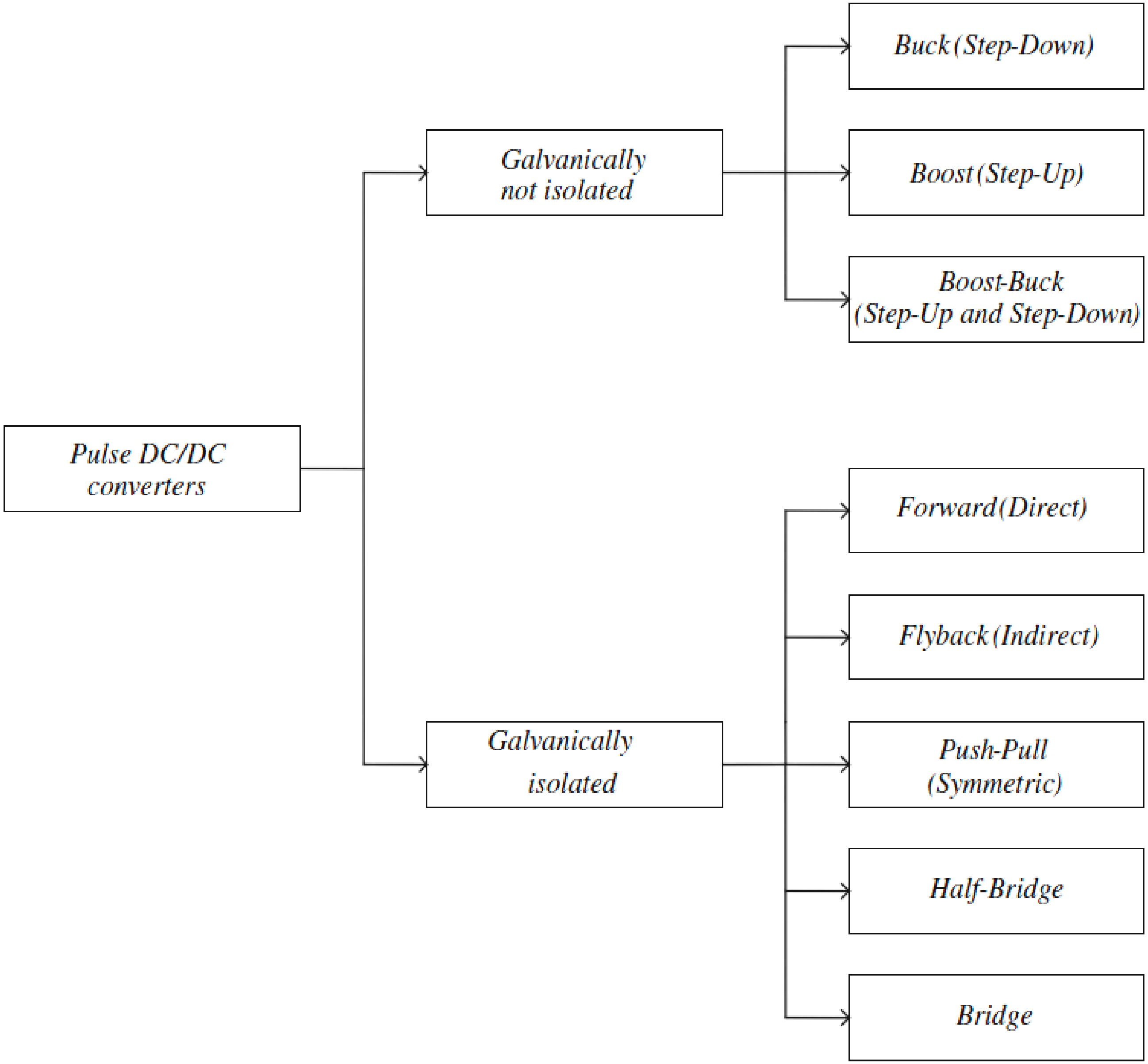
KOM3560
INDUSTRIAL ELECTRONICS

Spring : 2023

Lecture 4

DC Choppers – DC 2 DC Converters

Classification of pulse DC/DC converters according to the topology of the basic circuit;

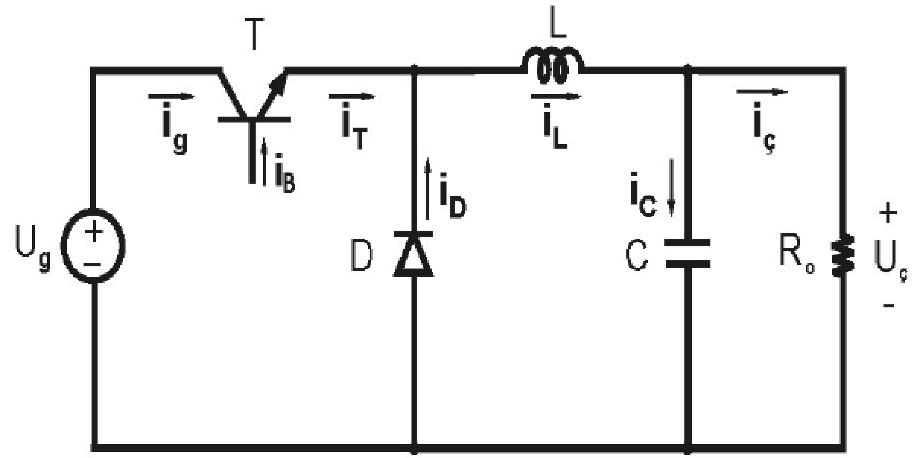


THE BUCK (STEP-DOWN) CONVERTER

$$\lambda = \frac{T_1}{T_P} = \frac{I_T}{I_L}, \qquad f_P = \frac{1}{T_P}$$

$$T_1 = \lambda T_P, \quad T_2 = (1-\lambda)T_P$$
$$I_T = \lambda I_L, \quad I_D = (1-\lambda)I_L$$

f_p : Anahtarlama (Darbe) Frekansı
λ : Bağıl İletim Süresi



i_L : Sürekli, kesintisiz
$U_g, U_ç$ ve $I_ç$: Sabit

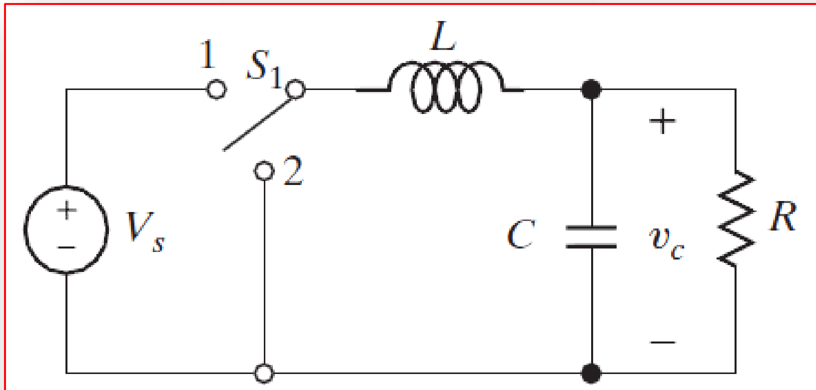
Assumptions

$\lambda = 2/3$ için,

U_g ve $I_ç$: 3 birim
$U_ç$ ve I_g : 2 birim

$$I_L = I_Ç$$
$$U_ç = \lambda U_g$$
$$I_g = \lambda I_ç$$

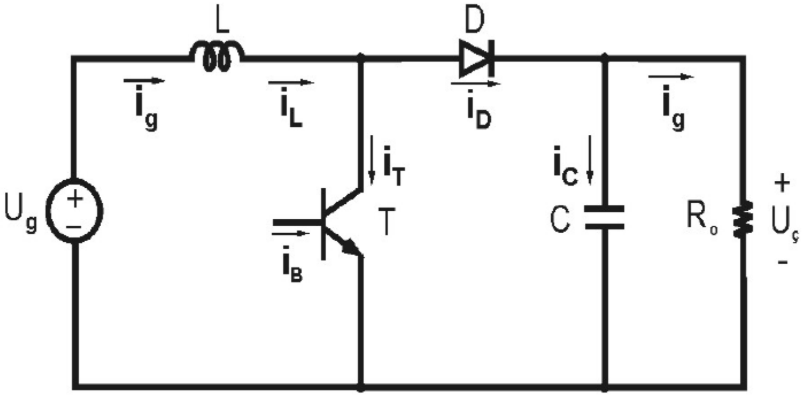
General definitons



(b) Switch representation

3/18/2023

THE BOOST CONVERTER



Output voltage

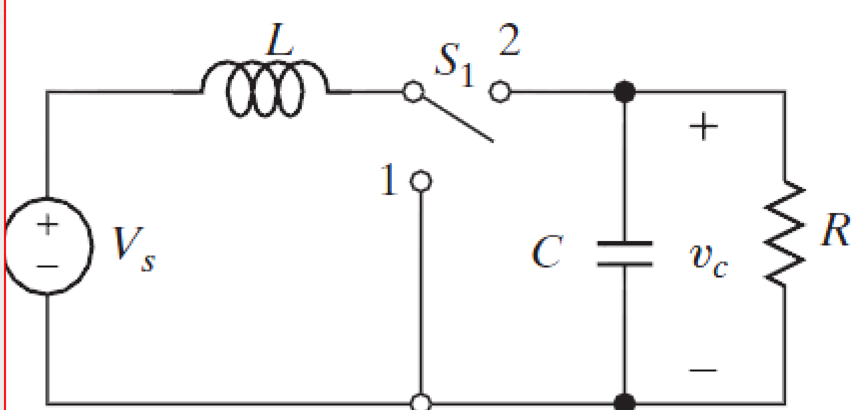
$$U_ç = \frac{1}{1-\lambda} U_g$$

Input current

$$I_g = \frac{1}{1-\lambda} I_ç$$

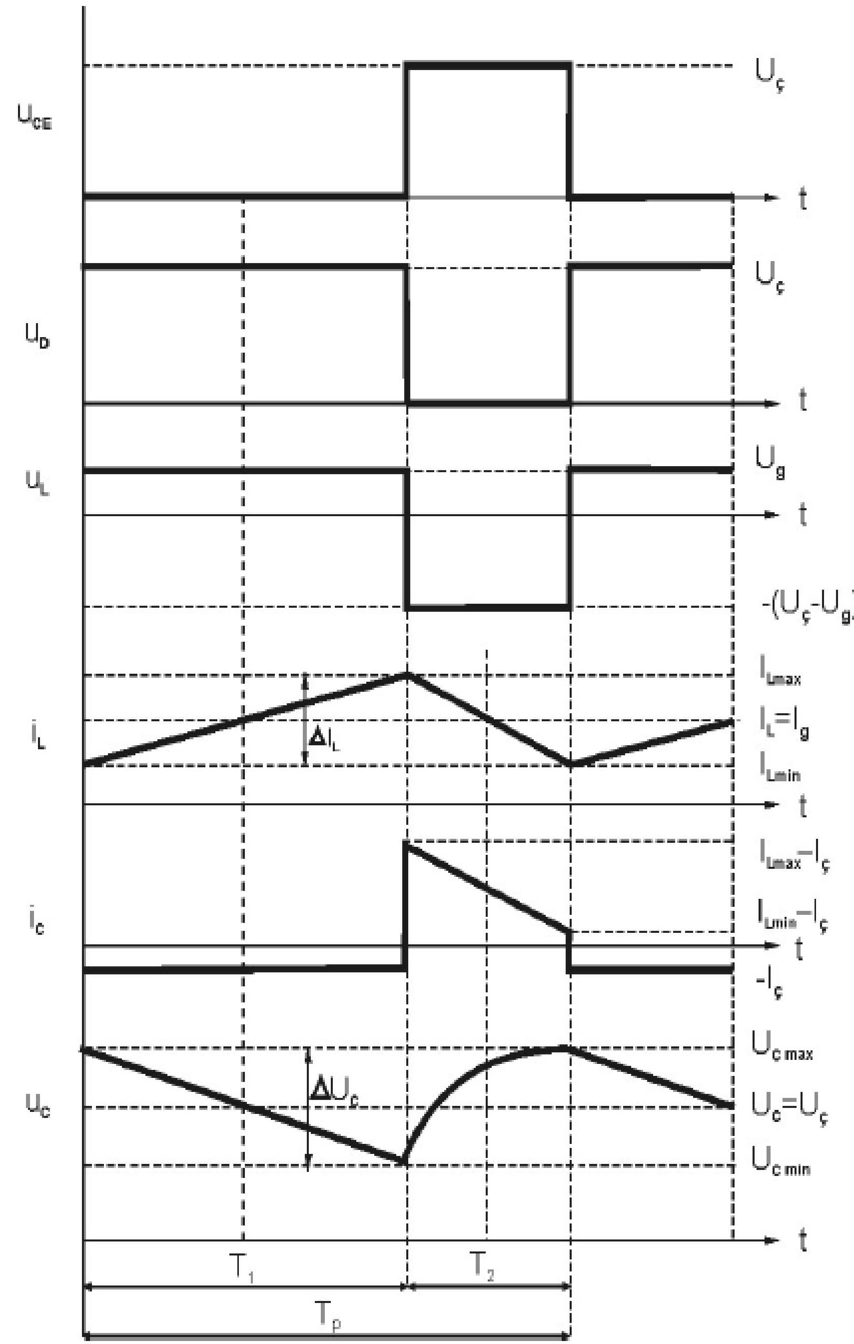
$$\Delta I_{L\,max} = \frac{V_ç}{4 f_p L}$$

$$\Delta V_C = \frac{\lambda I_ç}{f_p C}$$

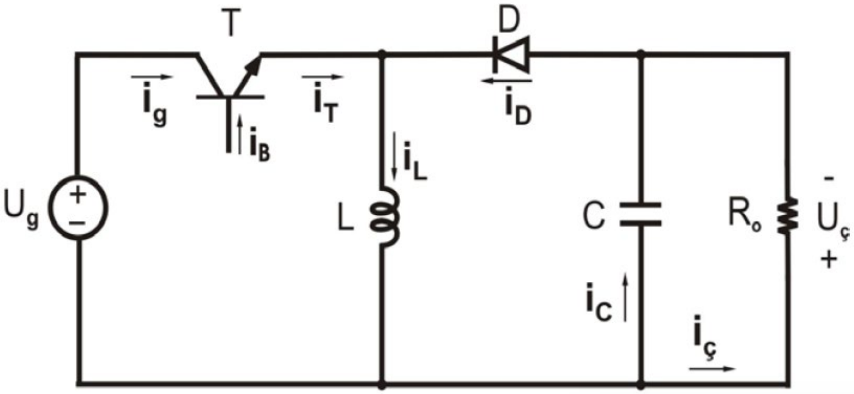


(b) Switch representation

λ=2/3 için Temel Dalga Şekilleri



THE BUCK-BOOST CONVERTER



Assumptions

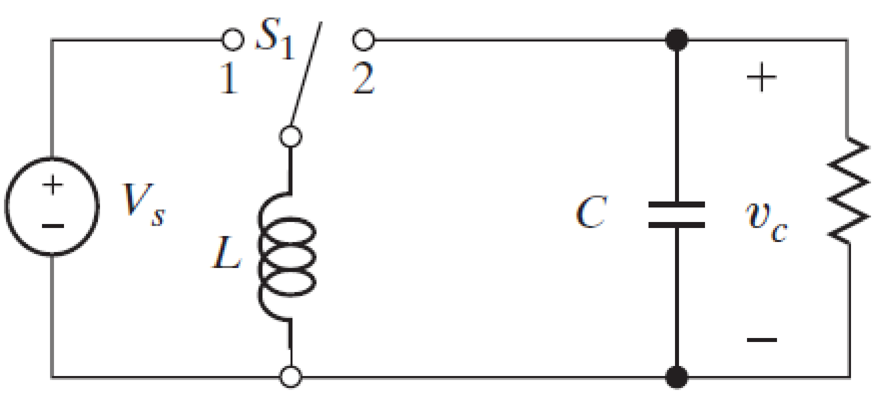
i_L : Sürekli, kesintisiz

$U_g, U_ç$ ve $I_ç$: Sabit

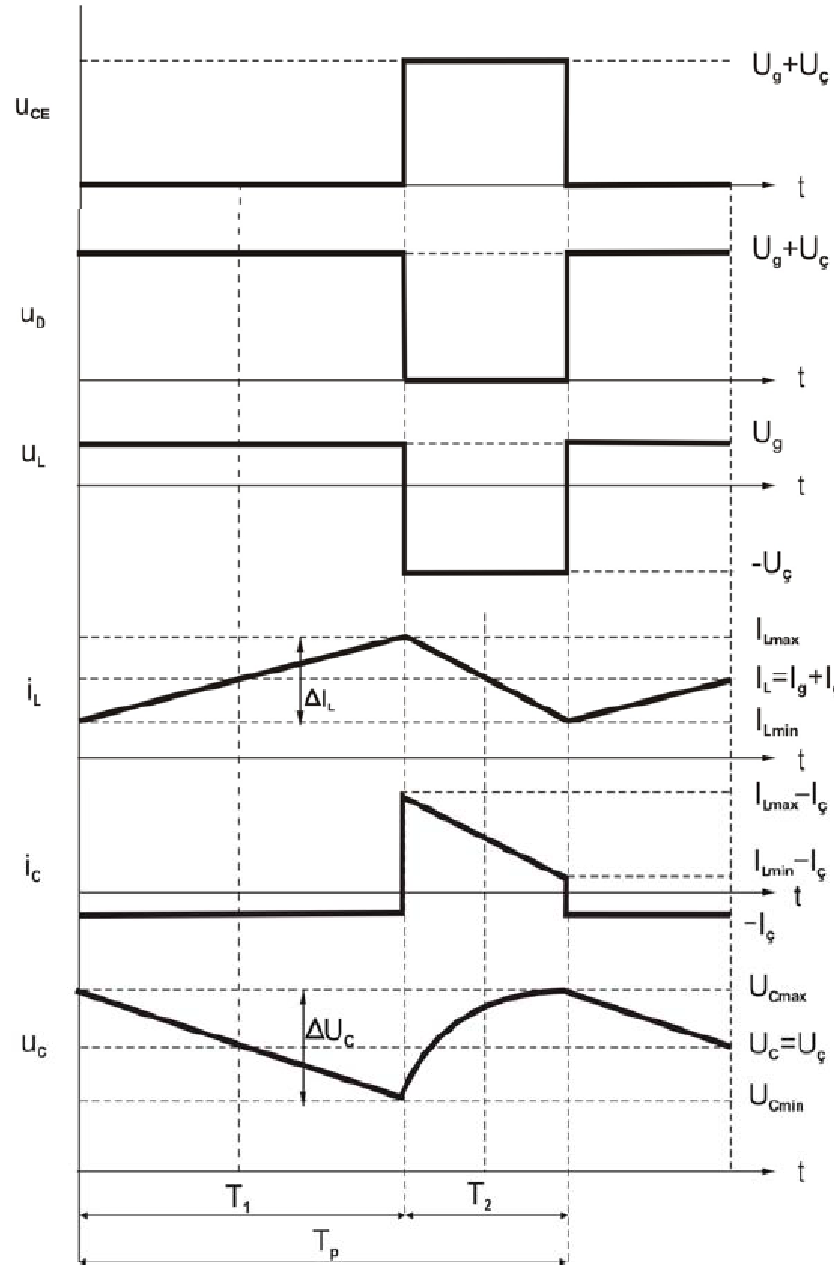
$$I_L = I_g + I_ç$$

$$U_ç = \frac{\lambda}{1-\lambda} U_g$$

$$I_g = \frac{\lambda}{1-\lambda} I_ç$$



(b) Switch representation



THE COMPARISON of BUCK BOOST CONVERTERs

Karşılaştırma Konusu	Düşürücü	Yükseltici	Düşürücü - Yükseltici
T_1 aralığında çalışma	V_i çıkışı besler. V_i, L'ye ilave bir enerji enjekte eder.	V_i, L'ye ilave bir enerji enjekte eder. C yükü besler.	V_i, L'ye ilave bir enerji enjekte eder. C yükü besler.
T_2 aralığında çalışma	L'deki ilave enerji çıkışa aktarılır.	V_i çıkışı besler. L'deki ilave enerji çıkışa aktarılır.	L'deki ilave enerji çıkışa aktarılır.
V_o çıkış gerilimi	λV_i	$\frac{1}{1-\lambda}V_i$	$\frac{\lambda}{1-\lambda}V_i$
I_i giriş akımı	λI_o	$\frac{1}{1-\lambda}I_o$	$\frac{\lambda}{1-\lambda}I_o$
V_o kontrol aralığı	0 ile V_i	V_i ile V_{omax}	- (0 ile V_{omax})
Güç elemanlarının maruz kaldığı gerilim	V_i	V_o	$V_i + V_o$
I_L endüktans akımı	I_o	I_i	$I_i + I_o$
I_i'deki dalgalanma	Büyük	Çok küçük	Büyük
I_o'daki dalgalanma	Çok küçük	Büyük	Büyük
V_o'daki dalgalanma	Çok küçük	Büyük	Büyük
V_o'ın yönü	Pozitif	Pozitif	Negatif
Boşta çalışma özelliği	Var	Yok	Yok

Example:

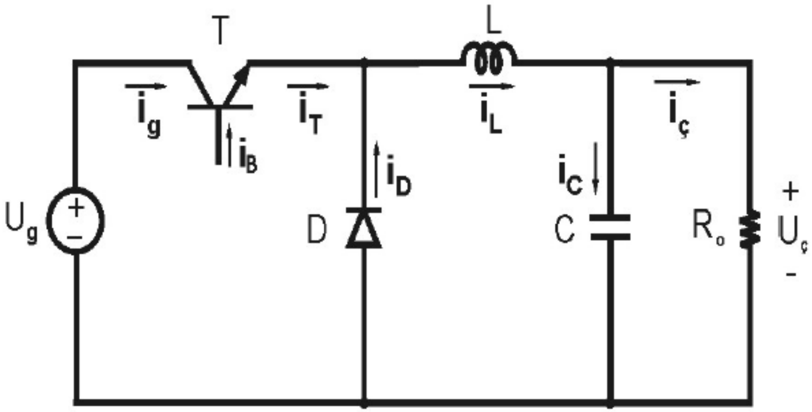
Consider a buck converter with the following circuit parameters; $U_g = 30V, f = 50kHz, I_ç = 1A$. Additionally, voltage drop across BJT and Diode in conduction mode are defined as $U_{CEsat} = 0,4V \; and \; U_D = 0,6V$

a) Derive the expression between the input and output currents in terms of duty cycle
b) Sketch the inductance current and voltage respectively for $\lambda = 1/2$ by ignoring voltage drop of power switching components and find the output voltage in terms of duty cycle and the input voltage
c) Without ignoring voltage drop of power switching components perform (b) again
d) Under ideal operating conditions, calculate duty cycle, input current and efficiency of the converter
e) Under practical operating conditions including component losses, calculate duty cycle, input current and efficiency of the converter

Example:

buck converter with $U_g = 30V, f = 50kHz, I_ç = 1A.\ U_{CEsat} = 0{,}4V \text{ and } U_D = 0{,}6V$

a) Derive the expression between the input and output currents in terms of duty cycle



$$I_L = I_T + I_D$$
$$I_T = \lambda . I_L$$
$$I_D = (1-\lambda).I_L$$
$$T_p = T_1 + T_2$$
$$T_1 = \lambda . T_p$$
$$T_2 = (1-\lambda).T_p$$
$$\lambda = \frac{T_1}{T_p} = \frac{I_T}{I_L}$$

General equations for DC-DC converters

For buck converter

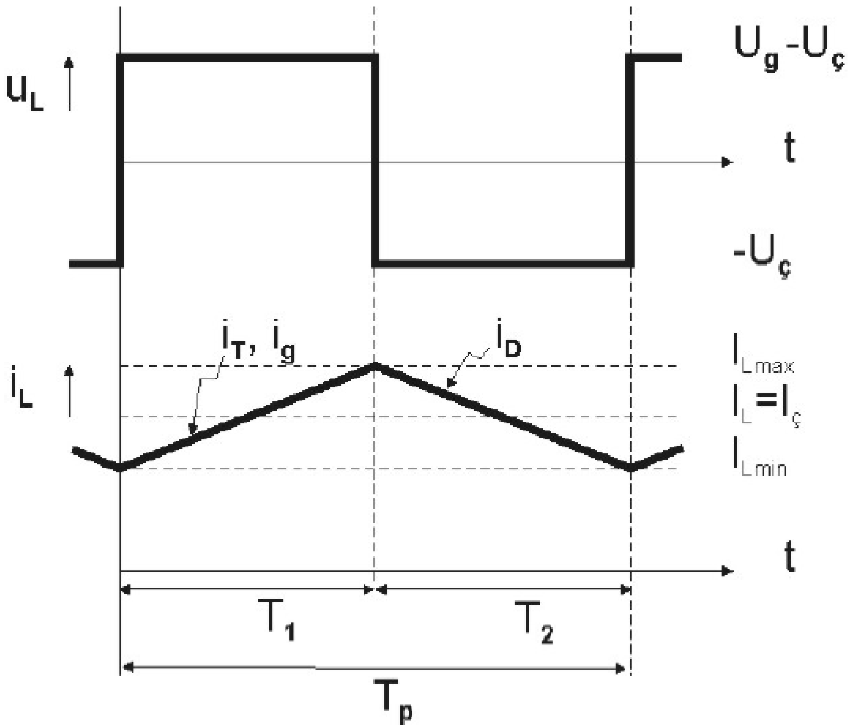
$$I_L = I_Ç$$
$$I_T = I_g$$

$$I_L = I_T + I_D$$
$$I_Ç = I_g + (1-\lambda).I_ç$$
$$I_Ç = I_Ç - \lambda.I_ç - I_Ç$$
$$I_g = \lambda.I_ç$$

Example:

buck converter with $U_g = 30V, f = 50kHz, I_ç = 1A$. $U_{CEsat} = 0{,}4V$ and $U_D = 0{,}6V$

a) Sketch the inductance current and voltage respectively for $\lambda=1/2$ by ignoring voltage drop of power switching components and find the output voltage in terms of duty cycle and the input voltage



From the equality of (+) and (-) wave form

$$T_1(U_g - U_Ç) = T_2 U_Ç$$

$$\lambda T_P (U_g - U_Ç) = (1-\lambda) T_P U_Ç$$

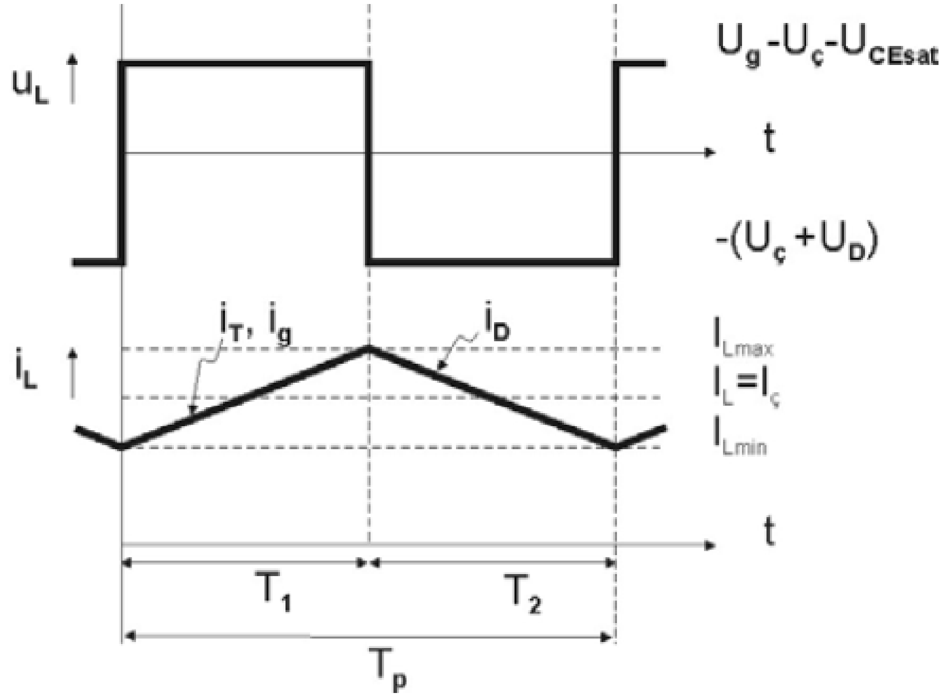
$$\lambda U_g - \lambda U_Ç = U_Ç - \lambda U_Ç$$

$$U_Ç = \lambda U_g$$

Example:

buck converter with $U_g = 30V, f = 50kHz, I_ç = 1A$. $U_{CEsat} = 0{,}4V$ and $U_D = 0{,}6V$

a) Without ignoring voltage drop of power switching components perform (b) again



From the equality of (+) and (-) wave form

$$T_1(U_g - U_Ç - U_{CEsat}) = T_2(U_Ç + U_D)$$

$$\lambda U_g - \lambda U_Ç - \lambda U_{CEsat} = U_Ç + U_D - \lambda U_Ç - \lambda U_D$$

$$U_Ç = \lambda(U_g - U_{CEsat} + U_D) - U_D$$

Example:

buck converter with $U_g = 30V, f = 50kHz, I_ç = 1A.\ U_{CEsat} = 0{,}4V\ and\ U_D = 0{,}6V$

a) Under ideal operating conditions, calculate duty cycle, input current and efficiency of the converter

$$U_ç = \lambda U_g$$
$$15 = \lambda 30$$
$$\lambda = 1/2$$
$$I_g = \lambda I_ç$$
$$I_g = \frac{1}{2} 1$$
$$I_g = 0{,}5\ A$$

$$\eta = \frac{P_ç}{P_g} = \frac{U_ç I_ç}{U_g I_g} = \frac{15.1}{30.0{,}5}$$

$$\eta = 1 \Rightarrow \%100$$

Example:

buck converter with $U_g = 30V, f = 50kHz, I_ç = 1A.\ U_{CEsat} = 0{,}4V\ and\ U_D = 0{,}6V$

a) Under practical operating conditions including component losses, calculate duty cycle, input current and efficiency of the converter

$$15 = \lambda (U_g - U_{CEsat} + U_D) - U_D$$

$$15 = \lambda (30 - 0{,}4 + 0{,}6) - 0{,}6$$

$$\Rightarrow \lambda \cong 0{,}517$$

$$I_g = \lambda I_ç$$

$$= 0{,}517.1$$

$$I_g = 0{,}517\ A$$

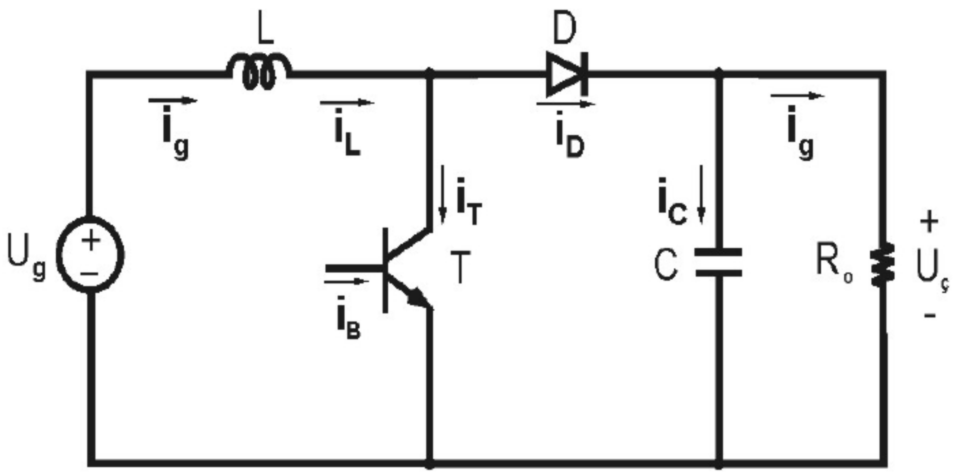
$$\eta = \frac{P_ç}{P_g} = \frac{U_ç I_ç}{U_g I_g} = \frac{15.1}{30.0{,}517}$$

$$\eta \cong 0{,}967 \quad \Rightarrow \%96{,}7$$

Example:

Consider a boost converter with the following circuit parameters; $U_g = 12V, f = 100kHz, I_ç = 1A\ and\ U_ç = 60.$

a) Find the input current, currents flowing through the power switching devices and the duty cycle
b) Find average value of the currents in conduction intervals of the power switching devices
c) Determine the duty cycle value and corresponding input current
d) Calculate the required inductance and capacitance values If 10% fluctuation in inductance current and 1% fluctuation in output voltage is allowed



Example:

Consider a boost converter with the following circuit parameters; $U_g = 12V, f = 100kHz, I_ç = 1A\ and\ U_ç = 60.$

a) Find the input current, currents flowing through the power switching devices and the duty cycle

If the losses on the components are ignored

$$P_g = P_Ç$$

$$U_g . I_g = U_Ç . I_Ç$$

$$12.I_g = 60.1$$

$$\Rightarrow \quad I_g = 5\ A$$

In boost converter;

$$I_L = I_g \text{ ve } I_D = I_Ç$$

$$I_L = I_g = 5\ A$$

$$I_D = I_Ç = 1\ A$$

$$I_L = I_T + I_D$$

$$I_T = \lambda . I_L$$

$$I_D = (1-\lambda) . I_L$$

$$T_p = T_1 + T_2$$

$$T_1 = \lambda . T_p$$

$$T_2 = (1-\lambda) . T_p$$

$$\lambda = \frac{T_1}{T_p} = \frac{I_T}{I_L}$$

$$I_L = I_T + I_D$$

$$I_T = \lambda . I_L$$

$$I_D = (1-\lambda) . I_L$$

$$I_L = I_T + I_D$$

$$5 = I_T + 1$$

$$\Rightarrow \quad I_T = 4\ A$$

$$I_T = \lambda . I_L$$

$$4 = \lambda . 5$$

$$\Rightarrow \quad \lambda = 4/5 = 0{,}8$$

Example:

Consider a boost converter with the following circuit parameters; $U_g = 12V, f = 100kHz, I_ç = 1A \ and \ U_ç = 60.$

a) Find average value of the currents in conduction intervals of the power switching devices

$$I_{T_{T1}} = I_{D_{T1}} = I_L \Longrightarrow I_{T_{T1}} = I_{D_{T1}} = I_L = 5 \text{ A}$$

b) Determine the duty cycle value and corresponding input current

$$U_Ç = 60 \text{ V}$$

$$U_g = 12 \text{ V}$$

$$U_Ç = \frac{1}{1-\lambda} U_g$$

$$60 = \frac{1}{1-\lambda} 12$$

$$60 - 60\lambda = 12$$

$$60\lambda = 48$$

$$\Rightarrow \lambda = \frac{48}{60} = \frac{4}{5} = 0{,}8$$

$$I_Ç = 1 \text{ A}$$

$$I_g = \frac{1}{1-\lambda} I_Ç = \frac{1}{1-0{,}8} 1$$

$$I_g = 5 \text{ A}$$

Example:

Consider a boost converter with the following circuit parameters; $U_g = 12V, f = 100kHz, I_ç = 1A\ and\ U_ç = 60.$

a) Calculate the required inductance and capacitance values If 10% fluctuation in inductance current and 1% fluctuation in output voltage is allowed

$$f_P = 100\ \text{kHZ}$$

$$T_P = \frac{1}{f_P} = \frac{1}{100.10^3}$$

$$T_P = 10\ \mu s$$

$$T_1 = \lambda . T_P = 0{,}8.10.10^{-6}$$

$$T_1 = 8\ \mu s$$

$$\frac{\Delta I_L}{I_L} = \frac{10}{100}\ \text{ve}\ \frac{\Delta U_C}{U_C} = \frac{1}{100}$$

$$\frac{\Delta I_L}{5} = \frac{10}{100}$$

$$\Rightarrow \Delta I_L = 0{,}5\ A$$

$$\frac{\Delta U_C}{U_C} = \frac{1}{100}$$

$$\Rightarrow \Delta U_C = 0{,}6\ V$$

$$\Delta I_L = \frac{U_g}{L} T_1$$

$$0{,}5 = \frac{12}{L} 8.10^{-6}$$

$$\Rightarrow L = 192\ \mu H$$

$$C.\Delta U_c = I_c.\Delta t$$

$$C.0{,}6 = 1.8.10^{-6}$$

$$\Rightarrow C = 13{,}33\ \mu F$$

Electrical isolation requirement

- A basic disadvantage of the dc-dc converters (buck, boost etc.) is the electrical connection between the input and the output.

- If the input supply is grounded, that same ground will be present on the output.

- A way to isolate the output from the input electrically is with a transformer.

- If the dc-dc converter has a first stage that rectifies an ac power source to dc, a transformer could be used on the ac side.

- However, not all applications require ac to dc conversion as a first stage.

- Moreover, a transformer operating at a low frequency (50 or 60 Hz) requires a large magnetic core and is therefore relatively large, heavy, and expensive.

Electrical isolation requirement

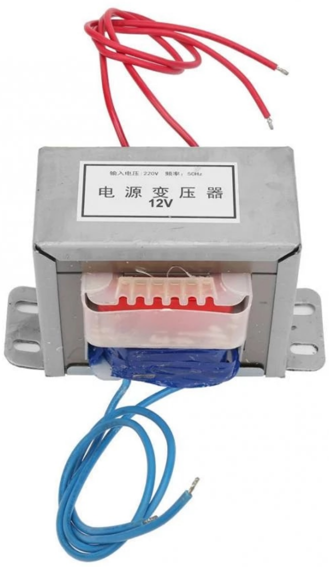
- A more efficient method of providing electrical isolation between input and output of a dc-dc converter is to use a transformer in the switching scheme.

- The switching frequency is much greater than the ac power-source frequency, enabling the transformer to be small.

- Additionally, the transformer turns ratio provides increased design flexibility in the overall relationship between the input and the output of the converter.

- With the use of multiple transformer windings, switching converters can be designed to provide multiple output voltages.

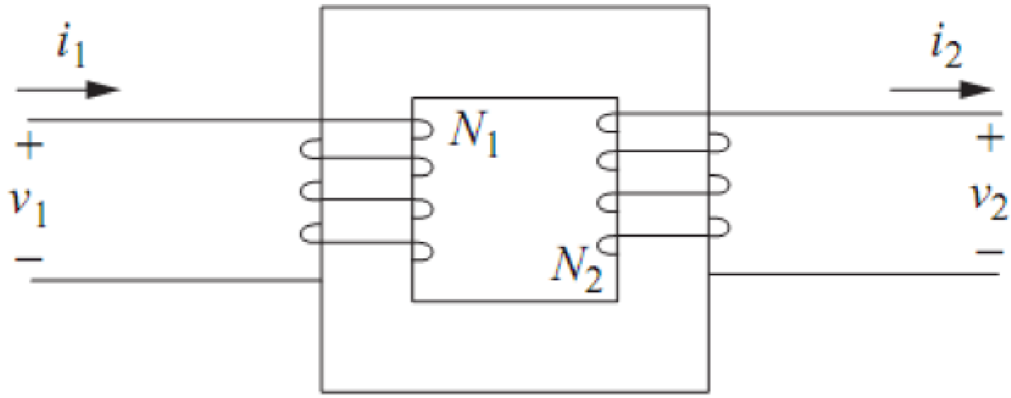
2.08 Kilograms



0.080 kg

Electrical isolation requirement

(a) Transformer;

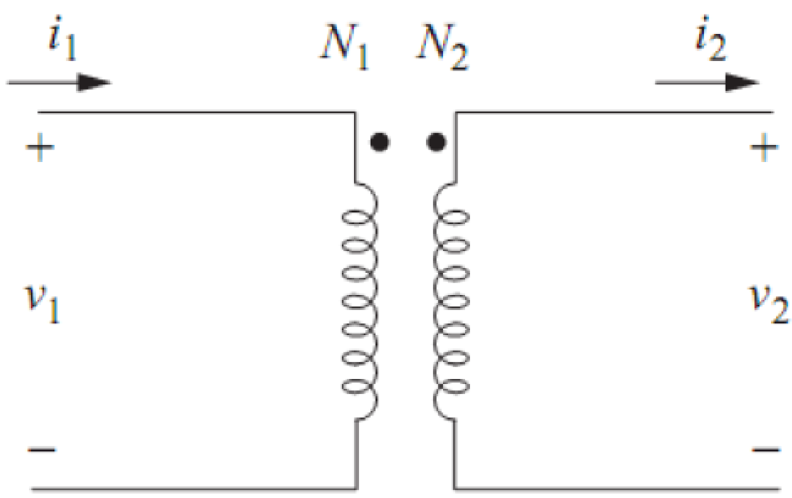


(a)

(b) Ideal model

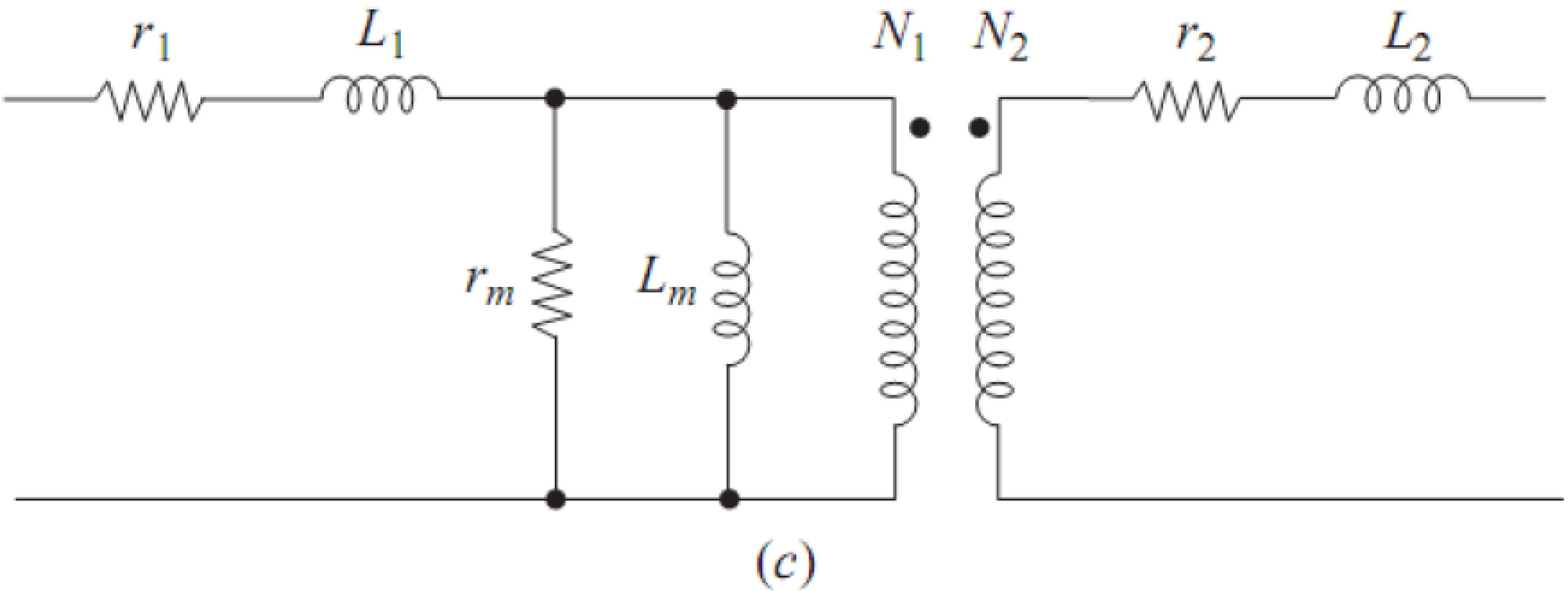
$$\frac{v_1}{v_2} = \frac{N_1}{N_2}$$

$$\frac{i_1}{i_2} = \frac{N_2}{N_1}$$



(b)

Electrical isolation requirement

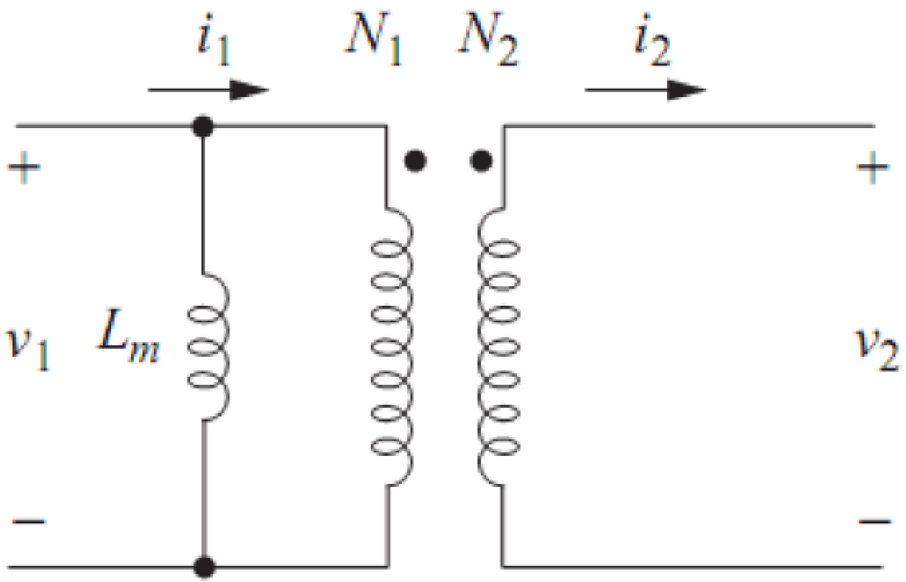


(c) Complete model

Electrical isolation requirement

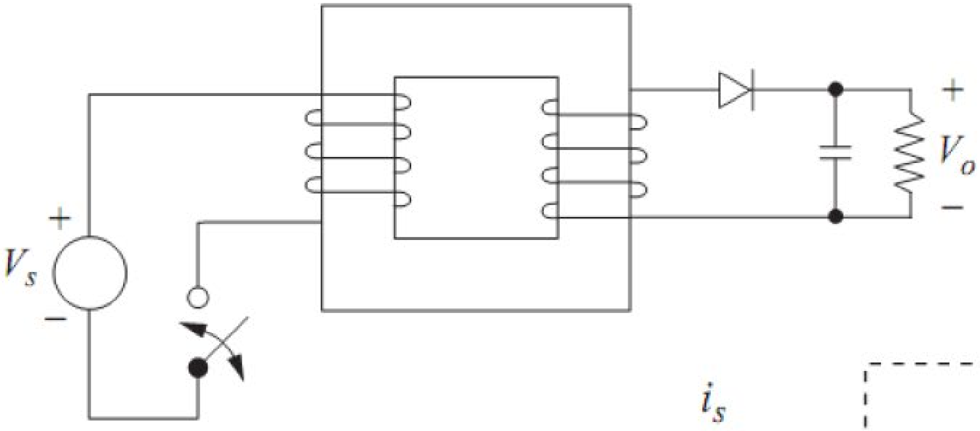
The leakage inductances L1 and L2 are usually not crucial to the general operation of the power electronics circuits described in this chapter, but they are important when considering switching transients.

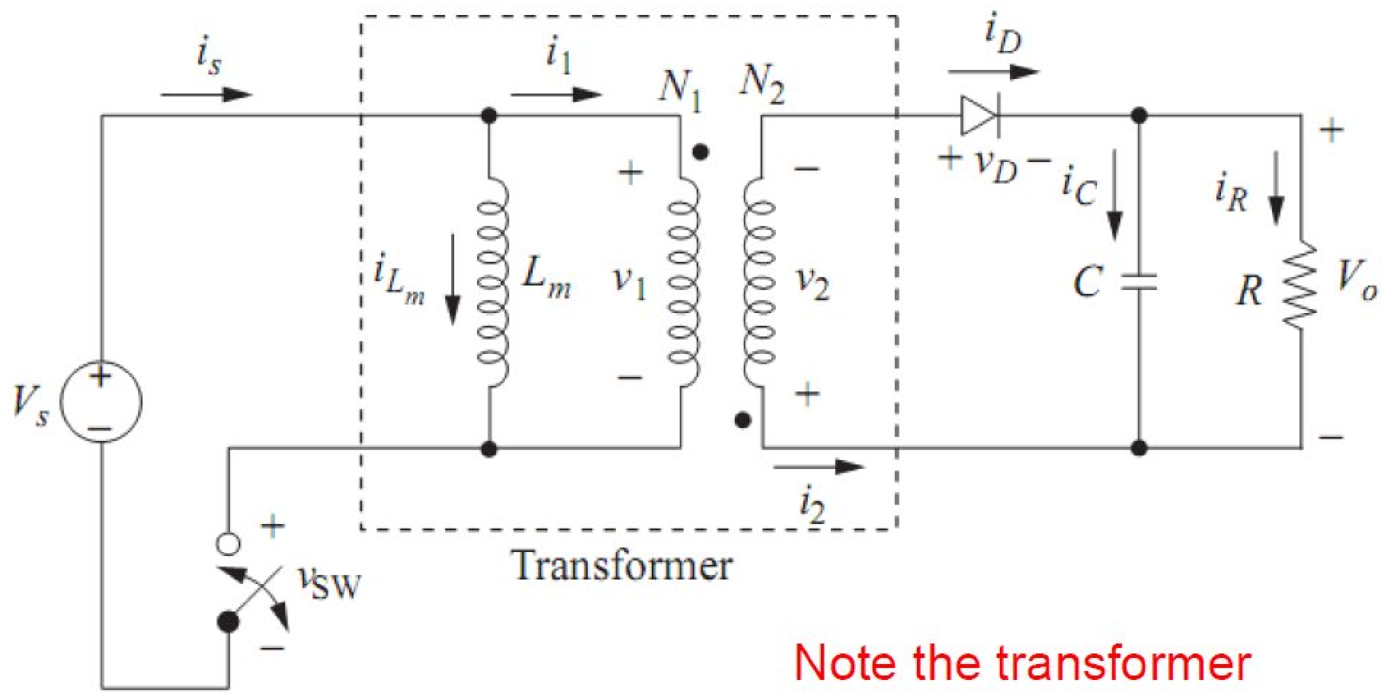
Magnetic core reset is important! The average voltage of Lm must be zero! Otherwise the transformer saturates!



(d)

Electrical isolation requirement

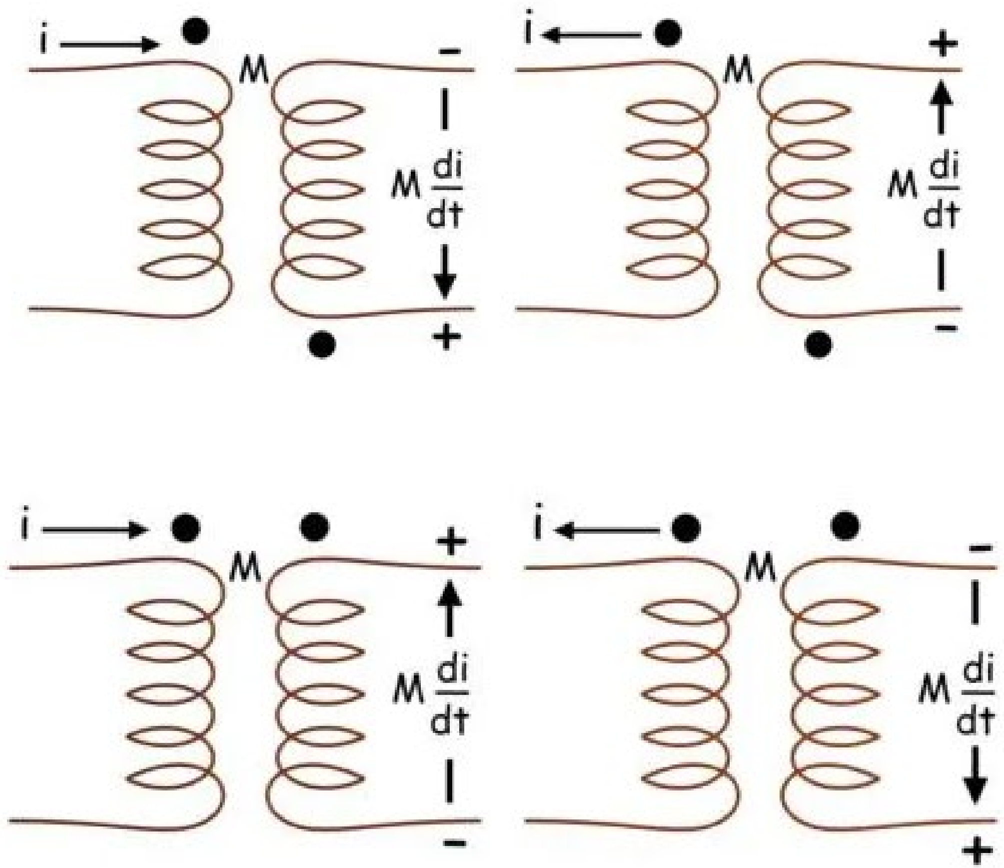




Note the transformer winding direction !!!

Electrical isolation requirement

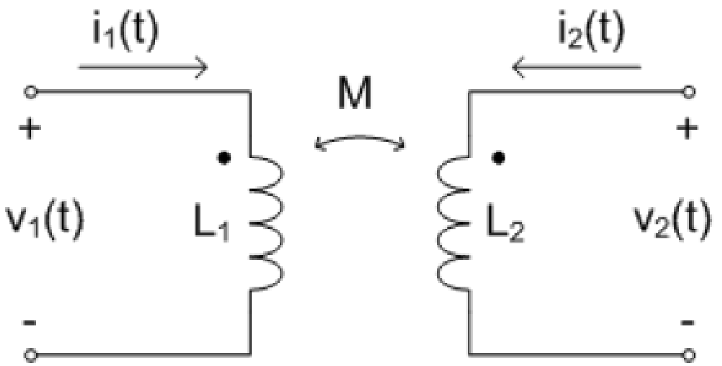
If at an instant, current is entering a coil through dotted end then mutually induced emf on the other coil will have the positive polarity at the dotted end of the later. It can be said in a different way that if the current is leaving a coil through the dotted end then mutually induced emf on the other coil will have the negative polarity at the dotted end of the later.



Electrical isolation requirement

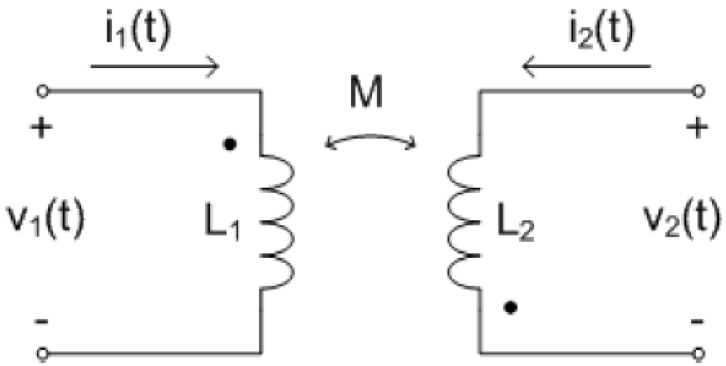
Mutual inductance

- Property of electric circuits in which a time-varying current in one inductor results in a voltage across a second inductor
- Due to flux linkage between the two inductors
- Denoted as **M**
- Units: **Henries (H)**
- ***Dot convention*** determines polarity of induced voltages:



$$v_1(t) = L_1\frac{di_1}{dt} + M\frac{di_2}{dt}$$

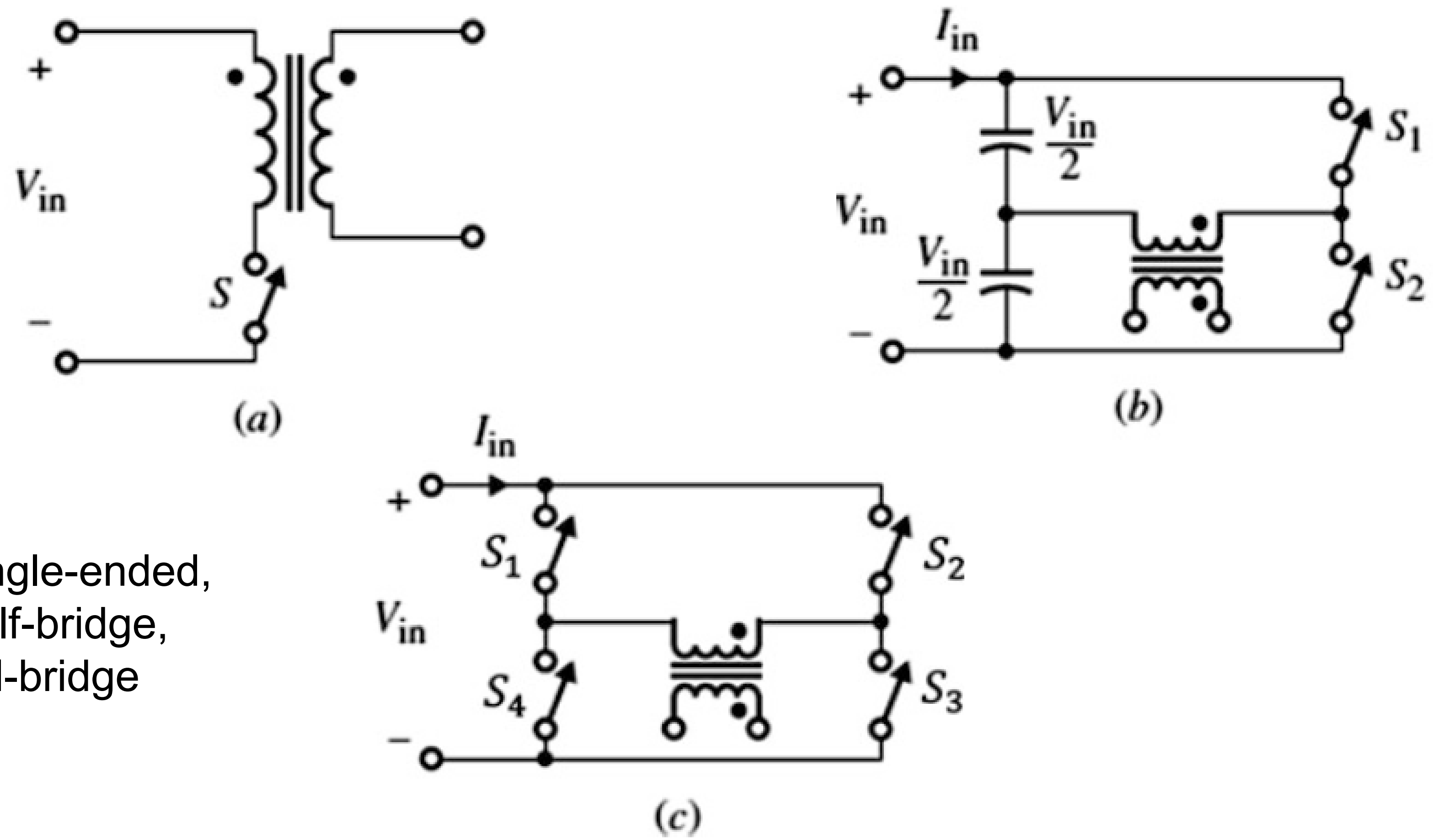
$$v_2(t) = L_2\frac{di_2}{dt} + M\frac{di_1}{dt}$$



$$v_1(t) = L_1\frac{di_1}{dt} - M\frac{di_2}{dt}$$

$$v_2(t) = L_2\frac{di_2}{dt} - M\frac{di_1}{dt}$$

Transformer Configurations

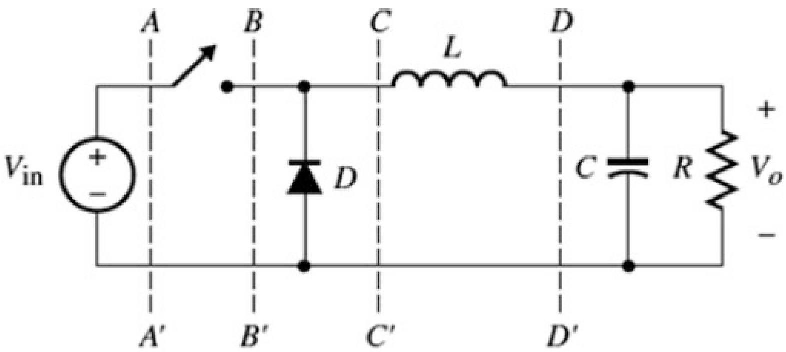


(a) single-ended,
(b) half-bridge,
(c) full-bridge

These configurations are the most popular ones in today's switch-mode power supply design

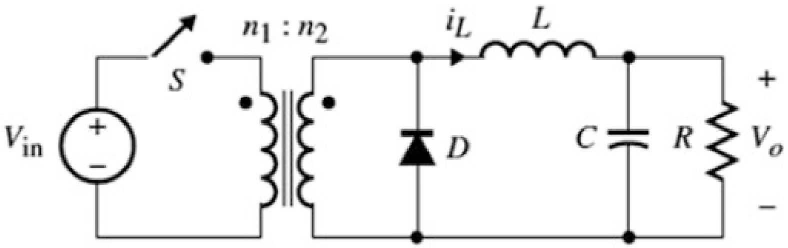
Forward Converter

Let us consider isolating the input and output voltages of the buck converter by inserting an ac transformer.



(a)

(a) Buck converter and

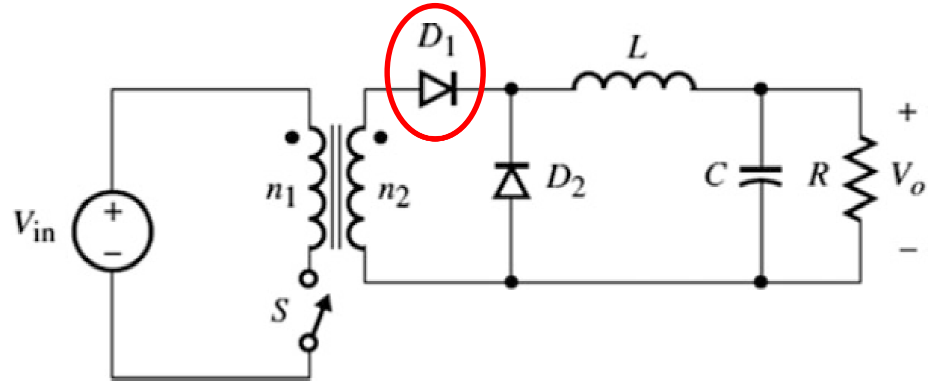


(b)

(b) isolated buck converter

The term “forward” indicates that the energy from the source is directly forwarded to the load.

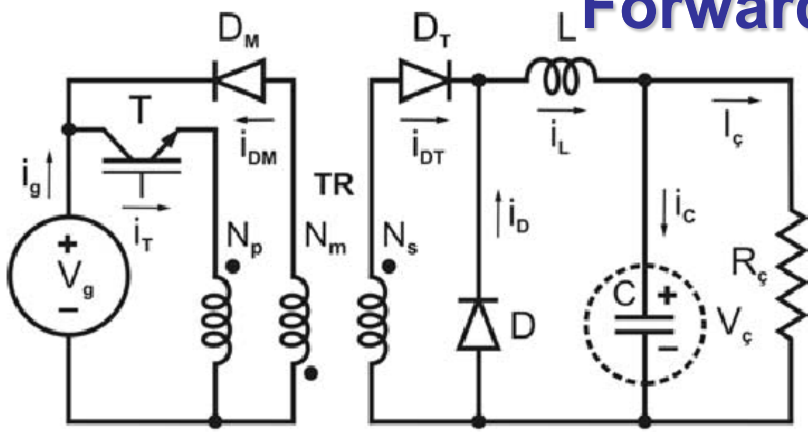
to avoid the problem of transformer saturation is to add another diode



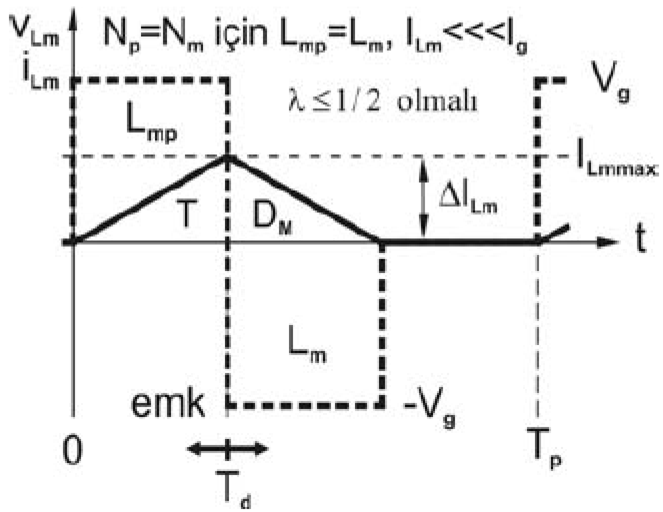
Isolated buck-derived converter, known as single-ended forward converter

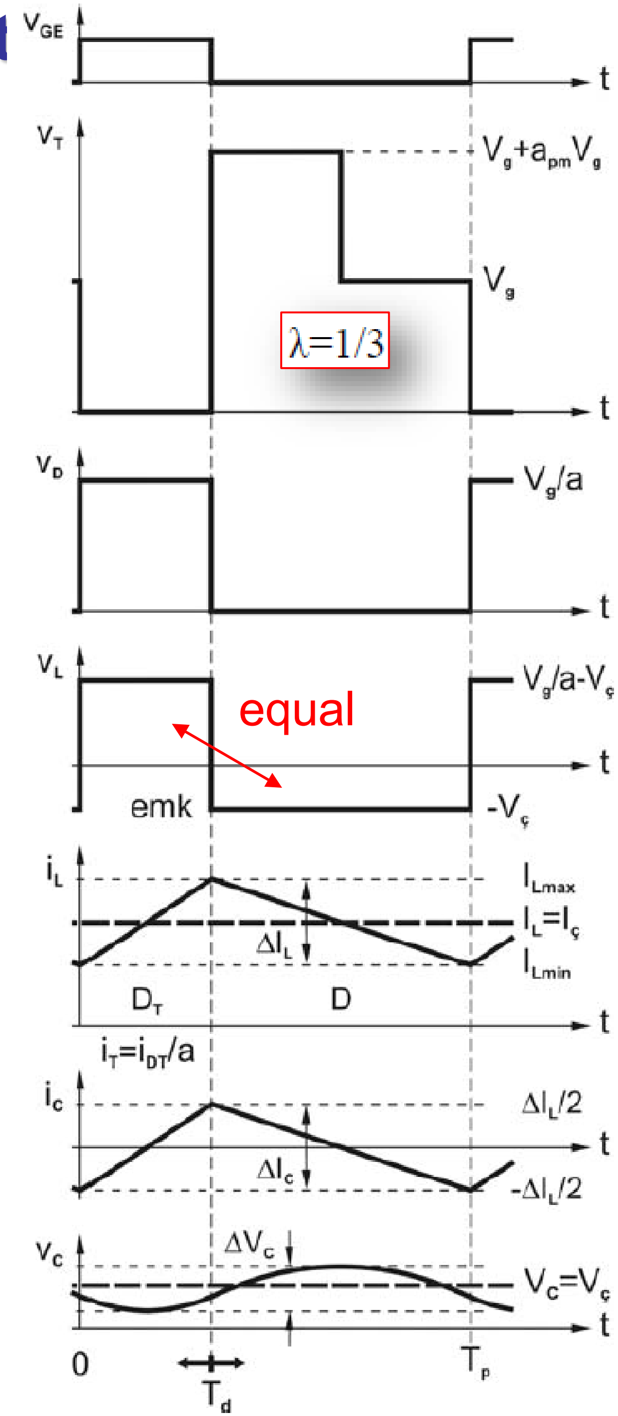
***This will not work properly since its magnetizing current will not be allowed to reset to zero, causing the magnetizing current to continuously increase linearly until it finally saturates the core. A more practical forward converter must include a transformer core resetting circuit as shown in next slide

Forward Convert



$a = N_p/N_s$, $a_{pm} = N_p/N_m$, $N_p = N_m$ için $L_{mp} = L_m$, $I_{Lm} <<< I_g$



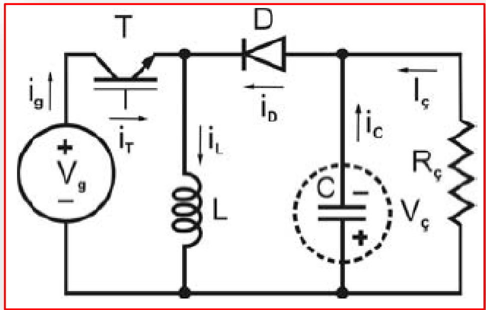


$$\boxed{V_ç = \lambda \frac{V_g}{a}}$$

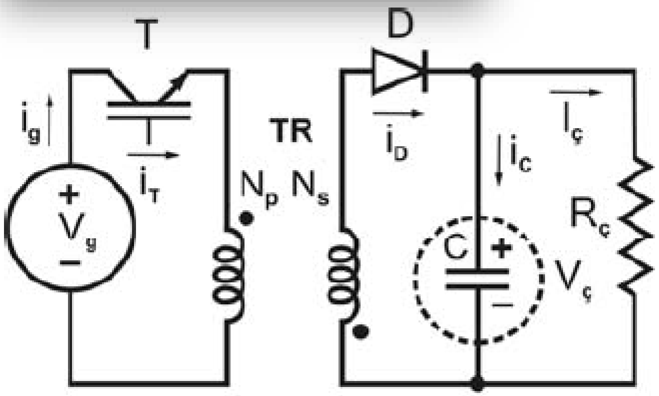
$$\boxed{0 < \lambda < 1/2}$$

100 W - 500 W

Flyback Converter

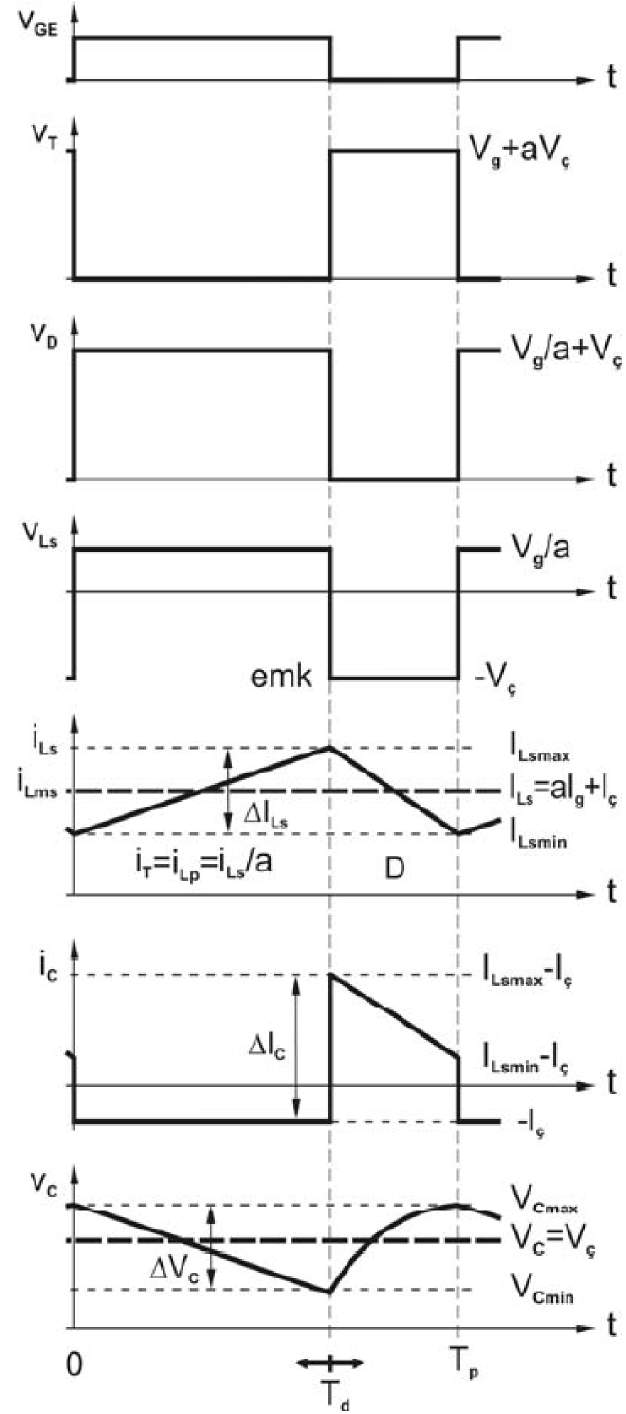


Buck-boost converter



$$V_ç = \frac{\lambda}{1-\lambda}\frac{V_g}{a}$$

$a=N_p/N_s$, $L_{mp}=L_p$, $L_{ms}=L_s$, $I_{Lmp}=I_g$



In the flyback converter, the energy storage is the transformer itself, which is why a transformer with an air gap is needed.

The forward converter uses a transformer without an air gap, so an additional storage choke is needed. The forward converter is therefore somewhat more complex in design, but also achieves a higher efficiency.

References

https://en.wikipedia.org/wiki/power_electronics
Prof. Mutlu Boztepe lecture notes
Güç Elektroniği, Prof. Dr. Hacı Bodur
Power Electronics, Muhammad H. Rashid
Power Electronics, Daniel W. Hart
Power Electronics, Dr M D Singh, Dr K B Khanchandani
Power Electronics, Soumitra Kumar Mandal
Power Electronics, Issa Batarseh, Ahmad Harb
Power Electronics, Branko L. Dokić, Branko Blanuša
Power Electronics, Ned Mohan
Basic Principles of Power Electronics, Klemens Heuman