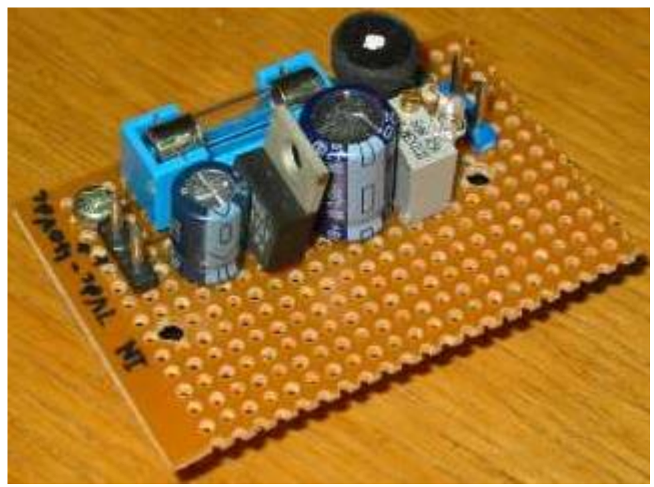
ELG4139: DC to DC Converters

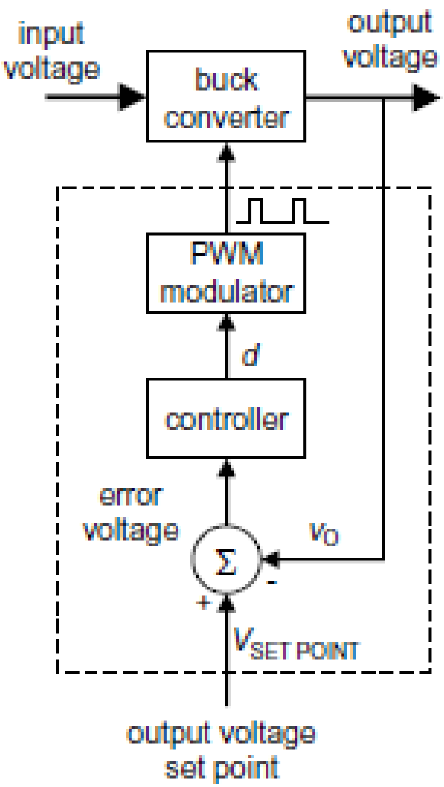
A dc-dc regulator/converter or other names known as buck or boost regulator, provides stable regulated output voltage to supply electric and electronic circuits.

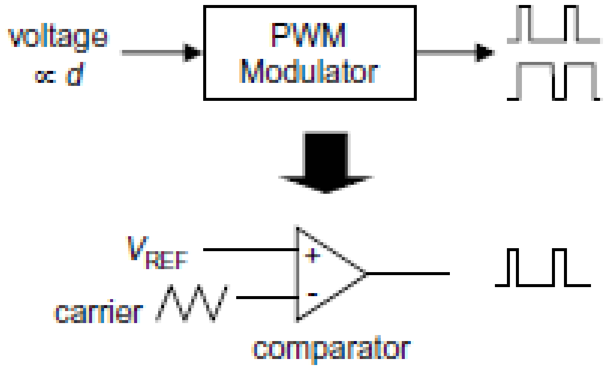


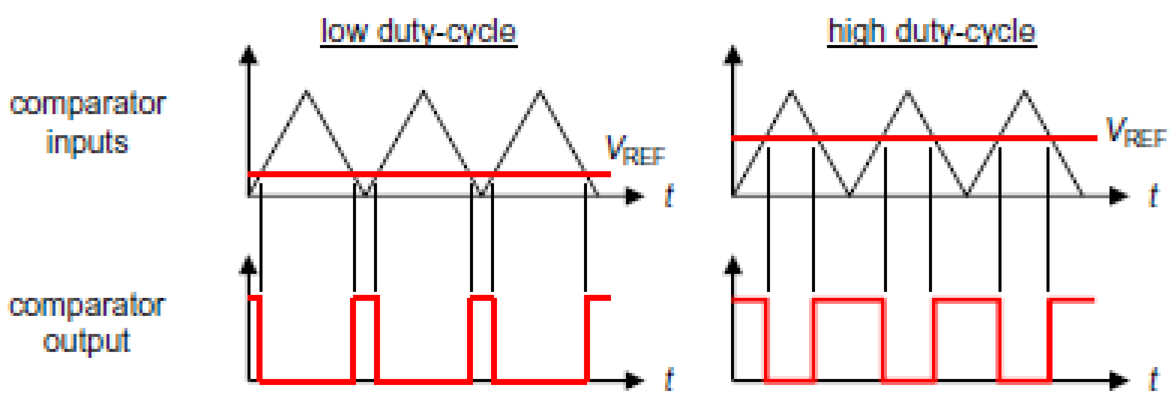
Principles of Step-Down Operation

- Source, Switch with a duty cycle, and a load.
- The switch can be implemented by using BJT, MOSFET, GTO, or IGBT.
- The duty cycle varies from 0 to 1 by varying the duty cycle, chopping duration, or the chopping frequency but usually with a variable duty cycle.
- The output voltage contains harmonics and a DC filter is required to smooth out the ripples.
- The duty cycle can be generated by comparing a DC reference signal with a saw-tooth carrier signal.
- The algorithm to generate the gating signal is first to generate a waveform of period T as a reference and a DC signal, then compare the two by comparator to generate the difference and then a hard limiter to obtain a square-wave gate pulse of width DT which must be applied to a switching device through an isolating circuit.

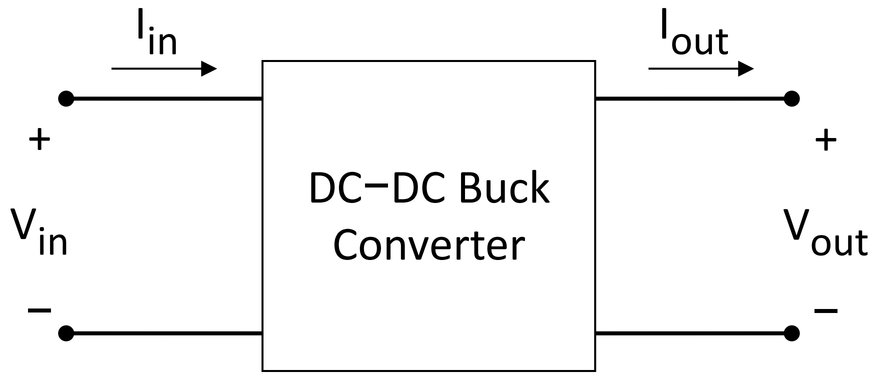
Pulse Width Modulator







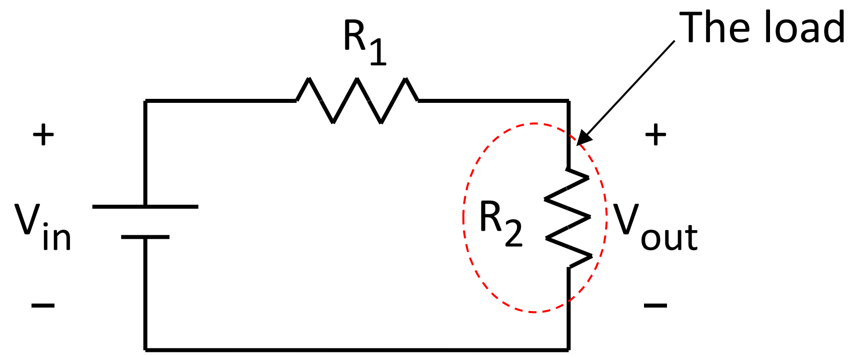
DC Conversion: To efficiently Reduce DC Voltage



Lossless objective: $P_{in} = P_{out}$, which means that $V_{in}I_{in} = V_{out}I_{out}$

$$\frac{V_{out}}{V_{in}} = \frac{I_{in}}{I_{out}}$$

DC–DC Converter: Non-Efficient Way!



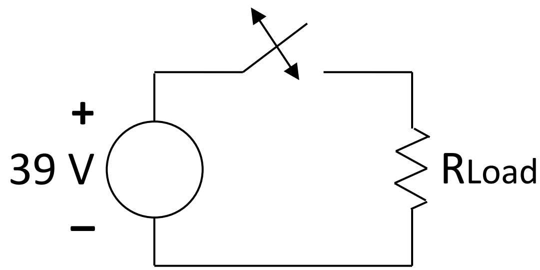
$$V_{out} = V_{in} \bullet \frac{R_2}{R_1 + R_2}$$

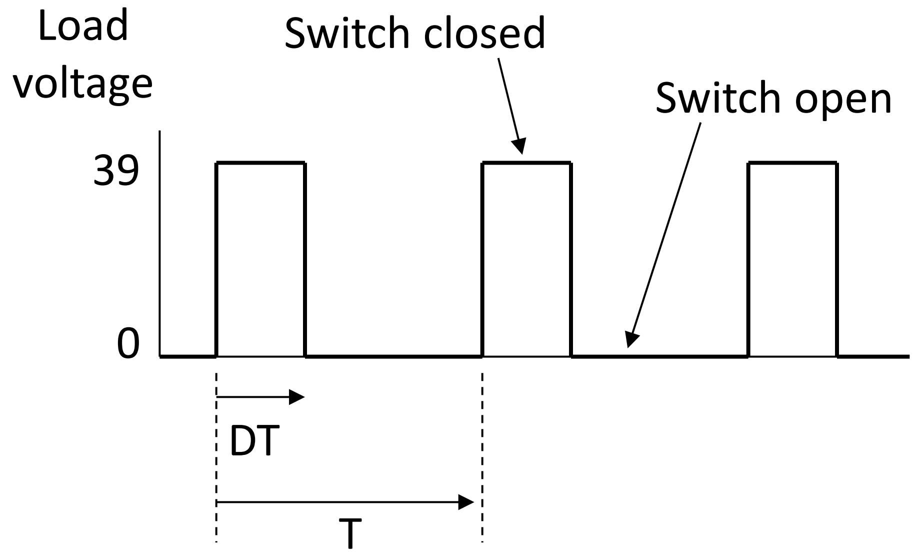
Voltage Divider

$$\eta = \frac{R_2}{R_1 + R_2} = \frac{V_{out}}{V_{in}}$$

If V_{in} = 39V, and V_{out} = 13V, efficiency η is only 33%!

Another Technique: Lossless Conversion

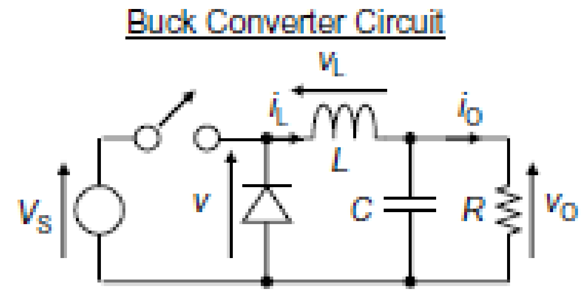


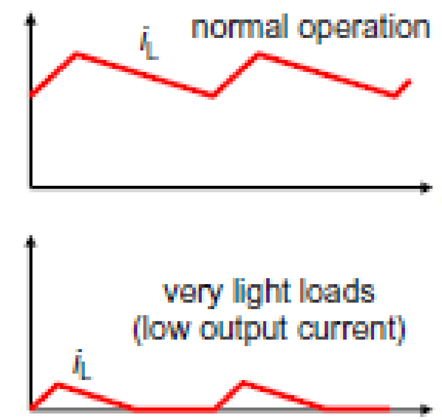


Switch state, Load voltage
Closed, 39 V
Open, 0 V

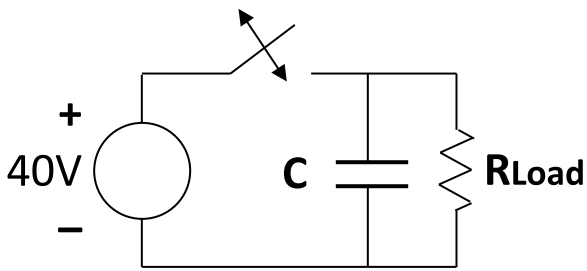
Buck (Step Down) Converter in Brief

- Step down converter
- Switch
- Low-pass LC filter
- Diode
- Transition Between
  - Continuous conduction
  - Discontinuous conduction

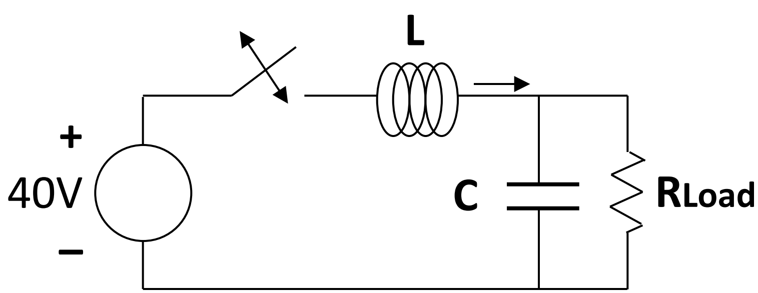




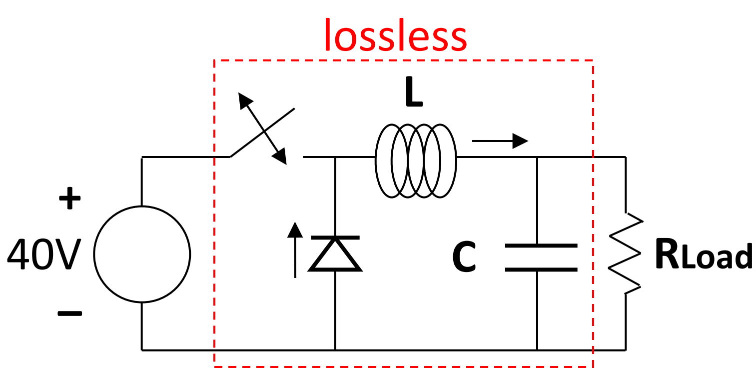
Examples of DC Conversion



Try adding a large C in parallel with the load to control ripple. But if the C has 13Vdc, then when the switch closes, the source current spikes to a huge value and burns out the switch.



Try adding an L to prevent the huge current spike. But now, if the L has current when the switch attempts to open, the inductor's current momentum and resulting *Ldi/dt* burns out the switch.



A DC-DC Buck Converter

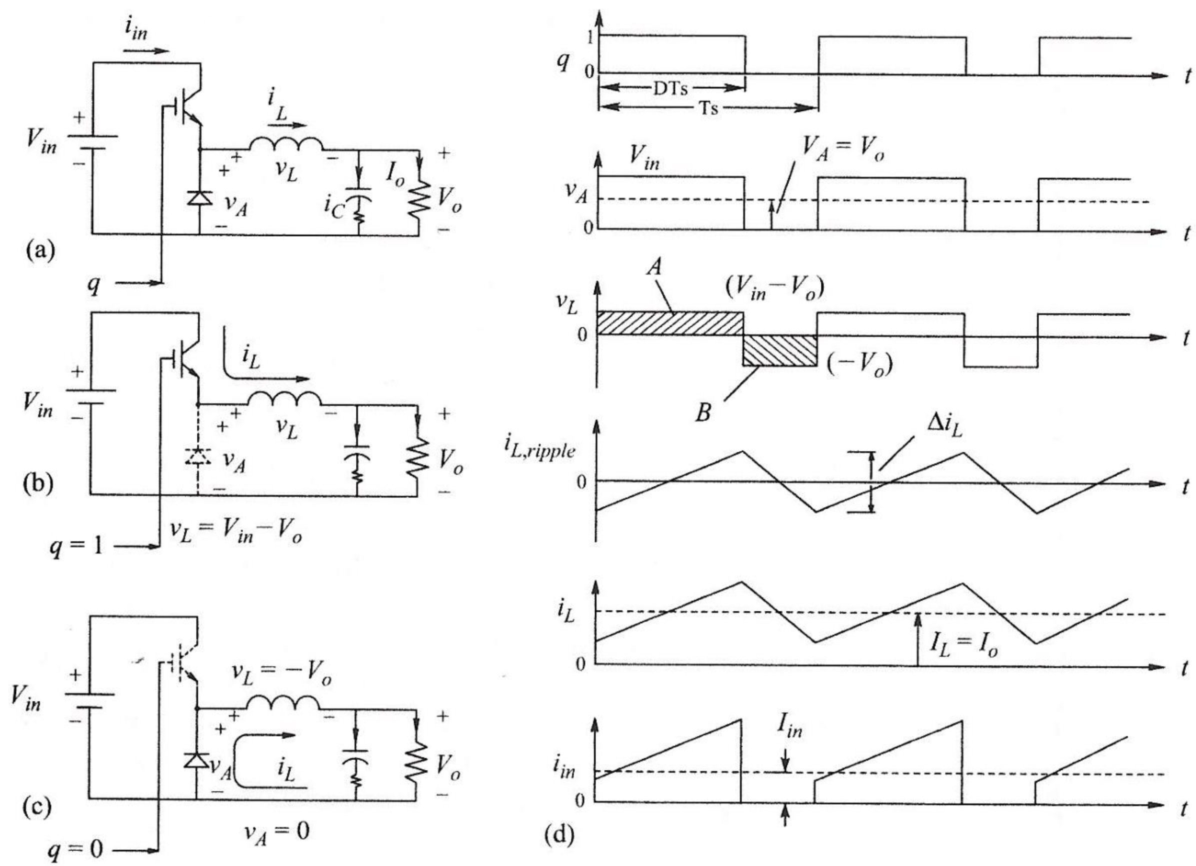
By adding a "free wheeling" diode, the switch can open and the inductor current can continue to flow. With high-frequency switching, the load voltage ripple can be reduced to a small value.

Buck Converters

- A buck converter or voltage regulator is also called a step down regulator since the output voltage is lower than the input voltage.
- In a simple example of a buck converter, a diode is connected in parallel with the input voltage source, a capacitor, and the load, which represents output voltage.
- A switch is connected between the input voltage source and the diode and an inductor is connected between the diode and the capacitor.
- A pulse width modulation controller controls the switch. In this project the microcontroller served as a pulse width modulation source

Buck Converter Analysis

- $V_o = V_A = DV_{in}$; D = switch duty ratio
- $\Delta_{iL} = \frac{1}{L}(V_{in} - V_o)DT_s = \frac{1}{L}V_o(1-D)T_s$
- $I_L = Io = \frac{Vo}{R}$



Capacitors and Inductors

Capacitors: $i(t) = C\dfrac{dv(t)}{dt}$ The voltage cannot change instantaneously

Capacitors tend to keep the voltage constant (voltage “inertia”). An ideal capacitor with infinite capacitance acts as a constant voltage source. Thus, a capacitor cannot be connected in parallel with a voltage source or a switch (otherwise KVL would be violated, i.e. there will be a short-circuit)

Inductors: $v(t) = L\dfrac{di(t)}{dt}$ The current cannot change instantaneously

Inductors tend to keep the current constant (current “inertia”). An ideal inductor with infinite inductance acts as a constant current source. Thus, an inductor cannot be connected in series with a current source or a switch (otherwise KCL would be violated)

Capacitor and Inductor

Examine the current passing through a capacitor that is operating in periodic steady state. The governing equation is

$$i(t) = C\frac{dv(t)}{dt} \quad \text{which leads to} \quad v(t) = v(t_o) + \frac{1}{C}\int_{t_o}^{t_{o+t}} i(t)dt$$

Since the capacitor is in periodic steady state, then the voltage at time t_o is the same as the voltage one period T later, so

$$v(t_o + T) = v(t_o), \quad \text{or} \quad v(t_o + T) - v(t_o) = 0 = \frac{1}{C}\int_{t_o}^{t_{o+T}} i(t)dt$$

The conclusion is that $\displaystyle\int_{t_o}^{t_{o+T}} i(t)dt = 0$

Examine the voltage across an inductor that is operating in periodic steady state. The governing equation is

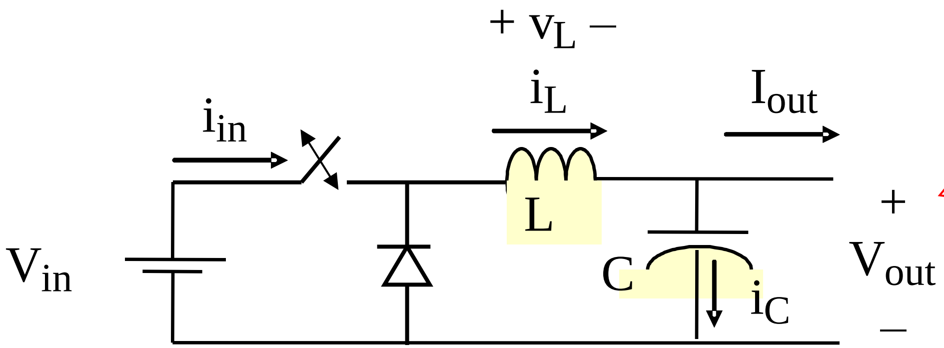
$$v(t) = L\frac{di(t)}{dt} \quad \text{which leads to} \quad i(t) = i(t_o) + \frac{1}{L}\int_{t_o}^{t_{o+t}} v(t)dt$$

Since the inductor is in periodic steady state, then the voltage at time t_o is the same as the voltage one period T later, so

$$i(t_o + T) = i(t_o), \quad \text{or} \quad i(t_o + T) - i(t_o) = 0 = \frac{1}{L}\int_{t_o}^{t_{o+T}} v(t)dt$$

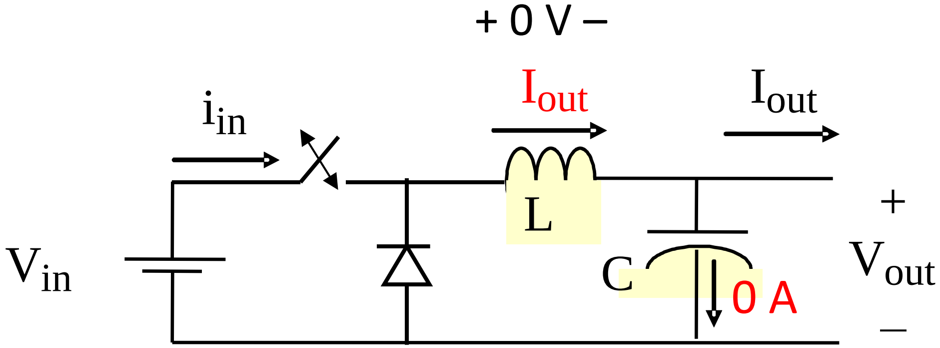
The conclusion is that $\displaystyle\int_{t_o}^{t_{o+T}} v(t)dt = 0$

Buck (step Down) Converter



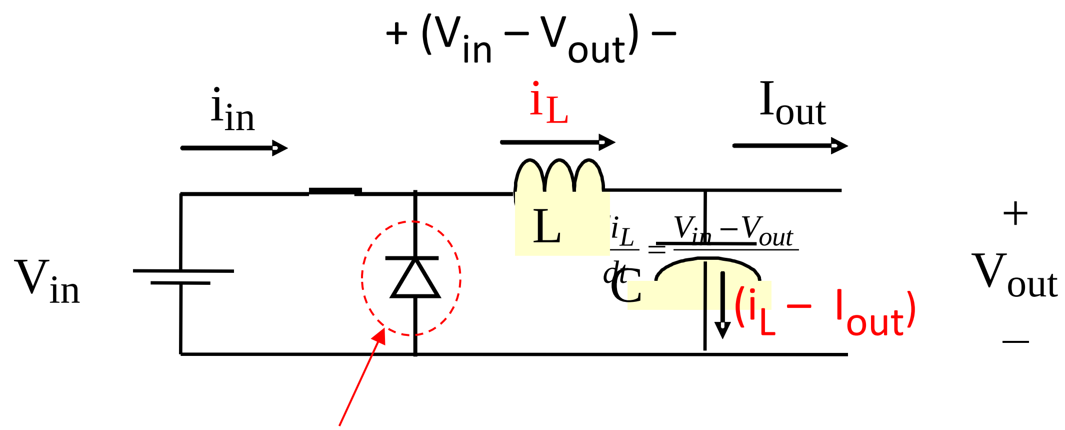
- Assume large C so that V_{out} has very low ripple
- Since V_{out} has very low ripple, then assume I_{out} has very low ripple

What do we learn from inductor voltage and capacitor current in the average sense?



Examining Inductor Voltages

Switch closed for DT seconds



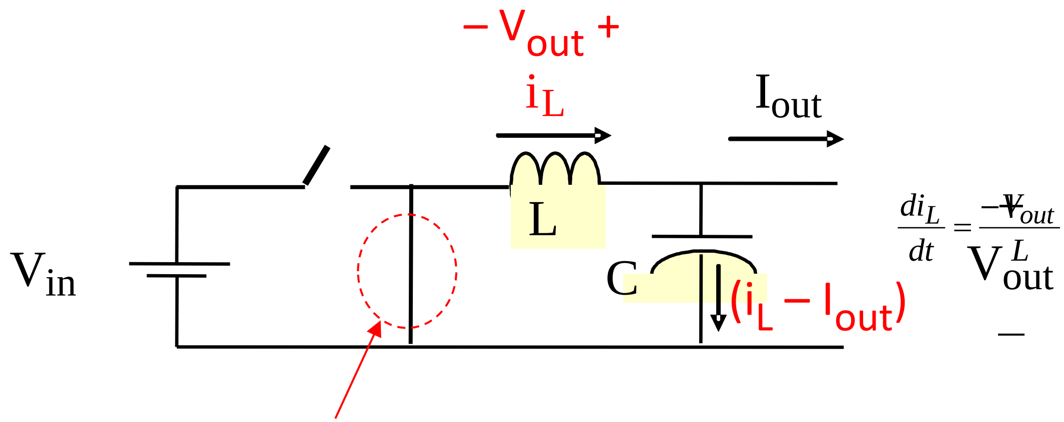
Reverse biased, thus the diode is open

$$v_L = L\frac{di_L}{dt}, \quad v_L = V_{in} - V_{out}, \quad V_{in} - V_{out} = L\frac{di_L}{dt},$$

for DT seconds

Note – if the switch stays closed, then $V_{out} = V_{in}$

Switch open for (1 – D)T seconds



i_L continues to flow, thus the diode is closed. This is the assumption of "continuous conduction" in the inductor which is the normal operating condition.

$$V_{out} = DV_{in}$$

$$v_L = L\frac{di_L}{dt}, \quad \boxed{v_L = -V_{out},} \quad -V_{out} = L\frac{di_L}{dt}, \quad I_{out} = \frac{I_{in}}{D}$$

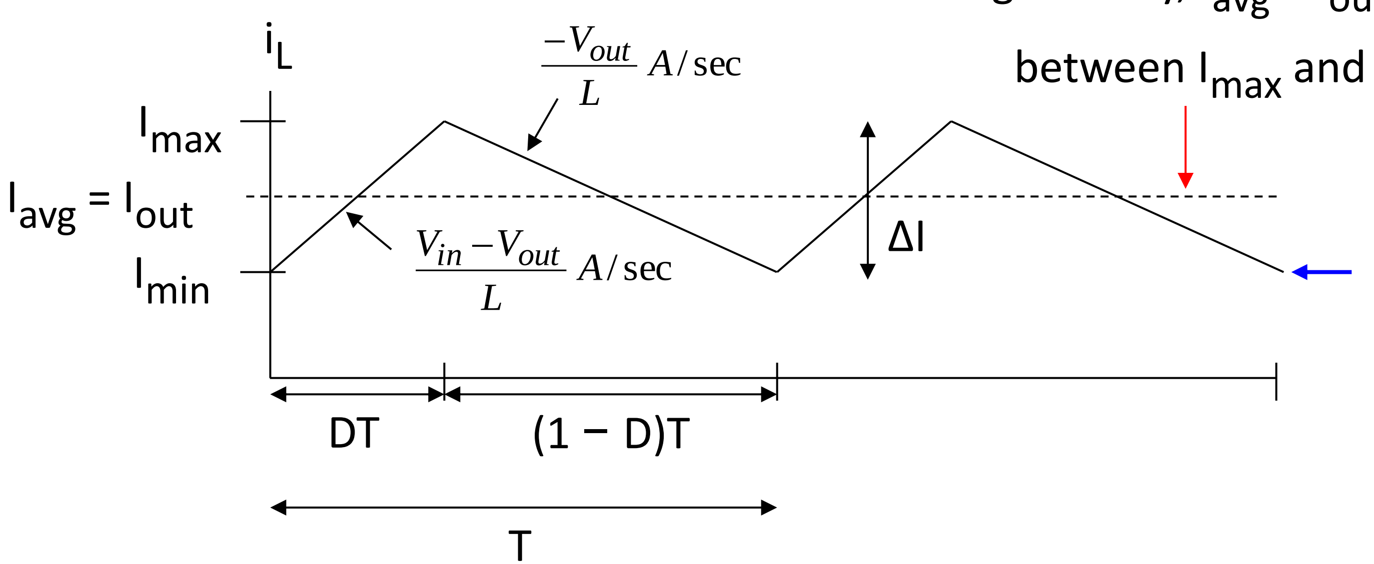
for (1−D)T seconds

The Inductor Current

Switch closed $\quad v_L = V_{in} - V_{out}, \dfrac{di_L}{dt} = \dfrac{V_{in} - V_{out}}{L}$

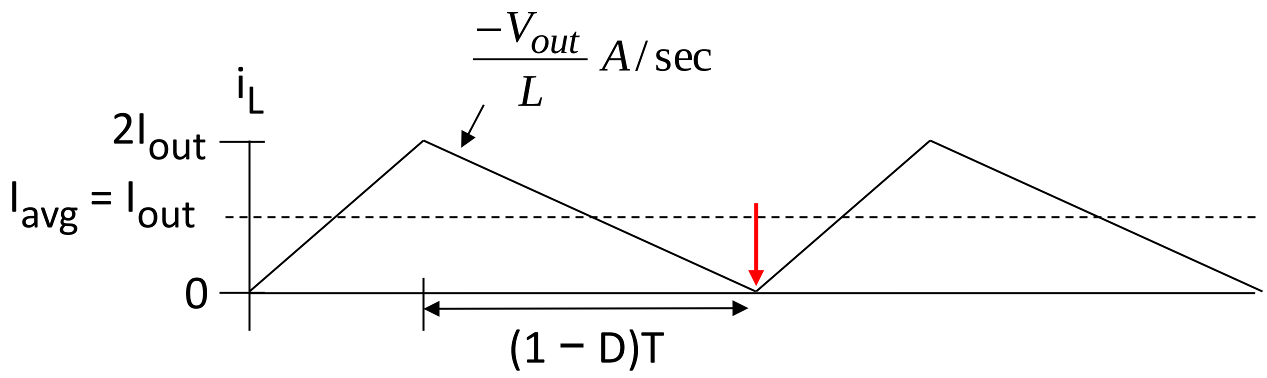
Switch open $\quad v_L = -V_{out}, \dfrac{di_L}{dt} = \dfrac{-V_{out}}{L}$

From geometry, $I_{avg} = I_{out}$ is halfway between I_{max} and I_{min}



Periodic – finishes a period where it started

Designing the Inductance



$$2I_{out} = \frac{V_{out}}{L_{onset}} \bullet (1-D)T = \frac{V_{out}(1-D)}{L_{onset} f}$$

$$L_{onset} = \frac{V_{out}(1-D)}{2I_{out} f}$$

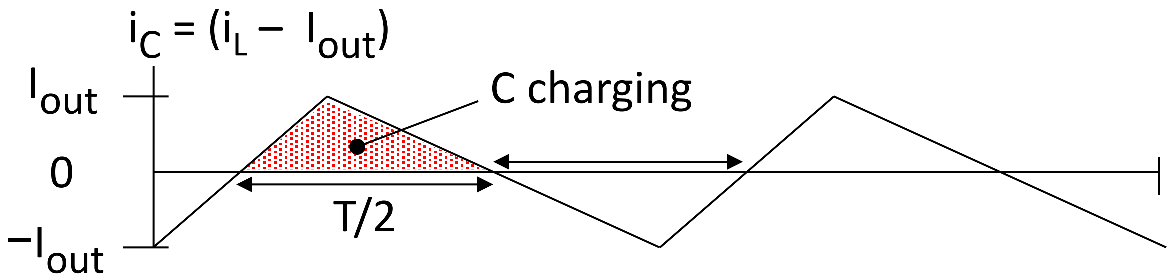
Then, considering the worst case (i.e., $D \rightarrow 0$),

$$L > \frac{V_{out}}{2I_{out} f}$$ guarantees continuous conduction

use max

use min

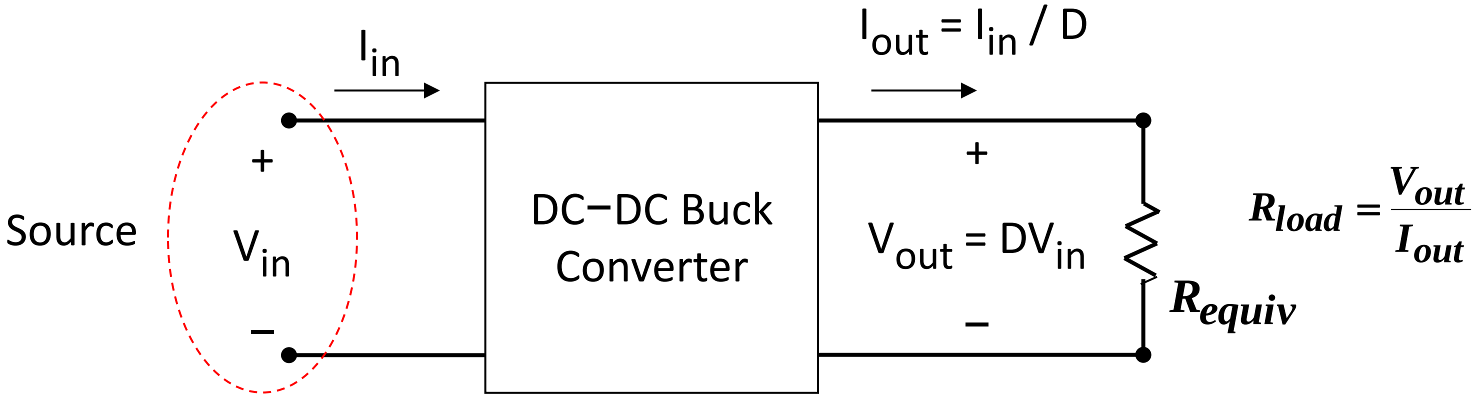
Designing the Capacitance

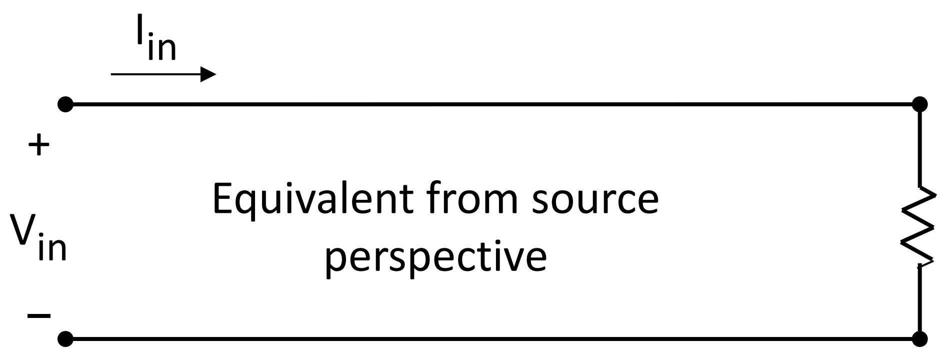


$$\Delta V = \frac{\Delta Q}{C} = \frac{\frac{1}{2} \bullet \frac{T}{2} \bullet I_{out}}{C} = \frac{T \bullet I_{out}}{4C} = \frac{I_{out}}{4Cf}$$

During the charging period, the *C* voltage moves from the min to the max. The area of the triangle shown above gives the peak-to-peak ripple voltage.

Impedance Matching





$$R_{equiv} = \frac{V_{in}}{I_{in}} = \frac{\frac{V_{out}}{D}}{I_{out} \bullet D} = \frac{V_{out}}{I_{out} \bullet D^2} = \frac{R_{load}}{D^2}$$

The buck converter makes the load resistance look larger to the source

Switching Mode Regulators

- DC converters can be used as switching-mode regulators to convert a DC voltage, normally unregulated, to a regulated DC output voltage. The regulation is normally achieved by PWM at a fixed frequency and the switching device is normally BJT, MOSFET, or IGBT.

- Buck Regulators
- Boost Regulators
- Buck-Boost Regulators
- Cuk Regulators

Designing a Buck Converter

- Design Criteria
  - Calculate the required inductor
  - Calculate the output capacitor
  - Select the input capacitor
  - Select the diode
  - Choose the MOSFET
  - Calculate the converter Efficiency
- For a Buck DC-DC converter we first calculate the required inductor and output capacitor specifications. Then determine the input capacitor, diode, and MOSFET characteristics. With the selected components, we will calculate the system efficiency.

Designing a Buck Converter

Assume:

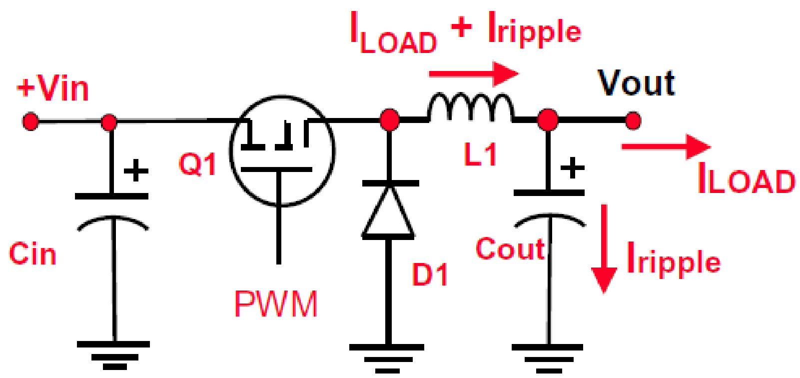
V_{in} = 12 V

V_{OUT} = 5 volts

I_{LOAD} = 2 amps

F_{sw} = 400 KHz

D = V_{in} / V_{out} = 5V /12V = 0.416



Define Ripple current:

I_{ripple} = 0.3 • I_{LOAD} (typically 30%)

For an Inductor: V = L • ΔI / ΔT

Rearrange and substitute:

L = (Vin – Vout) • (D / Fsw) / Iripple

Calculate:

L = 7 V • (0.416 / 400 kHz) / 0.6A

L = 12.12 uh

Select C, Diode (Schottky), and the MOSFET

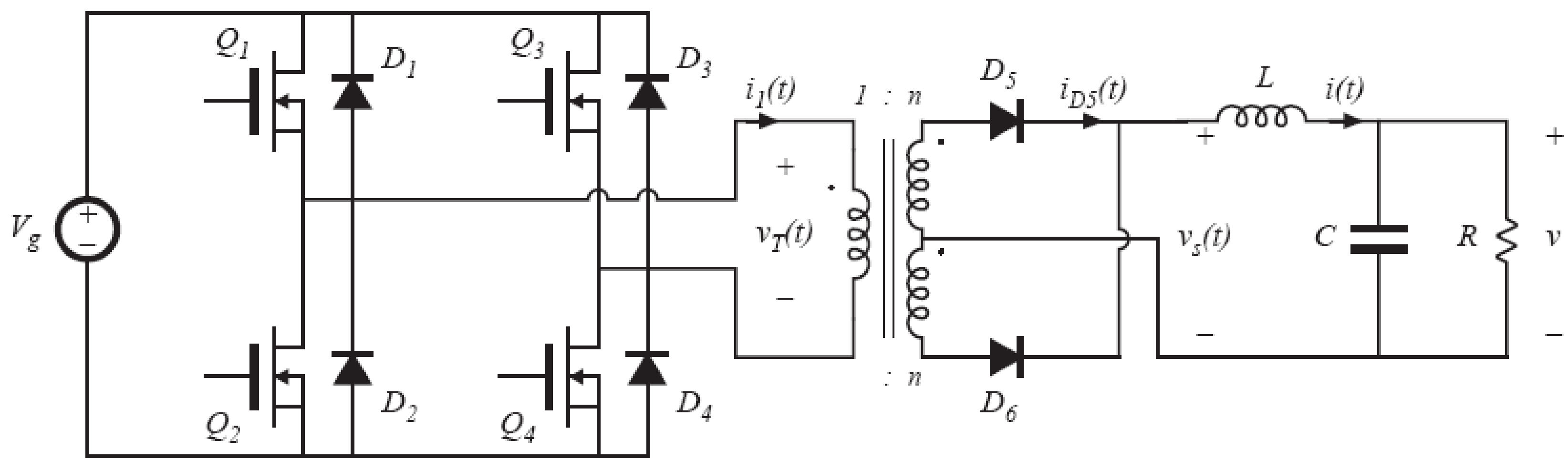
Calculate the Efficiency

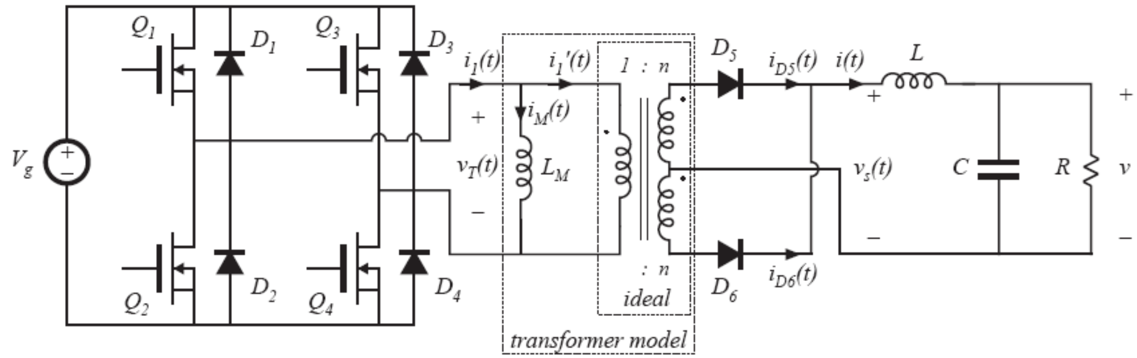
Example

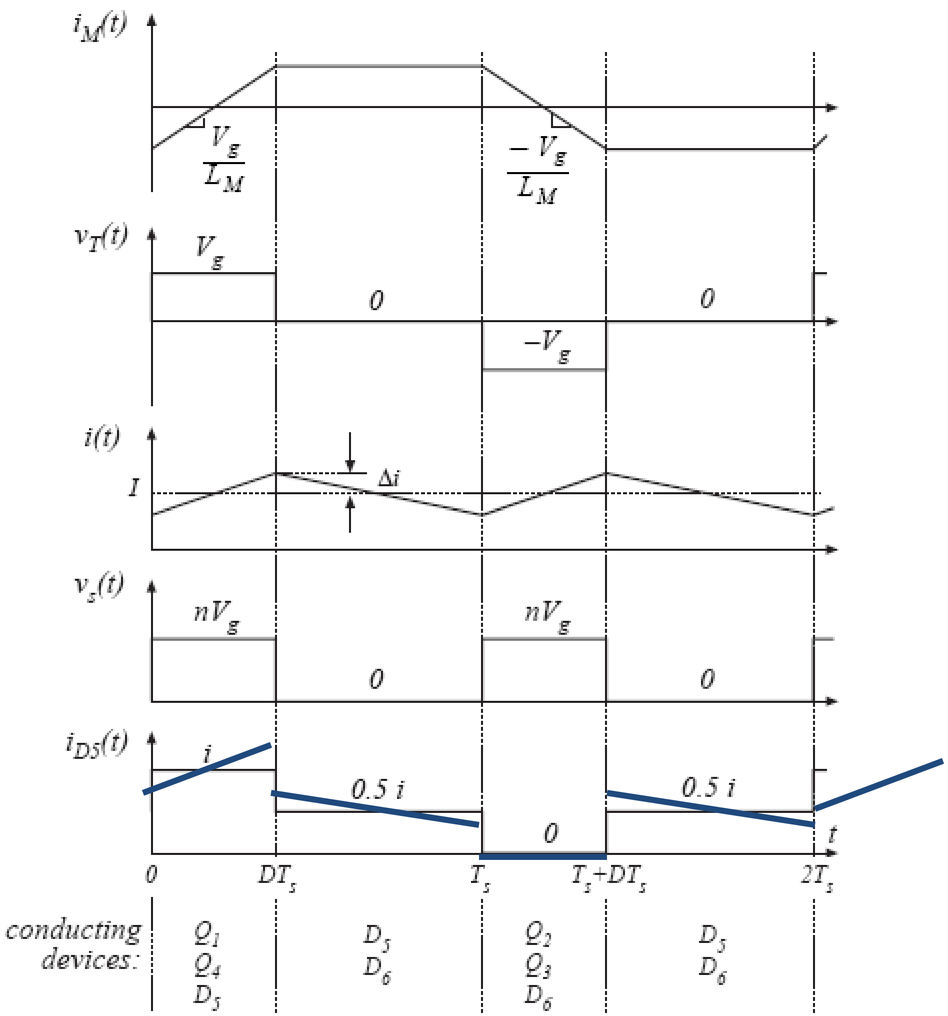
- In **Buck** converter, L = 24μF (steady-state): V_{in} = 20V; D = 0.6; P_o = 14V; f_s = 200 kHz. Calculate and draw the waveform.

Full-Bridge and Half-Bridge Isolated Buck Converters

Full-bridge isolated buck converter







During first switching period: transistors Q_1 and Q_4 conduct for time DT_s , applying voltseconds $Vg\ DT_s$ to primary winding

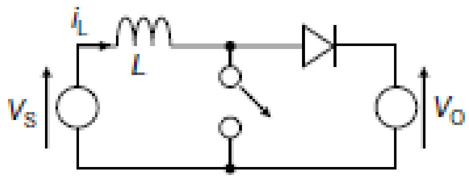
- During next switching period: transistors Q_2 and Q_3 conduct for time DT_s , applying voltseconds $-V_g\ DT_s$ to primary winding
- Transformer volt-second balance is obtained over two switching periods
- Effect of nonidealities?

Boost Converter

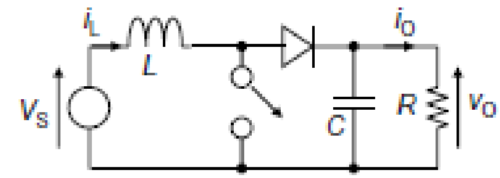
- As with the buck converter, the boost or step-up converter circuit consists of a switch, a diode, an inductor and a capacitor. Their positions in the circuit vary in comparison to the buck converter. In this case the switch is in parallel with the input voltage source, the capacitor and the load. The inductor is placed between the input voltage source and the switch and the diode is placed in-between the switch and the capacitor.

Boost (Step Up) Converter

- Step-up
- Same components
- Different topology!

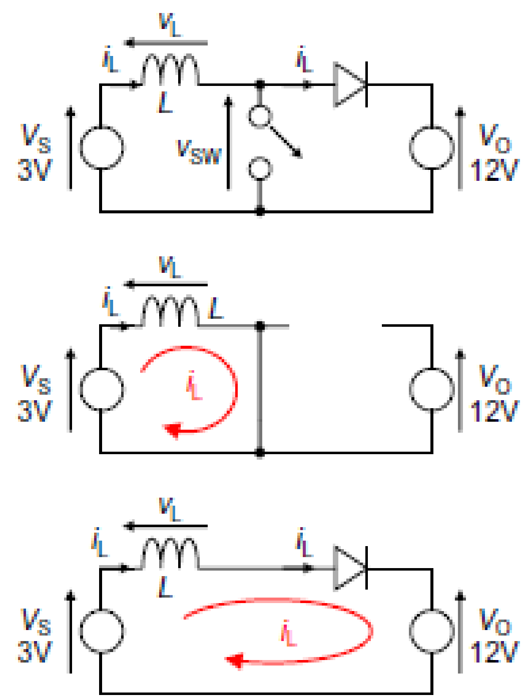


boost converter operating into a voltage source



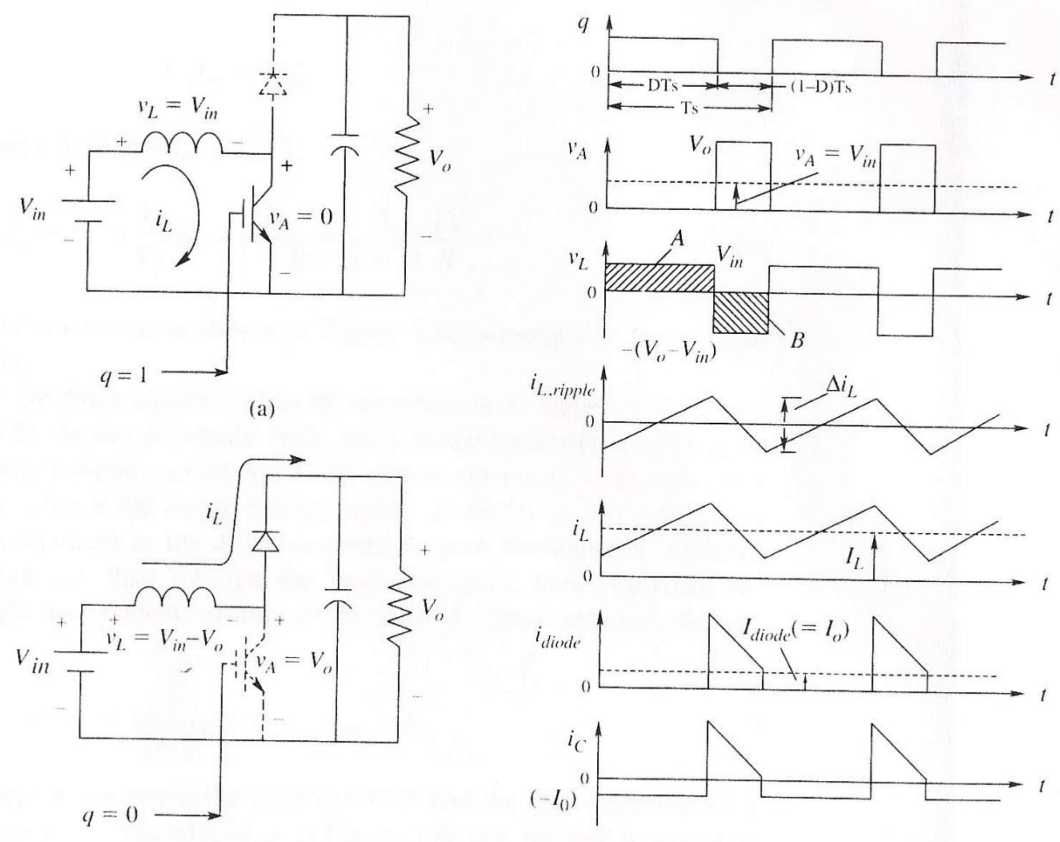
boost converter with resistive load

- See stages of operation



Boost Converter

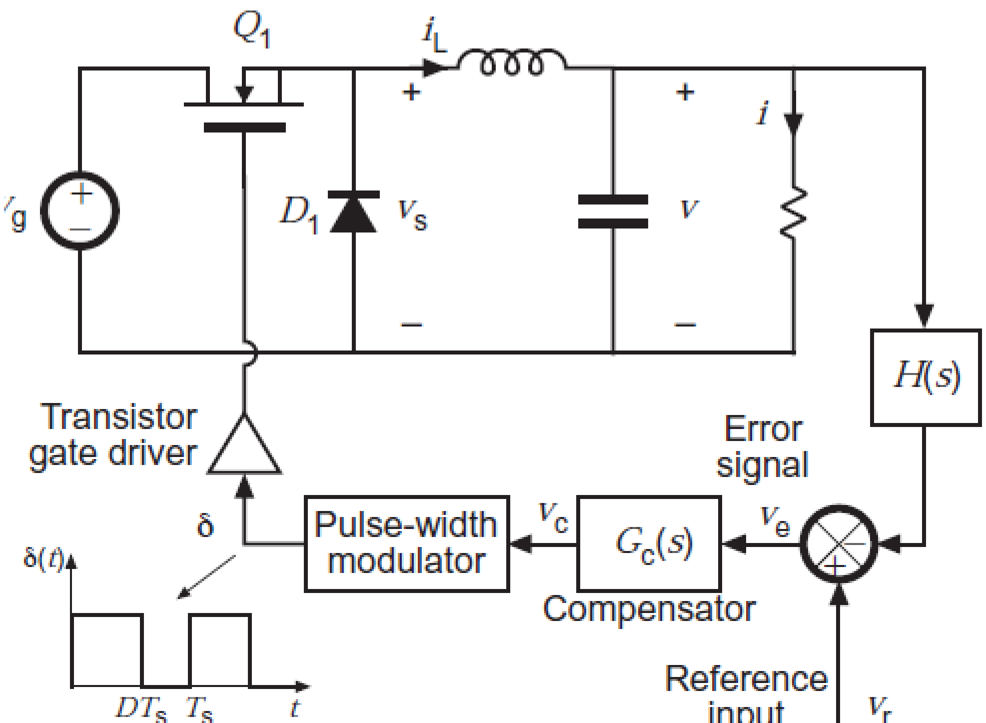
- $\Delta_{iL} = \frac{1}{L}(V_{in})DT_s = \frac{1}{L}(V_o - V_{in})(1-D)T_s$
- $\frac{V_o}{V_{in}} = \frac{1}{1-D}$

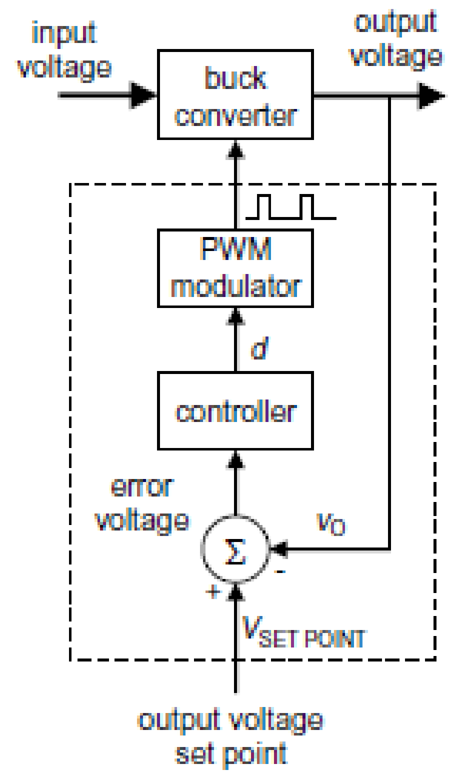


Example

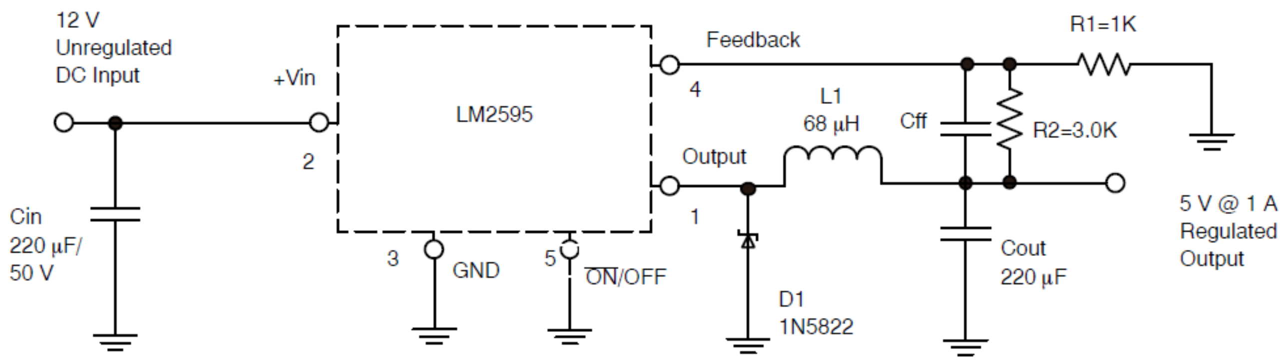
- Consider a boost converter, the inductor current has Δi_L=2 A. V_{in} = 5 V, V_o = 12 V, P_o = 11 W, f_s = 200 kHz. Calculate L and draw the waveform.

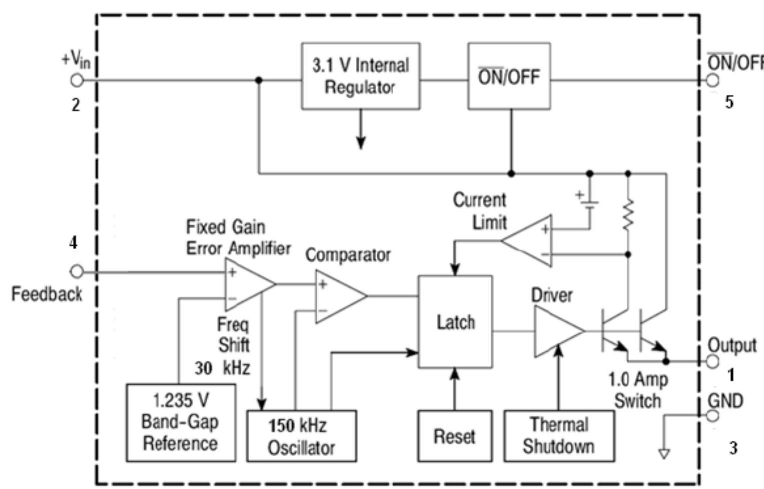
Control of DC to DC Converter





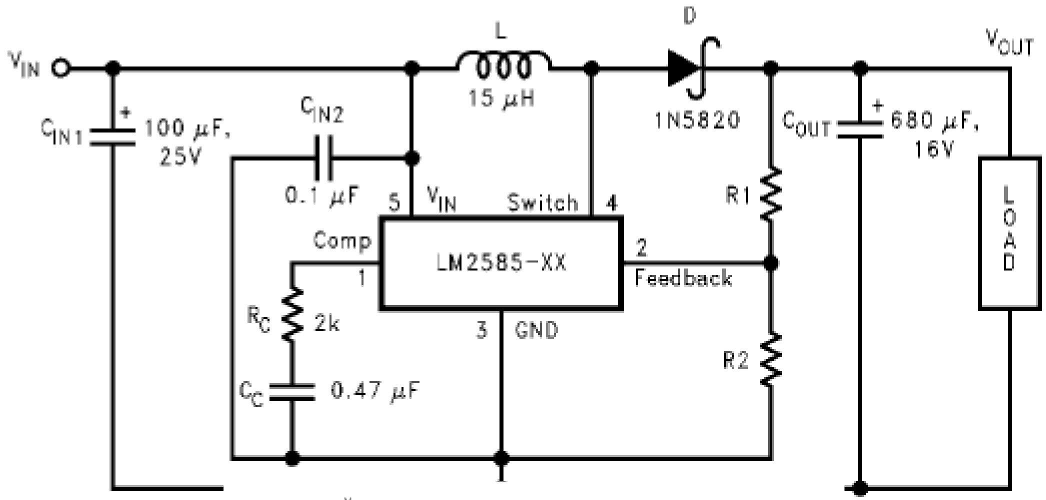
Switch, PWM, Electronics, Reference, and Buck Converter (LM2529: *Courtesy of National Semiconductors*)

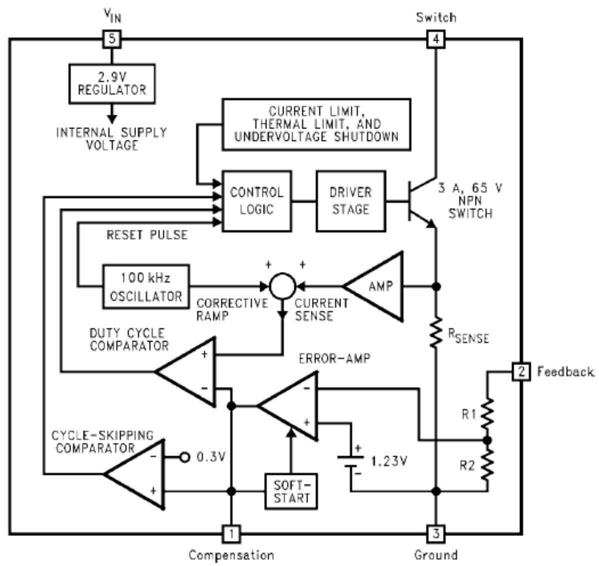




LM2585 with Boost Regulator

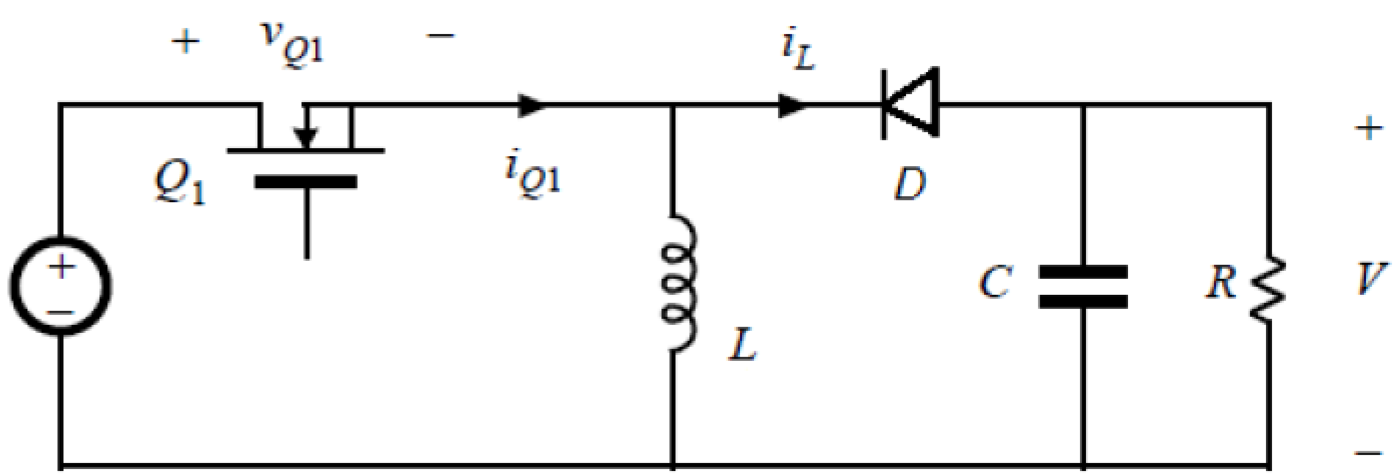
National Semiconductors





Inverting Buck Boost Converter

- The last and most important type of switching regulator is the buck-boost converter. In this converter, the buck and boost topologies covered earlier are combined into one. A buck-boost converter is also built using the same components used in the converters covered before. The inductor in this case is placed in parallel with the input voltage and the load capacitor. The switch or transistor is placed between the input and the inductor, while the diode is placed between the inductor and the load capacitor in a reverse direction.



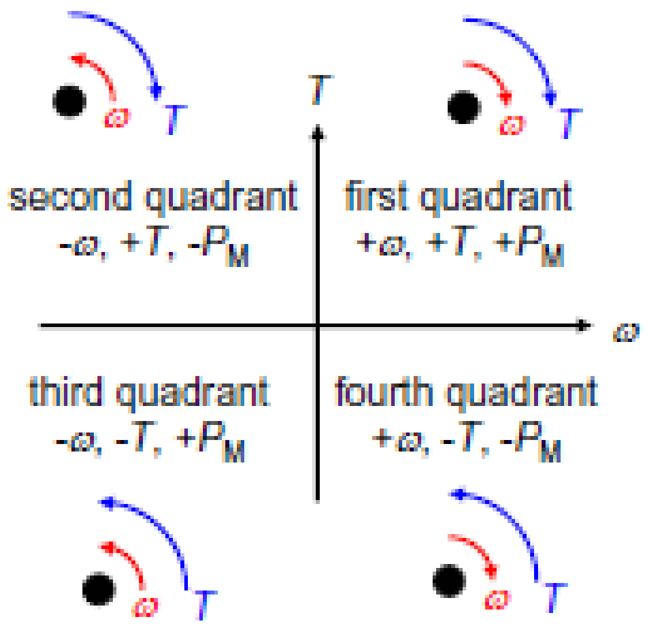
- In the OFF state of the circuit the inductor is used to supply energy to the RC load circuit. The inductor current that the load capacitor sees is in the reverse polarity to that of the input voltage.
- Therefore the name of this converter describes one of the main features of this converter, which is the reversal of the polarities between input and output voltages.
- For this reason, extreme attention should be paid in designing a circuit that uses this type of converter. This converter can be used when the output polarity is not important to the load.
- One of the main advantages of this converter is the low number of parts needed to implement the topology. Therefore losses in the circuitry are low.
- The main disadvantage to this topology is the fact that it operates in buck-boost mode only. So if buck-only mode or boost-only mode is needed this converter is not going to be able to meet the requirements.

Converter Classification

- First Quadrant Converter: Both load voltage and currents are positive.
- Second Quadrant Converter: Load current flows out of the load. Load voltage is positive, but the load current is negative.
- First and Second Quadrant Converter: Load current is either positive or negative; load voltage is positive.
- Third and Fourth Quadrant Converter: The load voltage is always negative. The load current is either positive or negative.
- Four Quadrant Converter: The load current is either positive or negative. The load voltage is either positive or negative.

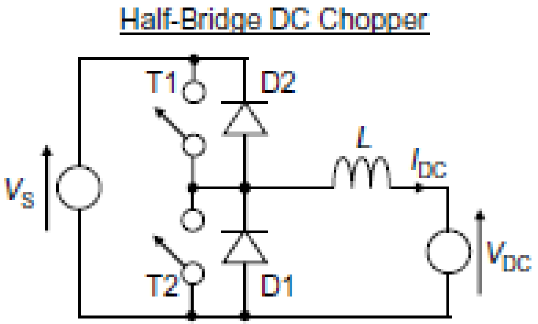
DC Motor Quadrant

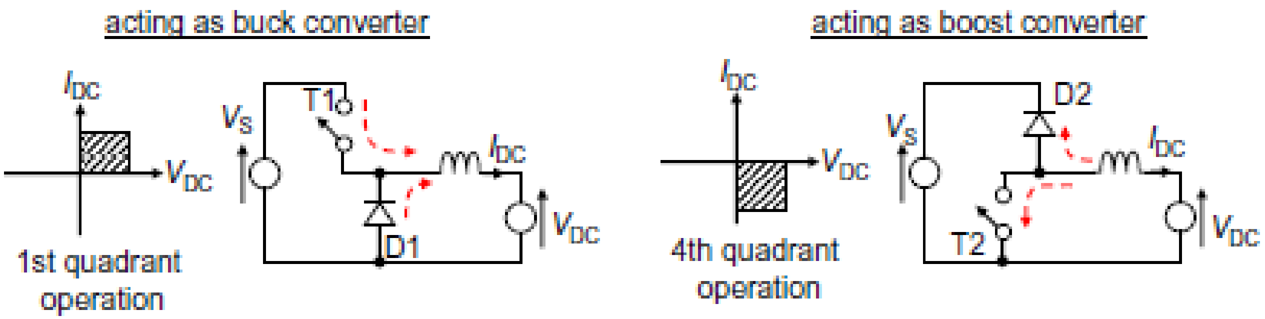
- **First:** Steady-State forward driving.
- **Fourth:** Regenerative breaking; machine trying to slow down; like breaking for traffic light.
- **Third:** Reverse steady-state driving.
- **Second:** Regenerative breaking.



Half-Bridge DC Chopper

- **Buck converter:** Motoring
- **Boost Converter: Generating**
- Two quadrant operating capability

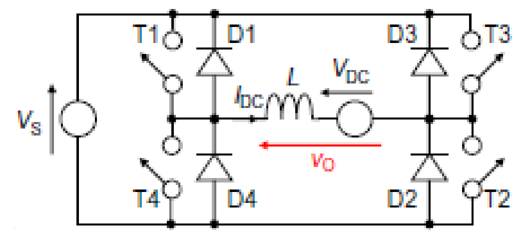




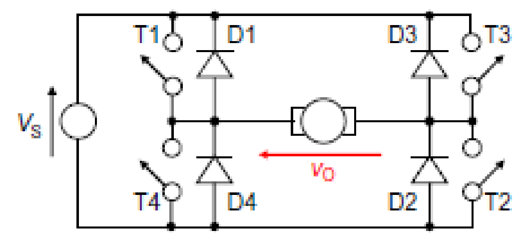
Full-Bridge DC Chopper

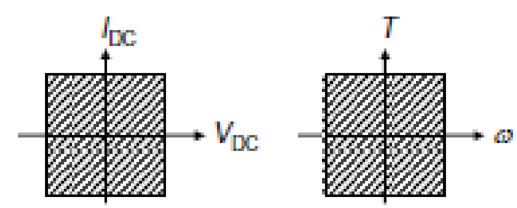
- Full-Quadrant Operation
- **T1 and T2 ON:** + Output voltage
- **T3 and T4 ON:** - Output voltage
- **DC current and torque:** + and –
- **DC voltage and speed:** + and –
- All quantities can be positive or negative

Full-Bridge DC Chopper



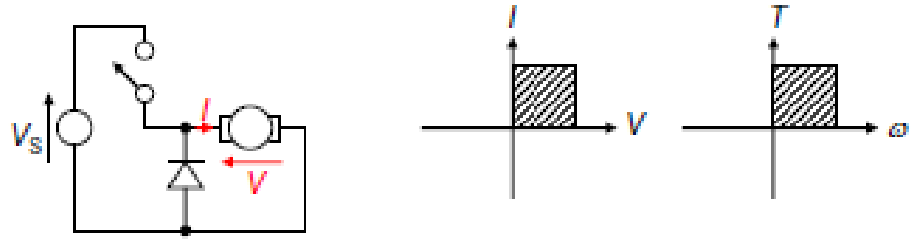
Full-Bridge DC Chopper with DC machine load



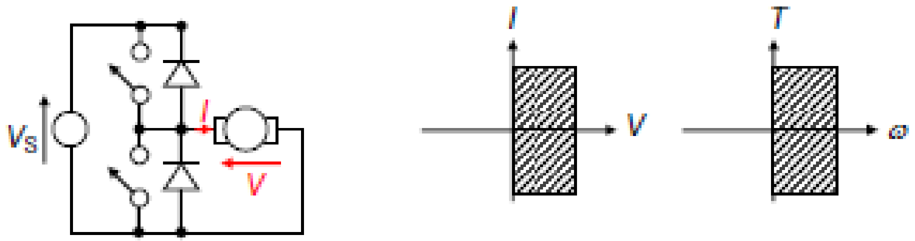


Summary of DC Choppers

- One Quadrant



- Half Bridge



- Full Bridge