32.2.2 The Boost SPS

The previous section covered the buck SPS, a DC-DC converter for stepping down a voltage. In this section we briefly cover the boost SPS, Fig. 32.25, for stepping up a DC voltage. Notice, in Fig. 32.25, that the amount of time the drain of MD is low is *DT* or the complement of the buck converter where *DT* was the amount of time the drain of MD was high.

Let's begin our analysis by assuming that MD, again neglecting the on resistance (so the drain of MD goes all the way to ground), is on so the change in current through *L* is

$$v_L = L \cdot \frac{di_L}{dt} = L \cdot \frac{\Delta i_{L,up}}{DT} = V_S \quad (32.42)$$

When MD is off, and neglecting the forward voltage drop of the Schottky diode, MD's drain is at V_{OUT} so

$$L \cdot \frac{-\Delta i_{L,dwn}}{(1-D)T} = V_S - V_{OUT} \quad (32.43)$$

noting that since $V_{OUT} > V_S$ (it's a boost SPS) the right side of this equation is negative. Further, we know that (for constant load current I_R)

$$\Delta i_{L,up} - \Delta i_{L,dwn} = 0 = \frac{DT \cdot V_S}{L} + \frac{(V_S - V_{OUT}) \cdot (1-D)T}{L} \quad (32.44)$$

or

$$V_{OUT} = \frac{V_S}{1-D} \quad (32.45)$$

This is the relationship between the supply voltage and output voltage of a boost converter.

Note, in Fig. 32.25, that the average of the current through the inductor, I_L, is not the same as the average load current, I_R, as it was with the buck SPS. We know that the power supplied by V_S should equal (neglecting switching resistance and other imperfections) to the power supplied to the load or

$$V_S I_L = V_{OUT} \cdot \underbrace{\frac{V_{OUT}}{R}}_{I_R} = \frac{V_S \cdot V_{OUT}}{(1-D)R} \quad (32.46)$$

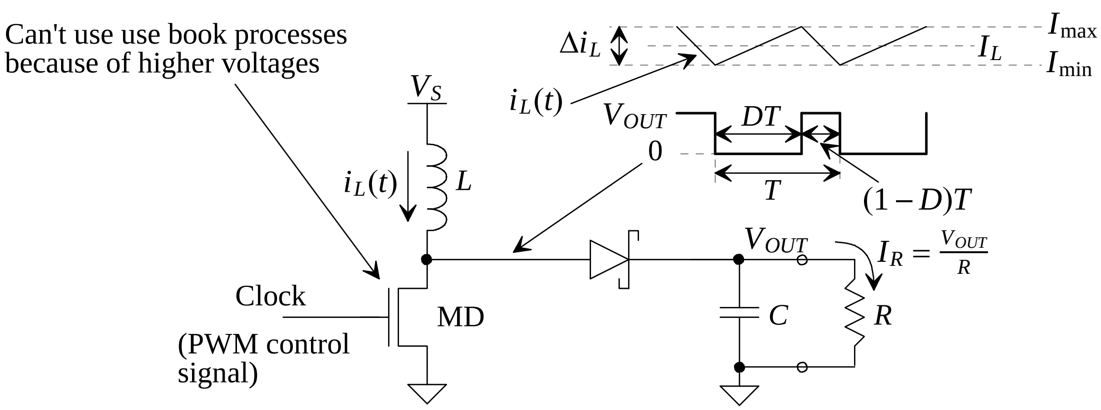

Figure 32.25 Boost switching power supply.

or

$$I_L = \frac{V_{OUT}}{(1-D)R} = \frac{I_R}{1-D} \tag{32.47}$$

This is the relationship between the average inductor and load currents.

Selecting the Inductor

The maximum and minimum currents through the inductor, but first noting the change in the inductor current is written as $\Delta i_L = \Delta i_{L,up} = \Delta i_{L,dwn}$, are

$$I_{\max} = I_L + \frac{\Delta i_L}{2} = V_{OUT}\left(\frac{1}{(1-D)R} + \frac{(1-D)\cdot D}{2Lf}\right) \tag{32.48}$$

$$I_{\min} = I_L - \frac{\Delta i_L}{2} = V_{OUT}\left(\frac{1}{(1-D)R} - \frac{(1-D)\cdot D}{2Lf}\right) \tag{32.49}$$

It's desirable to have $i_L(t)$ be positive because if it goes negative it indicates, again, that MD is conducting current from the source to drain. This doesn't consume energy from V_S but does result in power dissipation in MD as discussed for the buck SPS. We can calculate the minimum value of the inductor, for a given load R, to ensure that the $i_L(t)$ doesn't go negative by setting Eq. (32.49) to 0 and solving for L

$$L_{\min} = \frac{D(1-D)^2 R}{2f} \tag{32.50}$$

As we saw in Ex. 32.5 the load, R, is the *lightest load possible* (R is a big value), not the smallest, or heaviest load. Note that for larger values of R, that is for lighter loads, the inductor current *will* go negative. Using Eqs. (32.43) and (32.45) we can also determine the value of L in terms of the change in the inductor current as

$$L = \frac{V_{OUT}\cdot D\cdot(1-D)}{f\cdot \Delta i_L} \tag{32.51}$$

This equation is, in general, more useful when selecting an inductor value in a boost SPS.

Selecting the Capacitor

Lastly, let's calculate the value of the filter capacitor C for a particular output voltage ripple. When the diode is off (MU is on) the current supplied to the load is entirely from C. Therefore we can write

$$\frac{V_{OUT}}{R} = C\cdot\frac{\Delta V_{OUT}}{DT} \tag{32.52}$$

or

$$C_{\min} = \frac{D}{R\cdot f\cdot(\Delta V_{OUT}/V_{OUT})} \tag{32.53}$$

Here, unlike when we calculate $L_{\min}$, we want to use the smallest R, that is, heaviest load for the calculation. This ensures that under full-load conditions the output variation specifications are met.

Example 32.7

Using the boost SPS topology seen in Fig. 32.25 design a power supply that can supply 15V (= V_{OUT}) and up to 5 mA. Assume V_S = 5 V and f = 1 MHz. Comment on your design choices and simulate the operation of your design.

Using Eq. (32.45) we can calculate the value of D as 0.667. For the heaviest load R = 15V/5mA = 3kΩ (= I_R). Using Eq. (32.47) this means that the maximum average inductor current, I_L, is 15 mA. Let's set the maximum change in inductor current, Δi_L, to 750 µA (5% of the maximum average current). We can then use Eq. (32.51) to calculate L

$$L = \frac{15 \cdot \frac{2}{3} \cdot \frac{1}{3}}{10^6 \cdot 750\mu A} = 4,444\ \mu H$$

which we'll round up to 4700 µH, a standard inductor value. Assuming a maximum output ripple of 0.1% Eq. (32.53) can be used to calculate C

$$C = \frac{\frac{2}{3}}{3k \cdot 10^6 \cdot 0.001} = 0.22\ \mu F$$

Simulation results driving a 3k load are seen in Fig. 32.26. While V_{OUT} is close to what we designed for the current in the inductor is roughly 3 mA higher. Further, increasing the load to 30k makes the output voltage increase to above 19V. Clearly something is going on that is outside the discussion in this section beyond simply ignoring the forward voltage drop across the Schottky diode. ■

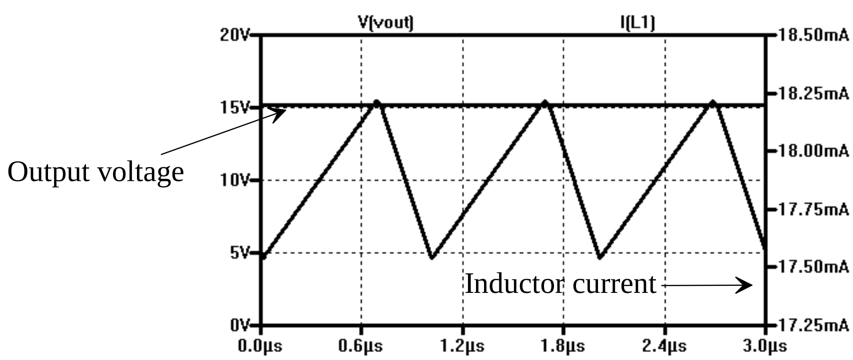

Figure 32.26 Simulating the boost SPS in Ex. 32.7 with a 3k load.

Consider the portion of the boost SPS shown in Fig. 32.27 showing the diode's parasitic junction capacitance (see Ch. 2). The diode's capacitance, C_{diode}, may have a (zero-bias depletion value, C_{j0}) value of 100pF, as an example for a power diode. This capacitance is discharged when the voltage on the drain goes from V_{OUT} to 0. We don't concern ourselves with when the drain goes from 0 to V_{OUT} because the diode turns on (and shunts the capacitance with its own small on resistance). Again, we are neglecting the voltage drop of the Schottky diode. When the MOSFET turns on the amount of

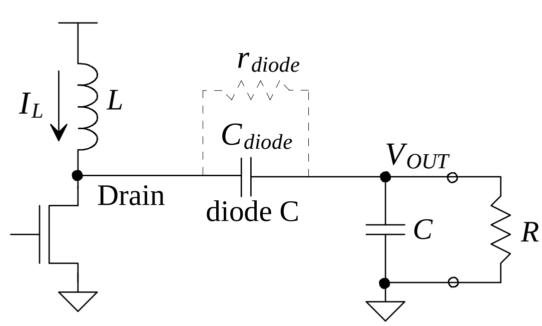

Figure 32.27 Capacitances in a boost SPS.

charge required to discharge the diode's capacitance is roughly (remember diode capacitance changes with reverse bias hence why we qualify this equation with "roughly")

$$Q = V_{OUT} \cdot C_{diode} \tag{32.54}$$

This charge is stolen from the capacitor every T seconds when the diode shuts off (the MOSFET turns on). We can estimate the extra current to make up for this stolen charge, noting that current from the inductor flows through the diode for only $(1 - D)T$ seconds every clock cycle T, using

$$I_{extra} = \frac{V_{OUT} \cdot C_{diode}}{(1-D)T} \tag{32.55}$$

Plugging in the numbers from Ex. 32.7, assuming 100pF diode capacitance (using the zero-bias capacitance is larger than the average capacitance when reverse biasing the diode, see Fig. 2.15, so we expect a larger current then what we'll simulate), we get

$$I_{extra} = \frac{15 \cdot 100pF}{0.333\mu s} = 4.5\ mA$$

The charge stolen from C to charge C_{diode} is 1.5 nC. Reviewing Ex. 32.7 we calculated an average inductor current of 15 mA; however, the simulations, Fig. 32.26, show an average current of, roughly, 17.9 mA or 2.9 mA above the calculated value. This is lower than what we calculated above but, given the overestimate of the diode's capacitance, this is expected.

Before moving on, Fig. 32.28 shows the current stolen from the capacitor, C in Ex. 32.7. The amount of charge can be estimated by calculating the area of the stolen current from, 11 to 17 ns, that is $6ns \cdot 150mA = 0.9\ nC$. While this is less than our estimate above of 1.5nC this is expected because we used the zero bias depletion capacitance of the diode instead of an estimate of the diode's capacitance when it's reversed biased. Note that as the load draws less and less current we reach a point where the only current supplied through the diode is to charge and discharge the diode's own capacitance, which makes controlling the output voltage a challenge without a control feedback loop (re-simulate the circuit in Ex. 32.7 with larger values of R).

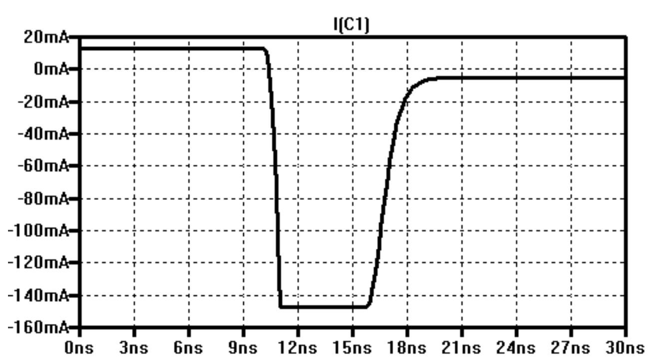

Figure 32.28 Current stolen from C in Ex. 32.7 when MOSFET turns on.

The key, less than profound, take-away from all of this discussion is to use a diode with as low a capacitance as possible. Here the diode selected is a bit of over kill (too big, and it has too much capacitance) for the tens of milliamps of current used (but the selection works well for illustrating this issue).