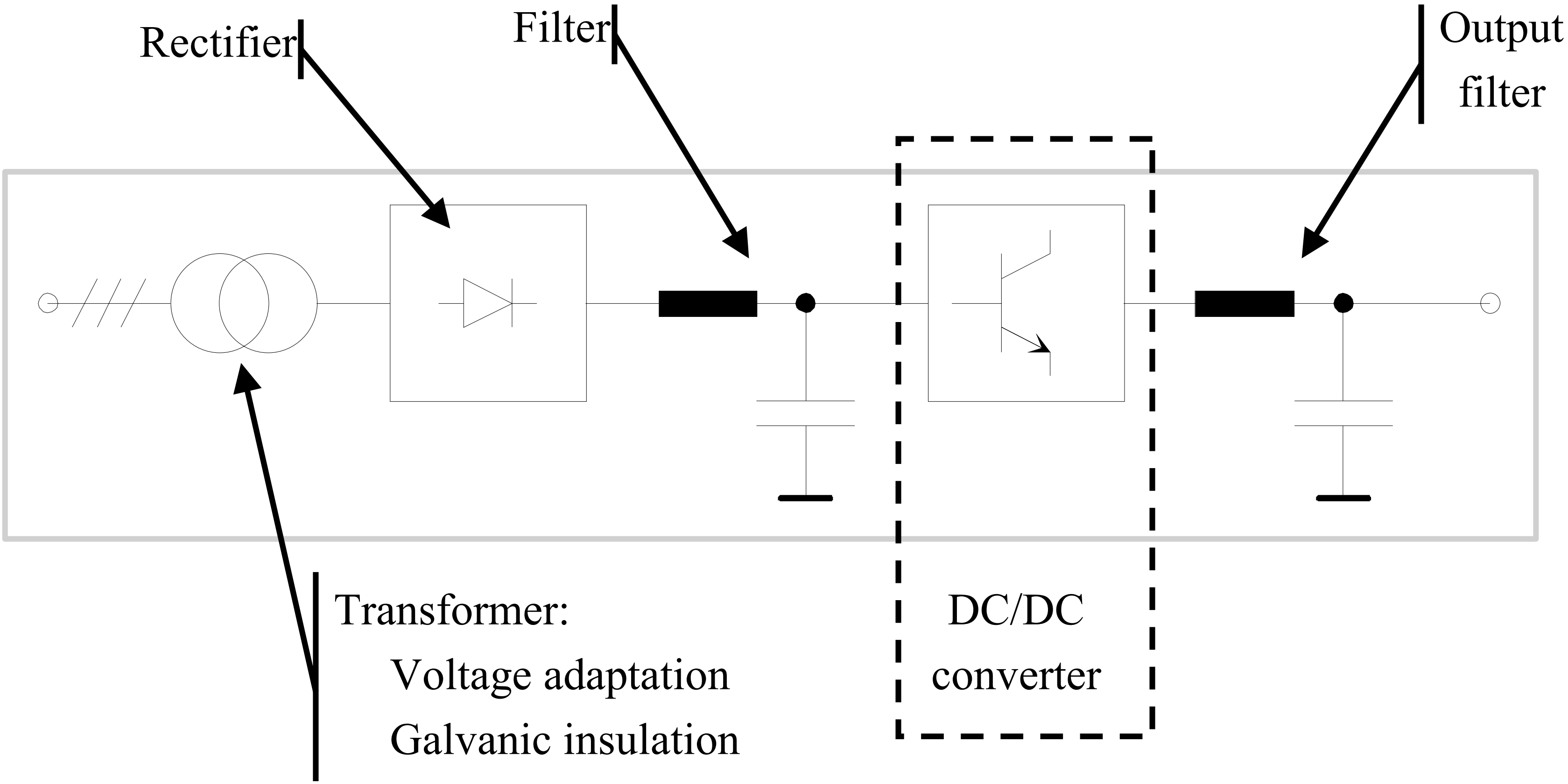
- Introduction
  - DC supplies: principle
  - Linear or Switched Mode Converters
  - Switched Mode Converters: main challenges
- DC/DC direct converters
  - Buck, boost, buck-boost converters
  - Multi channels converters
- Transformers for DC/DC converters
  - Principle, Model
  - Sizing of a transformer: weight, power and frequency
- DC/DC converters with transformers
  - Forward
  - Flyback
  - DC/AC/DC converters

Introduction

- DC supplies: principle
  - Switched mode converters are DC/DC converters
  - They are generally supplied from an AC network, via:
    - A transformer
      - ⇒For a galvanic insulation
      - ⇒For voltage level adaptation
    - A rectifier
      - ⇒In order to obtain a DC voltage source
  - Switched mode converters are used to generate controlled and adjustable DC voltage levels

Introduction

- DC supplies: principle
  - Typical (and possible) architecture



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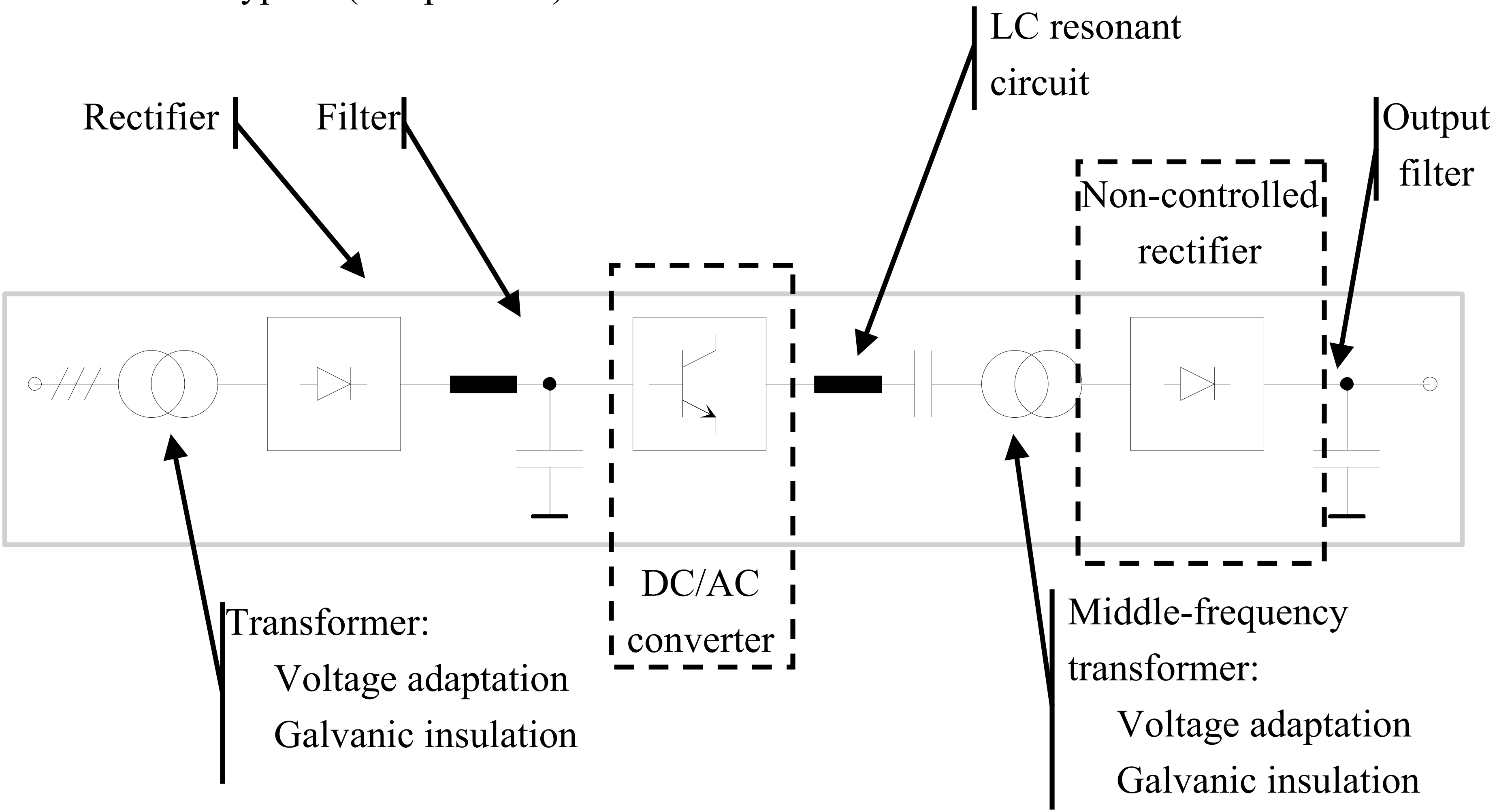
Introduction

- DC supplies: principle
  - Typical (and possible) architecture
    - Transformer : size and weight (?)
    - Rectifier: generally a diode rectifier
      - ⇒No regulation of the output voltage
    - Filter
      - ⇒Theoretically, a LC filter is needed
      - ⇒Taking into account the parasitic inductances of the AC network or the leakage inductances of the transformer, a single capacitor is generally used
      - ⇒The aim of this filter is to supply the DC/DC converter with a voltage source
    - DC/DC converter: dedicated for the control and regulation of the output voltage. Theoretically, two solutions can be investigated:
      - ⇒Linear converter
      - ⇒Switched mode converter: then an LC (or C) output filter is needed to lower ripple.

Introduction

- DC supplies: principle
  - Another typical (and possible) architecture

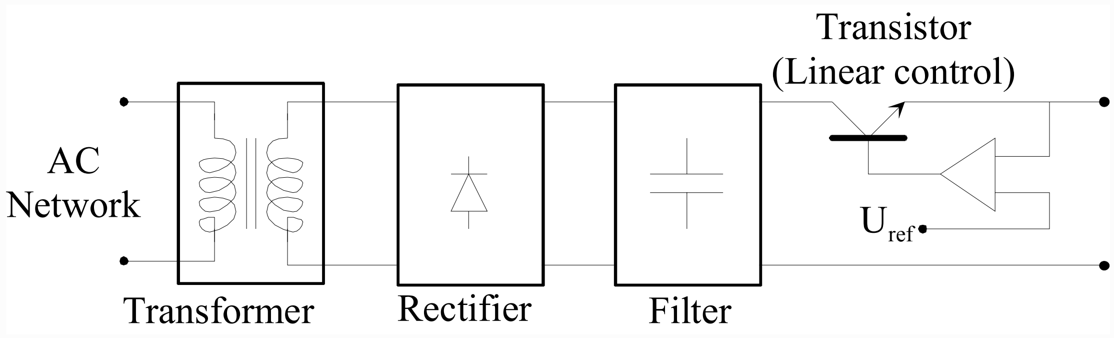


Introduction

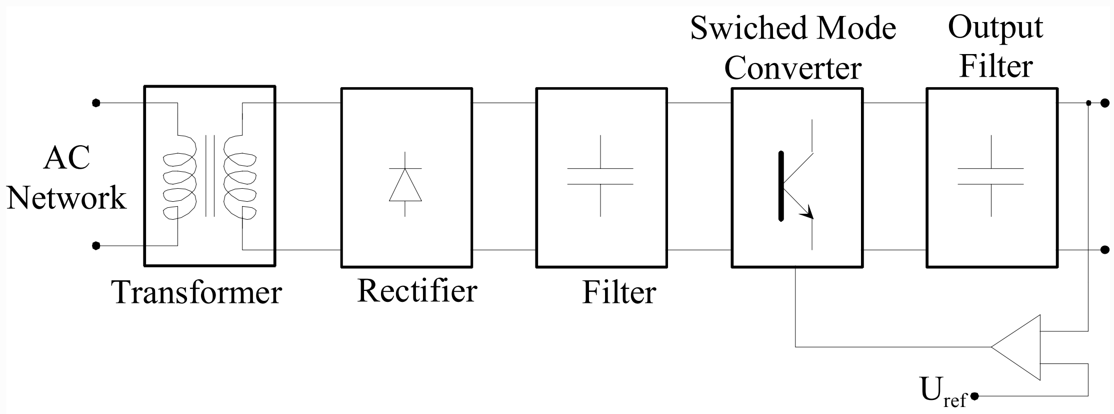
- DC supplies: principle
  - Another typical (and possible) architecture
    - Input Transformer (optional)
    - Rectifier, Filter
    - DC/AC converter
      ⇒In order to obtain transmit energy to an AC stage
    - LC resonant circuit (optional):
      ⇒For efficiency reasons, to obtain soft-switching condition for the DC/AC converter
    - Middle-frequency transformer:
      ⇒Voltage adaptation, Galvanic insulation
      ⇒Middle-frequency: reduction of weight and size
      ⇒Should avoid the use of the input transformer
    - Rectifier:
      ⇒Controlled or non-controlled, to obtain DC output voltage
      ⇒A LC (or C) filter is needed to lower ripple

Introduction

- Linear or Switched mode converters
  - Linear converter
    - Transistor driven in its linear characteristics



  - Switched mode converter
    - Output filter to lower output voltage ripple



Introduction

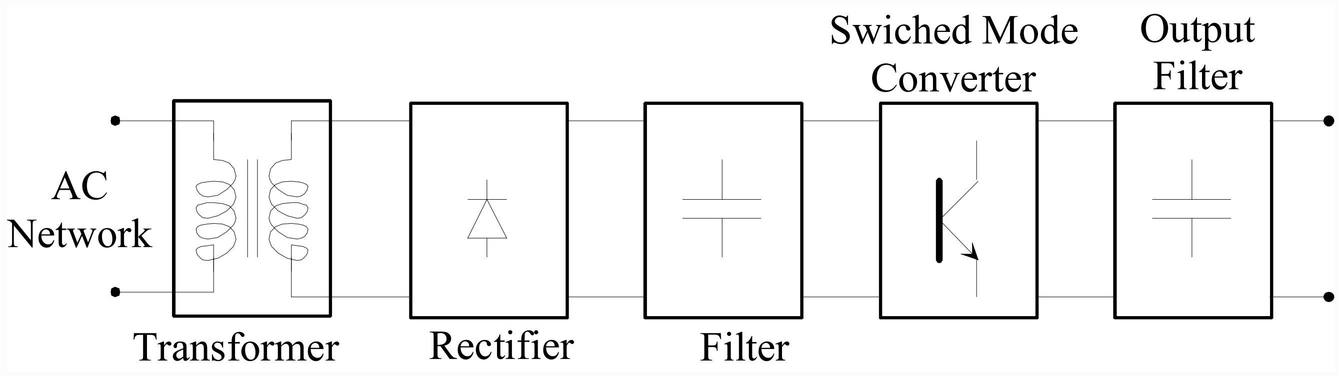
- Linear or Switched mode converters
  - Main properties: comparison

	Switched mode	Linear
Efficiency	65 à 90%	35 à 55%
Power per kilo	30 à 300W/kg	10 à 30W/kg
Power per l	50 à 300W/l	20 à 50W/l
Input voltage range	0.85 à $1.2U_n$	0.9 à $1.1U_n$
Dynamic	5% - 1ms	1% - 50us
Ouput voltage ripple	1%	0.1%
EMC	Importantes	Négligeables

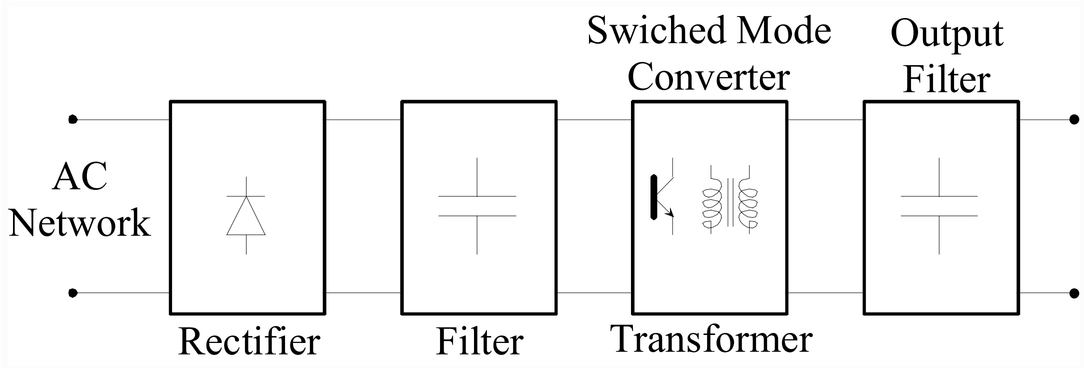
- Main interest for using switched mode power converters
  - Efficiency
  - Power density

Introduction

- Switched Mode Converters: main challenges
  - Switched mode converter: Main topology
    - Low frequency input filter (50Hz, 60Hz, 400Hz): size and weight!

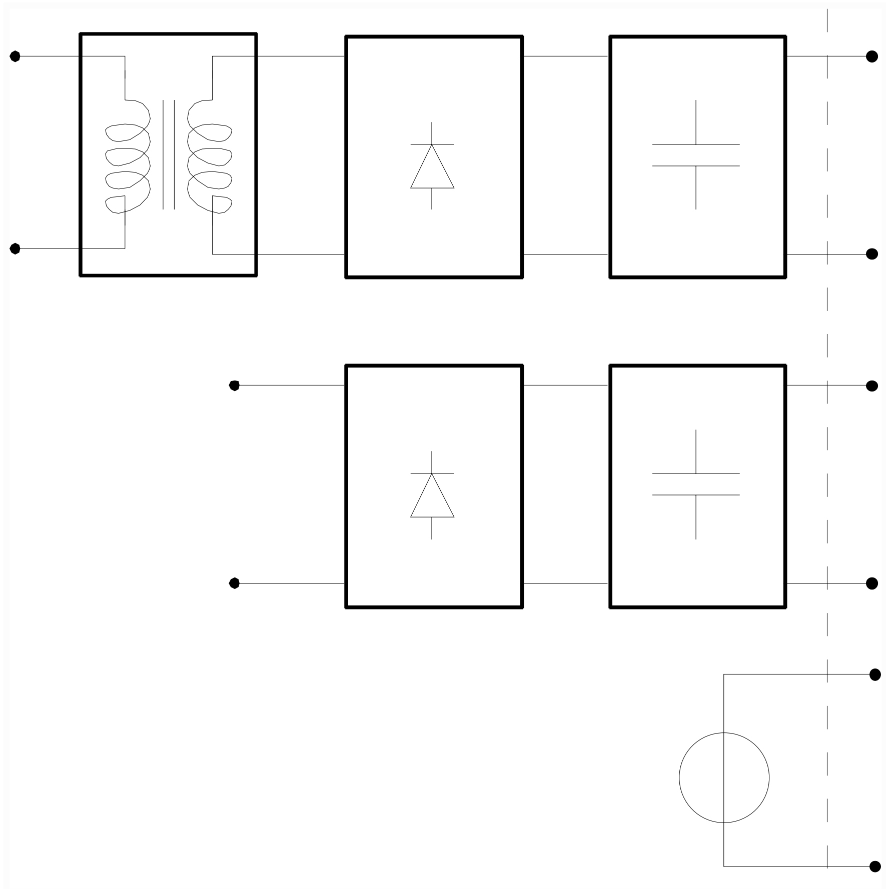


  - Switched mode converter: DC/DC converter with transformer
    - Middle frequency transformer: Switching frequency of the converter: size and weight…



Introduction

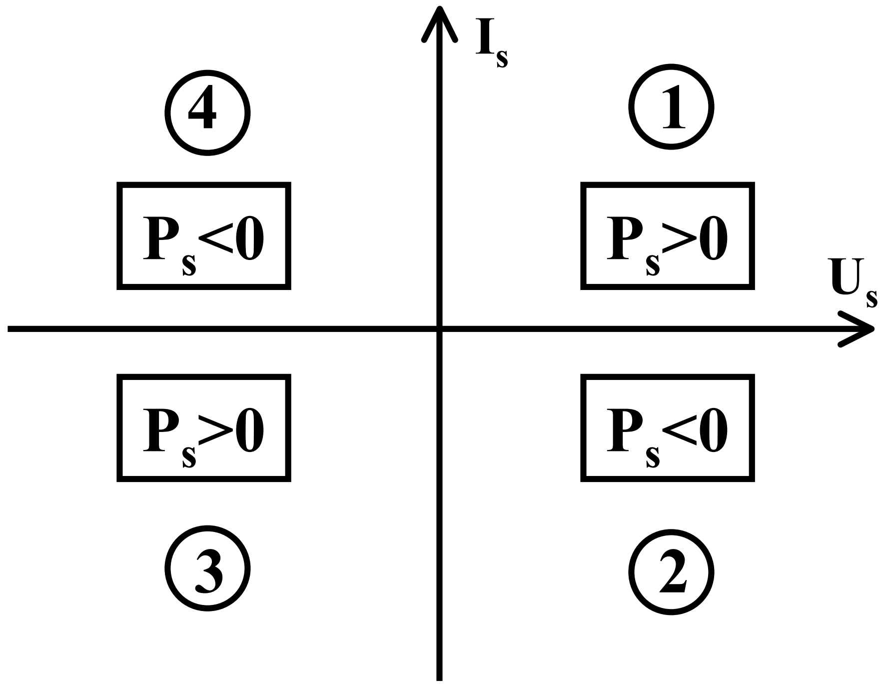
- Switched Mode Converters: Convention
  - This contribution will focus on Switched Mode converter topologies
  - (Input transformer) + Rectifier + Filter = Ideal voltage source



DC/DC converters

- Introduction
  - The aim of this presentation is to describe 1 quadrant switched mode converters
    - U_s is the output voltage
    - I_s is the output current
    - The power provided to the load is:

$$P_s = U_s I_s$$



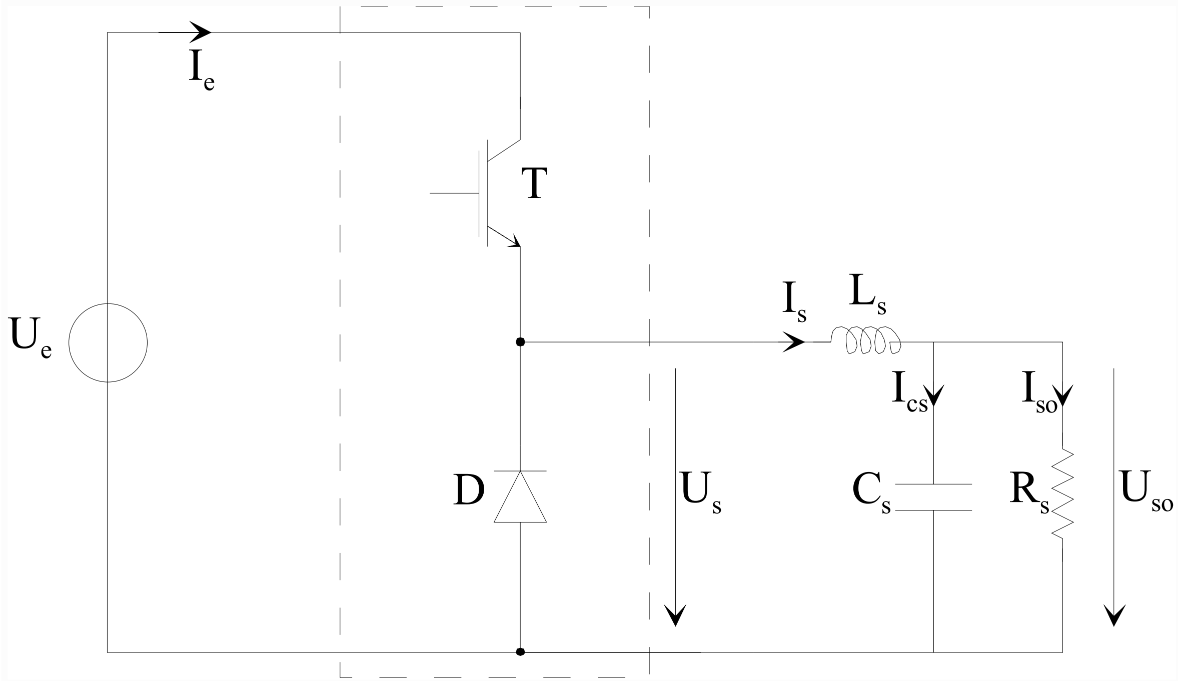
  - Depending on the topology and the components, DC/DC converters can be reversible or non-reversible
    - Converters affiliated with quadrant 1 ($U_s>0$ and $I_s<0$) will be considered

DC/DC converters

- Introduction
  - The aim of direct DC/DC converter is to manage an energy transfer between
    - A DC voltage source and a DC current source (Buck or step-down converter)
      - ⇒Such a converter allows the supply of loads with an adjustable voltage, lower than the input voltage
    - A DC current source and a DC voltage source (Boost or step-up converter)
      - ⇒Such a converter allows the supply of loads with an adjustable voltage, higher than the input voltage
    - A DC voltage source and a second DC voltage source (Buck-boost or step-up/down converter)
      - ⇒The control of the energy transfer between two voltage sources is allowed by an internal inductance, used as energy buffer in the energy flow process
      - ⇒Such a converter allows the supply of loads with an adjustable voltage, higher or lower than the input voltage
      - ⇒The buck-boost converter is not the association of a buck and a boost converters

DC/DC Converters

- Buck (step-down) converter:
  - Topology

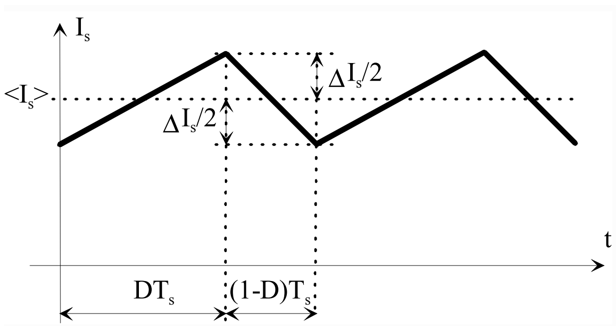


  - 1 Switching cell: transistor + Diode
  - Main parameter:
    - switching period T_s

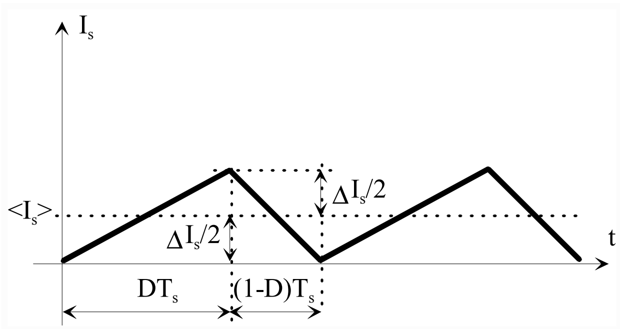
DC/DC Converters

- Buck (step-down) converter:
  - Continuous conduction mode:
    - The output current I_s is always positive
    - Each off-switching of the diode is trigged by the on-switching of the transistor
  - Discontinuous conduction mode:
    - Each off-switching of the diode is due to a natural decrease of the output current to 0, while the transistor is not immediately switched on.

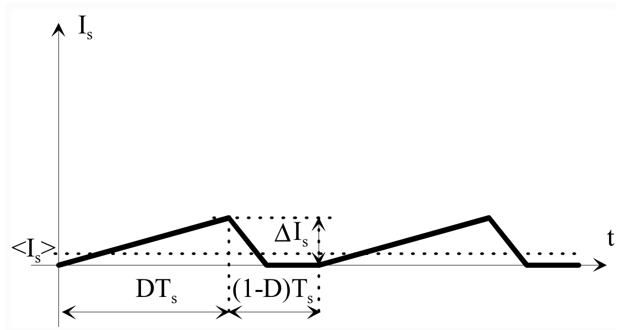
Continuous conduction mode



Critical conduction mode



Discontinuous conduction mode



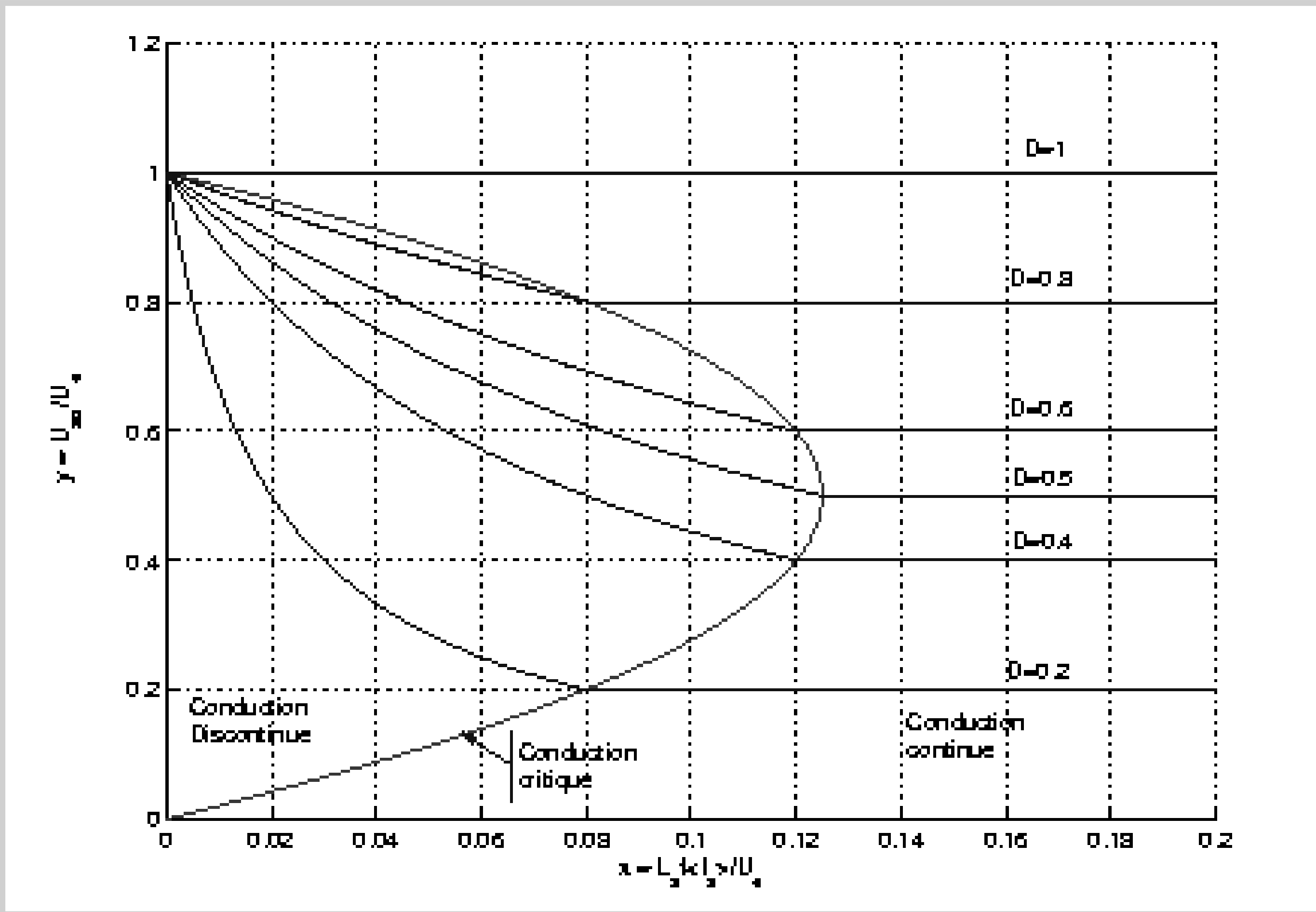
DC/DC Converters

- Buck (step-down) converter:
  - Summary:

	Normalized Variables	
• Continuous conduction mode : $$\langle U_s \rangle = U_{so} = DU_e$$	$$y = \frac{\langle U_s \rangle}{U_e} = \frac{U_{so}}{U_e}$$ $$x = \frac{L_s f \langle I_s \rangle}{U_e}$$	$$y = D$$
• Critical conduction : $$\langle I_{s\lim} \rangle = \frac{U_e}{2L_s f}(1-D)D$$		$$x_{\lim} = \frac{1}{2}y(1-y)$$
• Discontinuous conduction mode $$\langle U_s \rangle = U_{so} = U_e \frac{1}{1+\frac{2L_s f\langle I_s \rangle}{D^2 U_e}}$$		$$y = \frac{1}{1+\frac{2x}{D^2}}$$

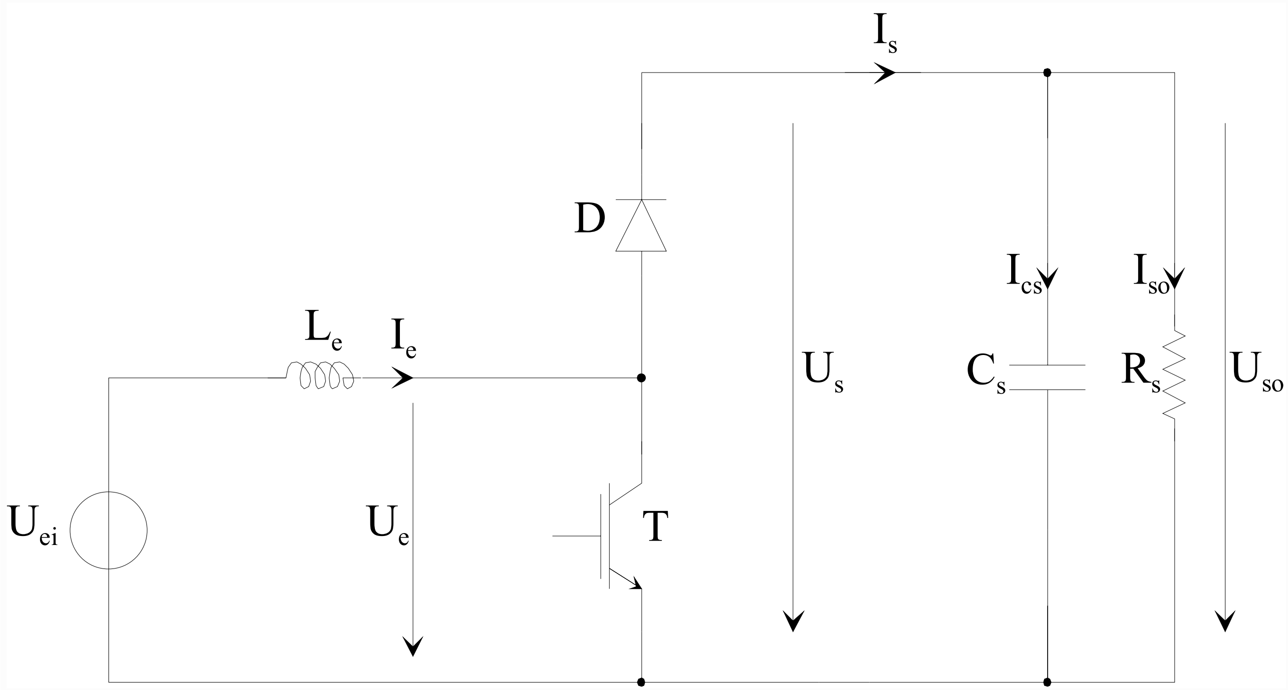
DC/DC Converters

- Buck (step-down) converter:
  - Output characteristics



DC/DC Converters

- Boost (step-up) converter:
  - Topology

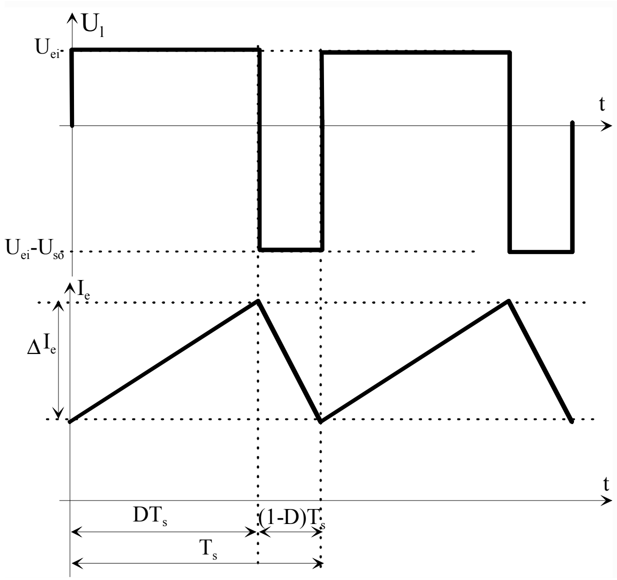


  - 1 Switching cell: transistor+diode
  - Main parameter
    - Switching period T_s

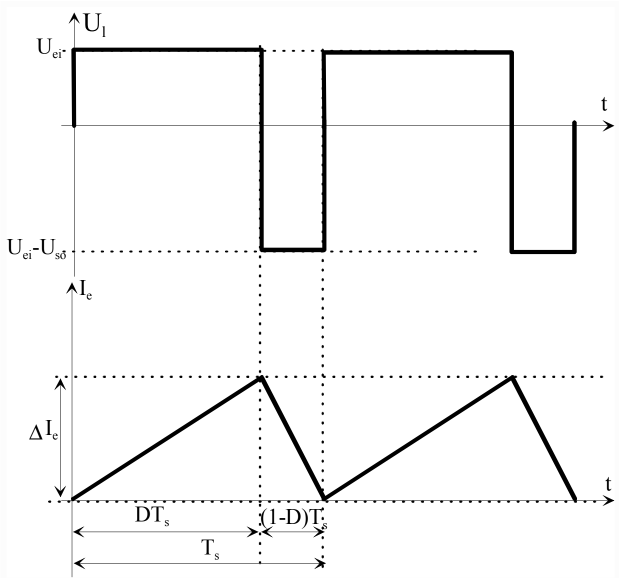
DC/DC Converters

- Boost (step-up) converter:
  - Continuous conduction mode:
    - The input current is always positive
    - Each off-switching of the diode is trigged by the on-switching of the transistor
  - Discontinuous conduction mode
    - Each off-switching of the diode is due to a natural decrease of the input current to 0, while the transistor is not immediately switched on.

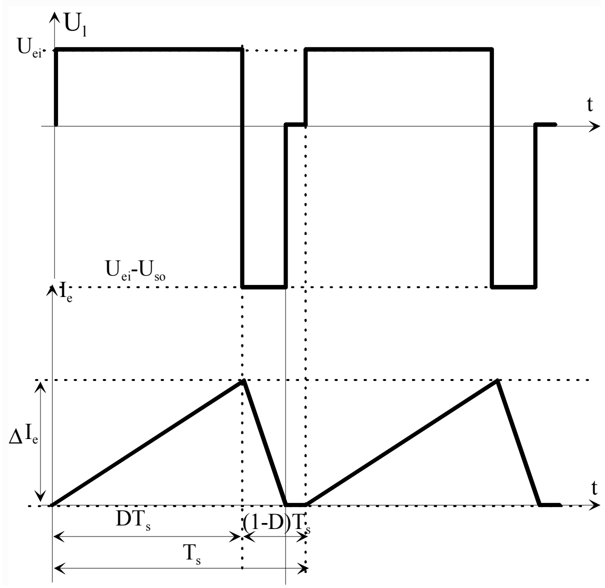
Continuous conduction mode



Critical conduction mode



Discontinuous conduction mode



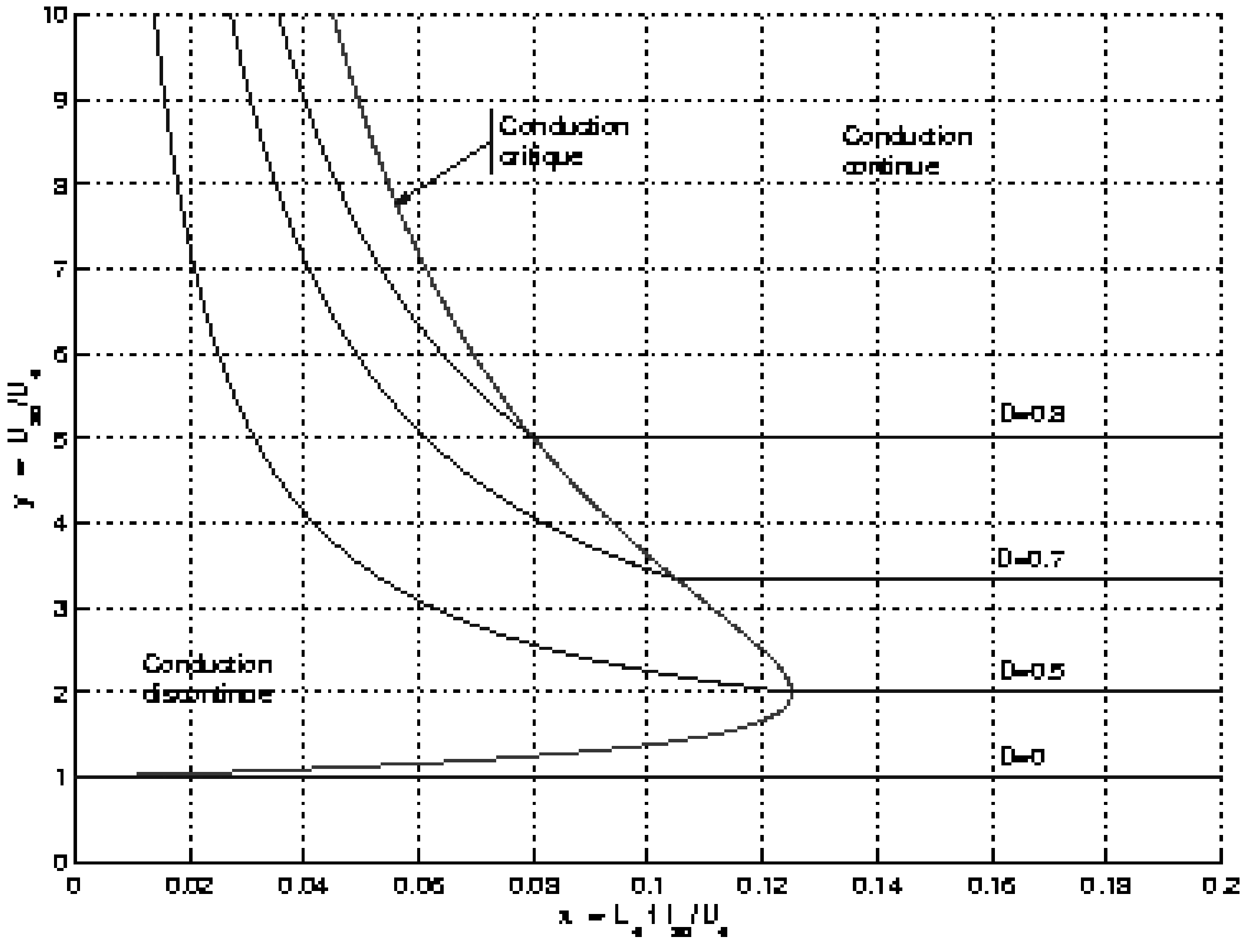
DC/DC Converters

- Boost (step-up) converter:
  - Summary

	Normalized Variables	
• Continuous conduction mode : $$U_{so} = \langle U_s \rangle = U_{ei} \frac{1}{1-D}$$	$$y = \frac{\langle U_s \rangle}{U_{ei}} = \frac{U_{so}}{U_{ei}}$$ $$x = \frac{L_e f \langle I_s \rangle}{U_{ei}}$$	$$y = \frac{1}{1-D}$$
• Critical conduction $$\langle I_{s\,lim} \rangle = \frac{U_{ei}}{2L_e f}(1-D)D$$		$$x_{lim} = \frac{1}{2}\frac{y-1}{y^2}$$
• Discontinuous conduction mode : $$\langle U_s \rangle = U_{so} = U_{ei}\left(1 + \frac{U_{ei}}{2L_e f \langle I_s \rangle} D^2\right)$$		$$y = 1 + \frac{D^2}{2x}$$

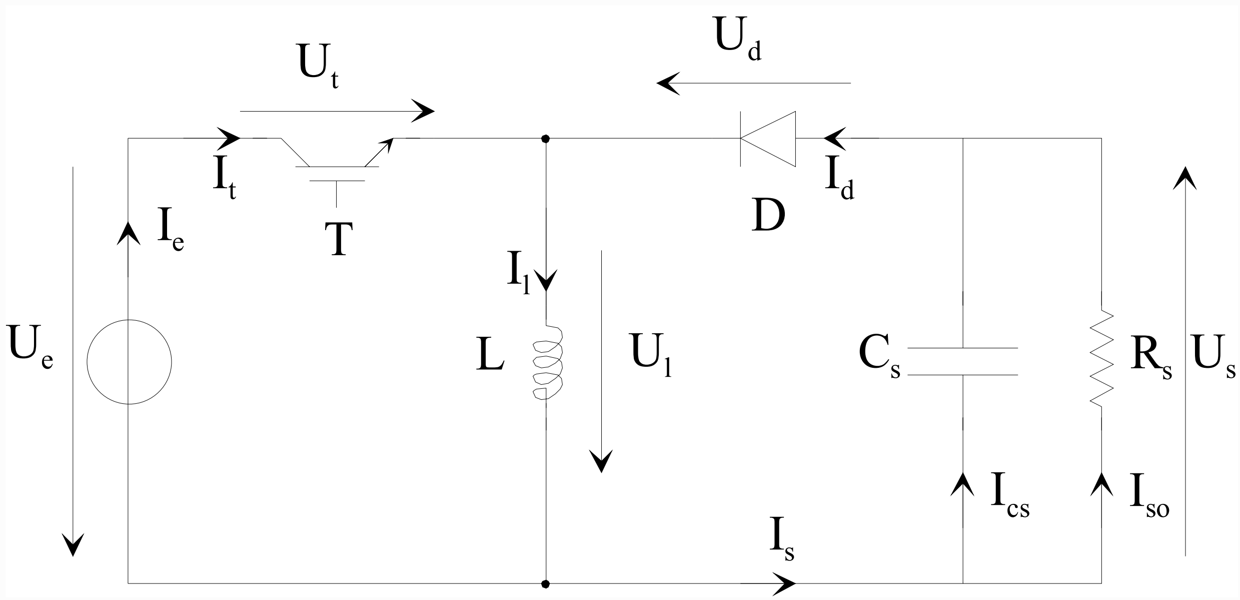
DC/DC Converters

- Boost (step-up) converter:
  - Output Characteristics



DC/DC Converters

- Buck-Boost (step-up/down) converter:
  - Also know as DC/DC inverter
  - Topology

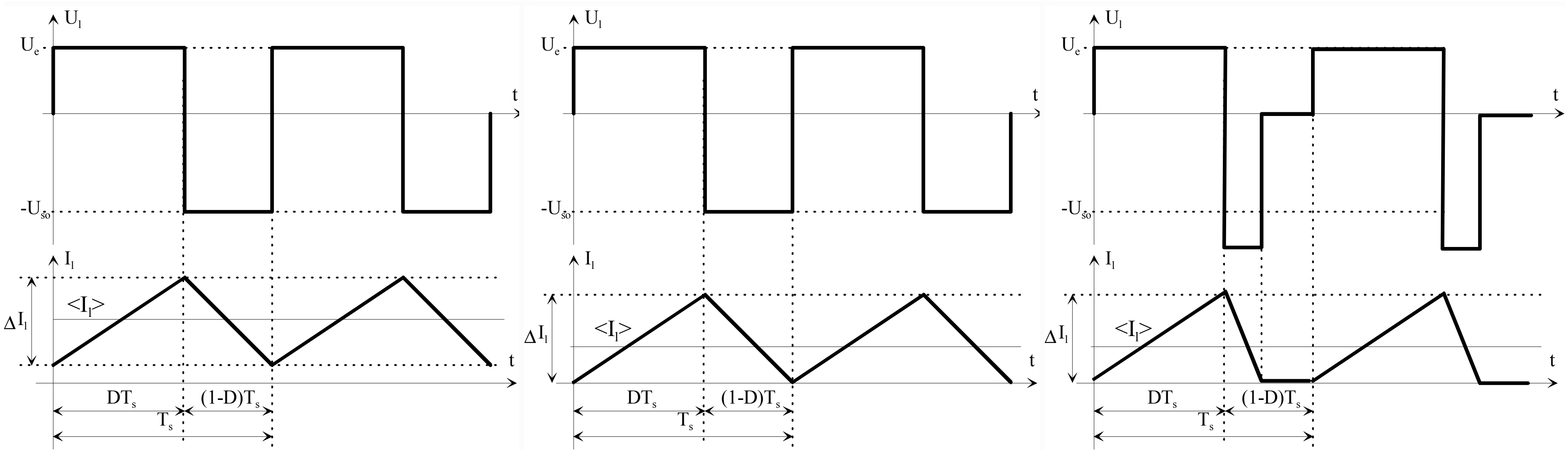


  - Energy transfer between 2 voltage sources is allowed by the internal inductance L
  - 1 Switching cell: transistor+diode
  - Main parameter
    - Switching period T_s

DC/DC Converters

- Buck-Boost (step-up/down) converter:
  - Continuous conduction mode:
    - The current in the inductor is always positive
    - Each off-switching of the diode is trigged by the on-switching of the transistor
  - Discontinuous conduction mode
    - Each off-switching of the diode is due to a natural decrease of the current in the inductor to 0, while the transistor is not immediately switched on.

Continuous conduction mode | Critical conduction mode | Discontinuous conduction mode



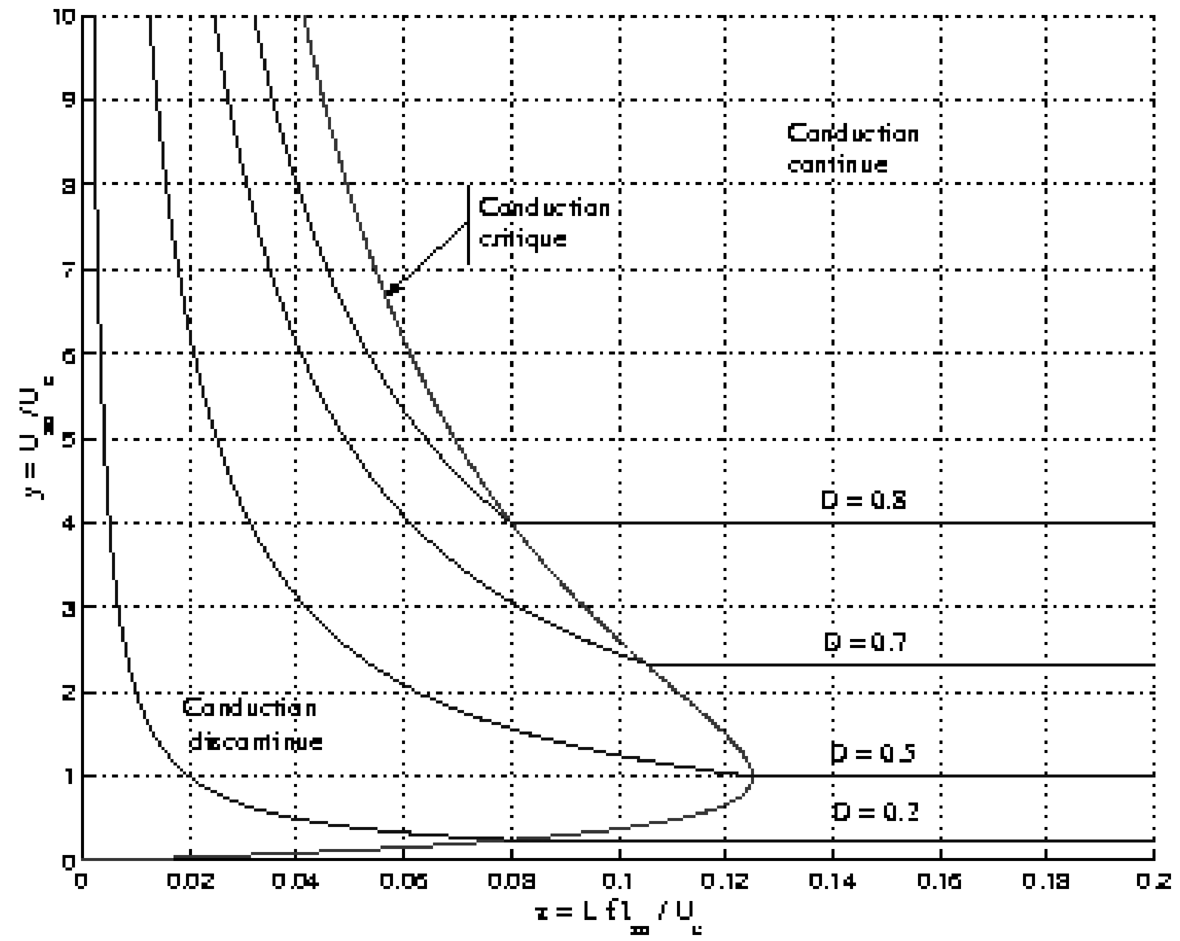
DC/DC Converters

- Buck-Boost (step-up/down) converter:
  - Summary

• Continuous conduction mode : $$U_{so} = \langle U_s \rangle = U_e \frac{D}{1-D}$$	**Normalized Variables**	$$y = \frac{D}{1-D}$$
• Critical conduction : $$\langle I_{s\lim} \rangle = \frac{1}{2Lf} \frac{U_e^2 U_{so}}{(U_e + U_{so})^2}$$	$$y = \frac{\langle U_s \rangle}{U_e} = \frac{U_{so}}{U_e}$$ $$x = \frac{Lf\langle I_s \rangle}{U_e}$$	$$x_{\lim} = \frac{1}{2} \frac{y}{(1+y)^2}$$
• Discontinuous conduction mode : $$\langle U_s \rangle = U_{so} = U_e \left(\frac{U_e}{2Lf\langle I_s \rangle} D^2 \right)$$		$$y = \frac{D^2}{2x}$$

DC/DC Converters

- Buck-Boost (step-up/down) converter:
  - Output Characteristics



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DC/DC Converters

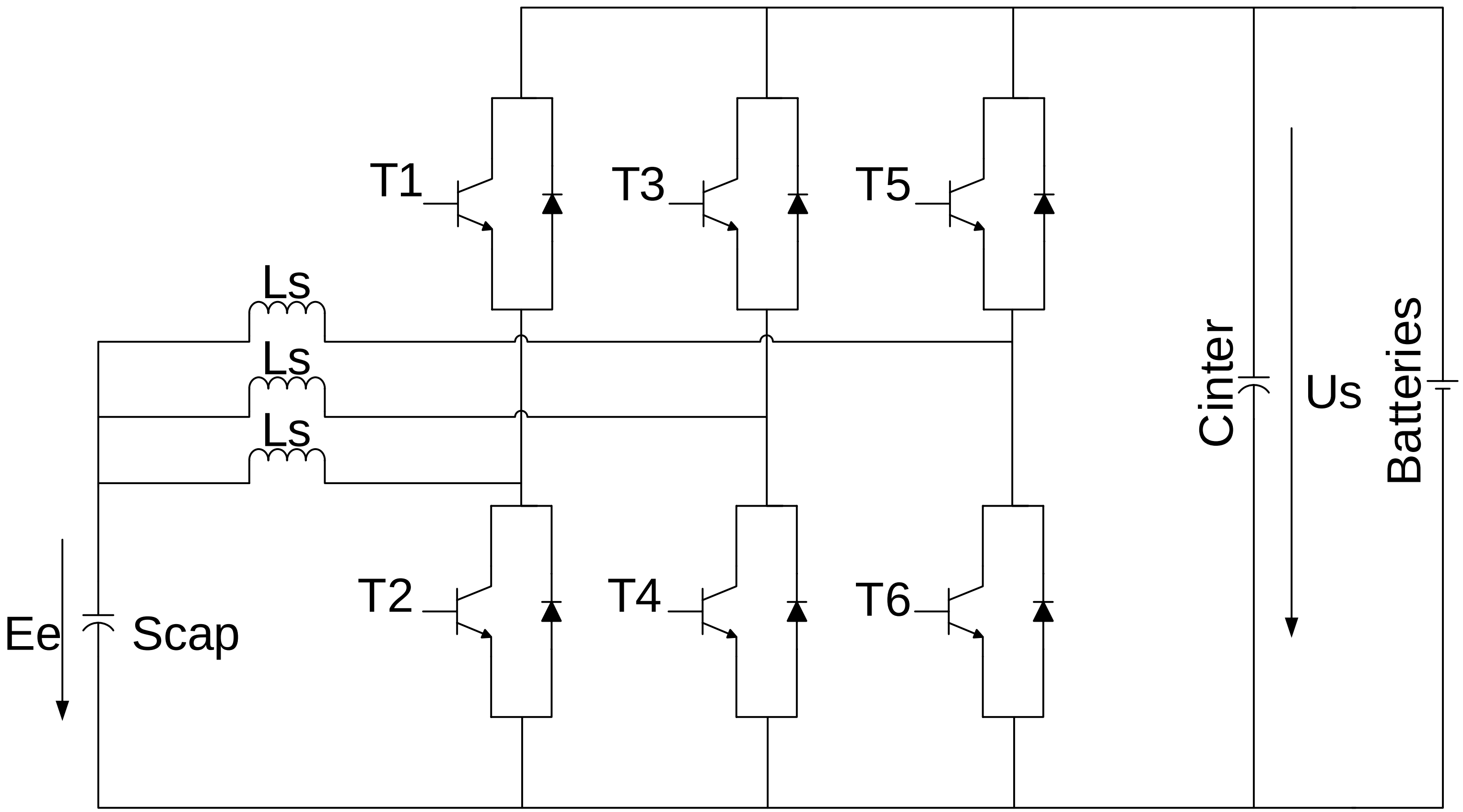
- Multi channels converters
  - Conventional buck or boost topologies,
  - Reduction of cooling devices
  - Increase of the efficiency
  - Soft-switching conditions
    - This can be obtained in the discontinuous conduction mode

      ⇒the off-switching of diodes is natural, and not due to the on-switching of transistors

      ⇒Switching current is 0A when transistors are switched on.

DC/DC Converters

- Multi channels converters
  - Example of a multi-channel boost converter



DC/DC Converters

- Multi channels converters
  - Example of a multi-channel boost converter
    - Each channel works in discontinuous conduction mode
    - The associated coil is then reduced (few micro-henri)
    - Strong current ripple, poor averaged value
    - On the low-voltage source:

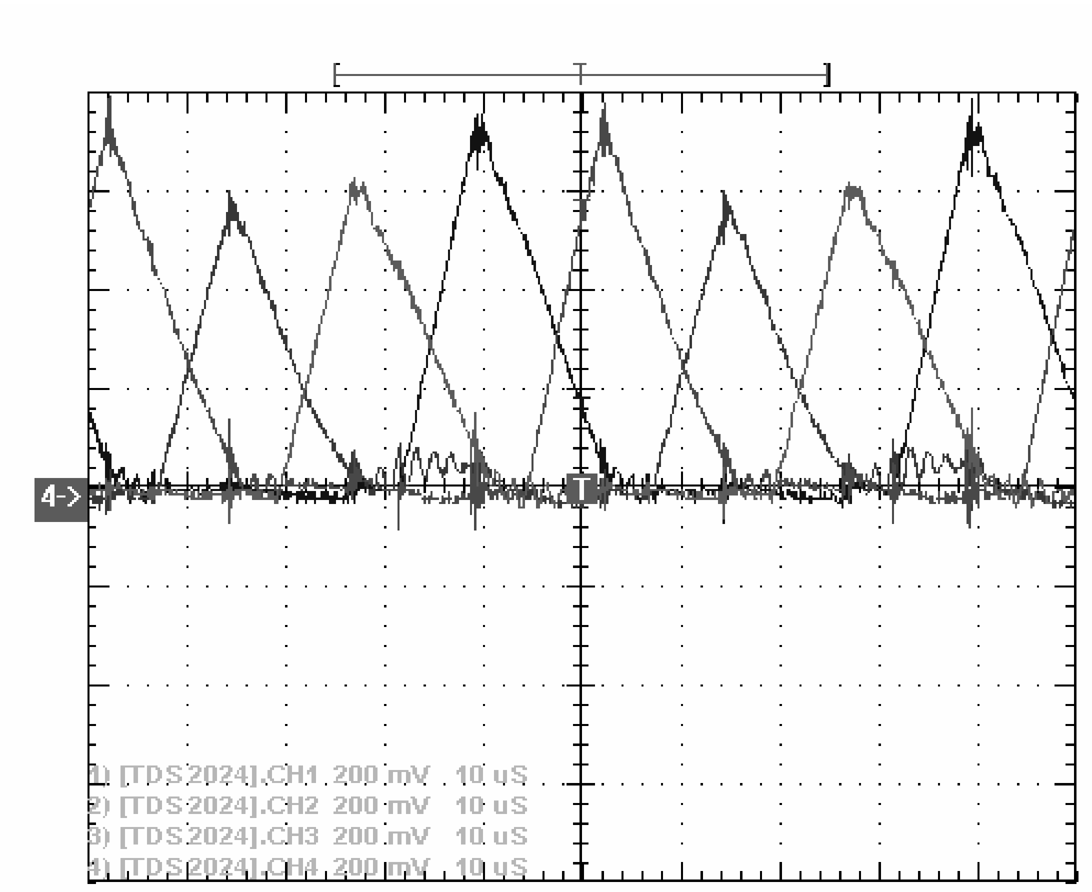
      ⇒averaged values of currents are summed

      ⇒As each leg is phase-shifted, current ripple are cancelled.

    - Such a solution offers high efficiency for applications of few kW.

DC/DC Converters

- Multi channels converters
  - Example of a multi-channel boost converter



Current shown for 4 channels

Vin = 18 V

Vout = 37.5 – 75 V

Iin max = 255 A (maximal power 4600 W)

Switching frequency : 20 kHz

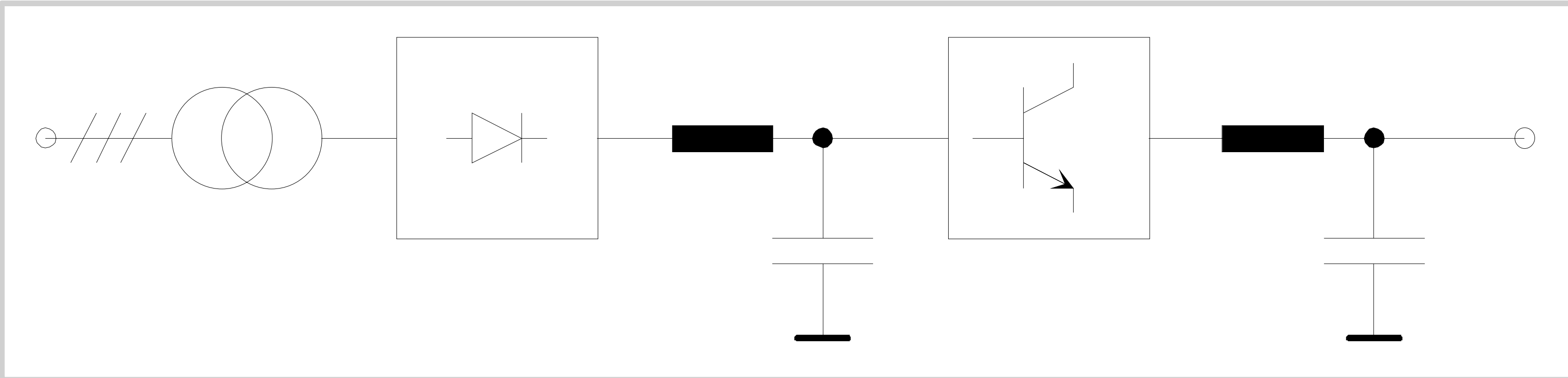
8 channels

Inductors used : 7.8 uH

(typical inductor for a classical converter : some mH)

Transformers for DC/DC converters

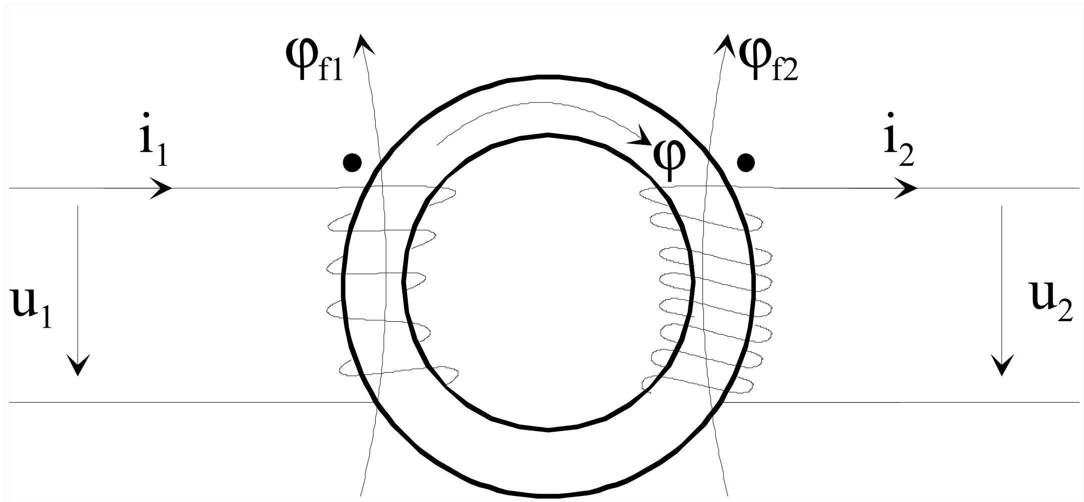
- Principle, Model
  - In switched mode converters, transformers are needed
    - To adapt voltage/current levels
    - To offer galvanic insulation



  - In several applications, transformers are the first devices in the energy-flow chain:
    - Sizing?
    - Volume?
    - Weight?

Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - Principle of a 2 windings transformer



- Sign conventions

  ⇒Voltages and currents are positives regarding conventions adopted in the figure

Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - First hypothesis:

      ⇒No leakage flux

      ⇒Reluctance of the magnetic circuit is 0

      ⇒Windings with no electric resistance

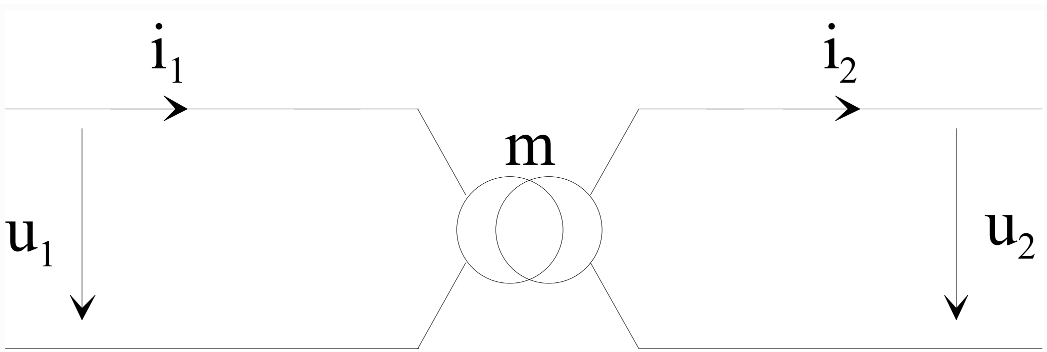
$$u_1 = n_1 \frac{d\varphi}{dt}$$

$$u_2 = n_2 \frac{d\varphi}{dt}$$

$$\Rightarrow \quad \frac{u_2}{u_1} = \frac{n_2}{n_1} = m$$

$$n_1 i_1 - n_2 i_2 = \Re \varphi = 0$$

$$\Rightarrow \quad \frac{i_1}{i_2} = \frac{n_2}{n_1} = m$$



Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - Second hypothesis:
      - ⇒No leakage flux
      - ⇒Reluctance of the magnetic circuit
      - ⇒Windings with no electric resistance

$$n_1 i_1 - n_2 i_2 = \Re\varphi \quad \Rightarrow \quad i_1 = \underbrace{\frac{n_2}{n_1} i_2}_{\text{Ideal transformer}} + \underbrace{\frac{\Re}{n_1}\varphi}_{i\mu}$$

$$\varphi_t = n_1 \varphi \quad \Rightarrow \quad \varphi_t = \underbrace{\frac{n_1^{\,2}}{\Re}}_{L_m} i_\mu$$

  - L_m: magnetic inductance of the transformer

Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - L_m: magnetic inductance of the transformer

$$u_1 = L_M \frac{di_\mu}{dt}$$

⇒The primary mean value of the voltage must be 0

- Magnetic energy stored into a transformer:

$$W = \frac{1}{2} L_M i_\mu{}^2 = \frac{1}{2} \Re \varphi^2$$

⇒The energy stored into the transformer cannot be discontinuous

- The flux is then a state variable

- Currents:

$$n_1 i_1 - n_2 i_2 = \Re \varphi$$

⇒Each discontinuity of the input current must be compensated by an equivalent discontinuity of the secondary side current

Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - third hypothesis:
      - ⇒Leakage flux
      - ⇒Reluctance of the magnetic circuit
      - ⇒Windings with no electric resistance

$$u_1 = \underbrace{n_1 \frac{d\varphi}{dt}}_{e_1} + n_1 \frac{d\varphi_{f1}}{dt}$$

$$u_2 = \underbrace{n_2 \frac{d\varphi}{dt}}_{e_2} + n_2 \frac{d\varphi_{f2}}{dt}$$

$$\frac{e_2}{e_1} = \frac{n_2}{n_1} = m$$

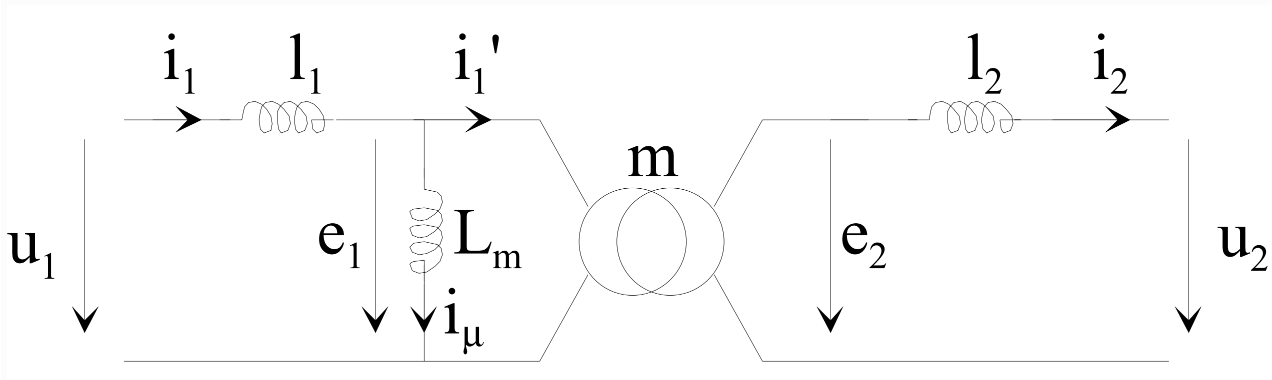
Transformers for DC/DC converters

- Principle, Model
  - General equations of a transformer:
    - third hypothesis:
      - ⇒Leakage flux
      - ⇒Reluctance of the magnetic circuit
      - ⇒Windings with no electric resistance
    - Introducing the notion of leakage inductances (considering that φ_{f1} and φ_{f2} are directly proportional to the primary and secondary currents)

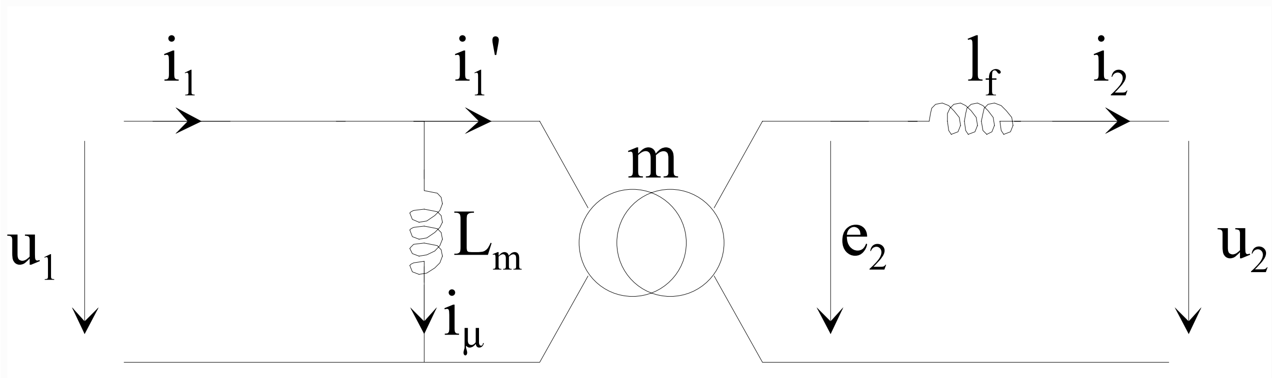
$$
\begin{aligned}
n_1 \frac{d\varphi_{f1}}{dt} &= l_1 \frac{di_1}{dt} \\
n_2 \frac{d\varphi_{f2}}{dt} &= -l_2 \frac{di_2}{dt}
\end{aligned}
\quad \Rightarrow \quad
\begin{aligned}
u_1 &= e_1 + l_1 \frac{di_1}{dt} \\
u_2 &= e_2 + l_2 \frac{di_2}{dt}
\end{aligned}
$$

Transformers for DC/DC converters

- Principle, Model
  - Model
    - Resistance of windings are neglected
    - Hysterese and iron losses are not takien into account

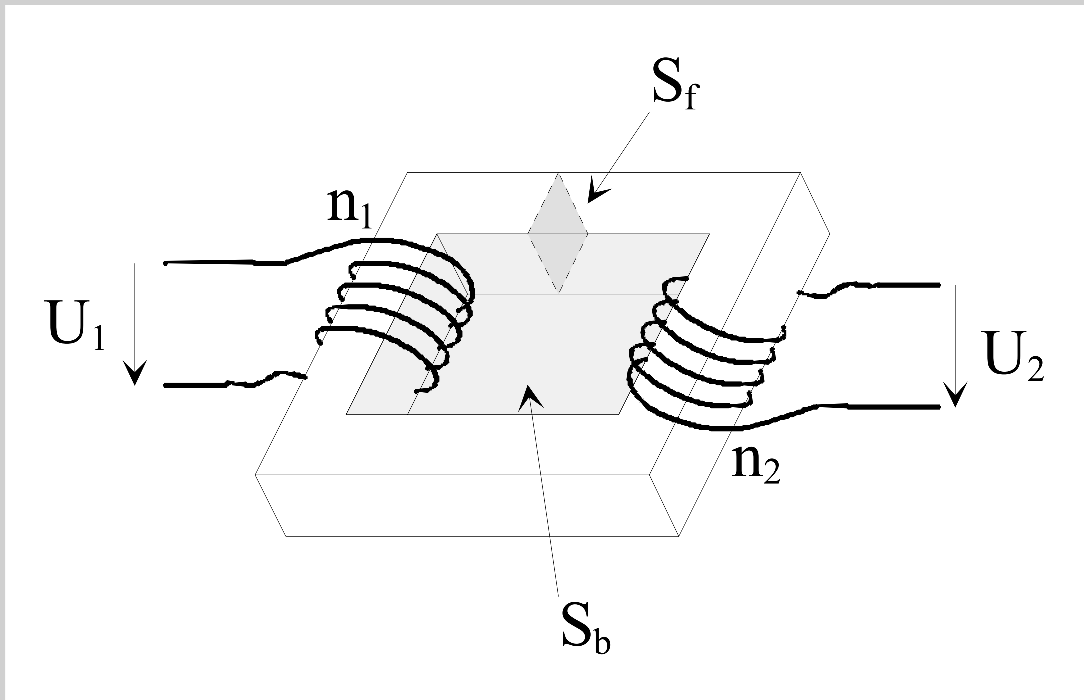


$$l_1 \quad \text{and} \quad l_2 \quad \ll L_m$$



Transformers for DC/DC converters

- Sizing of a transformer:
  - Main equations:



- S_f : section of the magnetic circuit
- S_b : surface allowed for windings

Transformers for DC/DC converters

- Sizing of a transformer:
  - Main equations: surface of the magnetic circuit

$$u_1(t) = n_1 \frac{d\varphi}{dt}$$

$$\varphi = BS_f \Rightarrow u_1(t) = n_1 S_f \frac{dB}{dt}$$

$$B = \frac{1}{n_1 S_f} \int u_1(t)dt$$

$$\Rightarrow B_M = \frac{U}{n_1 S_f f}$$

$$\Rightarrow S_f = \frac{U}{n_1 B_M f}$$

Transformers for DC/DC converters

- Sizing of a transformer:
  - Main equations: surface allowed for windings

$$S_b = n_1 s_1 K_{b1} + n_2 s_2 K_{b2} + \cdots + n_N s_N K_{bN}$$

$$S_b = n_1 \frac{I_{1eff}}{J_1} K_{b1} + n_2 \frac{I_{2eff}}{J_2} K_{b2} + \cdots + n_N \frac{I_{Neff}}{J_N} K_{bN}$$

$$\text{using}: n_i I_{ieff} = a_i n_1 I_{1eff}$$

$$S_b = n_1 I_{1eff} \sum_{i=1}^{N} \frac{a_i K_{bi}}{J_i}$$

Transformers for DC/DC converters

- Sizing of a transformer:
  - Main equations: definition of A_{TR}, defining the volume of the transformer

$$\mathbf{A_{TR} = S_f S_b}$$

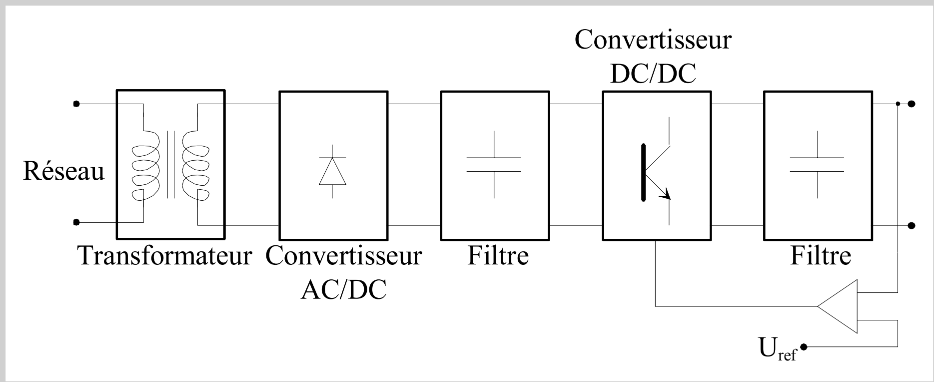
$$\mathbf{A_{TR} = \frac{UI_{1eff}}{B_M f} \sum_{i=1}^{N} \frac{a_i K_{bi}}{J_i}}$$

$$\mathbf{A_{TR} = \frac{P_1}{B_M f} \sum_{i=1}^{N} \frac{a_i K_{bi}}{J_i}}$$

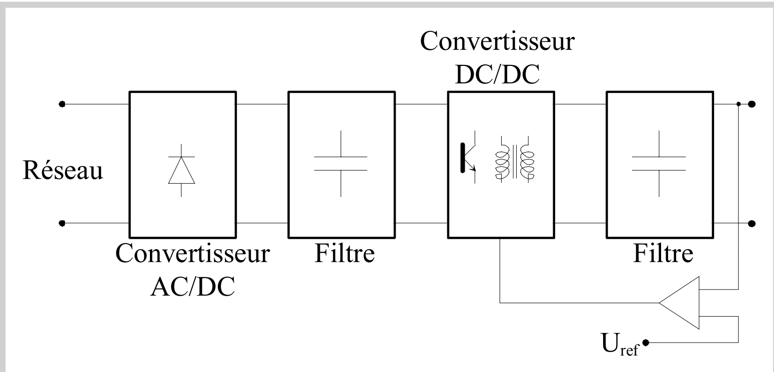
  - The volume of the transformer (and is weight) are directly linked to
    - The power
    - The frequency
  - The frequency has to be increased to lower volume and weight

DC/DC converters with transformers

- General principle
  - Such converters are identified from the conventional DC/DC converters
    - In conventional energy transfer chain, transformers are directly coupled to a low frequency power network



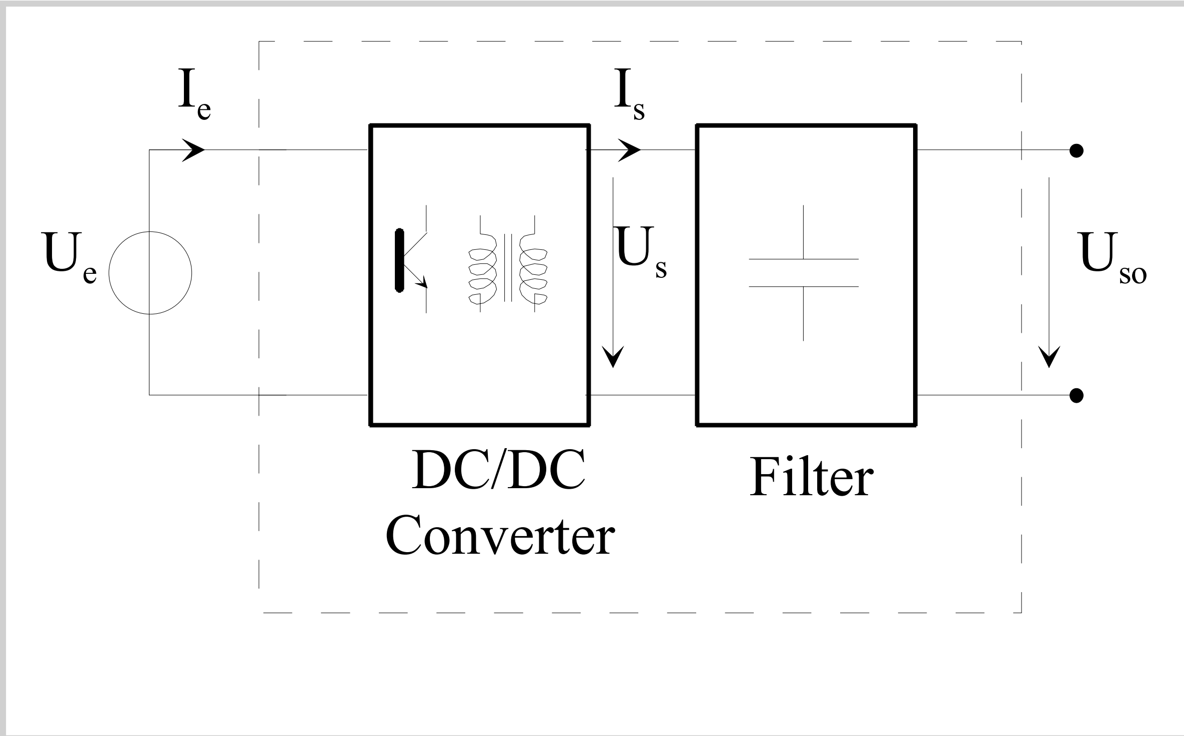
    - The transformer can be integrated directly into the DC/DC converter (when possible)



The working frequency is given by the switching frequency of the converter

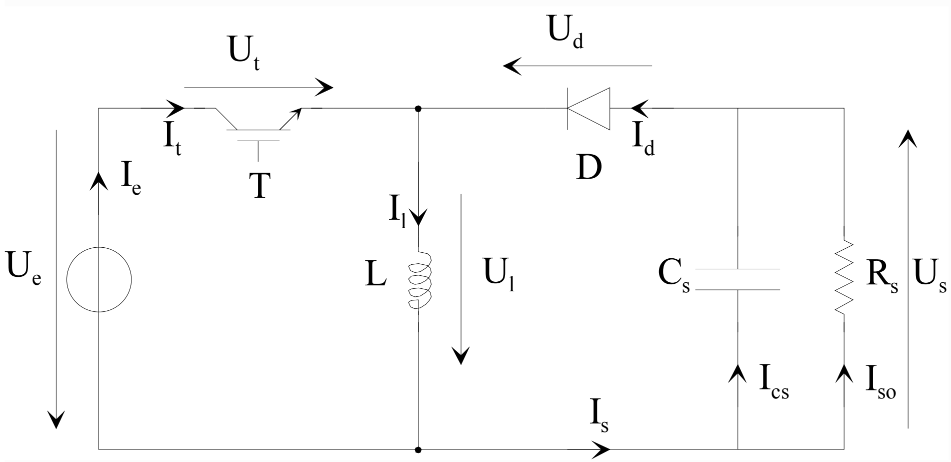
DC/DC converters with transformers

- General principle
  - Such converters are located directly of rectifier and an input filter
    - Convention:



DC/DC converters with transformers

- Flyback:
  - Converter deduced from the DC/DC Buck-boost converter



•When the transistor is ON, L is coupled to U_e

•When the diode is ON, L is coupled to the output

•Magnetic energy is alternatively stored in L from U_e, and then provided to the ouput

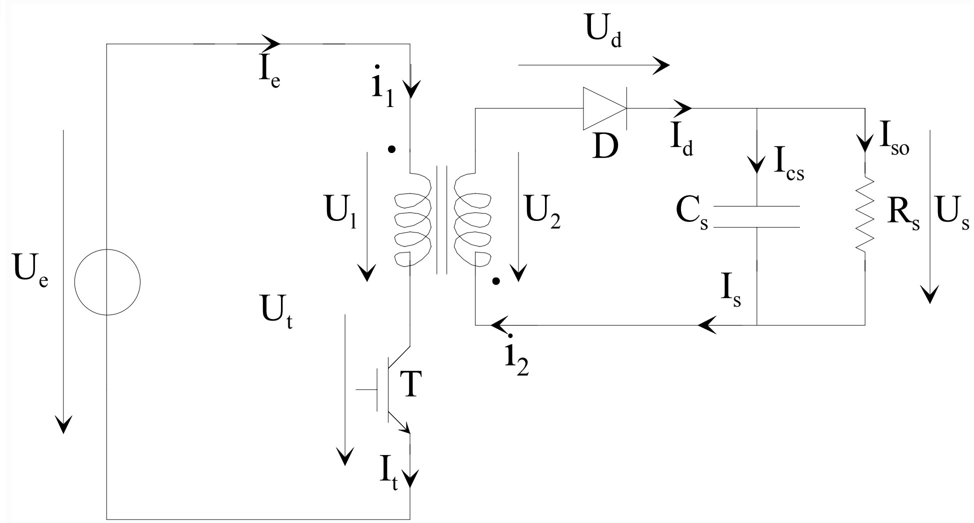
•The mean value of U_l is 0

•When the transistor is ON, the primary side of the transformer is coupled to U_e

•When the diode is ON, the secondary side is coupled to the output

•Magnetic energy is alternatively stored in L_m and then provided to the output

•The mean value of u_1 is 0



DC/DC converters with transformers

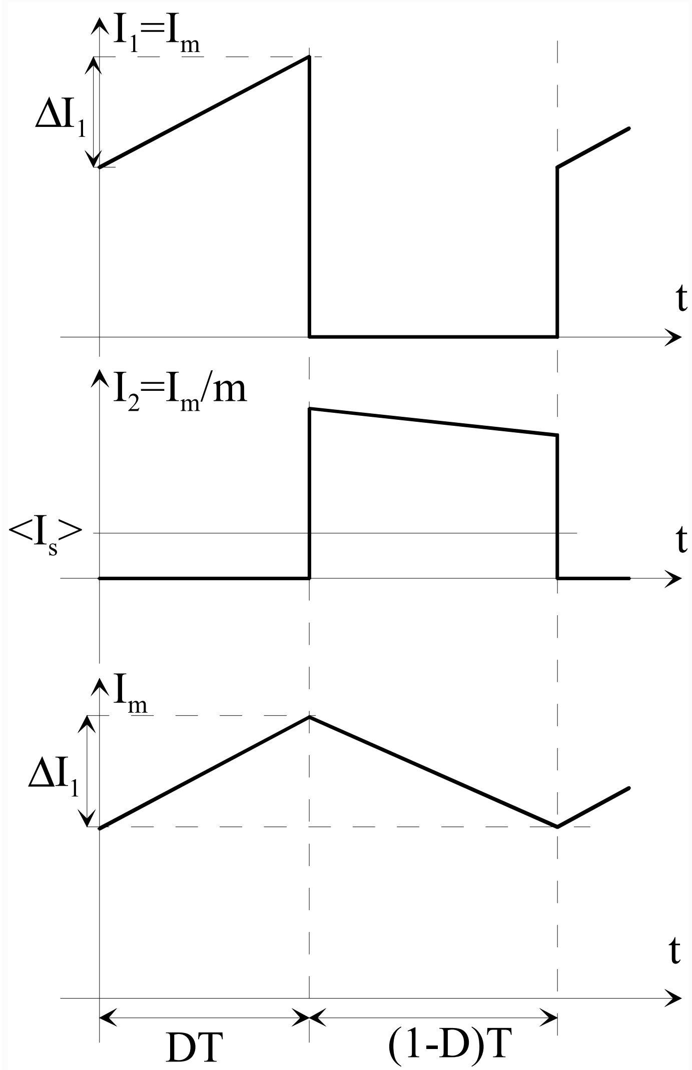
- Flyback:
  - Continuous conduction mode:
    - Voltages and currents waveforms

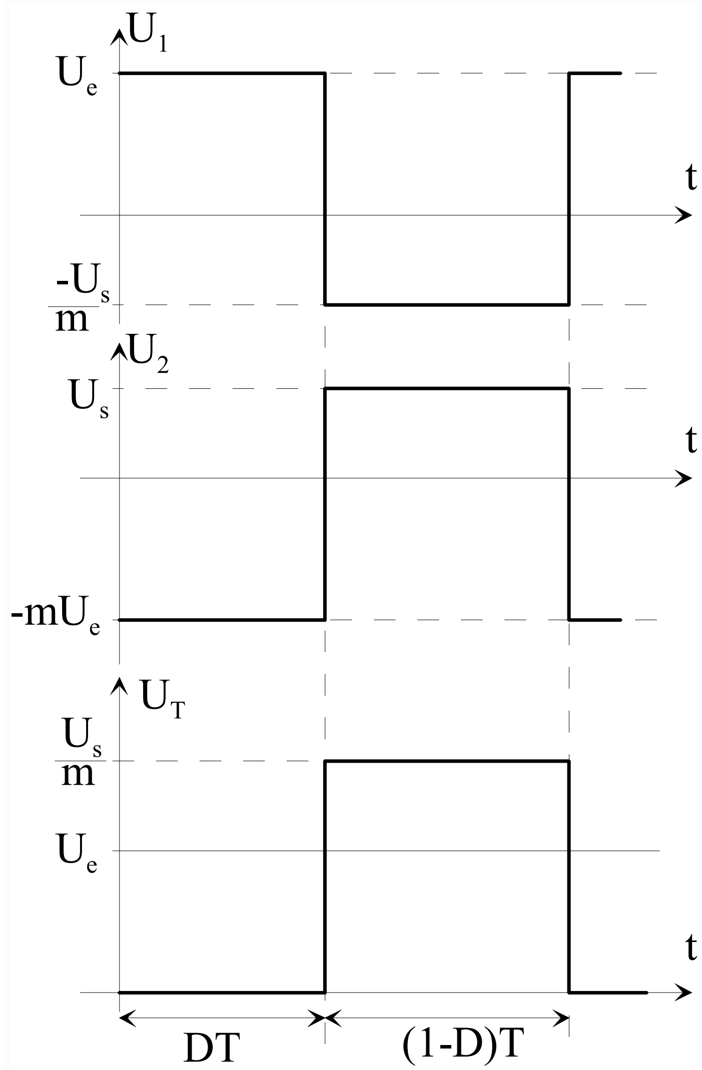
Transistor ON:

Energy is stored into the transformer

Transistor OFF:

Part of the stored energy is transmitted to the output





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DC/DC converters with transformers

- Flyback:
  - Continuous conduction mode:
    - Voltages and currents waveforms

⇒The transistor has to be able to support not only the input voltage but:

$$U_T > U_e + \frac{1}{m} U_s$$

⇒As energy needs to be stored into the transformer, the magnetic circuit can be huge

⇒Strong fluctuations of secondary and primary currents, wit leakage inductances: strong constraints on the components

DC/DC converters with transformers

- Flyback:
  - Continuous conduction mode:
    - Main equations:

⇒Duty cycle D: ratio between transistor conduction time and the switching period

$$D = \frac{t_1}{T}$$

⇒Output voltage

$$U_{so} = \langle U_s \rangle = m \frac{D}{1-D} U_e$$

⇒Current ripple: linked to the magnetization inductance

$$\Delta I_1 = \frac{U_e}{L_M f} D$$

⇒Input and output currents

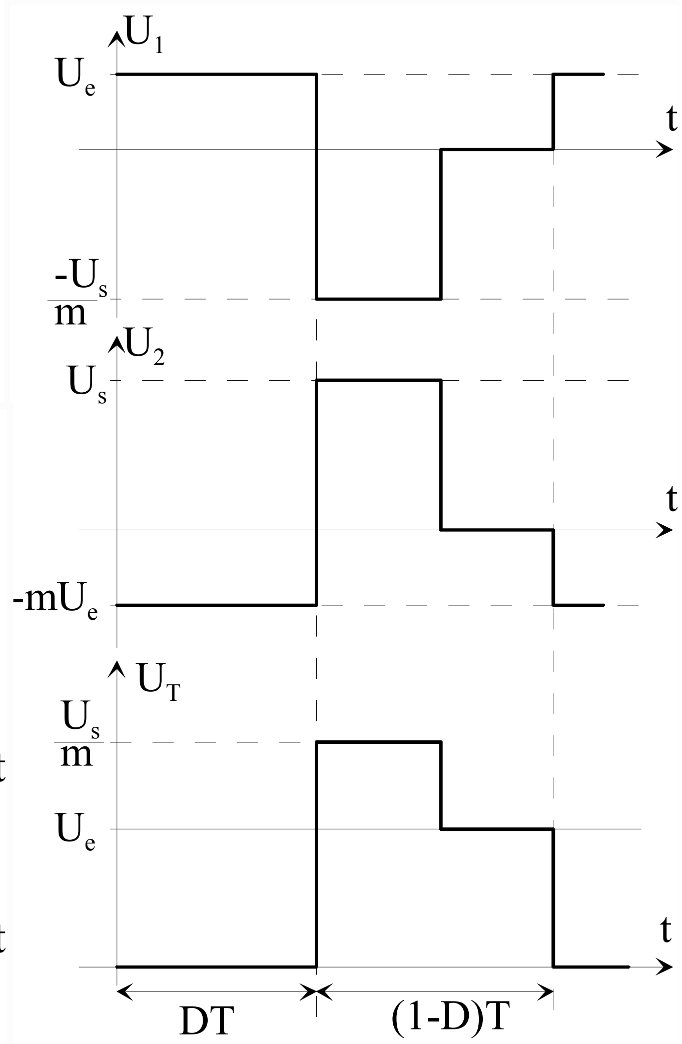
$$\langle I_e \rangle = \frac{D}{1-D} \langle I_s \rangle = \frac{D}{1-D} I_{so}$$

DC/DC converters with transformers

- Flyback:
  - Discontinuous conduction mode:
    - Voltages and currents waveforms

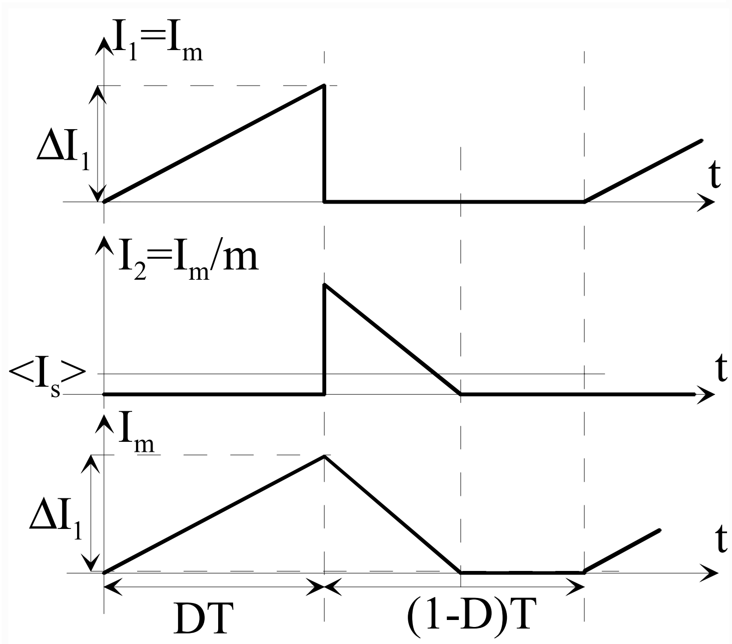
Transistor ON:

Energy is stored into the transformer



Transistor OFF:

Part of the stored energy is transmitted to the output



The demagnetization of the transformer is completed before the ON switching of the transistor

DC/DC converters with transformers

- Flyback:
  - Discontinuous conduction mode:
    - Voltages and currents waveforms

⇒The transistor has to be able to support not only the input voltage but:

$$U_T > U_e + \frac{1}{m} U_s$$

⇒As energy needs to be stored into the transformer, the magnetic circuit can be huge, but less than the case of the continuous conduction mode

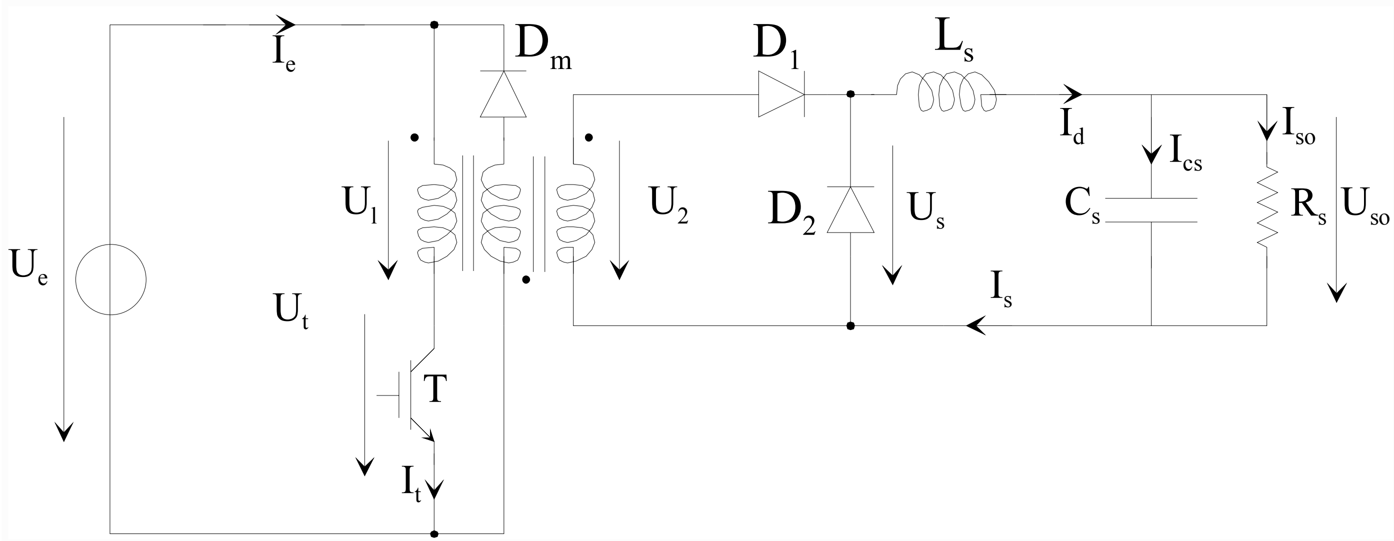
⇒Strong fluctuations of secondary and primary currents, regarding their mean values

⇒The output voltage is no more dependant of the transformation ratio m, but dependent of the load:

$$U_{so} = \langle U_s \rangle = D U_e \sqrt{\frac{R}{2 L_m f}}$$

DC/DC converters with transformers

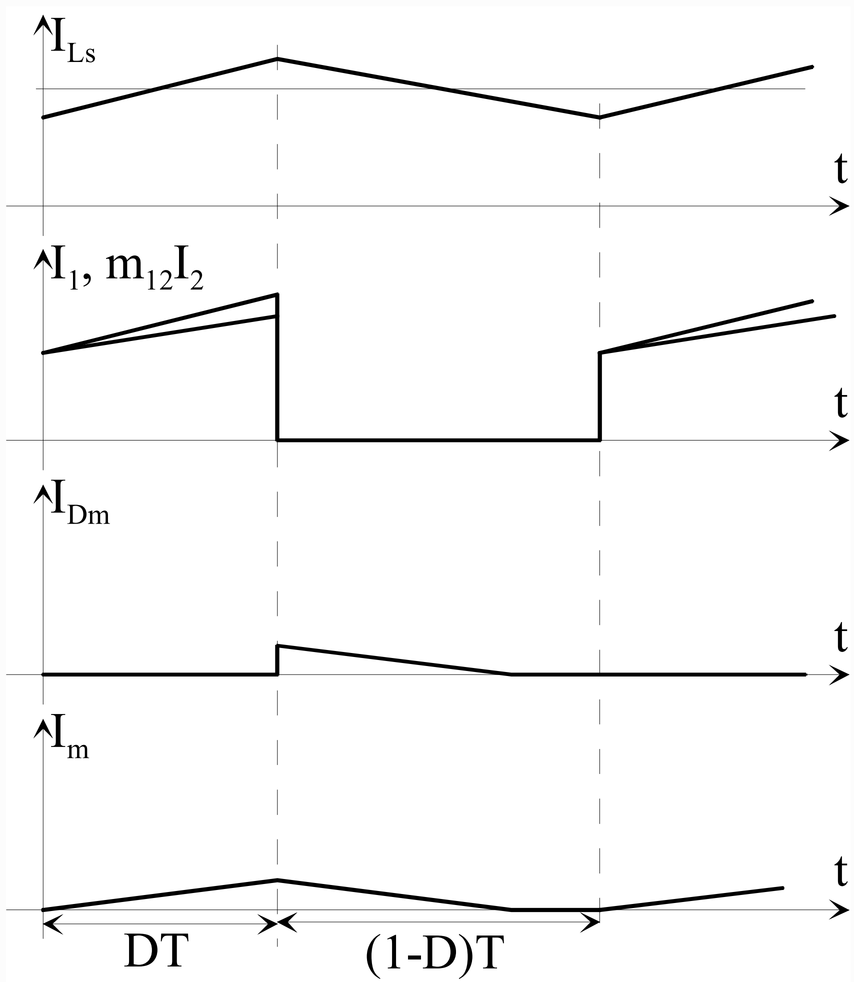
- Forward
  - Converter deduced from the DC/DC Buck converter

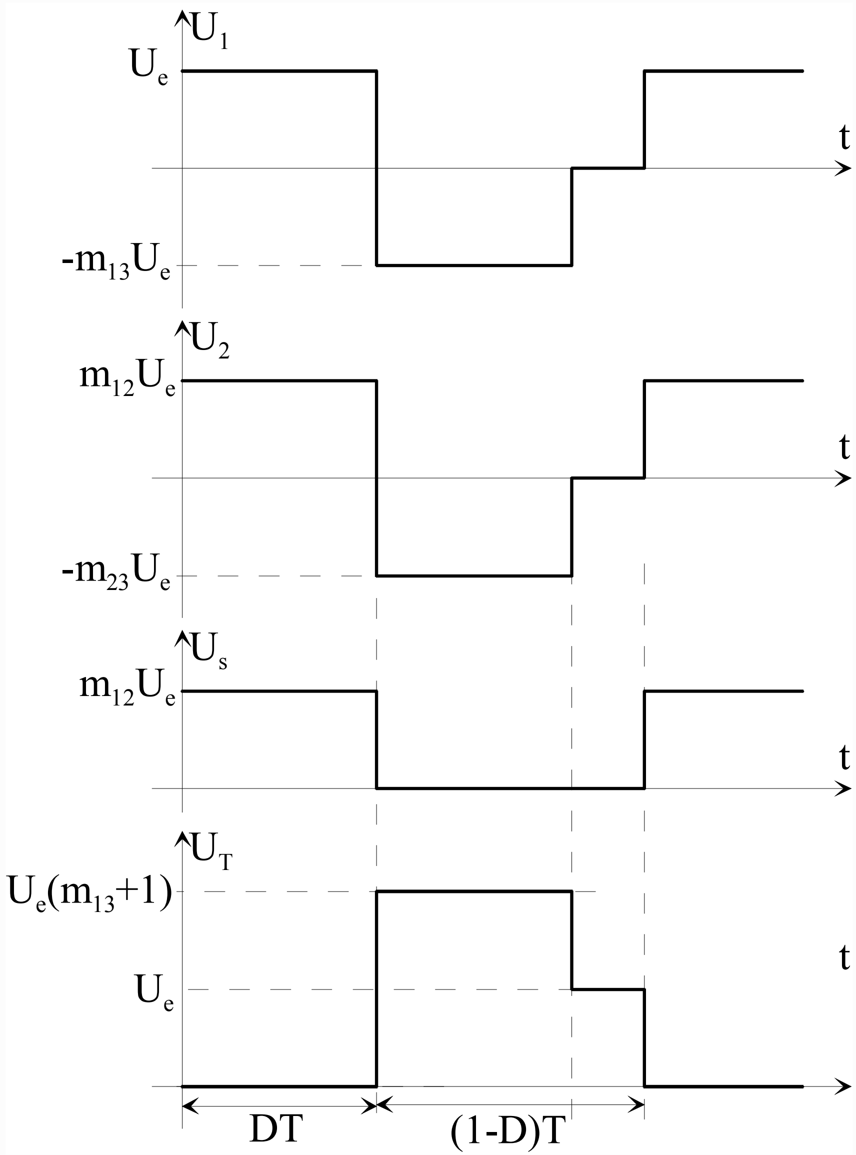


  - Energy flows directly from the primary side to the secondary side of the transformer when the transistor is ON.
  - A third winding is needed to control the magnetization current when the transistor is switched off.
  - From the voltage U_s the behaviour is that one of a buck converter.

DC/DC converters with transformers

- Forward
  - Voltage and current waveforms





DC/DC converters with transformers

- Forward
  - Voltage and current waveforms
    - When the transistor is ON:
      - ⇒The secondary voltage and U_s are $m_{12}U_e$
      - ⇒The primary current is the sum of the secondary current (modulo the ratio m_{12}) and the magnetization current.
    - When the transistor is switched off:
      - ⇒Primary and secondary currents are 0
      - ⇒The demagnetization circuit is ON
      - ⇒Primary and secondary voltages are negative
      - ⇒Transistor voltage is $m_{13}U_e+U_e$
    - When the demagnetization is completed:
      - ⇒Primary and secondary voltages and currents are 0 (free-wheeling mode)
    - Condition for a complete demagnetization of the transformer (before the conduction of the transistor)

$$D < \frac{m_{13}}{1+m_{13}}$$

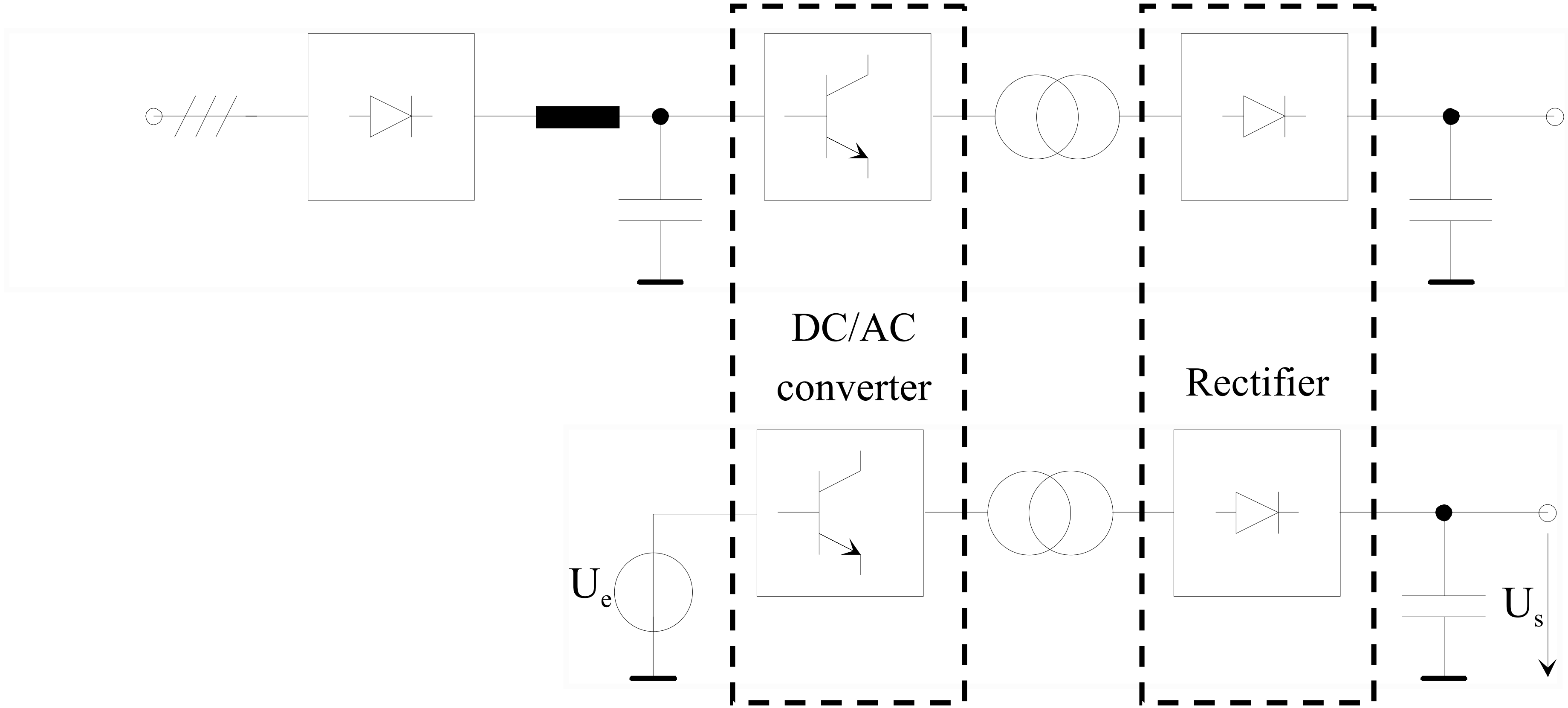
DC/DC converters with transformers

- Forward
  - From the voltage U_s, the behaviour of the forward is close of the buck
    - Limit: leakage inductances, with conduction of both D_1 and D_2 during the commutations of the transistor
    - Output characteristics of identical the the Buck, where the only difference is the factor m_{12} applied to U_e

    - Compared to the flyback, smaller transformer
    - Three windings are needed (more complex)
    - Leakage inductances need to be reduced as possible.

DC/DC converters with transformers

- DC/AC/DC Converters:
  - Principle:
    - Input Rectifier + input filter : voltage source



DC/DC converters with transformers

- DC/AC/DC Converters:
  - Principle:
    - First stage: Voltage inverter

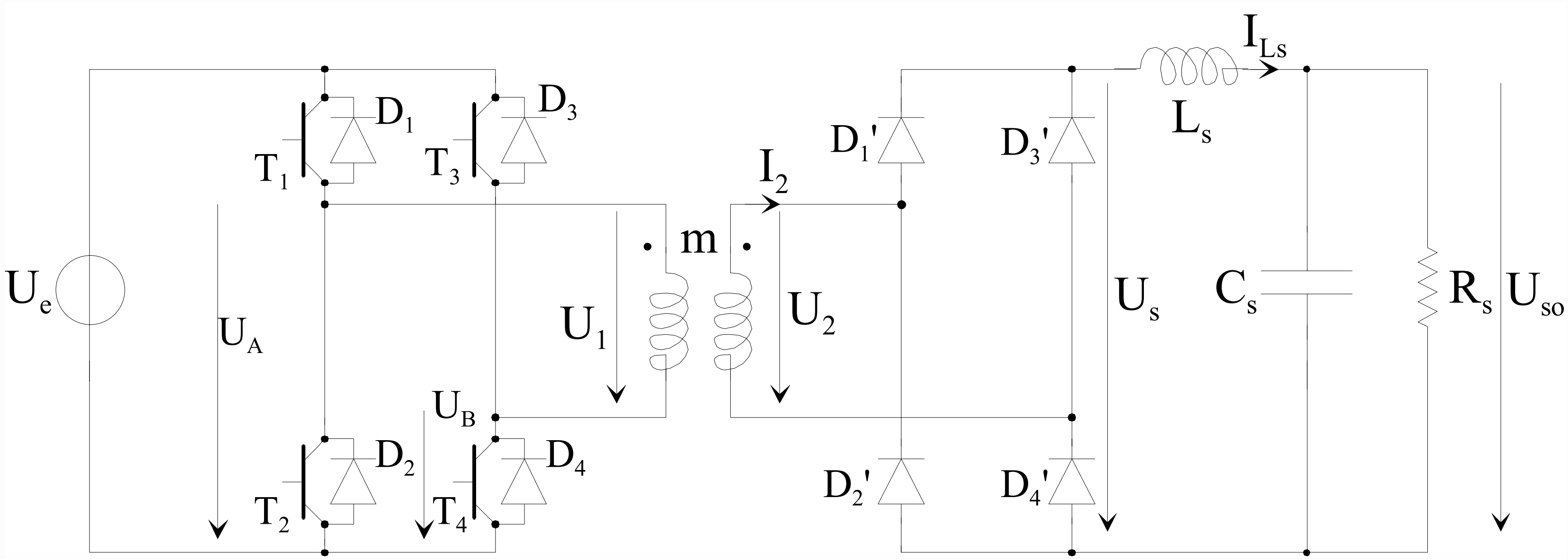
      ⇒Able to manage energy transfer between
      - a DC voltage source : from an input filter (C)
      - an AC current source : the primary side of a transformer
    - Second stage: medium frequency transformer

      ⇒Galvanic insulation, Voltage/current level adaptation
    - Third stage: rectifier

      ⇒Able to manage energy transfer between
      - An AC voltage source (secondary of the transformer. Leakage inductances?)
      - A DC current source
  - 1 quadrant converter:
    - Diodes for the rectifier
    - Output voltage level will be adjusted by the voltage inverter

DC/DC converters with transformers

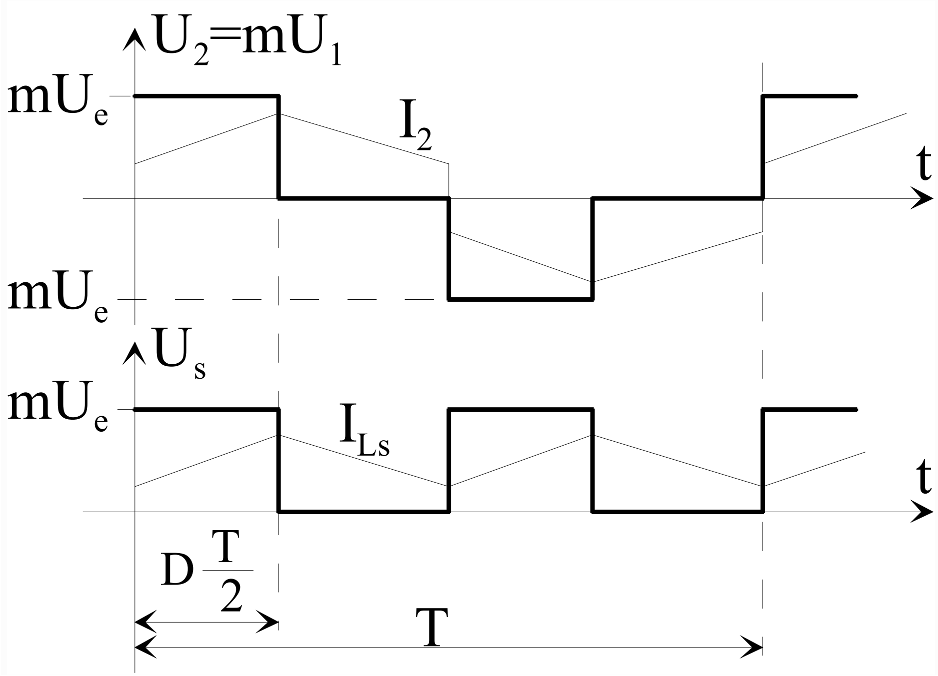
- DC/AC/DC Converters:
  - H-bridge voltage inverter + full H-bridge diode rectifier

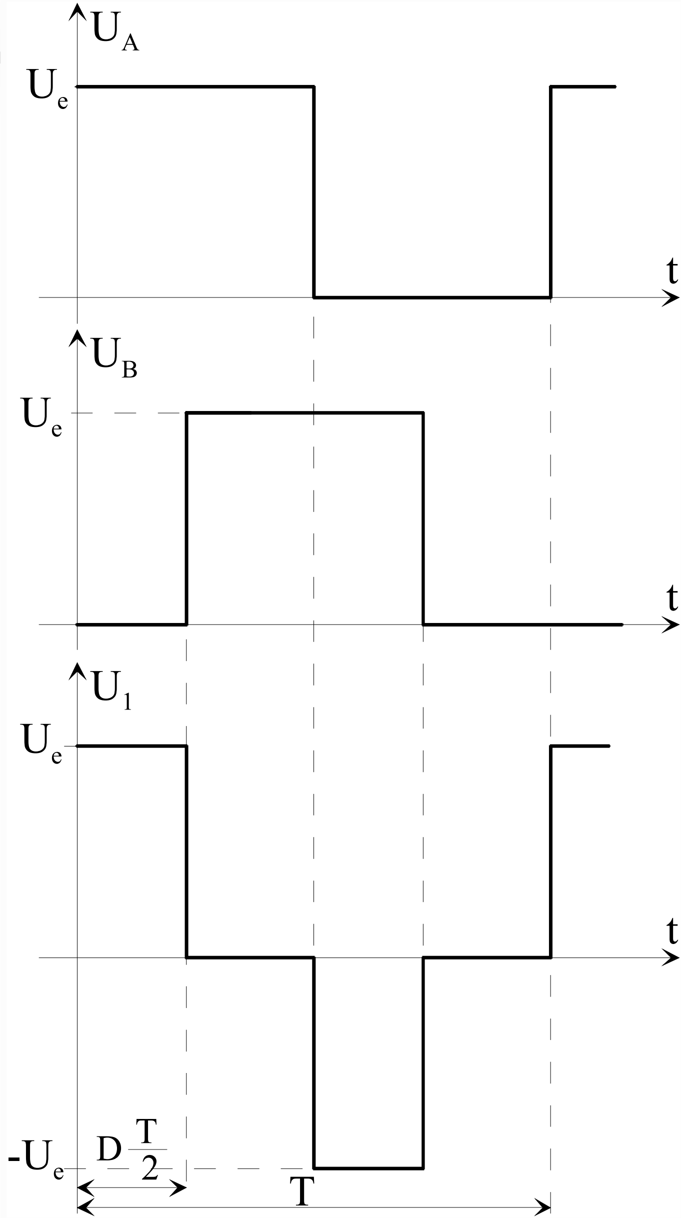


  - Voltage inverter
    - 2 switching cells: (T_1,D_1),(T_2,D_2) and (T_3,D_3),(T_4,D_4)
    - Each switching cell is controlled with the same switching frequency, duty cyle 50%
    - The 2nd switching cell can be phase-shifted from the first one

DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + full H-bridge diode rectifier
    - The duty cycle D defines the time delay between the two switching cells
    - The Width of the positive and negative pulse varies from 0 to T/2 when D varies from 0 to 1





DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + full H-bridge diode rectifier
    - From the voltage U_s, the behaviour is close to that one of a Buck Converter:

⇒Averaged output voltage

$$U_{so} = U_s = mDU_e$$

⇒Current ripple in L_s:

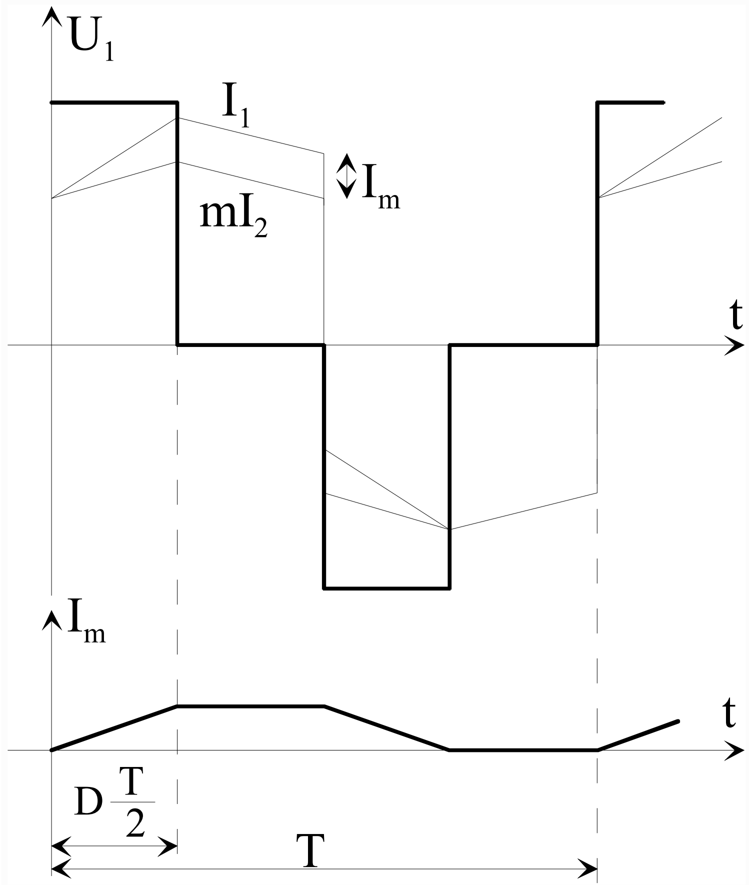
$$\Delta I_{Ls} = \frac{mU_e}{2L_sF}\left(1-D\right)D$$

⇒Averaged output current:

- Defines mainly the magnitude of the AC current in the secondary side of the transformer

DC/DC converters with transformers

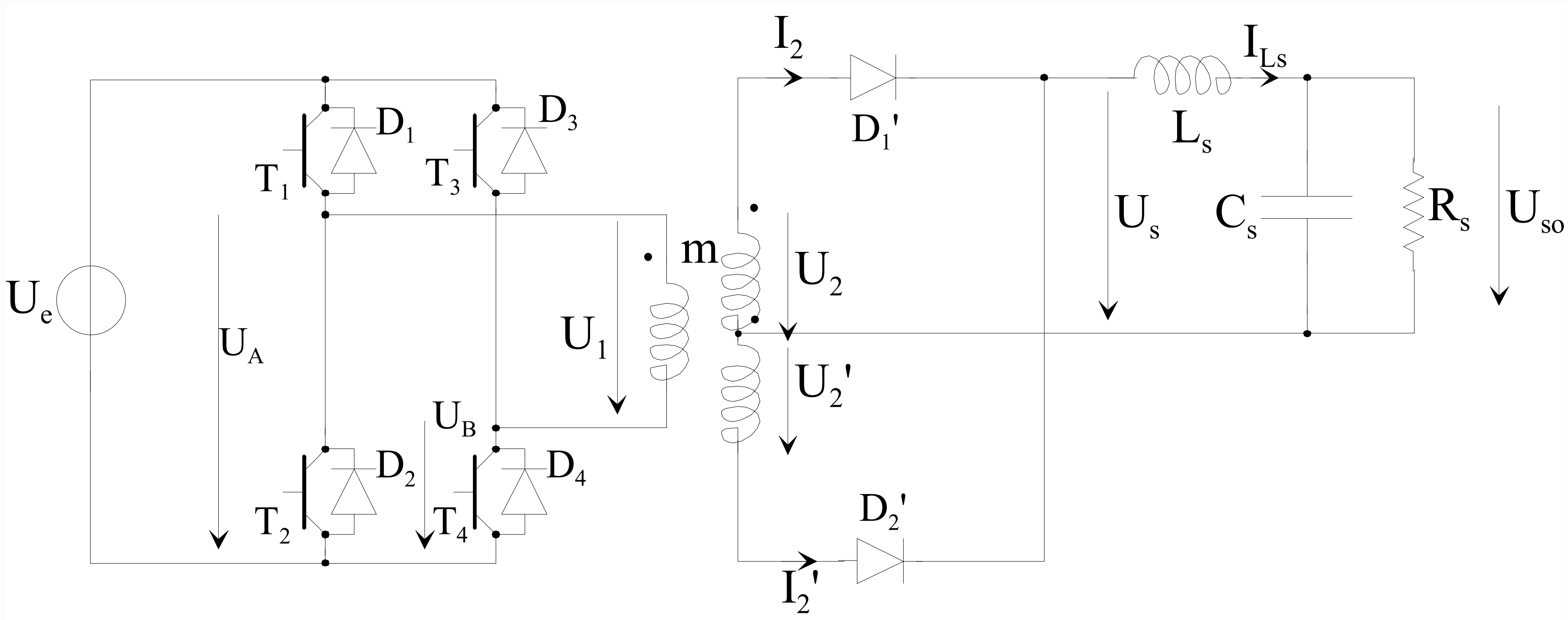
- DC/AC/DC Converters:
  - H-bridge voltage inverter + full H-bridge diode rectifier
    - Transformer Primary side currents



- The mean value of U_1 must be 0 to control the magnetization current of the transformer
  - The width of positive and negative pulse must be identical in one switching period

DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier



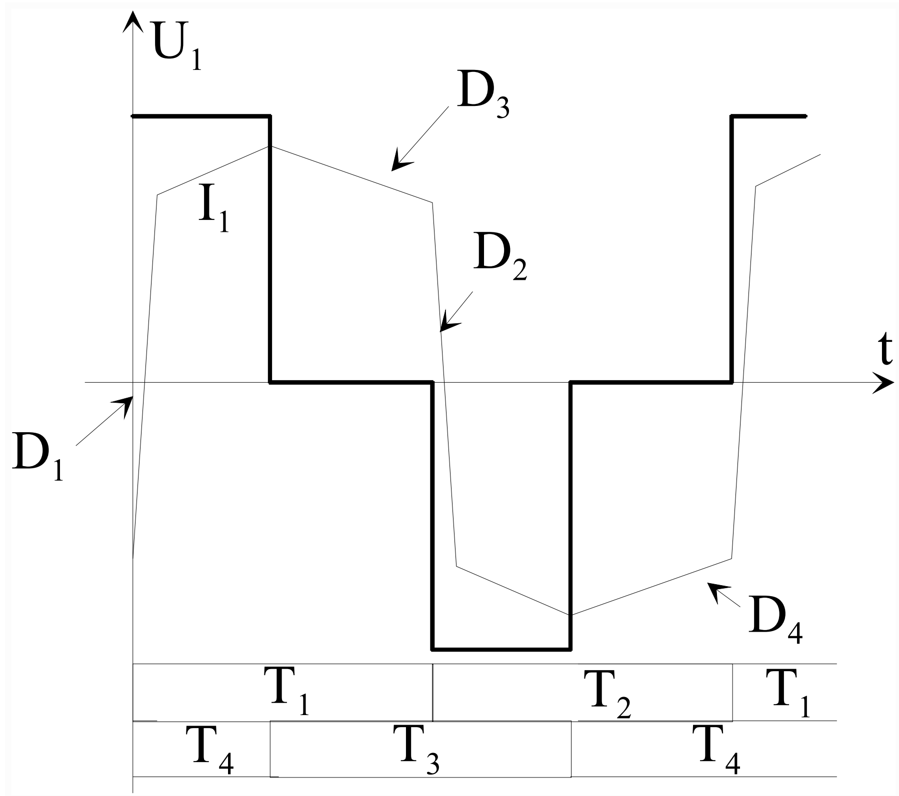
  - Equivalent solution compared to the full-bridge rectifier

DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier:
    - Efficiency:
      - ⇒Conduction losses
      - ⇒Switching losses:
        - Can be reduced if ZVT (Zero Voltage transition) is possible
        - Can be reduced if ZCS (Zero Current switching) is possible
    - Switching process must be analyzed to identify:
      - ⇒If natural ZVT and/or ZCS occur
      - ⇒The devices to add in order to allow ZVT and ZCS

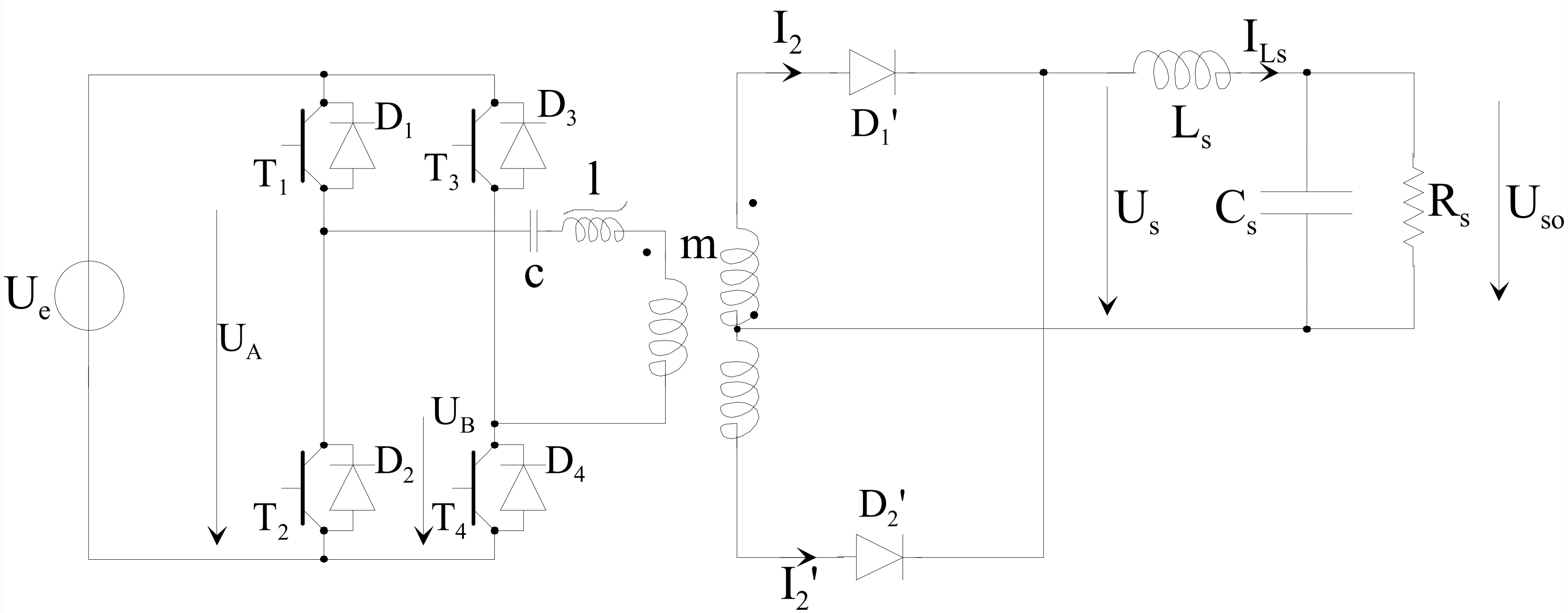
DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier:
    - Taking into account leakage inductances of the transformer
  - switching cells (T_3,D_3),(T_4,D_4) :
    - ZVT thanks to the free-wheeling phase
  - switching cells (T_1,D_1),(T_2,D_2):
    - ZVT only due to the leakage inductances of the transformer



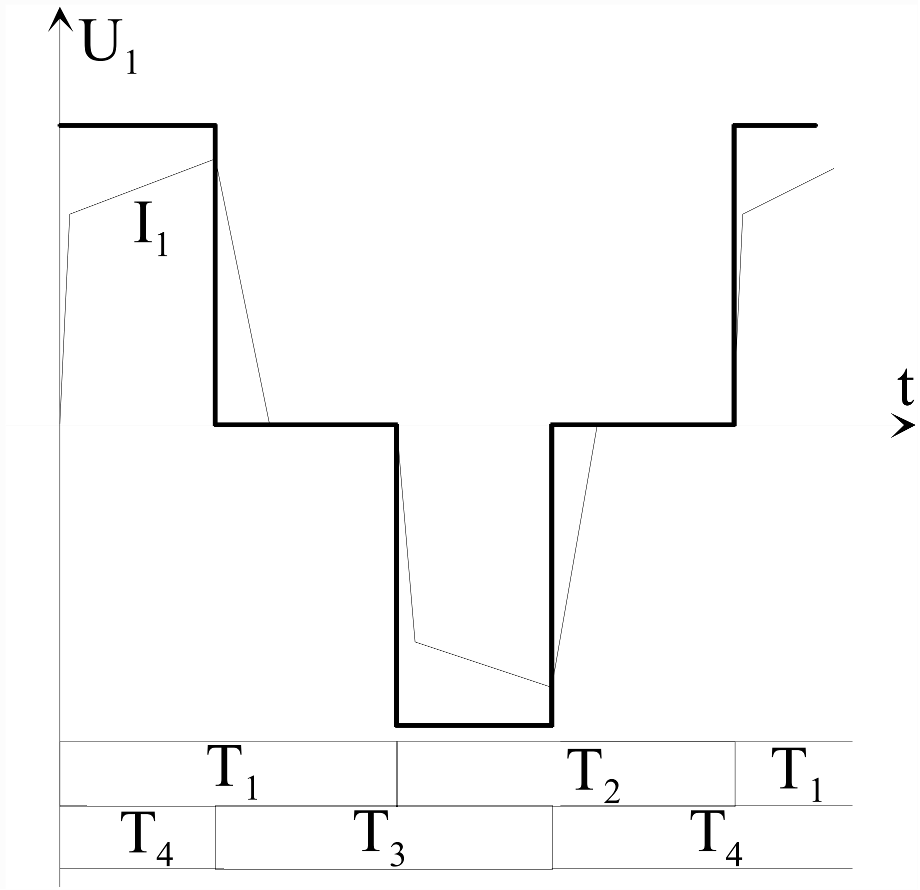
DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier:
    - Adding a dc blocking capacitor and a saturable inductor to allow ZCS conditions



DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier:
    - Adding a dc blocking capacitor and a saturable inductor to allow ZCS conditions
  - switching cells (T_3,D_3),(T_4,D_4) :
    - Each Turn ON of a transistor is made with ZCS and ZVS conditions
    - Each turn OFF of a transistor, capacitors are needed to limit the du/dt
  - switching cells (T_1,D_1),(T_2,D_2) :
    - Each Turn ON of a transistor is made with ZCS conditions
    - Each turn OFF of a transistor is also made with ZCS conditions



DC/DC converters with transformers

- DC/AC/DC Converters:
  - H-bridge voltage inverter + diode rectifier:
    - Adding a dc blocking capacitor and a saturable inductor to allow ZCS conditions

      ⇒Reduction of switching losses,

      ⇒Components such as IGBTs can be used

      ⇒High voltage, high power applications.