Project 3 – Power Supplies (Two Weeks)

BACKGROUND

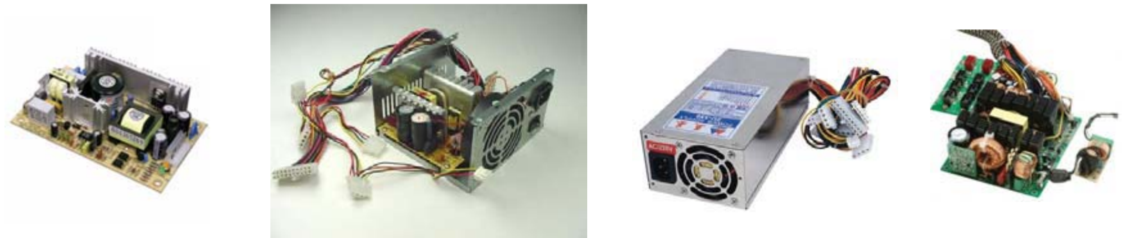
We live in the age of portable electronics. All handheld electronic devices, including cell phones, iPods, MP3 players, AM/FM radios, "walkie-talkies, PDA's, and laptop computers require sources of power that are usually obtained from batteries. Common batteries such as the AA, AAA, C, and D types may be found convenience stores, supermarkets, etc., but more commonly, handheld devices derive power from advanced battery types, such as lithium ion (Li-ion) and nickel-metal halide (NiMH).
A well-known problem with batteries, of course, is that they discharge over time and must be either

Common devices requires sources of low-voltage dc power

replaced or recharged. When an appliance is being used in a non-mobile setting (i.e., you're using your laptop at your desk), it's much more convenient to operate the device using power derived from an ac wall outlet. The device still expects power in low-voltage dc form. Thus, a myriad of common power supplies, or "ac-to-dc converters", exist to provide continuous power derived from ac "line" voltage (e.g., 120 volts in North and South America; 240 volts in Europe and Asia, 100 volts in Japan). Such, ac-to-dc converters are also instrumental to the recharging of depleted batteries. Power supplies of these types are sometimes referred to as battery eliminators, power adaptors, wall cubes, ac adaptors, or plug supplies:

Examples of ac-to-dc converters used to power portable devices

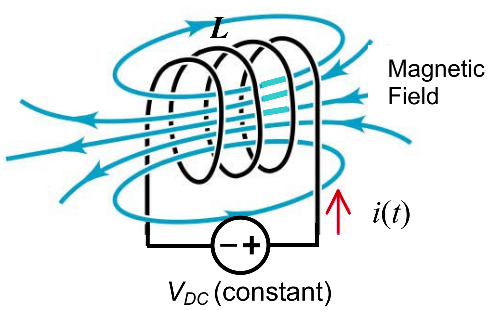
In the past, the ac-to-dc power supply of choice was the *linear* supply. A linear supply is typically formed from an transformers, some number of diodes, one or more capacitors, resistors, and (sometimes) a transistor or voltage regulator. While they are reliable, linear supplies are not the most energy efficient, and they are relatively costly compared to more modern power supply types. In the 1980's to 1990's, the availability of inexpensive and reliable power MOSFETs led to an alternative design technique known as the *switching power supply.* The power transistors in a "switcher" operate as non-linear switches whose states are changed between "on" and "off" at frequencies considerably higher than 50 or 60 Hz. The switching frequency in such a supply is typically in the range 20kHz to 200 kHz. The power supplies found inside fixed, desktop computers and similar devices are also of the switching, rather than linear, type. A consequence of high-frequency, switching power-supply technology is that low-cost power supplies can be designed that are much more efficient and compact than linear supplies delivering the same power. One primary reason is that the transformer – typically the most costly element in a linear supply – can be substantially reduced in size, and even eliminated entirely in favor of a single, small, ferrite core inductor. In this lab, we investigate some of the properties of both linear and switching power supplies.

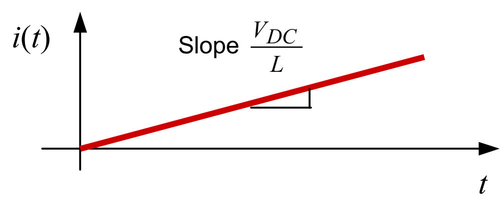


The power supplies found inside desktop computers are of the MOSFET switching type.
A “switcher” has a very small transformer, or sometimes just a small inductor instead of a transformer .

THE BOOST CONVERTER

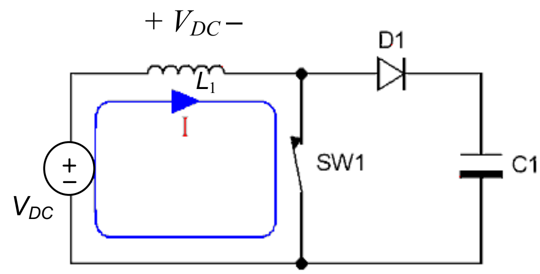
One of the simplest, transformer-free forms of switching power supply is the *boost converter*. Its operation is based on the principle of the inductor, a device that can store magnetic energy. As you (hopefully) recall from circuit theory, inductor behavior is governed by the simple derivative equation $v_L = L\frac{di_L}{dt}$. Thus, if a constant voltage V_{DC} is applied to an inductor, its current will rise linearly with slope $\frac{V_{DC}}{L}$. Such an action charges the inductor with energy stored within its magnetic field:

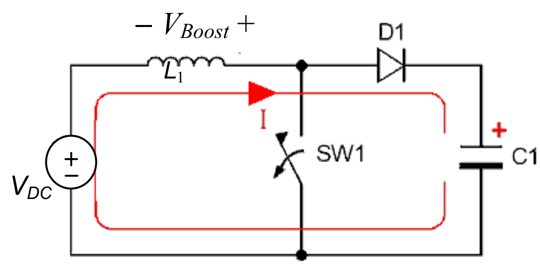




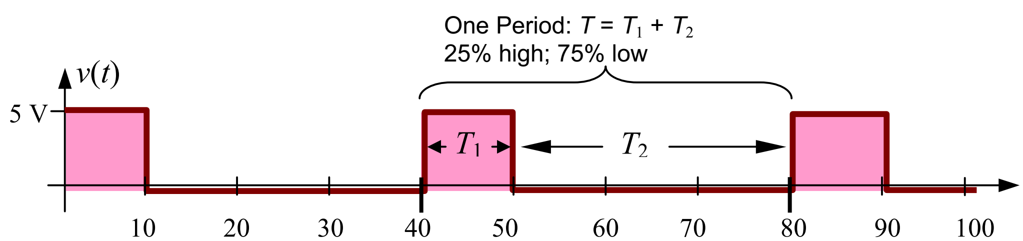
The basic layout of a boost converter is shown below. Properly designed, it has the ability to accept a “raw” dc voltage V_{DC} as its input, then produce a dc output voltage whose voltage is *higher* than V_{DC} (i.e., the voltage is “boosted”). Note that this voltage increase is accomplished without the aid of a step-up transformer.

The operation of the boost converter can be explained as follows. The switch is turned on at a rapid rate (on the order of tens of kilohertz), but at a variable duty cycle (discussed below). When the switch is ON, the current through the inductor increases and the energy stored in the inductor builds up. When the switch is OFF, current through the inductor, though now decreasing, continues to flow via the diode D_1, thus charging the capacitor.





The *duty cycle* is defined as the percentage of time that a periodic square-wave signal is high relative to the total period. This relationship can be summarized by the following exemplary diagram that illustrates a 25% duty cycle:



Example of a 25% duty-cycle, 25-kHz, 5-V square wave voltage (period $T = 40$ µs)

In the case of the boost converter, a square-wave signal of adjustable duty cycle is used to switch the transistor SW_1 between its ON and OFF states.

An important property of the circuit is that, in steady state, any current increase di_L that occurs during the switch ON time must be met by an equal-but-opposite decrease $-di_L$ during the switch's OFF time. Were this condition not met, the inductor current i_L would eventually increase without bound. Given that $di_L = v_L dt$ in general, and also that $v_L = V_{DC}$ during the ON interval, the above requirement can be summarized as follows:

$$V_{DC}T_1 = -v_L T_2 = V_{Boost}\, T_2$$

Here, $V_{Boost} = V_{DC}\,(T_1/T_2)$ becomes a voltage that *adds* to V_{DC} during the OFF interval. This boosting voltage thus charges the capacitor to

$$V_{DC} + V_{DC}\left(\frac{T_1}{T_2}\right) - V_f = V_{DC}\left(1 + \frac{T_1}{T_2}\right) - V_f$$

where V_f is the diode's forward drop. Thus, by changing the duty-cycle ratio T_1/T_2, the voltage across the load can be adjusted to be larger than the source voltage V_{DC}.

REVERSE ENGINEERING

The term *reverse engineering* refers to the process by which an engineer dissects someone else's product to learn how it works. This design method is particularly useful if the goal is to create your own version of a competitor's product using your own technology. Reverse engineering is practiced on a regular basis by companies worldwide. Although it may sometimes appear to be an unfair practice, it can be a good way to avoid infringing on an approach taken by a competitor. Reverse engineering one your own designs can also be good way to understand its operation if its documentation trail has been lost or is inadequate.

One obvious way to reverse engineer something is to take it apart. Reverse engineering in the software realm is common and even encouraged in the arena of the Web. The open-source nature of hypertext mark-up language (HTML) code, upon which Web pages are based, has from its outset fostered an open exchange of information that is still the hallmark of the Internet. One need only select the “view page source” option in any browser to completely reverse engineer someone else’s Web page.

A reverse-engineered iPod. Note the broken screen on the right: a casualty of the disassembly process.

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Open-source HTML code

PROJECT ASSIGNMENTS

Laboratory Goal:	To analyze, reverse-engineer, and design power supply circuits.
Learning Objectives:	Operation of half-wave and bridge (full-wave) rectifiers, voltage regulators, and switching power supplies
Suggested Tools:	Diodes, capacitors, etc, ac transformer, multimeter, oscilloscope, PSPICE.

Level 1: Old Technology

a) Obtain the following 6-V ac-to-dc converter ("power adapter") from your lab TA or from the PHO105 parts counter: Marlin P. Jones AD-6500RDU (*www.mpja.com*) The supply should have already had its cover cut open and reattached with tape or a rubber band. Due to the potential 120-VAC shock hazard, *do not take off the cover* until part (b). Measure the voltage (to three decimal places) versus current characteristic for this supply from zero load up to its rated current of 500 mA. Also measure the peak-to-peak output ripple component versus load current over this same current range. Plot and save your data for part (c).

b) Now, *unplug the adapter from the ac wall outlet,* and take off the plastic cover. Using **non-destructive** methods, reverse engineer the supply. Specifically, determine and draw the circuit diagram for the supply, labeling the values of all parts plus the part numbers of any semiconductor components.

c) Look up the characteristics of the various parts in the supply, then use PSPICE to show that your recorded results from part (a) are consistent with the intended function of the power supply. Specifically, show that your *v-i* ripple-versus-load current measurements are, in fact, predicted by your reverse engineered circuit model.

Level 2: New Technology
Using the 33-mH inductor contained in your parts kit, design a boost converter that accepts 5-V dc as its input and produces an output in the range 8 V to 12 V. (Pick a target value of 10 V for a 50% duty cycle, then experiment with varying the latter.
Notes:

- We *highly* suggest that you simulate your design in PSPICE before attempting to build it.
- You can derive a square wave of variable duty cycle using the HP waveform generator on your bench. You must set the dc offset to half the value of the peak-to-peak voltage value.
- Choose a 1-MΩ resistor for your load. In order to drive higher currents, you would preferably need a larger inductor than the solitary value included in your electronics kit.
- Choose a filter capacitor that is not too small (so that ripple will be minimal) but not too large (thereby being too difficult to charge.)
- A PN2222 or 2N2222 transistor can be used for the switch, but it will require a current limiting resistor between the square wave source and ground. Any of the n-channel MOSFET devices in your kit can also be used for the switch SW_1.

Level 3: Modern Technology, Part II
Using the same principles applicable to Level 2, design and build a *buck converter* that produces an output voltage of 1 to 3 V for a 5-V dc input.