TAMPEREEN TEKNILLINEN YLIOPISTO

Aspects on designing switched-mode power electronic converter for photovoltaic application

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Content

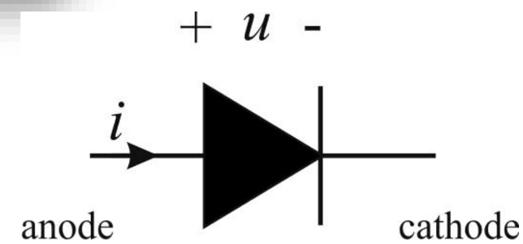
Diode

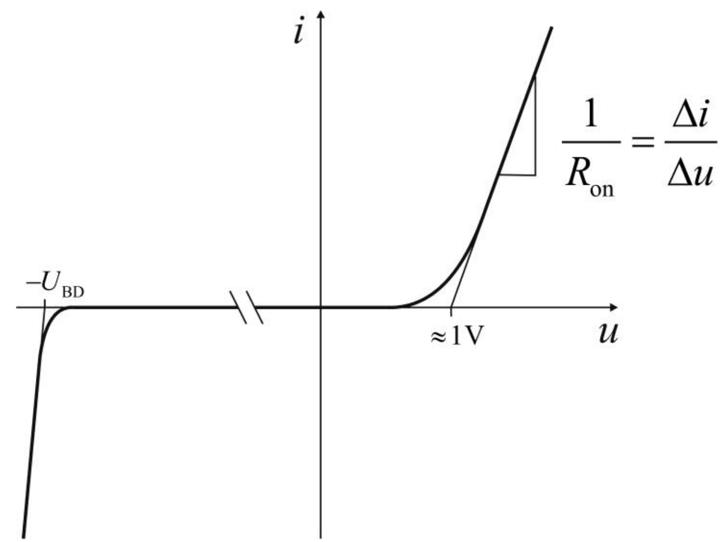
- Diode conducts current when positive voltage is applied between anode and cathode.

- Diode turns off when the current drops to zero and voltage goes negative, i.e. diodes cannot be actively controlled on or off

- Real diodes have a small forward voltage drop (0,7-1,4V) and resistive voltage drop
- Voltage drop can be estimated from the knee of the ui-curve
- On-state resistance can be estimated from the slope of the ui-curve

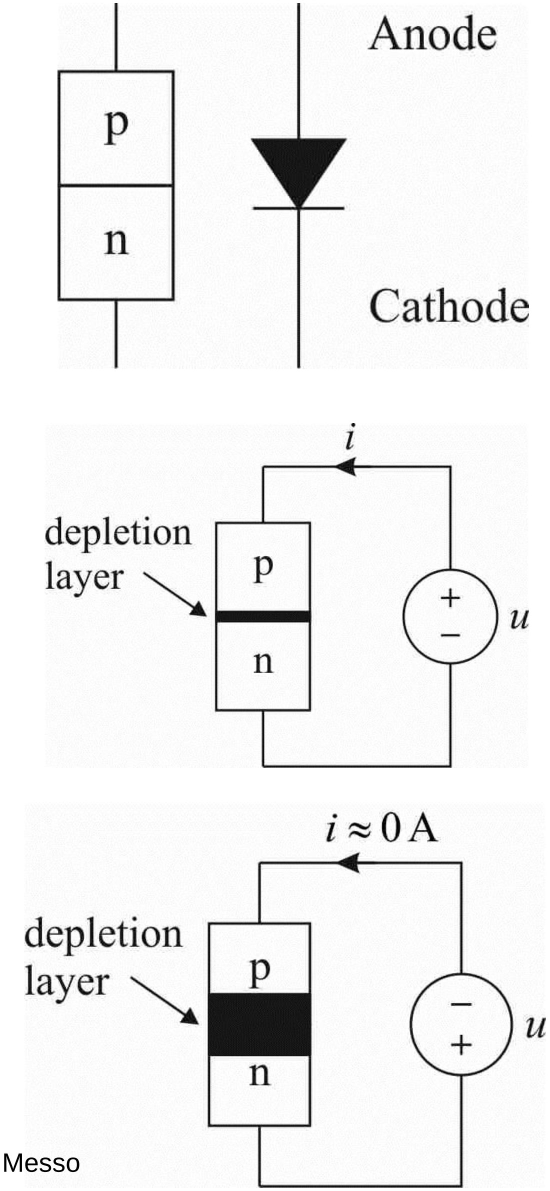
- Exceeding the current rating or maximum reverse voltage will destroy the diode





Diode as a switch

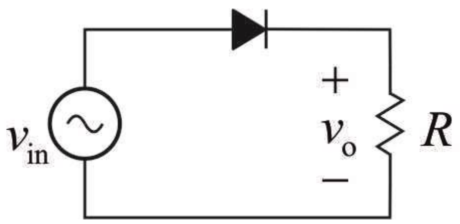
- PN-junction diode is formed by joining two different types of semiconductor material
- The junction conducts current when depletion layer (tyhjennysalue) is made narrower by forward voltage
- The junction block current when the pn-junction gets wider due to reverse voltage
- Forward voltage of a pn-junction diode is 0.7 – 1.4 V



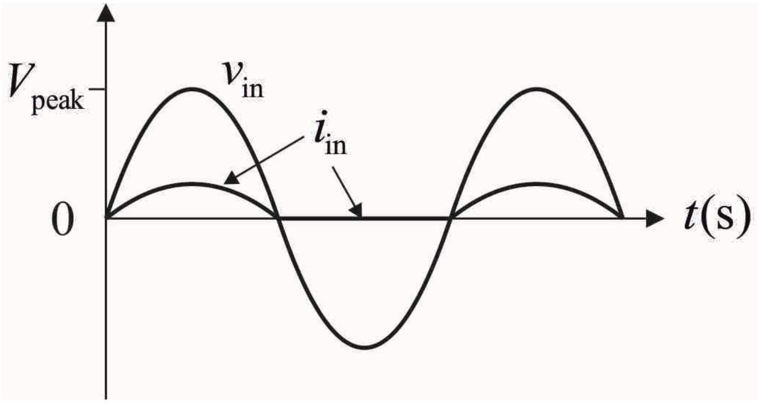
Picture: PhD Tuomas Messo

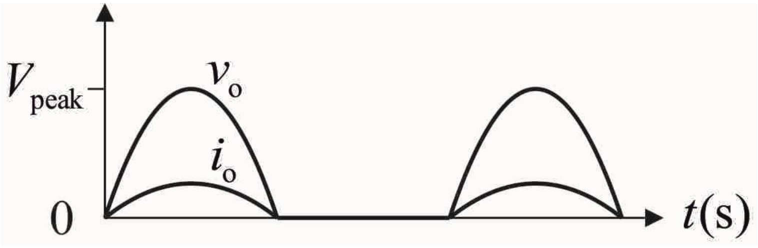
Half-wave rectifier

- The simplest way to transform AC into DC is to use a series diode



- Diode conducts when voltage over it is positive and blocks when it is reverse-biased
- Diode has to block negative source voltage





Picture: PhD Tuomas Messo

Diode applications

- Passive rectifiers
- DC-DC converters

powerelectronics.com

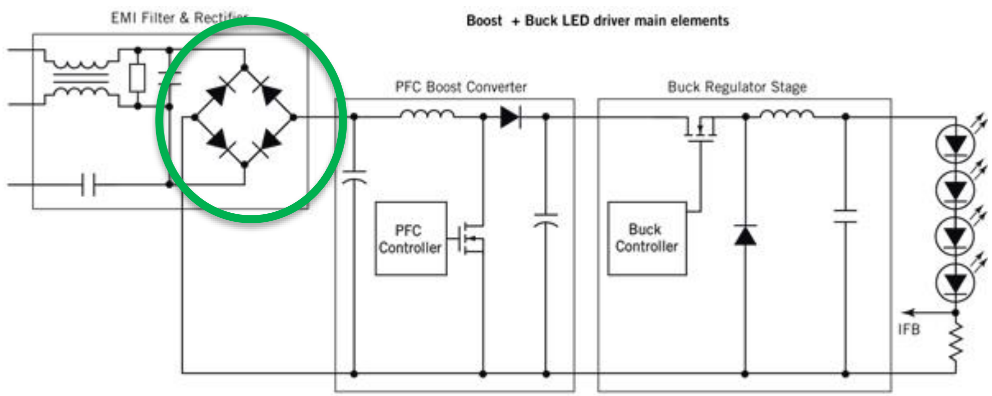
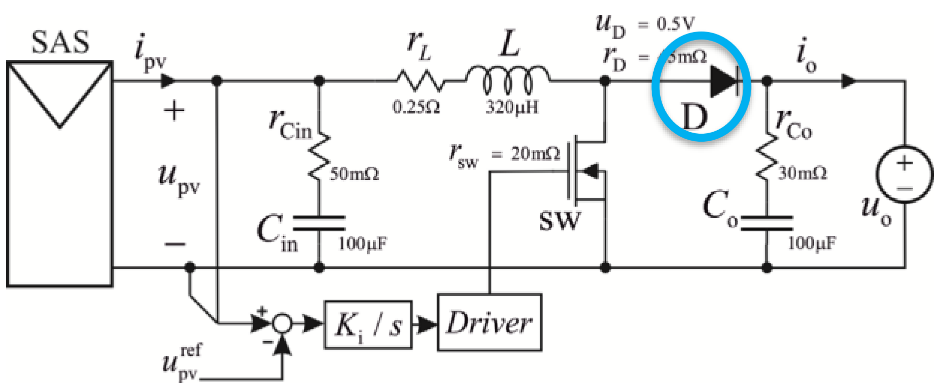


Fig. 1. Boost+Buck LED driver main elements

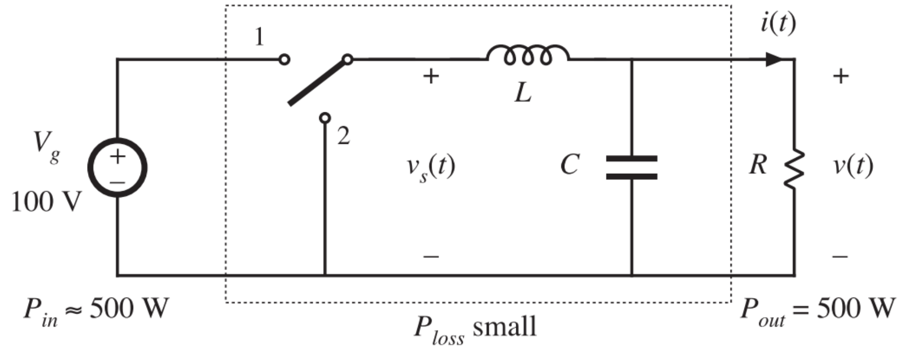


Content

1. Diode
2. MOSFET
3. Steady-state analysis principles, analysis in continuous conduction mode (CCM)
4. Buck converter
5. Boost converter
6. Buck-boost converter
7. Applications

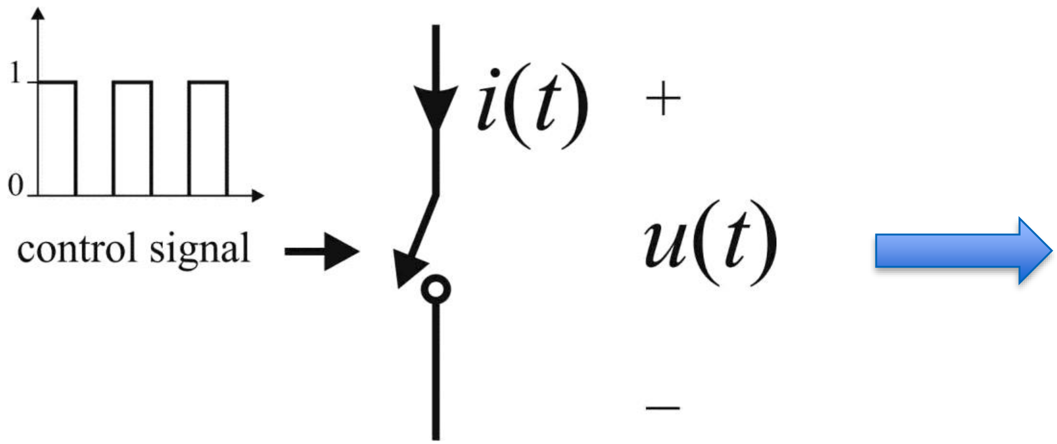
Power electronic switches

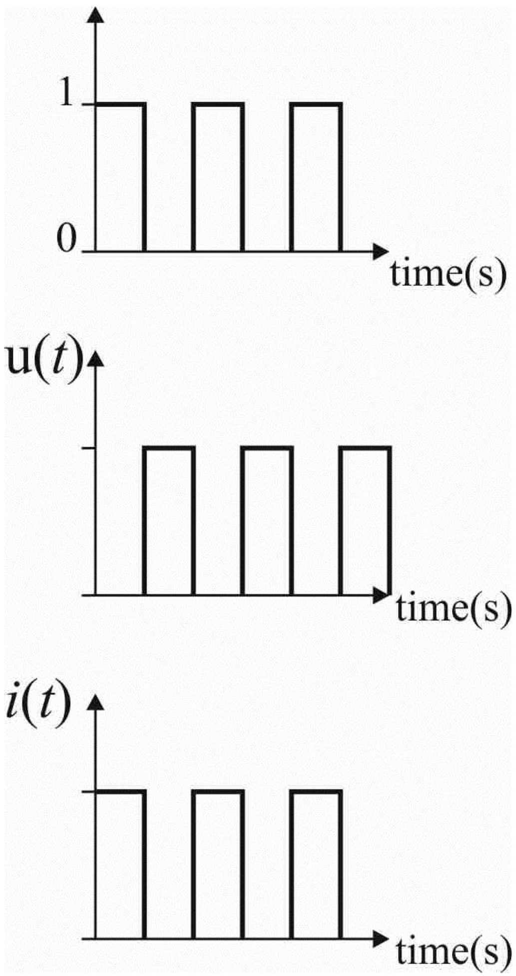
- It was mentioned already that the rectifier can be designed by using diodes. Diodes are not controllable -> the produced DC voltage amplitude is directly proportional into AC voltage amplitude. The controllable rectifier/inverter can be realized by using switches based on semiconductors
- We want to generate 50V DC voltage to the load, therefore we need controllable switch
- Active switches can be controlled on and off
- We need to generate the square wave from the DC source by connecting and disconnecting it from the circuit. To do that we need a reliable switch that is controllable by an electrical signal



Ideal switch

- Ideal switch blocks any voltage when turned off
- Ideal switch conducts any current with zero losses when turned on
- Ideal switch can change its state instantaneously

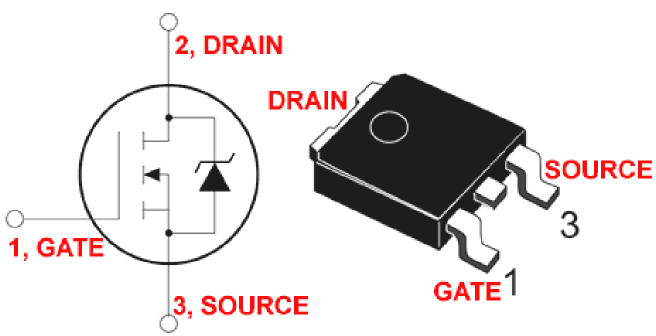


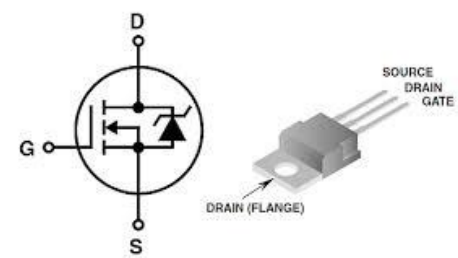


MOSFET (metal–oxide–semiconductor field-effect transistor)

- Voltage controlled device
- Low switching losses (f_{sw} 10MHz, V_{max} 1200V, I_{max} 150A)
- MOSFET requires very little current to turn on (less than 1mA), while delivering a much higher current to a load.
- The "metal" in the name MOSFET is a misnomer because the metal gate material is now often a layer of polysilicon. The "oxide" in the name can be a misnomer, as different dielectric materials are used.

- MOSFET invented in 1959. The first commercial MOSFET in 1964.
- The MOSFET is by far the most common transistor in both digital and analog circuits.
- MOSFETs are used in digital integrated circuits (microprocessors etc.), in power electronic applications (switched-mode power supplies, variable-frequency drives etc.) and in RF-amplifiers

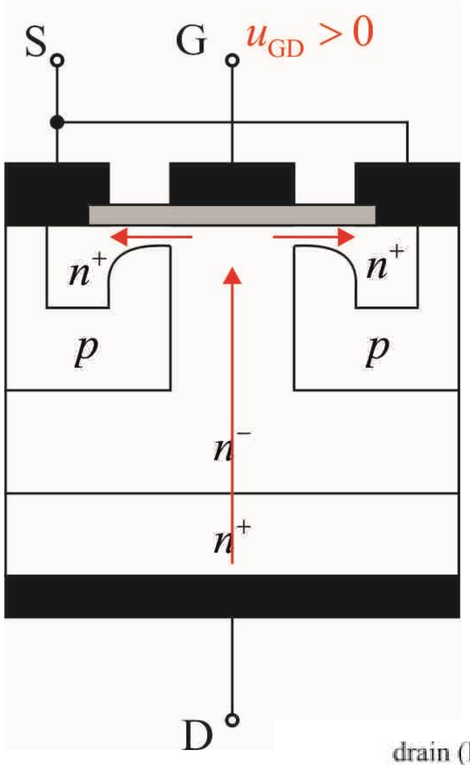


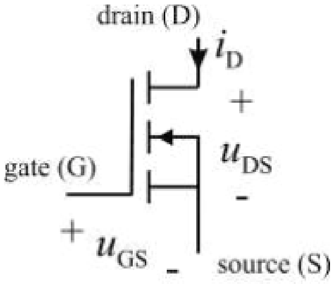


MOSFET operating principle

- MOSFET is a four-terminal device with source (S), gate (G), drain (D), and body (B) terminals.
- The body (or substrate) of the MOSFET is often connected to the source terminal, making it a three-terminal device.

- The flow of electrons from the drain to the source is controlled by the voltage applied to the gate.
- Positive voltage at the gate will attract negative charge carriers beneath the silicon oxide layer (npn-type)
  - Conducting channel (called inversion layer) with low resistance is formed
  - No gate current is required to maintain the inversion layer
  - The current between drain and source is controlled by the voltage which is applied to the gate. This is known as enhancement mode.

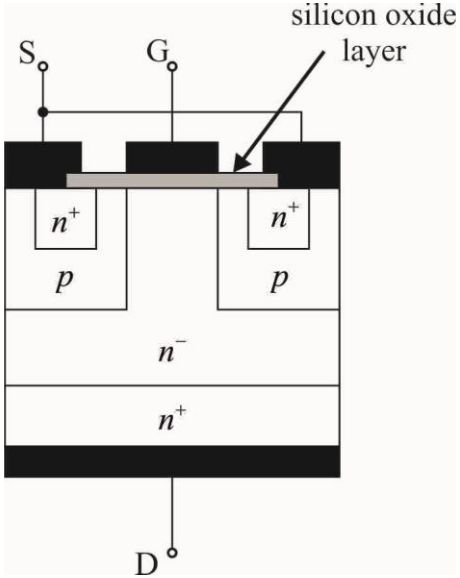


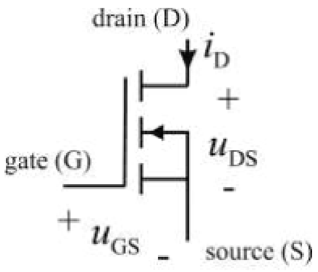


Picture: PhD Tuomas Messo

MOSFET operating principle

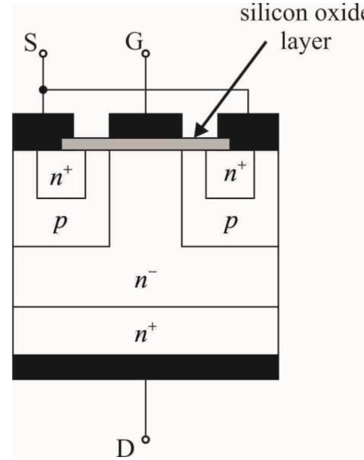
- In the off-state (no gate voltage) p-type material between n-type regions prevents current from flowing from source to drain.
- Gate is electrically insulated from the main current carrying channel (a silicon oxide layer)
  -> extremely high input resistance

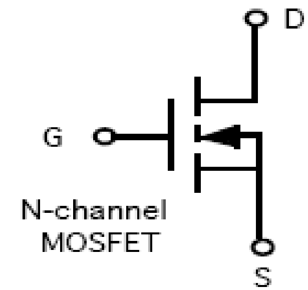




Picture: PhD Tuomas Messo

MOSFET N-type and P-type





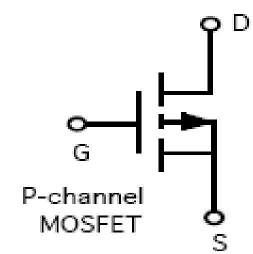
MOSFETs are available in two basic forms:

1. Enhancement Type (N-type/N-channel)

- The transistor requires V_{GS} to switch the device "ON".
- The enhancement mode MOSFET is equivalent to a "Normally Open" switch.
- Gate current flows only during transition between on and off-states
- n+ means the n-type semiconductor is more heavily doped and has more charge carriers

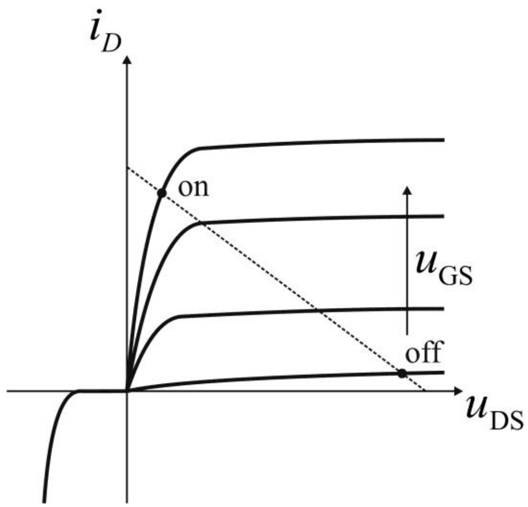
2. Depletion Type (P-type/P-channel)

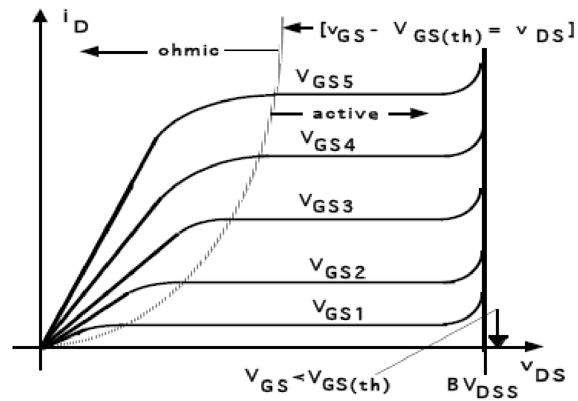
- The transistor requires V_{GS} to switch the device "OFF".
- The depletion mode MOSFET is equivalent to a "Normally Closed" switch.
- The channel contain holes
- $R_{ds,on}$ is three-times higher with P-type MOSFET than with N-type.
- Therefore N-type MOSFETs are mostly used.

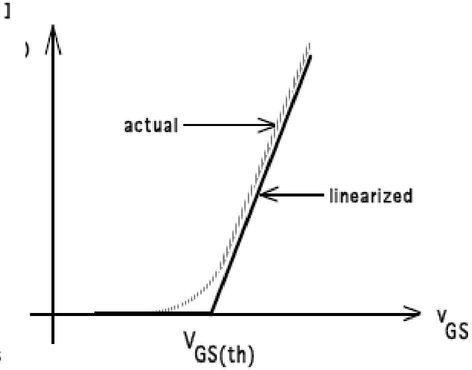


MOSFET IV-characteristics

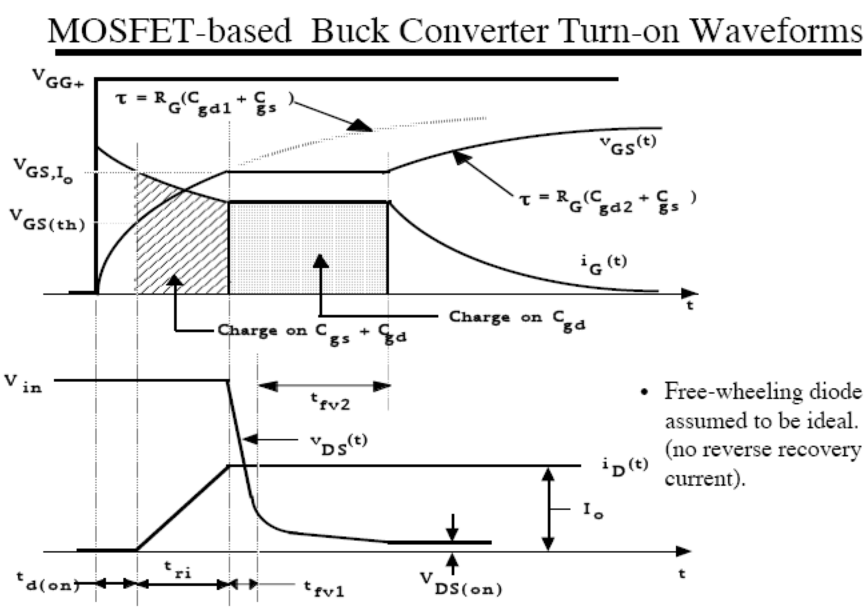
- Low on-state resistance and extremely high off-state resistance.
- MOSFET drain current vs. drain-to-source voltage for several values of V_{GS}-$V_{GS(TH).}$
- The boundary between linear (Ohmic) and saturation (active) modes is indicated by the upward curving parabola.
- Operation of the MOSFET where small changes of V_{GS} results in linear changes of the drain to source current in linear mode.

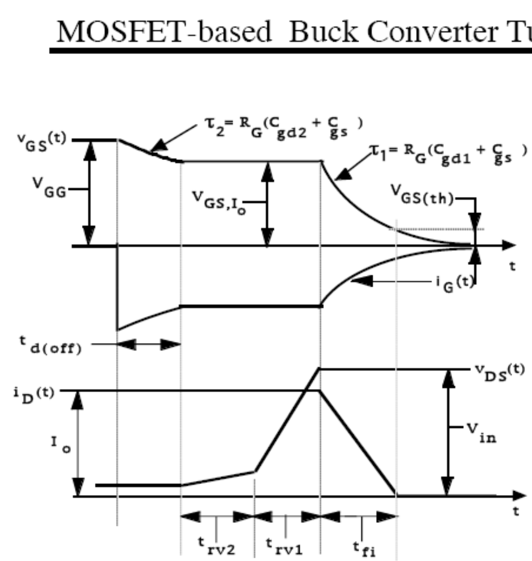




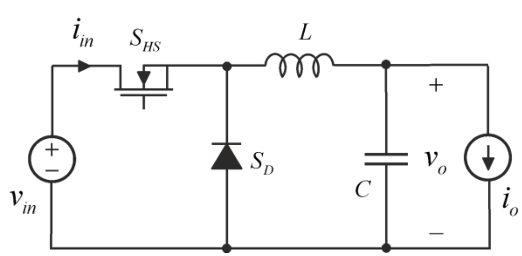


MOSFET turn on/off waveforms





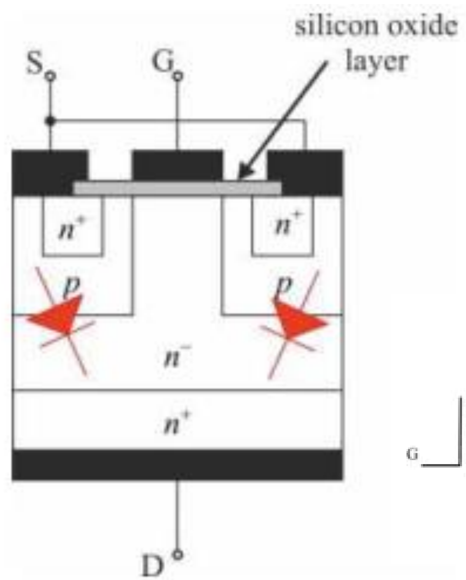
- Assume ideal free-wheeling diode.
- Essentially the inverse of the turn-on process.
- Model quantitatively using the same equivalent circuits as for turn-on. Simply use correct driving voltages and initial conditions

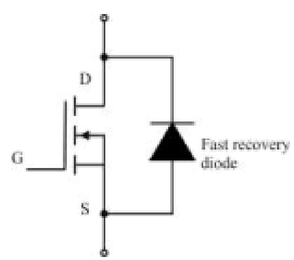


Picture: Mohan, Undeland, Robbins: Power Electronics

MOSFET parasitic body diode

- MOSFET contains a diode due to the p-n-structure when looking from source to drain. The diode is so called body diode and allows current flow in the opposite direction.
- The parasitic body diode is typically very slow (i.e., t_{rr} is long), and therefore, it is not recommended to be used in the switching procedures but under special conditions (i.e., soft switching schemes). The additional gate resistor is typically in the order of 10 ohms or less depending on the used switching frequency. An external diode can be connected anti-parallel with the MOSFET.





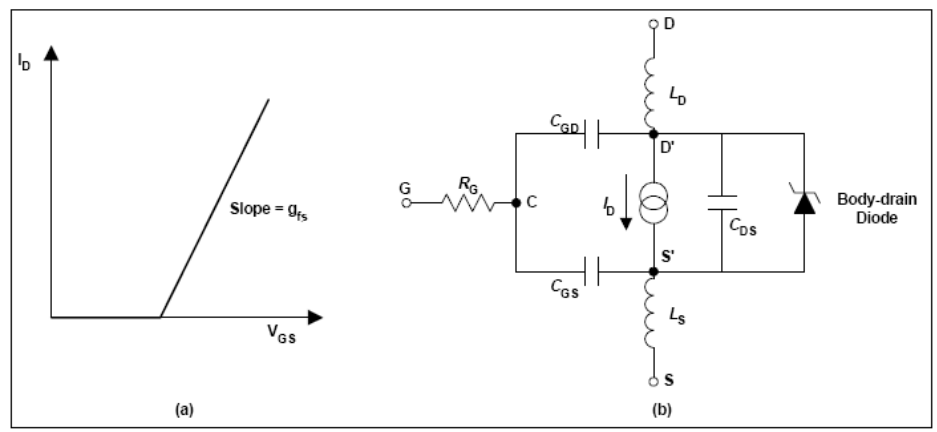


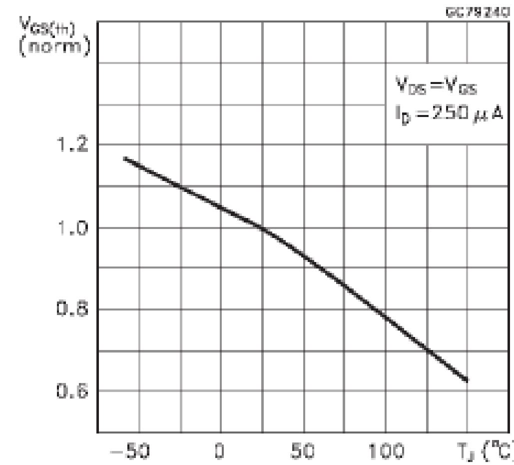
Figure 11. Power MOSFET (a) Transfer characteristics, (b) Equivalent Circuit Showing Components That Have Greatest Effect on Switching

MOSFET threshold voltage and resistance

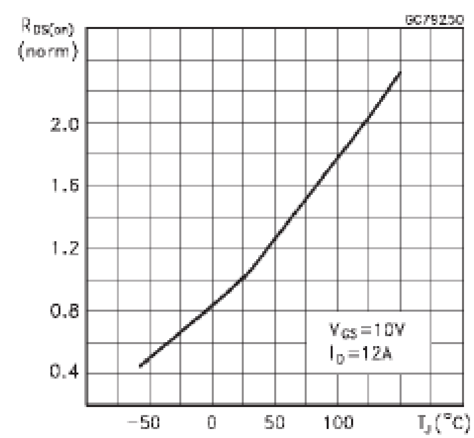
https://www.youtube.com/watch?v=o4_NeqlJgOs

- The gate threshold voltage (V_{TH}) is typically 2- 4 V but have negative temperature coefficient i.e., has tendency to decrease with increasing temperature: Should be considered when implementing gate drive circuits. In FETs the gate voltage should be at least 10 V but is limited to +/- 20 V typically.
- The FET's conduction losses are related to the on-state resistance $r_{DS(on)}$. The value of the resistance has positive temperature coefficient. Therefore, for loss calculation the value presented at room temperature has to be multiplied by a factor of 1.6. The positive temp. coefficient means that MOSFETs may be connected in parallel. Separate gate resistor should be used to avoid parasitic oscillation.
- The conduction losses of MOSFET are computed based on the RMS value of the current and on-state resistance $r_{DS(on)}$.

Normalized Gate Threshold Voltage vs



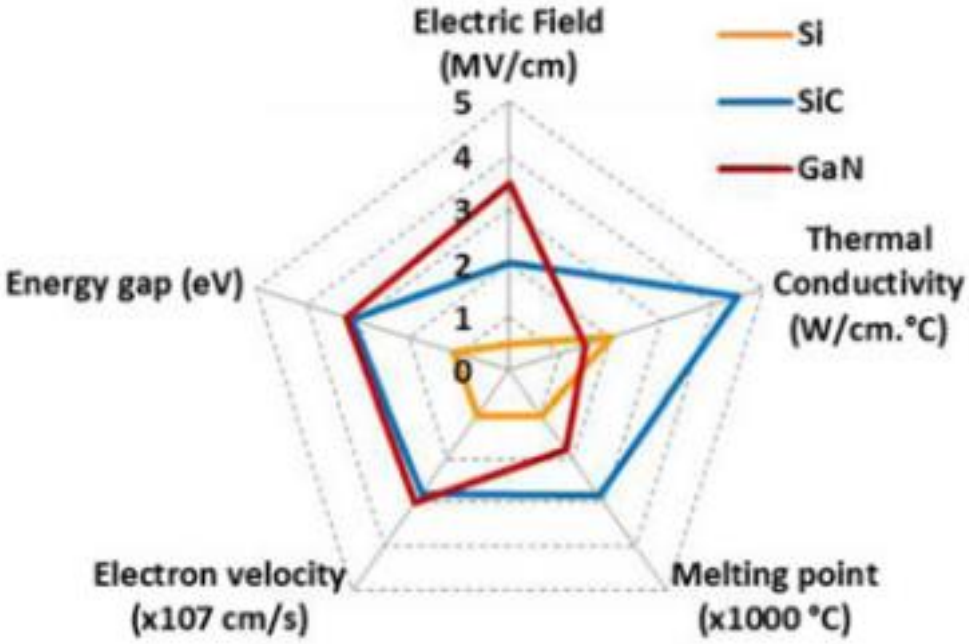
Normalized On Resistance vs Temperature

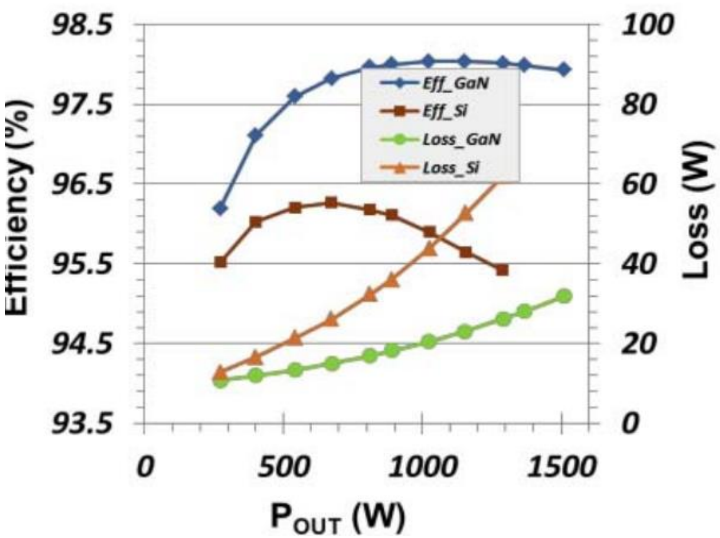


$$P_{loss}=\frac{1}{T}\int_0^T r_{ds,on}\, i_{rms}^{\ 2}\, dt$$

Wide band gap (WBG) devices: GaN (gallium-nitride)

- High frequency, high voltage, and high efficiency switching devices
- GaN MOSFETs have been offered since 2009





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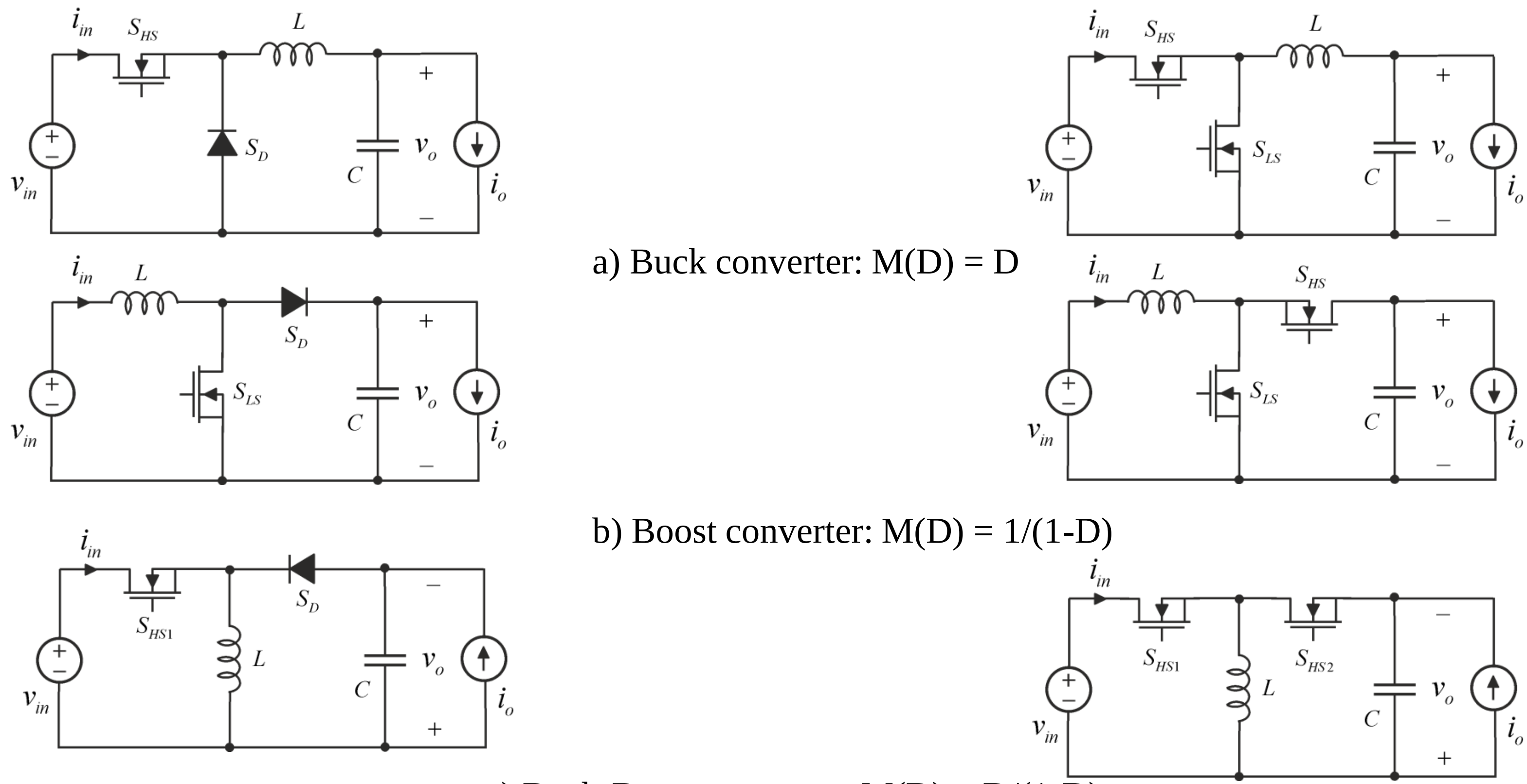
Non-Isolated Switched-Mode Converters

The three non-isolated DC/DC converters are given in Fig. 4.1 where $M(D) \approx V_o/V_{in}$ and D denotes the pulse or duty ratio (i.e., T_{on}/T_s: T_{on} equals the conduction time of a certain switch component and T_s the cycle time or inverse of switching frequency f_s). The complement of D (1-D) is usually denoted by D'.



a) Buck converter: M(D) = D

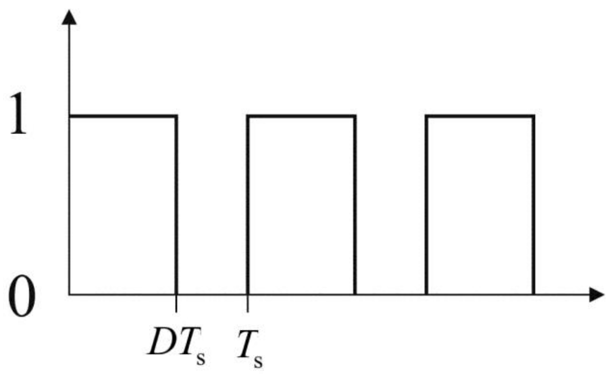
b) Boost converter: M(D) = 1/(1-D)

c) Buck-Boost converter: M(D) = D/(1-D)

Fig. 4.1 Basic non-isolated ideal switched-mode DC/DC converters

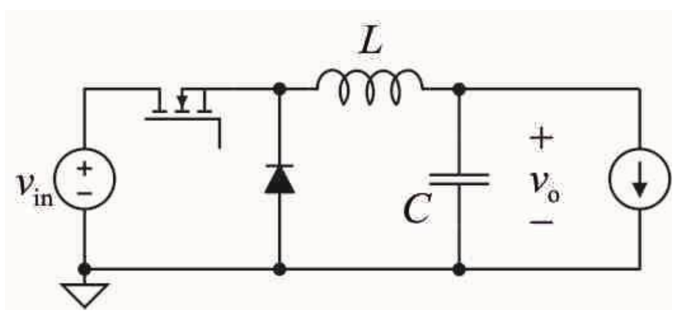
Definition of Duty Ratio

- Duty ratio or duty cycle is defined as the percentage of one period in which the switch is conducting



$$T_{on} = DT_s$$
$$T_{off} = (1-D)T_s = D'T_s$$
$$T_s = T_{on} + T_{off}$$

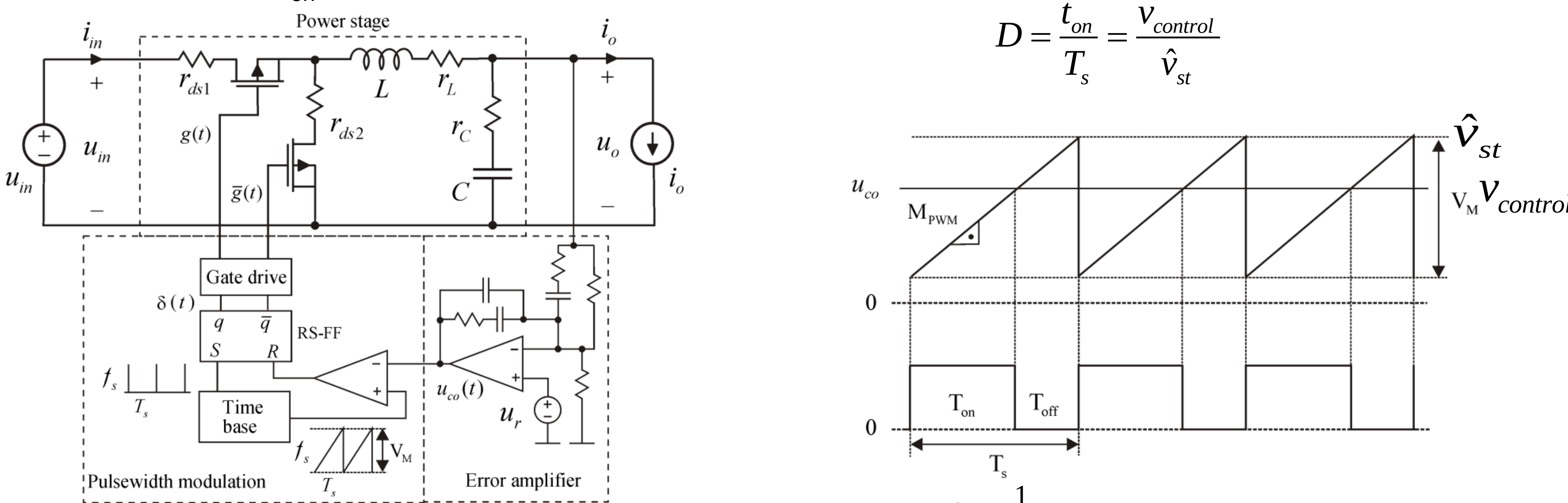
- Duty ratio is usually given as a number between 0 and 1, not as a percentual value. Switch signal is still a pulse!



Non-Isolated Switched-Mode Converters

- The converters are usually feedback-controlled, where certain output variable (e.g. output voltage) is kept constant regardless of the changes in the input variables (i.e., input voltage and/or output-load current) as depicted in Fig. 4.2a. The duty ratio is usually generated based on a linear ramp signal as depicted in Fig. 4.2b. This kind of control principle is known as direct-duty-ratio control. The on-time T_{on} is related to the on-time of the high-side MOSFET.

$$D = \frac{t_{on}}{T_s} = \frac{v_{control}}{\hat{v}_{st}}$$



$$f_{sw} = \frac{1}{T_s}$$

a) b)

Fig. 4.2 Output-voltage feedback-controlled buck converter: a) Schematics, and b) duty-ratio generation

Picture: Professor Teuvo Suntio

Kirchoff’s current and voltage laws

- Analyzing power electronic circuits usually starts by utilizing Kirchhoff’s current and voltage laws
- **KVL**: Sum of voltages along a closed loop in a circuit equals zero.

$$\sum_{k=1}^{n} V_{\mathrm{k}} = 0$$

- **KCL**: Same amount of current entering a node must also flow out of it.

$$\sum_{k=1}^{n} I_{\mathrm{k}} = 0$$

Inductor voltage and capacitor current in steady state

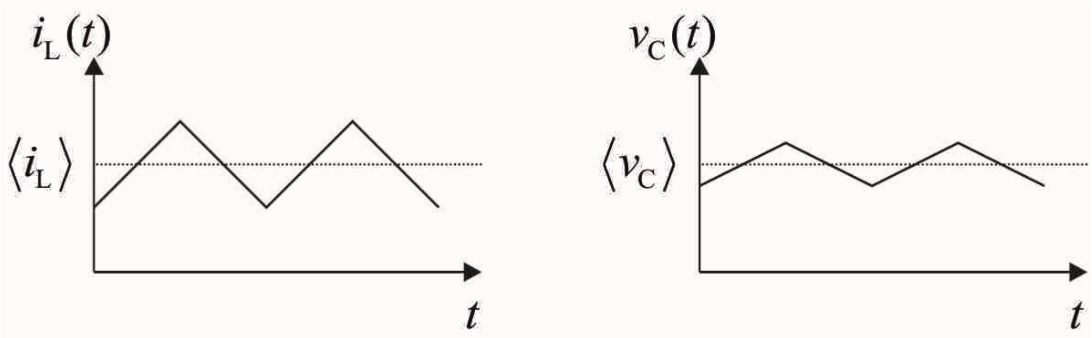
- Value of inductor current depends on inductance and voltage applied of the inductor

$$v_{\mathrm{L}} = L\frac{\mathrm{d}i_{\mathrm{L}}}{\mathrm{d}t} \quad \Rightarrow \quad i_{\mathrm{L}}(t) = \frac{1}{L}\int_{t_0}^{t} v_{\mathrm{L}}(t)\,\mathrm{d}t + i_{\mathrm{o}}(t_0)$$

- Capacitor voltage depends on the current flowing toward the capacitor

$$i_{\mathrm{C}} = C\frac{\mathrm{d}v_{\mathrm{C}}}{\mathrm{d}t} \quad \Rightarrow \quad v_{\mathrm{C}}(t) = \frac{1}{C}\int_{t_0}^{t} i_{\mathrm{C}}(t)\,\mathrm{d}t + i_{\mathrm{C}}(t_0)$$

- Steady-state operating point is reached when the start transient is over and electrical quantities of the load and source do not change significantly. Currents of the inductors and capacitor voltages have a constant dc-value superimposed with switching ripple.



Steady-State Analysis Principles

- Steady-state operating point is reached when the start transient is over and electrical quantities of the load and source do not change significantly.
- The input-to-output relations as well as the steady-state values of the inductor currents and capacitor voltages can be computed by applying Voltsec (Vs) and Ampsec (As, Charge) balances to the average inductor voltage and average capacitor currents. The overall procedures are as follows:

1) Identify the subcircuit structures of the converter during the on and off times.
2) Compute the equations for the voltages across the inductors and construct their averages by multiplying the on-time equations with the duty ratio D and the off-time equations with its complement D' and sum the equations together. Vs-balance means that the average voltage across an inductor has to be zero (i.e., the average inductor-current derivative is zero).
3) Compute the average charge flowing into the capacitors and leaving it (discharge). As-balance or charge balance dictates that the average change of charge has to be zero.

Conduction modes

- The converter can operate either in continuous (CCM), boundary (BCM), or discontinuous (DCM) conduction mode
- The conduction modes are related to the behavior of inductor current during the switching cycle.
- The CCM mode is such that the inductor current has to different derivatives or slopes within the switching cycle. Inductor current does not drop to zero.
- The BCM mode is such that the inductor current touches the zero level momentarily.
- The DCM mode is such that the inductor current is zero during a part of the cycle. DCM mode appears only when there is a diode in the circuit as part of the PWM switch.

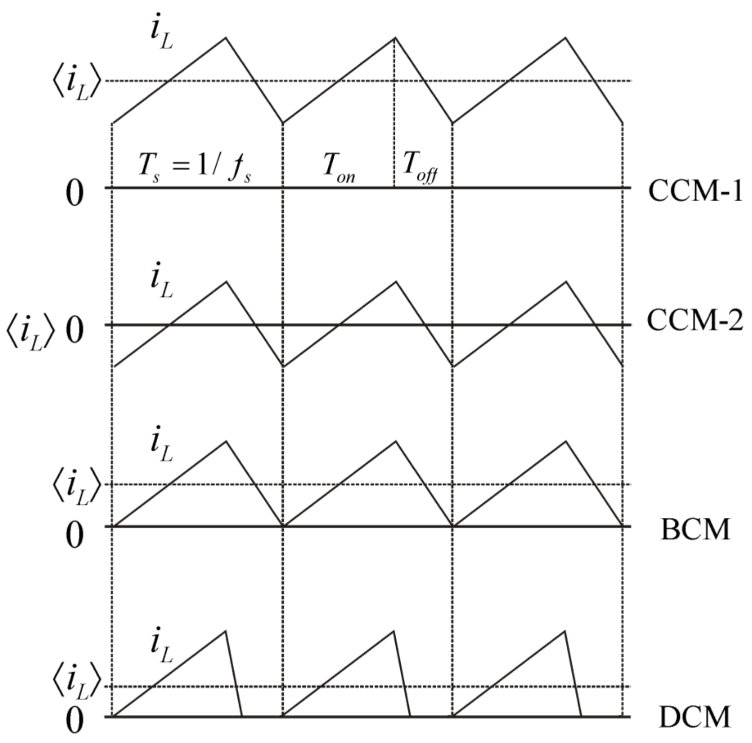


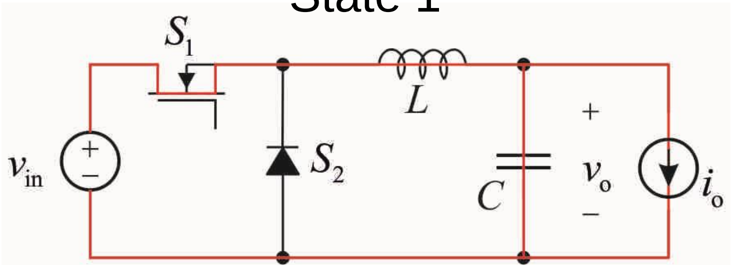
Fig. 4.3 Definition of the conduction modes in terms of the inductor-current behavior during the switching cycle.

Picture: Professor Teuvo Suntio

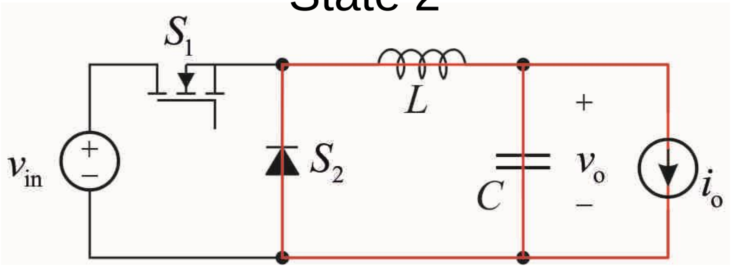
CCM vs. DCM

- Analyzing DC-DC converters that operate in CCM is usually easier since there are only two possible switching states

State 1

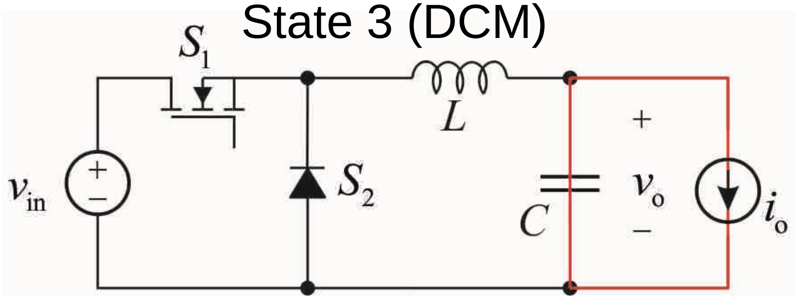


State 2



- Converter which operates in DCM has three possible switching states

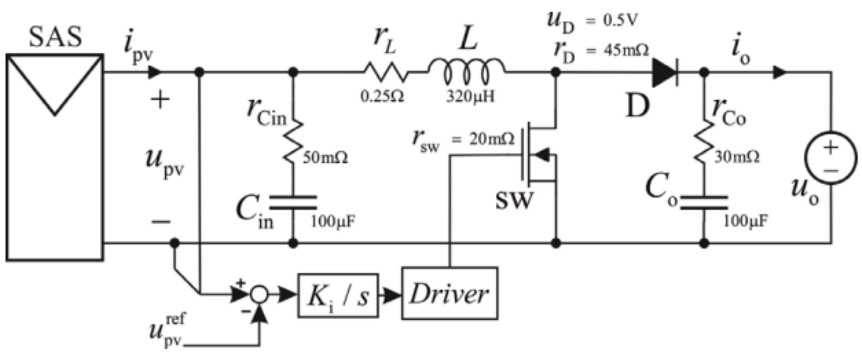
State 3 (DCM)



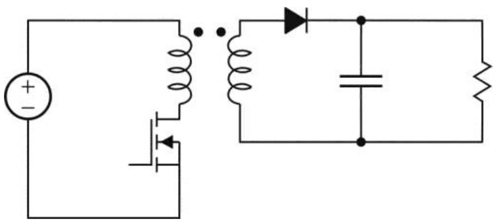
Picture: Assistant Professor Tuomas Messo

CCM vs. DCM

- Converters that are used in e.g. fuel cells and photovoltaic applications are designed to operate in CCM



- Low-power converters, such as mobile phone chargers are usually designed to operate in DCM (flyback-converter) since smaller inductor can be used



Picture: Assistant Professor Tuomas Messo

Volt-Second Balance

- No net change in inductor current over a complete switching period in steady-state

- Inductor current is periodic:

$$i_{\mathrm{L}}\left(nT_{\mathrm{s}}\right)=i_{\mathrm{L}}\left(\left(n+1\right)T_{\mathrm{s}}\right)$$

- Inductor volt-second balance: *Net change of energy stored in the magnetic field of the inductor is zero during a switching period at steady-state.*

$$i_{\mathrm{L}}\left(T_{\mathrm{s}}\right)-i_{\mathrm{L}}\left(0\right)=\frac{1}{L}\int_{0}^{T_{\mathrm{s}}}v_{\mathrm{L}}\left(t\right)\mathrm{d}t=0$$

- Volt-seconds over a switching period is equal to zero in steady-state

$$\int_{0}^{T_{\mathrm{s}}}v_{\mathrm{L}}\left(t\right)\mathrm{d}t=0$$

- This also means that average voltage over an inductor is equal to zero

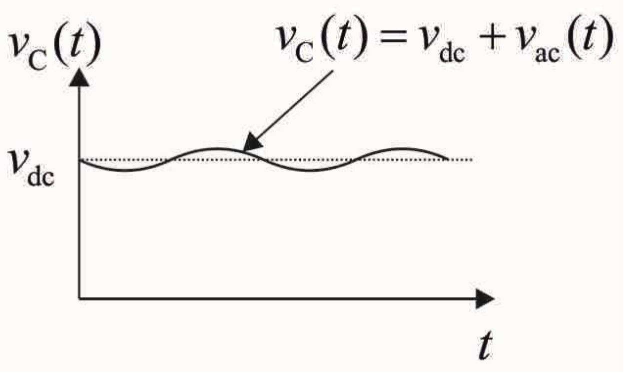
$$\frac{1}{T_{\mathrm{s}}}\int_{0}^{T_{\mathrm{s}}}v_{\mathrm{L}}\left(t\right)\mathrm{d}t=\left\langle u_{\mathrm{L}}\right\rangle=0$$

- Volt-second balance is positive → inductor current increases. Volt-second balance is negative → inductor current decreases. Volt-second balance equals zero → Steady-state

Ampere-Second Balance

- As-balance or charge balance dictates that the average change of charge has to be zero.
- The average or DC current flowing through the capacitors is zero (i.e., the average capacitor-voltage derivative is zero).

- There is usually very strict requirements on DC voltage ripple -> Capacitor voltage is supposed to be constant, ripple is limited to be max. 1-2 %



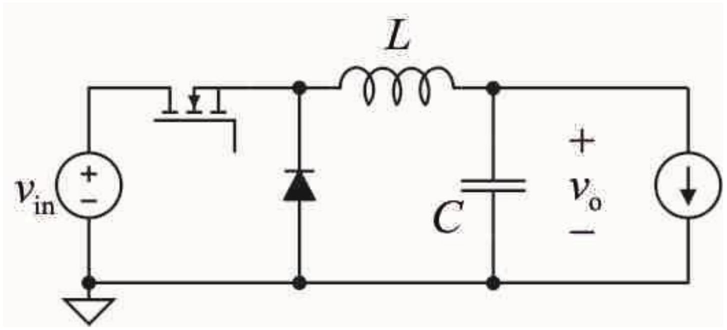
- Capacitor voltage can in many cases be approximated by the DC-component
- This procedure is called the **small-ripple approximation**

Content

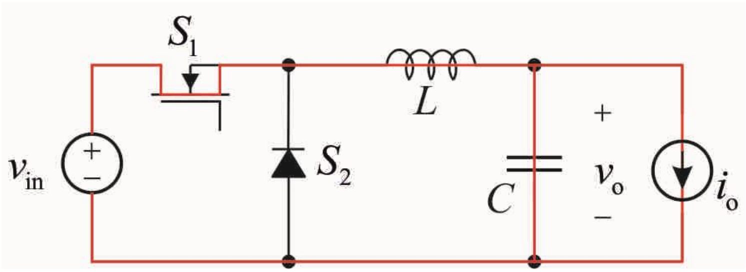
1. Diode
2. MOSFET
3. Steady-state analysis principles, analysis in continuous conduction mode (CCM)
4. Buck converter
5. Boost converter
6. Buck-boost converter
7. Applications

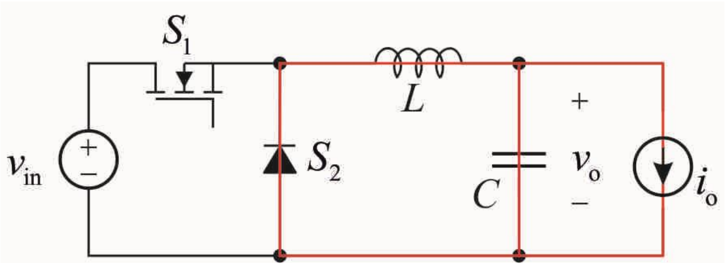
Buck-Type DC-DC Converter

- Buck converter is often treated as the simplest DC-DC converter
- Output voltage is always smaller than the input voltage



- Two switching states (with continuous inductor current):



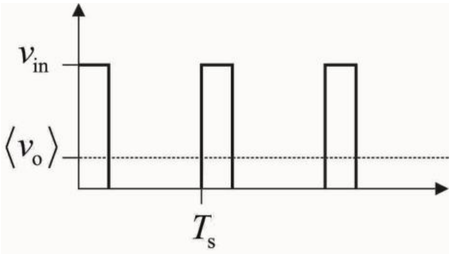


Picture: Assistant Professor Tuomas Messo

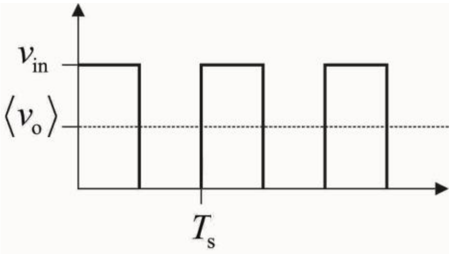
Buck-Type DC-DC Converter

- Output voltage can be controlled between 0 and v_{in}

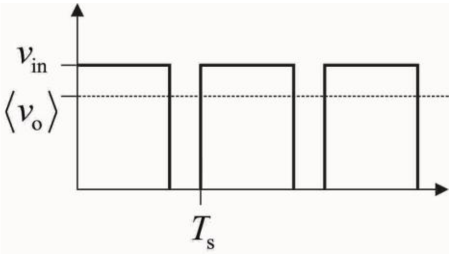
$D = 0.25$



$D = 0.5$

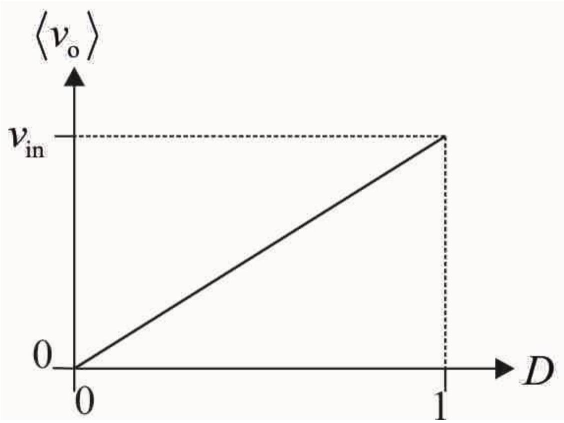


$D = 0.75$



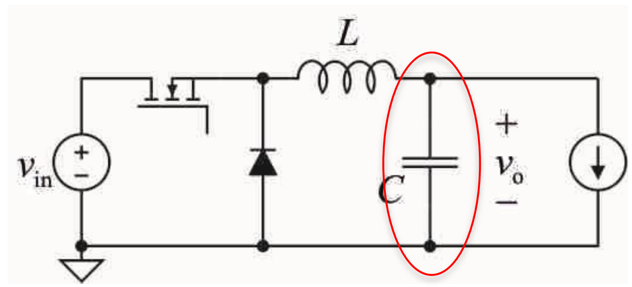
- Output voltage depends linearly from the duty ratio and input voltage

$$\langle v_o \rangle = D v_{in}$$



Buck-Type DC-DC Converter

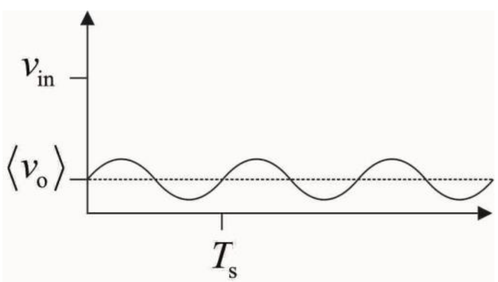
- Output capacitor is used to reduce output voltage ripple

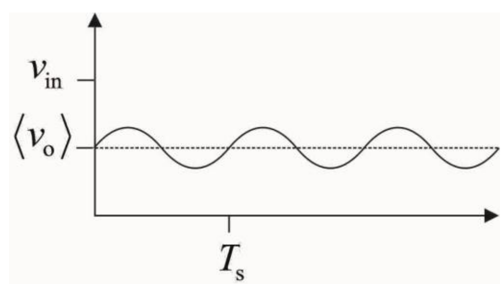


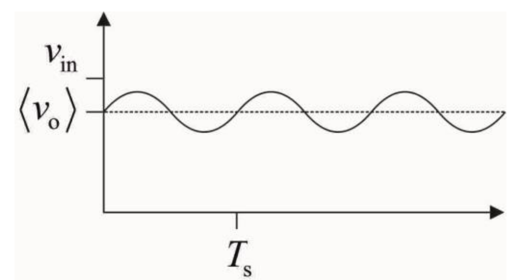
$D = 0.25$

$D = 0.5$

$D = 0.75$

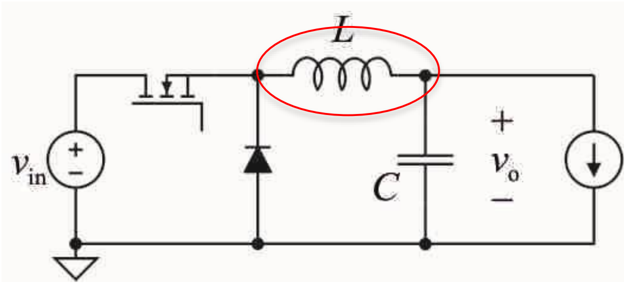






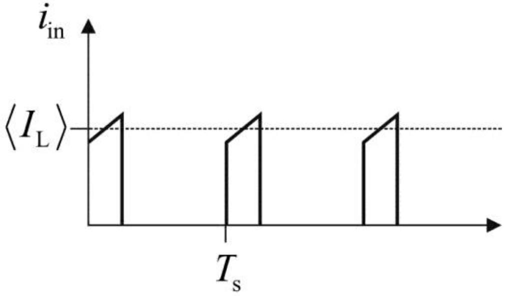
Buck-Type DC-DC Converter

- Inductor is used to filter the load current

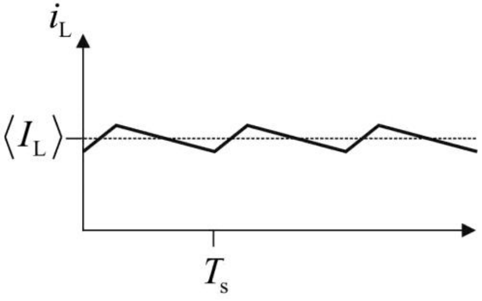


- Input current of a Buck converter is discontinuous

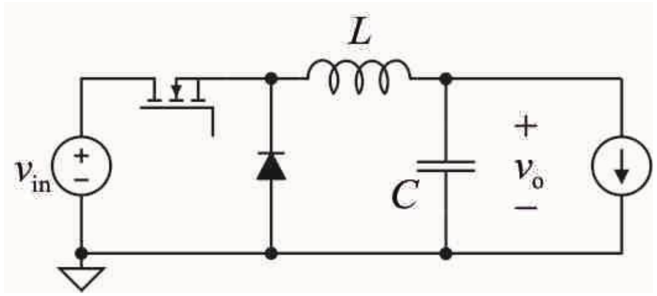
Input current

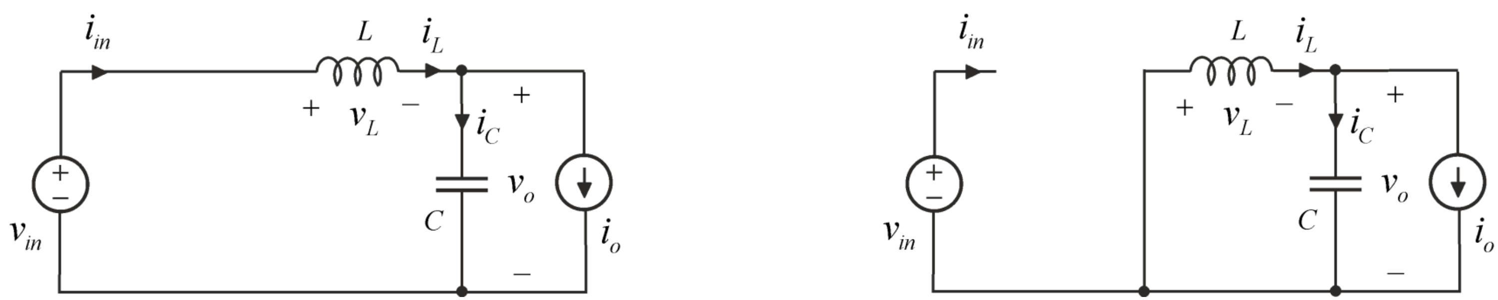


Inductor current



Buck in CCM





a) b)

Fig. 4.4 a) On-time and b) off-time subcircuits of a buck converter

On-time equations

KVL: 1) $v_{L1} = V_{in} - V_o$

KCL: 2) $i_{C1} = i_L - I_o$

3) $V_o = V_c$

Off-time equations

1) $v_{L2} = -V_o$

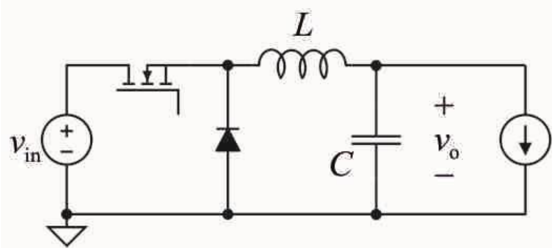
2) $i_{C2} = i_L - I_o$

3) $V_o = V_C$

Buck in CCM

Averaging: $$D \cdot v_{L_1} + D' \cdot v_{L_2} = 0 \;\; \& \;\; D \cdot i_{c_1} + D' \cdot i_{c_2} = 0$$

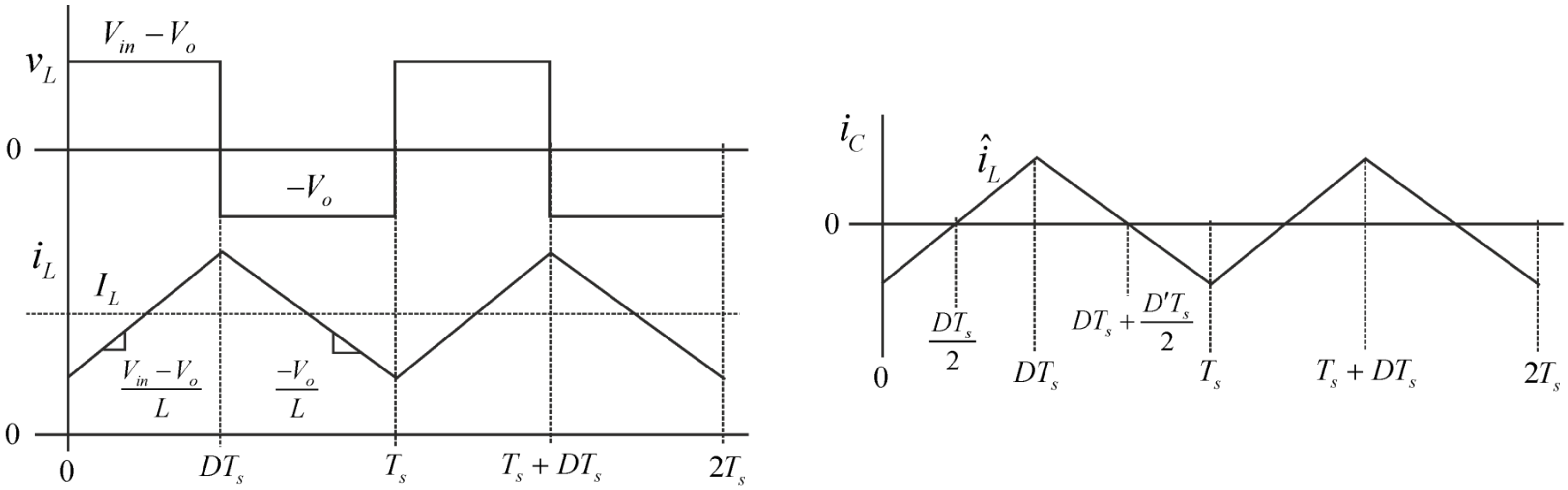
$$D \cdot (V_{in} - V_o) + D' \cdot (-V_o) = 0$$
$$\rightarrow 1)\;\; DV_{in} + (D + D')(-V_o) = 0$$
$$\rightarrow 2)\; DV_{in} - V_o = 0$$



$$D \cdot (I_L - I_o) + D' \cdot (I_L - I_o) = 0$$
$$\rightarrow 3) I_L - I_o = 0$$

$$\therefore V_o = DV_{in} \quad \& \quad I_L = I_o$$

Buck in CCM



a) b)

Fig. 4.5 a) Inductor voltage and current waveforms and b) capacitor current waveform of a buck converter

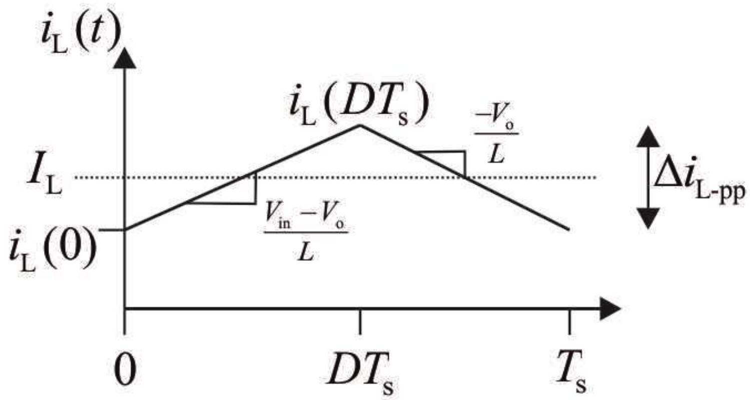
Peak-to-peak inductor current ripple component:

$$\hat{i}_{L-pp} = \frac{V_{in} - V_o}{L} \cdot DT_s = \frac{V_o}{L} D'T_s$$

Based on this information, the inductance L of the inductor can be determined when the peak-to-peak ripple current is defined. Its usual value is 20 – 40 % of I_L.

Buck in CCM

- Inductor current can be depicted when the steady-state inductor current is known
- The sketched waveform can also be used to calculate the inductor current ripple which can be used in inductor sizing



- Note that some textbooks define inductor current ripple as peak-to-average and some as peak-to-peak value

Selection of Inductance Value in CCM

- The inductance value is selected based on the defined peak-to-peak inductor-current ripple value shown in Fig. 4.12. This peak-to-peak ripple value can be computed based either on the up slope (m_1) or down slope (m_2) of the inductor-current instantaneous value. The slope equals its derivative, respectively. The average inductor current $\langle i_L \rangle$ lies exactly in the middle of the ripple band. The peak-to peak ripple can be computed by applying the on-time ($v_{L\text{-on}}$) or off-time ($v_{L\text{-off}}$) voltage across the inductor defined earlier for the basic converters. The usual value for $\Delta i_{L\text{-pp}}$ equals 20 – 40 % of $\langle i_L \rangle$.

$$m_1 = \frac{v_{L-on}}{L} \rightarrow \Delta i_{L-pp} = \frac{v_{L-on} D T_s}{L} \rightarrow L = \frac{v_{L-on} D T_s}{\Delta i_{L-pp}}$$

$$m_2 = \frac{v_{L-off}}{L} \rightarrow \Delta i_{L-pp} = \frac{\left| v_{L-off} D' T_s \right|}{L} \rightarrow L = \frac{\left| v_{L-off} D' T_s \right|}{\Delta i_{L-pp}}$$

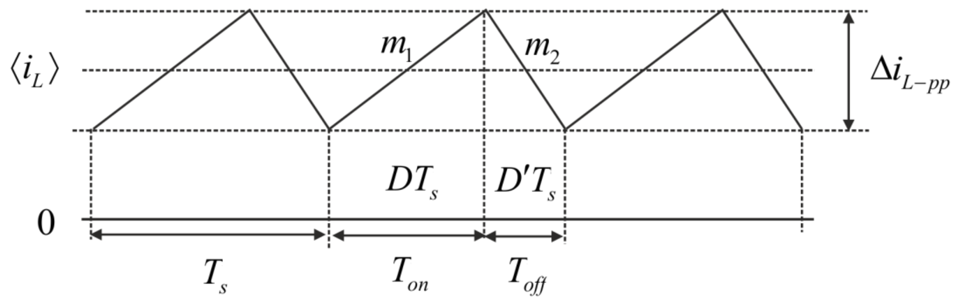
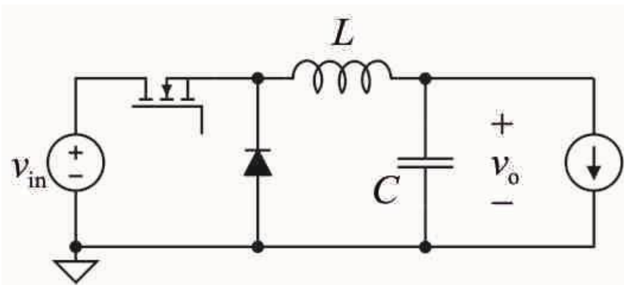


Fig. 4.12 Inductor-current-waveform in CCM

Buck in CCM



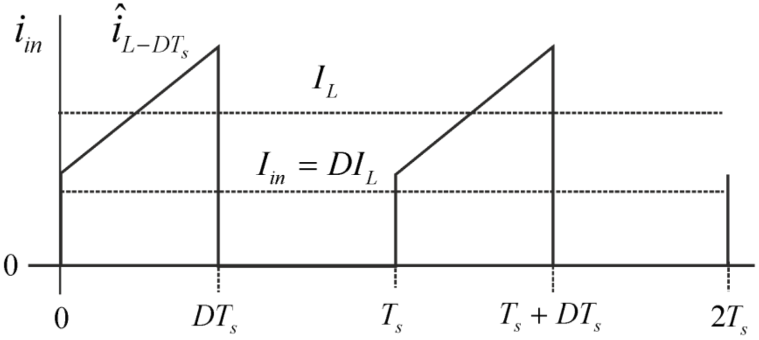


Fig. 4.6 Input current waveform of a buck converter

Examle: Buck

The output voltage is 20 V.

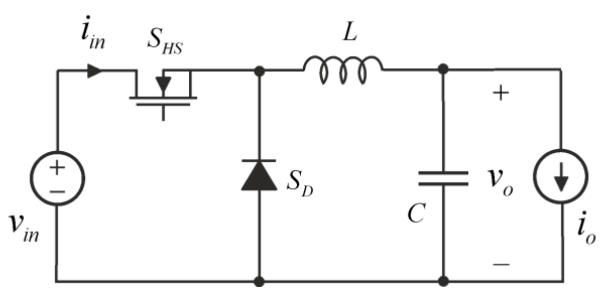
a) Is the converter operates in CCM, BCM or DCM region?

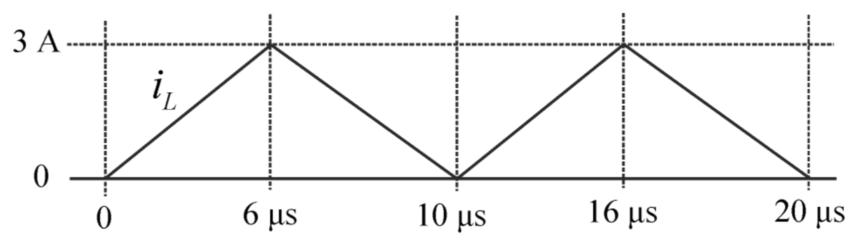
b) What is the average output current?

c) What is duty ratio?

d) What is the input voltage value?

e) What is the inductance L value?





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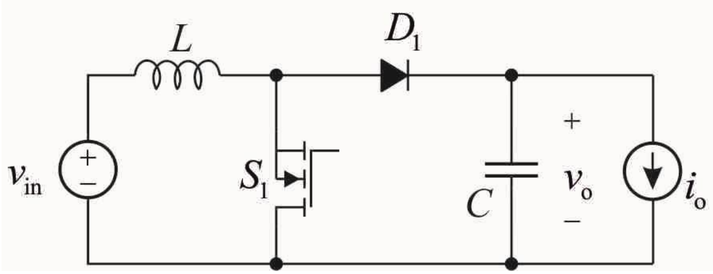
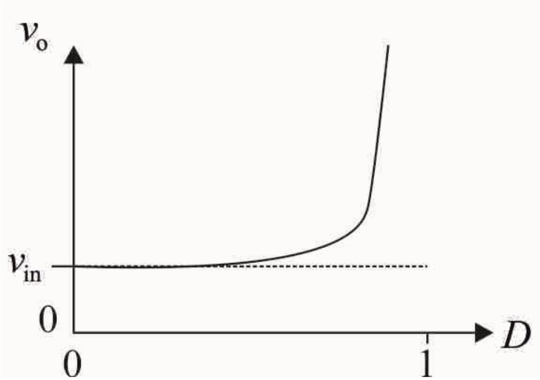
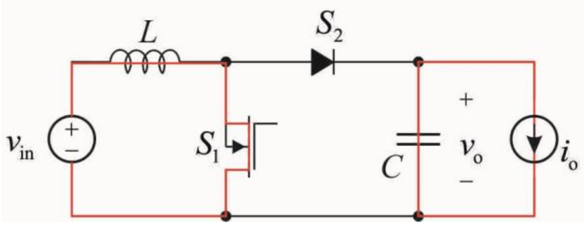
Boost Converter

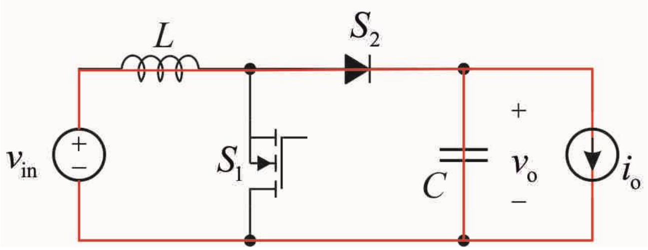
- Boost converter is a step-up converter. Output voltage is greater than the input voltage
- The diode prevents current flowing back into the source when transistor is conducting





- Output voltage is determined by: $$v_o = \frac{v_{in}}{1-D}$$
- Boost converter has two switching states in CCM:

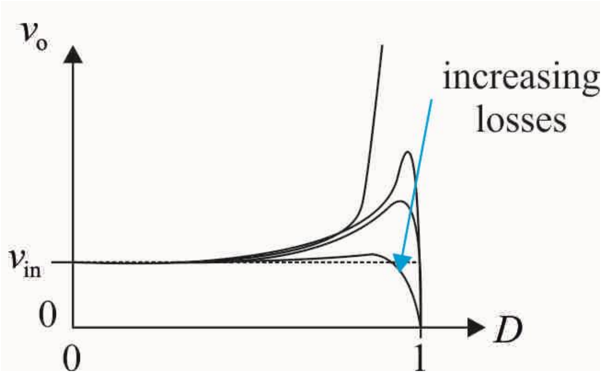




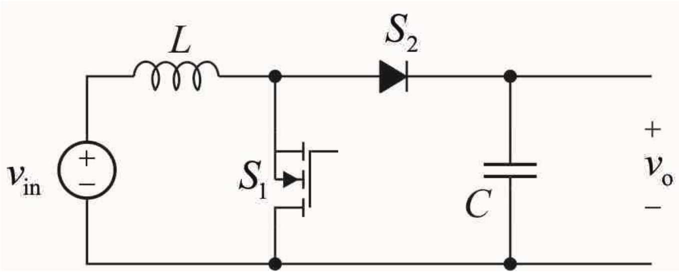
- Energy is stored in the magnetic field of the inductor during on-time. Energy is transferred to the load through the diode when the switch S1 is not conducting

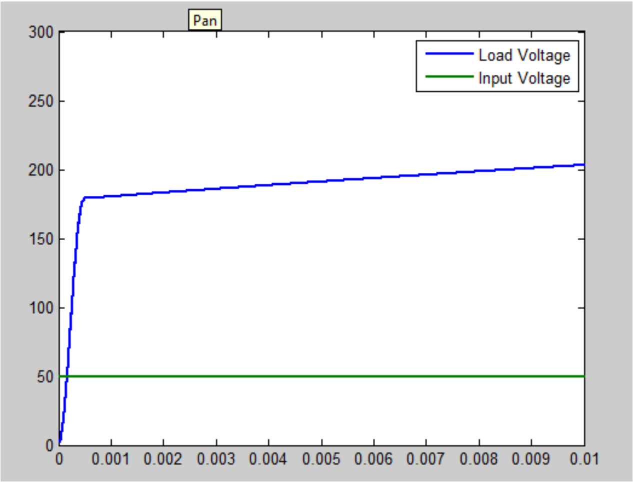
Boost Converter – real world limitations

- Voltage gain tends to infinity in the ideal case.
- In a real converter some of the electrical power is transformed into heat. Therefore, infinite voltage gain cannot be achieved.

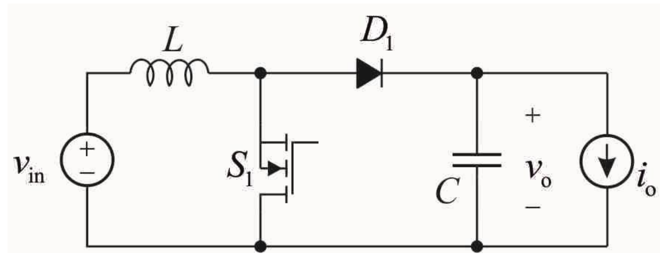


- Boost converter does not work without load -> output voltage tends to infinity
- Duty ratio should be set to zero when the load is disconnected -> Output voltage equals source voltage





Boost in CCM



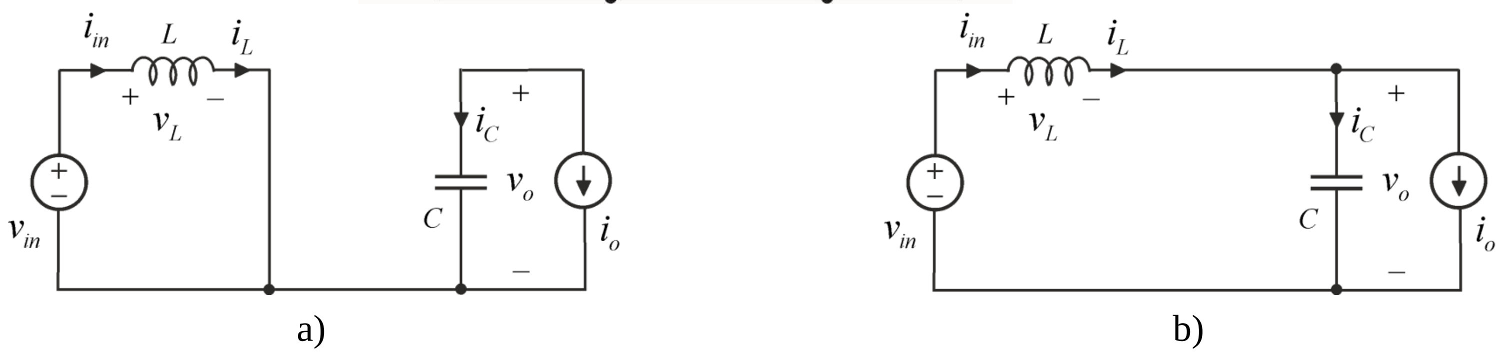


Fig. 4.7 a) On-time and b) off-time subcircuits of a boost converter

On-time equations

KVL: 1) $v_{L1} = V_{in}$

KCL: 2) $i_{C1} = -I_o$

3) $V_o = V_C$

Off-time equations

1) $v_{L2} = V_{in} - V_o$

2) $i_{C2} = I_L - I_o$

3) $V_o = V_c$

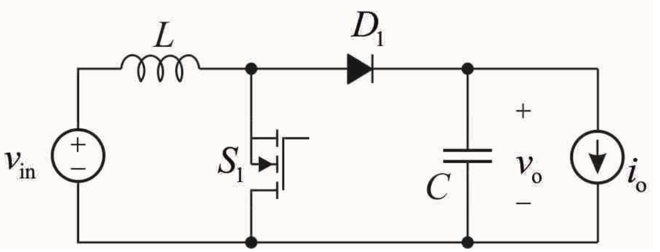
Boost in CCM

Averaging: $$D \cdot v_{L_1} + D' \cdot v_{L_2} = 0 \;\; \& \;\; D \cdot i_{C_1} + D' \cdot i_{C_2} = 0$$

$$D \cdot V_{in} + D' \cdot (V_{in} - V_o) = 0$$
$$\rightarrow 1) \;\; (D + D')V_{in} - D'V_o = 0$$

$$D \cdot (-I_o) + D' \cdot (I_L - I_o) = 0$$
$$\rightarrow 2) \;\; D'I_L - (D + D')I_o = 0$$

$$\therefore V_o = \frac{V_{in}}{D'} \quad \& \quad I_L = \frac{I_o}{D'}$$



Boost in CCM

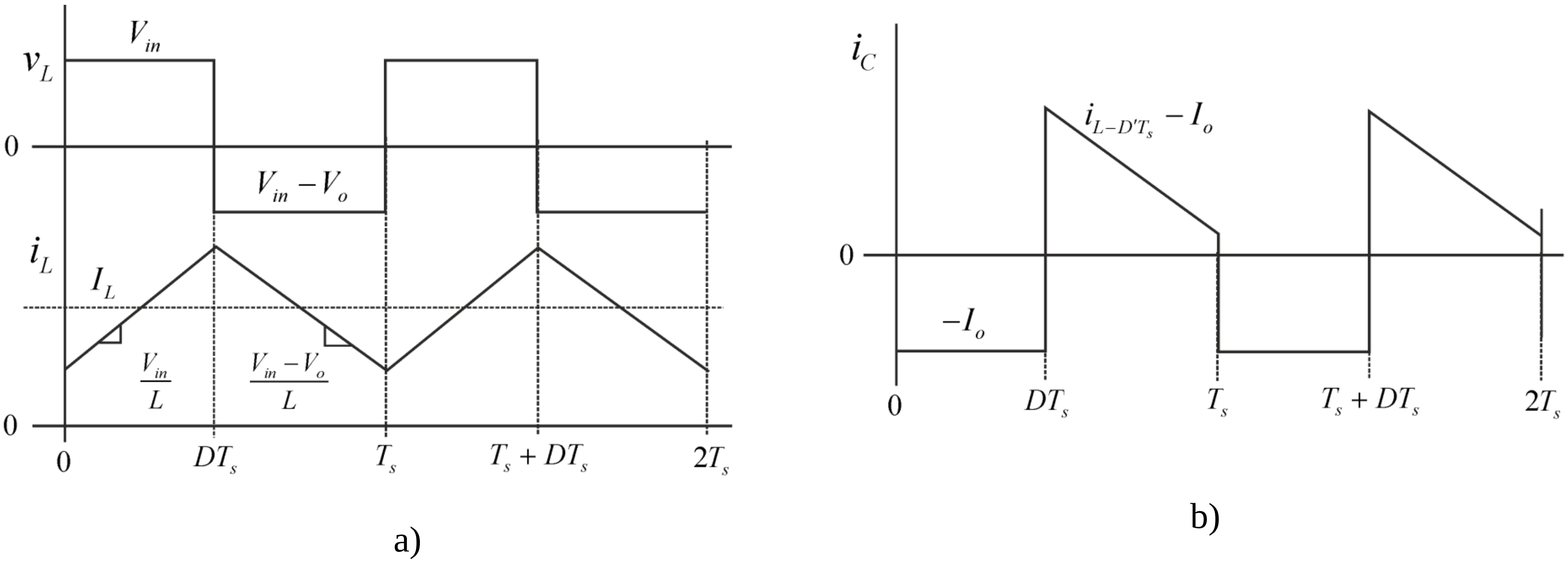


Fig. 4.8 a) Inductor voltage and current waveforms and b) capacitor current waveform of a boost converter

Peak-to-peak inductor current ripple component:

$$\hat{i}_{L-pp} = \frac{V_{in}}{L} \cdot DT_s = \frac{V_{in} - V_o}{L} D'T_s$$

Based on this information, the inductance L of the inductor can be determined when the peak-to-peak ripple current is defined. Its usual value is 20 – 40 % of I_L.

Boost in CCM

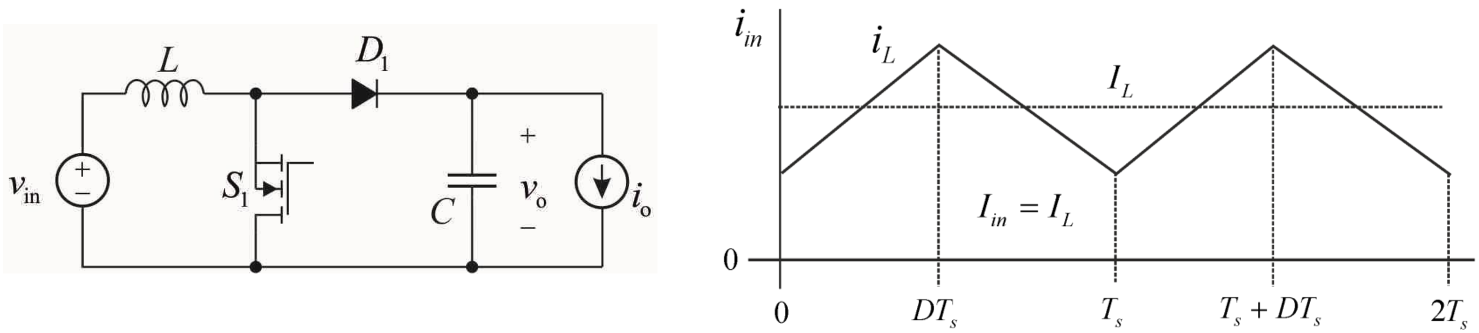


Fig. 4.9 Input-current waveform of a boost converter

Examle: Boost

The input voltage is 20 V.

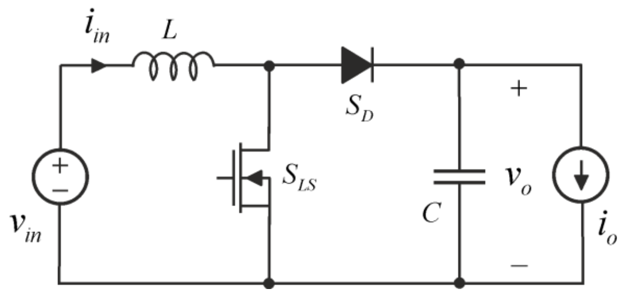
a) Is the converter operates in CCM, BCM or DCM region?

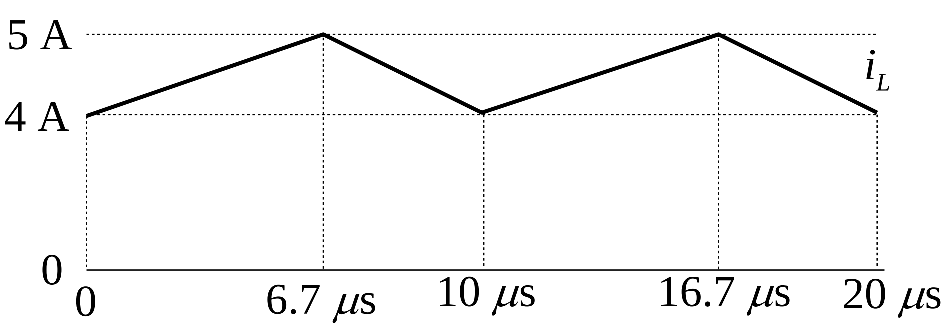
b) What is the average input current?

c) What is duty ratio?

d) What is the output voltage value?

e) What is the inductance L value?

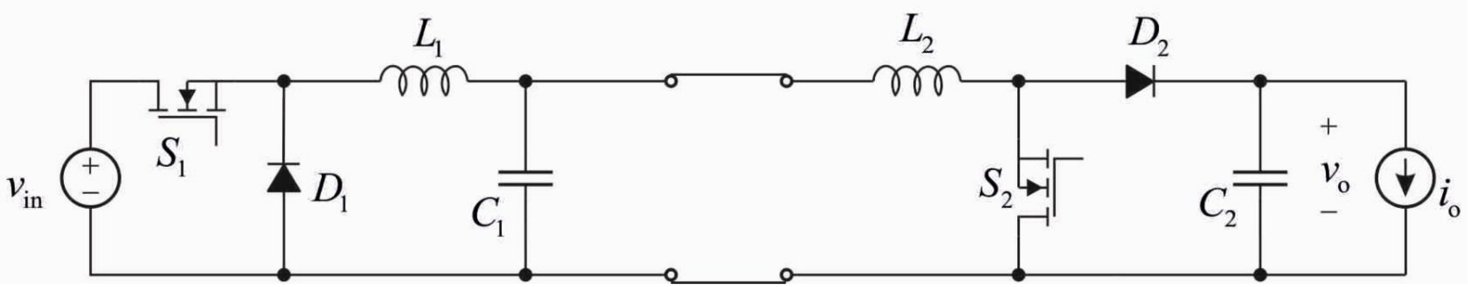




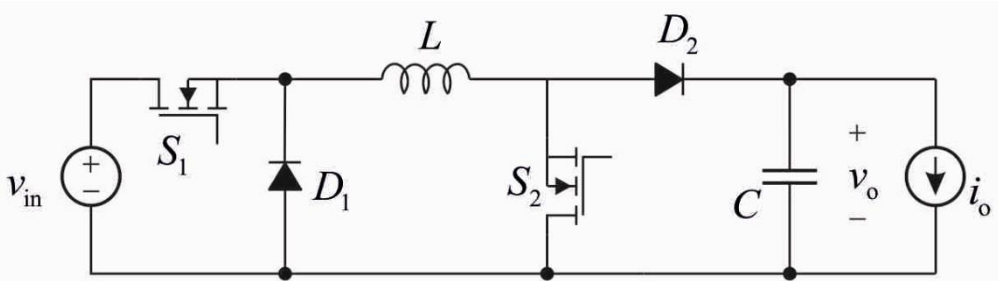
Content

Buck-Boost

- The idea behind a Buck-Boost converter is the cascade-connection of Buck and Boost converters



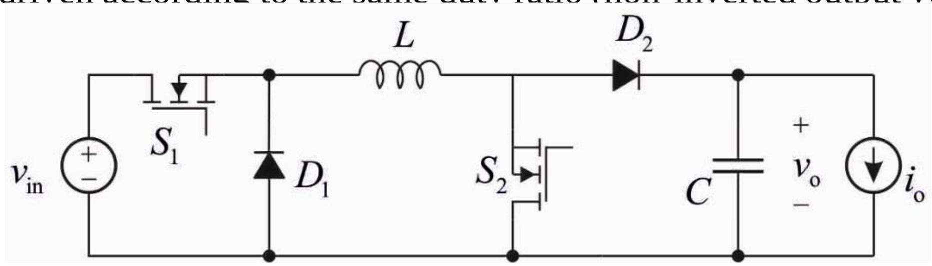
- Capacitor C1 can be removed and inductors L1 and L2 merged together



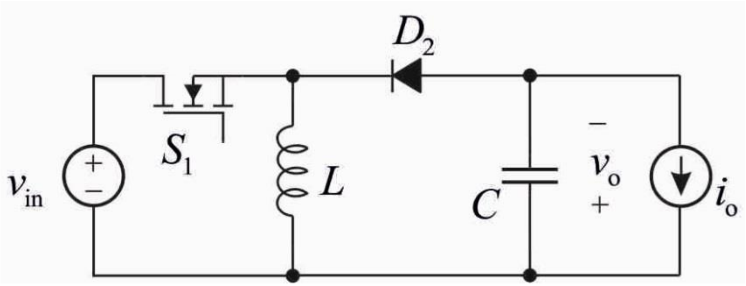
Picture: Assistant Professor Tuomas Messo

Buck-Boost

- Switches are driven according to the same duty ratio (non-inverted output voltage)



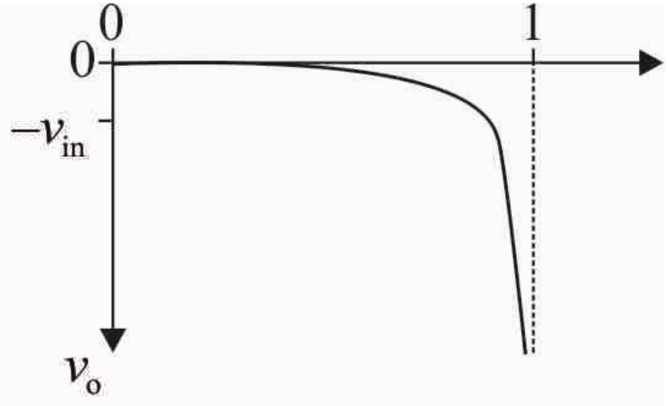
- The circuit can be simplified by eliminating excessive switches and rearranging (inverted output voltage)



Buck-Boost in CCM

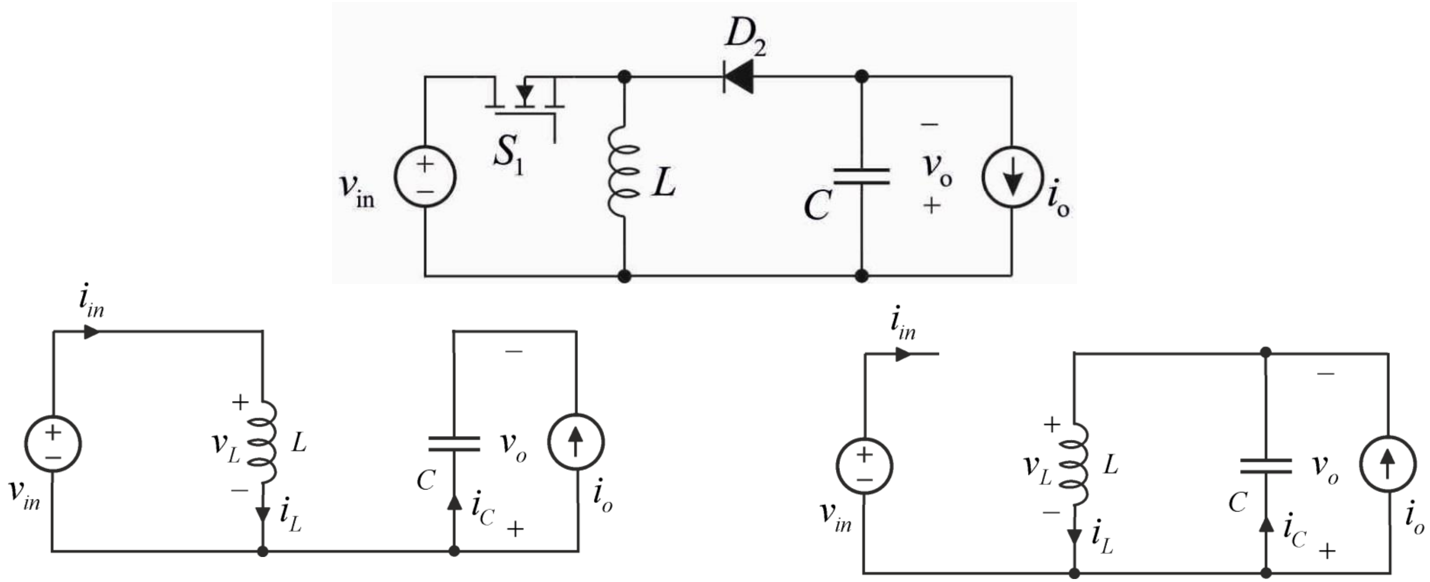
- Buck-Boost can produce produce ideally any dc voltage

$$v_o = \frac{-D}{1-D} \cdot v_{in}$$



- However, the polarity of the output voltage is reversed
- Maximum DC gain is limited by losses just as for any DC-DC converter

Buck-Boost in CCM



a) b)

Fig. 4.10 a) On-time and b) off-time subcircuits of a buck-boost converter

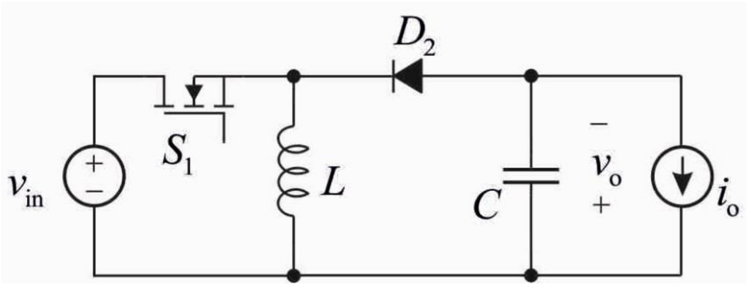
	On-time equations	Off-time equations
KVL:	1) $v_{L1} = V_{in}$	1) $v_{L2} = -V_o$
KCL:	2) $i_{C1} = -I_o$	2) $i_{C2} = I_L - I_o$
	3) $V_o = V_C$	3) $V_o = V_C$

Buck-Boost in CCM

Averaging: $D \cdot v_{L_1} + D' \cdot v_{L_2} = 0 \quad D \cdot i_{c_1} + D' \cdot i_{c_2} = 0$

$DV_{in} - D'V_o = 0$

$\rightarrow 1) \quad DV_{in} - D'V_o = 0$



$D \cdot (-I_o) + D' \cdot (I_L - I_o) = 0$

$\rightarrow 2) \quad D'I_L - I_o = 0$

$$\therefore V_o = \frac{D}{D'} V_{in} \quad \& \quad I_L = \frac{I_o}{D'}$$

Buck-Boost in CCM

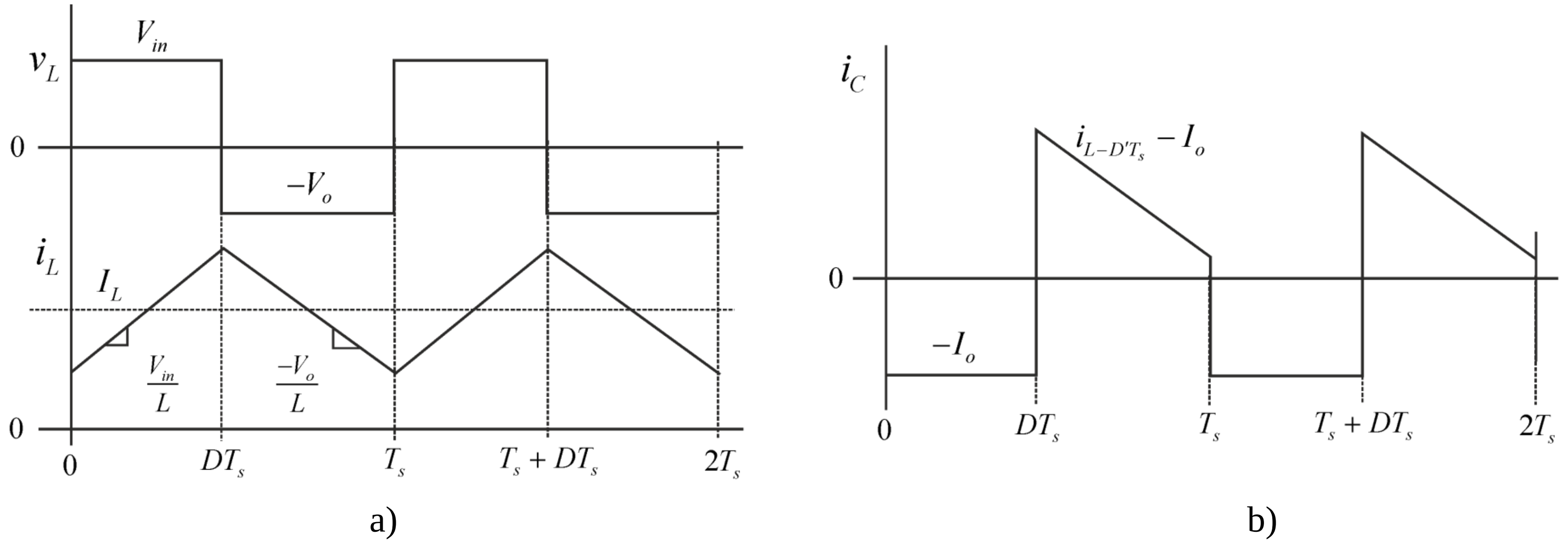


Fig. 4.11 a) Inductor voltage and current waveforms and b) capacitor current waveform of a buck-boost converter

Peak-to-peak inductor current ripple component:

$$\hat{i}_{L-pp} = \frac{V_{in}}{L} \cdot DT_s = \frac{V_o}{L} D'T_s$$

Based on this information, the inductance L of the inductor can be determined when the peak-to-peak ripple current is defined. Its usual value is 20 – 40 % of I_L.

Buck-Boost in CCM

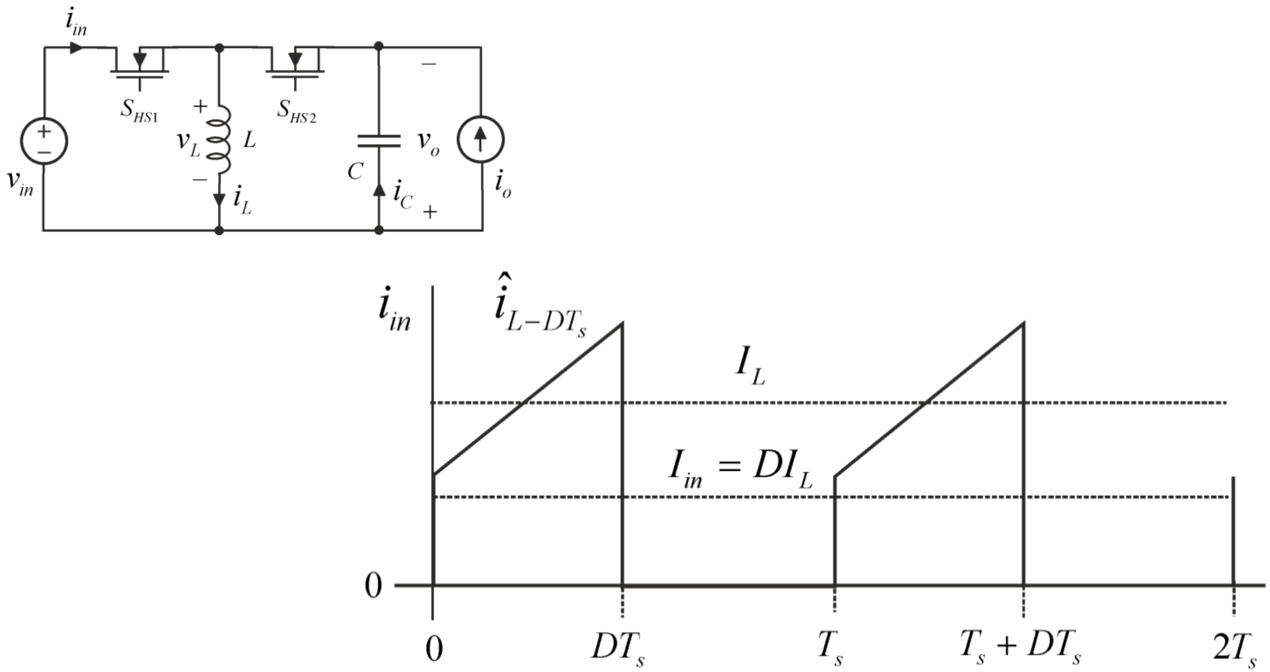


Fig. 4.11 Input-current waveform of a buck-boost converter

Content

Buck-Type (Step-down) Applications

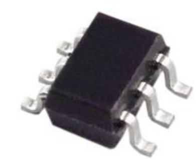
- Buck-type converters are usually used in applications where voltage and power levels are low, e.g., microprocessors
  - 0.5-0.6 V regulated voltage with 5-10 mV voltage regulation
  - Currents up to 200 A, with 100 A/us slewing rates

19-3997; Rev 4; 2/09

EVALUATION KIT AVAILABLE

MAXIM

Tiny 500mA, 4MHz/2MHz Synchronous Step-Down DC-DC Converters



Applications

Microprocessor/DSP Core Power

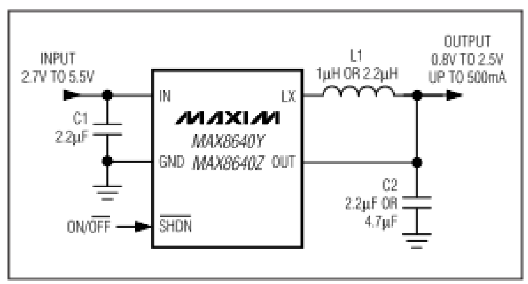
I/O Power

Cell Phones, PDAs, DSCs, MP3s

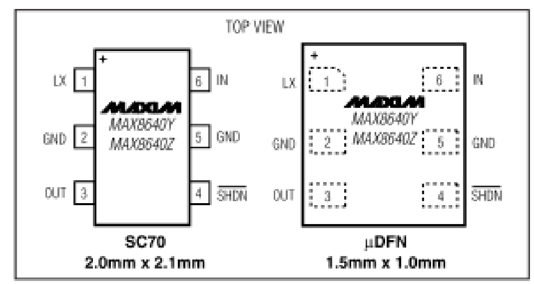
Other Handhelds Where Space Is Limited

maximintegrated.com

Typical Operating Circuit



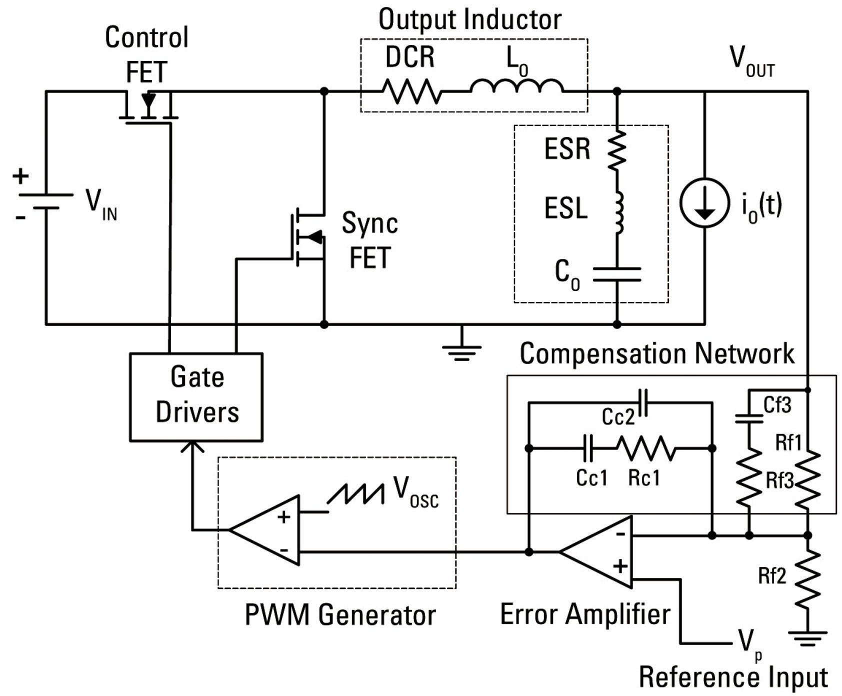
Pin Configurations



MAXIM ***Maxim Integrated Products*** 1

Buck-Type (Step-down) Applications

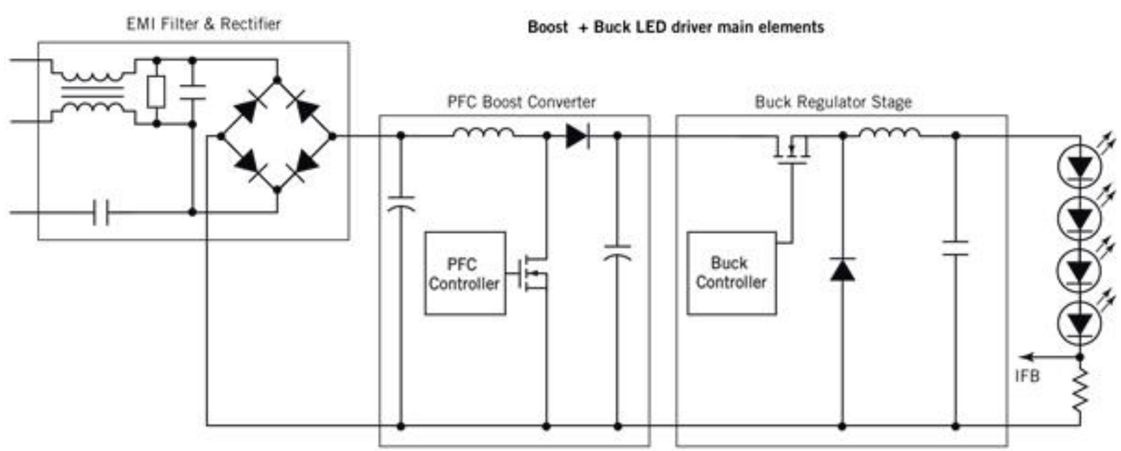
- Output voltage of the Buck converter can be sensed and fed back to an error amplifier to regulate load voltage
- Real converter includes also gate drivers and a PWM generator



embedded.com

Buck-Type (Step-down) Applications

- LED Drivers step down the voltage and control the LED current
- Lighting is estimated to consume 16 – 20 % of electricity in commercial buildings and 20-40% in households
- AC from the grid voltage has to be rectified to dc (diode bridge)
- Can employ a power-factor-correction (PFC) Boost-converter



powerelectronics.com

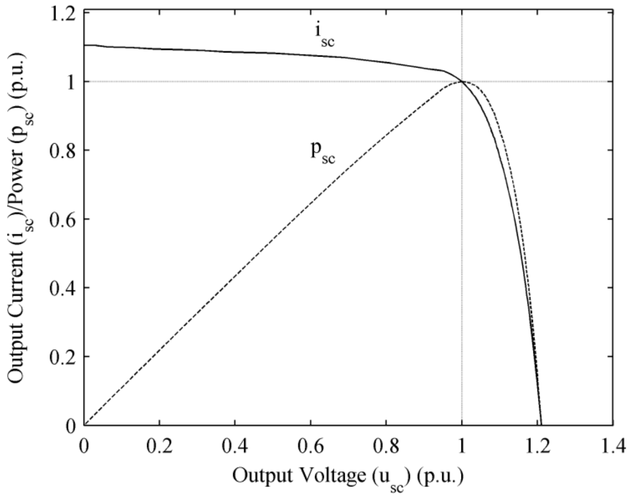
Fig. 1. Boost+Buck LED driver main elements

Renewable Energy Applications

- DC-DC converter regulates the voltage of the photovoltaic generator

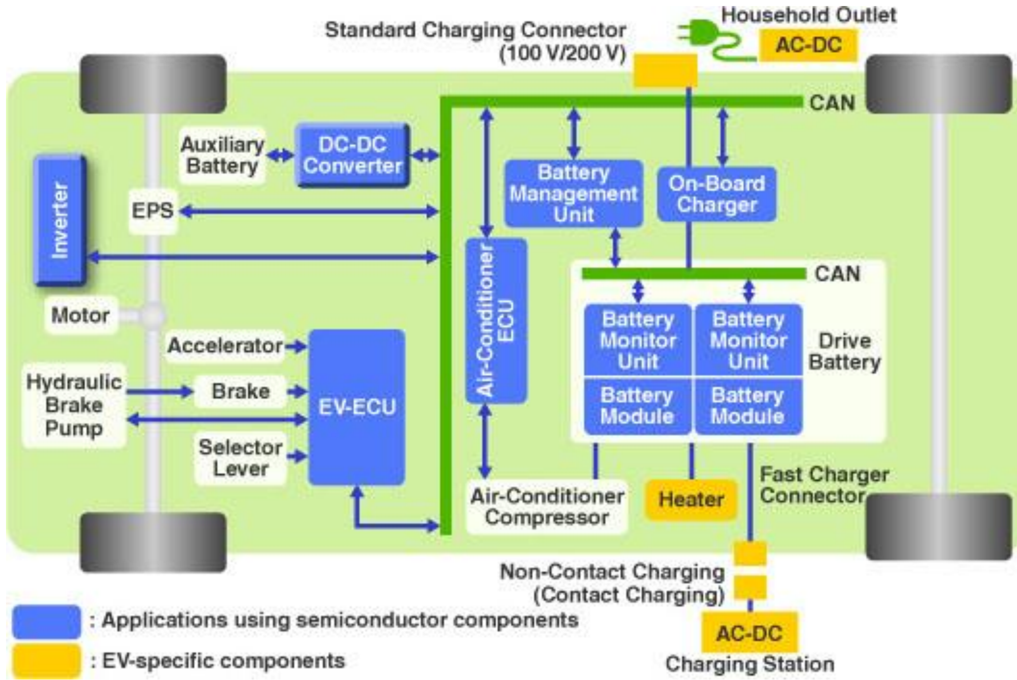
- Photovoltaic module produces its maximum power at a certain operating point (maximum power point - MPP)

pv-magazine.com



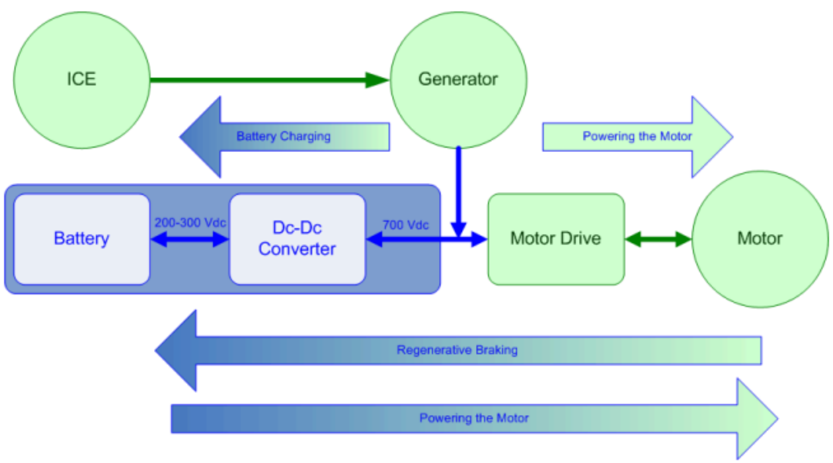
Transportation Applications

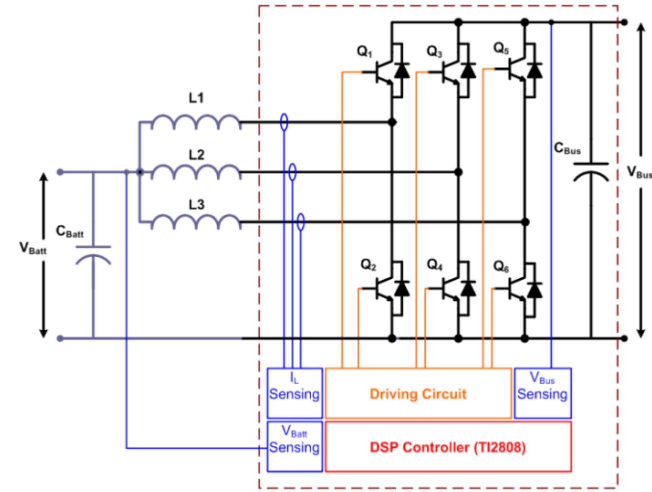
- Battery management and DC-link voltage control in electric vehicles
  - Power levels up to 100 kW
  - DC-link voltage has to be maintained at a constant value
  - Battery needs to be recharged during regenerative braking
  - Bidirectional power flow is required



Transportation Applications

- Regenerative braking requires bi-directional power flow
- Can be accomplished using a Boost converter with two transistors
- Paralleled converters can be used to reduce current ripple (interleaving)

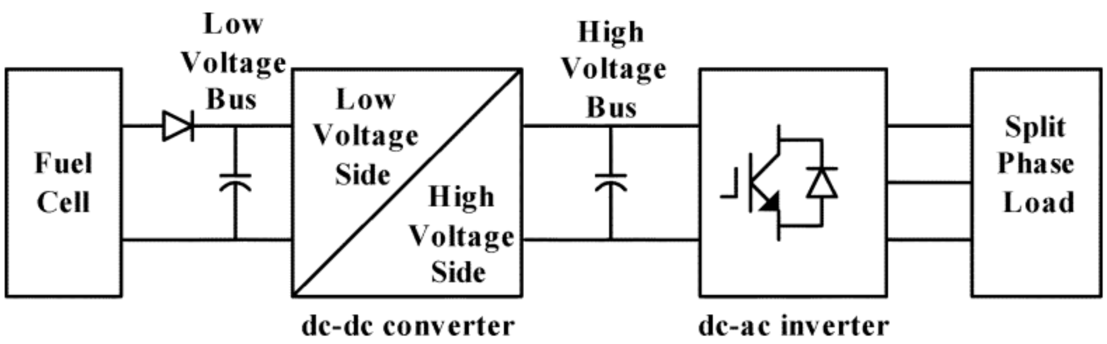




M. Pepper et. al., “Bi-Directional DCM DC to DC Converter for Hybrid Electric Vehicles”, IEEE Power Electronics Specialists Conference, PESC, pp. 3088-3092, 2008

Fuel Cell Applications

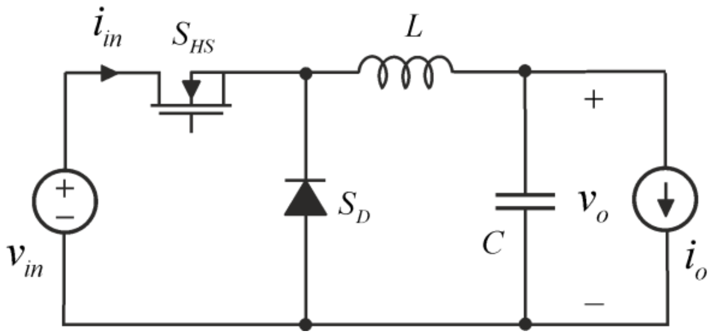
- Low voltage produced by fuels cells can be boosted by an isolated full-bridge dc-dc converter (Buck-type converter)
- Output power of a fuel cell is maximized a certain operating point, therefore, control of the electrical variables of the fuel cell is important



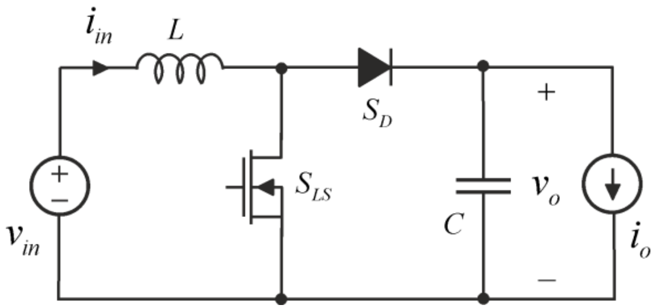
J. Wang et. al., "Low Cost Fuel Cell Converter System for Residential Power Generation", IEEE Transactions on Power Electronics, vol. 19, no. 5, pp. 1315-1322, 2004

Conclusion: Basic Switched-Mode Converters

- $M(D) \approx V_o/V_{in}$ and D denotes the pulse or duty ratio
- T_{on}/T_s: T_{on} equals the conduction time of a certain switch component
- T_s the cycle time or inverse of switching frequency f_s
- The complement of D (1-D) is usually denoted by D'.



a) Buck converter: M(D) = D



b) Boost converter: M(D) = 1/(1-D)

Recap

Buck converter

- https://www.youtube.com/watch?v=CEhBN5_fO5o
- https://www.youtube.com/watch?v=m8rK9gU30v4

Boost converter

- https://www.youtube.com/watch?v=wJU7AJgERG8
- https://www.youtube.com/watch?v=QnUhjnbZ0T8