Switched-mode Power Supplies (SMPS)

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:

* The transformer size is reduced;

* Rectifier diodes have a smaller current rating;

* Heatsinks can be smaller;

* A cooling fan is not usually needed;

* The supply can have a wider input voltage range (no voltage selector needed);

* Hold-up time is generally longer;

* The power density (watts per cm^3) is greater.

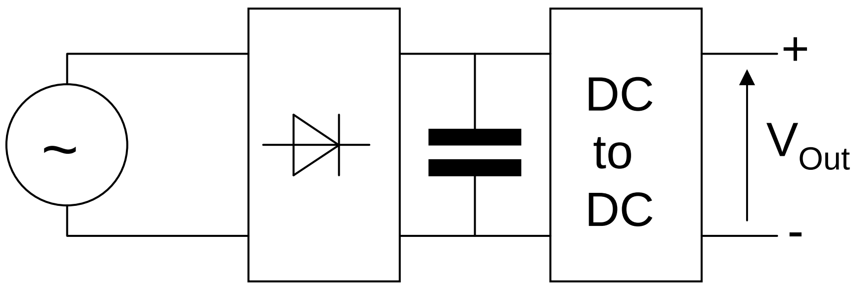
* The weight is lower.

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

* The SMPS is electrically very noisy;

* 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 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 amplifier and camera.

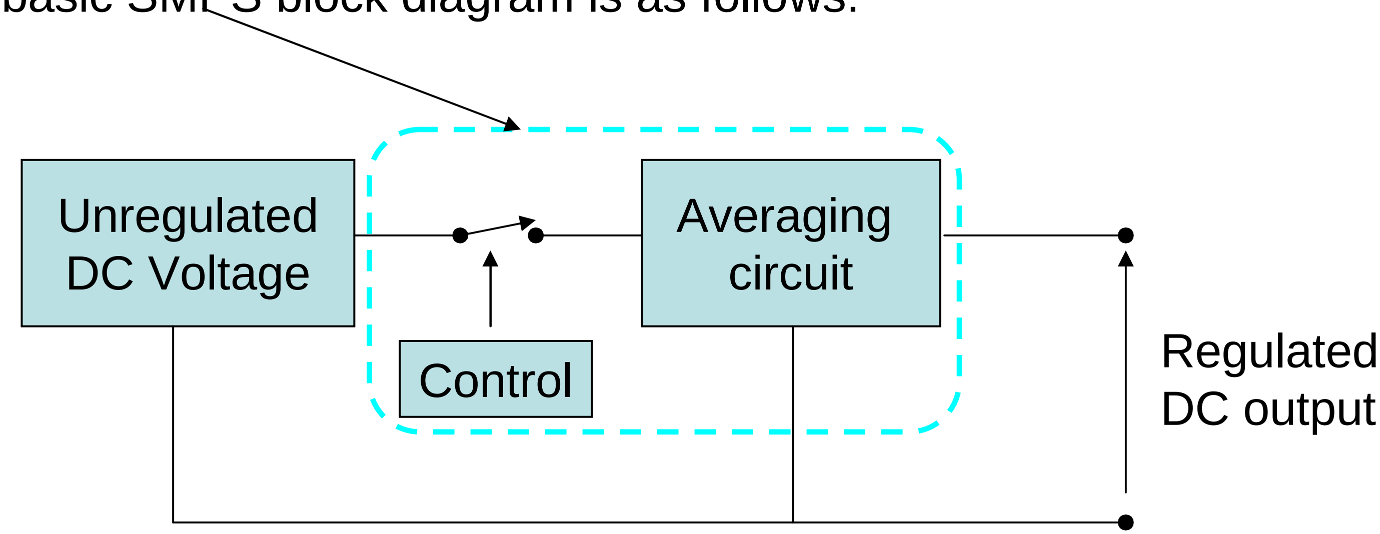
SMPSs come in many different varieties. For the purposes of this course we will consider three of the most commonly used types:

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

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

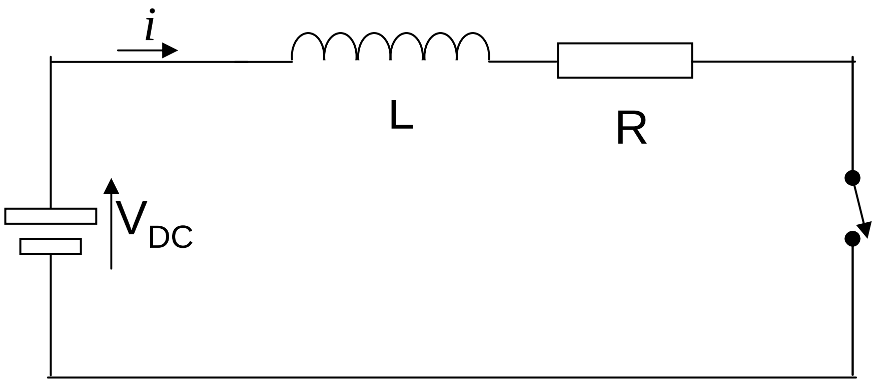
3. The “buck-boost” or flyback converter. [$V_{Out} <> V_{in}$]

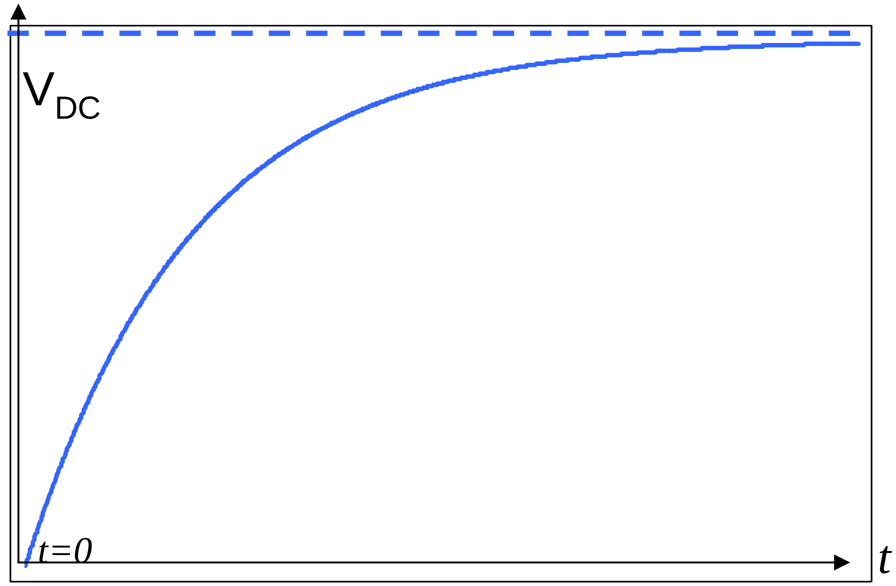
The basic SMPS block diagram is as follows:



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:



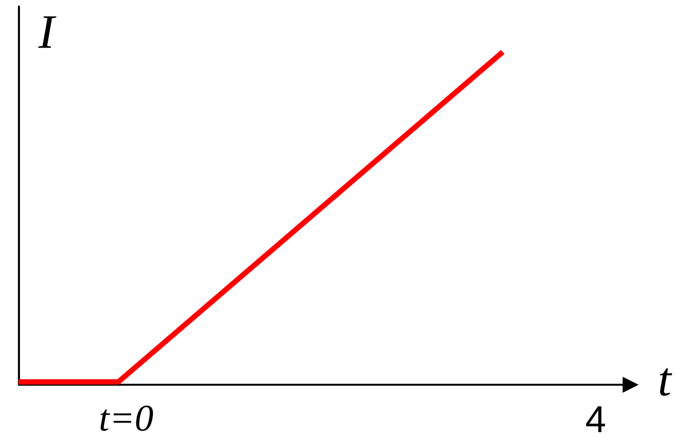


We can write the voltage equation for

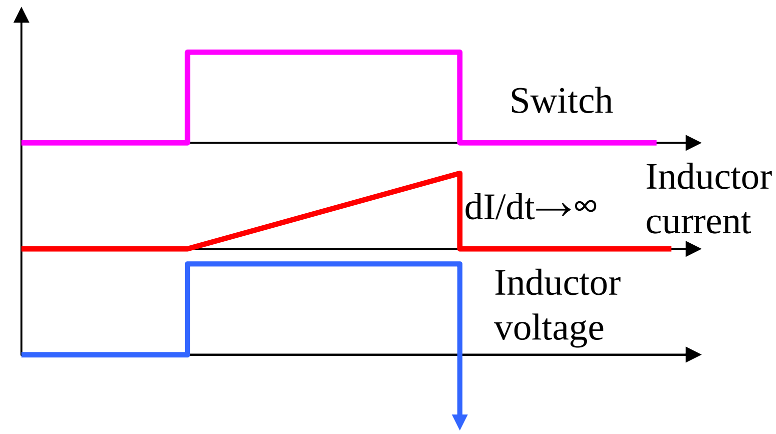
this circuit as $V_{DC} = V_R + V_L = I_L R_L + L\frac{dI}{dt}$

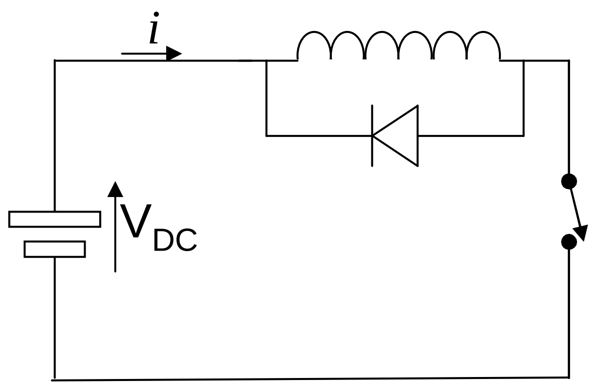
When the value of R is very small we can neglect the IR term and hence $V_L = L\frac{dI}{dt}$

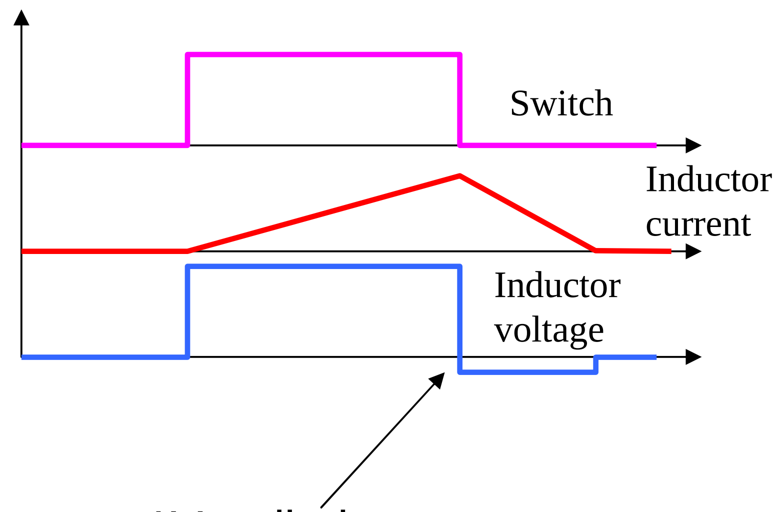
Hence we can approximate the voltage across the inductor to be a constant and therefore the current through the inductor to rise linearly when the switch is closed.



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.

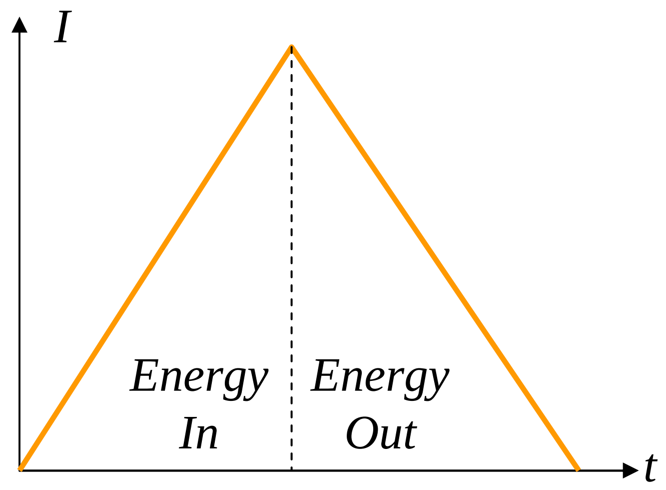




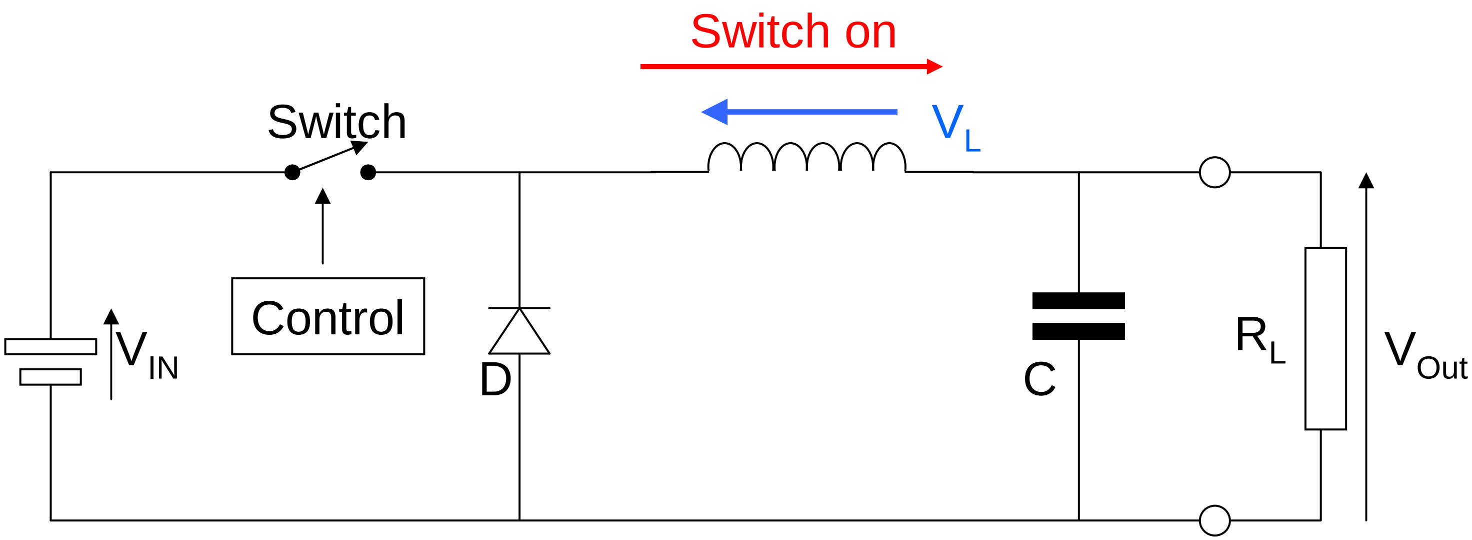


-1V = diode conduction voltage drop

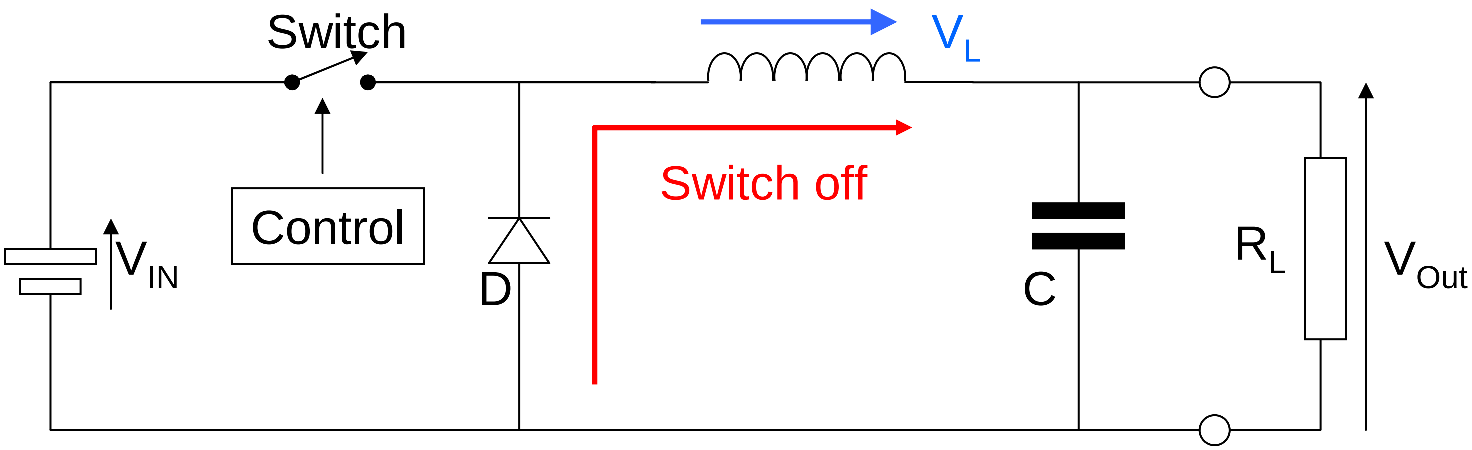
The energy stored in an inductor is $\frac{1}{2}LI^2$. When current through the inductor is increasing, additional energy is being stored in the magnetic field. If the current is decreasing then energy is being removed from the magnetic field. Assuming a perfect inductor, the energy (i.e. number of joules)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



The buck converter.



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 ("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.

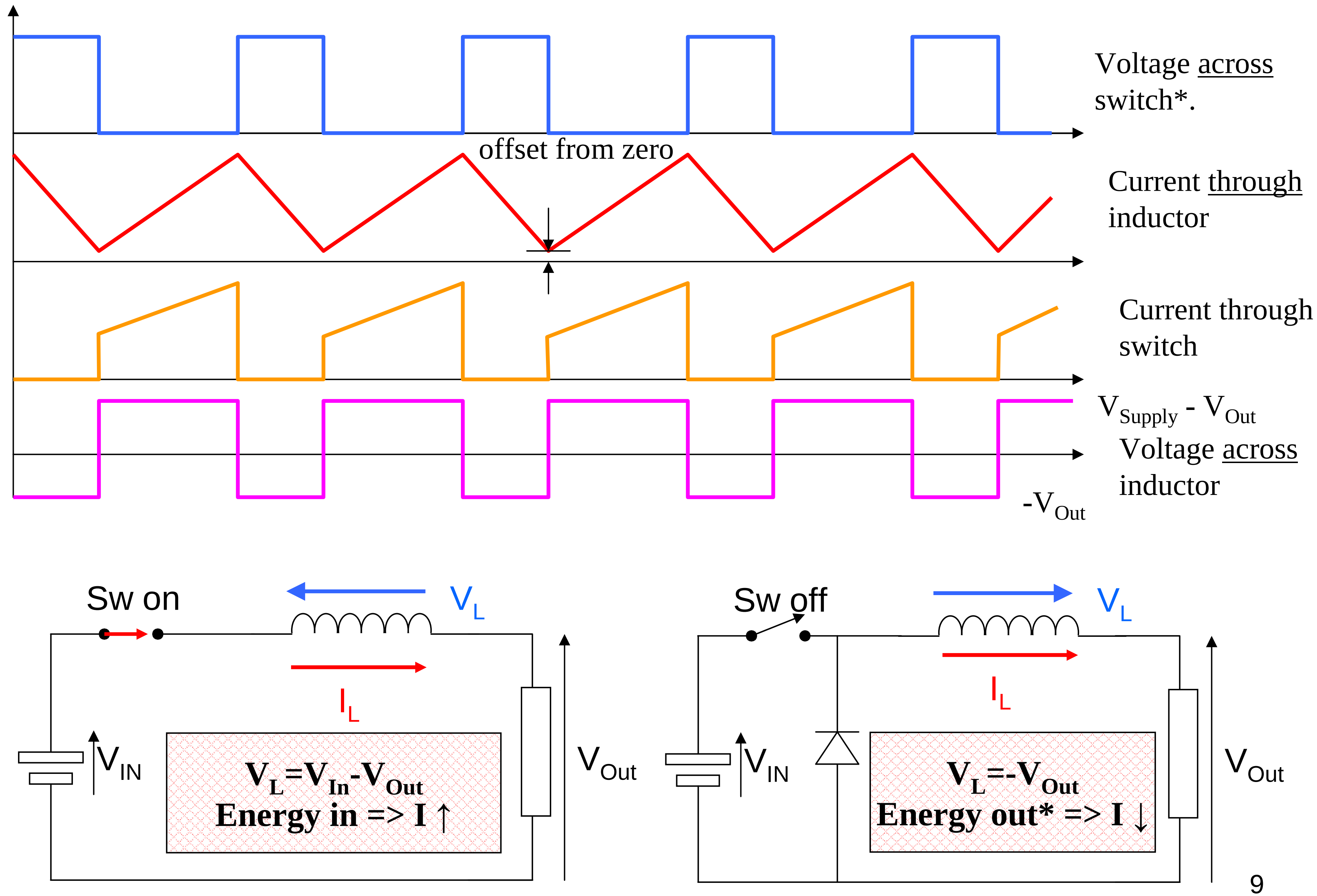


As soon as the switch is opened, the potential on the switched side of the inductor goes sharply negative (but the current continues to flow) as the energy in the magnetic field tries to maintain the current through the inductor. This has the effect of bringing the diode into conduction (hence $V_L = -V_{Out} + 1V$), 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 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.

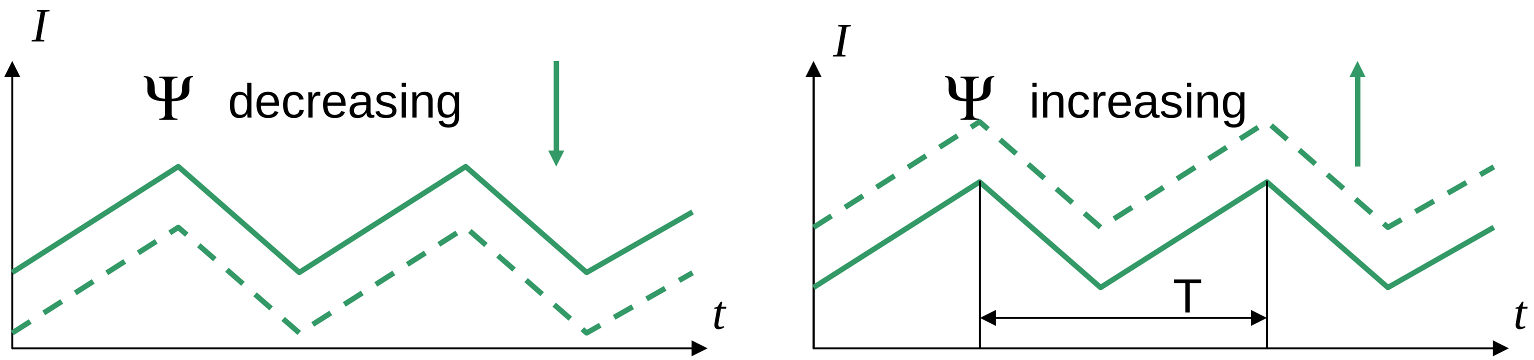


* Ignoring the voltage drop across the diode, which we will do to simplify the analysis.

Flux linkage analysis.

Definition: Magnetic flux linkage Ψ is defined as the integral of the inductor voltage. In other words, between each PWM period T there should not be, for steady-state operation, a net increase or decrease of flux.

If the flux was decreasing the average inductor current would drop. Conversely, if the flux was increasing the average inductor current would rise.



Mathematically stated, the integral of the inductor voltage over one PWM period is 0.

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

A useful physical interpretation of this is that the energy stored in the magnetic field returns to the same value for each PWM period.

Looking now at the voltage waveform across the inductor:

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

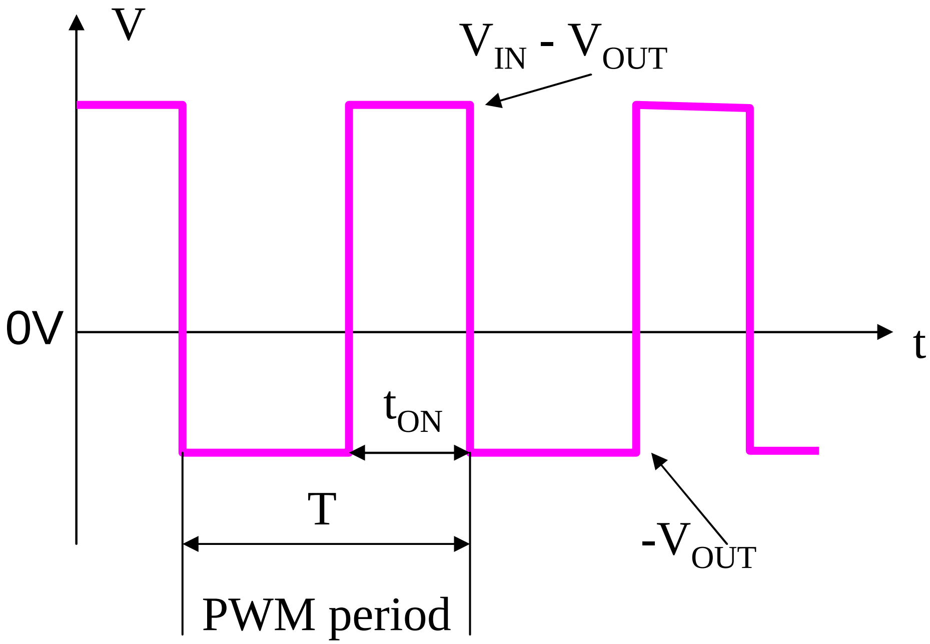
$$=> \int_0^{t_{ON}} \left(V_{IN} - V_{OUT}\right) dt + \int_{t_{ON}}^{T} -V_{OUT} dt = 0$$

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

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

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

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



If we plot this relationship, we see:

1. By varying the duty cycle of the switch, the output voltage can be set to any voltage between zero (φ=0%) and V_{IN} (φ=100%).

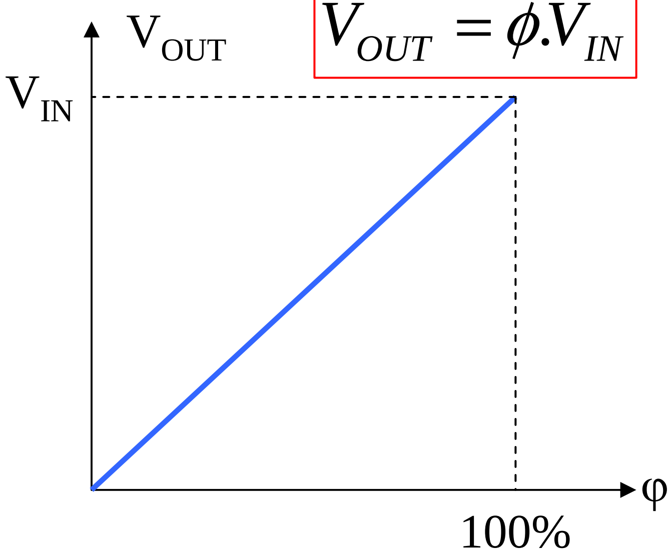
2. The output voltage never exceeds the input voltage.

3. The output voltage is independent of the load on the output. The power delivered to the load is proportional to the current in the inductor.

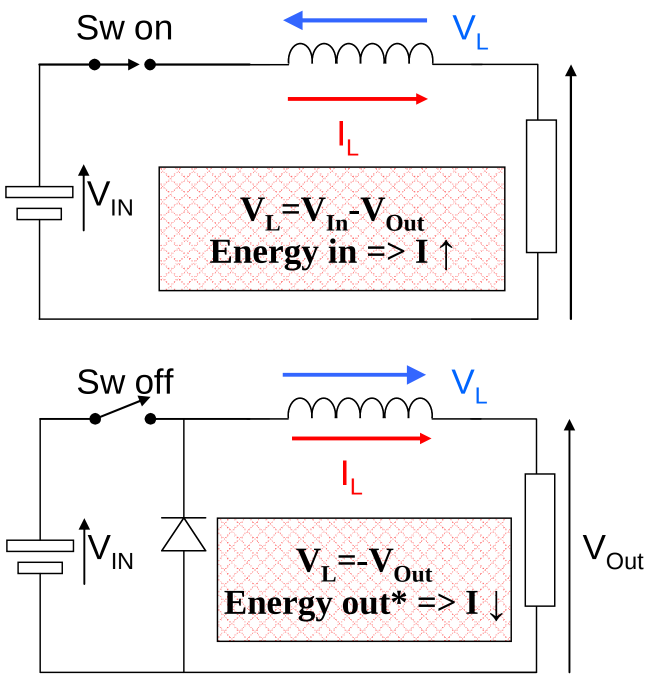
[Actually there is a small reduction due to losses in the system that have not been included in the analysis – but assume lossless for this course.)

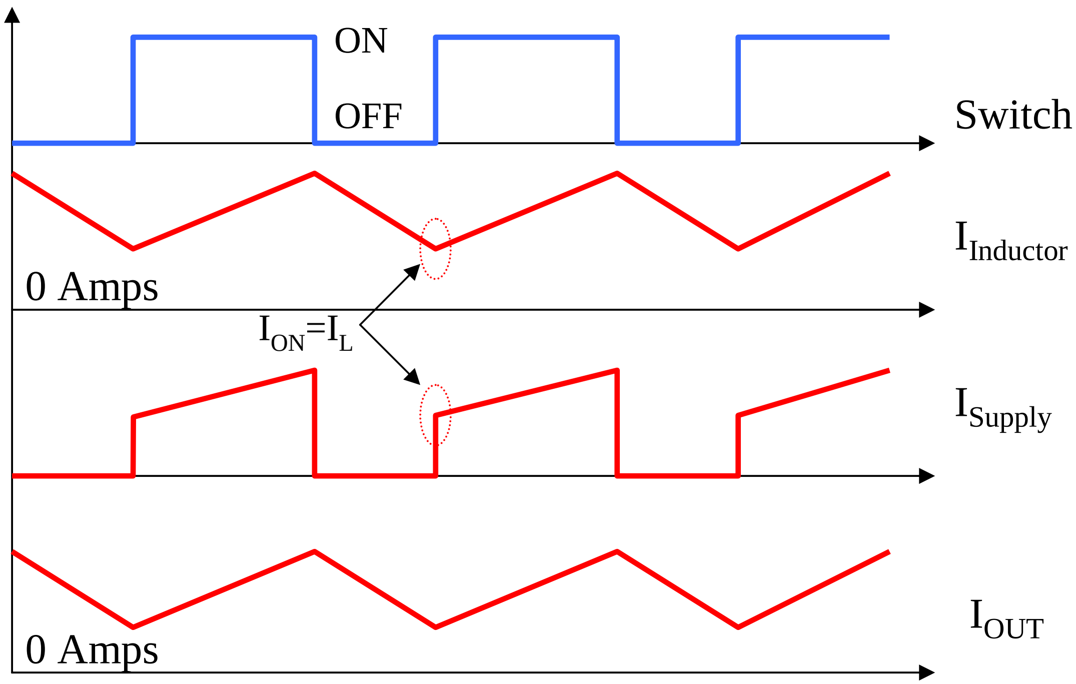
Note that this relationship is true only if current is always flowing in the inductor, i.e. the SMPS is operating in ***continuous mode***.

$$\boxed{V_{OUT} = \phi . V_{IN}}$$



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} x I_{Mean})

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

Note that if the smoothing capacitor on the output is sufficiently large then the output voltage is essentially constant. The typical PWM switching frequency is > 20KHz (above audible frequency) so ΔT on the capacitor is < 50μS.

We can use the preceding current equation to make two very important observations:

1. The *average* current in the inductor is the average load current.

E.g. $P_{Load} = 100W$ and $V_{Load} = 5V \Rightarrow I_{Load} = I_{Inductor} = 20A$

2. The *average* input current is less than the output current for $\varphi < 100\%$. In the linear power supply the output current could never exceed the input current.

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