Power Electronics
Lecture 4

FLYBACK and FORWARD converters

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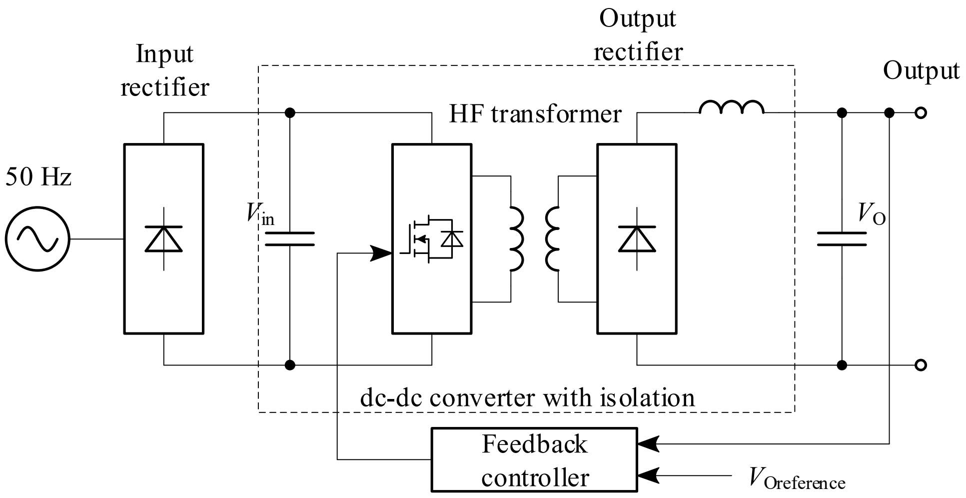
Block diagram of SMPS

The switched mode power supply (SMPS) consists of:

- the input rectifier,
- Dc transformer converter with high frequency transformer
- Feedback controller



List of dc-dc converters

Among number of dc-dc converters with isolation there are:

- FLYBACK converter
- FORWARD converter
- Forward 2T converter
- Push-pull converter
- Full-bridge dc-dc converter
- Half-bridge dc-dc converter
- Dual Active Bridge converter (DAB)
- LLC resonand converter

All converters have galvanic isolation between input and output guaranteed by HF transformer

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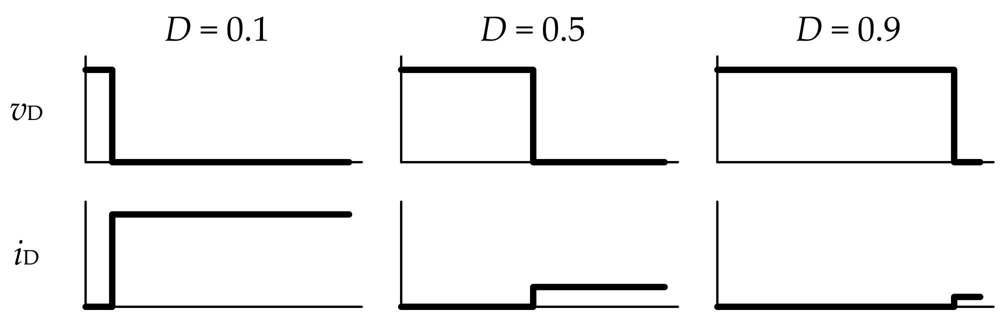
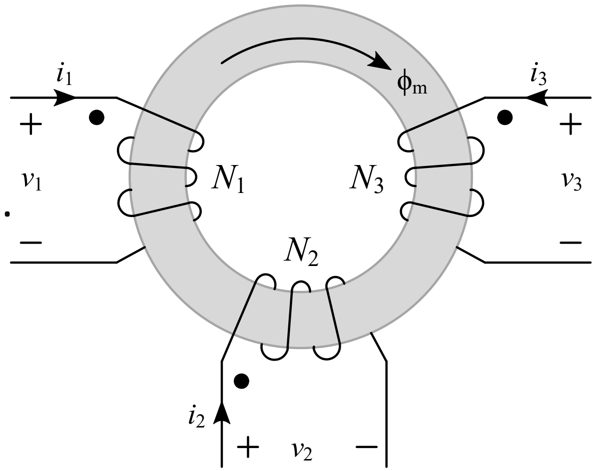
Need for HF transformer

Galvanic isolation provides a barrier that prevents dangerous high voltage from passing from the input to the output.
It provides the safety from electrical shock at the output.
The disadvantage of the usage of HF transformer is a lower converter efficiency and larger size.
The HF transformer allows to operate with duty cycles close to 0.5 and to limit the use of semiconductor devices with both large voltage and current ratings.



Diode voltage and current waveforms in BUCK converter.

Transformer is an electrical device which is composed of windings wound on magnetic core. Winding currents produces inside of the magnetic core the magnetic flux.



From Farady's Law: When all windings are linked by the same flux ϕm the induced voltages are as follows:

$$v_1 = N_1 \frac{d\phi_m}{dt}; v_2 = N_2 \frac{d\phi_m}{dt}; v_3 = N_3 \frac{d\phi_m}{dt}$$

From Amper's Law: Net amper-turns applied to the core is equal to product of magnetic flux and core reluctance R_m

$$N_1 i_1 + N_2 i_2 + N_3 i_3 = \phi_m R_m$$

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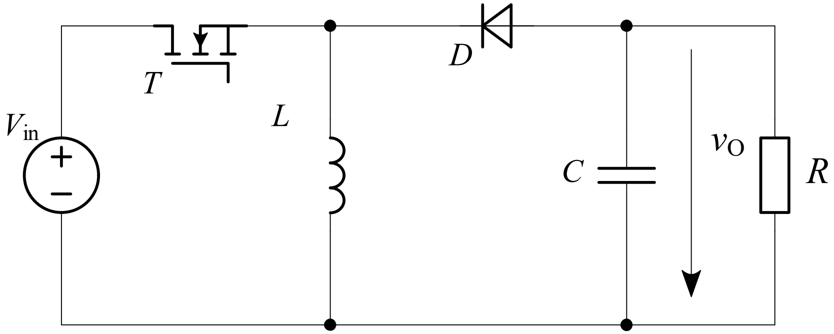
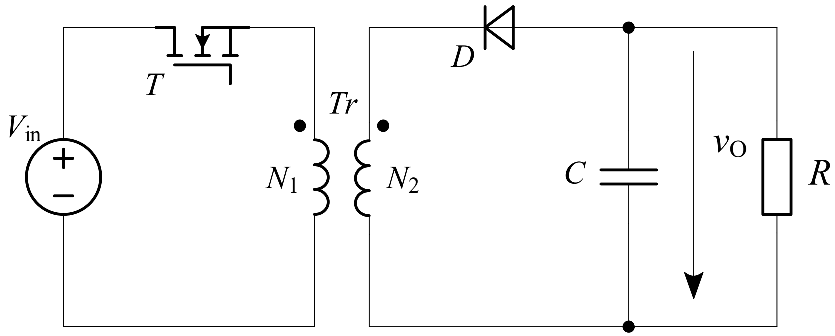
Flyback converter

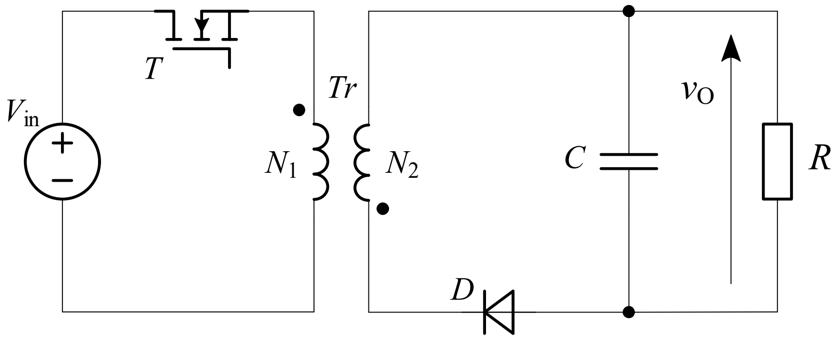
Flyback converter topology can be derived from the buck-boost topology:



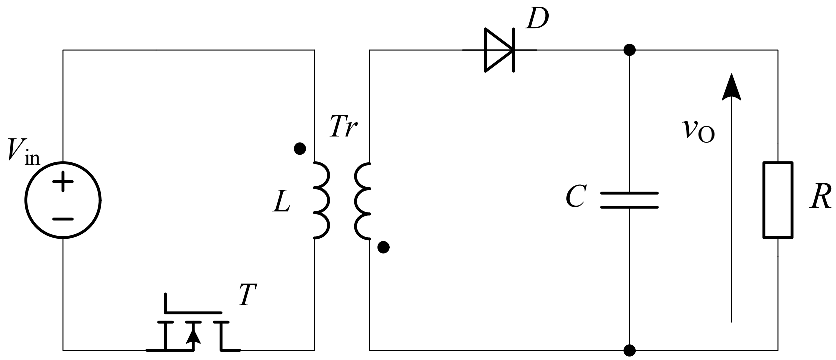
The buck-boost converter with HF transformer



Flipping the output side of the converter



Rearanging components



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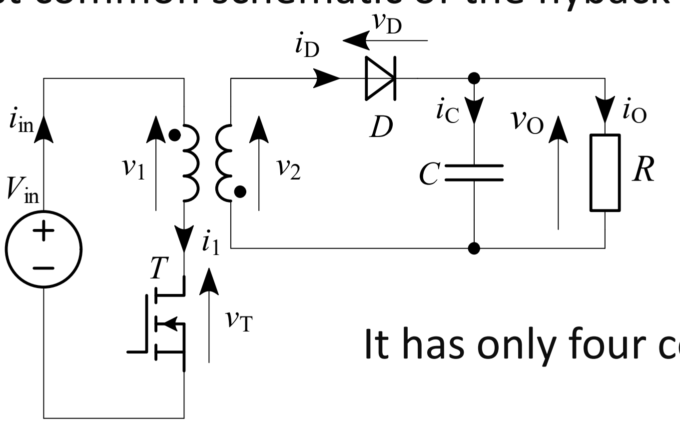
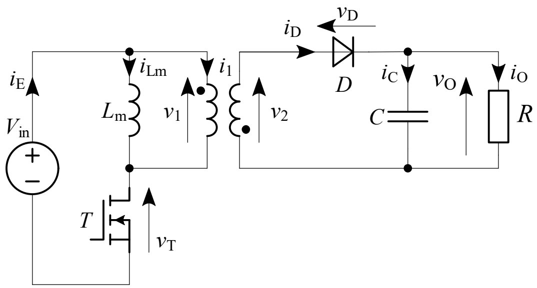
Flyback converter

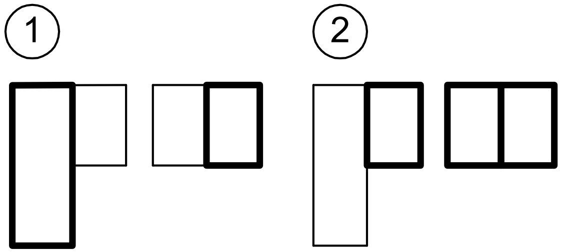
The most common schematic of the flyback converter

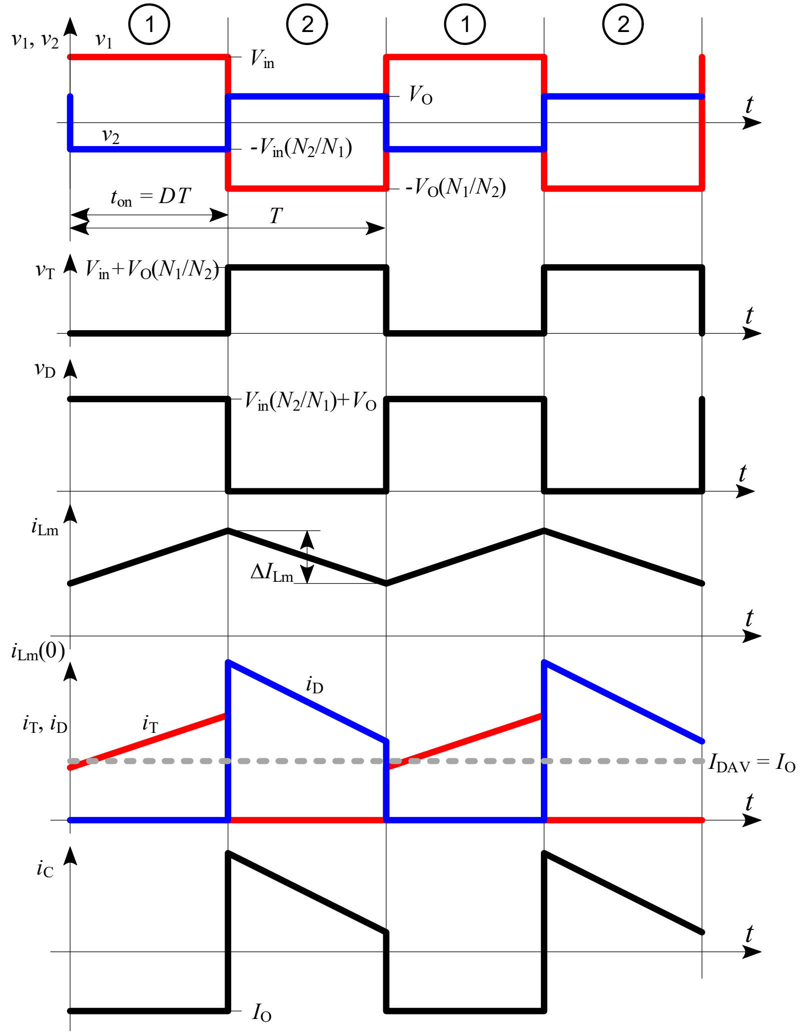


It has only four components!

Assuming that converter works in CCM







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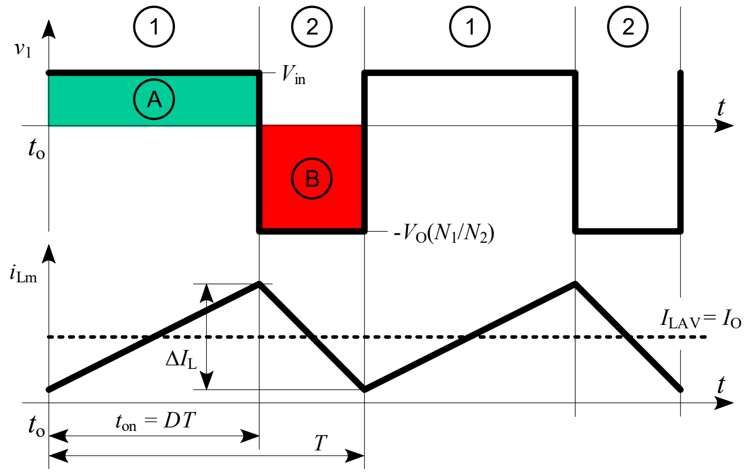
Output voltage in CCM

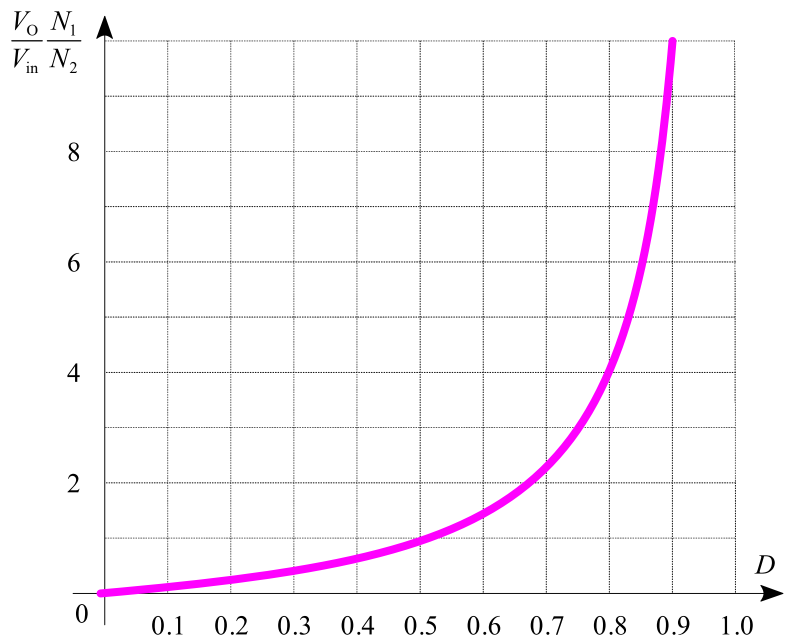
In the steady state the transformer primary or secondary side voltages must have average values equal to zero.



$$V_{in}DT - \frac{N_1}{N_2}V_O(1-D)T = 0$$

$$V_O = \frac{N_2}{N_1}V_{in}\frac{D}{1-D} \quad or \quad D = \frac{\frac{V_O}{V_{in}}}{\frac{N_2}{N_1}+\frac{V_O}{V_{in}}}$$

The output voltage characteristic is similar to buck-boost characteristic with N_2/N_1 term allowing to increase or decrease the output voltage referred to input voltage.



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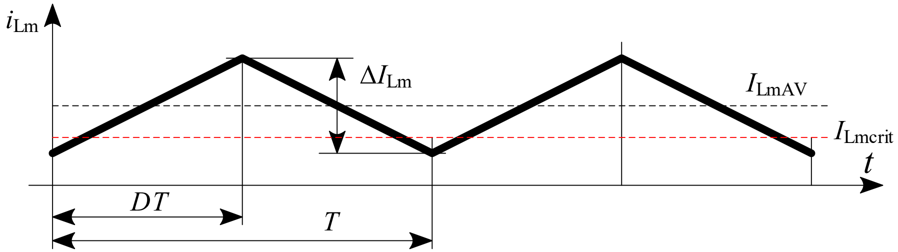
Magnetizing current

The converter operation mode is defined basing on the magnetizing current.

When $I_{\mathrm{LmAV}} > I_{\mathrm{Lmcrit}}$ the converter operates in CCM.



In the lossless converter the input current is given as:

$$I_{\mathrm{in}} = \frac{V_{\mathrm{O}}}{V_{\mathrm{in}}} I_{\mathrm{O}}$$

The input current is a part of the magnetizing current.

$$I_{\mathrm{in}} = I_{\mathrm{LmAV}} D \Rightarrow I_{\mathrm{LmAV}} = \frac{I_{\mathrm{in}}}{D} = \frac{V_{\mathrm{O}}}{V_{\mathrm{in}} D} I_{\mathrm{O}}$$

$$I_{\mathrm{LmAV}} = I_{\mathrm{O}} \frac{N_2}{N_1} \frac{1}{1-D}$$

The critical magnetizing current is given as:

$$I_{\mathrm{Lmcrit}} = \frac{1}{2} \Delta I_{\mathrm{Lm}}$$

Where ΔI_{L} is a peak-to-peak value of the magnetizing current:

$$\Delta I_{\mathrm{Lm}} = \frac{V_{\mathrm{in}} DT}{L_{\mathrm{m}}}$$

Thus:

$$I_{\mathrm{Lmcrit}} = \frac{V_{\mathrm{in}} DT}{2 L_{\mathrm{m}}}$$

The critical output current is given as:

$$I_{\mathrm{Ocrit}} = \frac{N_1}{N_2} I_{\mathrm{Lmcrit}} (1-D) = \frac{N_1}{N_2} \frac{V_{\mathrm{in}} T}{2 L_{\mathrm{m}}} D(1-D)$$

$$I_{\mathrm{Ocrit}} = \left(\frac{N_1}{N_2} \right)^2 \frac{V_{\mathrm{O}} T}{2 L_{\mathrm{m}}} (1-D)^2$$

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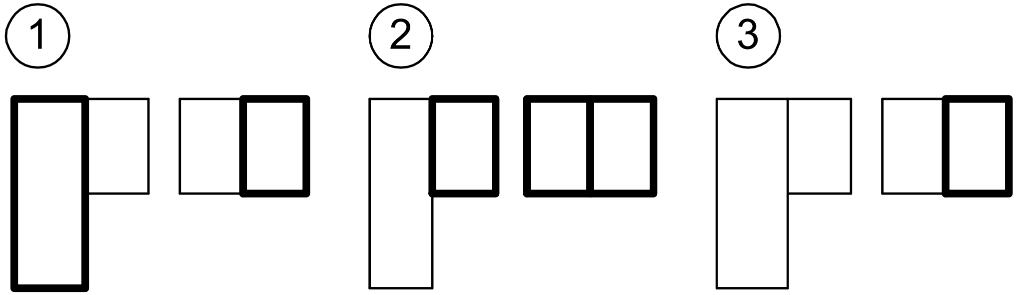
Operation in DCM

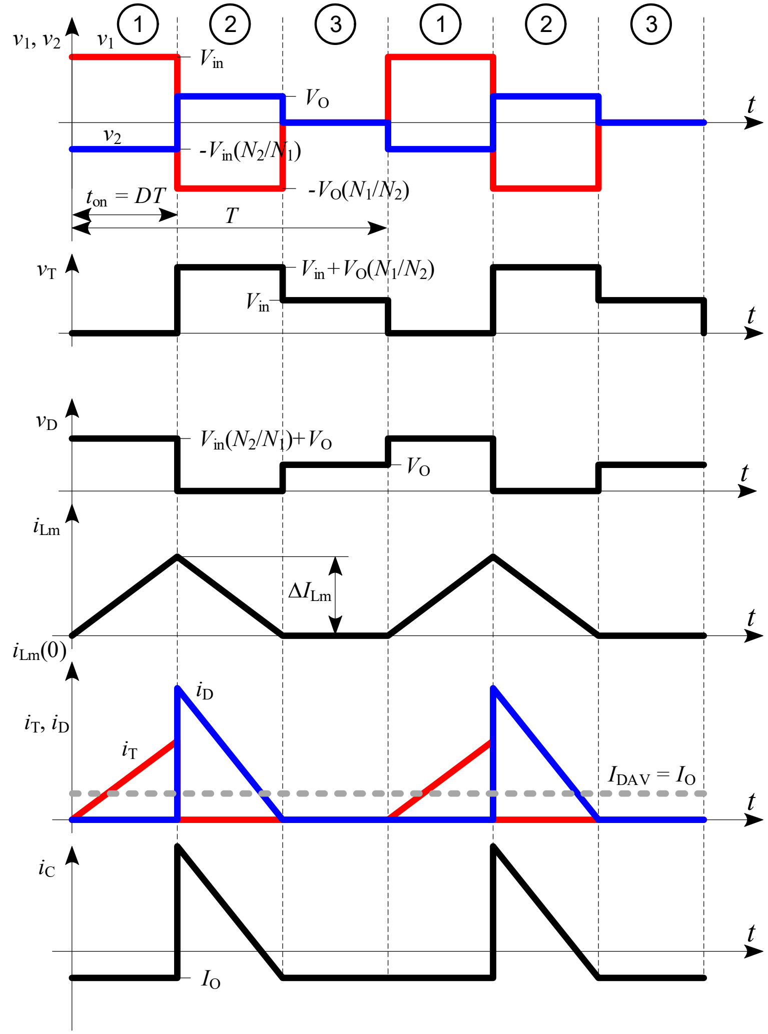
When the output current $I_O < I_{Ocrit}$ the converter operates in discontinuous conduction mode



There are similar formula as for a buck-boost converter, however they differ in term N_1/N_2.

$$I_O = \frac{N_1}{N_2}\frac{1}{2}\Delta I_{Lm} D_1 = \frac{N_1}{N_2}\frac{V_{in}T}{2L_m} D D_1 = \frac{N_1}{N_2}\frac{V_{in}T}{2L_m} D^2 \frac{N_2}{N_1}\frac{V_{in}}{V_O} \Rightarrow$$

$$\frac{V_O}{V_{in}} = \frac{V_{in}T}{2L_m I_O} D^2 = \left(\frac{N_2}{N_1}\right)^2 D^2 \frac{I_{ref}}{I_O} = \left(\frac{N_2}{N_1}\right)^2 \frac{1}{\frac{I_O}{I_{ref}}\frac{1}{D^2}} \text{ for } I_{ref} = \frac{V_{in}T}{2L_m\left(\frac{N_2}{N_1}\right)^2}$$



Output characteristics

In DCM
$$\frac{V_O}{V_{in}}=\left(\frac{N_2}{N_1}\right)^2\frac{D^2}{\frac{I_O}{I_{ref}}}\Rightarrow\frac{V_O}{V_{in}}\frac{N_1}{N_2}=\frac{D^2}{\frac{I_O}{I_{ref}}\frac{N_1}{N_2}}$$

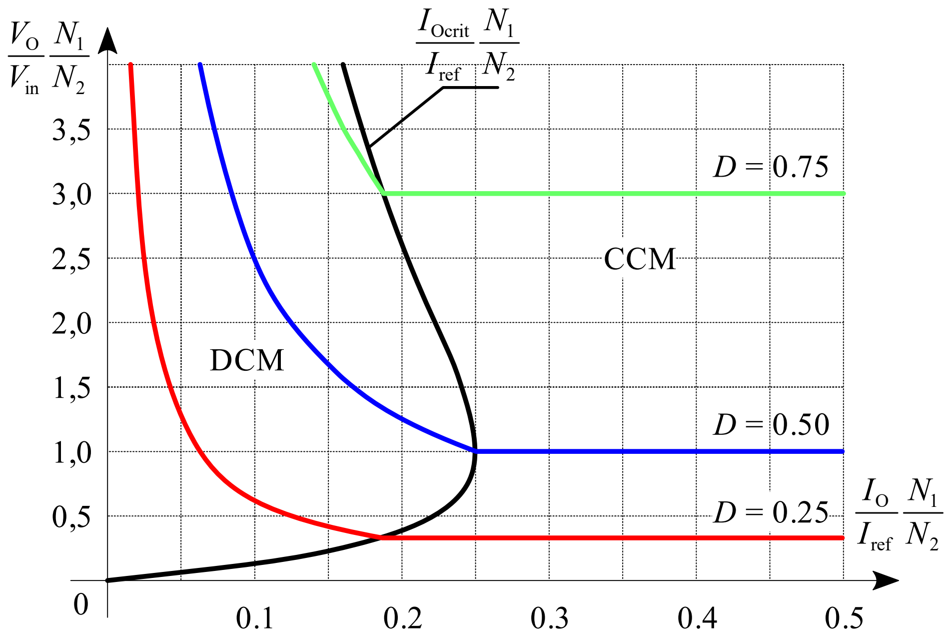
In CCM
$$\frac{V_O}{V_{in}}=\frac{N_2}{N_1}\frac{D}{1-D}\Rightarrow\frac{V_O}{V_{in}}\frac{N_1}{N_2}=\frac{D}{1-D}$$

At CCM/DCM boundary

$$I_{Ocrit}=\frac{N_1}{N_2}\frac{V_{in}T}{2L_m}D(1-D)\overset{I_{ref}=\frac{V_{in}T}{2L_m\left(\frac{N_2}{N_1}\right)^2}}{=}\frac{N_2}{N_1}I_{ref}D(1-D)\overset{D=\frac{\frac{V_O}{V_{in}}}{\frac{N_2}{N_1}+\frac{V_O}{V_{in}}}}{=}$$

$$=\left(\frac{N_2}{N_1}\right)^2 I_{ref}\frac{\frac{V_O}{V_{in}}}{\left(\frac{N_2}{N_1}+\frac{V_O}{V_{in}}\right)^2}\Rightarrow\frac{N_1}{N_2}\frac{I_{Ocrit}}{I_{ref}}=\frac{\frac{N_1}{N_2}\frac{V_O}{V_{in}}}{\left(1+\frac{N_1}{N_2}\frac{V_O}{V_{in}}\right)^2}$$

The output characteristic for V_{in} = const (scales depend on N_1/N_2 ratio)



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Flyback with V_O = const

The output characteristic for V_O = const

Defining output reference current: $I_{Oref} = \frac{V_O T}{2L_m \left(\frac{N_2}{N_1}\right)^2}$

The critical output current is:

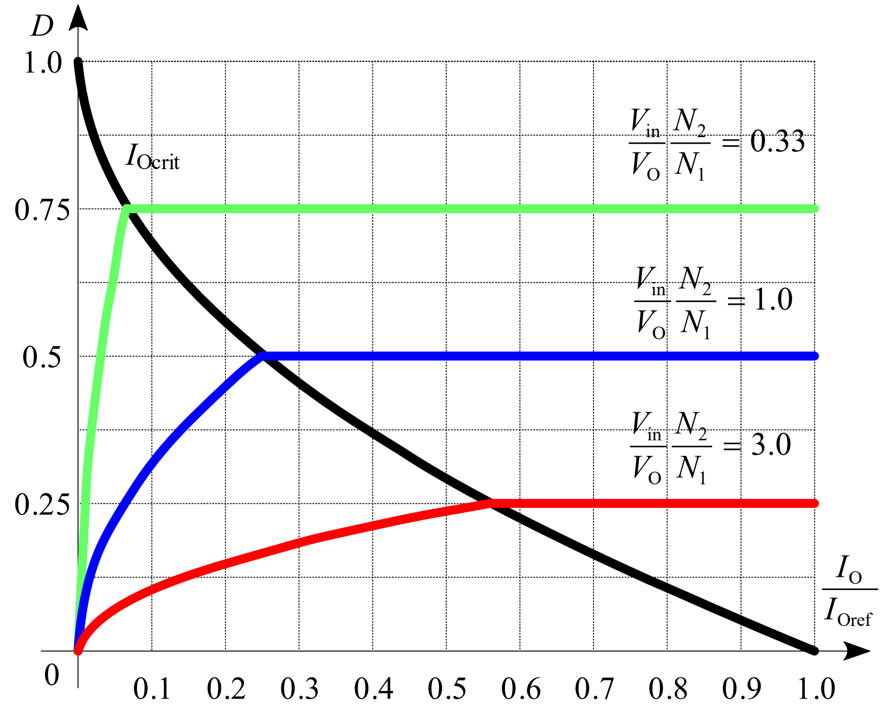
$$I_{Ocrit} = \frac{V_{in} T}{2L_m \left(\frac{N_2}{N_1}\right)^2} \frac{N_1}{N_2} D(1-D) =$$

$$= I_{Oref} (1-D)^2$$

The relation between the output current and duty cycle in DCM is:

$$\frac{V_O}{V_{in}} \frac{N_1}{N_2} = \frac{D^2}{\frac{I_O}{I_{ref}} \frac{N_1}{N_2}} \Rightarrow \frac{I_O}{I_{Oref}} = \frac{D^2}{\left(\frac{V_O}{V_{in}} \frac{N_1}{N_2}\right)^2}$$

The output characteristic for V_O = const



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Flyback converter example #1

Flyback converter example as a smartphone charger

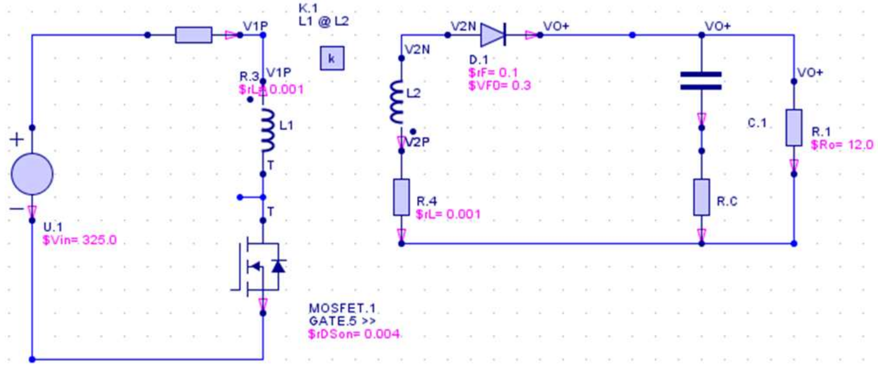
Input voltage:	$V_{in} = 325$ V,
Output voltage:	$V_{out} = 12$ V,
Switching frequency:	$f = 150$ kHz,
Output capacitance:	$C = 10$ uF,
Output power:	$P_O = 12$ W,
Transformer magnetizing ind.	$L_1 = 3200$ μH,
Transformer turn ratio:	$N_1/N_2 = 10$

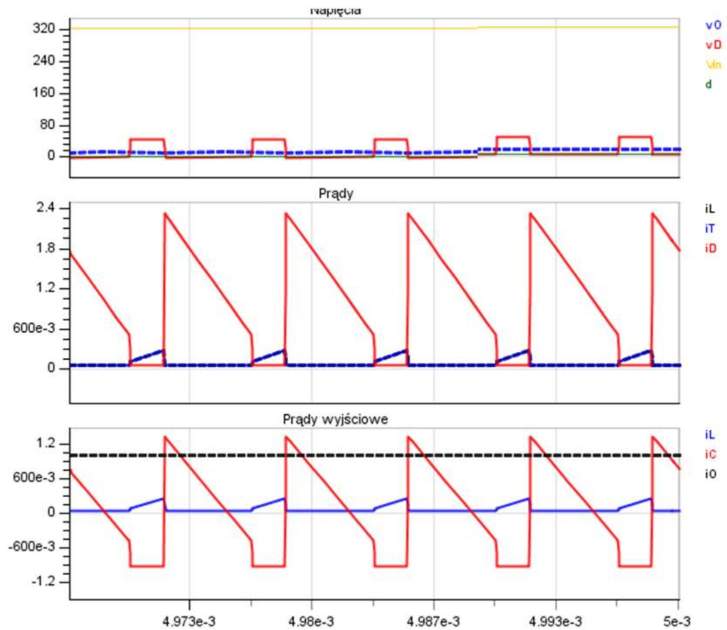
$$I_O = \frac{P_O}{V_O} = \frac{12\ \text{W}}{12\ \text{V}} = 1.0\ \text{A} \qquad R = \frac{V_O}{I_O} = \frac{12\ \text{V}}{1.0\ \text{A}} = 12\ \Omega$$

$$I_{in} = \frac{P_{in}}{V_{in}} = \frac{12\ \text{W}}{325\ \text{V}} = 34.2\ \text{mA} \qquad \frac{D}{1-D} = \frac{V_O}{V_{in}}\frac{N_1}{N_2} \Rightarrow D = 0.27$$

$$\Delta I_{Lm} = \frac{V_{in}}{L_m} DT \Rightarrow = \frac{325\,\text{V}}{3.20\,\text{mH}} 0.27 \cdot 6.67\ \mu\text{s} = 182\,\text{mA}$$

GeckoCIRCUITS model of the flyback converter





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Flyback converter example #2

Flyback converter example in battery level voltage applications

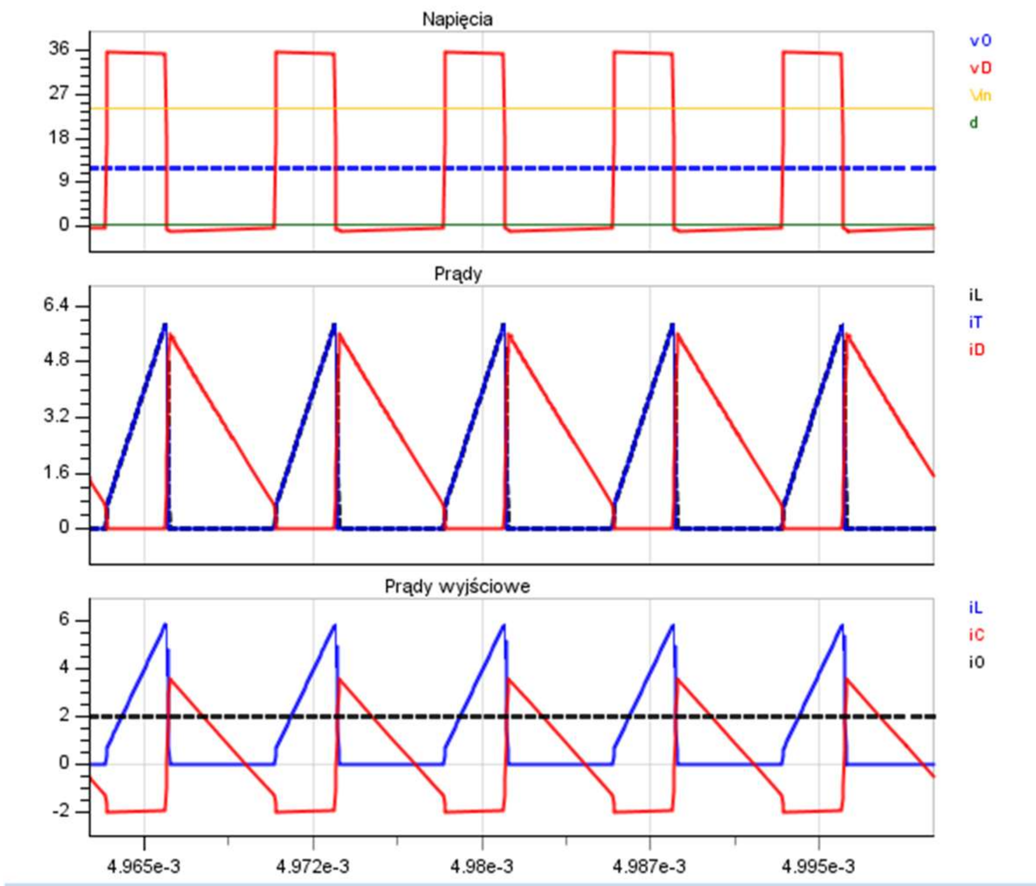
Input voltage:	$V_{in} = 24$ V,
Output voltage:	$V_O = 12$ V,
Switching frequency:	$f = 133$ kHz, ($T = 7.5$ µs)
Output capacitance:	$C = 60$ uF,
Output power:	$P_O = 24$ W,
Magnetizing inductance	$L_m = 12$ µH
Turn ratio	$N_2/N_2 = 1$

$$I_O = \frac{P_O}{V_O} = \frac{24\ \text{W}}{12\ \text{V}} = 2.0\ \text{A} \qquad R = \frac{V_O}{I_O} = \frac{12\ \text{V}}{2.0\ \text{A}} = 6.0\ \Omega$$

$$D = \frac{\frac{V_O}{V_{in}}}{\frac{N_2}{N_1} + \frac{V_O}{V_{in}}} = 0.33 \qquad \Delta I_L = \frac{V_{in}}{L_m} DT = \frac{24\ \text{V}}{12\ \mu\text{H}} 0.33 \cdot 7.5\ \mu\text{s} = 5.0\ \text{A}$$

$$I_{in} = \frac{P}{V_{in}} = \frac{24\ \text{W}}{24\ \text{V}} = 1.0\ \text{A} \quad I_{LmAV} = \frac{I_{in}}{D} = 3.0\ \text{A}$$

GeckoCIRCUITS model of the flyback converter



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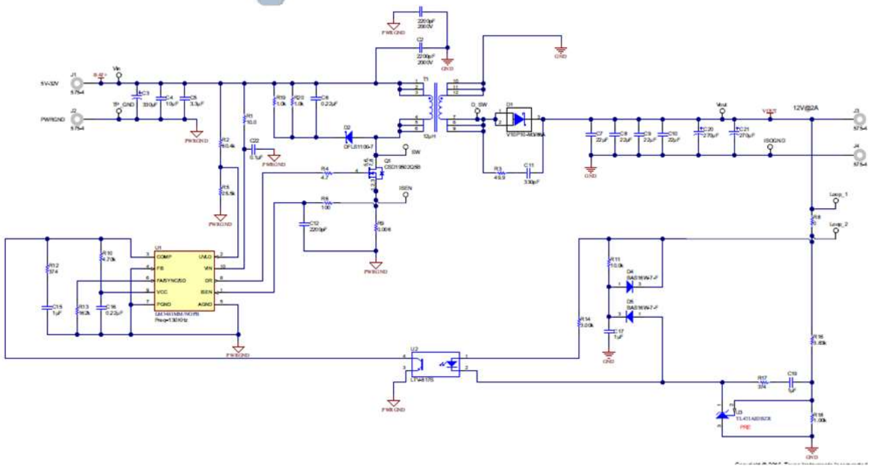
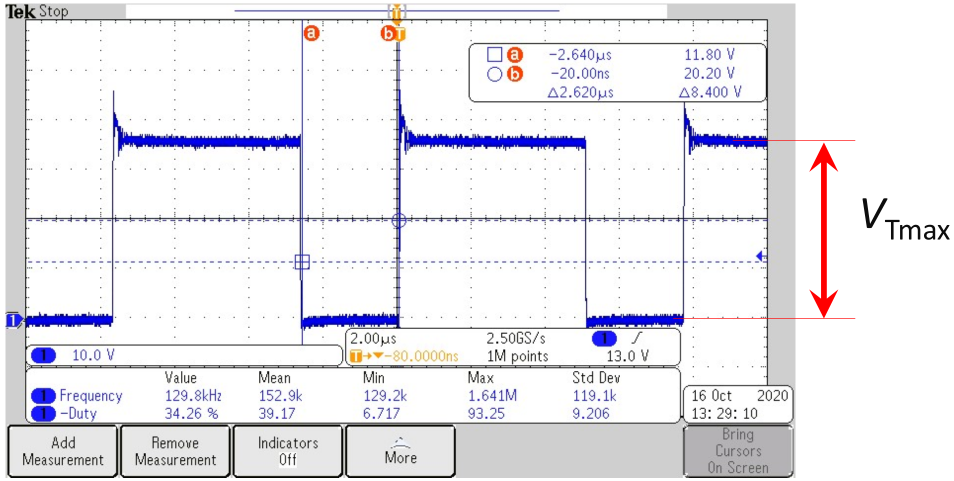
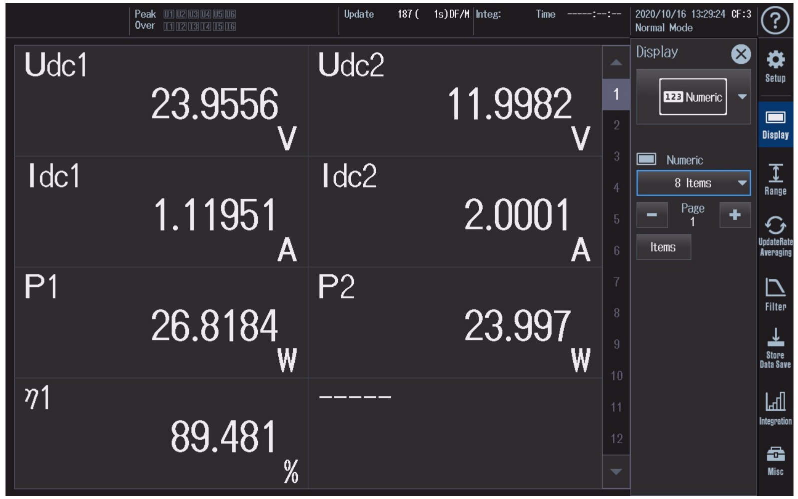
Flyback laboratory model

The LM381-Flyback Evaluation Module has been tested for the same conditions as in Example 2.



$$D = 0.33; V_{in} = 24\text{ V}; V_O = 12\text{ V};\ V_{T\max} = V_{in} + nV_O = 36\text{V}$$





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Flyback transfromer

The Flyback transformer stores the energy in its magnetizing inductance similarly as inductors.

In the transfomer magnetic core the air gap is needed.

The air gap allows to store energy given as:

$$W_{\mathrm{m}} = L_{\mathrm{m}} \frac{i_{\mathrm{Lm}}{}^{2}}{2}$$

The maximum energy occurs for the maximum current

$$W_{\mathrm{m,max}} = L_{\mathrm{m}} \frac{i_{\mathrm{Lmmax}}{}^{2}}{2} = 12\,\mu\mathrm{H} \frac{(5.5\ \mathrm{A})^{2}}{2} = 181.5\ \mu\mathrm{J}$$

$$i_{\mathrm{Lmax}} = I_{\mathrm{LmAV}} + \frac{1}{2}\Delta I_{\mathrm{Lm}} = 3.0\ \mathrm{A} + 2.5\ \mathrm{A} = 5.5\ \mathrm{A}$$

In every switching period the energy transfer from input to output is equal:

$$W_{\mathrm{O}} = \frac{L_{\mathrm{m}}}{2}\left[i_{\mathrm{Lmmax}}{}^{2} - i_{\mathrm{Lmmin}}{}^{2}\right] = \frac{12\,\mu\mathrm{H}}{2}\left[(5.5\ \mathrm{A})^{2} - (0.5\ \mathrm{A})^{2}\right] = 180\ \mu\mathrm{J}$$

One of many transformer design approaches is the usage of core geometry *Ap* coefficient:

$$A_{p} = A_{\mathrm{c}} A_{\mathrm{w}} = \frac{L_{\mathrm{m}} i_{\mathrm{Lmmax}} I_{\mathrm{rms}}}{k_{w} J_{\max} B_{\max}} = \frac{12\,\mu\mathrm{H} \cdot 5.5\,\mathrm{A} \cdot 3.32\,\mathrm{A}}{0.4 \cdot 4{,}0 \dfrac{\mathrm{A}}{\mathrm{mm}^{2}} \cdot 0.35\ \mathrm{T}} = 391\ \mathrm{mm}^{4}$$

where:

A_{c} is the core magnetic area,

A_{w} is the core winding area,

k_{w} is the winding fill factor, k_{w} = 0.4

$J_{\max}$ is the maximum current density, $J_{\max}$ = 4 A/mm^2

$B_{\max}$ is the maximum flux density, $B_{\max}$ = 0.35 T, (ferrites)

The magnetic core E16 can be chosen with A_p = 830 mm^4. In the LM381-Flyback Evaluation Module E25 core is selected having A_p = 4800 mm^4 and saturation current equal to 17.5 A.

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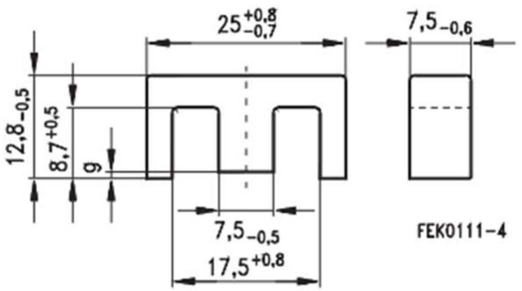
Flyback transfromer

E25 core dimensions:



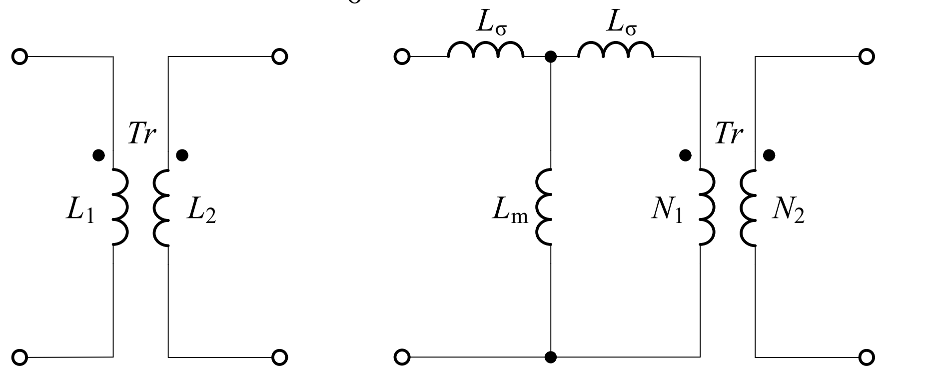
The turn number for inductors is calculated from:

$$N_1 = L_m \frac{i_{\mathrm{Lmmax}}}{A_m B_{\max}} = 12\,\mu\mathrm{H} \frac{17.5\,\mathrm{A}}{51\,\mathrm{mm}^2\, 0.35\,\mathrm{T}} \approx 12$$

The air gap length is calculated from:

$$l_g = N\mu_0 \frac{I_{\max}}{B_{\max}} = 12 \cdot 4\pi \cdot 10^{-7}\, \frac{\mathrm{H}}{\mathrm{m}} \frac{17.5\,\mathrm{A}}{0.35\,\mathrm{T}} \approx 0.75\,\mathrm{mm}$$

Transformer windings are imperfectly coupled, therefore in its model together with the magnetizing inductance L_m the leakage inductances L_σ are present.



$$L_1 = L_m + L_\sigma \quad L_2 = \left(\frac{N_2}{N_1}\right)^2 L_m + L_\sigma$$

The leakage inductance L_σ is smaller than L_m.

$$L_\sigma = L_1 (1 - k)$$

$$L_m = L_1 k$$

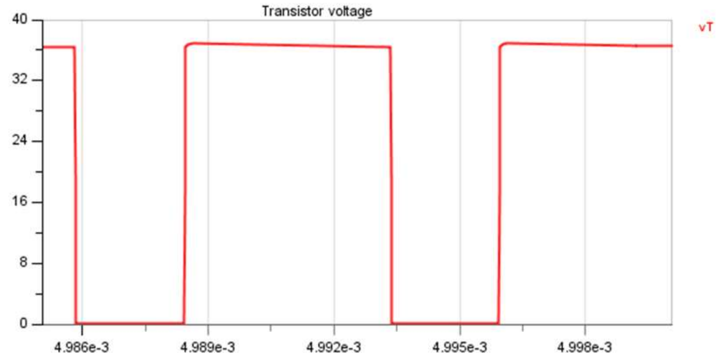
Where k is the coupling factor (ideally k = 1).

The coupling factor depends on transformer geometry.

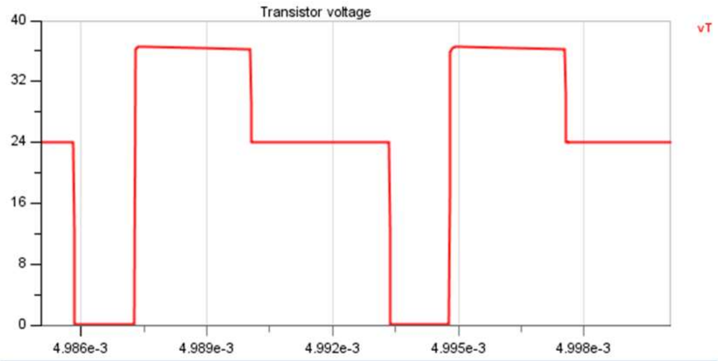
Influence of leakage inductance

The leakage inductance impacts on transistor voltage.

In case of zero leakage inductance (k = 1)

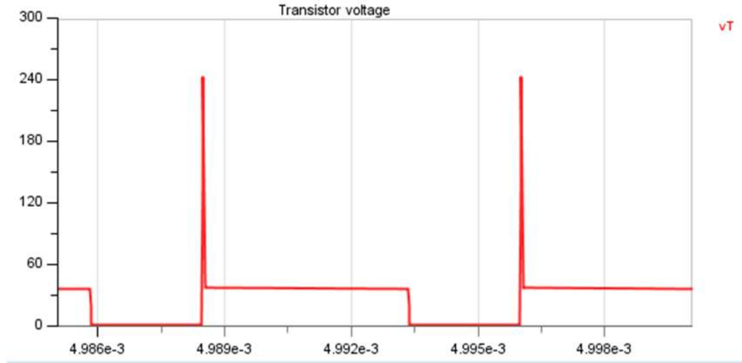


In CCM

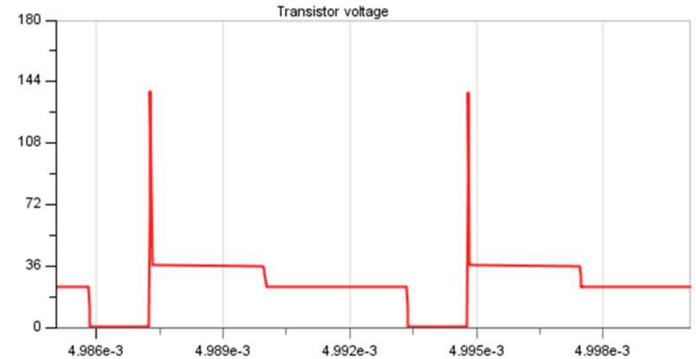


In DCM

In case of nonzero leakage inductance (k = 0.985)



In CCM



In DCM

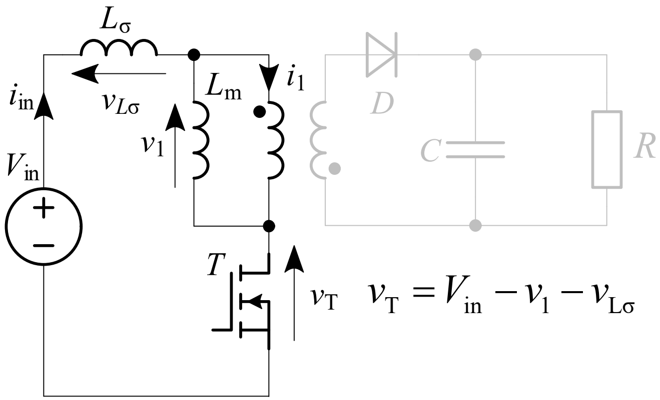
The overvoltage on transistor can be much higher than rated $V_{in}+V_O(N_1/N_2)$ and will cause the damage to transistor .

Influence of leakage inductance

The overvoltage on transistor occur due to its fast switching off lasting for t_{off} of the maximum current i_{Lmax}.

Voltage across the leakage inductance $v_{L\sigma}$ increases the transistor voltage v_T.

$$v_{L\sigma} = L_\sigma \frac{di}{dt} = -L_\sigma \frac{i_{Lmax}}{t_{off}}$$

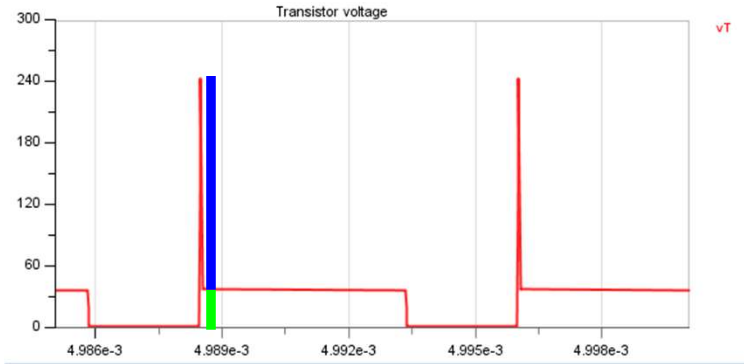


$$v_T = V_{in} - v_1 - v_{L\sigma}$$

After transistor switching off the primary side transformer voltage is $v_1 = -V_O N_1/N_2$

The value of the overvoltage across transistor is

$$v_T = V_{in} + V_O\left(\frac{N_1}{N_2}\right) + L_\sigma \frac{i_{Lmax}}{t_{off}}$$

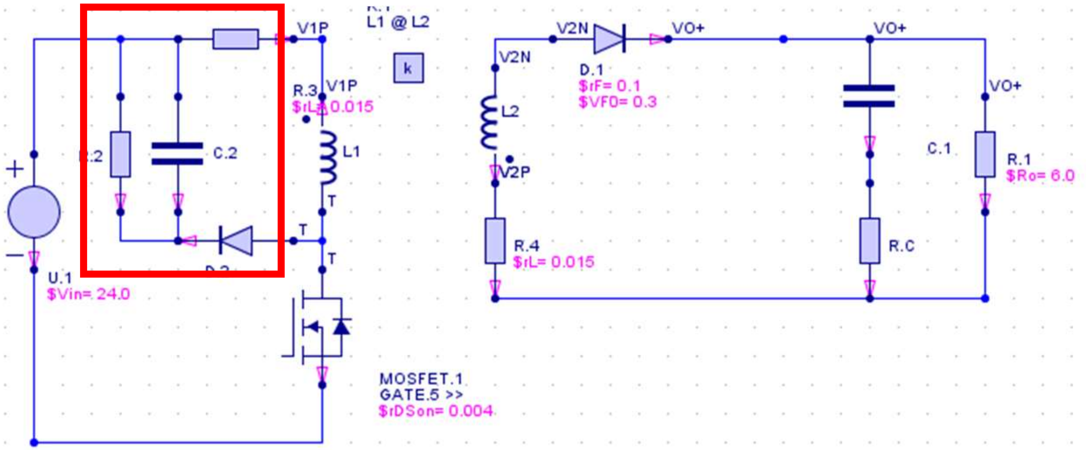


The leakage inductance voltage can be evaluated basing on transistor switching time which is at a level of a few nanoseconds to several nanoseconds. In previous example #2 $L_\sigma = 12\ \mu H$ and $i_{Lmax} = 5.5\ A$.

$$v_{L\sigma} = -L_\sigma \frac{i_{Lmax}}{t_{off}} = 12 \cdot 10^{-6}\,H \frac{5.5\,A}{10 \cdot 10^{-9}\,s} = 6600\,V$$

Reduction of overvoltage

The overvoltage on transistor can be reduced by using RCD network also referred as snubber circuit.

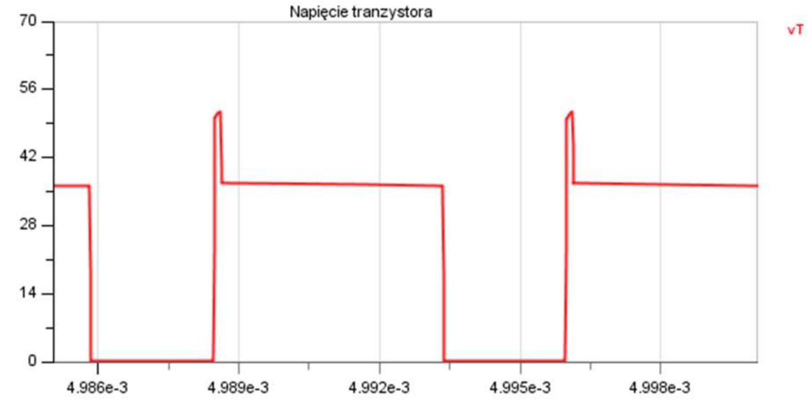


The snubber capacitor stores the energy from the lakage inductance. The voltage across this capacitor depends on the energy, capacitance and snubber resistance.

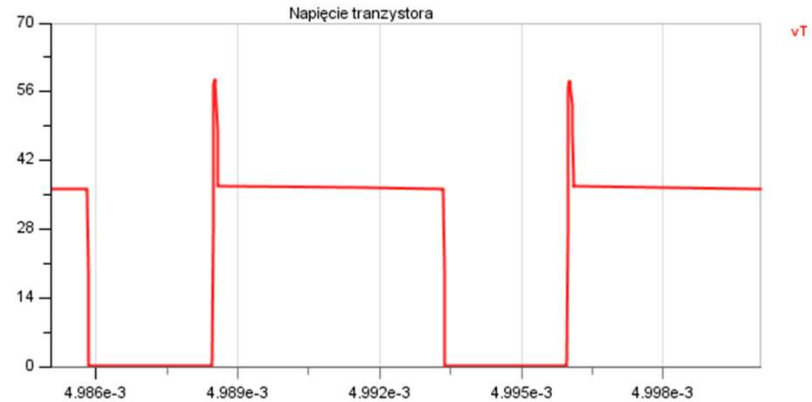
$$V_{\text{Csnubber}} > V_{\text{O}}\left(\frac{N_1}{N_2}\right)$$

The transistor peak voltage is limited to $V_{\text{in}}+V_{\text{Csnubber}}$

$$C_{\text{snubber}} = 220\ \text{nF}; \quad R_{\text{snubber}} = 500\ \Omega$$



$$C_{\text{snubber}} = 100\ \text{nF}; \quad R_{\text{snubber}} = 1000\ \Omega$$



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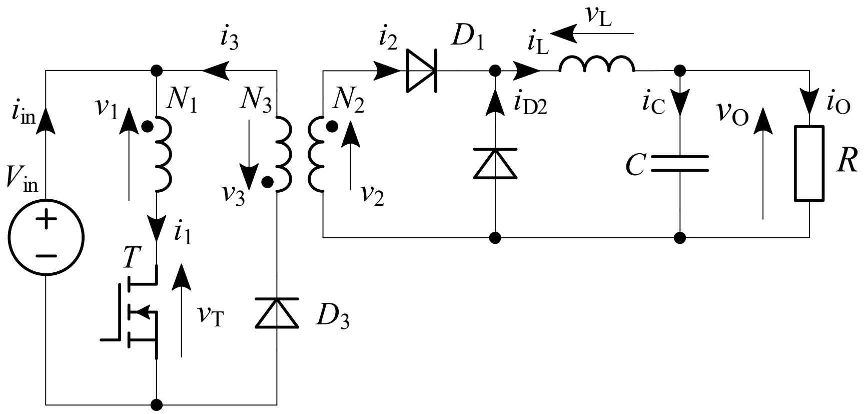
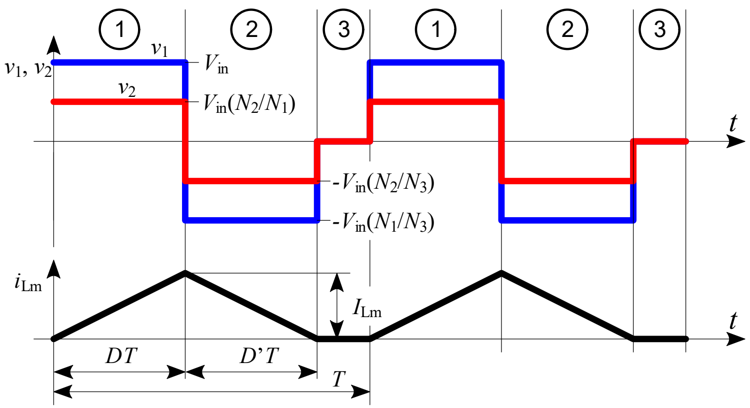
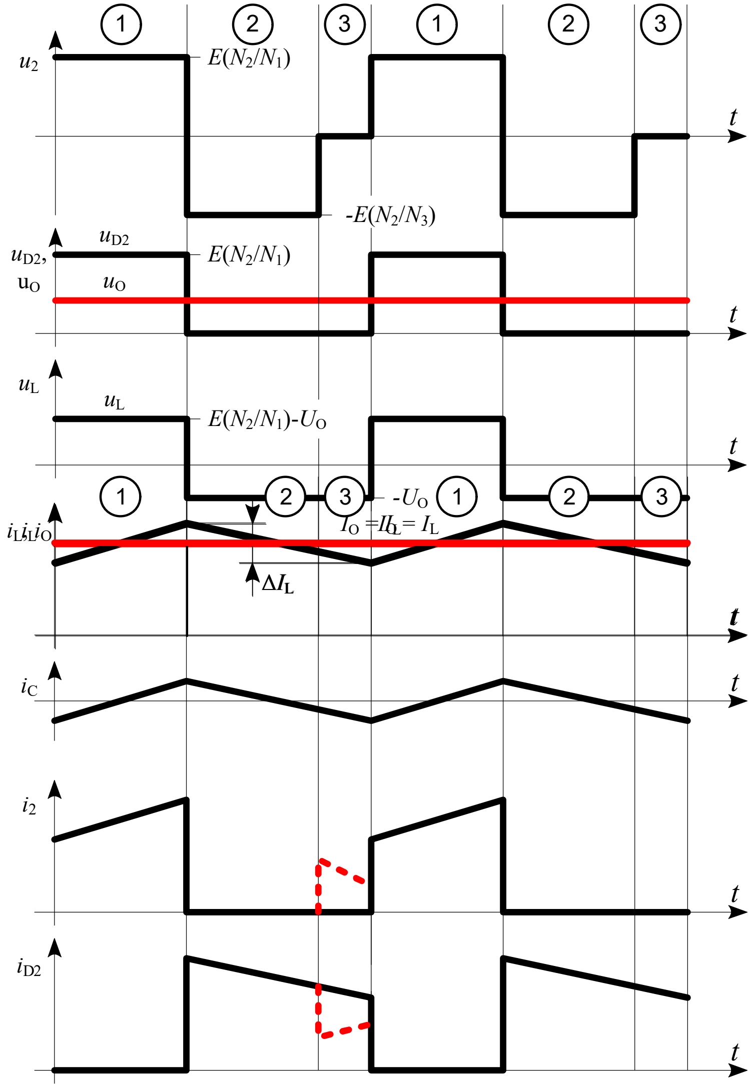
Forward converter

The schematic of the forward converter



Duty cycle is limited to D = 0.5 (when $N_3 = N_1$)





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