

5.0 V, 2.0 A Flyback Converter

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APPLICATION NOTE

The design of a switching power supply is an iterative process which involves many variables that have to be adjusted in order to obtain an optimized solution. However, there are trade-offs which allow for a simple low cost, low component, single sided board design method. This application note provides a simple approach to designing a converter utilizing the ON Semiconductor NCP1055 high voltage switch regulator. The easy-to-follow step-by-step procedure guides the user into designing the different blocks that constitute the power supply, mainly the input block, the power stage, the magnetics, the snubber, the output block, and the feedback loop. The circuit diagram, bill of material, and PCB layout are also included at the end of the application note. This power supply is specifically designed for a 5.0 V, 2.0 A output and a maximum duty cycle of 48%. It meets IEC and UL requirements. EMI is minimal and a 70% achievable efficiency or greater is possible.

The NCP1055 is a family of monolithic high voltage switching regulators designed to work in rectified AC line sources and flyback converter applications. They are capable of providing an output power ranging from 6.0 W to 40 W with a fixed AC input of 100 V, 115 V, or 230 V and 3.0 W to 20 W with a variable AC input ranging from 85 V to 265 V. This device features an on-chip 700 V SENSEFET™ power switch circuit, an active startup regulator circuit which eliminates the need for an auxiliary bias winding on the converter transformer, fault logic with a programmable timer for converter overload protection. Protective features provide power switch current limiting, input under voltage lockout with hysteresis, thermal shutdown, and restart fault detection. For more information, please contact an ON Semiconductor sales representative or log on to www.onsemi.com.

Design Parameters

The first step in designing a power supply is to define and predetermine the input and output parameters.

Universal Input Voltage Range:

$$V_{in(min)} = 85 \text{ VAC}, V_{in(max)} = 265 \text{ VAC}$$

Output Specifications:

$$V_{out} = 5.0 \text{ V} \pm 2\%, I_{out} = 2 \text{ A}$$

Input Power:

$P_{in} = \frac{P_{out}}{\text{est. eff}}$, an efficiency of 0.78 is a good starting point for a flyback converter using MOSFET technology:

$$P_{out} = 5 \cdot 2.0 = 10 \text{ W} \\ \therefore P_{in} = \frac{10}{0.78} = 12.82 \text{ W}$$

DC Rail Voltages at Low Line and High Line:

$$V_{peak(min)} = V_{in(min)} \cdot \sqrt{2} = 85 \cdot \sqrt{2} = 120.21 \text{ VDC} \\ V_{peak(max)} = V_{in(max)} \cdot \sqrt{2} = 265 \cdot \sqrt{2} = 374.77 \text{ VDC}$$

Average Input Current at Low Line:

$$I_{in(avg)} = \frac{P_{in}}{V_{in(low)}}$$

where $V_{in(low)} = V_{peak(min)} - V_{ripple} - V_{diode}$;

$$V_{ripple} = 32\% V_{peak(min)}$$

$$I_{in(avg)} = \frac{12.82}{80.2} = 0.160 \text{ A}$$

Input Peak Current:

$$I_{peak} = 2 \cdot I_{in(avg)} \cdot \frac{t_{sw}}{t_{on}}$$

$$I_{peak} = 2 \cdot 0.160 \cdot \frac{10 \mu\text{s}}{4.8 \mu\text{s}} = 0.667 \text{ A}$$

The component losses can be evaluated and budgetized with the following formula:

$$P_{\text{loss}} = P_{\text{in}} (1 - \text{eff}) \cdot P_{\%} \text{ where } P_{\%} \text{ is the percentage loss of the desired circuit section per total power supply loss.}$$

Usually, 35% of the losses come from the power MOSFET, 60% from the output rectifier, 5% from the magnetics, and 5% from miscellaneous sources.

$$\begin{aligned} \text{Estimated Power Loss} &= P_{\text{in}} - P_{\text{out}} = 12.82 - 10 = 2.82 \text{ W} \\ \text{MOSFET Power Losses} &= 2.82 \cdot 35\% = 0.987 \text{ W} \\ \text{Rectifier Power Losses} &= 2.82 \cdot 60\% = 1.692 \text{ W} \end{aligned}$$

Circuit Description

Input Block

The input block of the power supply consists of a fuse, an EMI filter, a diode bridge rectifier, and an input bulk capacitor.

Fuse

The fuse F1 is protecting the circuit from current surges occurring at turn on. In this application, F1 is rated for 2.0 A, 125 VAC.

EMI Filter

The EMI filter is suppressing common mode and differential mode noise and is very dependent upon board layout, component selection, etc. An X capacitor C1 and a common mode choke L1 are placed across the AC lines to attenuate differential mode noise, see Figure 1. The EMI inductor is slowing down any transient voltage surge to reduce high frequency noise. Both the capacitor and choke should be placed before the diode bridge and as close to the AC line input as possible to minimize RFI.

Diode Bridge Rectifier

In order to choose the right diode bridge rectifier, the values of the forward and surge currents and DC blocking voltage must be considered. The surge current can reach values up to five times that of the average input rms current. It is therefore necessary to select a rectifier capable of handling such large currents.

DC Blocking Voltage is calculated at high line:

$$V_R \geq V_{\text{peak(max)}} = V_{\text{in(max)}} \cdot \sqrt{2} = 375 \text{ VDC}$$

Forward Current:

$$I_F \geq 1.5 \cdot I_{\text{in(avg)}} = 1.5 \cdot 0.160 = 0.240 \text{ A}$$

Surge Current:

$$I_{\text{FSM}} \geq 5 \cdot I_F = 5 \cdot 0.240 = 1.2 \text{ A}$$

Input Bulk Capacitor

The purpose of the input bulk capacitor C2 is to hold up the rectified line voltage and also to filter out common mode noise. It is placed between the bridge rectifier output and ground. The size of the bulk capacitor depends on peak rectified input voltage and the ripple voltage magnitude. A larger capacitor will lower the ripple voltage on the DC input line, but will induce a larger surge current when the supply is powered up. Assuming a ripple magnitude of about 32% of the peak rectified voltage at low line, C_{bulk} can then be calculated using:

$$\begin{aligned} C_{\text{bulk}} &= \frac{P_{\text{in}}}{\text{fac} \cdot (V_{\text{peak(min)}}^2 - V_{\text{in(low)}}^2)} \\ &= \frac{12.82}{60 \cdot (120^2 - 80.22^2)} = 27 \mu\text{F} \end{aligned}$$

Select the closest standard capacitor of 33 μF with low ESR. Aluminum electrolytics are preferred because of their sturdiness and high reliability.

Power Stage

At the heart of the power stage is the ON Semiconductor NCP1055. The NCP1055 is a high voltage switching regulator that uses a fixed-frequency, duty cycle controlled oscillator. Rectified AC line voltage is applied to the startup circuit Pin 5 through the primary winding of the transformer. The circuit then routes current to the supply capacitor C5 which is typically connected to Pin 1. A switching cycle begins when the oscillator charges and discharges an on chip timing capacitor which generates a square wave signal used to pulse width modulate the power switch circuit. The control input pin is monitoring source or sink current drawn by an optocoupler. When the power supply output is greater than the reference voltage, the optocoupler begins to conduct pulling on the control input. The output of the control input is then sampled continuously during t_{on} and has the ability to either turn the power switch circuit on or off at any time within t_{on}.

Magnetics Calculations

The next step is the design of the flyback transformer. The design of the magnetics block is the most important and delicate part of the whole design process because it will determine how well the power supply will perform. The flyback-mode transformer functions by first conducting current in the primary winding, thus storing energy in the core of the transformer. The core energy is then transferred to the secondary winding when the primary side is turned off. The core and bobbin are standard EFD20 sizes.

In order for the regulator to operate in discontinuous mode under worse case conditions and to maximize power, the maximum on time is 48% of the full period, therefore the maximum primary inductance is calculated based on a maximum duty cycle of 48%. Using a larger inductance than calculated will cause the power supply output to fall out of regulation.

$$L_{pri} = \frac{V_{in(low)} \cdot \partial_{max}}{I_{peak} \cdot f_{op}}, \text{ where } \partial_{max} \text{ is the maximum duty cycle}$$

$$L_{pri} = \frac{80.2 \cdot 0.48}{0.667 \cdot 100 \cdot 10^3} = 0.577 \text{ mH}$$

Primary flyback voltage:

$$V_{FB} = \frac{V_{in(low)} \cdot t_{on}}{t_{off}} = \frac{80.2 \cdot 4.8 \cdot 10^{-6}}{5.2 \cdot 10^{-6}}$$

$$= 74.03 \text{ V, where } t_{on} \text{ is } 4.8 \mu\text{s}$$

Primary to secondary turns ratio:

$$\frac{N_{pri}}{N_{sec}} = \frac{V_{FB}}{V_{out} + V_F} = \frac{74.03}{5 + 0.525} = 13.4 \approx 13 \text{ turns}$$

By rearranging the above equation and solving for N_{sec} yields ≈ 1 turn.

Energy entering the core during on-time (when the power switch is conducting):

$$E_{stored} = \frac{L_{pri} \cdot I_{peak}^2}{2}, \text{ where the stored energy is measured in Joules.}$$

$$E_{stored} = \frac{0.577 \cdot 10^{-3} \cdot 0.667^2}{2}$$

$$= 1.28 \times 10^{-4} \text{ Joules}$$

One can double check if the power capability of the transformer is large enough to supply enough power to the output with the following equation:

$$P_{in(core)} = \frac{L_{pri} \cdot I_{peak}^2}{2} \cdot f_{op} > P_{out}$$

$$P_{in(core)} = 1.28 \times 10^{-4} \cdot 100 \text{ kHz} = 12.8 \text{ W} > P_{out}$$

$$= 10 \text{ W}$$

Input Snubber

Because of the high dv/dt characteristic of the power transistor drain voltage and of the transformer leakage inductance, voltage spikes and ringing occur at the drain when the power switch is turned off. Resistor R1, C3, D5 compromise an RCD snubber. In parallel to the primary winding are R2 and C4 which compromise an RC ringing damper which slows down the dv/dt and reduces the peak voltage therefore decreasing the ringing due

to high frequency noise. Since $i = C \cdot \frac{dv}{dt}$, increasing the capacitance will also reduce the magnitude of the voltage ripple. The snubber and ringing damper act together to protect the IC from voltage transients greater than 700 V and reduce radiated noise.

Output Block

The output consists of a diode rectifier, a pi-filter, and a voltage regulator. For a flyback converter with an output voltage less than 7.5 V, a Schottky rectifier provides the maximum efficiency and is therefore the best choice. The Schottky rectifier used is the ON Semiconductor 1N5822, in which $V_R = 40 \text{ V}$, $I_F = 3.0 \text{ A}$, and $V_F = 0.525 \text{ V}$. The main purpose of this rectifier is to take the secondary voltage and convert it to a DC voltage. The following equations are used in selecting the Schottky rectifier:

Maximum reverse peak voltage (calculated at high line):

$$V_{Rout} > V_{out} + \left[V_{peak(max)} \cdot \frac{N_{sec}}{N_{pri}} \right]$$

$$V_{Rout} > 5 + \left[375 \cdot \frac{1}{13} \right] = 33.85 \text{ V}$$

For discontinuous mode, the maximum forward peak current can be approximated using:

$$I_{Fout} = 4 \cdot I_{out} = 8 \text{ A}$$

Diode D6 along with C7, C8, C9, L2, and C11 rectify the transformer secondary and filter the output in order to provide a tightly regulated DC output. Capacitor C7, C8 and C9 are placed in parallel in order to reduce ESR. In addition, the voltage rating of C7, C8 and C9 should be high enough for them to withstand the voltage spikes and the output voltage. L2 and C11 form a low pass filter that attenuates high frequency noise.

Output filter capacitor:

$$C_{out} = \frac{I_{out(max)} \cdot T_{off(max)}}{V_{ripple(desired)}}, \text{ where } T_{off(max)}$$

$$= \partial_{min} \cdot \frac{1}{f_{op}}$$

$$\text{and } V_{ripple(desired)} = 40 \text{ mV}$$

$$C_{out} = \frac{8 \cdot 0.52 \cdot \frac{1}{100 \cdot 10^3}}{0.040} = 1040 \mu\text{F}$$

Output filter choke (designed for a break frequency of 4.0 kHz):

$$L = \left[\frac{1}{2 \cdot \pi \cdot f \cdot \sqrt{C}} \right]^2, \text{ where } C = C_{11} = 330 \mu\text{F} \text{ and } f$$

is the corner frequency.

$$L = \left[\frac{1}{2 \cdot \pi \cdot 4k \cdot \sqrt{330 \mu\text{F}}} \right]^2 = 4.8 \mu\text{H}$$

Feedback Loop

The feedback loop is composed of an optocoupler, a shunt regulator, a compensation capacitor and a resistor divider. The optocoupler isolates the AC input from the DC output. As a shunt regulator, the ON Semiconductor TL431 is used to regulate the output voltage. This monolithic voltage reference is programmable from V_{ref} to 36 V using two external resistors. It exhibits a wide current range of 1.0 mA to 100 mA and is an excellent replacement for Zener diodes. The reference voltage of the TL431 is set at 2.5 V, for a 5.0 V output voltage, by a resistor divider R5 and R6 (low tolerance, 2.0 kΩ resistors). The TL431 monitors the 5.0 V

output voltage and compares the divided down voltage to its 2.5 V internal reference. A small increase in the output voltage will cause the shunt regulator to start conducting, thus sinking current through the optocoupler's LED. In turn, the optocoupler transistor becomes forward biased and starts driving current into the control input pin of the NCP1055. The power switch duty cycle is then adjusted accordingly. A compensation capacitor C10 of 0.1 μF is placed between the cathode and the reference pin of the TL431 for improved stability. The resistor R3 limits the current going through the optocoupler to a safe level and prevents damage to the optocoupler.

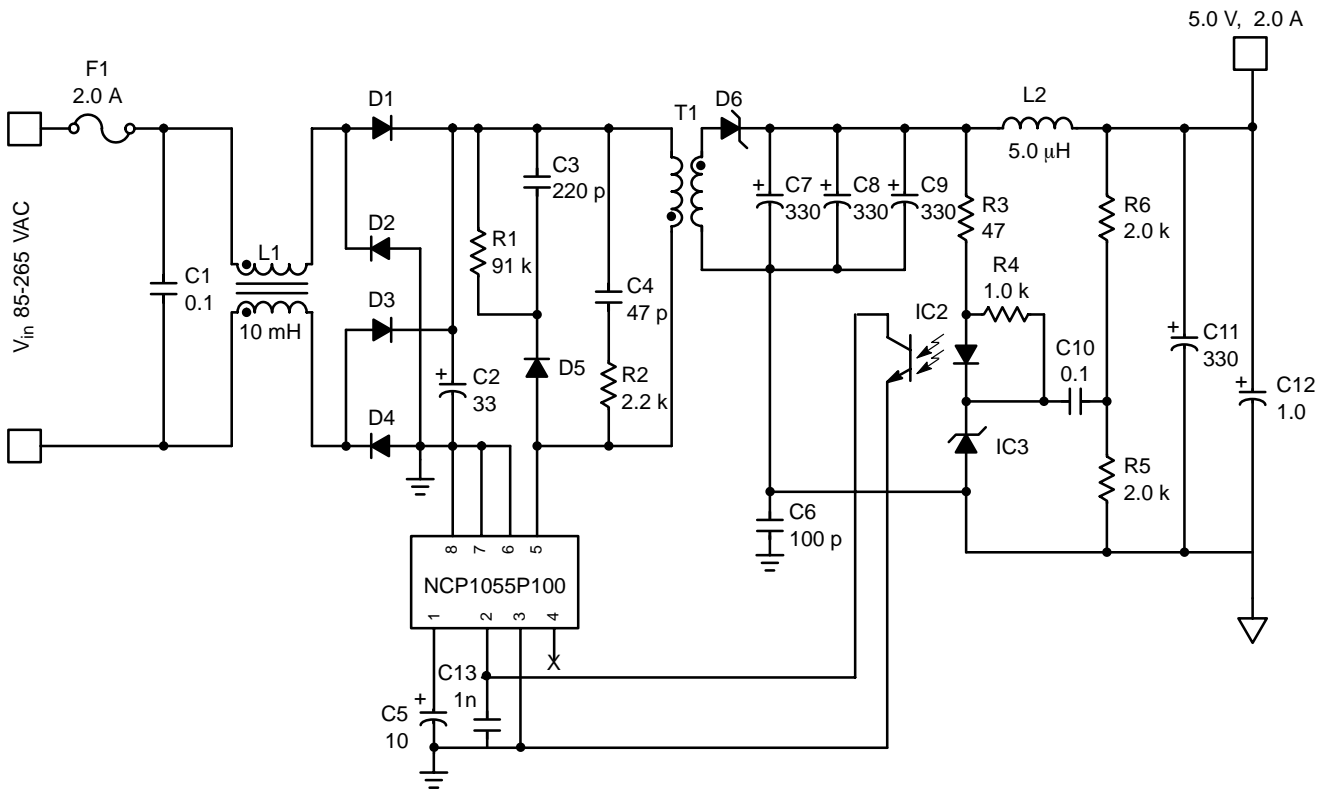


Figure 1. Circuit Diagram

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Table 1. Bill of Materials

Ref.	Component Value	Qty.	Part Number	Manufacturer
IC1	IC, 680 mA, 100 kHz, DIP8	1	NCP1055P100	ON Semiconductor
IC2	Optocoupler, Dip	1	SFH615A-4	Isocom
IC3	2.5 V Shunt Reg., TO-92	1	TL431AILP	ON Semiconductor
D1-4	1.0 A, 800 V, Gen. Purp.	4	1N4006	ON Semiconductor
D5	1.0 A, 600 V, Ultra Fast	1	MUR160TR	ON Semiconductor
D6	3.0 A, 40 V, Schottky	1	1N5822	ON Semiconductor
T1	Flyback Transformer	1	31592	Midcom
L1	Choke, Common Mode, 10 mH	1	40479	Midcom
L2	Choke, Power, 5.0 μ H	1	40480	Midcom
C1	0.1 μ F, Film, Radial	1	XSC275V104-M15S	Nissei
C2	33 μ F, 400 V, Radial	1	400V33-HS	United Chem-Con
C3	220 pF, 1.0 kV, 10%, Disc	1	NCD221K1KVY5F	NIC Components
C4	47 pF, 1.0 kV, 10%, Disc	1	NCD470K1KVSL	NIC Components
C5	10 μ F, 16 V, 20%, Radial	1	16V10	United Chem-Con
C6	100 pF, 1.0 kV, 10%, Disc	1	NCD101K1KVY5FAB2	NIC Components
C7-9, C11	330 μ F, 10 V, Radial	4	10V330-HOSS	United Chem-Con
C10	0.1 μ F, 50 V, Cer., Radial, 10%	1	SR215C104KAA	AVX
C12	1.0 μ F, 35 V, Tant., Radial, 10%	1	105X9050	AVX
C13	0.001 μ F, 50 V, Cer., Radial, 10%	1	SR211C102KAA	AVX
R1	91 k Ω , 1.0 W	1	MO-1-91K-5TR	SEI
R2	2.2 k Ω , 1/2 W, 5%	1	1/2W-2.2K-5B	SEI
R3	47 Ω , 1/4 W, 5%	1	1/4W-47R-5	SEI
R4	1.0 k Ω , 1/4 W, 5%	1	1/4W-1K-5B	SEI
R5, R6	2.0 k Ω , 1/4 W, 1%	2	CCF-55-2001FTR	SEI
F1	2.0 A, axial	1	251002TR1	LittleFuse
J1-2	Term. Block, 2 Pos., Plug and Header	1	1757242	Phoenix Contact
			1757019	
J3-4	Term. Block, 2 Pos., Inv. Plug and Header	1	1786404	Phoenix Contact
			1786174	

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Table 2. Converter Test Data and Results

Test	Conditions	Data	Results
Line Regulation	Vin = 85 VAC; Iout = 2.0 A Vin = 265 VAC; Iout = 2.0 A	Vout = 4.971 V Vout = 4.982 V	Δ 11 mV
Load Regulation	Vin = 85 VAC; Iout = 0 = 0.200 A = 1.0 A = 2.0 A	Vout = 4.994 V = 4.991 V = 4.985 V = 4.971 V	Δ 23 mV
	Vin = 110 VAC; Iout = 0 = 0.200 A = 1.0 A = 2.0 A	Vout = 4.993 V = 4.991 V = 4.986 V = 4.976 V	Δ 17 mV
	Vin = 230 VAC; Iout = 0 = 0.200 A = 1.0 A = 2.0 A	Vout = 4.993 V = 4.991 V = 4.987 V = 4.981 V	Δ 12 mV
	Vin = 265 VAC; Iout = 0 = 0.200 A = 1.0 A = 2.0 A	Vout = 4.994 V = 4.991 V = 4.987 V = 4.982 V	Δ 12 mV
Efficiency	Vin = 85 VAC	Vout = 4.971 V; Iout = 2.0 A; Pout = 9.942, Pin = 13.64 W	72.8 %
	= 110 VAC	Vout = 4.976 V; Iout = 2.0 A; Pout = 9.952, Pin = 13.41 W	74.2 %
	= 230 VAC	Vout = 4.981 V; Iout = 2.0 A; Pout = 9.942, Pin = 13.47 W	73.8 %
	= 265 VAC	Vout = 4.982 V; Iout = 2.0 A; Pout = 9.964, Pin = 13.67 W	72.8 %
Output Ripple Voltage	Vin = 85 VAC; Iout = 2.0 A		100 mVp-p
	Vin = 265 VAC; Iout = 2.0 A		230 mVp-p

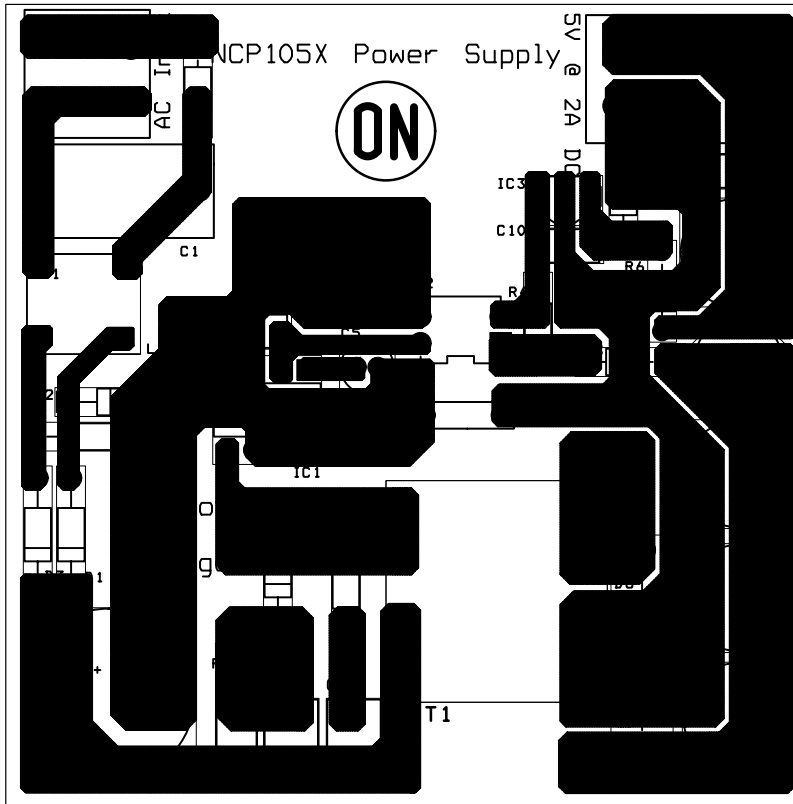


Figure 2. PCB Metal Layer

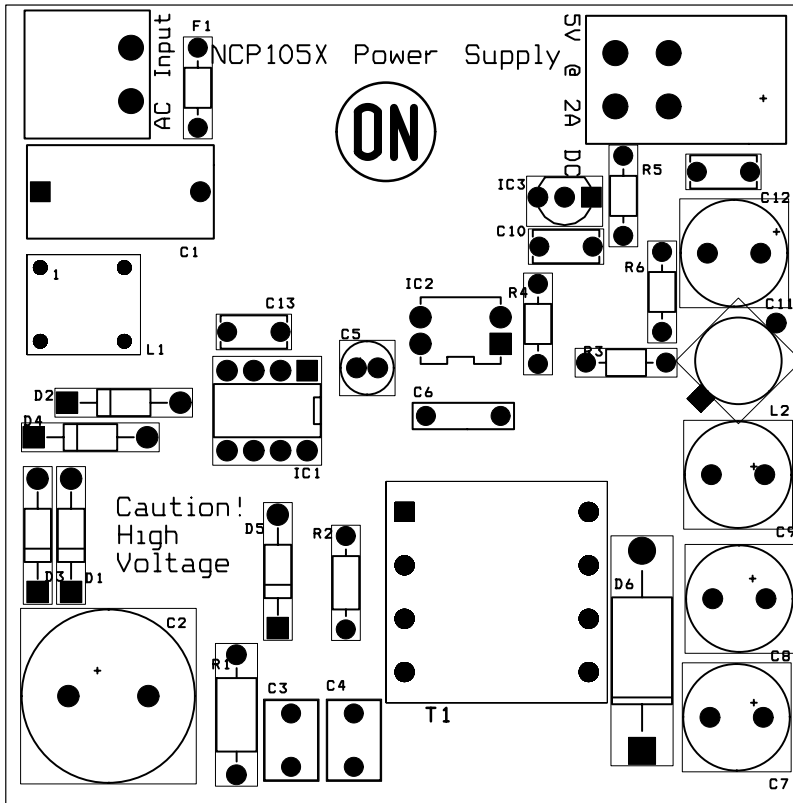



Figure 3. PCB Silk Screen

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2. Pressman, Abraham I., *Switching Power Supply Design, Second Edition*, McGraw-Hill, 1998.
3. Motorola, Inc., *Handling EMI in Switch Mode Power Supply Design*, AN-SMPS-EMI, Motorola, Inc., 1998.

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