Power Electronics
Lecture 2

BUCK converter

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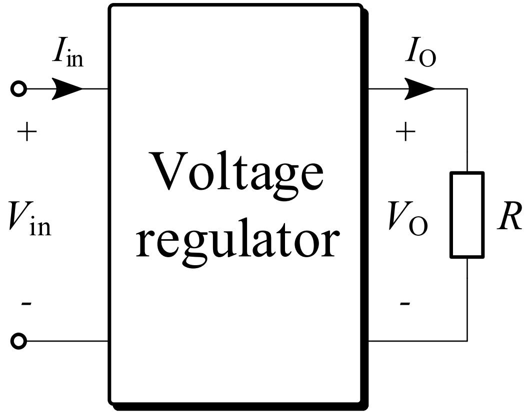
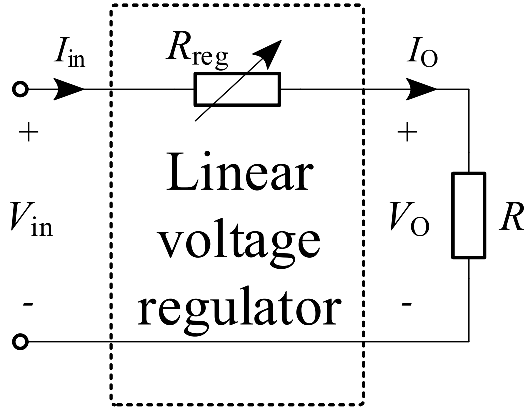
Voltage regulator

Voltage regulator maintains the constant output voltage V_O regardless the input voltage V_{in} and the output current I_O





In an ideal lossless voltage regulator $P_{in} = P_O$

$$P_{in} = P_O \Rightarrow V_{in} \times I_{in} = V_O \times I_O$$

$$I_{in} = I_O \frac{V_O}{V_{in}}$$

In a linear regulator $I_{in} = I_O$ and $V_{in} = V_O + I_O R_{reg}$

$$P_{in} = V_{in} \times I_{in} = \left(I_O R_{reg} + V_O \right) \times I_O = I_O{}^2 R_{reg} + V_O \times I_O = I_O{}^2 R_{reg} + P_O$$

A linear regulator is not an ideal because great amount of energy is lost on R_{reg}.

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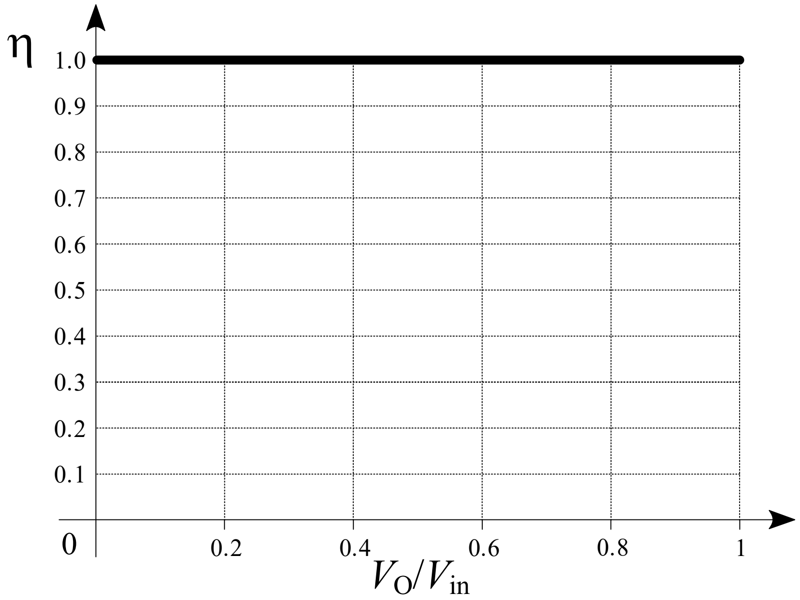
Efficiency of idear and linear regulators

Efficiency of an ideal regulator

$$P_{in} = P_O$$

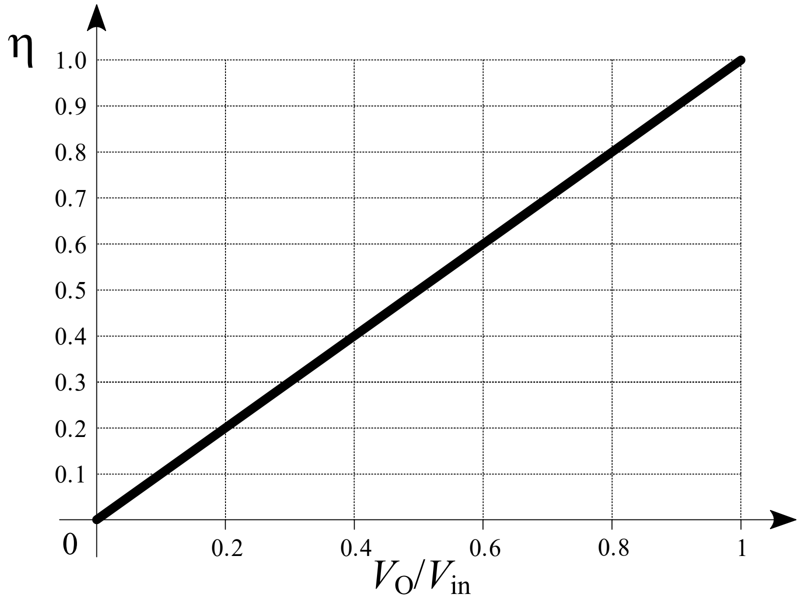
$$\eta = \frac{P_O}{P_{in}} = 1$$



Efficiency of a linear regulator

$$P_{in} \neq P_O$$

$$\eta = \frac{P_O}{P_{in}} = \frac{V_O \times I_O}{V_{in} \times I_{in}} \overset{I_{in}=I_O}{=} \frac{V_O}{V_{in}}$$



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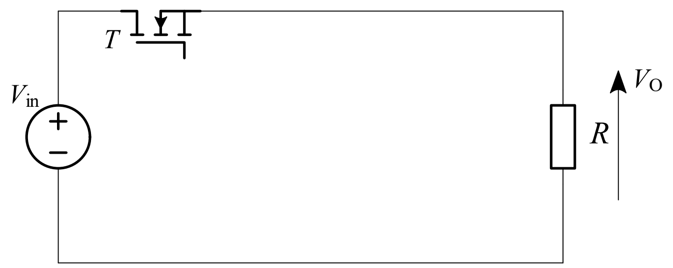
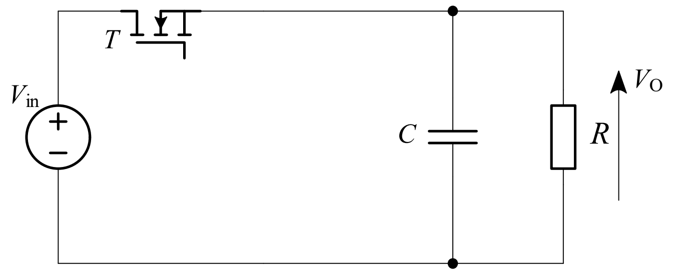
Derivation of BUCK converter topology in four steps

Applying the switch *T* increases the efficiency



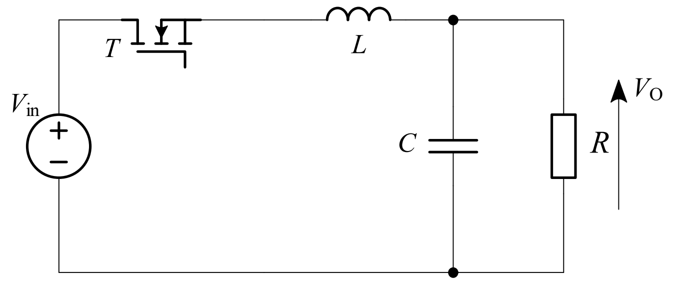
The output voltage is rectangular but not constant

The output capacitor *C* keeps the voltage constant



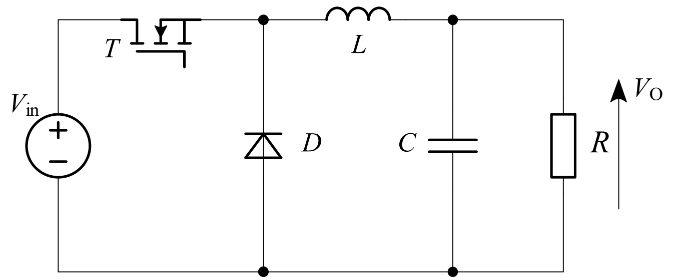
Capacitors should not be connected directly to voltage sources

The inductor *L* interconnects the capacitor and V_{in}



The switch should not disconnect the inductor current

Diode protects the switch against voltage surge



BUCK converter topology also known as step down converter

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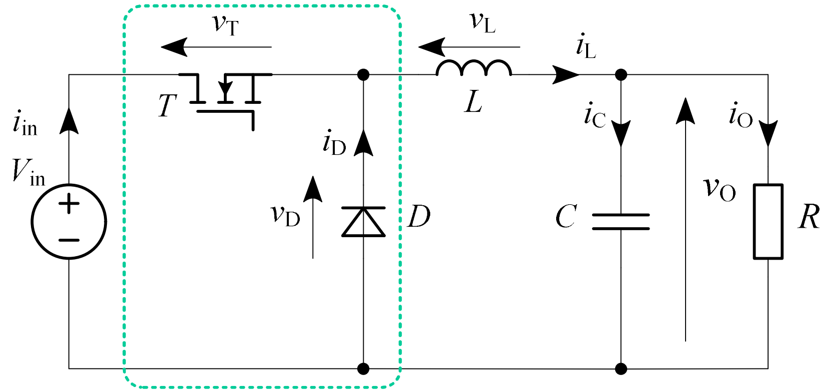
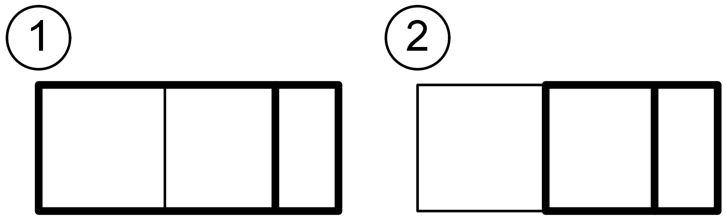
Buck converter

The buck converter (a step-down converter) utilizes switching power block

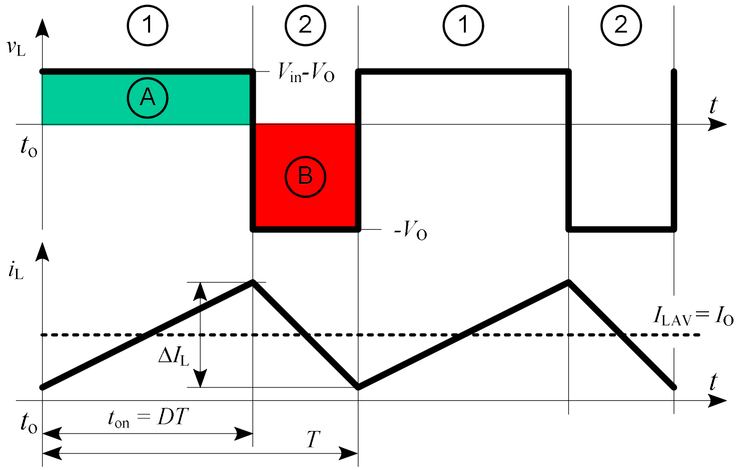


Transistor T works in on- and off-state which corresponds to two equivalent circuits (with marked current paths)



Inductor voltage allows to determine the inductor current which is one of the buck converter state variable.

In steady state operation:



A = B

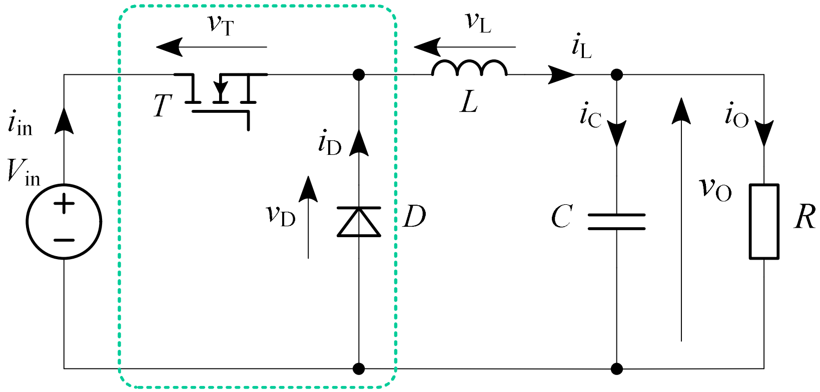
$$v_L(t) = L\frac{di(t)}{dt}$$

$$i_L(t) = i_L(t_o) + \frac{1}{L}\int_{t_o}^{t_o+t} v(t)dt \qquad i_L(T+t_o) = i_L(t_o) + \underbrace{\frac{1}{L}\int_{t_o}^{T+t_o} v(t)dt}_{0}$$

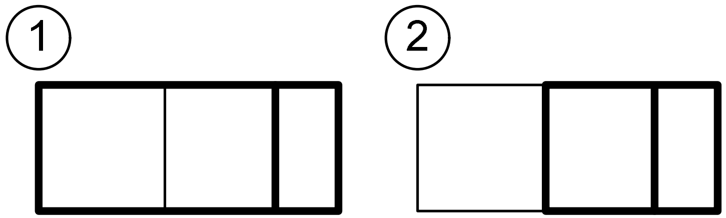
$$\Delta I_{L1} = \frac{1}{L}\int_{t_o}^{t_o+DT} (V_{in} - V_O)dt = \frac{(V_{in} - V_O)}{L} DT \qquad where\, D = \frac{t_{on}}{T}$$

Buck converter

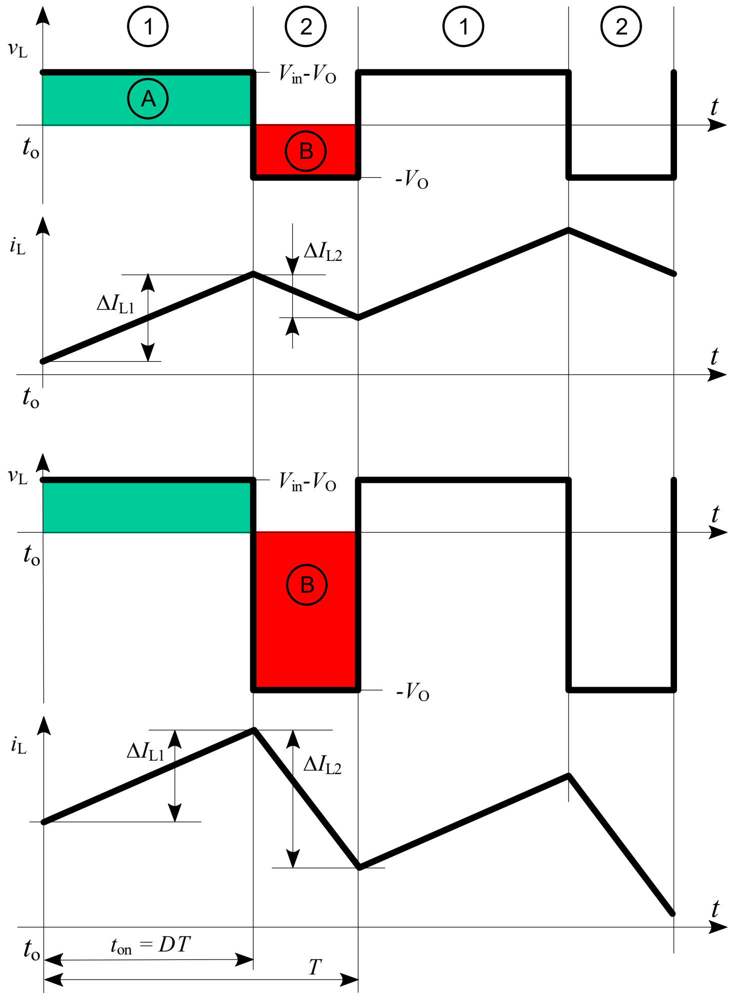
The buck converter (a step-down converter) utilizes
switching power block



Transistor *T* works in on- and off-state which corresponds to two equivalent circuits (with marked current paths)



Operation not in steady state:



A > B

$$\Delta I_{L1} = \frac{(V_{in} - V_O)}{L} DT$$

$$\Delta I_{L2} = -\frac{V_O}{L}(1-D)T$$

A < B

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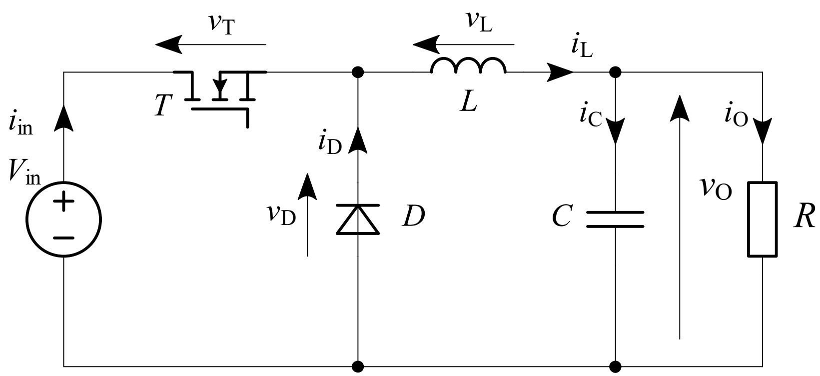
Capacitor current and voltage



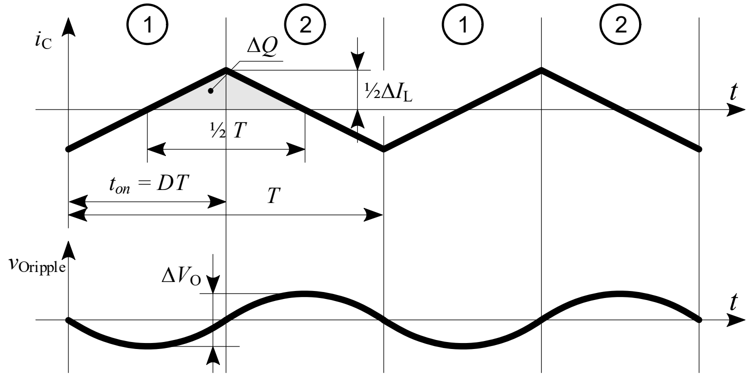
The capacitor current is given as $v_o(t) = v_o(t_o) + \frac{1}{C}\int_{t_o}^{t_o+t} i_C(t)dt$

which leads to $v_o(T+t_o) = v_o(t_o) + \underbrace{\frac{1}{C}\int_{t_o}^{T+t_o} i_C(t)dt}_{0}$

Which means that capacitor current in the periodic steady state has the average value equal to zero

$$I_{CAV} = \frac{1}{T}\int_{t_o}^{T+t_o} i_C(t)dt = 0$$

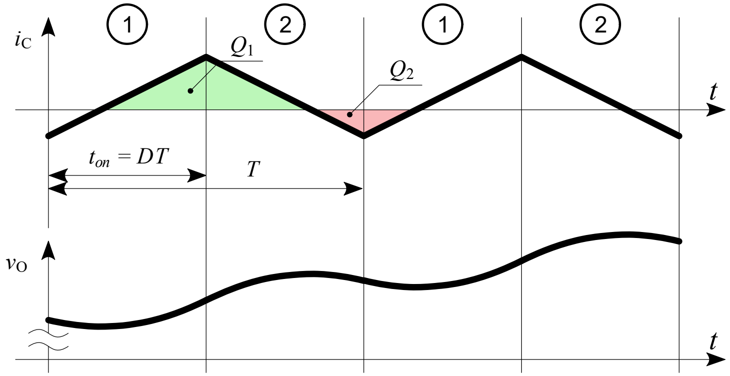
Operation in steady state:



$$\Delta Q = \frac{1}{2}\cdot\frac{T}{2}\cdot\frac{\Delta I_L}{2} = \frac{T\Delta I_L}{8} = \frac{\Delta I_L}{8f} = \frac{V_{in} - V_O}{8f^2L}D$$

Operation not in steady state:

$Q_1 > Q_2$



$$\Delta V_O = \frac{\Delta Q}{C} = \frac{V_{in} - V_O}{8f^2LC}D \overset{V_O = V_{in}D}{=} \frac{V_{in}D(1-D)}{8f^2LC}$$

The output voltage increases

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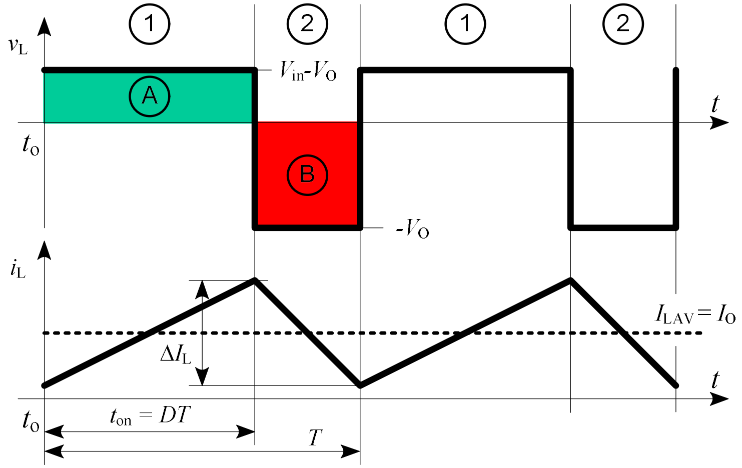
The output voltage

Due to the inductor voltage is zero in a steady state it is possible to derive the output voltage as a function of duty cycle D and input voltage V_{in}.



$$\text{Area}_A - \text{Area}_B = 0$$

$$(V_{in} - V_O)DT - V_O(1-D)T = 0$$

$$V_{in}D - V_O D - V_O + V_O D = 0$$

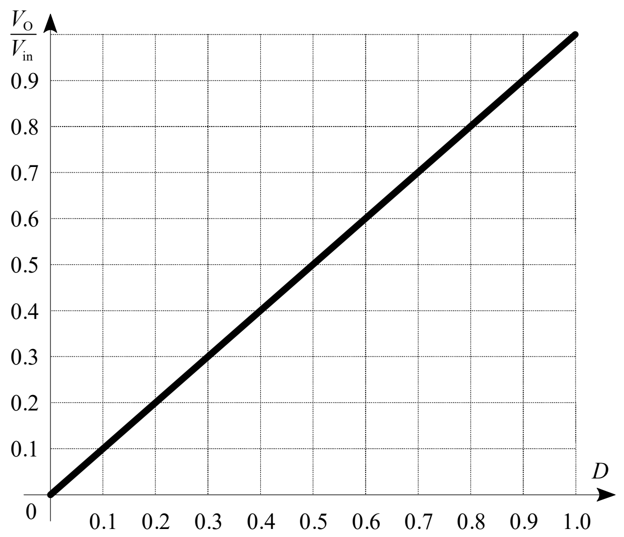
$$V_{in}D - V_O = 0$$

$$\boxed{V_O = V_{in}D}$$

The output voltage $V_O = V_{in}D$ is only true when the converter works in continuous conduction mode CCM

The output voltage control characteristic

$$\frac{V_O}{V_{in}} = D$$



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CCM operation

Continuous conduction mode (CCM) means that the converter operates with the continuous inductor current

Inductor current ripple is given as:

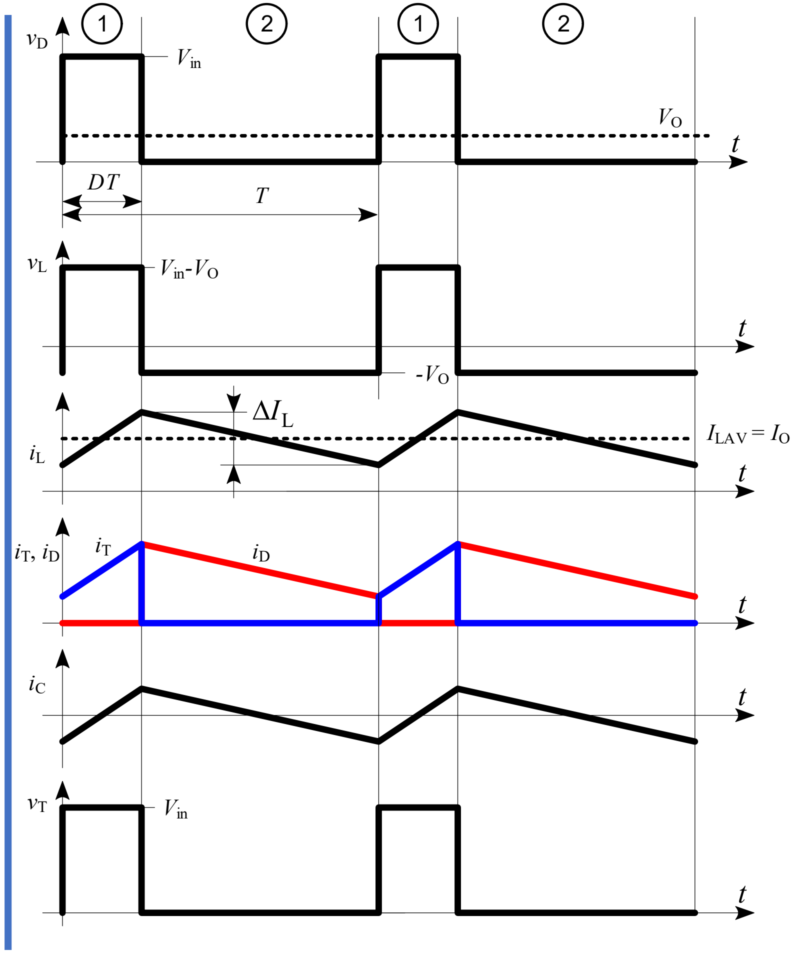
$$\Delta I_L = \frac{1}{L}\int_0^{DT} v_L(t)dt = \frac{V_{in} - V_O}{L} DT$$

$$\Delta I_L \overset{V_O = V_{in} D}{=} \frac{V_{in} T}{L} D(1-D)$$

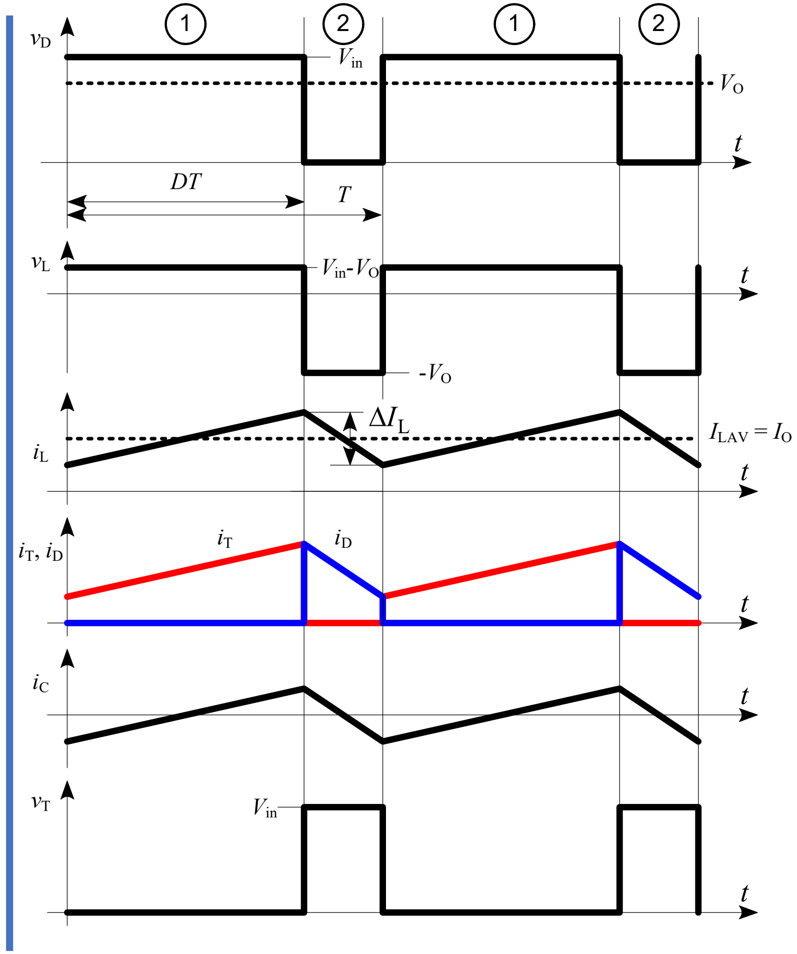
$$\Delta I_L = \frac{V_O T}{L}(1-D) = \frac{V_{in} T}{L} D(1-D)$$

It is assumed that the output voltage ripples are zero

D = 0.25



D = 0.75

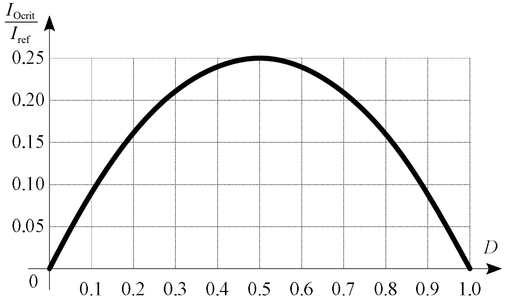


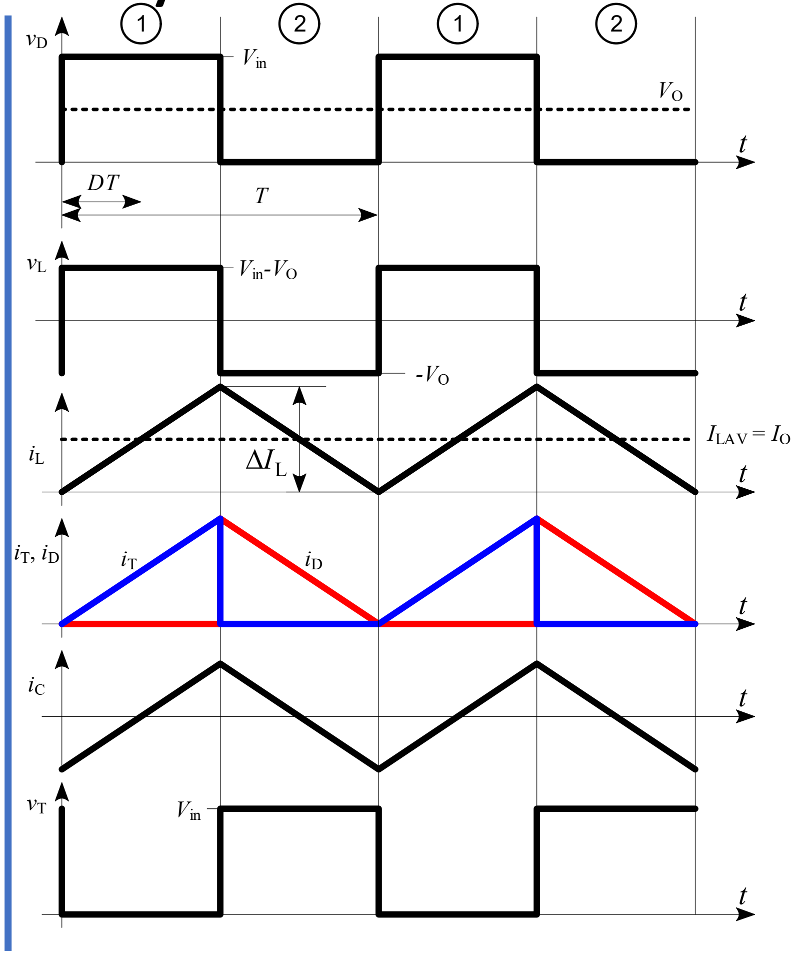
CCM/DCM boundary

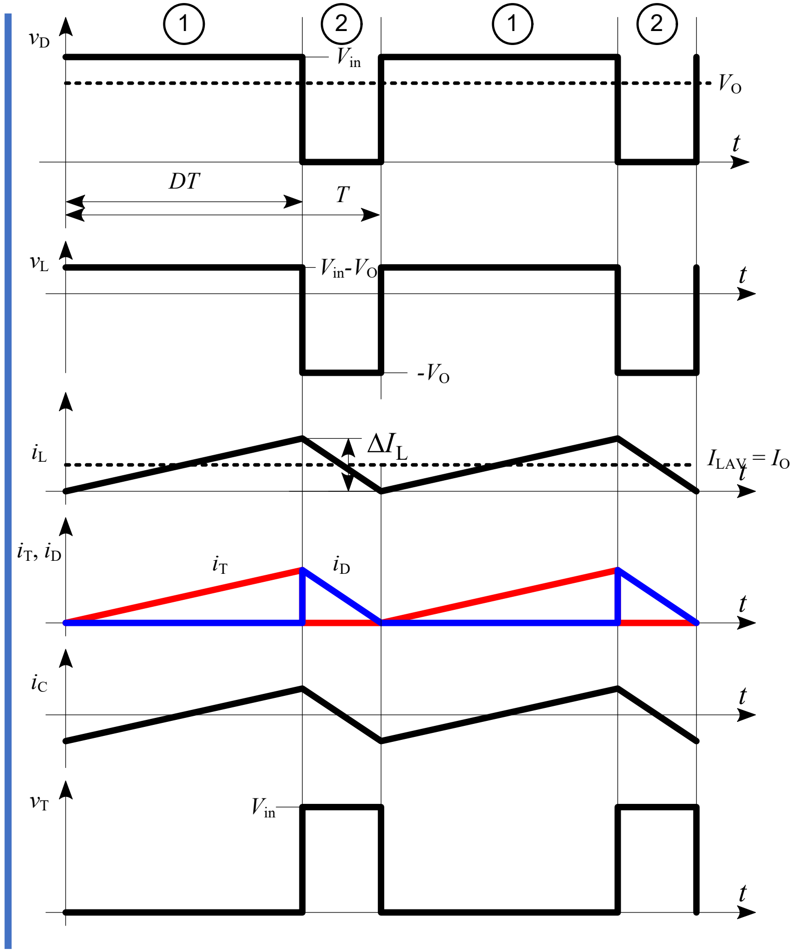
When the output current $I_O = I_{Ocrit} = ½\Delta I_L$ the converter operates at boundary between continuous conduction mode (CCM) and discontinuous conduction mode (DCM)

$$I_{Ocrit} = \frac{1}{2}\Delta I_L = \frac{V_{in}T}{2L}D(1-D)$$

$$I_{Ocrit} \overset{I_{ref}=\frac{V_{in}T}{2L}}{=} I_{ref}D(1-D)$$

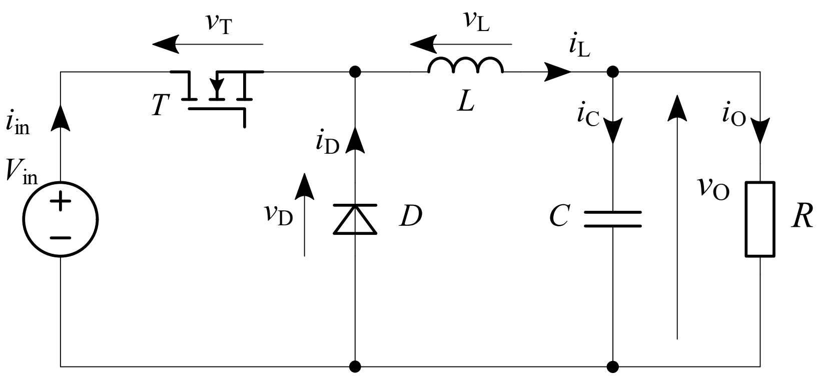


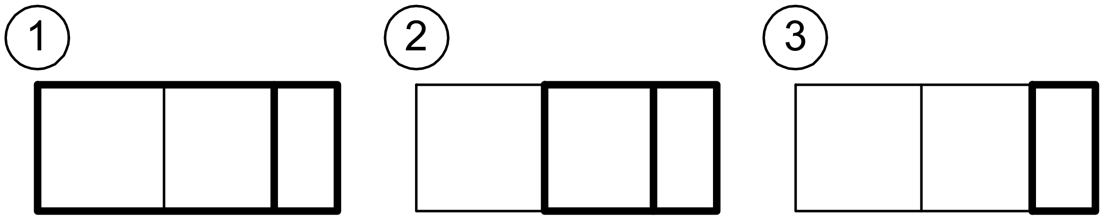




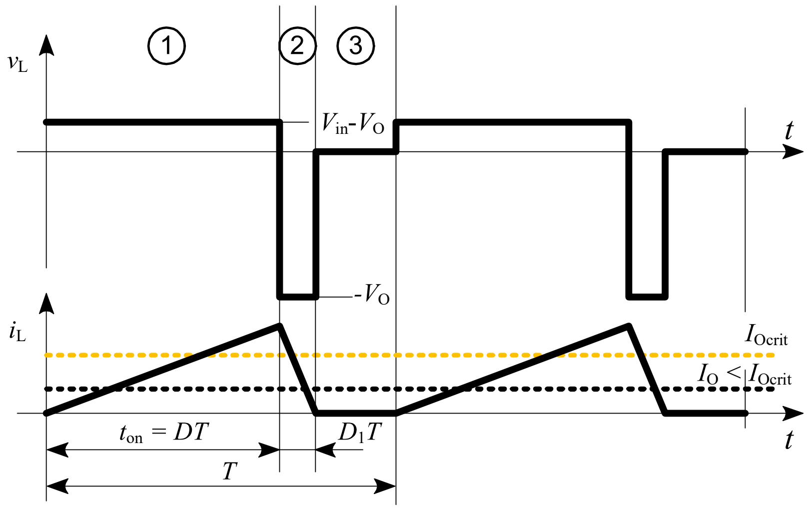
DCM operation

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





$t \in (0, DT)$ $\quad$ $t \in (DT, D_1T)$ $\quad$ $t \in (D_1T, T)$



$$V_{LAV} = (V_{in} - V_O)D + (-V_O)D_1 = 0$$

$$D_1 = \frac{V_{in} - V_O}{V_O} D$$

$$I_O = \frac{1}{2}\Delta I_L (D + D_1), \text{ where } \Delta I_L = \frac{V_{in} - V_O}{L} DT$$

$$I_O = \frac{1}{2}\frac{V_{in} - V_O}{L} DT\left(D + \frac{V_{in} - V_O}{V_O} D\right) = \frac{V_{in} - V_O}{2L} TD^2\left(1 + \frac{V_{in} - V_O}{V_O}\right)$$

$$I_O = \frac{V_{in} - V_O}{2L} TD^2\left(\frac{V_{in}}{V_O}\right) \overset{I_{ref} = \frac{V_{in}T}{2L}}{=} I_{ref}\frac{V_{in} - V_O}{V_O} D^2$$

Output characteristics

In DCM the output voltage V_O is dependent on the output current I_O, input voltage V_{in} and duty cycle D

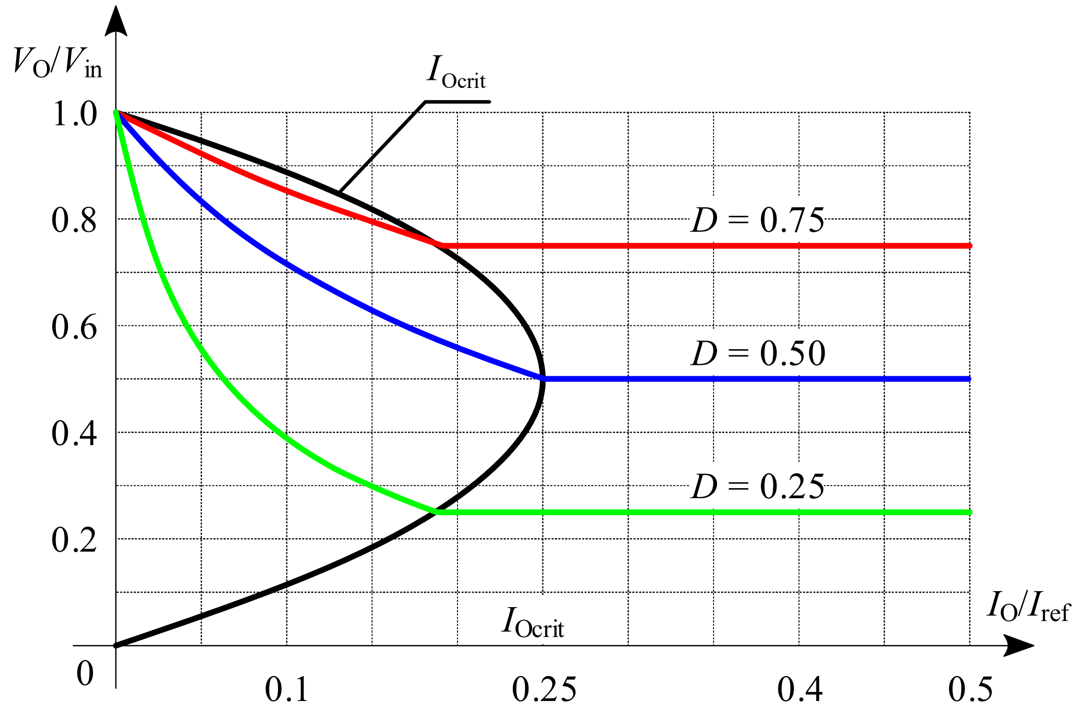
$$I_O = I_{ref}\frac{V_{in}-V_O}{V_O}D^2 = I_{ref}\left(\frac{V_{in}}{V_O}-1\right)D^2$$

In DCM
$$\frac{I_O}{I_{ref}}\frac{1}{D^2} = \left(\frac{V_{in}}{V_O}-1\right) \Rightarrow \frac{V_{in}}{V_O} = \frac{I_O}{I_{ref}}\frac{1}{D^2}+1$$

$$\frac{V_O}{V_{in}} = \frac{1}{\frac{I_O}{I_{ref}}\frac{1}{D^2}+1}$$

In CCM
$$\frac{V_O}{V_{in}} = D$$

At CCM/DCM boundary
$$I_{Ocrit} \overset{I_{ref}=\frac{V_{in}T}{2L}}{=} I_{ref}D(1-D)$$



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Buck with V_O = const

$$I_O = \frac{V_{in} - V_O}{2L} T D^2 \left(\frac{V_{in}}{V_O}\right) \overset{I_{Oref} = \frac{V_O T}{2L}}{=} I_{Oref}\left(V_{in} - V_O\right)\frac{V_{in}}{V_O^{\ 2}} D^2$$

In DCM

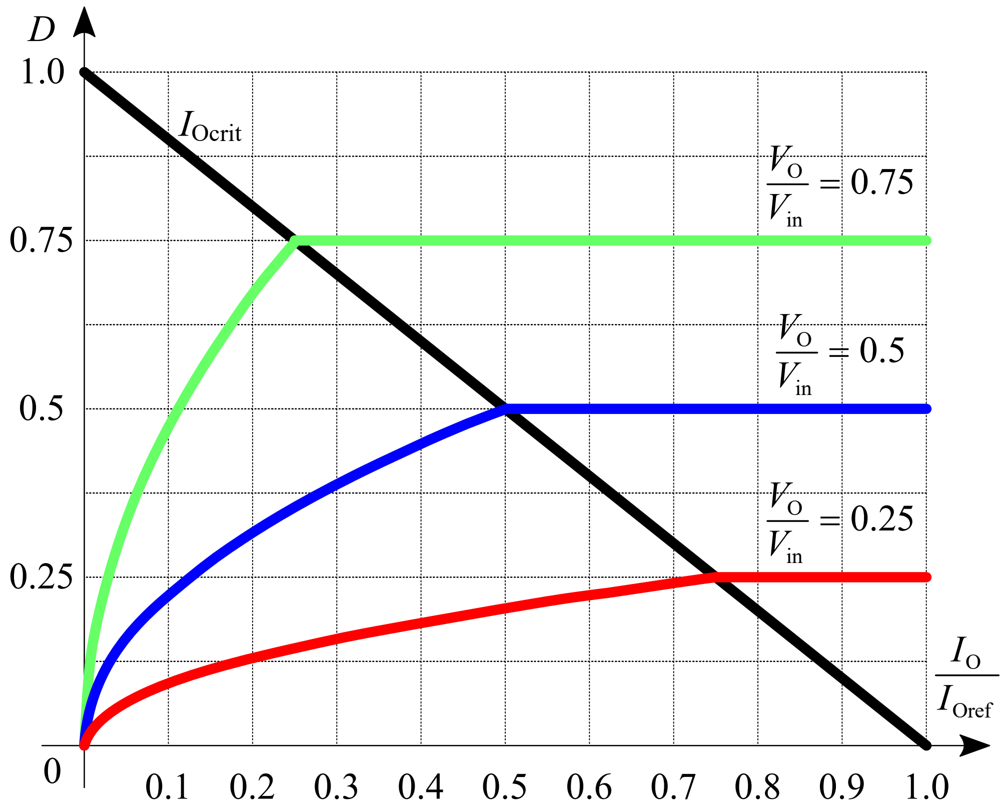
$$D^2 = \frac{\frac{I_O}{I_{Oref}}}{\left(\frac{V_{in}}{V_O}\right)^2 - \frac{V_{in}}{V_O}} \Rightarrow D = \sqrt{\frac{\frac{I_O}{I_{Oref}}}{\left(\frac{V_{in}}{V_O}\right)^2 - \frac{V_{in}}{V_O}}}$$

In CCM $\quad D = \frac{V_O}{V_{in}}$

At CCM/DCM boundary

$$I_{Ocrit} = \frac{V_{in} T}{2L}\frac{V_O}{V_O} D(1-D)$$

$$I_{Ocrit} \overset{I_{Oref} = \frac{V_O T}{2L}}{=} I_{Oref}\frac{V_{in}}{V_O} D(1-D) = I_{Oref}\frac{1}{D} D(1-D) = I_{Oref}(1-D)$$



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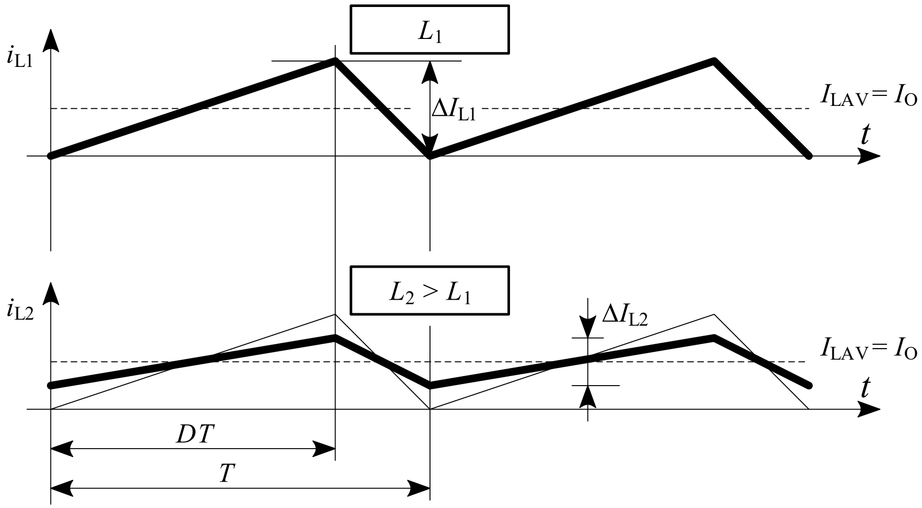
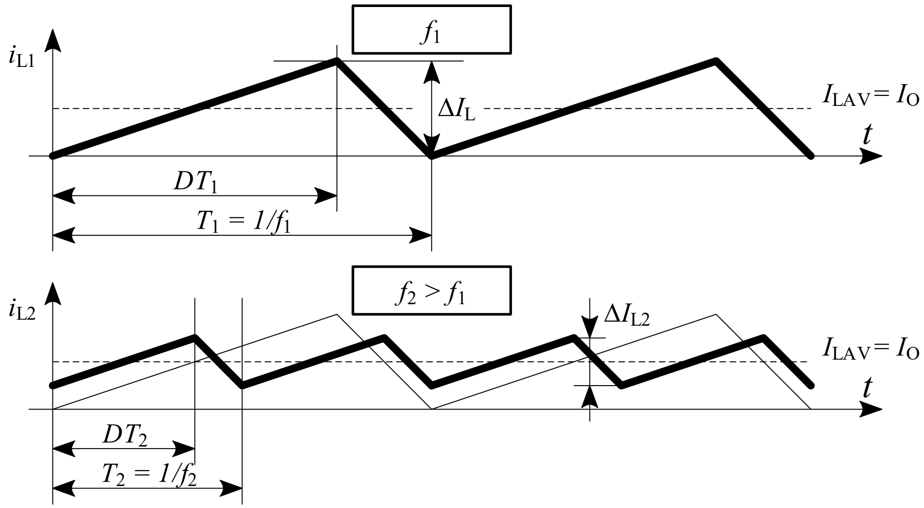
Parameter influence

When the buck converter operates at DCM/CCM and inductance increases



The converter will work in CCM

When the buck converter operates at DCM/CCM and frequency increases



The converter will work in CCM

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