Switching DC regulators

Introduction.

Linear DC regulators suffer from a major problem: power loss. They regulate the output voltage by controlling the conductivity of a series transistor. This is extremely inefficient. Switching regulators overcome this problem by switching the input on and off (quickly) and filtering the resulting pulsed output. Efficiencies over 95% are regularly achieved making this class of regulator very popular for higher power and battery applications. Switching regulators can also produce a output voltages that are greater than the input supply and also of opposite polarity.

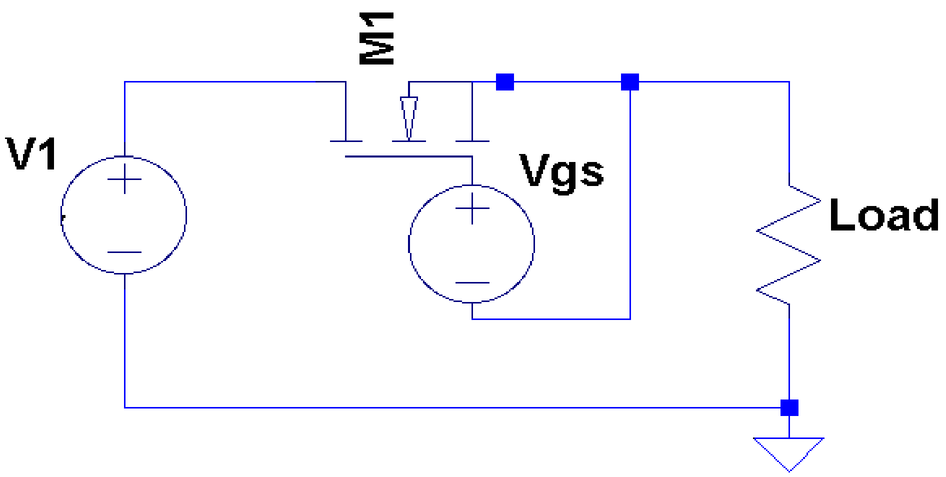
When analysing switching regulators it is common to make certain assumptions:
1) Inductors are assumed to be (and hopefully are) big enough such that current changes in them are linear
2) Capacitors are assumed to be big enough such that charge transfers that take place during a normal switching cycle lead to approximately no change in their terminal voltages.
3) Switches are more or less ideal – i.e. when they are on, they are “fully on” with zero volts across them and when they are off they carry no current.
Having said the above, there are times when we need to look at the non-ideal behaviour of switching supplies. At these times some or all of these assumptions may be dropped.

The step down switching regulator (the 'Buck' regulator)

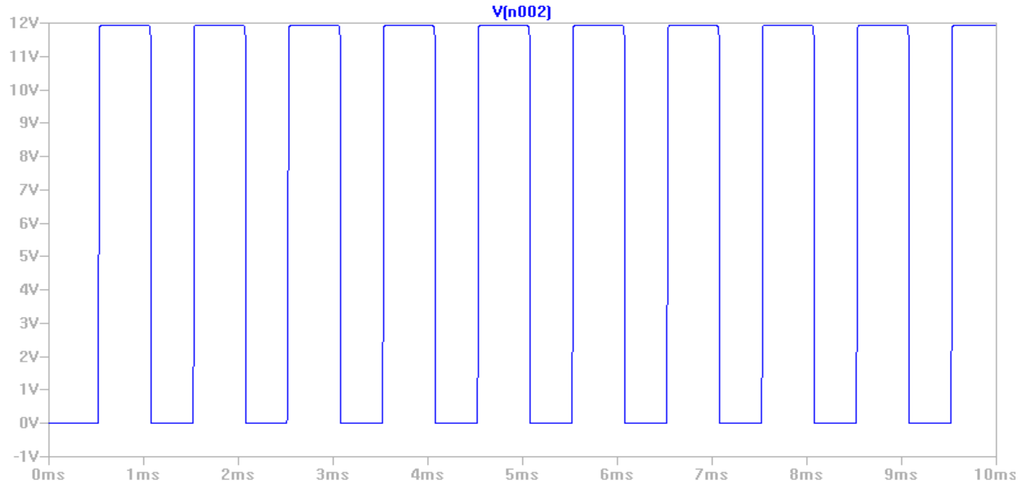
Conceptually this is the easiest of the switching regulators to understand. It works like this:

“If the input power source is turned on for X% of the time then the output voltage is X/100 times the input voltage.”

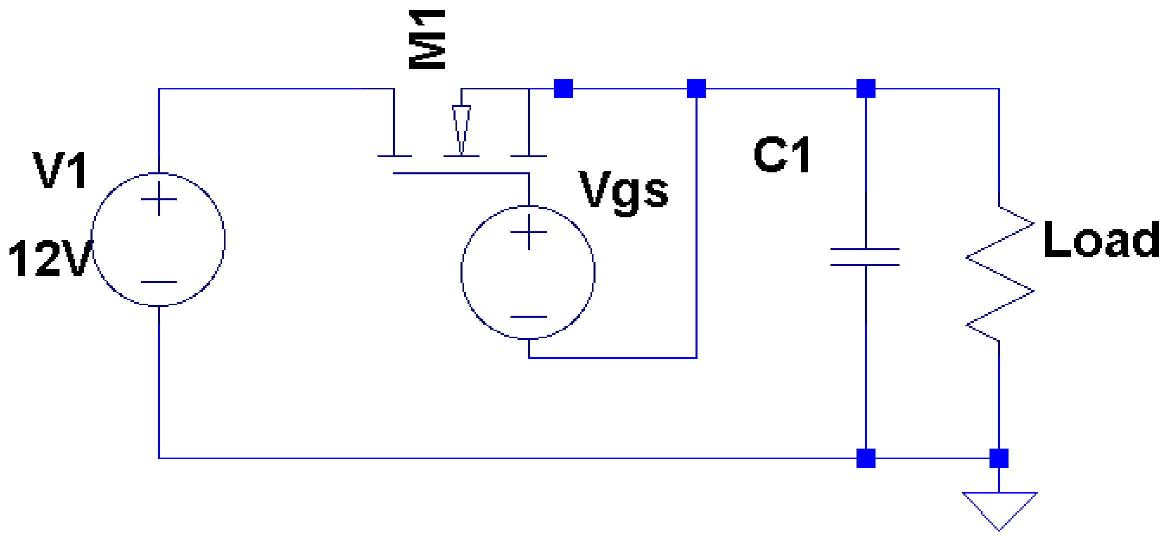
So, to make a buck regulator we need a switch that can be used to turn on and off the input supply. We also need a filter to smooth out the chopped output from the switch into a stable output. Most of the hard sums lie here.
Lets begin with a simple switching circuit as shown below;



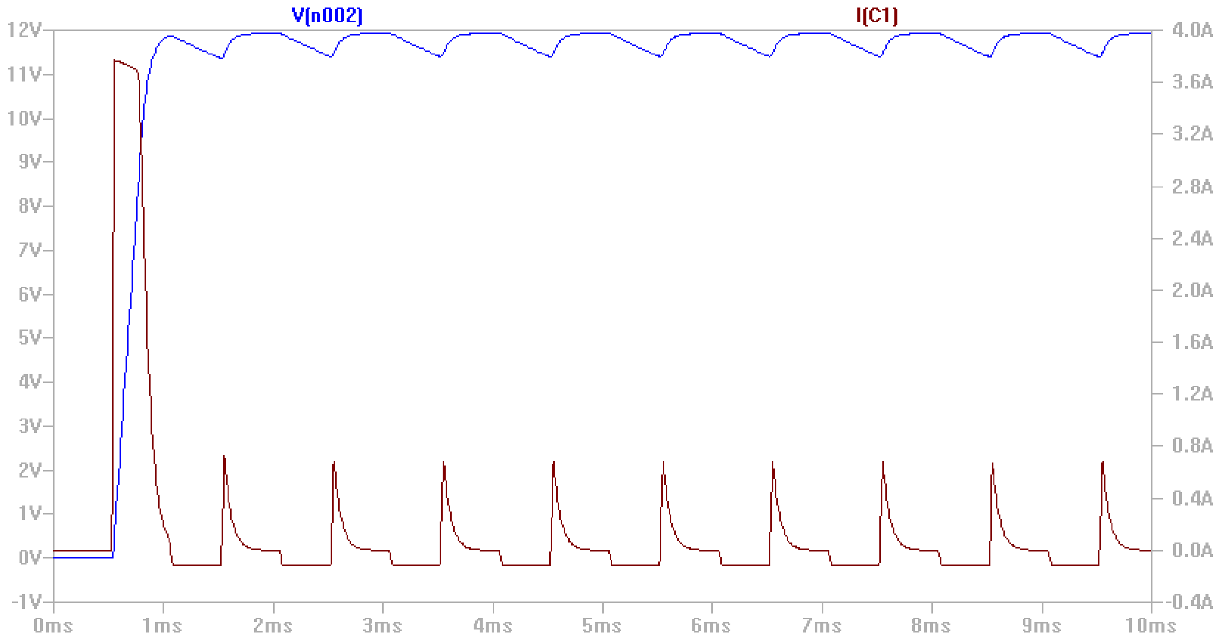
There is no output filter in this case. The MOSFET is simply used to turn on and off the input supply. The control voltage (Vgs) switches high and low at 50% duty at a rate of 1kHz (which is low for switching power supplies).
The output voltage looks like this:



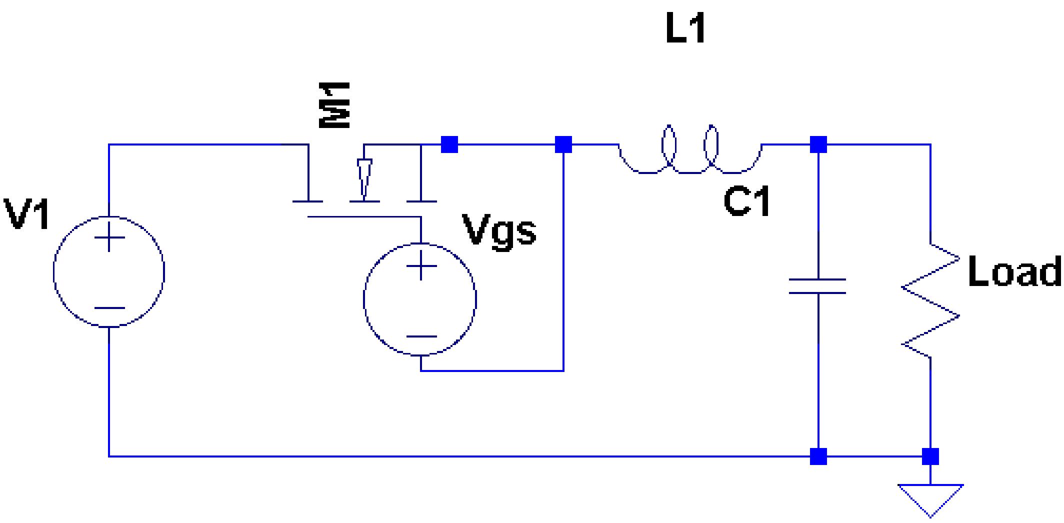
Not a very steady DC supply at all. We could filter this using a single capacitor as shown below.



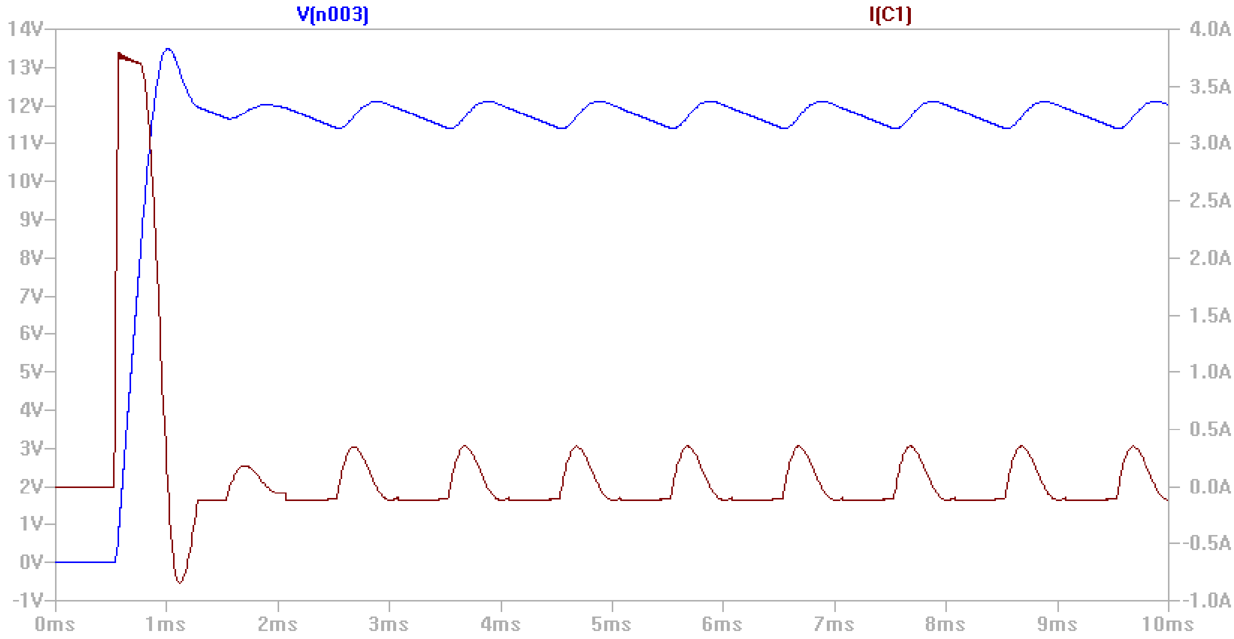
While this is easy to do, it does however have one big drawback. When the MOSFET turns on, there is very little resistance between the capacitor and the input supply. This will lead to large charging current spikes in the capacitor which may cause problems for the MOSFET, the input supply and neighbouring components/devices (radio interference, power supply noise). The output voltage and capacitor current is shown below. Note the shape of the capacitor current.



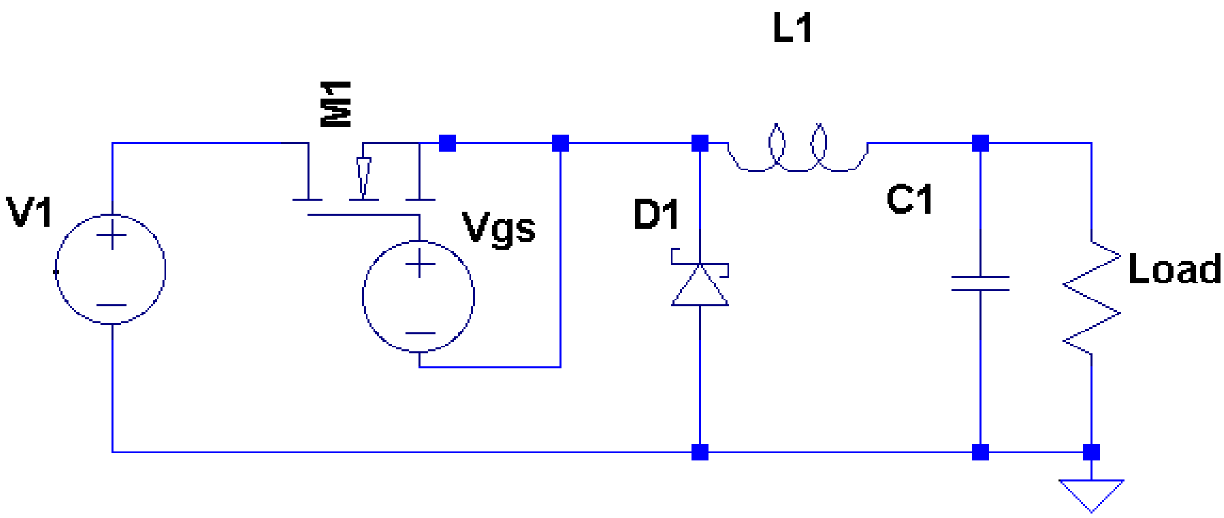
The output voltage is quite smooth however the charging current is a problem. We could fix this by including an inductor in the circuit. **<u>Inductors resist changes of current</u>**. This gives us the following circuit.



The output voltage and capacitor current are now as shown below.



The capacitor current is now less "spiky" and will cause fewer noise problems all around. The output voltage (V(n003)) is still quite smooth.
We are left with a slight problem however. When the MOSFET turns off, one end of the inductor is effectively disconnected from the rest of the circuit. Remembering that inductors resist changes of current (a voltage is induced across them to retard changes in current flow) this presents a problem because we are going from the situation where the current was non zero to a state where it is actually zero really quickly (MOSFETS switch really fast). This can result in large voltage spikes across the inductor which may damage the MOSFET and/or the load. We can fix this by adding a flyback diode as shown below.



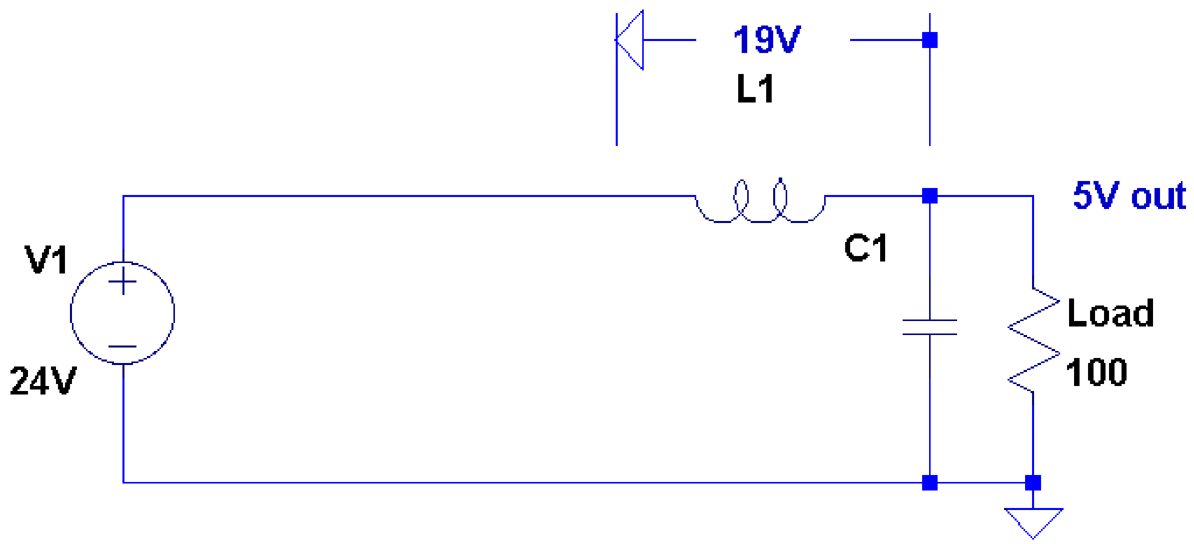
This odd looking symbol for a diode (D1) is in fact a Schottky diode – a very fast diode commonly used in switching power supplies (they are a bit too expensive to use in rectifiers and tend not to be very good at blocking high reverse voltages). This finally is our complete Buck voltage regulator.

Design example.

Design the output filter for a Buck regulator that will limit the current ripple to +/- 10% of the average load current. The output voltage must be kept to +/- 1% of the nominal output value. The switching frequency is 100kHz, the input voltage is 24V and the desired output voltage is 5V. The load can be modelled as a 100Ω resistance.

The regulator has two states: Switch-On and Switch-Off. The equivalent circuits for these are as follows:

Switch-on



What can we say about this? Well, the inductor must block 19V during this interval. If it manages to do this, then this will imply a certain rate of rise of current within it. Remember, for an inductor, the voltage across it (VL) is given by:

$$V_L = L\frac{di_L}{dt} \quad \ldots\ldots(1)$$

We know VL, we want to figure out a value for L and we don't know the rate of change of current in the inductor – or do we? If we assume that the current changes linearly (see above) then we can say:

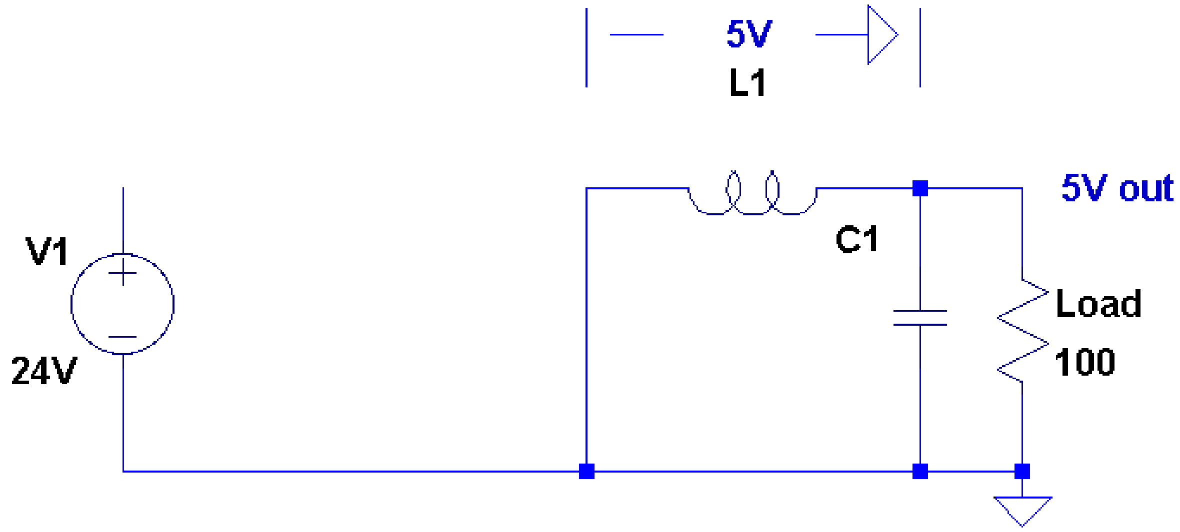
$$\frac{di_L}{dt} = \frac{\Delta I_L}{T_{ON}}$$

How does this help?

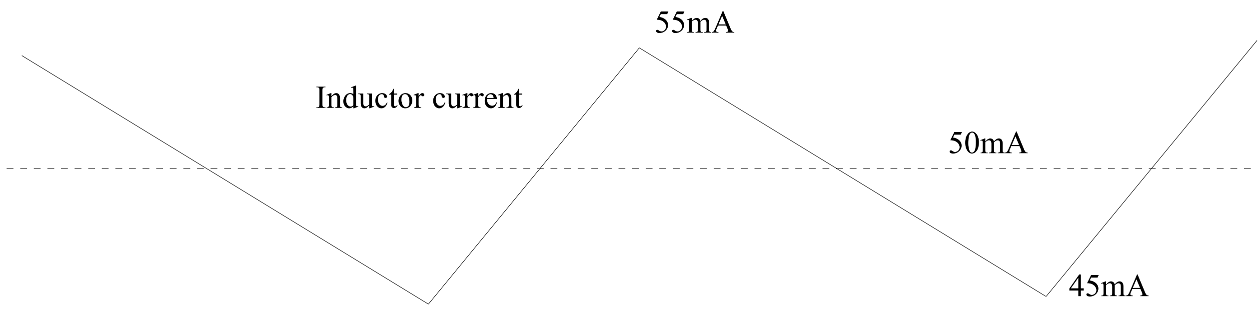
Well, TON is the time over which the switch is on. Do we know this? Well, we were told that the output voltage is 5V and the input is 24V. This means that the switch must be on for 5/24th's of the time. The switching frequency is stated as 100kHz so a full switching cycle takes 10µs. The on time is therefore approximately 2µs. How about the change in inductor current ΔI_L? We are told that the inductor current is not to vary by more than +/-10% of the average load current. The average load current must be 5/100 = 50mA. A 10% swing either side of this is 20% of 50mA which is 10mA. We can now say that $\frac{di_L}{dt} = \frac{10\text{x}10^{-3}}{2\text{x}10^{-6}}$ which is 5000 A/s

Putting this back into equation 1 we are left with a value for L of 3.8mH.

Switch-Off



Figuring out the size of the capacitor is a little more difficult. When the switch is on, the current in the inductor is rising. The load current is hopefully constant however so where does this extra charge go? Into the capacitor of course. The capacitor is supposed to be able to absorb this charge with little or no change in its terminal voltage. Looking at the steady state inductor current we see the following:



The area under the above trace has the units of Time x Current – which is charge. We therefore have a measure of the amount of charge our capacitor needs to absorb over a switching cycle. We also know the magnitude of the permitted voltage change. Above the 50mA line we have a triangle whose area (and hence charge) is given by

$$\Delta Q=\frac{1}{2}\frac{T}{2}x\,5\text{mA}$$

$$\Delta Q=\frac{10\text{x}10^{-6}}{4}5\,x\,10^{-3}$$

$$\Delta Q=12.5\,x\,10^{-9}\,Coulombs$$

The permitted voltage change is 1% of 5V which is 50mV so using Q=CV we get a value for C as follows:

$$C = \frac{\Delta Q}{\Delta V}$$

$$C = \frac{12.5\,x\,10^{-9}}{50\,x\,10^{-3}}$$

$$C = 0.25\,\mu\,F$$

The step up switching regulator (the 'Boost' regulator)

The step-up of boost regulator produces an output voltage that is greater than the input one. This unusual feat is achieved by first storing lots of energy in the magnetic field of an inductor and then dumping that energy into a capacitor.

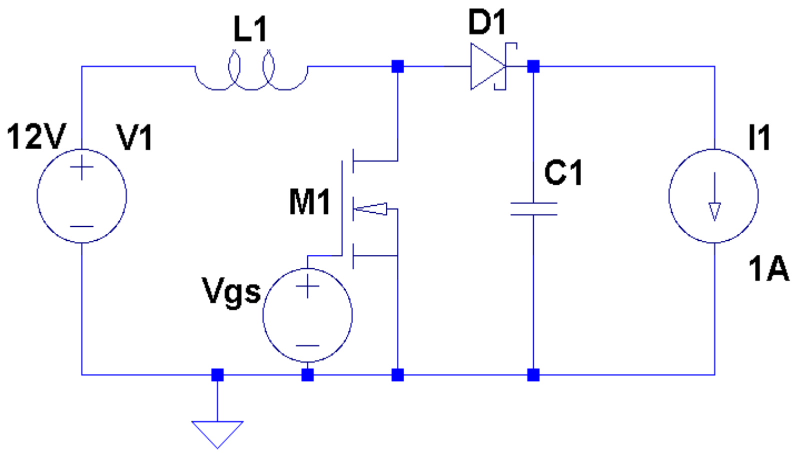


Figure 1.1

When M1 is on (Ton), current builds in inductor L1 as shown below. At the end of Ton the energy in L1 is at its maximum

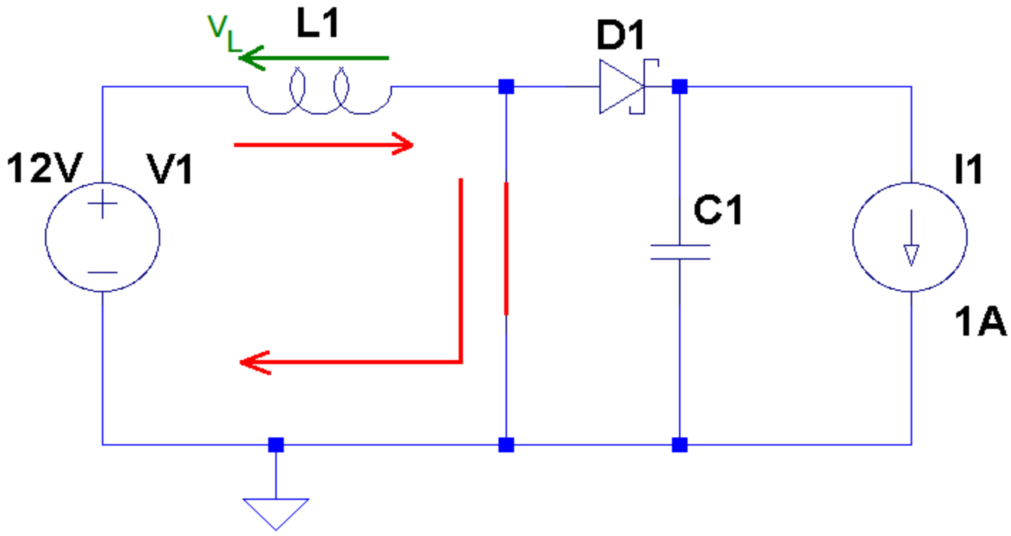


Figure 1.2

When M1 opens, the current in L1 can not stop so it continues to flow by pushing through D1 and on into the load and C1. This raises the voltage on C1 as shown below

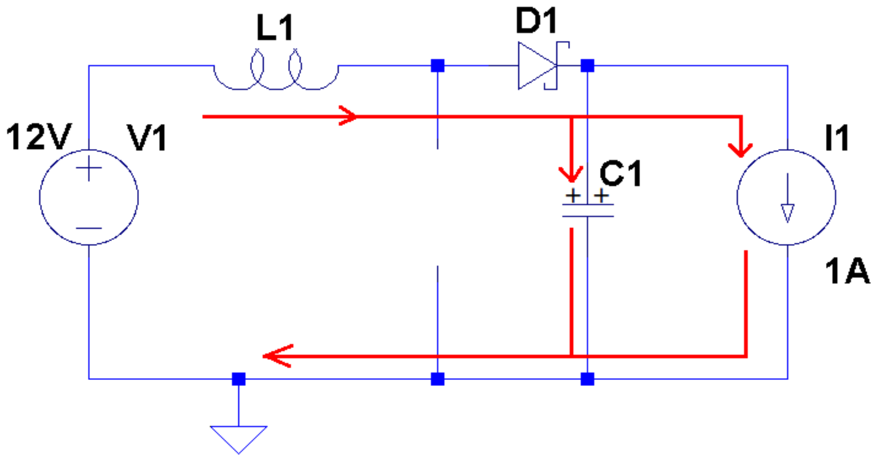


Figure 1.3

When M1 next turns on, C1 continues to supply the load current and L1 is re-energized by the power supply V1.

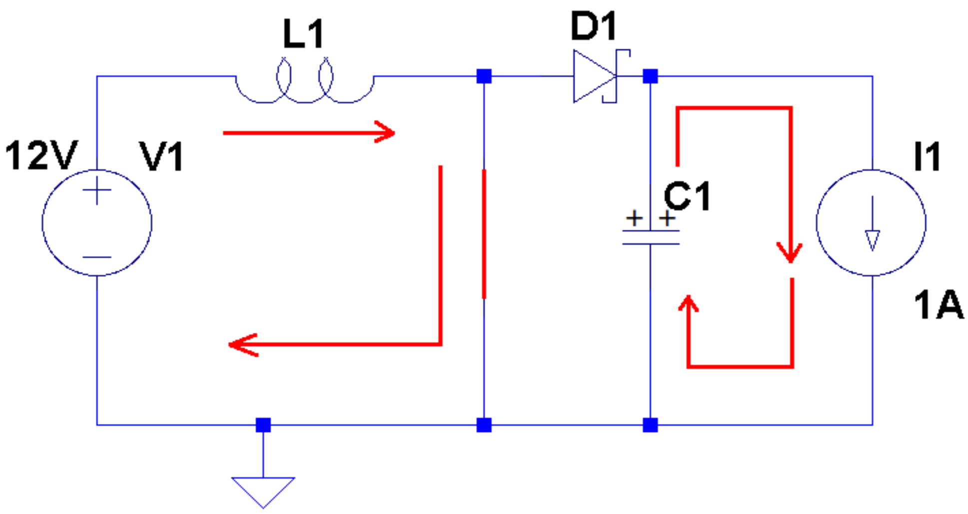


Figure 1.4

The figure below shows the various waveforms associated with a Boost regulator operating at 100kHz with a 50% **Duty cycle** (The term Duty Cycle refers to the percentage "on" time of the regulator's switch (M1)). The lower trace (V(n003)) is the output voltage. Note this is approximately twice the input voltage.

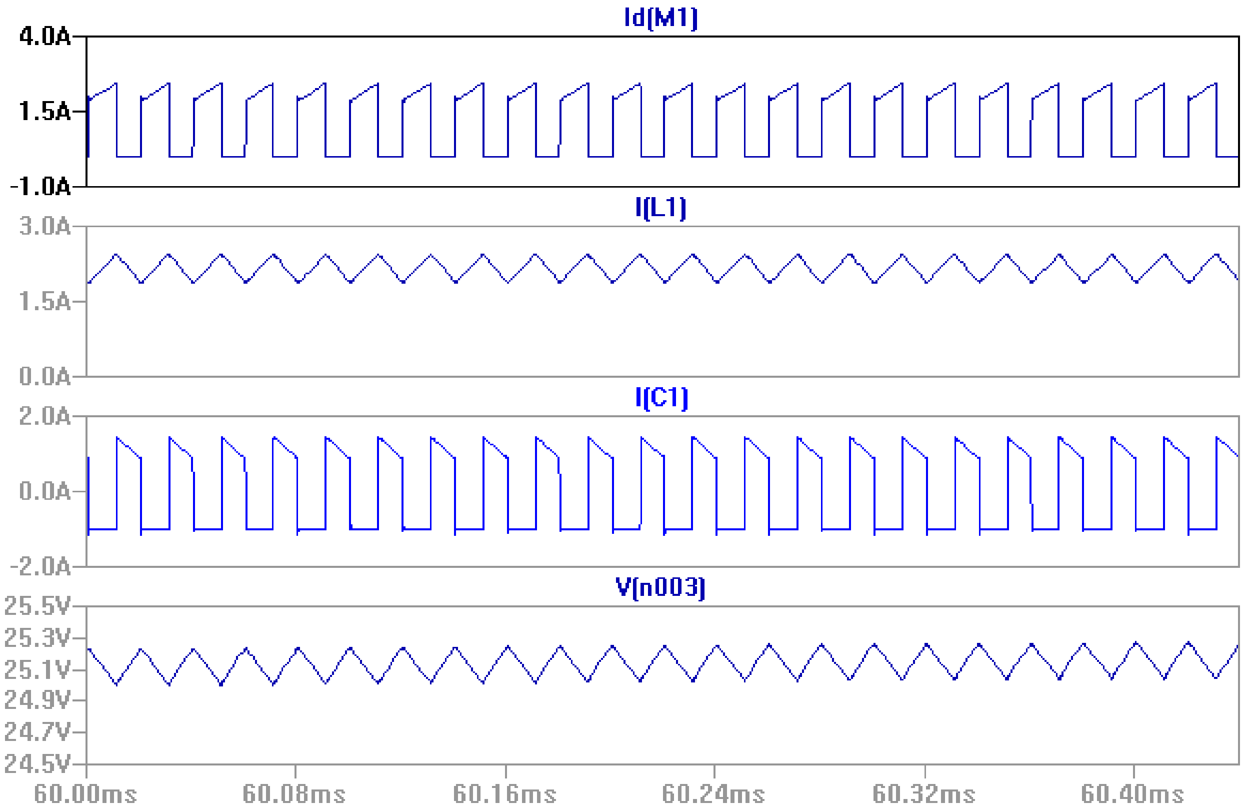


Figure 1.5

Steady state mathematical analysis

Examining Figure 1.2 we can say the following:

$$V_i = L\frac{di_L}{dt}$$

Assuming the current rises and falls linearly, this can be written as

$$V_i = L\frac{\Delta i_{Lon}}{T_{on}} \quad \text{................(1)}$$

Where Δi_{Lon} is the change in current that takes place when the MOSFET is on i.e. during T_{on}

Now, examining Figure 1.3 and looking at the outer voltage loop we can write the following:

$$V_i = L\frac{di_L}{dt} + V_o$$

Again, assuming the inductor current rises and falls linearly we can write that as:

$$V_i = L\frac{\Delta i_{Loff}}{T_{off}} + V_o \quad \text{......................(2)}$$

Looking at Figure 1.5 we can see that the current in the inductor rises and falls by the same amount during the on and off times. This means that:

$$\Delta i_{Lon} = -\Delta i_{Loff}$$

Using this with equation (2) we can now write

$$V_i = L\frac{-\Delta i_{Lon}}{T_{off}} + V_o \quad \text{..................(3)}$$

From equation (1) we can say

$$\Delta i_{Lon} = \frac{T_{on} V_i}{L}$$

Putting this into equation 3 we now get

$$V_i = L\frac{\frac{-T_{on} V_i}{L}}{T_{off}} + V_o$$

Both L's will now cancel and we are left with

$$V_i = \frac{-T_{on} V_i}{T_{off}} + V_o$$

$$V_i\left(1 + \frac{T_{on}}{T_{off}}\right) = V_o \quad \text{.............(4)}$$

The Duty Cycle of a switch is usually assigned the symbol D. The 'On' and off times for the switch are given by:

$$T_{on} = DT$$
$$T_{off} = (1-D)T$$

Putting these expressions into equation (4) we get

$$V_i\left(1 + \frac{DT}{(1-D)T}\right) = V_o$$

The 'T's cancel and we get

$$V_i\left(1 + \frac{D}{(1-D)}\right) = V_o$$

This can be simplified further as follows

$$V_i\left(\frac{1-D}{(1-D)}+\frac{D}{(1-D)}\right)=V_o$$

Which finally leaves us with:

$$\frac{V_i}{(1-D)}=V_o \quad \text{…......................(5)}$$

This equation predicts the output voltage that will be achieved for different duty cycles. For example, suppose Vi is 12V and the Duty Cycle of M1 is 80%. The output voltage will then be 60V. (In practice, very high duty cycles may not be possible to achieve).

The step up/down switching regulator (the 'Buck-Boost' regulator)

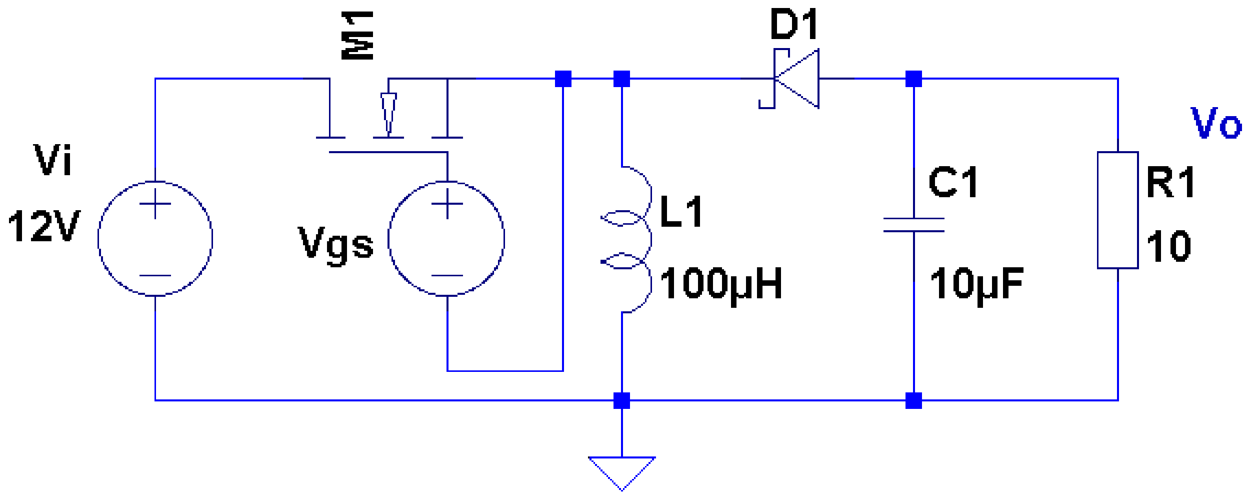


Figure 1. The buck boost regulator

The figure above shows a buck-boost regulator. The magnitude of the output voltage from this regulator can be less than or greater than that of the input voltage – depending upon the duty cycle of the main switching element (M1 in this case). The sign of the output voltage is opposite that of the input.

Operation

When M1 is on, current (and hence energy) builds in L1. D1 is reverse biased and will behave like an open circuit

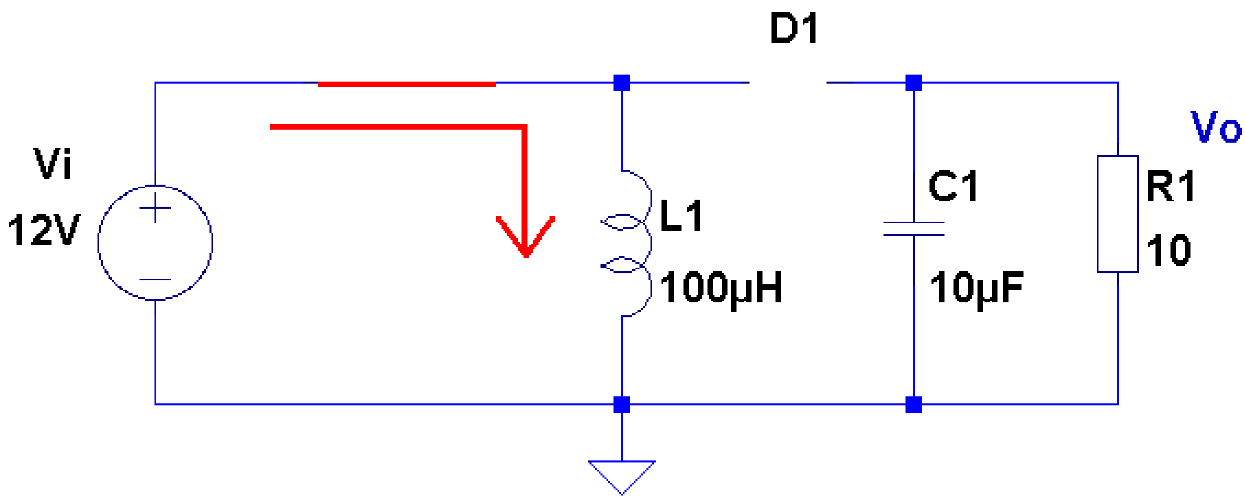


Figure 2. M1 is turned on for the first time. Energy builds in L1

When M1 is turned off, the current continues to flow in L1 as shown in Figure 3 below. D1 turns on. Note the polarity of the output voltage.

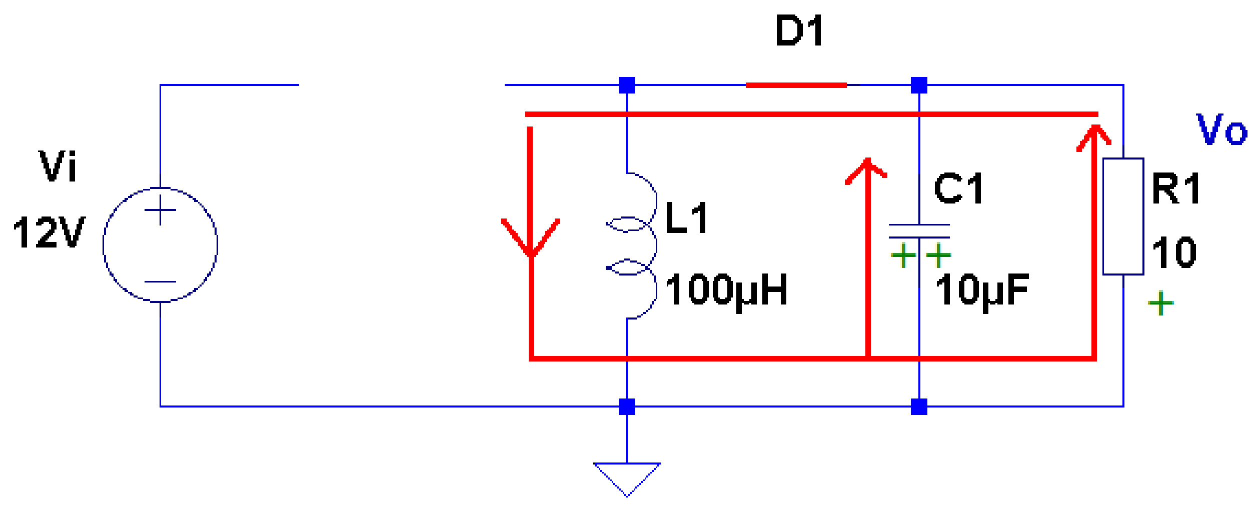


Figure 3. M1 off for first time, C1 is charged up

Finally, the cycle restarts and M1 closes again. During this interval, C1 maintains the output voltage

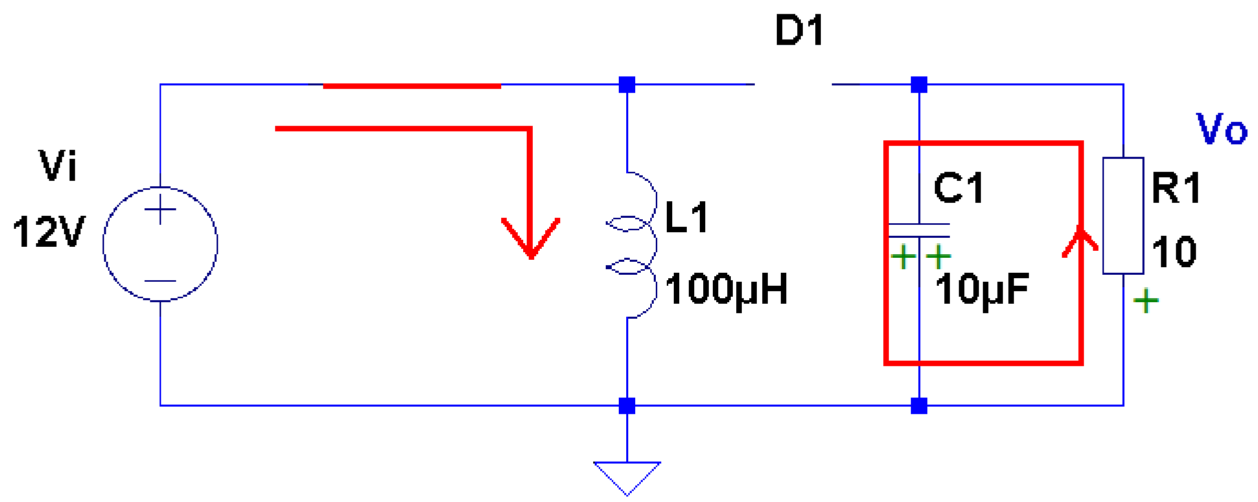


Figure 3. M1 back on. L1 energy is topped up and C1 maintains load voltage.

Static analysis.

Referring to Figure 2, we can say the following:

$$V_i = L\frac{\Delta i_{Lon}}{T_{on}} \quad ....(1)$$

Now referring to Figure 3, we can say the following

$$L\frac{\Delta i_{Loff}}{T_{off}} = V_o \quad ....(2)$$

At steady state, the change in current in the 'off' time is equal and opposite to that during the 'on' time. In other words:

$$\Delta i_{Loff} = -\Delta i_{Lon}$$

Substituting this into (2) above we get

$$V_o = -L \frac{\Delta i_{Lon}}{T_{off}} \quad \text{.....(3)}$$

Dividing (3) by equation (1) we get

$$\frac{V_o}{V_i} = \frac{-T_{on}}{T_{off}}$$

$$\frac{V_o}{V_i} = \frac{-DT}{(1-D)T}$$

$$\frac{V_o}{V_i} = \frac{-D}{(1-D)}$$

So, if the duty cycle D is 0.5, the output voltage should be equal and opposite that of the input.

Exercises

1) A Buck regulator delivers an output voltage of 5V and an output current of 2A. The efficiency of the regulator is 90% and it is operated from a 12V supply. The switching frequency of its main switching element is 100kHz.

    1. If the peak inductor current is to be limited to 2.5A calculate its minimum inductance.
    2. If the output voltage ripple is to be limited to 50mV (peak to peak), calculate a suitable value for the output capacitance
    3. What is the average input current?
    4. What is the peak input current?
    5. Verify your results by simulating with LTSpice.
    6. What happens to the output voltage as you lower the output current. Why is this?

2) A Boost regulator is required to step up a 12V supply to 48V. The regulator must deliver a current of 1A. The operating frequency has been chosen to be 50kHz and the main switching transistor has a maximum rated current of 5A. If the output voltage ripple is to be kept below 100mV (peak to peak), calculate suitable values for L and C.

    Verify your results by simulation using LTSpice.

3) A Buck-Boost regulator is required to produce and output voltage of -15V from a 5V input supply. The output current is 500mA. If output capacitor of 47µF is fitted and the output voltage ripple must be maintained below 50mV (pk-pk)

    1. Calculate a suitable operating frequency for the power supply
    2. Choose a suitable inductor from http://ie.farnell.com such that the inductor ripple current is no more than 100mA (peak to peak).
    3. Choose a suitable transistor from the farnell site
    4. Simulate the operation of the circuit using LTSpice.