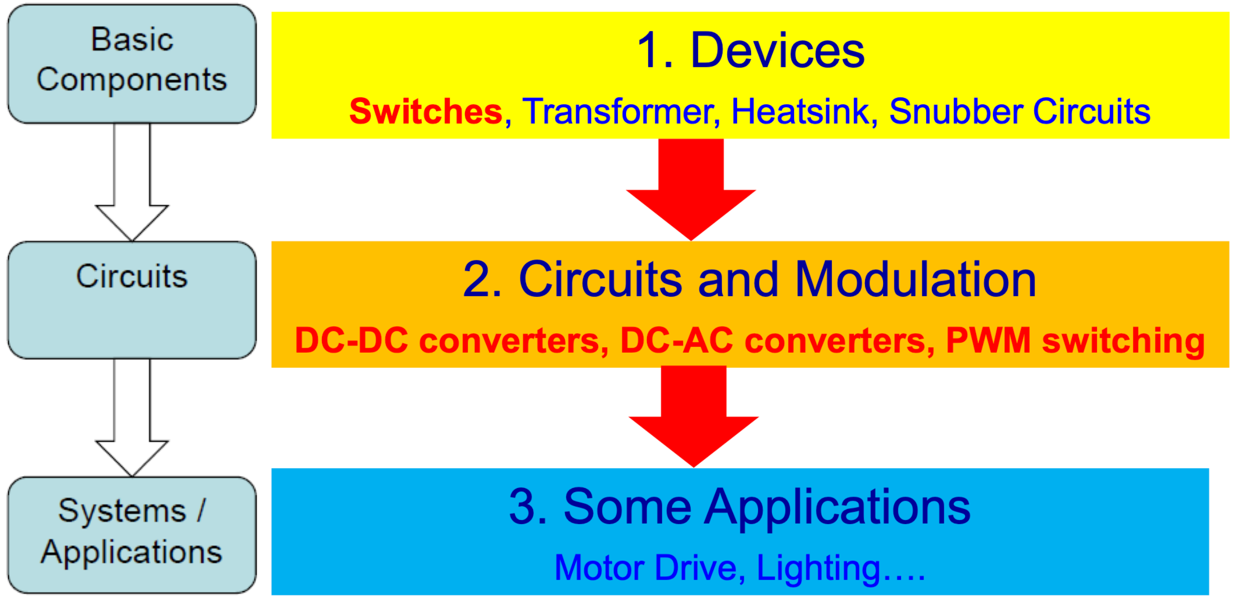
University of Glasgow

Course Structure

UESTC3022

Power Electronics

Week-9



Today's plan

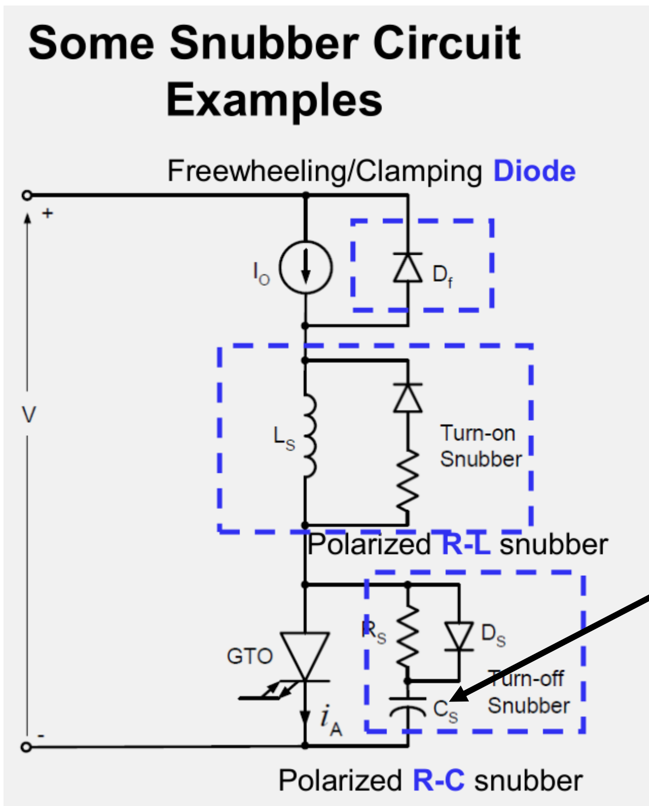
- Quick recap of Snubber Circuits
- Q&A around Snubber Circuits
- DC-DC converters (Switched Mode Power Supplies)
  - Switched Mode Power Converter – 1
  - Switched Mode Power Converter – 2

What we learned last week?

- Snubber Circuits
  - Why? -> functions
  - Where? -> for protection
  - How? -> different configurations
- Classes of Snubber Circuits
- Types of Snubber circuits
  - Voltage snubbers (turn off)
  - Current snubbers (turn on)
  - Overvoltage snubbers

Q&A around Snubber Circuits

1.



Polarity of the Capacitor with the cathode of diode

Q&A around Snubber Circuits

2. On slide 4 of Lecture 7, it says, "limiting device voltages during turn-off transients" and "limiting the rate-of-rise of voltages .... at device turn-off".

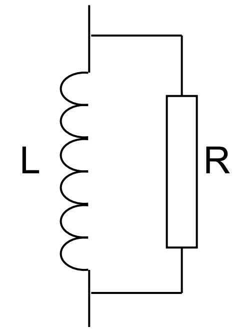
I don't understand the difference between "turn-off transients" and "at device turn-off". Why during turn-off transients, just limit voltage?

Function of Snubber Ciruit

- Limiting device voltages during turn-off transients
- Limiting device currents during turn-on transients
- Limiting the rate-of-rise (di/dt) of currents through the semiconductor device at device turn-on
- Limiting the rate-of-rise (dv/dt) of voltages across the semiconductor device at device turn-off
- Shaping the switching trajectory of the device as it turns on/off

Q&A around Snubber Circuits

3. Clarity on the application of RL



<u>Current snubbers. (电流缓冲电路 或 开通缓冲电路）</u>

The main purpose of a current snubber is as a means of controlling the rate of rise of current in a switch. Recalling that the current through an inductor cannot change instantaneously, this means that when the switch closes, the current through it must be zero. The voltage across the inductor can rise instantaneously, and it is this voltage that will cause current to start to flow through the inductor (from $V=L\,dI/dt$).

<u>Simple RL snubber.</u>

The parallel RL snubber is the dual of the series RC circuit just discussed. It is not used very often because the value of R tends to be too large to damp circuit ringing. If R is reduced to be effective on ringing, the power dissipation tends to be very high.

[Ferrite beads are simple RL circuits . However, their power dissipation is poor and generally they aren’t used in power electronic circuits. Having said that, they are extremely useful because at low frequency the inductance dominates whereas at high frequency (F > 10MHz) the resistance dominates.]

Q&A around Snubber Circuits

4. Optimal Snubber Capacitance = 3x Parasitic Capacitance (C_{switch})

NOTE: Usually the added capacitance, which is snubber capacitor Cs, is chosen to be approximately three times larger than total parasitic capacitance, Cp. Therefore, the total resonance parasitic capacitor is approximately one third of the added capacitance.

Smaller values for Cs result in lower dissipation in Rs but also less damping. Higher values for Cs give better damping but also reduce the loss in the switch at the expense of higher loss in Rs. The total circuit loss however, tends to stay almost the same over a wide range for Cs

Power Electronics

Switched Mode DC-DC Converters I:

Concepts and Buck Converter

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Please read Chapter 7 in the textbook

Switched-mode Power Supplies (SMPS)开关电源

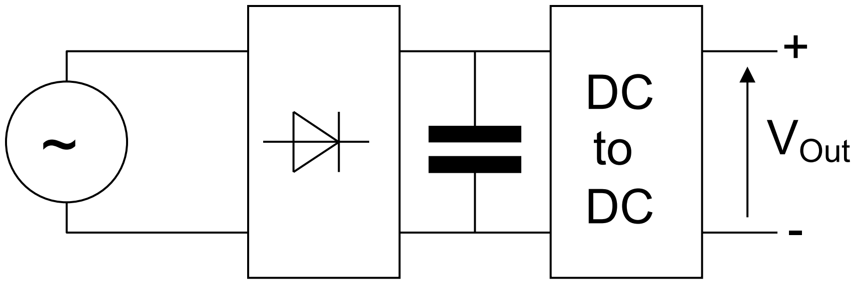
We saw how the linear power supply was very easy to build but suffered from relatively low efficiency. Where efficiency is an important consideration, the SMPS should be the supply of choice. For even moderately-sized power supplies the **advantages** of the SMPS efficiency can be considerable:

1. The transformer size is reduced;
2. Rectifier diodes have a smaller current rating;
3. Heatsinks 散热片can be smaller;
4. A cooling fan is not usually needed;
5. The supply can have a wider input voltage range (no voltage selector needed);
6. The power density 功率密度(watts per cm^3) is greater.
7. The weight is lower.

However, against these advantages, the following **disadvantages** must be considered:

1. The SMPS is electrically very noisy;
2. The filtering necessary to ensure feedback stability does make the transient response of the SMPS much slower (10 X) than an equivalent linear supply.

The principal function 主要功能 of an SMPS is to convert one DC voltage to another very efficiently. In the PC for example the 240V mains is rectified and used as the input to the computer’s PSU which is invariably an SMPS.



In a mobile phone a miniature SMPS is used to convert the battery voltage into multiple different DC voltages for the microprocessor, display, RF 射频 amplifier and camera.

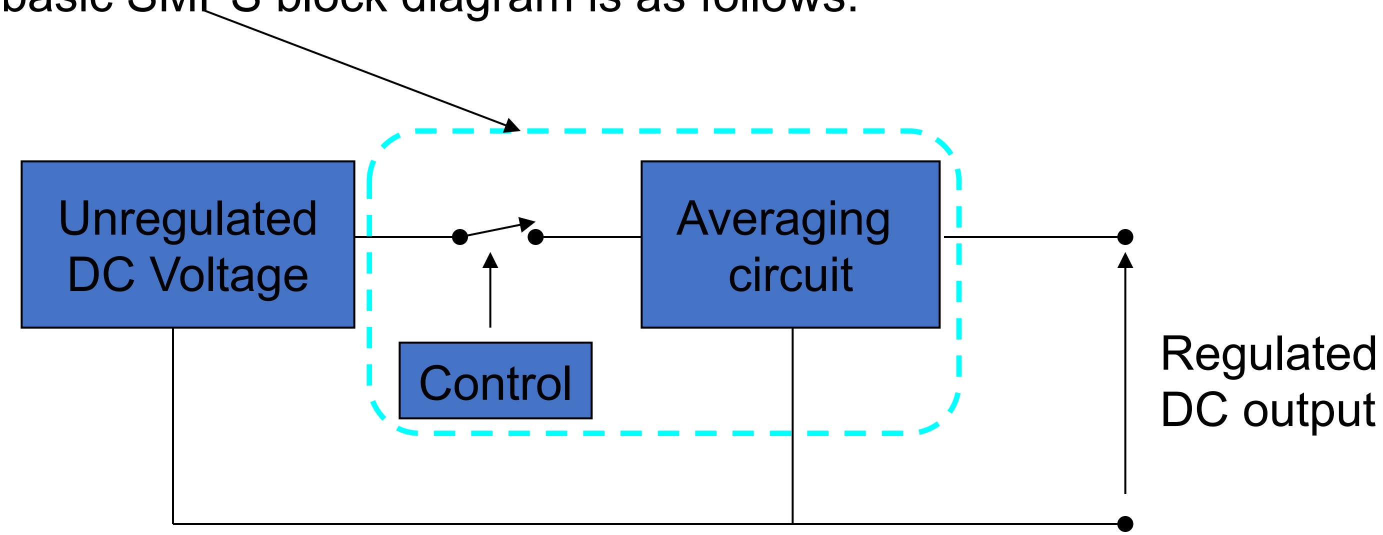
SMPSs come in many different varieties. For the purposes of this course, we will consider three of the most commonly used types:

1. The step-down or "buck" converter. [$V_{Out} < V_{in}$]

2. The step-up or "boost" converter. [$V_{Out} > V_{in}$]

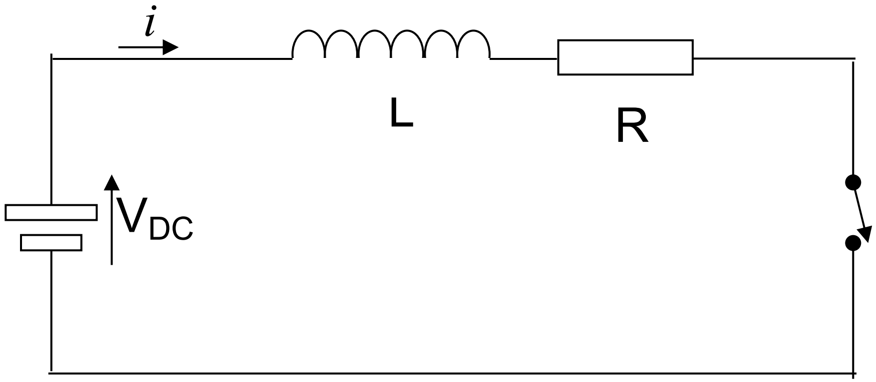
3. The "buck-boost" or flyback converter. [$V_{Out} <> V_{in}$]

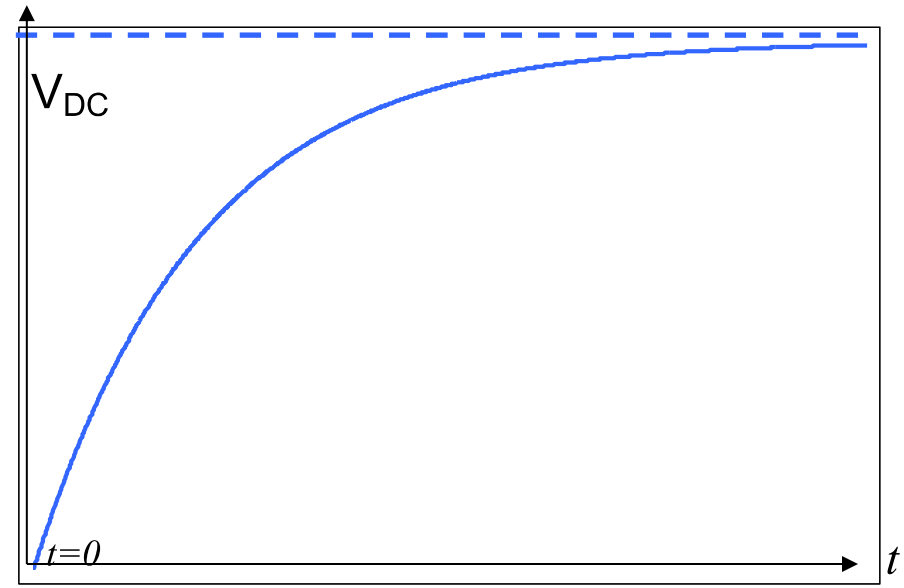
The basic SMPS block diagram is as follows:



The two important components here are the switch (usually a MOSFET) and the averaging circuit that will include an inductor.

Recall the basic RL series circuit 阻感串联电路:



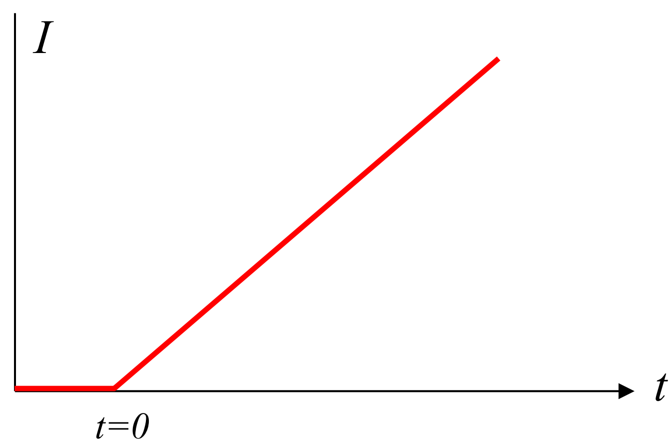


We can write the voltage equation for

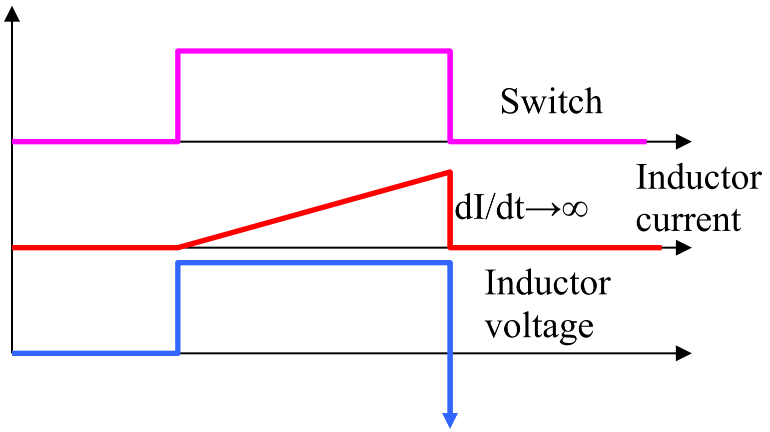
this circuit as $V_{DC} = V_R + V_L = I_L R_L + L\dfrac{dI}{dt}$

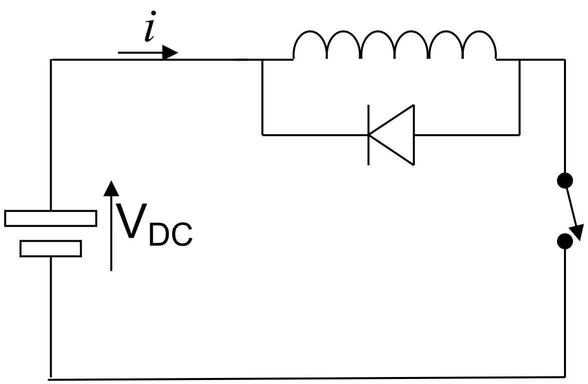
When the value of R is very small, we can neglect the IR term and hence $V_L = L\dfrac{dI}{dt}$

Hence, we can approximate the voltage across the inductor to be a constant and therefore the current through the inductor to rise linearly when the switch is closed.

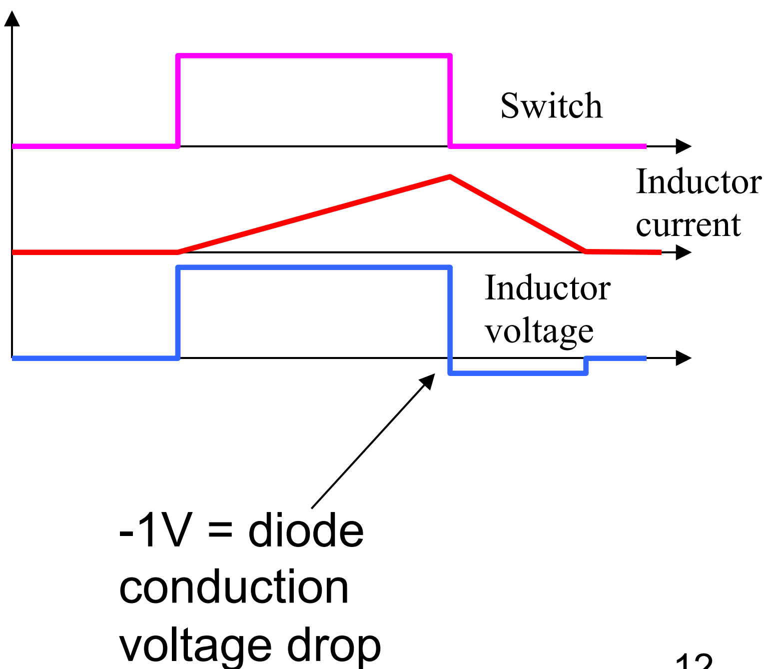


As previously discussed, as the current in the inductor rises, energy is stored in the magnetic field. When the switch is opened, the inductor tries to maintain the current flowing through it and thus the voltage across the inductor reverses. It is necessary to provide a return path for the inductor current when the switch is opened, and this is usually done by adding a diode across the inductor.

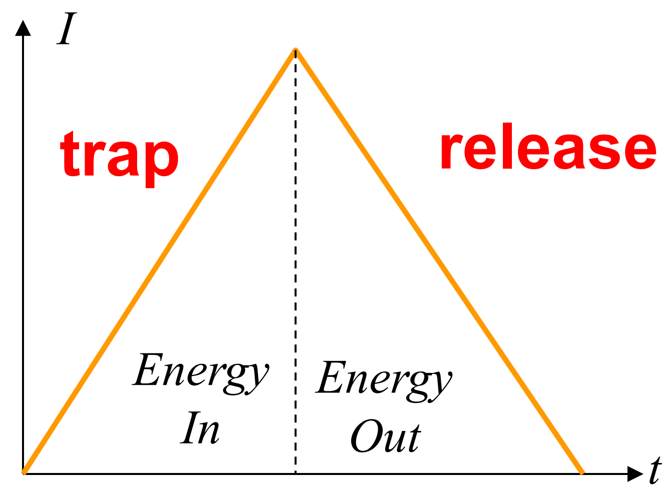




Non-Dissipative Recovery



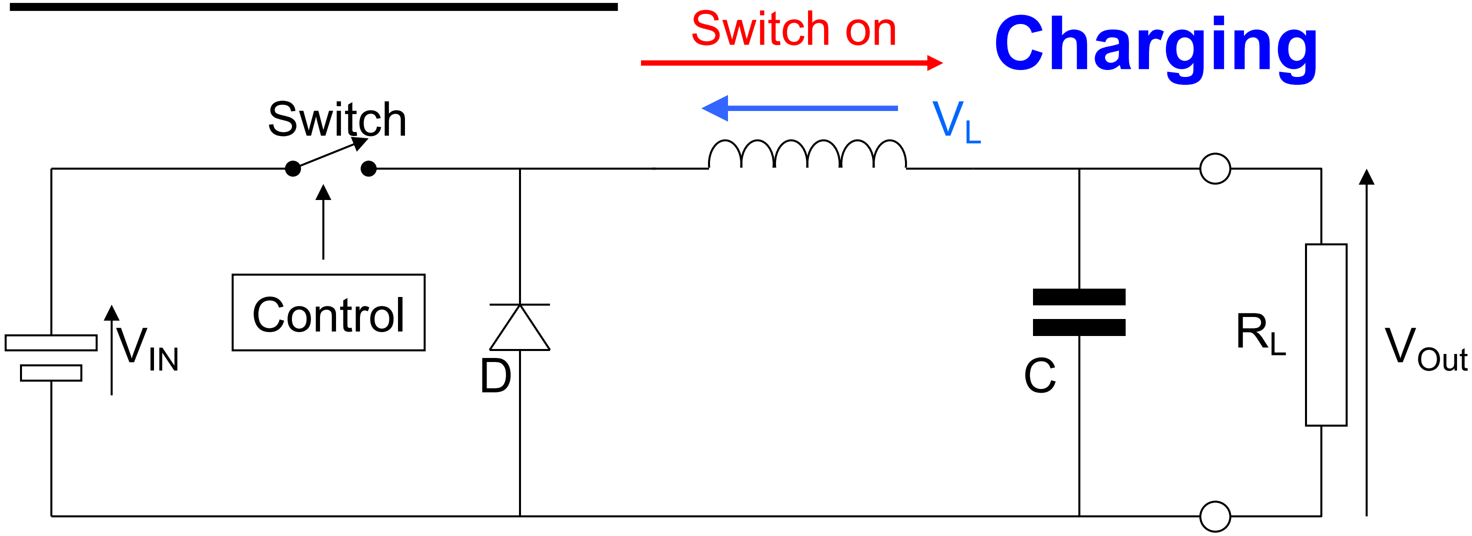
The energy stored in an inductor is $\frac{1}{2}LI^2$. When current through the inductor is increasing, additional energy is being stored in the magnetic field. If the current is decreasing, then energy is being removed from the magnetic field. Assuming a perfect inductor, the energy (i.e., number of joules) returned to the circuit is exactly the same as was originally added.



For Power Conversion, released power from energy storage devices is expected to be delivered to the load as much as possible. Dissipative Energy Recovery is not acceptable.

How to recover the trapped energy in switch-mode power conversion?

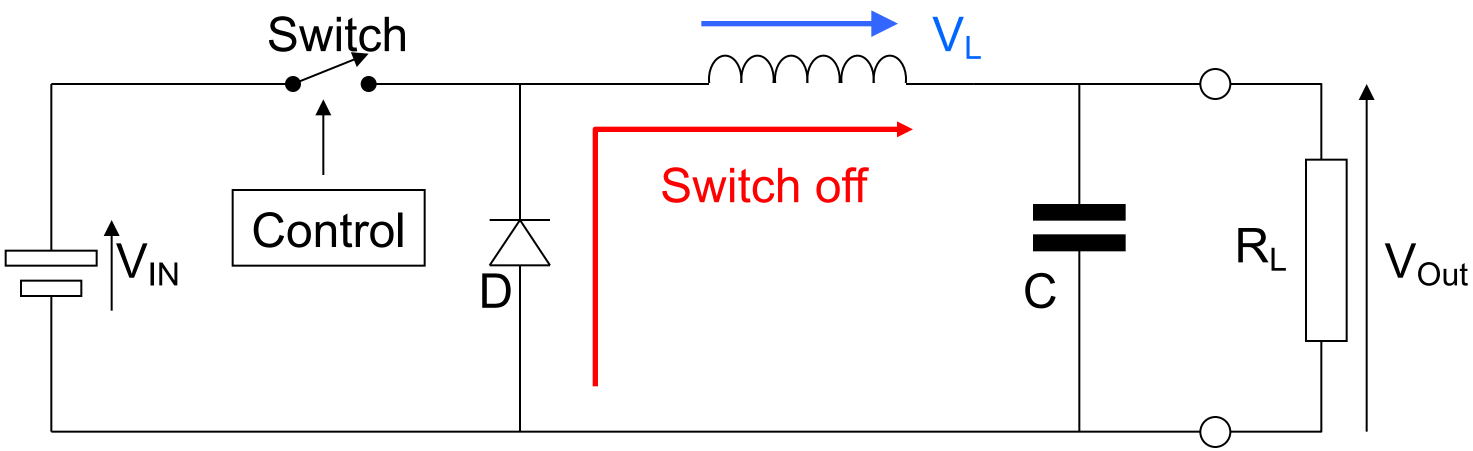
The Buck Converter



Circuit State I

The circuit shows the SMPS circuit for a buck converter. When the switch is first closed, current starts to flow through the inductor and into the capacitor. The voltage across the inductor, V_L, is the difference between the input voltage V_{In} and the output voltage V_{Out}. The diode is reverse biased 偏置 ("off") by the supply voltage V_{In} and does not conduct any current. The rate of change of current into the capacitor is limited by the inductor ($V = L\ di/dt$). At some point T_{off} the switch is opened. At this point the current through the inductor has risen to I_{Max} and the energy in the inductor ($\frac{1}{2}LI^2$) is stored in its magnetic field.

Discharging



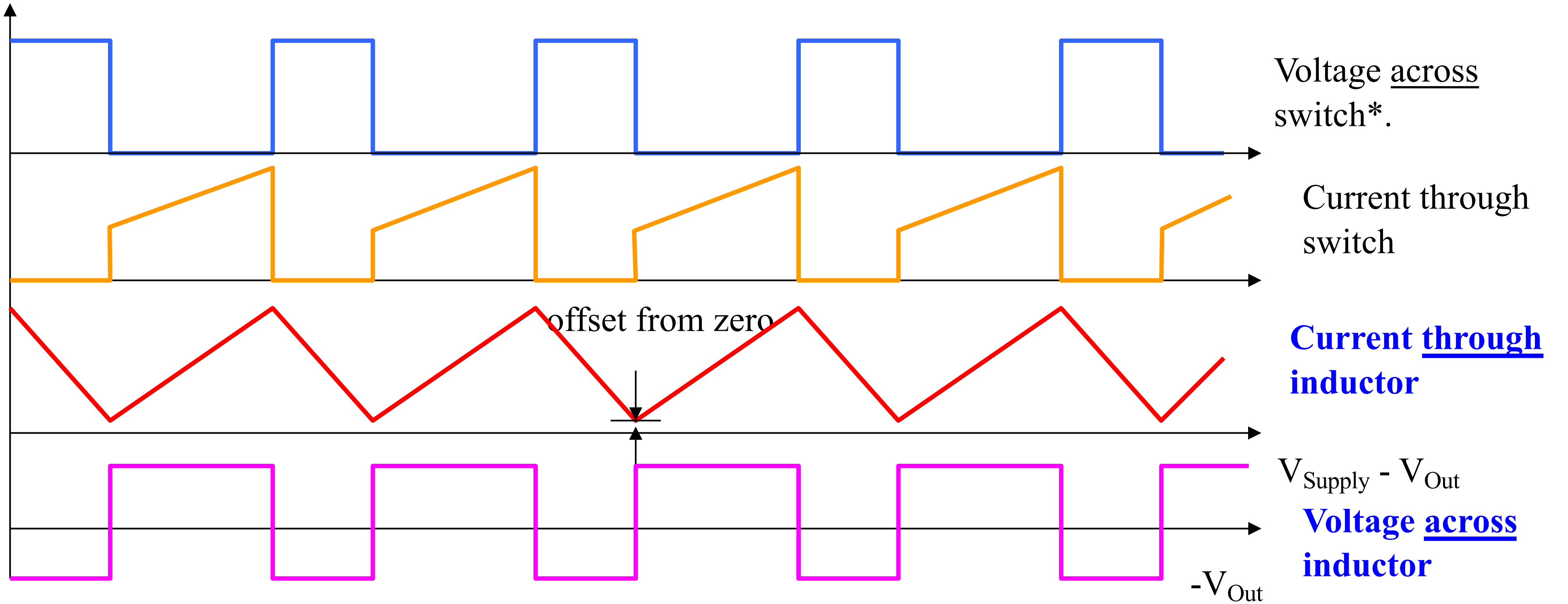
Circuit State II

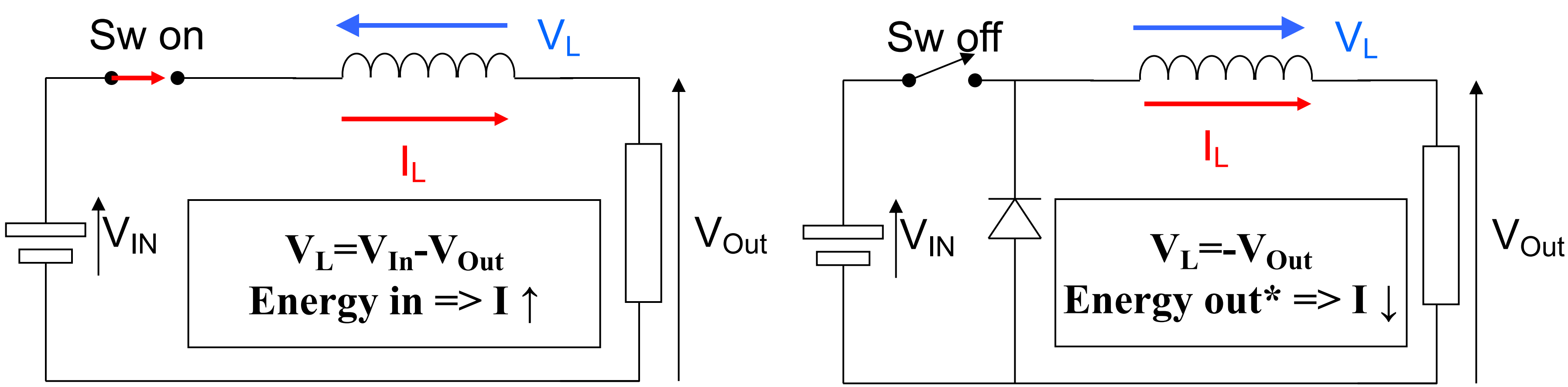
As soon as the switch is opened, the potential on the switched side of the inductor goes sharply negative (but the current continues to flow) as the energy in the magnetic field tries to maintain the current through the inductor. This has the effect of bringing the diode into conduction (hence $V_L = -V_{Out} + 1V$), thereby completing the circuit and enabling the current to continue to flow into the capacitor. As the energy in the inductor falls so the current diminishes but the capacitor continues to be charged (more slowly). If we ignore the diode voltage drop, the voltage across the inductor is now $-V_{Out}$.

The switching frequency, supply voltage and inductor value are all chosen such that there is always current flowing in the inductor. This is called ***continuous mode***, i.e., continuous current in the inductor.

All of the circuitry necessary to implement the control function is available in an IC.

Buck converter switching waveforms.





* Ignoring the voltage drop across the diode, which we will do to simplify the analysis.

Looking now at the voltage waveform across the inductor:

$$\Psi = \int_0^T V_L dt = 0$$

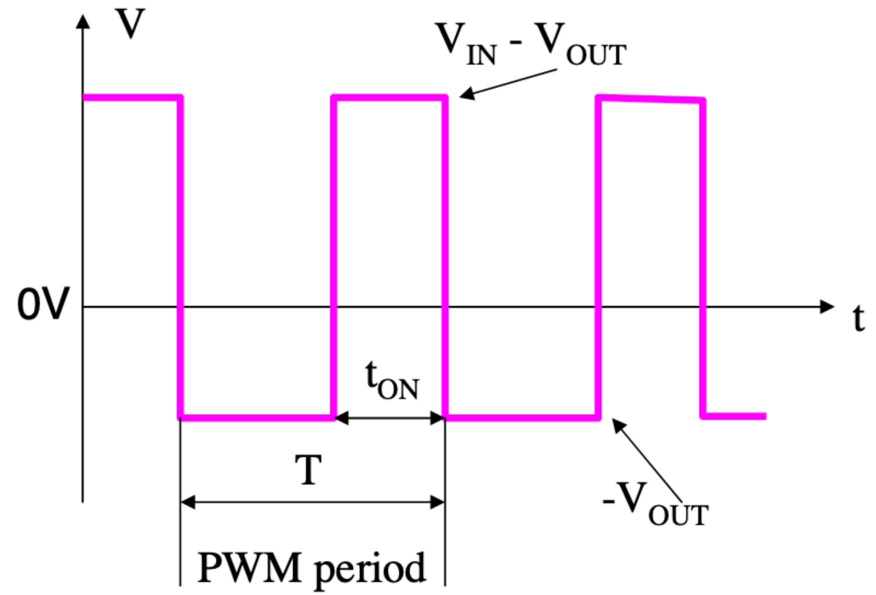
$$=> \int_0^{t_{ON}} \left(V_{IN} - V_{OUT}\right) dt + \int_{t_{ON}}^T -V_{OUT} dt = 0$$

$$=> \left(V_{IN} - V_{OUT}\right) t_{ON} - V_{OUT}.T + V_{OUT}.t_{ON} = 0$$

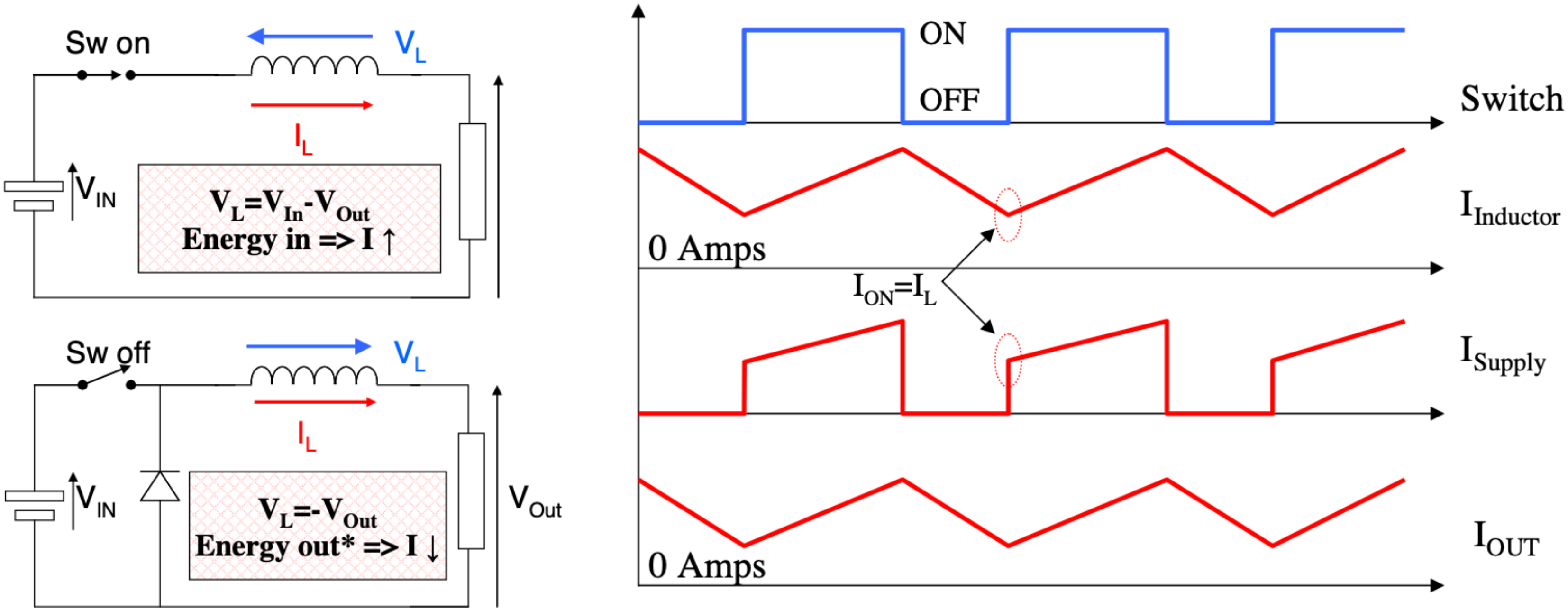
$$=> V_{IN}.t_{ON} - V_{OUT}.T = 0$$

$$=> V_{OUT} = \frac{V_{IN}.t_{ON}}{T}$$

$$=> \boxed{V_{OUT} = V_{IN}.\phi} \quad (Remember\ \phi = \frac{t_{On}}{T})$$



Reminding ourselves about the currents in the circuit:



Sticking with our assumption of a lossless system:

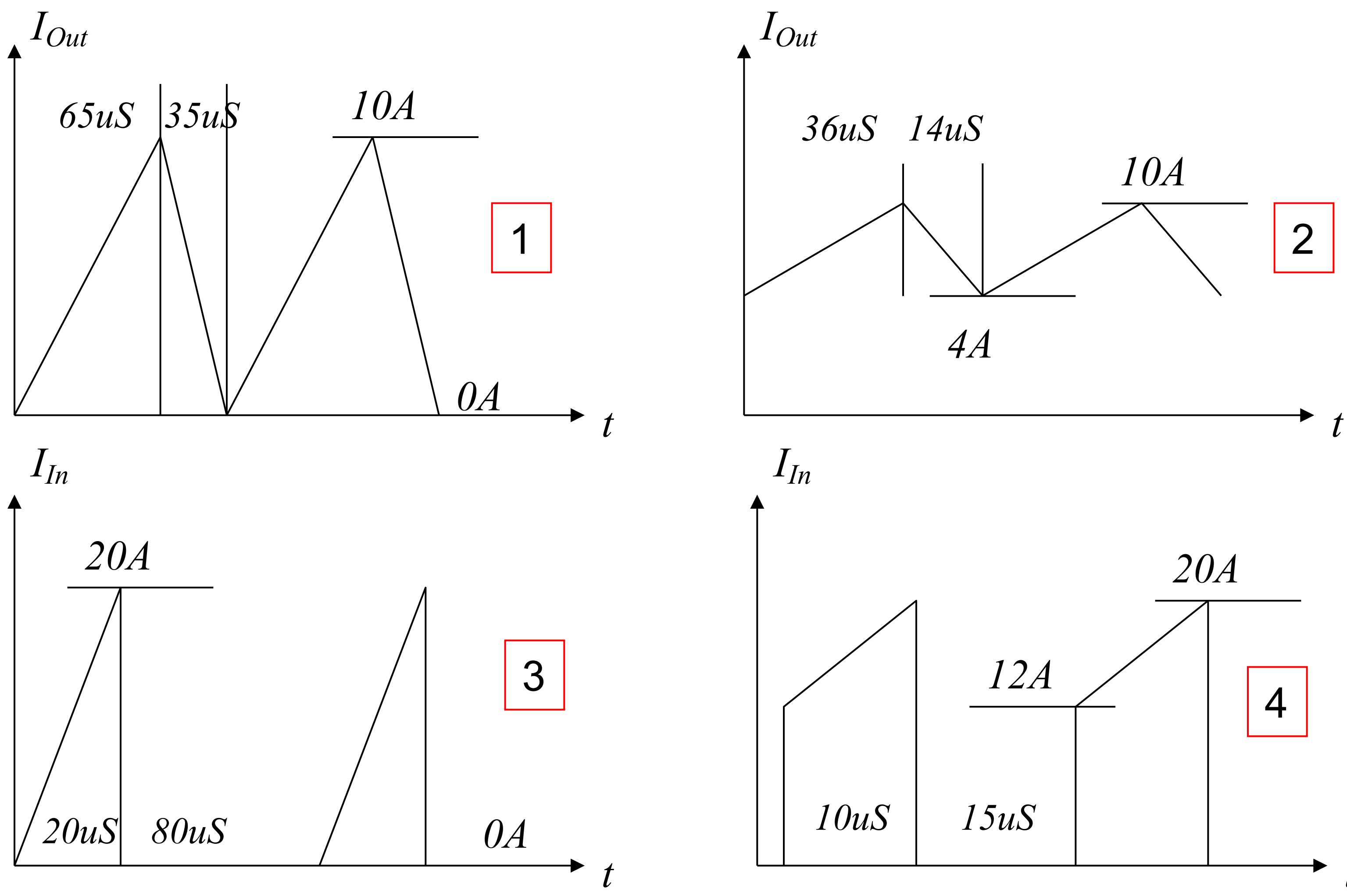
Output power = input power => $V_{OUT} I_{OUT(Mean)} = V_{IN} I_{IN(Mean)}$

Setting $V_{OUT} = \varphi V_{IN}$, we have $I_{OUT(Mean)} = I_{IN(Mean)} / \varphi$

(Remember for a DC voltage, average power = $V_{DC} \times I_{Mean}$)

Buck tutorial.

Determine the mean output voltage, current and power for the following operating points. Assume 100% conversion efficiency and continuous mode operation. V_{In}=100V



Solutions to Buck tutorial questions

1.
V_{In} = 100V
$V_{Out} = \Phi.V_{In}$ = 65V
$I_{Out\ (Ave)}$ = 5A
P_{Out} = 325W

2.
V_{In} = 100V
$V_{Out} = \Phi.V_{In}$ = 72V
$I_{Out\ (Ave)}$ = 7A
P_{Out} = 504W

3.
V_{In} = 100V
$V_{Out} = \Phi.V_{In}$ = 20V
$I_{In(Ave)}$=2A
$I_{Out\ (Ave)}$ = 10A
P_{Out} = 200W

4.
V_{In} = 100V
$V_{Out} = \Phi.V_{In}$ = 40V
$I_{In(Ave)}$=16A x 40% = 6.4A
$I_{Out\ (Ave)}$ = 16A
P_{Out} = 640W

Typical DC to DC Converter applications.

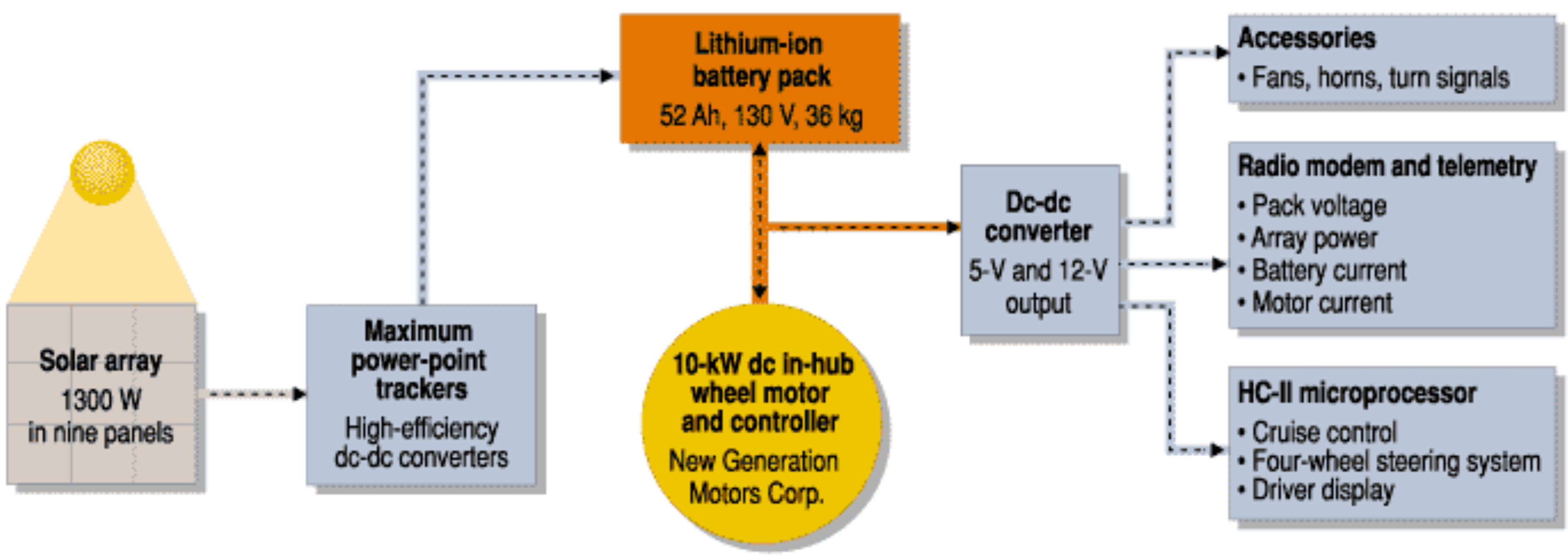
* DC Motor drives (e.g. Robotics)

* Power Factor Correction (PFC功率因数校正) and Active Filters有源滤波器.

* Photovoltaic光伏 systems e.g. peak power tracking converters to transfer energy from the PV array to the load (satellites).

* Automotive汽车 applications – raising the battery voltage to another voltage e.g. High Intensity Discharge headlamps.

* Solar vehicles



Power Electronics

Switched Mode DC-DC Converters II:

Boost Converter and Buck-Boost Converter

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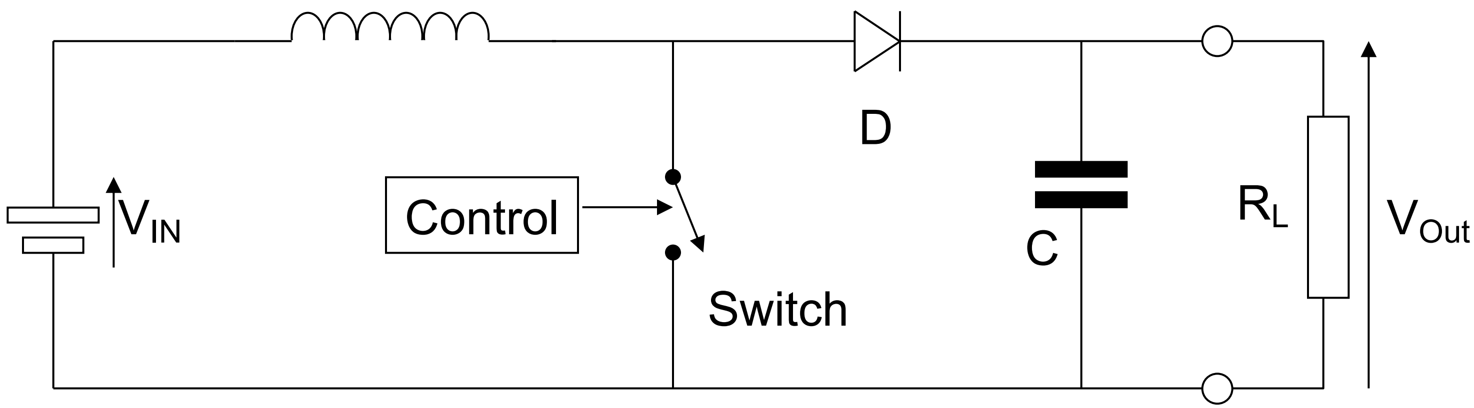
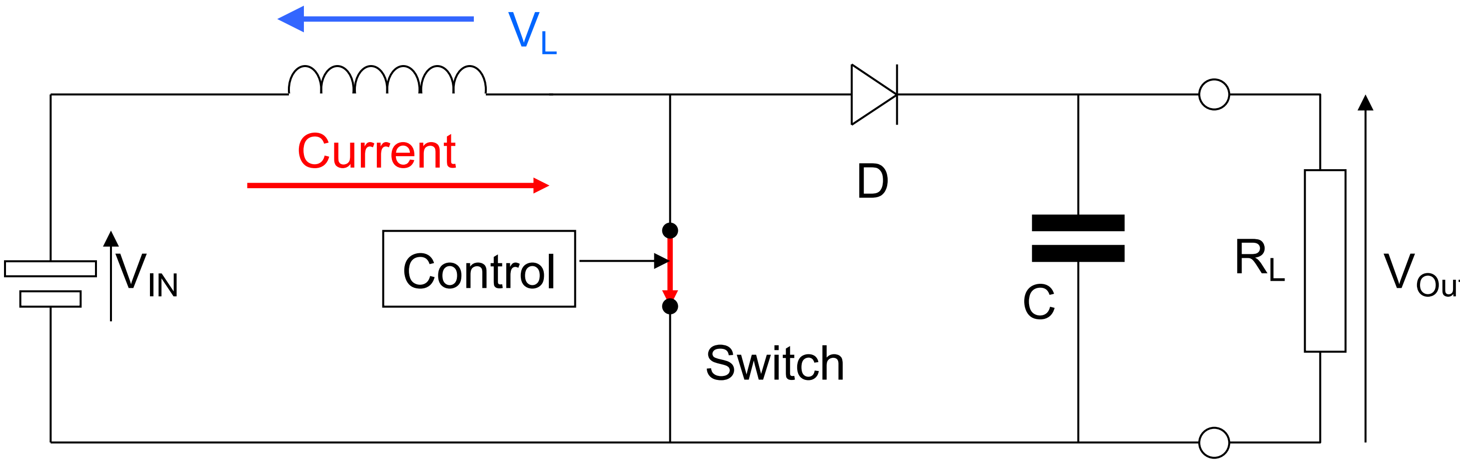
Please read Chapter 7 in the textbook

The boost (step-up) converter. ($V_{Out} > V_{In}$)



The boost converter is used to increase the output voltage (V_{Out}) above the input voltage (V_{In}). As in the case of the buck converter we will assume the circuit operates in **continuous mode**, i.e., current is always flowing in the inductor.

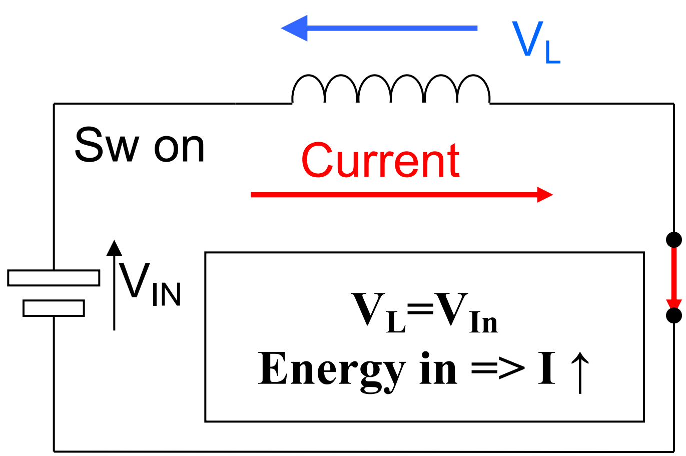
If we disregard the switch for a moment and examine the circuit, we see that in the steady state the output voltage is connected to the input voltage via an inductor (assume zero resistance) and a diode. Hence the output voltage will be one diode drop (1V) beneath the input voltage. As with the buck, ignore the voltage drop across the diode.

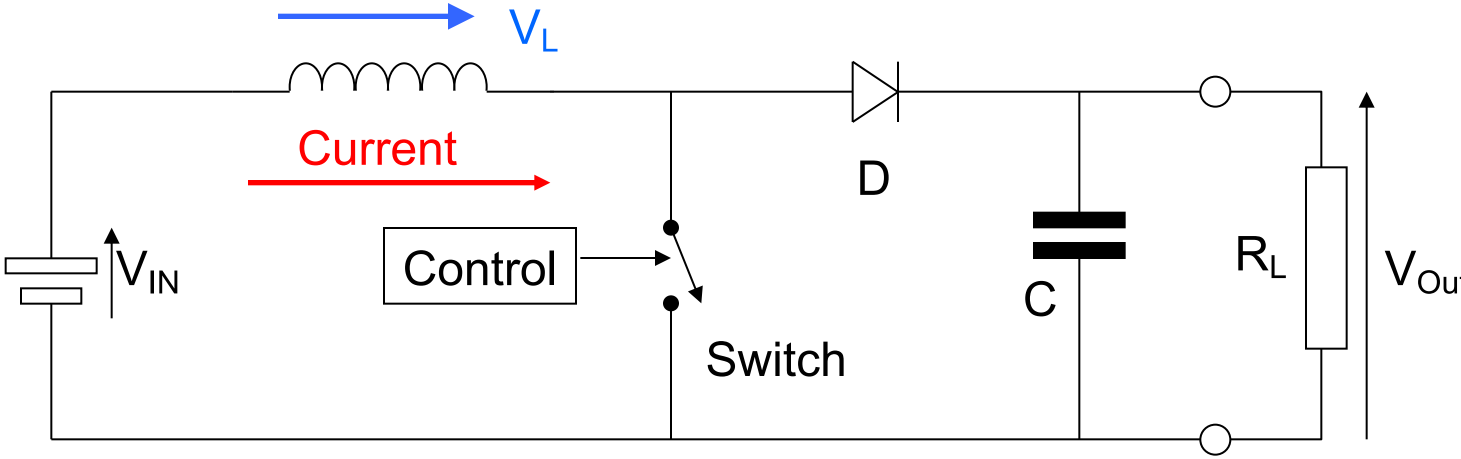


Now consider the circuit when the switch is closed. Any voltage on capacitor C will ensure the diode is reverse biased and therefore the output circuit is “disconnected” from the input. [Because the diode’s anode is connected to ground via the switch.]

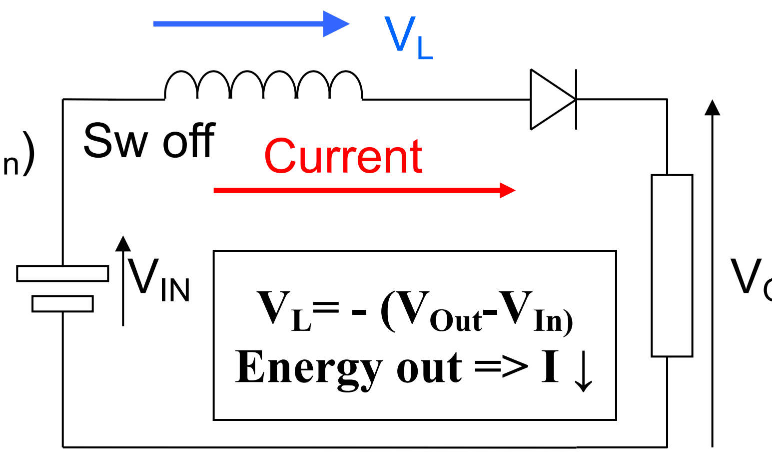
The inductor is connected across the supply (V_{In}) and hence current will start to build through it with the energy being stored in the magnetic field. During this phase, $V_L = V_{In}$.

Switch ON: Charging the inductor !!!





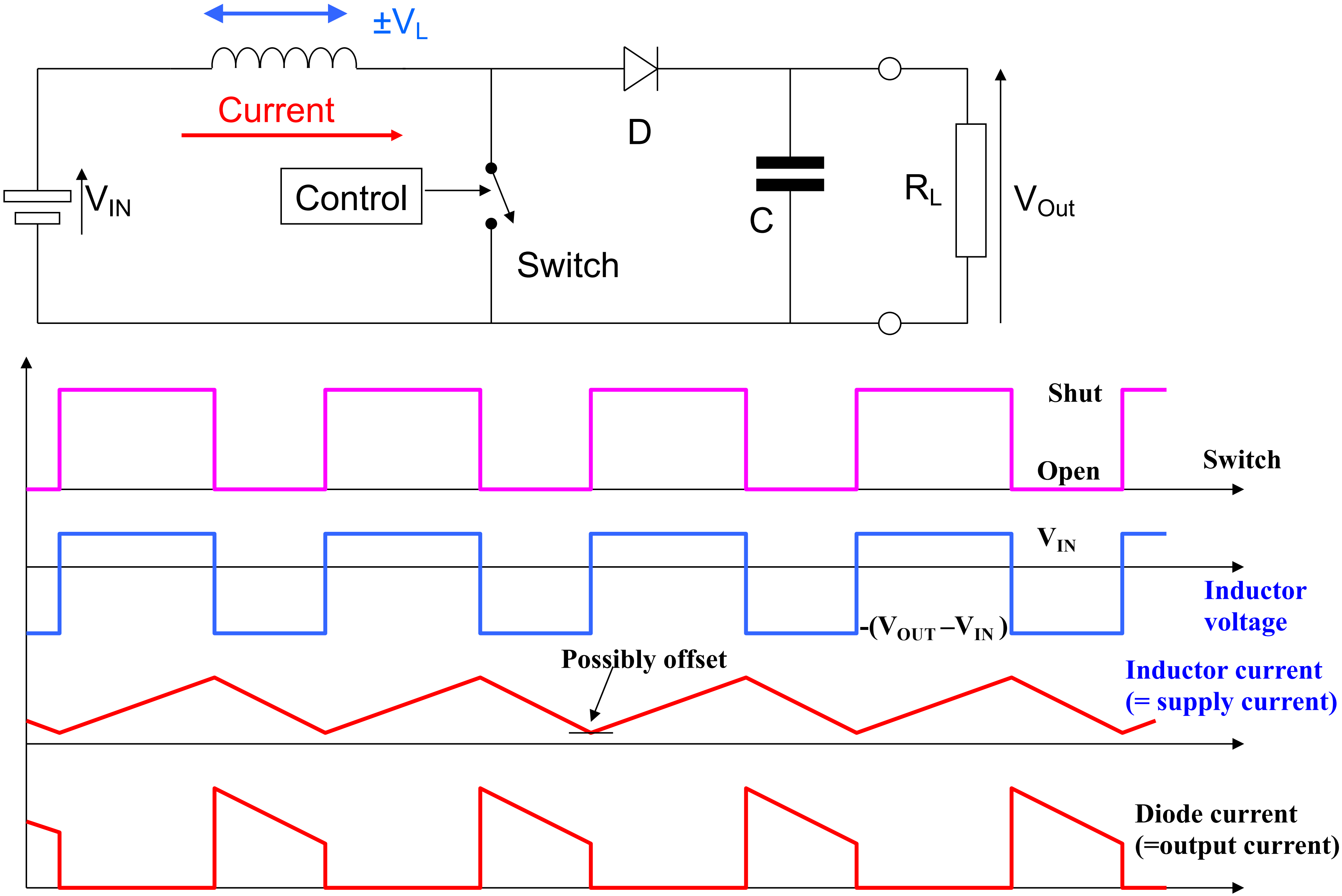
When the switch is opened, the inductor wants to maintain the current flow and with the supply side of the inductor still held at V_{In}, the potential at the opposite side of the inductor rises until the diode starts to conduct. The inductor voltage during this phase is the difference between the input voltage (V_{In}) and the output voltage (V_{Out}). Note also that the sign of the voltage has changed when compared with the inductor charging period.



So $V_{Inductor} = -(V_{Out} - V_{In}) = V_{In} - V_{Out}$.

As energy is transferred from the inductor's magnetic field so the current flowing through the inductor and diode falls.

Switch OFF: Discharging the inductor !!!



Note that current always flows in the inductor (continuous mode again)

As with the buck converter, magnetic flux linkage Ψ is defined as the integral of the inductor voltage. During steady state load conditions the instantaneous value of the flux must be the same on consecutive PWM periods, otherwise there would be a net increase or decrease of flux.

From an energy point of view the magnetic field at any point on consecutive PWM periods is the same. Hence we can write:

$$\boxed{\Psi = \int_0^T V_L dt = 0}$$

$$\Psi = \int_0^T V_L dt = 0$$

$$=> \int_0^{t_{ON}} V_{IN}\, dt + \int_{t_{ON}}^{T} -(V_{OUT} - V_{IN})dt = 0$$

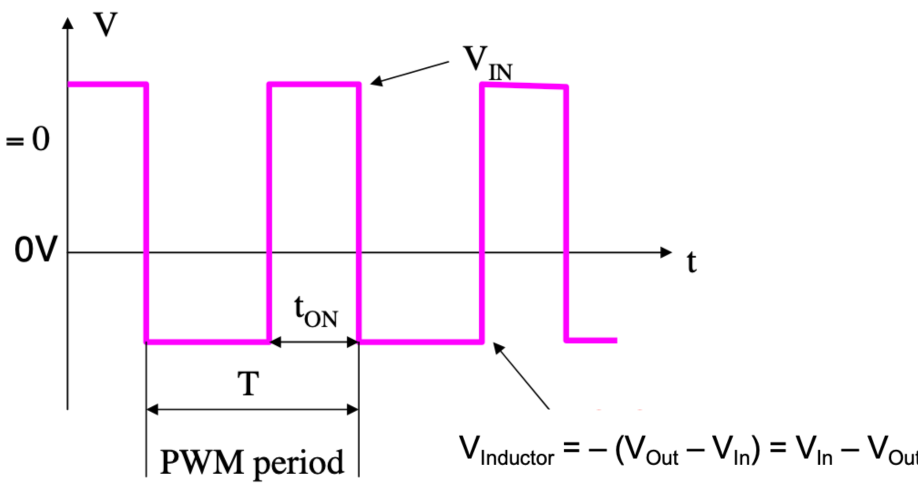
$$=> V_{IN}.t_{ON} - V_{OUT}.T + V_{IN}.T + V_{OUT}.t_{ON} - V_{IN}.t_{ON} = 0$$

$$=> T(V_{OUT} - V_{IN}) = V_{OUT}.t_{ON}$$

$$=> V_{OUT} - V_{IN} = \phi.V_{OUT}$$

$$=> V_{OUT}(1-\phi) = V_{IN}$$

$$=> V_{OUT} = \frac{V_{IN}}{1-\phi}$$



Sticking with our assumption of a lossless system:

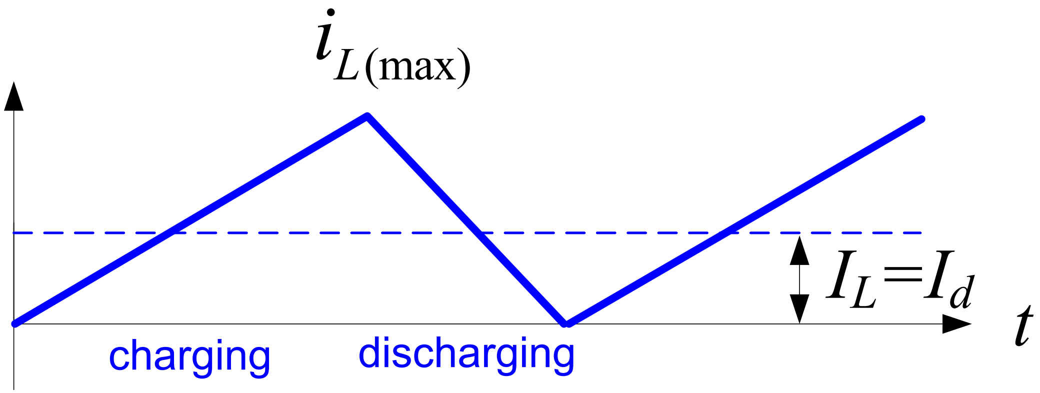
Output power = input power => $V_{OUT}I_{OUT(Mean)} = V_{IN}I_{IN(Mean)}$

Setting $V_{OUT} = V_{IN} / (1- \varphi)$, we have $I_{OUT(Mean)} = (1- \varphi).I_{IN(Mean)}$

(Remember for a DC voltage, average power = V_{DC} x I_{Mean})

Operation at the Boundary Condition.

If the inductor current falls to zero for a vanishingly short time at the end of the PWM period, this is called the *"boundary condition"*. It is useful in that this permits the value of the inductance to be calculated for a given switching frequency and current.



Average inductor current I_{LB} at this boundary :

$$\boxed{I_{LB} = \frac{1}{2} i_{L(\max)}}$$

I_L: average inductor current

Example.

A boost converter is required to provide a constant 24V / 100W output from an input voltage that varies between 9V and 15V. For a switching frequency of 20KHz and assuming 100% efficiency and operation in continuous mode, determine the following:

1. The required PWM duty cycle range to maintain a 24V DC output.

2. The average input current when the input voltage is 15V.

3. The value of the inductor required if the instantaneous current through the inductor at the end of the PWM period is zero. Calculate the value for both 9V and 15V input.

Example.

A boost converter is required to provide a constant 24V / 100W output from an input voltage that varies between 9V and 15V. For a switching frequency of 20KHz and assuming 100% efficiency and operation in continuous mode, determine the following:

1. The required PWM duty cycle range to maintain a 24V DC output.

2. The average input current when the input voltage is 15V.

3. The value of the inductor required if the instantaneous current through the inductor at the end of the PWM period is zero. Calculate the value for both 9V and 15V input.

Solution.

1. For continuous mode boost converter we have:

$$V_{OUT} = \frac{V_{IN}}{1-\phi} \Rightarrow \phi = 1 - \frac{V_{IN}}{V_{OUT}}$$

$$For\ V_{IN} = 9V, \phi = 1 - \frac{9}{24} = 62.5\%$$

$$For\ V_{IN} = 15V, \phi = 1 - \frac{15}{24} = 37.5\%$$

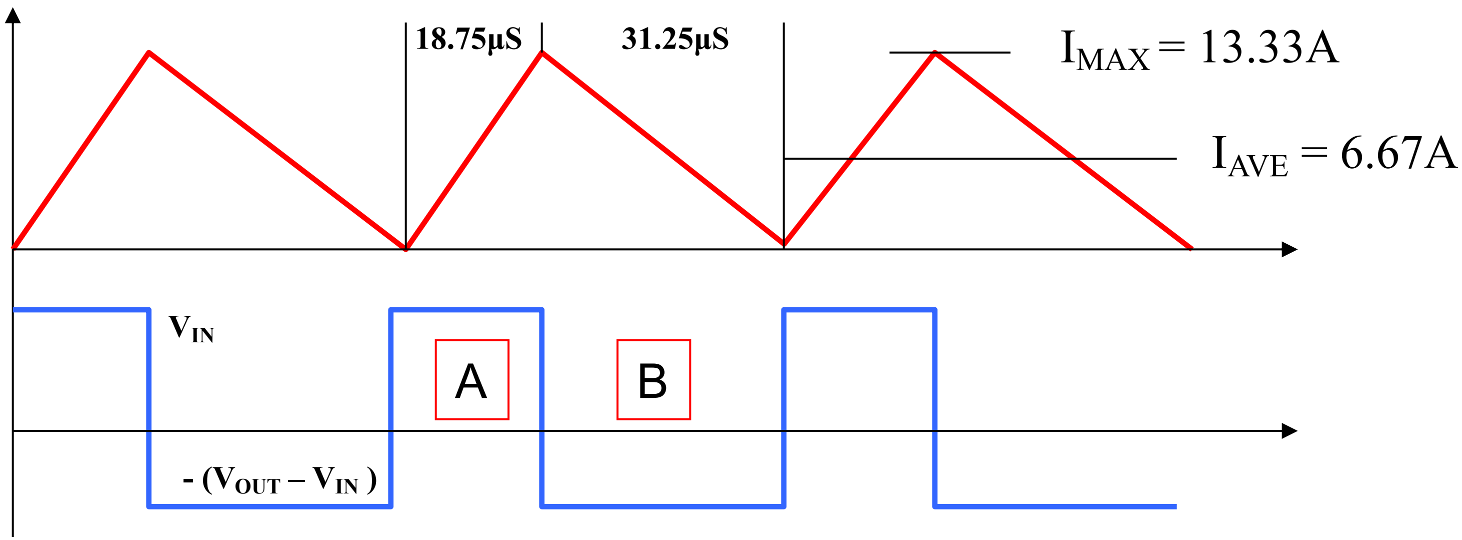
2. Assuming 100% efficiency:

$$V_{IN} I_{IN(MEAN)} = V_{OUT} I_{OUT(MEAN)} = 100W$$

$$For\ V_{IN} = 15V, I_{IN(MEAN)} = \frac{100W}{15V} = 6.67A$$

3. For a boost converter. the inductor current = input current. At 15V, φ=37.5% and $I_{IN(AVE)}$=6.67A. We know that at the end of the PWM period the inductor current is zero, hence we can construct the current waveform:

$I_{MAX} = 2 \text{ x } I_{AVE} = 13.33A$



$F_{SWITCH} = 20KHz$, $\varphi = 37.5\% \Rightarrow T_{ON} = 18.75\mu S$

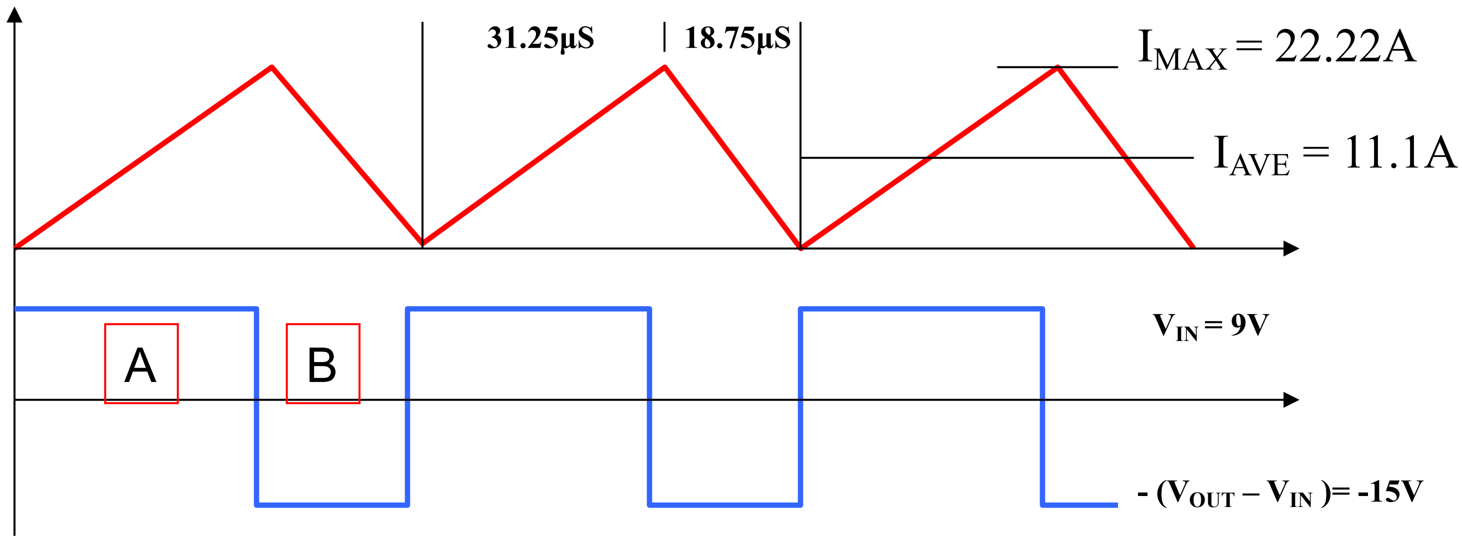
$$V = L\frac{di}{dt} \Rightarrow L = V\frac{\Delta t}{\Delta i}$$

$$For \quad A : L = \frac{15V \times 18.75\mu S}{13.\dot{3}A} = \boxed{21\mu H}$$

$$For \quad B : L = \frac{-(24V - 15V) \times 31.25\mu S}{-13.\dot{3}A} = \boxed{21\mu H}$$

Now we need to work out the average input current when the input voltage is 9V. At 9V, φ=62.5% and $I_{IN(AVE)}$=11.1A.

$$I_{MAX} = 2 \text{ x } I_{AVE} = 22.22\text{A}$$



$$F_{SWITCH} = 20\text{KHz},\ \varphi = 62.5\% \Rightarrow T_{ON} = 31.25\mu\text{S}$$

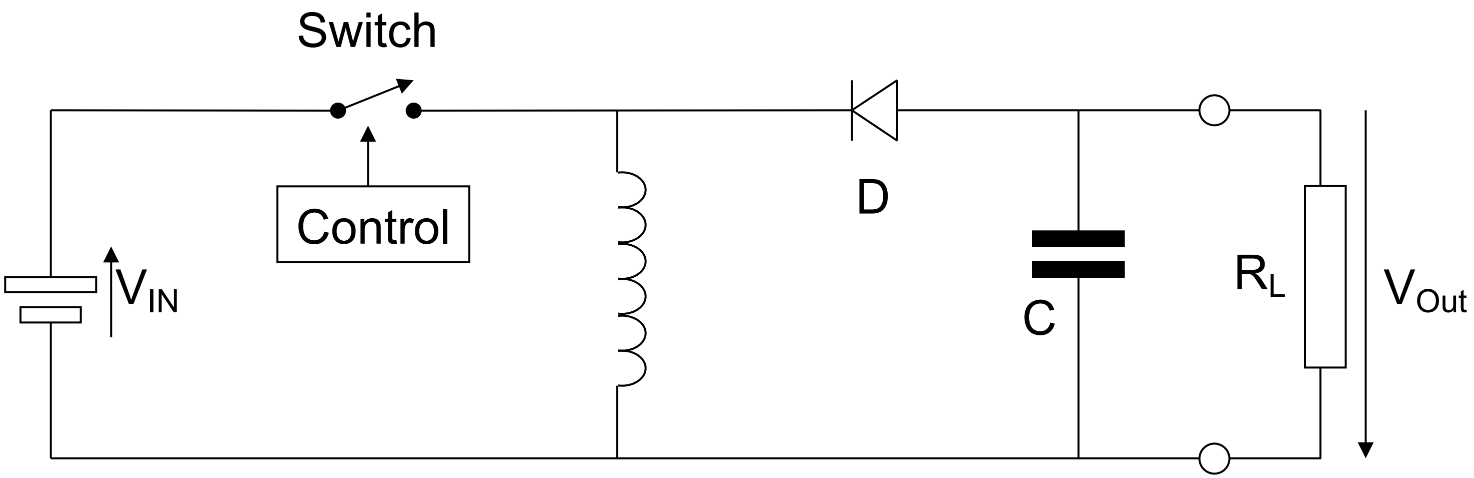
$$V = L\frac{di}{dt} \Rightarrow L = V\frac{\Delta t}{\Delta i}$$

$$For\ \ A: L = \frac{9V \times 31.25\mu S}{22.\dot{2}A}\boxed{= 12.66\mu H}$$

$$For\ \ B: L = \frac{-15V \times 18.75\mu S}{-22.\dot{2}A}\boxed{= 12.66\mu H}$$

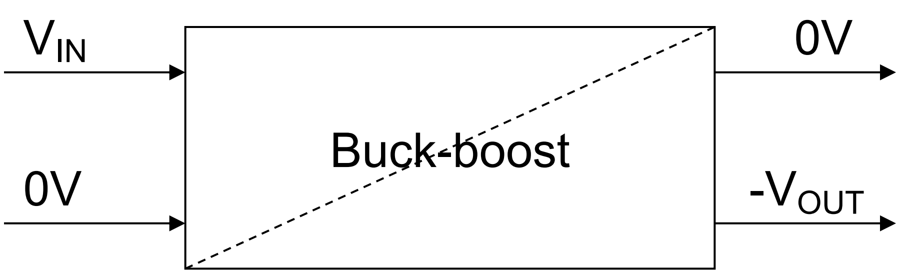
If we compare these values with the case for 15V we see the inductor value is smaller – this is expected since ΔI is greater because of the lower input voltage and the reduced input voltage able to establish the current in the inductor.

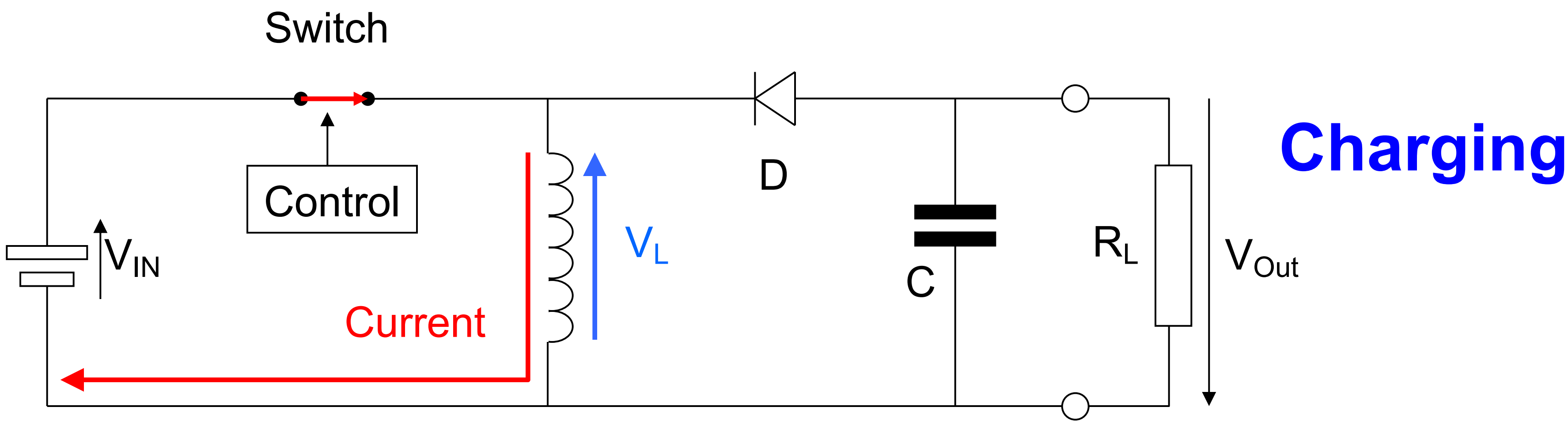
The buck-boost (FLYBACK) converter (V_{OUT} <> V_{IN}).



Note polarity of output voltage!

The Buck-Boost converter is able to produce output voltages that are higher or lower than the input voltage. Once again we will consider the continuous mode system. Note that the output is negative with respect to the 0V side of the input voltage.



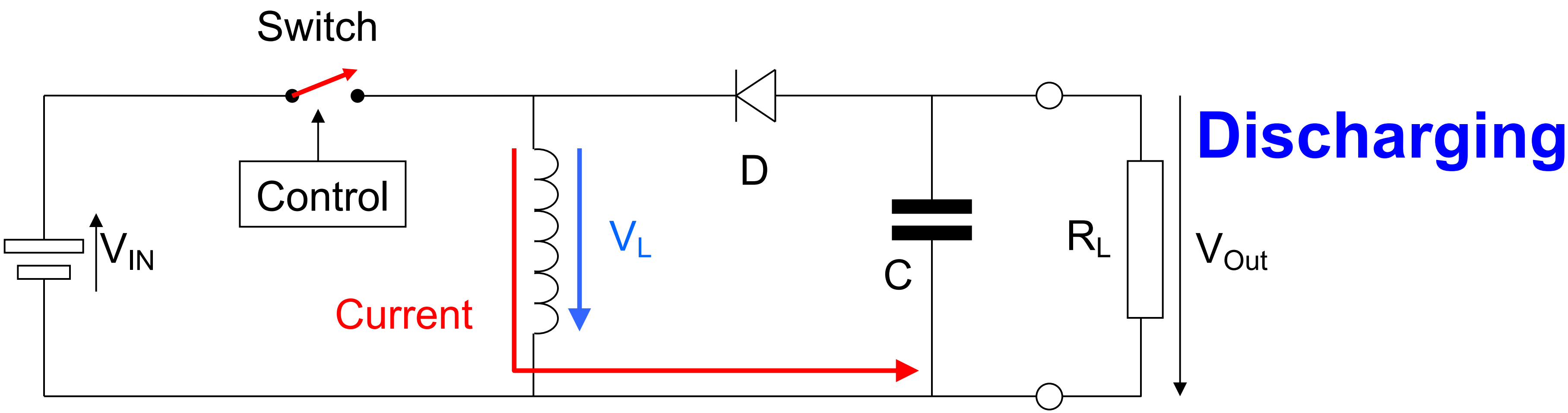


Before starting …
… Notice that when the switch is open there is no connection between the input to the supply and its output. Hence we can conclude that the supply is capable of delivering 0V output regardless of the input voltage for a 0% duty cycle on the switch.

With the switch closed, the input voltage is imposed across the inductor and the current through the inductor starts to rise. The diode is “off” since the cathode is more positive than the anode.

Hence for the “on” period, $V_L = V_{IN}$.

Note that with the diode reverse biased, the only route for the current to take that completes the circuit is back through the supply to the converter.



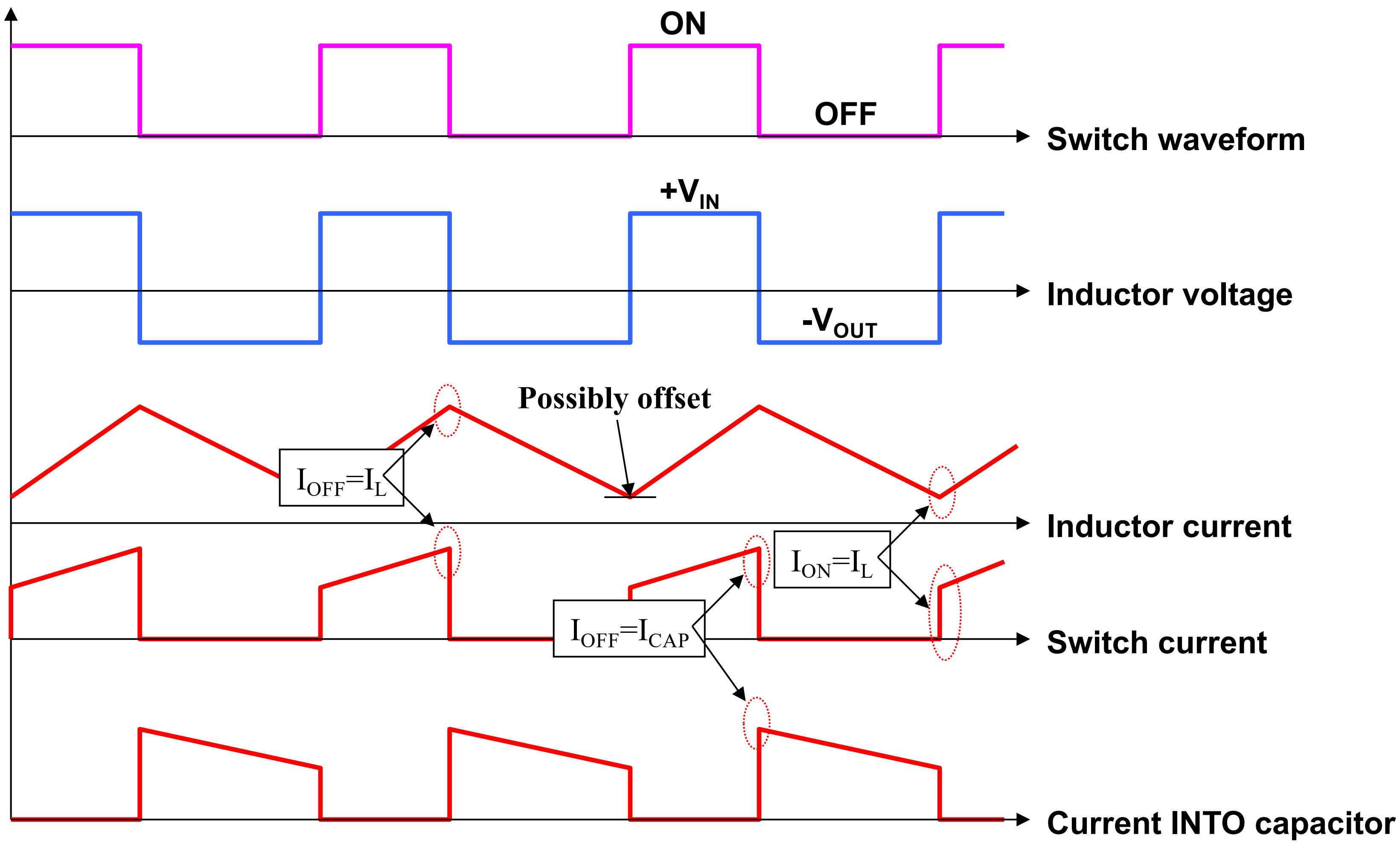
When the switch is opened the voltage on the inductor reverses polarity, the diode starts to conduct and hence the inductor current flows into the capacitor.

During this “off” period, $V_L = -V_{OUT}$ and this is maintained as the current in the inductor falls to its value at the end of the PWM period.

Note that with the switch opened there is no return path for current through the input to the converter and hence the only route the inductor current can follow is into the capacitor and load.

Also note that the capacitor will supply current to the load when there is no current contribution from the inductor.

Waveforms for the buck-boost converter.



$$\Psi = \int_0^T V_L dt = 0$$

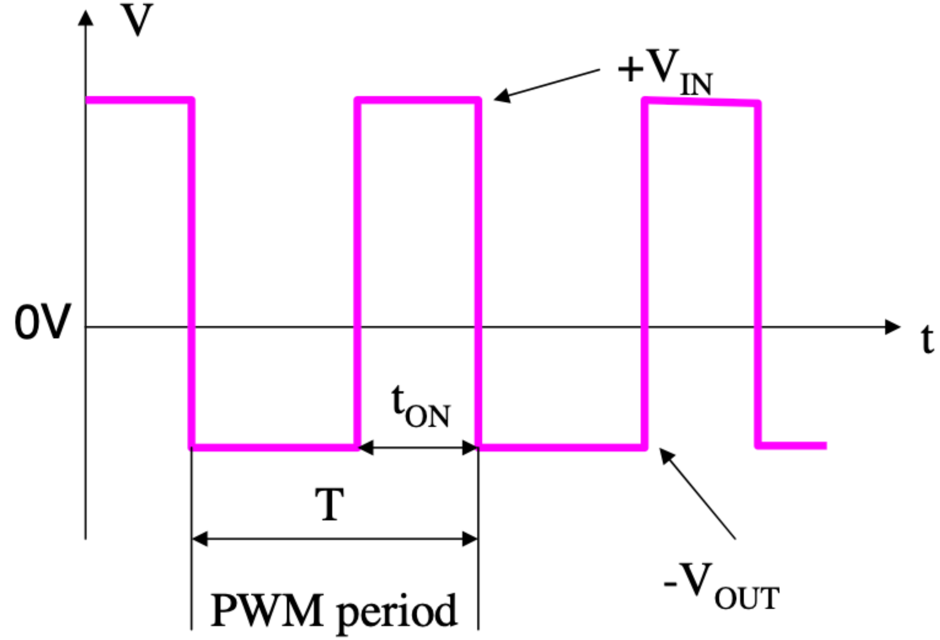
$$\Rightarrow \Psi = \int_0^{t_{ON}} +V_{IN}\, dt + \int_{t_{ON}}^{T} -V_{OUT} dt = 0$$

$$\Rightarrow \Psi = V_{IN}.t_{ON} - V_{OUT}(T - t_{ON}) = 0$$

$$\Rightarrow V_{IN}.t_{ON} = V_{OUT}(T - t_{ON})$$

$$\Rightarrow V_{IN}.\phi = V_{OUT}(1-\phi)$$

$$\Rightarrow V_{OUT} = \frac{V_{IN}.\phi}{(1-\phi)}$$



Sticking with our assumption of a lossless system:

Output power = input power => $V_{OUT}I_{OUT(Mean)} = V_{IN}I_{IN(Mean)}$

Setting $V_{OUT} = \varphi.V_{IN} / (1- \varphi)$, we have $I_{OUT(Mean)} = (1- \varphi).I_{IN(Mean)} / \varphi$

(Remember for a DC voltage, average power = V_{DC} x I_{Mean})

Converter summary

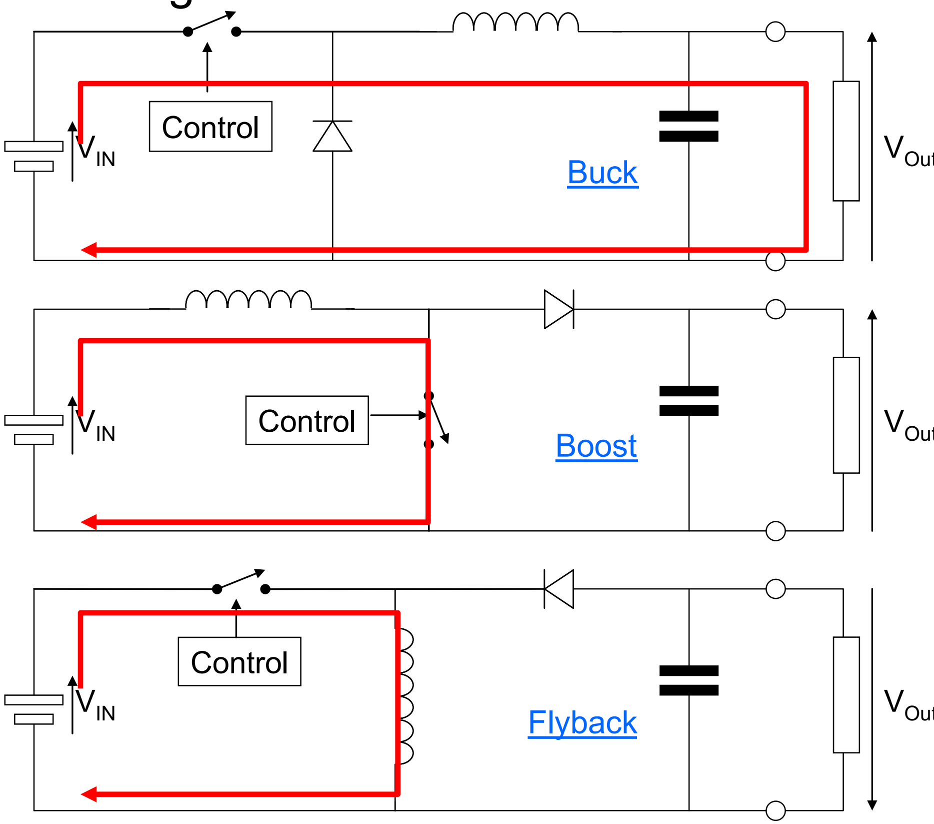
For all converters, assume $V_{IN} I_{IN(Ave)} = V_{OUT} I_{OUT(Ave)}$

Type	Voltage Equation	Current Equation
Buck ($V_{OUT} < V_{IN}$)	$V_{OUT} = \phi . V_{IN}$	$I_{OUT(Ave)} = \dfrac{I_{IN(Ave)}}{\phi}$
Boost ($V_{OUT} > V_{IN}$)	$V_{OUT} = \dfrac{V_{IN}}{1-\phi}$	$I_{OUT(Ave)} = (1-\phi).I_{IN(Ave)}$
Buck-boost ($V_{OUT} <> V_{IN}$)	$V_{OUT} = \dfrac{\phi . V_{IN}}{1-\phi}$	$I_{OUT(Ave)} = \dfrac{(1-\phi).I_{IN(Ave)}}{\phi}$

The following diagrams summarise the energy flow in the circuit for each converter type during the storage and release phases of operation.

Charging the Inductor

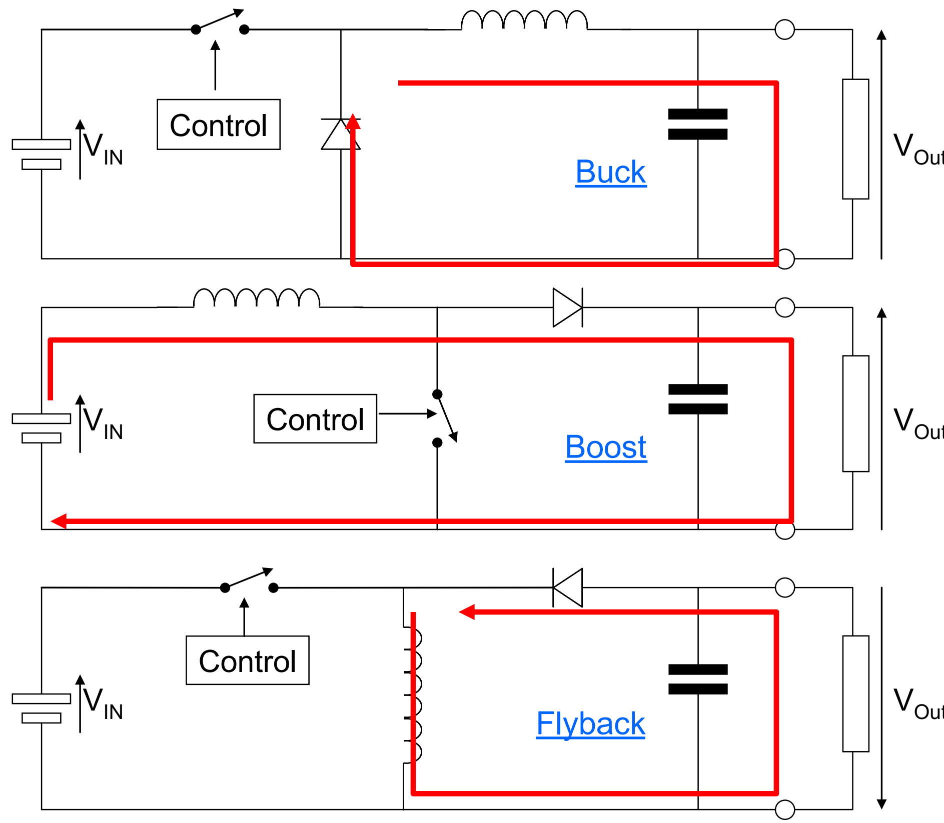
Storage



Switch ON

Discharging the Inductor

Release



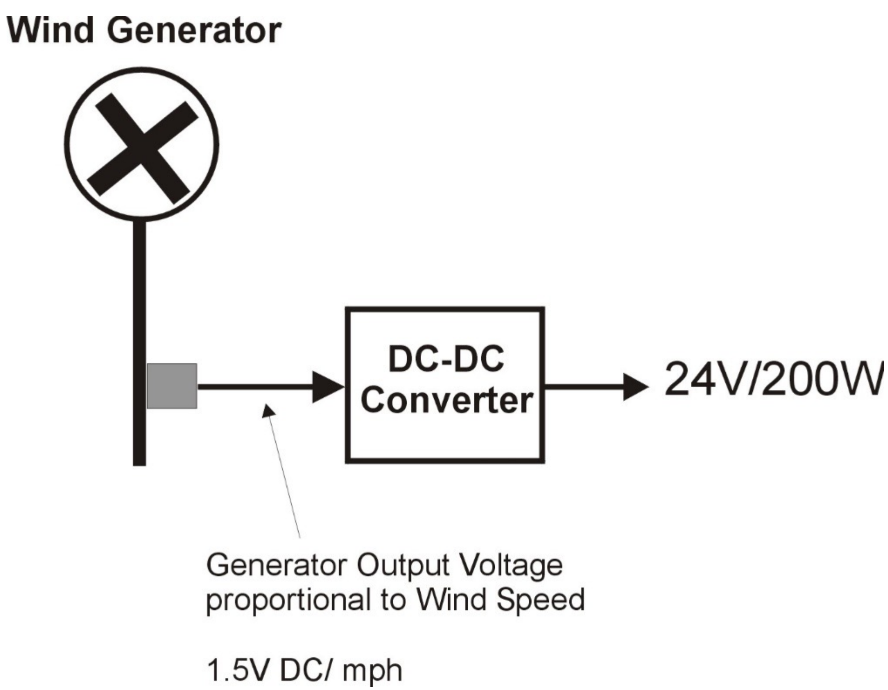
Switch OFF

Question.

A small wind turbine generates 1.5V DC per MPH of wind speed.

For operation over the range 8 MPH to 32 MPH, determine the following:

1. The type of converter to be used;
2. The required range of duty cycle for these wind speeds;
3. The average input current to the converter at 32MPH;
4. The peak input current @ 32 MPH assuming operation at the boundary condition.



Solution.

For a wind speed of 8MPH, the turbine output voltage is 8 x 1.5 = 12v. At a wind speed of 32 MPH the output voltage is 48V. Hence use a buck-boost converter since V_{IN} can be less than or greater than the output voltage.

For the BB, $$V_{OUT} = \frac{\phi . V_{IN}}{1-\phi} \Rightarrow \phi = \frac{V_{OUT}}{V_{IN} + V_{OUT}}$$

For 8MPH, φ = 24 / (12 + 24) = 66.6%
For 32 MPH, φ = 24 / (48 + 24) = 33.3%

Assuming 100% efficiency, for P_{OUT} = 200W, $I_{IN\ (Ave)}$ = 200 / 48 = 4.16A (ave) and $I_{IN\ (Peak)}$ = 2 x $I_{IN(ave)}$ = 8.33A (since @ boundary condition => initial current is zero).

Don’t forget to divide the peak input current by the duty cycle according to which value of φ you’re working with!

What have we learned today?

- DC-DC Converters
- Switched Mode Power Supplies (Converters)
  - Buck Converter
  - Boost Converter
  - Buck-Boost Converter

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