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Considerations in Designing the Printed Circuit Boards of Embedded Switching Power Supplies

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1. Introduction

The importance of a good printed circuit board (PCB) layout in switching power supplies cannot be overstated. Developing the schematic and debugging the breadboard is a good start, but the final, critical challenge is to layout the PCB. Fortunately, understanding the phenomenon behind the operation of the typical switching power supply makes the effort much easier.

2. Discussion

The primary rule for the designer is to be involved with every aspect of the design of the switching power supply, including the PCB. He or she is the only person who best understands the functional requirements of the power supply within the final product. In doing this, the power supply designer should never allow a PCB designer to use the auto-routing routines within the PCB layout program. The autorouter routine only strives to connect nodes that utilize the same signal as stated in the netlist. It disregards the length of the traces needed to accomplish this. The autorouter also considers all grounds the same signal and connects them together without consideration of the actual types of signals running through certain traces. For the power supply designer and the PCB designer to execute a good PCB layout, knowing the signals that flow between components is very important.

Appreciating the subtle "black magic" aspects to the PCB layout is essential to the success of the product. These layout factors can affect the performance of the switching power supply and can also affect the product's ability to be released into the market. The aspects of the product's opera-tion that affect the printed circuit board design are: radiated electromagnetic interference (radiated EMI), conducted EMI, power supply stability, efficiency and operational longevity.   The two forms of EMI are tested by regulatory approval bodies such as UL, IEC, and numerous other regulatory bodies throughout the world. The product must pass these stringent EMI tests before it can be sold into its respective market. The remaining factors affect the product's basic operation and customer satisfaction.
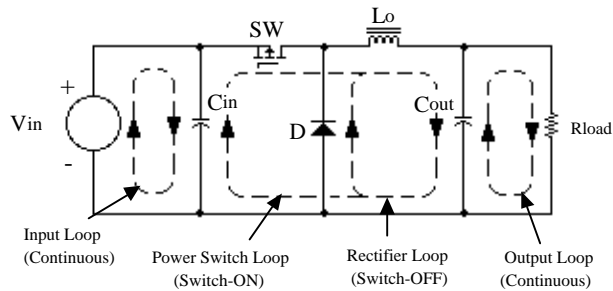
3. Current Loops

Switching power supplies have large current pulses with very sharp edges flowing within the power supply circuit. These large current pulses have the greatest effect on the creation of EMI, and should be the primary focus of the PCB designer. These currents flow in definable "loops" and the circuits carrying these currents should be laid-out first. The low-level control circuitry is then subsequently coupled into specific spots in the layout. These loops are diagrammed in figure 1 for the three major basic topologies of switching power supplies. All of the other topologies are varia-tions of these three.

The loops shown in figure 1 can be listed in the order of their greatest affect on noise generation and operational performance:

      1. The power switch high current loop.
      2. The rectifier high current loop.
      3. The input source loop.
      4. The output load loop.

+The input source and output load current loops are filtered by input and output EMI filters (not shown). Their currents are composed of largely DC current. The AC components of these currents are created by the power supply and should be kept to a minimum. These AC components are the elements that make-up conducted EMI. Any AC energy that is allowed to pass over a long enough length of a conductor, is radiated into the product's environment.

The input and output loops are of secondary concern because the large AC pulses seen inside the supply are filtered by the input filter and output filter capacitors respectively. This makes their potential for creating high frequency noise problems less than the two AC loops. These loops should be analyzed later since they are directly measured by the regulatory agencies. The power switch and rectifier current loops are entirely AC, or more appropriately, pulsating DC. They have trapezoidal current waveforms with high peak currents and very sharp edges (di/dt).

a. Buck Converter
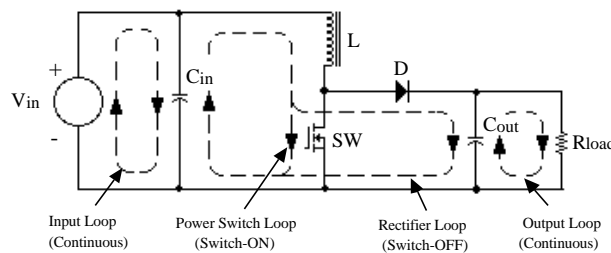
b. Boost Converter
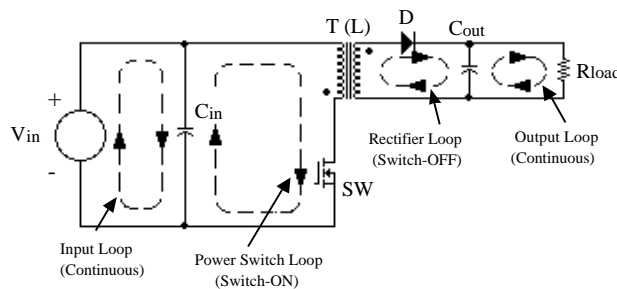
c. Transformer Isolated Converters

Figure 1. The Major Current Loops within Switching Power Supply Topologies

Some representative waveforms can be seen in figure 2. PWM switching power supplies operate in one of these two modes: the *discontinuous-mode*, as seen in figure 2A, and the *continuous-mode* as seen in figure 2B. The discontinuous-mode is when the output rectifier(s) is allowed to completely empty the magnetic element of its magnetic energy before the power switch once again turns-on. The continuous-mode is when some residual energy is allowed to remain in the magnetic element when the power switch begins to turn-on for the next cycle. The current flowing at the end of each period is rapidly interrupted by high speed switches which result in very high di/dt transitions.

I_{SW}

I_D

2a. Discontiuous-mode

I_{SW}

I_D
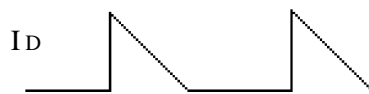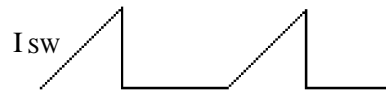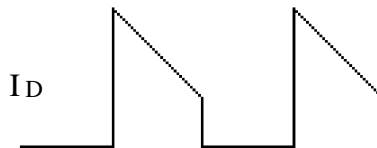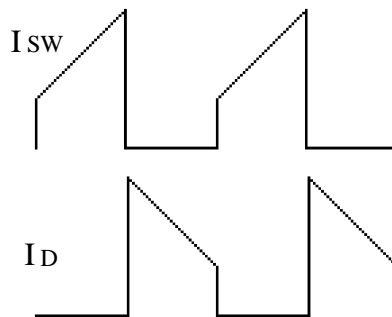
2b. Continuous-mode

Figure 2. The Modes of Operation of Switching Power Supplies

Simultaneously, there are also high rates of dV/dt occurring on these signals. This creates high periodic power impulses which are rich in high frequency components. The power switch and rectifier loops, as a result, are very "noisy" and deserve extraordinary attention. The input power switch loop flows between the input filter capacitor (C_{in}), through the primary winding of the transformer (or inductor), to the power switch and back through the ground to the input capacitor. The rectifier loop flows between the secondary winding of the transformer (or output of the inductor), through the rectifier to the output filter capacitor (C_{out}), and returns through the ground to the transformer or inductor. There is always a filter capacitor comprising part of both loops because the capacitors are the only local source or sink of the high-frequency current needed by the switching power supply. The input source and output load current loops can be viewed as low frequency currents that charge or discharge the input and output filter capacitors respectively, at a virtual DC rate.

The power switch loop and the output rectifier loop(s) should be laid out so that the "loop" has a very small circumference and is composed of traces that are short in length and wide in width. First, the circumference of the loop controls the amount of RF energy that can be radiated at lower frequencies where a significant amount of conducted RF energy exists. By making the loop circumference as short as possible, one does not provide an efficient antenna for these lower noise frequencies. A typical power supply conducts noise frequency components that remain very high until about 100 times the switching frequency and then fall at a rate of between -20 to -40 dB per decade. The lower the frequency a loop is allowed to radiate, the more energy is allowed to escape into the environment. Secondly, the width of the traces used within the high current loops directly dictate the amount of voltage drop which will appear around the loop. This voltage drop, when created by high current, also creates RF radiation. The inductance and resistance exhibited by a trace is inversely proportional to its width. Inductance lowers the frequency response of a loop and therefore is a more efficient antenna at lower frequencies. So the loop traces should be as wide as possible. Wide traces also provide better heatsinking for the power switch and rectifier(s). An example of a layout for the power switch and rectifier loops in a buck converter is shown in figure 3. Notice the very short distances between all members of the two main AC loops.
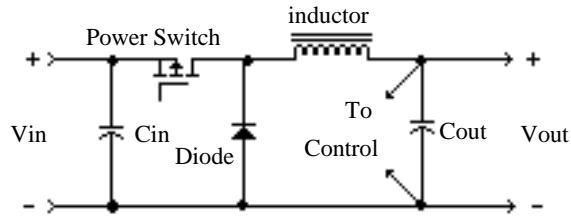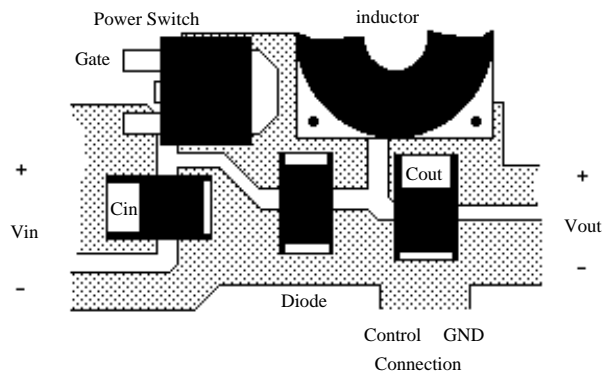

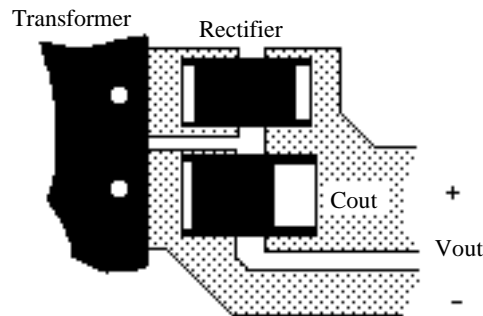Schematic.

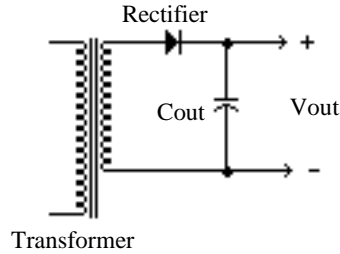Figure 3. Example layout for a Buck Converter Power Stage

Figure 4. Example Layout for a Transformer-isolated Output

The output rectifier loop in transformer-isolated topologies have the same layout requirements as the input power switch loop. An example layout for the rectifier loop within a flyback converter can be seen in figure 4.

4. Paralleled Capacitors.

Paralleling capacitors is a common technique for lowering the overall equivalent series resistance (ESR) and equivalent series inductance (ESL) of a filter capacitor. This allows the resulting filter capacitor to source or sink higher levels of ripple current with much less internal heating. Here, the PC board layout has a direct affect upon how much "sharing" occurs in the current and heating of the paralleled capacitors. The physical characteristics of the PCB layout between the other components in the loop and each capacitor must be as identical as possible. If the layout is not identical, the capacitor with the lower series trace impedance will see higher peak currents and become hotter (i^2R). To promote this sharing, there should be a form of layout symmetry to both leads of the capacitors. Once again the traces between the components within the loop should be as short and wide as possible. Any parasitic impedance that is introduced by the layout effectively isolates the capacitor from the loop. This makes the high frequency current pulses seek other sources or sinks outside the loop. This creates more conducted EMI when the high current pulses are allowed to escape from the loop and enter the external circuitry.   Examples of layouts for paralleled capacitors can be seen in figure 5.
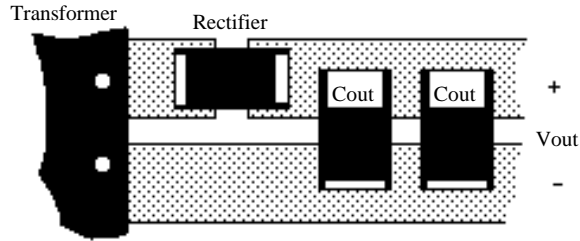
a. non-optimal layout.
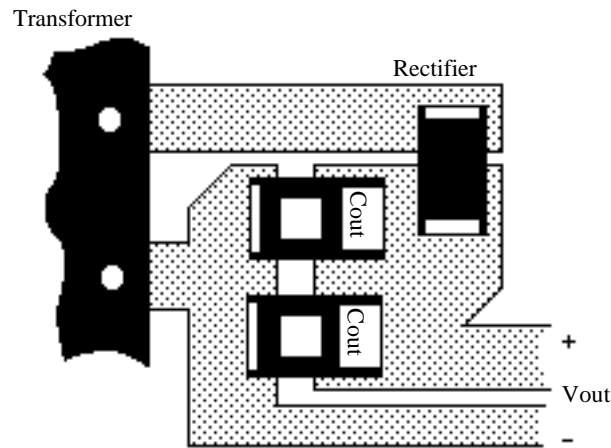
b. better layout.

Figure 5. Laying out Parallel Capacitors

5. Grounds

The grounds within a switching power supply are considered separately, even though they make-up one leg of the high current loops previously discussed. They are special in that they represent the lowest potential return path for the currents and the potential from which all other signals are measured. They have both DC and AC signals being conducted between various points in the physical ground system. There are sections of the ground system that should be considered separately from one another. If these grounds are interconnected improperly, the power supply can become unstable.
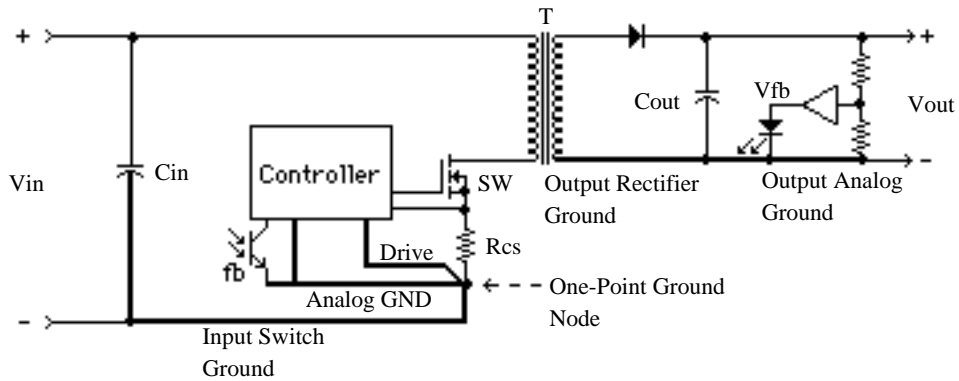
There are three grounds within a switching power supply: 1. the input high-current ground, 2. the output high-current ground and 3. the low-level control ground. The grounds for the three major switching power supply topologies are shown in figure 6.
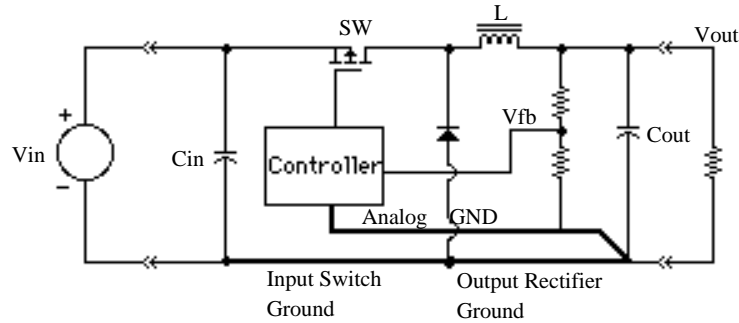
a. The Buck Converter
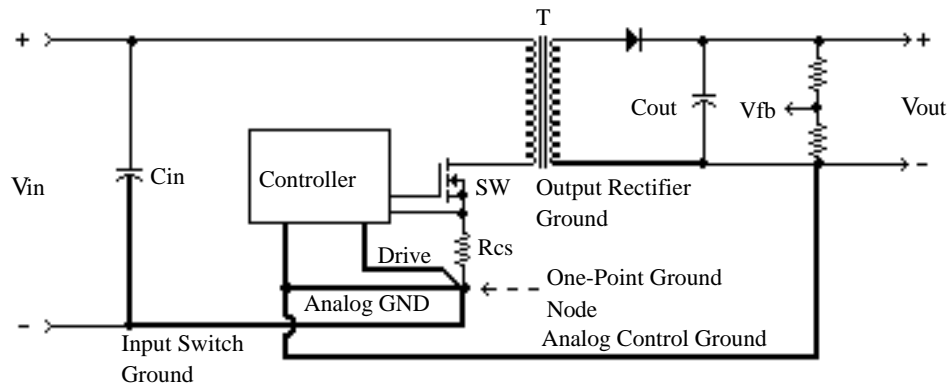
b. Non-isolated, Transformer-based Topologies.

c. Isolated, Transformer-based Topologies

Figure 6. Ground Arrangements for various Topologies

As one may notice from the diagrams in figure 6, the connection of the low-level control ground to the overall grounding system is very specific. The first factor to understand is that the power supply controller's main purpose is to precisely regulate the output voltage. To do this, the high-gain error amplifier should be directly connected to the bottom of the output filter capacitor. In this way, noise voltages from the high current loops are not summed into the low-level sense signals. Secondly, the controller usually needs to sense a small signal across a current sensing resistor as well as drive the gate or base of a power switch.

If there are separate analog and power ground pins on the controller IC, they should be routed separately to the ground side of the current sensing resistor. If the IC does not have separate ground pins, then the trace between the IC and the ground end of the current sense resistor should be short and wide.

Another good practice to reduce radiated EMI is to place large areas of ground plane on the opposite side of the PCB and around these high current traces. The ground planes act as electrostatic shields for some of the RF energy already radiated. These large conductor areas trap radiated EMI and dissipate them within eddy currents created by the RF energy.

One last and very important factor in designing PCB layouts for switching power supplies is the capacitive coupling of the AC node voltages into their heatsinks or into nearby ground planes. The problem is very severe in through-hole designs, but can also be a problem in surface-mount applications.

The problem is created by the high AC voltages that appear on specific nodes within the switching power supply. Examples of these nodes are the drain connection of the power switch, the AC node connected to an output rectifier, and any snubber or clamp networks connected to these nodes.

In through-hole applications, the power switch is typically a power package with a tab which is bolted to a heatsink with a 5 mil (0.005 inch, 0.13 mm) insulator between them. The drain tab of the power switch has AC peak-to-peak voltages of either one or two times the input voltage. In many supplies, the heatsink is earth grounded which provides a path for the capacitively coupled noise energy to exit the enclosure. Insulator makers have pads that have embedded foil which cuts the capacitance in half.

The problem is less significant in surface-mount applications since the capacitance formed by 0.062 inch (1.6 mm) thick F4 material is much smaller. Additionally, it is rare that earth ground is brought onto the PCB, but the noise could couple into other sensitive signals. The goal is to reduce this parasitic capacitance by creating PCB structures that exhibit low capacitance, such as locating susceptable signals one the same side instead of underneath the noisy node or cross-hatching any ground planes beneath the noisy node.

7. The EMI Filter Layout

Now is the appropriate time to consider the layout of the EMI filter. An EMI filter is needed anytime a power lead or leads are allowed to exit the product's enclosure, which hopefully also provides some RF shielding. These filters are intended to reduce, but cannot completely eliminate, the high frequency currents conducted within the DC input and/or output wiring. Conducted EMI is tested by the regulatory bodies by placing a special cur-rent transformer (a line impedance stabilization network (LISN)) in series with the input and/or output power lines. The tester then plots the spectrum of the emerging current waveform from DC to over 1 GHz. The product under test must emit a current spectrum lower than the specified limits at all frequencies.

The filters are designed to not pass the high frequency noise created by the PWM switching power supply. If the parasitic factors of the filter components themselves are not well known and the components are not laid-out properly, some switching energy can couple around the filter components to traces on the other side of the filter. This allows some of the high frequency energy to escape into the environment or into the rest of the system. Once in the external wiring, this conducted RF energy will then radiate into the surrounding environment as radiated EMI.

Some good guidelines are to place the EMI filter as close as possible to the point where its signal exits the enclosure. The layout of the actual EMI circuitry should also be as close to "in-line" as possible. "Zig-zaging" the layout can cause input and output traces to be in close proximity to each other, thus promoting inductive coupling.

Example Printed Circuit Board Designs

The design examples are those of DC/DC power supplies which are usually part of a larger printed circuit board. They generally are powered from an external AC/DC power supply. Therefore the following examples are designed as layouts, that are part of a larger PCB not bounded by edges of a PCB.

The primary focus of the following PCB examples is that of the physical PCB design. The examples have not been built and debugged. Sub-circuits such as snubbers and clamps may need to be added to make the designs practical.

The buck (step-down) converter:

This design example would provide an output voltage of 3.3 VDC and can deliver up to 3 Amps to a load. It is powered from a 12 volt battery pack or from a wall transformer. The input voltage may go as high as 30 VDC which makes it applicable for many portable applications such as notebook computers. This circuit may be easily"scaled" to operate at different input voltages or to deliver a different output voltage or maximum current. The semiconductors, filter capacitors, the inductor, and obviously the PCB layout would have to be modified to operate optimally for any new requirements.

Specifications

Input Voltage: +5V - +30 VDC
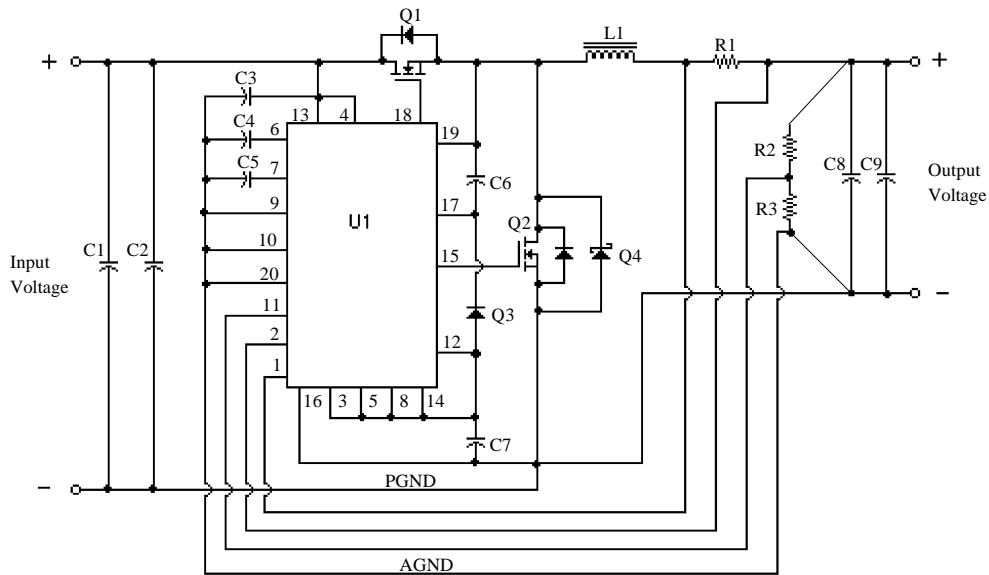Output Voltage: +3.3V +/- 2 %
Maximum output current: 3 Amps

Figure 7. Schematic of the Buck (Step-down) Converter

Parts List for the Buck Converter in Figure 7:

| Designation	Mfr	Part No.	Value	Rating	Package
C1	Sprague	593D226X0035E2W	22uF	35V	E-case
C2	Sprague	593D226X0035E2W	22uF	35V	E-case
C3	Mepco	C105M1206ZFLB	0.1uF	50V	1206
C4	Mepco	C102M0805ZFLB	1nF	50V	805
C5	Sprague	293D155X0010A2T	1.5uF	10V	A-case
C6	Mepco	C102M0805ZFLB	1nF	50V	805
C7	Sprague	293D475X0010B2T	4.7uF	10V	B-case
C8	Sprague	594D227X0010D2T	220uF	10V	D-case
C9	Sprague	594D227X0010D2T	220uF	10V	D-case
L1	Coilcraft	DO3316-103	10uH	3.8A	Custom
Q1	Fairchild	FDS4410	-	10A,30V	SO8
Q2	Fairchild	FDS4410	-	10A,30V	SO8
Q3	Fairchild	MMBD914	-	0.1A,100V	SOT23
Q4	Fairchild	MBRS130L	-	1A, 30V	SMC
R1	Dale	WSL-2010-R020F	20mý	1%	2010
R2	Dale	CRCW08052211FB02	2.11K	1%	805
R3	Dale	CRCW08051101FB02	1.10K	1%	805
U1	MAXIM	MAX1636	-		SO20-W
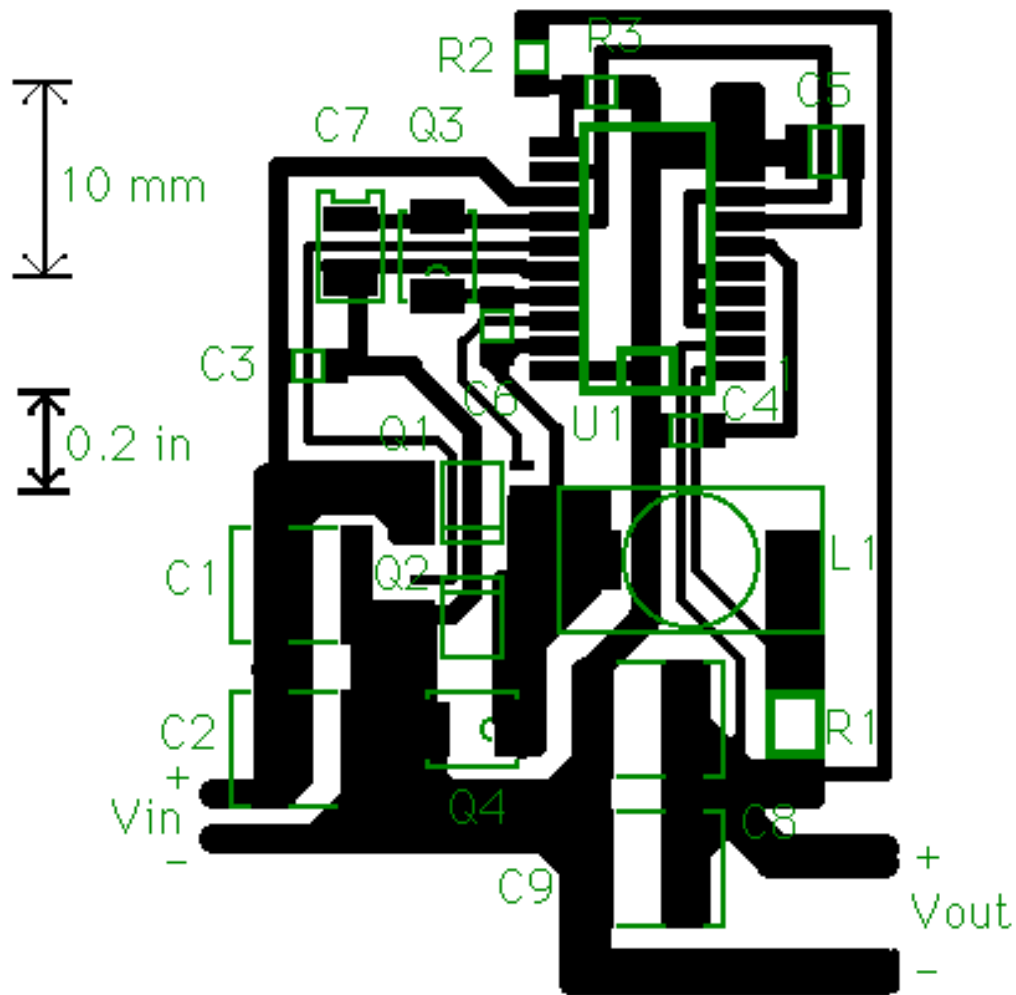
Figure 8. PCB Layout for the Buck Converter

The boost converter
This design example derives its input power from a +5V logic supply and could provide power to any associated analog functions or interface circuits. Once again, the design can be scaled.

Specifications

Input Voltage: +5V - 7 VDC
Output Voltage: +12V +/- 2 %
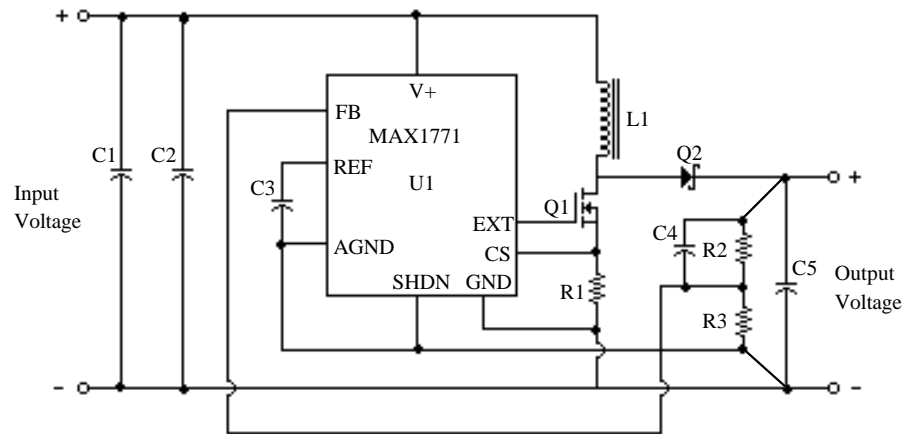Maximum output current: 0.5 Amps

Figure 9. Boost (Step-up) Converter

Parts List:

| Designation	Mfr	Part No.	Value	Rating	Package
C1	Sprague	293D107X0010D2T	100uF	10V	D-case
C2	Mepco	C105M1206ZFLB	0.1uF	50V	1206
C3	Mepco	C105M1206ZFLB	0.1uF	50V	120
C4	Mepco	C101M0805ZFLB	100pF	50V	805
C5	Sprague	293D686X0016D2T	68uF	16V	D-case
C6	Sprague	293D686X0016D2T	68uF	16V	D-case
C7	Sprague	293D686X0016D2T	68uF	16V	D-case
L1	Coilcraft	DO3316-223	22uH	2.6A	Custom
Q1	Fairchild	FDS6612	-	8.4A,30V	SO8
Q2	Fairchild	MBRS130L	-	1A, 30V	SMB
R1	Dale	WSL-2010-R040F	40mý	1%	2010
R2	Dale	CRCW08051273FB02	127K	1%	805
R3	Dale	CRCW08051822FB02	18.2K	1%	805
U1	MAXIM	MAX1771	-	17V(max)	SO8
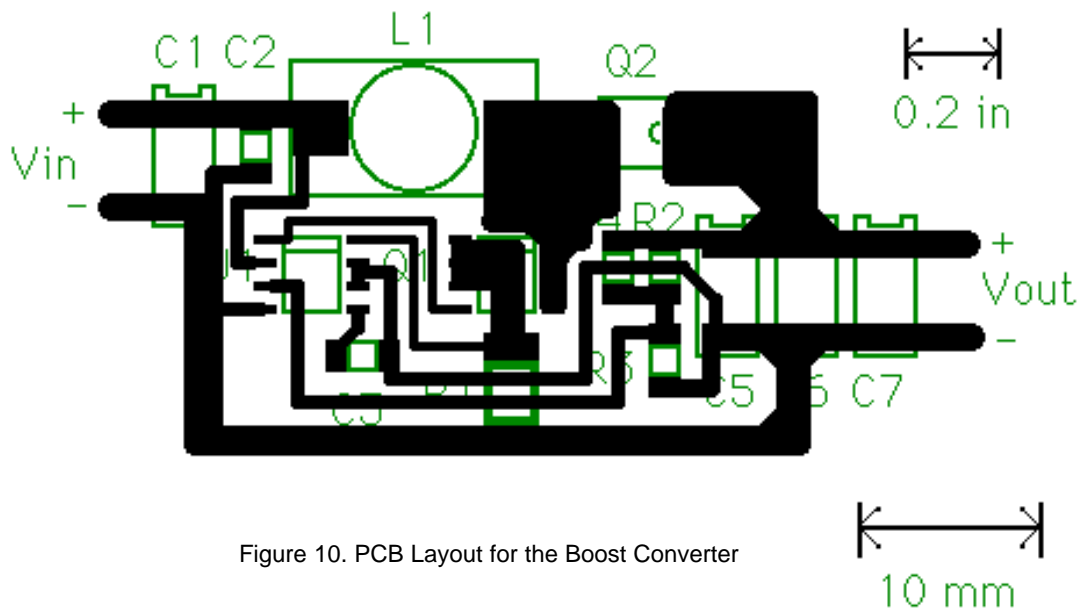
Figure 10. PCB Layout for the Boost Converter

The flyback converter

This flyback converter can be used as a step-up, step-down and/or an inverting power supply. Its transformer is more complicated to design, but its added cost can be recovered considering the flyback converter can replace two or more buck or boost supplies within a system.

Specifications

Input Voltage: +5V - +24 VDC
Outputs: +5V +/- 2 % at 0.75A (max)
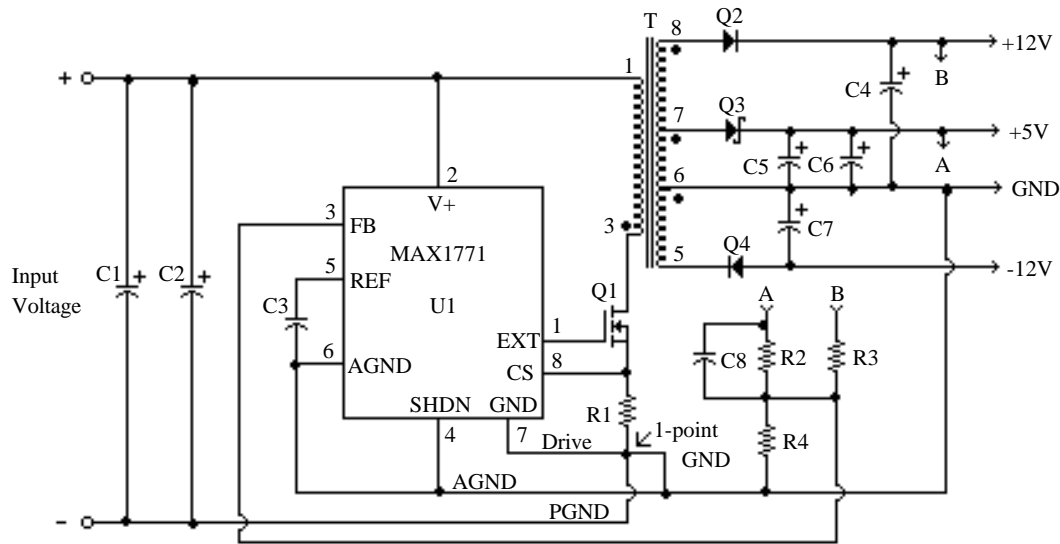 +12V +/- 5% at 0.25A (max)
  -12V +/- 8% at 0.25A (max)

Figure 11. A Flyback Converter

Parts List for the flyback converter in figure 11:

| Designation	Mfr	Part No:	Value	Rating	Package
C1	Sprague	293D107X0010D2T	100uF	10V	D-case
C2	Sprague	293D107X0010D2T	100uF	10V	D-case
C3	Mepco	C105M1206ZFLB	0.1uF	50V	1206
C4	Sprague	293D686X0016D2T	68uF	16V	D-case
C5	Sprague	594D227X0010D2T	220uF	10V	D-case
C6	Sprague	594D227X0010D2T	220uF	10V	D-case
C7	Sprague	293D686X0016D2T	68uF	16V	D-case
C8	Mepco	C101M0805ZFLB	100pF	50V	805
L1	Philips	EFD10-core	-	-	Custom
Q1	Fairchild	FDS4410	-	10A,30V	SO8
Q2	Fairchild	MBRS140	-	1A,40V	SMB
Q3	Fairchild	MBR340	-	3A, 40V	SMC
Q4	Fairchild	MBRS140	-	1A,40V	SMB
R1	Dale	WSL-2010-R010F	10mý	1%	2010
R2	Dale	CRCW08055622FB02	56.2K	1%	805
R3	Dale	CRCW08054023FB02	402K	1%	805
R4	Dale	CRCW08051822FB02	18.2K	1%	805
U1	MAXIM	MAX1771	-		SO8
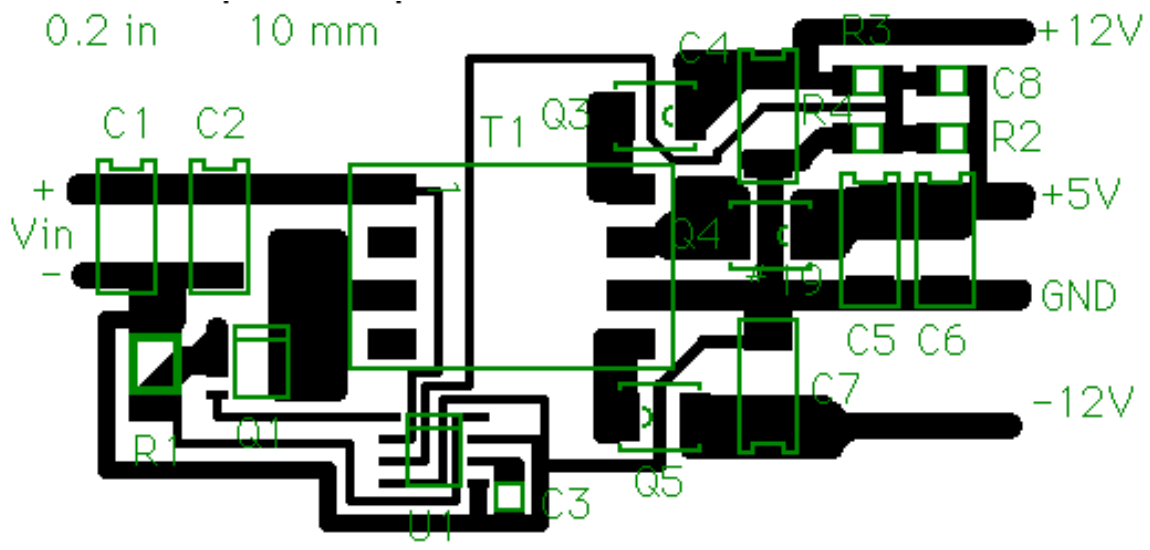
Figure 12. PCB Layout for a flyback converter

References

1.   Brown, Marty, *Power Supply Cookbook*, Butterworth-Heinemann, 1994, pp 89-94, 224, 216-225.

2.   Brown, Marty, *Practical Switching Power Suppy Design*, Academic Press, Inc., 1990, pp 115-119, 125-128.

3.   Linear Technology, Linear View v2.0, CD, Linear Technology Corp. 1997.

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FASTr™	SuperSOT™-6	
GTO™	SuperSOT™-8	
HiSeC™	TinyLogic™	

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