

Low Cost Boost Converters Using LM3578A

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ABSTRACT

The LM3578A integrated circuit is a switching regulator with all the power, control, and protection features. It operates over a wide input voltage range. This together with its low-cost makes it a very popular choice for use in switching regulators. This paper will present several low cost boost converter circuits developed using the LM3578A switching regulator. The operation and the design of the boost converter will also be discussed in detail.

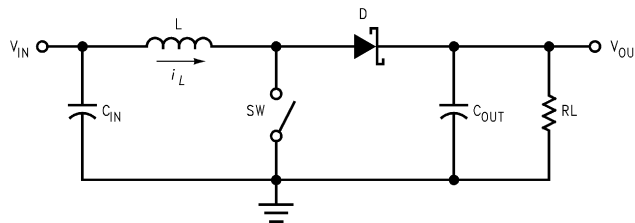
1. INTRODUCTION

The Boost or Step-up converter converts a DC voltage to a higher DC voltage. Figure 1 shows the basic boost topology. When the switch SW is turned on, energy is stored in the inductor L and the inductor current i_L ramps up at a slope determined by the input voltage. Diode D is off during this period. Once the switch, SW, turns off, diode D starts to conduct and the energy stored in the inductor is released to the load. Current in the inductor ramps down at a slope determined by the difference between the input and output voltages.

Modes of Operation

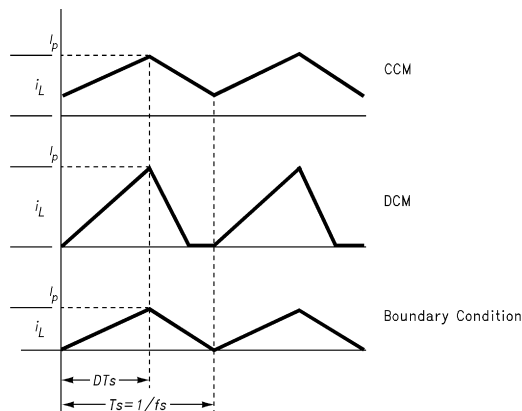
Based on the amount of energy that is delivered to the load during each switching period, the boost converter can be classified into continuous or discontinuous conduction mode. If all the energy stored in the inductor is delivered to the load during each switching cycle, the mode of operation is classified as discontinuous conduction mode (DCM). In this mode, the inductor current ramps down all the way to zero during the switch off-time. If only part of the energy is delivered to the load, then the converter is said to be operating in continuous conduction mode (CCM). Figure 2 shows the inductor current waveforms for all the modes of operation.

The mode of operation is a fundamental factor in determining the electrical characteristics of the converter. The characteristics vary significantly from one mode to the other.



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FIGURE 1. Basic Boost Topology



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FIGURE 2. Inductor Current (i_L) Waveforms

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Continuous versus Discontinuous Mode

Both modes of operation have advantages and disadvantages. The main disadvantage in using CCM is the inherent stability problems (caused by the right-half-plane zero and the double pole in the small-signal control to output voltage transfer function). However, the switch and output diode peak currents are larger when the converter is operating in discontinuous mode. Larger peak currents necessitate using power switch and output diode with larger current and power dissipation ratings. Larger peak currents also force the designer to use larger output capacitors. The larger peak currents also cause greater EMI/RFI problems.

The mode of operation can be selected by the user. For very low load currents, discontinuous mode is preferred over continuous mode. If the load current requirements are high, then in order to minimize the peak currents and the associated problems, continuous mode is preferred. Two of the circuits presented in Section 3 have very low load current requirements. Hence, they have been selected to operate in discontinuous mode. The third circuit has very high peak current requirements and is selected to operate in continuous mode.

2. SELECTION OF BOOST POWER STAGE COMPONENTS

The boost converter design involves the selection of the inductor, the input and output capacitors, the power switch (included in the LM3578A), and the output diode. In order to select these components, it is necessary to know the duty cycle range and the peak currents.

Knowing the maximum and minimum input voltages, the output voltage, and the voltage drops across the output diode and the switch, the maximum and minimum duty cycles are calculated. Next, the average inductor current can be estimated from the load current and duty cycle. Now, assuming the peak to peak inductor current ripple to be certain percentage of the average inductor current ripple, the peak inductor current can be estimated. The inductor value can be calculated using the ripple current, switching frequency, input voltage, and duty cycle information. Finally, it is necessary to establish the boundary condition, i.e. the critical value of the inductor below which the converter will operate in discontinuous mode.

Once the inductor value has been chosen and the peak currents have been established, the other components can be selected very easily. The following paragraphs outline the selection of the boost power stage components, in a step by step approach.

Selection of the Boost Inductor

STEP 1: Given the maximum and minimum input voltages, the maximum and minimum duty cycles can be calculated using the following equations:

$$D_{max} = \frac{(V_o + V_d - V_{in(min)})}{(V_o + V_d - V_{ce(sat)})} \quad (1)$$

$$D_{min} = \frac{(V_o + V_d - V_{in(max)})}{(V_o + V_d - V_{ce(sat)})} \quad (2)$$

In equations (1) and (2), V_o is the output voltage, V_d is the forward voltage drop of the output diode D, and $V_{ce(sat)}$ is the on state voltage of the switch, SW. $V_{in(max)}$ and $V_{in(min)}$ are the maximum and minimum input voltages respectively.

STEP 2: The average inductor current (maximum) can be calculated using the output current, I_o as follows:

$$I_{L(avg)} = \frac{I_o}{1 - D_{max}} \quad (3)$$

STEP 3: Assume the peak to peak inductor current ripple, ΔI_L to be a certain percentage of the average inductor current calculated in equation (3). The peak inductor current is then given by:

$$I_p = I_{L(avg)} + \frac{\Delta I_L}{2} \quad (4)$$

STEP 4: Knowing the switching frequency, f_s the required inductance value can be selected using the equation:

$$L_{(min)} = \frac{(V_{in(min)} - V_{ce(sat)}) D_{max}}{f_s \Delta I_L} \quad (5)$$

STEP 5: Calculate the boundary condition, i.e., the minimum inductance required to operate the inductor in continuous mode.

At the boundary between CCM and DCM modes of operation, the peak inductor current, I_p is same as the peak to peak inductor current ripple, ΔI_L , as shown in Figure 2. Hence, the average inductor current is given by:

$$I_{L(avg)} = \frac{I_p}{2} \quad (6)$$

Using equations (3) and (6)

$$I_p = \frac{2I_o}{1 - D_{max}} \quad (7)$$

The critical value of the inductance to maintain the converter in continuous mode of operation, derived from equations (5) and (7) is given by:

$$L_{(crit)} = \frac{(V_{in(min)} - V_{ce(sat)}) D_{max} (1 - D_{max})}{2 f_s I_o} \quad (8)$$

Using an inductance value lower than the critical value will result in discontinuous mode of operation. It can also be observed from equations (5) and (8) that increasing the switching frequency helps in reducing the size of the inductor.

Selection of Power Switch

The power switch is internal to the LM3578A. In general, it is necessary to ensure that the estimated peak switch current (which is nothing but the peak inductor current, I_p calculated above) does not exceed the rated current of the switch. It is also necessary to ensure that the off-state voltage rating of the switch is never exceeded. The internal transistor in the LM3578A switching regulator is rated for a peak current of 750 mA. The off-state sustaining voltage of the internal transistor is 50V.

Selection of the Output Capacitor

In the boost converter, the instantaneous value of currents entering and exiting the output capacitor is very high, since there is no inductive element between the output diode and the capacitor. This high current flows through the equivalent series resistance (ESR) and equivalent series inductance (ESL) of the capacitor. ESR increases the capacitor tem-

perature and increases ripple voltage. ESL adds sharp spikes to the ripple voltage waveform. Hence, it is desired to use output capacitors with very low ESR and ESL.

The peak to peak output ripple voltage, ΔV_o , is given by

$$\Delta V_o = \frac{I_{o\max}(1 - D_{\min})}{f_s C_o} + I_p R_{esr} \quad (9)$$

where $I_{o\max}$ is the maximum output current. The output capacitor, C_o can be selected using the above equation. It should be noted that the ripple voltage due to the ESR, (R_{esr}) is dominant in equation (9). Also, ESL will add sharp spikes over the ripple voltage given by equation (9). The ESR of the selected capacitor can be determined from the manufacturer catalogs or by actual bench measurement. If the value of the ripple exceeds the desired ripple voltage, then there are two choices- paralleling two or more capacitors to lower the effective ESR and ESL, or using a secondary LC filter. In general, low values of ESR are achieved by using large value capacitors or by paralleling smaller value capacitors. (Note: Tantalum capacitors are known to have very low ESR. But they are expensive when compared to electrolytic capacitors.)

Selection of the Input Capacitor

In boost switching regulators, triangular ripple current is drawn from the supply voltage due to the switching action. This appears as noise on the input line. This problem is less severe in boost converter due to the presence of inductor in series with input line. Select the input capacitor for

$$I_{rms} = \frac{I_p}{\sqrt{12}} \quad (10)$$

From equation (10), it can be observed that the rms current value is very low. Hence, a very small value capacitor is sufficient for boost converters.

Selection of the Output Diode

As in all switching power supplies, two factors govern the choice of output rectifier—the forward voltage drop, V_F , and the reverse recovery time, t_{rr} . V_F determines the forward conduction loss and should be as low as possible. The reverse recovery time of the diode (and also the forward recovery time) should be as low as possible for minimizing the switching losses and RFI problems. Schottky rectifiers have very low forward voltage drops and reverse recovery times.

The maximum reverse bias voltage on the output rectifier is given by:

$$V_r = V_o - V_{ce(sat)} \quad (11)$$

Select a Schottky diode satisfying the reverse voltage and peak current ratings given by equations (4) and (11) respectively.

3. LOW COST BOOST CONVERTERS

This section will present several low-cost boost circuits based on the LM3578A switching regulator. The LM3578A IC is a switching regulator featuring an internal comparator, oscillator, protection circuitry and a transistor. This IC operates from supply voltages ranging from 2V to 40V. This wide supply voltage range, together with its low cost makes it very popular. The transistor internal to LM3578A can handle currents only up to 750 mA. However, for higher load current requirements, this internal transistor can be used to drive an external transistor with higher current rating such as the npn transistor, D44C3A.

(a) Voltage Doubler Circuit

Figure 3 shows a low-cost voltage doubler circuit used typically in the RF card of a cable modem. This converter uses the LM3578A switching regulator for performing the required power conversion. The inductor and other power stage components are selected using the procedure discussed in Section 2. The converter specifications are as follows:

Input Voltage, $V_{IN} = 12V$

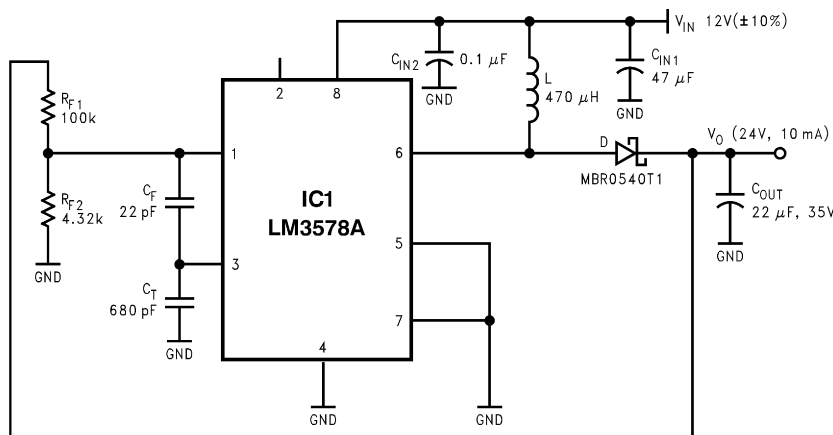
Output Voltage $V_{OUT} = 24V$

Load Current $I_L = 10 \text{ mA (max.)}$

Switching Frequency, $f_s = 100 \text{ kHz}$

Since the load current requirements are very low, this converter is chosen to operate in discontinuous conduction mode. The output voltage is maintained at 24V by the feedback network consisting of the resistors, R_{f1} and R_{f2} . The reference pin (pin 1) is set at 1V using these resistors. Capacitor C_{IN2} is needed to ensure low noise at the input.

The switching frequency is set by using the timing capacitor C_T . Choosing a value of 680 pF for C_T sets the switching frequency at 100 kHz. Capacitor C_1 (typically between 10-25 pF), together with the feedback resistors (R_{F1} and R_{F2}), is used for compensation. For more details on the choice of the above components, please refer to the data sheet for LM3578A.



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FIGURE 3.

Parts List

Designator	Value/Rating	Description
IC1	—	LM3578M, Switching Regulator
D	40V, 0.5A	MBR0540T1, Output Diode
L	470 μ H, 60 mA	Boost Inductor
C _{IN1}	47 μ F, 16V	Input Capacitor
C _{IN2}	0.1 μ F, 50V	Input Capacitor (Ceramic)
C _{OUT}	22 μ F, 35V	Output Capacitor
R _{F1}	100k	Feedback Resistor
R _{F2}	5k	Feedback Resistor
C _F	22 pF	Feedback Capacitor
C _T	680 pF	Timing Capacitor, Sets the Switching Frequency

(b) Boost Converter for Wide Band Tuners

Figure 4 shows a 5V to 27V boost converter used typically to create a high voltage for wide band tuners. Wide band cable and DSS tuners require about 27V at 5 mA load current to bias the VCO varactor. The converter specifications are as follows:

Input Voltage, $V_{IN} = 5V$

Output Voltage, $V_{OUT} = 27V$

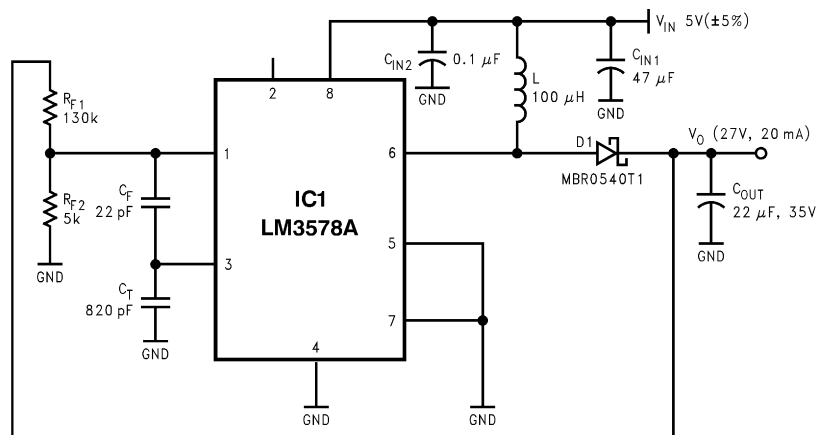
Load Current $I_L = 20$ mA (max.)

Switching Frequency, $f_s = 90$ kHz

Input Ripple Voltage: 17 mV

Output Ripple Voltage: 58 mV

The design of this circuit is very straightforward and is very similar to the design of the voltage doubler circuit discussed above. As in previous case, since the load current requirements are very low, this converter is chosen to operate in discontinuous conduction mode. The feedback resistors (R_{F1} and R_{F2}), the timing capacitor, C_T and the compensation capacitor, C_C are chosen in the same way. In order to ensure low noise at the input, it is essential to add a high-frequency ceramic capacitor C_{IN2} at the input rail, as shown in Figure 4.



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FIGURE 4.

Parts List

Designator	Value/Rating	Description
IC1	—	LM3578M, Switching Regulator
D	40V, 0.5A	MBR0540T1, Output Diode
L	100 μH, 100 mA	Boost Inductor
C _{IN1}	47 μF, 10V	Input Capacitor
C _{IN2}	0.1 μF, 10V	Input Capacitor (Ceramic)
C _{OUT}	22 μF, 35V	Output Capacitor
R _{F1}	130k	Feedback Resistor
R _{F2}	5k	Feedback Resistor
C _F	22 pF	Feedback Capacitor
C _T	820 pF	Timing Capacitor, Sets the Switching Frequency

(c) Low Cost Boost Circuit for I/O Cards

Figure 5 shows a low cost boost converter which converts a 3.3V input to 5V at 600 mA load current. This circuit is typically used in I/O cards.

Converter Specifications:

Input Voltage, $V_{in} = 3.3V (\pm 10\%)$

Output Voltage = 5V (±5%)

Output Current = 0 mA–600 mA

Efficiency = 80%

The maximum and minimum duty cycles calculated using equations (1) and (2) are equal to 0.52 and 0.4 respectively.

The average inductor current calculated using equation (3) is:

$$I_{L(avg.)} = \frac{I_{o(max)}}{1 - D_{max}} = \frac{0.6}{1 - 0.52} = 1.25A$$

Assuming the peak to peak ripple current to be 50% of the average inductor current, the peak current calculated using equation (4) is equal to:

$$I_{L(peak)} = I_{L(avg)} + \frac{\Delta I_L}{2} = 1.25 + \frac{0.5 \times 1.25}{2} = 1.563A$$

The peak current calculated above is very much higher than the rated current of the internal switch in the LM3578A. Hence, it is necessary to use an external transistor or a FET. The selected external switch should be capable of handling the high peak currents. The internal transistor in LM3578A can handle up to 750 mA. So the current gain of the external transistor should be sufficient at the peak primary current. The off state voltage rating, V_{CE} , of the transistor should be at least 10V. One npn transistor meeting these requirements is D44C3A. The current gain (h_{fe}) of this transistor at the peak current of 1.563A is about 50. So the maximum current that the internal transistor needs to provide is equal to $1.563/50 = 31$ mA, which is very much less than the rated current of the internal transistor.

The circuit shown in Figure 5 performs the required conversion using LM3578A and D44C3A npn transistor. The power stage components are selected using the procedure discussed in Section 2. From the above calculations, it can be

seen that the peak current requirements are very high. Hence, this converter is chosen to operate in continuous conduction mode. The boost converter operating in continuous mode has inherent stability problems (due to the right half plane zero and the double pole in the small-signal control to output transfer function). Hence, additional compensation is needed in the control loop. This additional compensation is provided by the capacitor C_{C1} (typically around 1 nF) and the resistor R_{C1} (typically between 100k and 200k).

The current limiting in this circuit is activated whenever pin 7 is pulled 110 mV above the ground. The voltage across the current sense resistor, R_{sn} is sensed in order to prevent excessive current through the external switch. The value of R_{sn} is given by:

$$R_{sn} = \frac{0.110}{I_{lim}} \Omega \quad (12)$$

where I_{lim} is the desired current limit set point. As an example, for the circuit shown in Figure 5, the peak switch current calculated above is 1.563A. Hence, if the desired current, I_{lim} is set at 2A, then the value of the current-sense resistor will be $R_{sn} = 0.110/2 = 0.055\Omega$.

For cost reasons, the current-sense resistor can also be fabricated on a copper trace. Reference[1] describes the procedure for calculating the trace length and width.

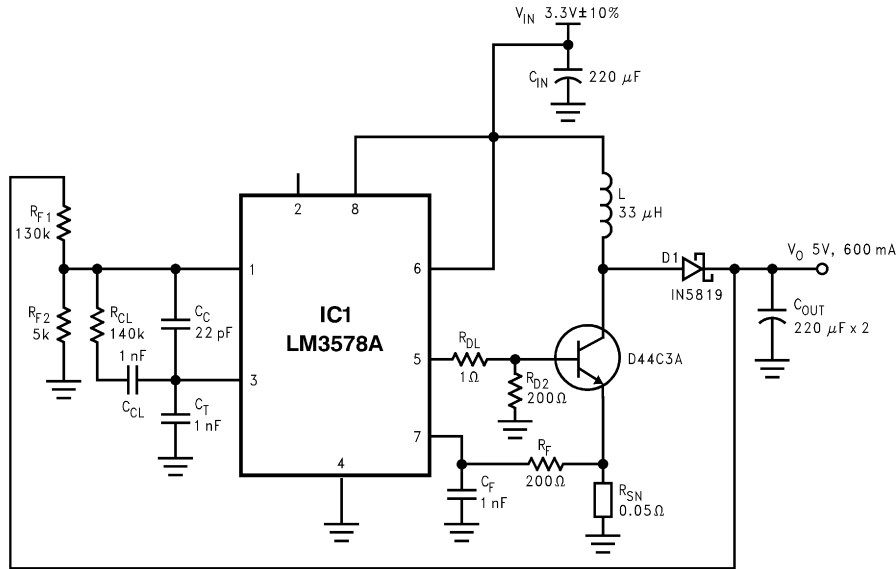


FIGURE 5.

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Parts List

Designator	Value/Rating	Description
IC1	—	LM3578A Switching Regulator
Q ₁	5A, 30V	D44C3A, NPM Transistor
D ₁	1A, 40V	Diode, 1N5819
L	Lp-33 μH, Ip-2.0A	Inductor
C _{in}	220 μF, 6.3V	Input Capacitor
C _o	2 x 220 μF, 10V	Output Capacitor
R _{sn}	0.050Ω, 1W	Current Sense Resistor/Copper Trace
R _{F1}	40.06k, 1/4W	Feedback Resistor
R _{F2}	10k, 1/4W	Feedback Resistor
R _{d1}	1Ω, 1/4W	Base Drive Resistor
R _{d2}	200Ω, 1/4W	Base Drive Resistor
R _f	2000Ω, 1/4W	Resistor for Spike Suppression
C _f	1 nF	Capacitor for Spike Suppression
C _T	820 pF	Timing Capacitor

Parts List (Continued)

Designator	Value/Rating	Description
C_c	22 pF	Compensation Capacitor
C_{c1}	1 nF	Compensation Capacitor
R_{c1}	140k	Compensation Capacitor

4. SUMMARY

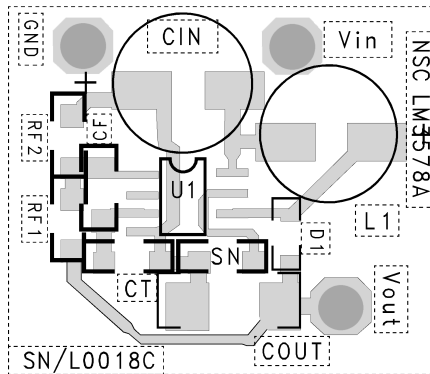
This paper has presented several low cost boost converters, designed using the LM3578A switching regulator. The circuits can be used in many different applications. The parts list has been provided for these circuits. Recommended layouts for these circuits have been presented in the appendix.

Layout is very critical in these circuits. Pins 1, 2, and 7 of LM3578A are very noise sensitive. So these pins should be placed away from high frequency noise sources in the circuit. It is also necessary to have the feedback trace away from the inductor. In order to avoid false triggering of current limiting circuitry, filtering is very much essential for the sensed current. It is also important to note that the current sense voltage shut down level has very high tolerance. The voltage can vary from 80 mV to 160 mV (typical value is 100 mV). This factor should be taken into consideration while selecting the current sense resistor.

The compensation capacitor, C_c connected between pins 1 and 3 should be typically between 10 to 25 pF. Using a larger value for C_c will start effecting the switching frequency. It is also necessary to note that LM3578A can skip pulses at very low load currents when the minimum duty cycle of each pulse provides more energy than the load demands. Under these conditions, the controller internal to the LM3578A starts skipping pulses to maintain the output voltage at its correct value. This mode of operation is also known as burst mode.

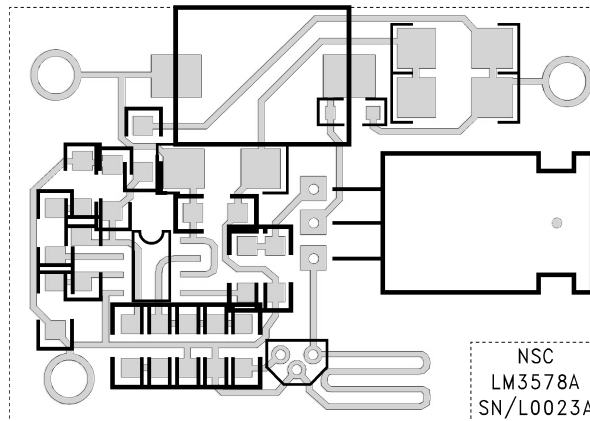
Although only three boost circuits have been presented, the design approach for other voltage and current levels is the same.

APPENDIX



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FIGURE 6. PCB Layout for the Circuits Shown in Figures 3, 4 (Scale: 2:1)



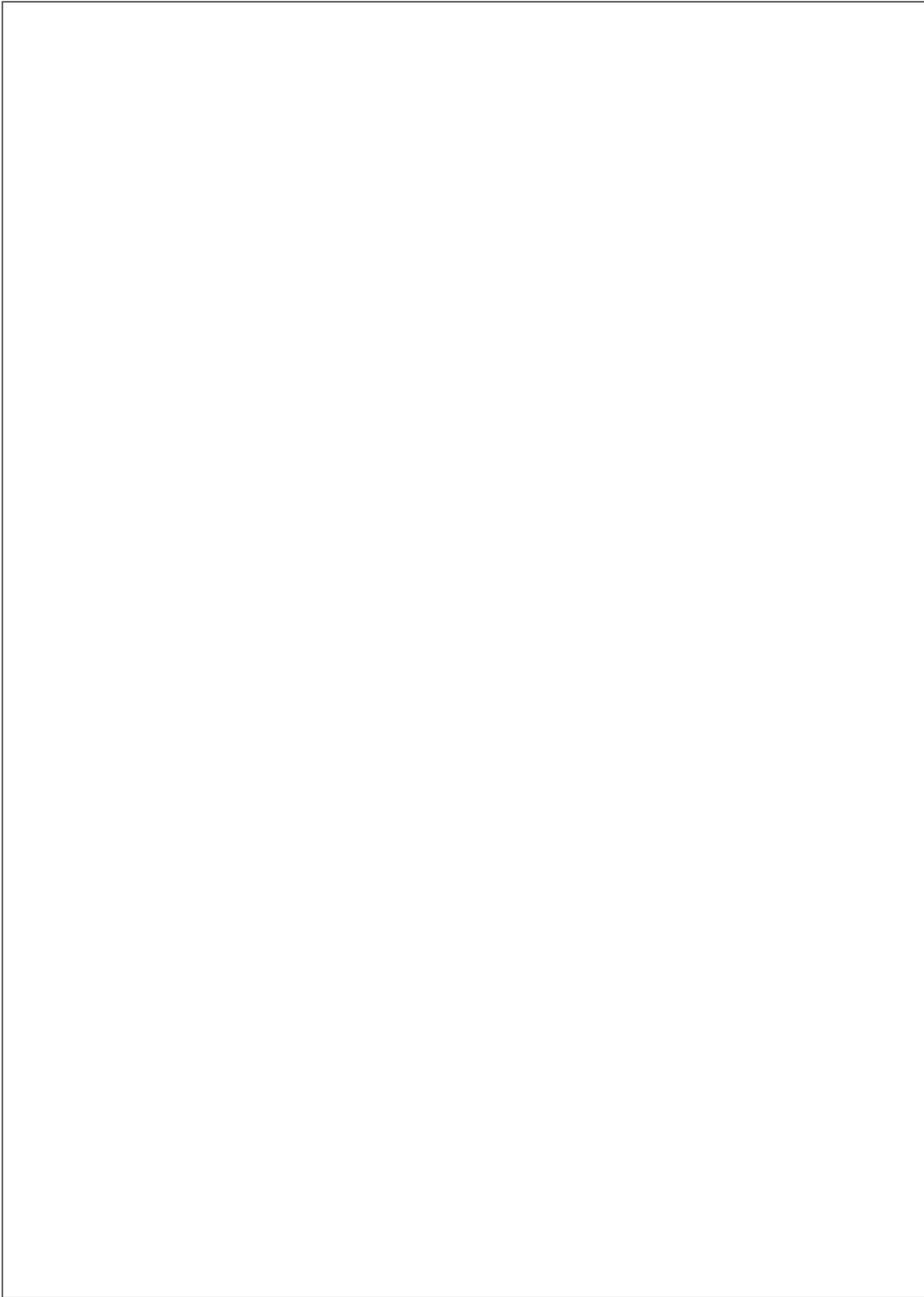
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Note: Copper trace is used as current sense resistor.

FIGURE 7. PCB Layout for the Circuit Shown in Figure 5 (Scale: 2:1)

REFERENCES

1. National Semiconductor Application Note, AN1055: "Low Cost Multiple Output Flyback Converter for I/O Cards", 1996.
2. National Power ICs Databook.



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