AN-1878 LM5085 Evaluation Board

1 Introduction

The LM5085EVAL evaluation board provides the design engineer with a fully functional buck regulator, employing the LM5085 PFET switching controller which uses the constant on-time (COT) operating principle. This evaluation board provides a 5 V output over an input range of 5.5 V to 55 V. The circuit delivers load currents to 4.5A, with current limit set at ≅7.6A. The board is populated with all components except C5. Its use is described later in this document.

The board's specification are:

- Input Voltage: 5.5 V to 55 V, 60 V maximum
- Output Voltage: 5 V
- Maximum load current: 4.5A for V_{IN} >8 V
- Minimum load current: 0A
- Current Limit Threshold: ≅7.6A
- Measured Efficiency: 97.2% (V_{IN} = 5.5 V, I_{OUT} = 0.6Amps)
- Nominal Switching Frequency: 300 kHz
- Size: 3.1 in. x 1.5 in. x 0.78 in

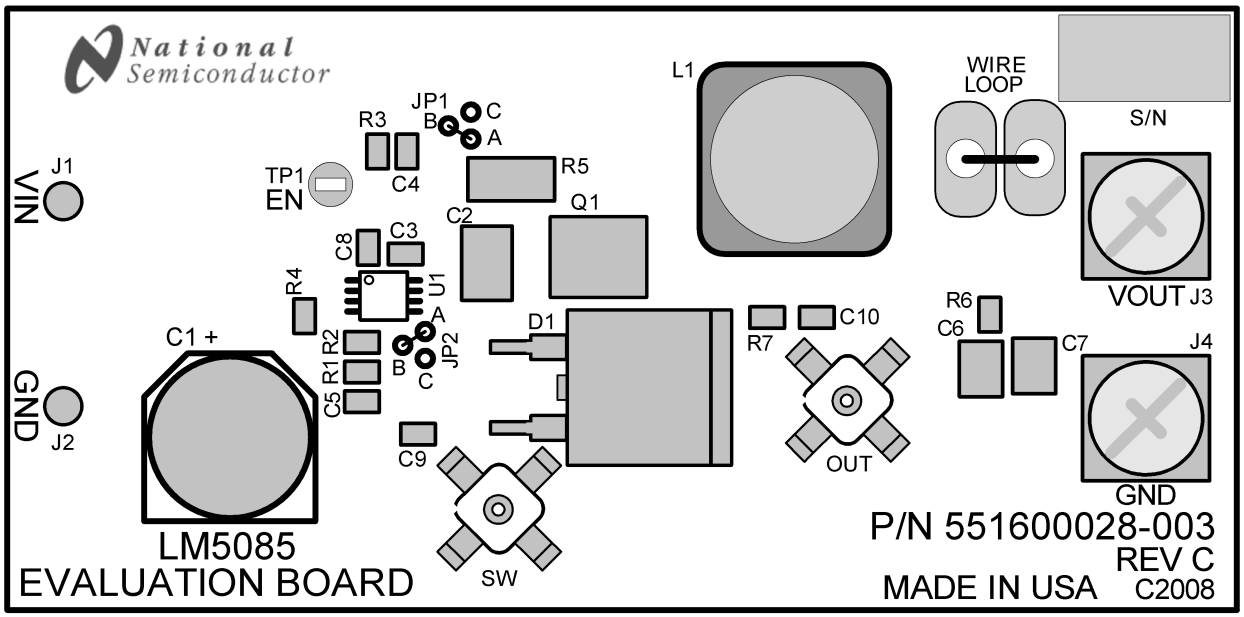


Figure 1. Evaluation Board - Top Side

2 Theory of Operation

For the evaluation board schematic, see Figure 7. When the circuit is in regulation, the on-time at the PGATE output pin is determined by R4 and the voltage at V_{IN} according to Equation 1:

$$t_{ON} = \frac{1.65 \times 10^{-7} \times (R4 + 1.4)}{V_{IN} - 1.36V + R4/3167} + 50 \text{ ns} \quad (1)$$

where R4 is in kohms. The on-time at the SW node (junction of Q1, L1 and D1) is longer than the above calculated on-time due to the difference of the turn-on and turn-off delay of Q1. The data sheet for the Si7465 PFET indicates a typical turn-on delay of 8 ns, and a typical turn-off delay of 65 ns, resulting in an additional 57 ns at the SW node. The SW on-time of this evaluation board ranges from ≅3479 ns at V_{IN} = 5.5 V, to ≅357 ns at V_{IN} = 55 V. The on-time varies inversely with V_{IN} to maintain a nearly constant switching frequency.

During the off-time, the load current is supplied by the inductor and the output capacitor (C6, C7). When the output voltage falls sufficiently that the voltage at FB is below the reference voltage (1.25 V), the regulation comparator initiates a new on-time period. For stable, fixed frequency operation, a minimum of 25 mV of ripple is required at the FB pin to switch the regulation comparator. The required ripple is generated by R7 and C10, and supplied to the FB pin via C9.

The current limit threshold is set by the sense resistor (R5), and R3 at the ADJ pin, and is ≅7.6A on this board. A current sink at the ADJ pin sets a constant voltage across R3. When the voltage across R5 exceeds the voltage across R3 the current limit comparator switches to shut off Q1, and the LM5085 forces a longer-than-normal off-time. The long off-time is a function of the input voltage (V_{IN}) and the voltage at the FB pin, and is necessary to allow the inductor current to decrease at least as much, if not more, than the current increase that occurred during the on-time.

The circuit may be shutdown at any time by grounding the Enable test point (EN, TP1). Removing the ground connection allows normal operation to resume.

For a detailed block diagram and a complete description of the various functional blocks, see the *LM5085 75V Constant On-Time PFET Buck Switching Controller Data Sheet* (SNVS565).

3 Board Layout and Probing

Figure 1 shows the placement of the circuit components. The following should be kept in mind when the board is powered:

- When operating at high input voltage and continuous conduction mode forced air flow is necessary to prevent overheating of the LM5085 controller.
- When operating at high load current forced air flow may be necessary to prevent overheating of Q1, D1, and L1. These components may be hot to the touch.
- Use CAUTION when probing the circuit at high input voltages to prevent injury, as well as possible damage to the circuit.
- At maximum load current (4.5A), the wire size and length used to connect the source voltage, and the load, becomes important. Ensure there is not a significant drop in the wires supplying the input current and the load current.

4 Board Connection/Start-up

The input connections are made to the J1 (+) and J2 (-) connectors. The load is connected to the J3 (V_{OUT}) and J4 (GND) terminals. Ensure the wires are adequately sized for the intended load current. Before start-up a voltmeter should be connected to the input terminals, and one to the output terminals. The load current should be monitored with an ammeter or a current probe. It is recommended that the input voltage be increased gradually to 4.5 V, at which time the output voltage should be slightly less than 4.5 V, depending on the load current. The output is regulated at 5 V when the input voltage is increased above 5 V. If the output voltage is correct, then increase the input voltage as desired and proceed with evaluating the circuit. DO NOT EXCEED 60 V AT V_{IN}. Exceeding 60 V can result in damage to Q1 and/or D1.

5 Load Current Derating

Although the maximum load current for this evaluation board is specified as 4.5A, the data sheet for the Si7465 PFET specifies a maximum continuous current of 3.2A. Since the input current, which is the average current though Q1, increases as the input voltage is decreased, the load current must be derated at low input voltage, seeFigure 2.

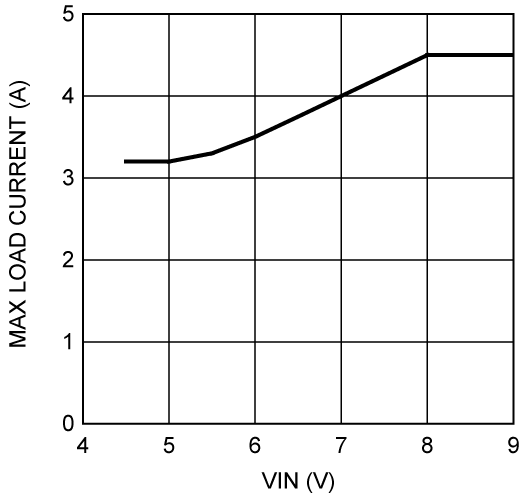


Figure 2. Maximum Load Current Derating

6 Operating at Low Voltage

When the input voltage is less than 5 V the PFET (Q1) is on continuously (100% duty cycle), and the output voltage is equal to the input voltage, minus voltage drops across the sense resistor, Q1 and the inductor. As the input voltage is increased above 5 V, switching commences at the PGATE pin and the SW node as the LM5085 regulates the output at 5 V. Since the LM5085 does not have a required minimum off-time, the circuit transitions smoothly from 100% duty cycle to a regulated output.

7 Current Limit

The LM5085 peak current limit detection operates by sensing the voltage across either the $R_{DS(ON)}$ of Q1, or a sense resistor (R5), during the on-time and comparing it to the voltage across R3 at the ADJ pin. The current limit threshold is reached when the sensed voltage exceeds the voltage across R3. When current limit is reached Q1 is immediately switched off. The current limit function is much more accurate and stable over temperature when a sense resistor is used. The $R_{DS(ON)}$ of a MOSFET has a wide process variation and a large temperature coefficient.

Current sensing is disabled for a blanking time of ≅100 ns at the beginning of each on-time to prevent false triggering of the current limit comparator due to leading edge current spikes. After Q1 is turned off due to current limit detection, Q1 is held off for a longer-than-normal off-time. The extended off-time is a function of the input voltage and the voltage at the FB pin, as shown below in the graph “Current Limit Off-time vs. V_{IN} and V_{FB}”. The current limit off-time can be calculated from Equation 2:

$$t_{OFF(CL)} = \frac{4 \times 10^{-6} \times ((V_{IN}/31) + 0.15)}{(V_{FB} \times 0.93) + 0.28V} \quad (2)$$

The longer-than-normal forced off-time allows the inductor current to decrease to a low level before the next on-time. This cycle-by-cycle monitoring, followed by a long forced off-time, provides effective protection from output load faults over a wide range of operating conditions.

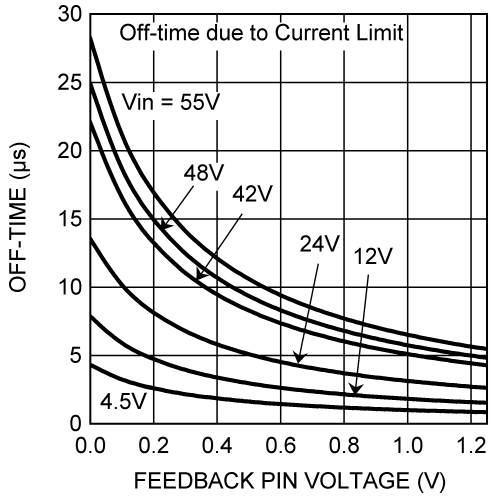


Figure 3. Current Limit Off-time vs. V_{IN} and V_{FB}

7.1 Sense Resistor Method

This evaluation board is supplied configured for the sense resistor method of current limit detection. Jumpers A-B are in place at both jumper locations (JP1, JP2), which connects the ADJ pin resistor (R3) and the ISEN pin across the sense resistor (R5). If the voltage across R5 exceeds the voltage across R3 during the on-time, the current limit comparator switches to turn off Q1. The voltage across R3 is set by an internal 40 µA current sink at the ADJ pin. The current at which the current limit comparator switches is calculated from Equation 3:

$$I_{CL} = 40\ \mu A \times R3/R5 \tag{3}$$

With R5 = 10 mΩ and R3 = 1.91 kΩ, the nominal current limit threshold calculates to 7.64A. Since that is the peak of the inductor current waveform, the load current is equal to that peak value minus one half the ripple current amplitude. At V_{IN} = 5.5 V, the ripple amplitude is 116 mAp-p, and the load current at current limit is equal to 7.6 A. At V_{IN} = 55 V, the ripple amplitude is 1190 mAp-p, and the load current at current limit is equal to 7A.

Using the tolerances for the ADJ pin current and the current limit comparator offset, the maximum current limit threshold calculates to Equation 4:

$$I_{CL(max)} = \frac{(1.91\ k\Omega \times 48\ \mu A) + 9\ mV}{0.01\Omega} = 10.1A \tag{4}$$

and the load current at current limit calculates to 10A at 5.5 V, and 9.5A at 55 V. The minimum current limit thresholds calculate to Equation 5:

$$I_{CL(min)} = \frac{(1.91\ k\Omega \times 32\ \mu A) - 9\ mV}{0.01\Omega} = 5.21A \tag{5}$$

and the load current at current limit calculates to 5.15A at 5.5 V, and 4.62A at 55 V.

To change the current limit threshold, the value for R5 should be chosen to achieve 50 mV to 100 mV across it at current limit, staying within the practical limitations of power dissipation and physical size of the resistor. A larger value for R5 reduces the effects of the current limit comparator offset, but at the expense of higher power dissipation. After selecting the value for R5, calculate the value for R3 by rearranging Equation 3. For a procedure to account for ripple current amplitude and tolerances when selecting the resistor for the ADJ pin, see the *Applications Information* section of the *LM5085 75V Constant On-Time PFET Buck Switching Controller Data Sheet* (SNVS565).

7.2 Q1 $R_{DS(ON)}$ method

To configure the evaluation board to use the $R_{DS(ON)}$ of Q1 for current limit detection, move the jumpers at both JP1 and JP2 from the A-B position to the B-C position. This change connects the ADJ pin resistor (R3) and the ISEN pin across Q1. Since the sense resistance is now the $R_{DS(ON)}$ of Q1, R3 must be changed. The data sheet for the Si7465 PFET lists the typical $R_{DS(ON)}$ as 51 mΩ at V_{GS} = 10 V, and 64 mΩ at V_{GS} = 4.5 V. Therefore, the $R_{DS(ON)}$ is estimated to be nominally 57 mΩ at V_{GS} = 7.7 V. To achieve the same nominal current limit threshold as above (7.64A), using *Equation 6* in the *LM5085 75V Constant On-Time PFET Buck Switching Controller Data Sheet* (SNVS565) R3 calculates to:

$$R3 = \frac{7.64A \times 0.057\Omega}{40\ \mu A} = 10.9\ k\Omega \quad (6)$$

The load current is equal to the current limit threshold minus half the current ripple amplitude. R3 can be changed to set other current limit detection thresholds.

8 Output Ripple Control

The LM5085 requires a minimum of 25 mVp-p ripple at the FB pin, in phase with the switching waveform at the SW node, for proper operation. On this evaluation board, the required ripple is generated by R7, C9, and C10, allowing the ripple at V_{OUT} to be kept to a minimum, as described in Section 8.1. Alternatively, the required ripple at the FB pin can be supplied from ripple generated at V_{OUT} and passed through the feedback resistors, as described in Section 8.2 and Section 8.3, using one or two less external components.

8.1 Minimum Output Ripple

This evaluation board is configured for minimum ripple at V_{OUT} by using components R7, C9 and C10. The ripple voltage required by the FB pin is generated by R7 and C10 since the SW node switches from ≅-1 V to V_{IN}, and the right end of C10 is a virtual ground. The values for R7 and C10 are chosen to generate a 25-40 mVp-p triangle waveform at their junction. That triangle wave is then coupled to the FB pin through C9. The following procedure is used to calculate values for R7, C9 and C10:

1) Calculate the voltage V_A:

$$V_A = V_{OUT} - (V_{SW} \times (1 - (V_{OUT}/V_{IN(min)}))) \quad (7)$$

where, V_{SW} is the absolute value of the voltage at the SW node during the off-time, typically 0.5 V to 1 V depending on the diode, and V_{IN} is the minimum input voltage. Using a typical value of 0.65 V for V_{SW}, V_A calculates to 4.94 V. This is the approximate DC voltage at the R7/C10 junction, and is used in Equation 8.

2) Calculate the R7xC10 product:

$$R7 \times C10 = \frac{(V_{IN} - V_A) \times t_{ON}}{\Delta V} \quad (8)$$

where, t_{ON} is the maximum on-time (≅3479 ns), V_{IN} is the minimum input voltage, and ΔV is the desired ripple amplitude at the R7/C10 junction, 25 mVp-p for this example.

$$R7 \times C10 = \frac{(5.5V - 4.94V) \times 3479\ ns}{0.025V} = 7.79 \times 10^{-5} \quad (9)$$

R7 and C10 are then chosen from the standard value components to satisfy the above product. On this evaluation board, C10 is set at 3300 pF. R7 calculate to be 23.6 kΩ, and a standard value 23.2 kΩ resistor is used. C9 is chosen to be 0.01 µF, large compared to C10. The circuit as supplied on this EVB is shown in Figure 4.

The output ripple, which ranges from ≅14 mVp-p at V_{IN} = 5.5 V to ≅54 mVp-p at V_{IN} = 55 V, is determined primarily by the ESR of the output capacitance (C6, C7), and the inductor's ripple current, which ranges from 116 mAp-p to 1190 mAp-p over the input voltage range, see Figure 11.

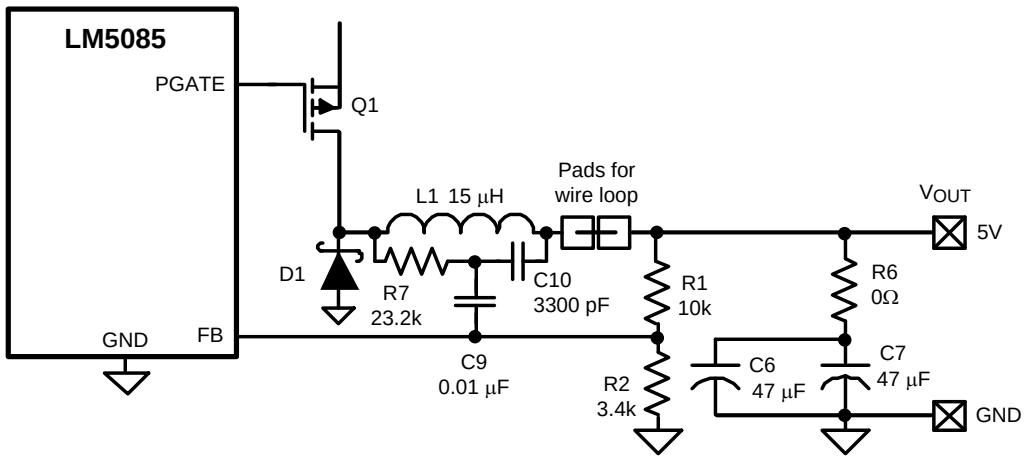


Figure 4. Minimum Ripple Using R7, C9, C10

8.2 Reduced Ripple Level Configuration

This configuration generates more ripple at V_{OUT} than the above configuration, but uses one less capacitor. If some ripple is acceptable in the application, this configuration is slightly more economical, and simpler. R6 and C5 are used instead of R7, C9 and C10, as shown in Figure 5.

Ripple is generated at V_{OUT} as the inductor's ripple current flows through R6, and that ripple voltage is passed to the FB pin via C5. The ripple at V_{OUT} can be set as low as 25 mVp-p since it is not attenuated by R1 and R2. The minimum value for R6 is calculated from Equation 10:

$$R6 = \frac{25\ mV}{I_{OR(min)}} \tag{10}$$

where, $I_{OR(min)}$ is the minimum inductor's ripple current, which occurs at minimum input voltage, and is 116 mAp-p at 5.5 V. The minimum value for R6 calculates to 0.22 Ωs. Using a standard value 0.27 Ω resistor for R6, the ripple at V_{OUT} ranges from 31 mVp-p to 321 mVp-p over the input voltage range, see Figure 11.

The minimum value for C5 is determined from Equation 11:

$$C5 = \frac{3 \times t_{ON(max)}}{R1//R2} \tag{11}$$

Where $t_{ON(max)}$ is the maximum on-time, 3479 ns in this evaluation board. The minimum value for C5 calculates to 4113 pF.

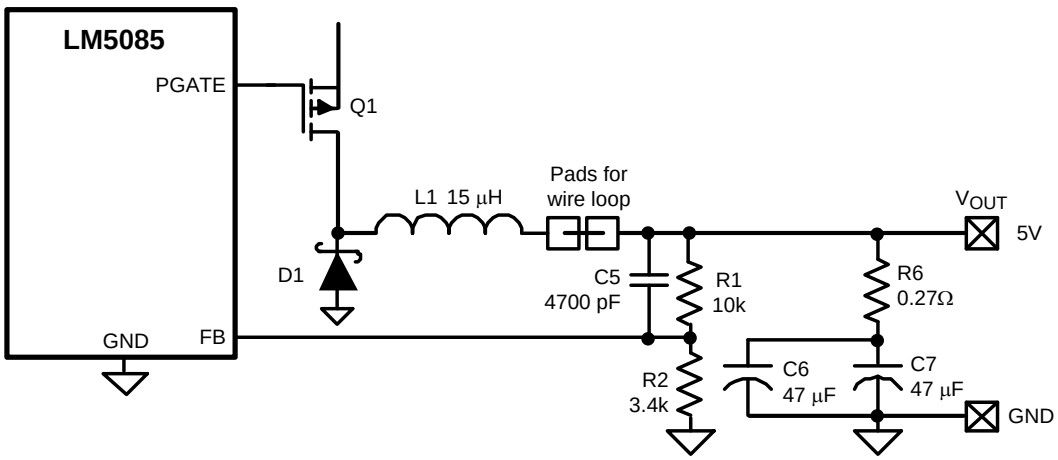


Figure 5. Reduced Ripple Configuration

8.3 Lowest Cost Configuration

This configuration is the same as Section 8.2, but with C5 removed. The ripple at the FB pin is attenuated from that at V_{OUT} by the feedback resistors (R1, R2). Since ≥25 mVp-p are required at the FB pin, R6 is chosen to generate ≥100 mV at V_{OUT}. Since the minimum ripple current in this circuit is 11 mAp-p the minimum value for R6 calculates to 0.86 Ωs. Using a standard value 1.0 Ωs resistor for R6, the ripple at V_{OUT} ranges from ≅116 mVp-p to ≅1190 mVp-p over the input voltage range, see Figure 11. If the application can accept this ripple level, this is the most economical solution. The circuit is shown in Figure 6.

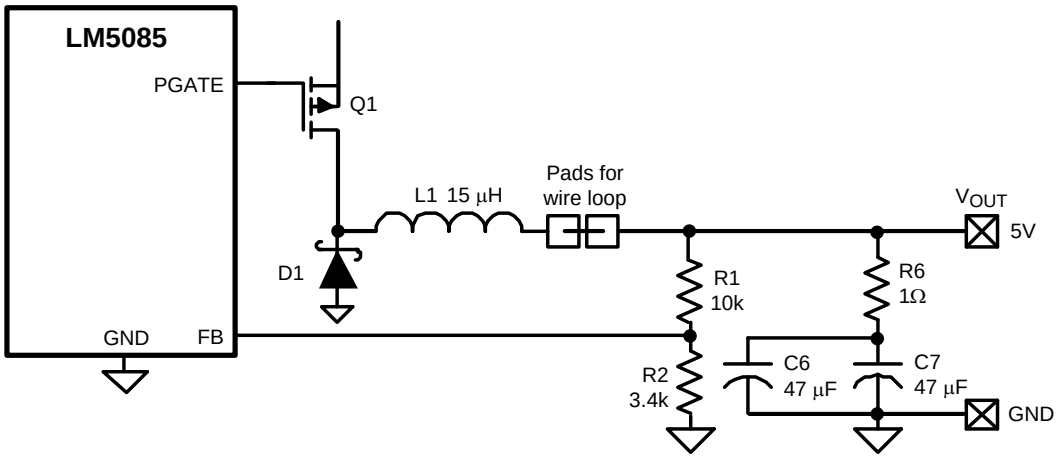


Figure 6. Lowest Cost Configuration

9 Monitor The Inductor Current

The inductor's current can be monitored or viewed on a scope with a current probe. Remove the jumper from the WIRE LOOP pads, and install an appropriate current loop across the pads. In this way, the inductor's ripple current and peak current can be accurately determined.

10 Scope Probe Adapters

Scope probe adapters are provided on this evaluation board for monitoring the waveform at the SW node, and at the circuit's output (V_{OUT}), without using the probe's ground lead that can pick up noise from the switching waveforms. The probe adapters are suitable for Tektronix P6137 or similar probes, with a 0.135" diameter.

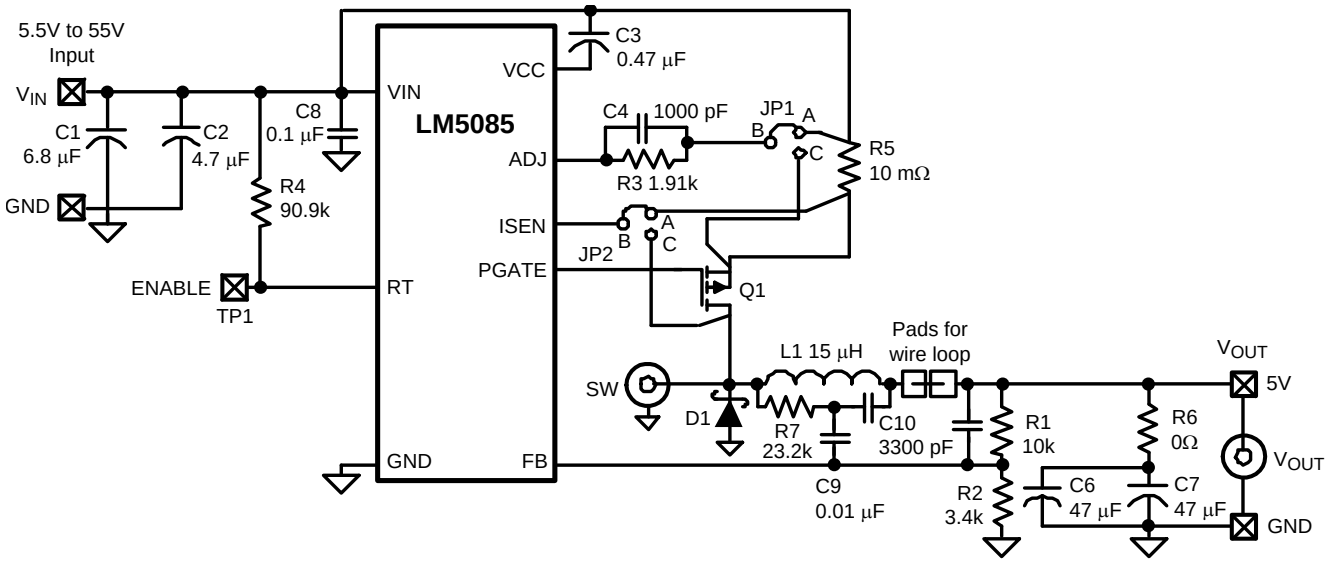


Figure 7. Complete Evaluation Board Schematic

Table 1. Bill of Materials (BOM)

Item	Description	Mfg Part Number	Package	Value
C1	Ceramic Capacitor	United Chemicon KTS101B685M55N0T00	2220	6.8 µF, 100 V
C2	Ceramic Capacitor	United Chemicon KTS101B475M43N0T00	1812	4.7 µF, 100 V
C3	Ceramic Capacitor	TDK C2012X7R1C474K	0805	0.47 µF, 16 V
C4	Ceramic Capacitor	TDK C2012X7R2A102K	0805	1000 pF, 100 V
C5	Ceramic Capacitor	Unpopulated	0805	
C6, C7	Ceramic Capacitor	TDK C3225X5R0J476M	1210	47 µF, 6.3 V
C8	Ceramic Capacitor	TDK C2012X7R2A104K	0805	0.1 µF, 100 V
C9	Ceramic Capacitor	TDK C2012X7R2A103K	0805	0.01 µF, 100 V
C10	Ceramic Capacitor	TKD C2012X7R2A332K	0805	3300 pF, 100 V
D1	Schottky Diode	On Semi MBRB2060CT	D2PAK	60 V, 20A
L1	Power Inductor	Wurth XXL 7447709150	12 mm x 12 mm x 10 mm	15 µH
Q1	P-Channel MOSFET	Vishay Si7465DP	SO-8 Power	60 V, 5A
R1	Resistor	Vishay CRCW08051002F	0805	10k
R2	Resistor	Vishay CRCW08053401F	0805	3.4k
R3	Resistor	Vishay CRCW08051911F	0805	1.91k
R4	Resistor	Vishay CRCW08059092F	0805	90.9k
R5	Resistor	Vishay WSL2010R0100F	2010	0.01 Ω
R6	Resistor	Vishay CRCW08050000Z	0805	0 Ω
R7	Resistor	Vishay CRCW08052322F	0805	23.2k
U1	Switching Regulator	Texas Instruments LM5085	VSSOP8	

11 Circuit Performance

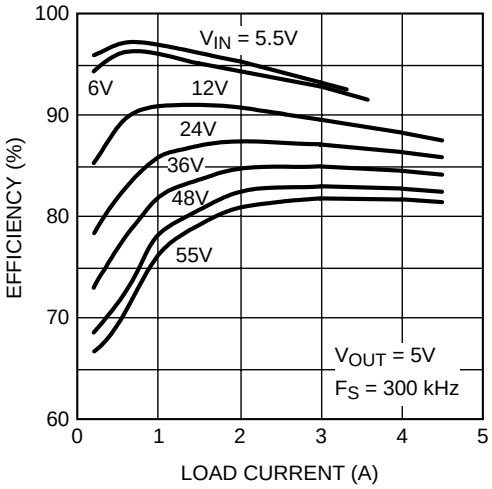


Figure 8. Efficiency vs Load Current

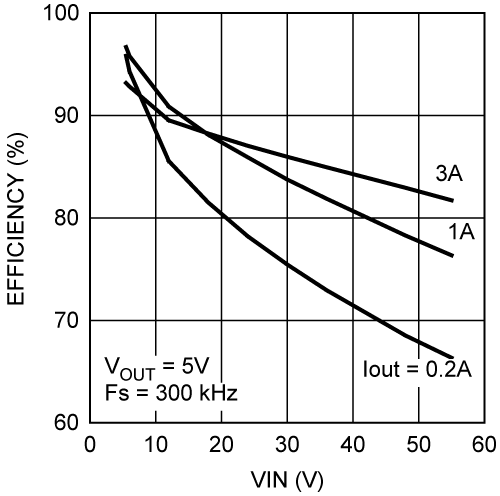


Figure 9. Efficiency vs Input Voltage

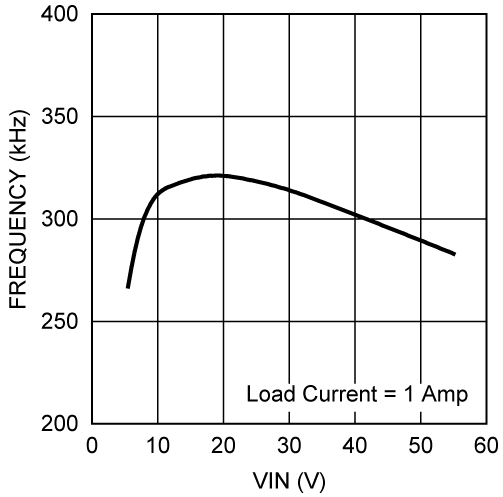


Figure 10. Switching Frequency vs. Input Voltage

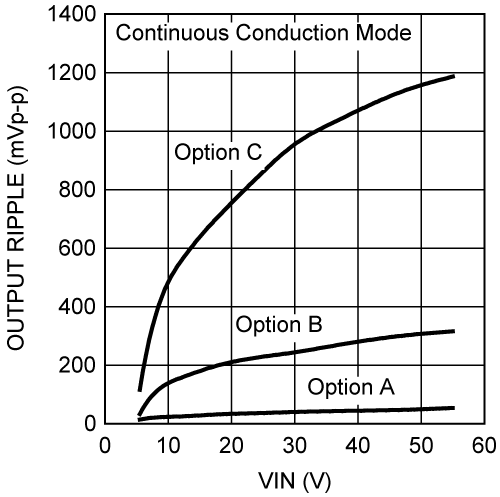


Figure 11. Output Voltage Ripple

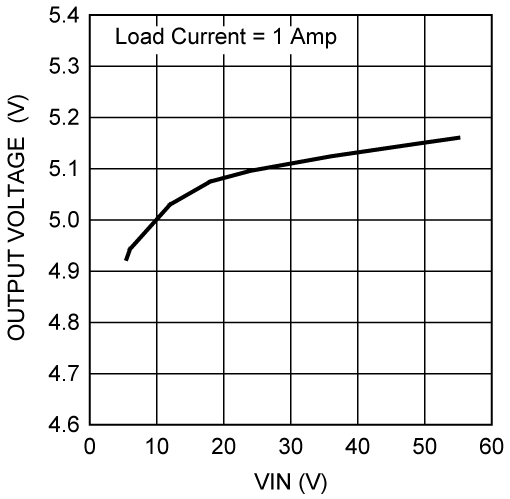


Figure 12. Line Regulation

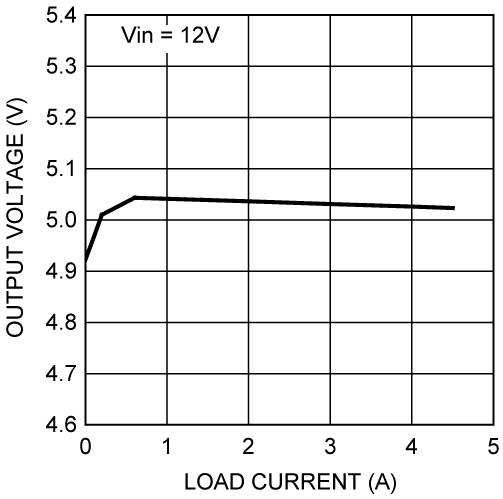
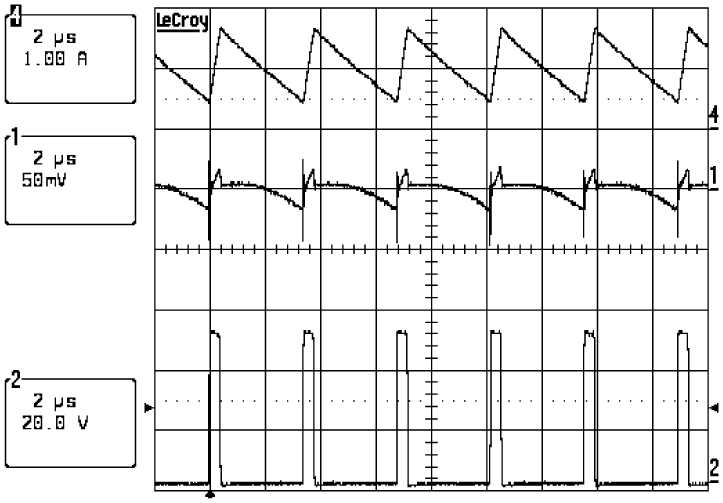


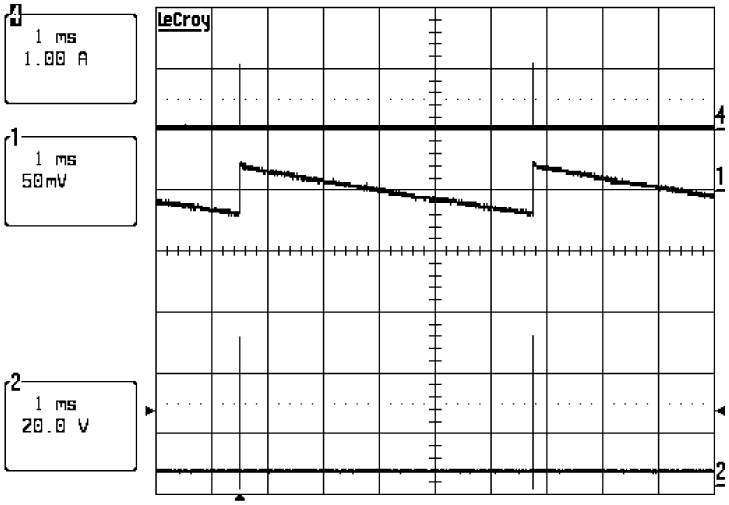
Figure 13. Load Regulation

12 Typical Waveforms



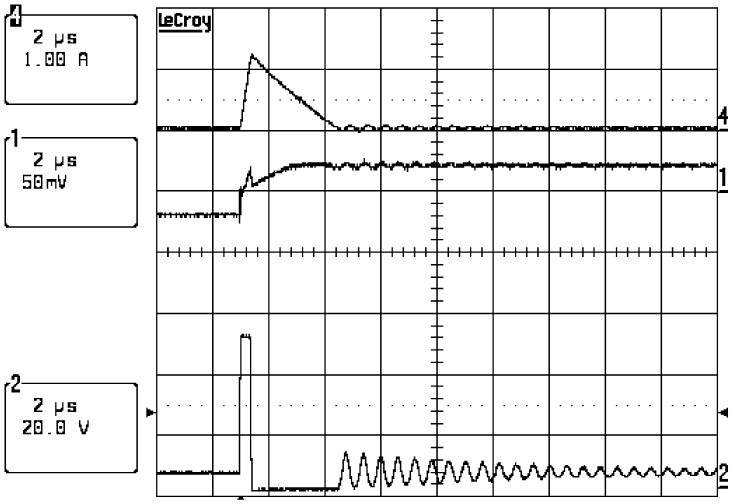
Trace 4 = Inductor Current
Trace 1 = V_{OUT}
Trace 2 = SW Node
V_{IN} = 48 V, I_{OUT} = 1Amp
Minimum Ripple Configuration (Option A)

Figure 14. Continuous Conduction Mode



Trace 4 = Inductor Current
Trace 1 = V_{OUT}
Trace 2 = SW Node
V_{IN} = 48 V, I_{OUT} = 0

Figure 15. Discontinuous Conduction Mode



Trace 4 = Inductor Current
Trace 1 = V_{OUT}
Trace 2 = SW Node
V_{IN} = 48 V, I_{OUT} = 0

Figure 16. Discontinuous Conduction Mode (Expanded Scale)

13 PC Board Layout

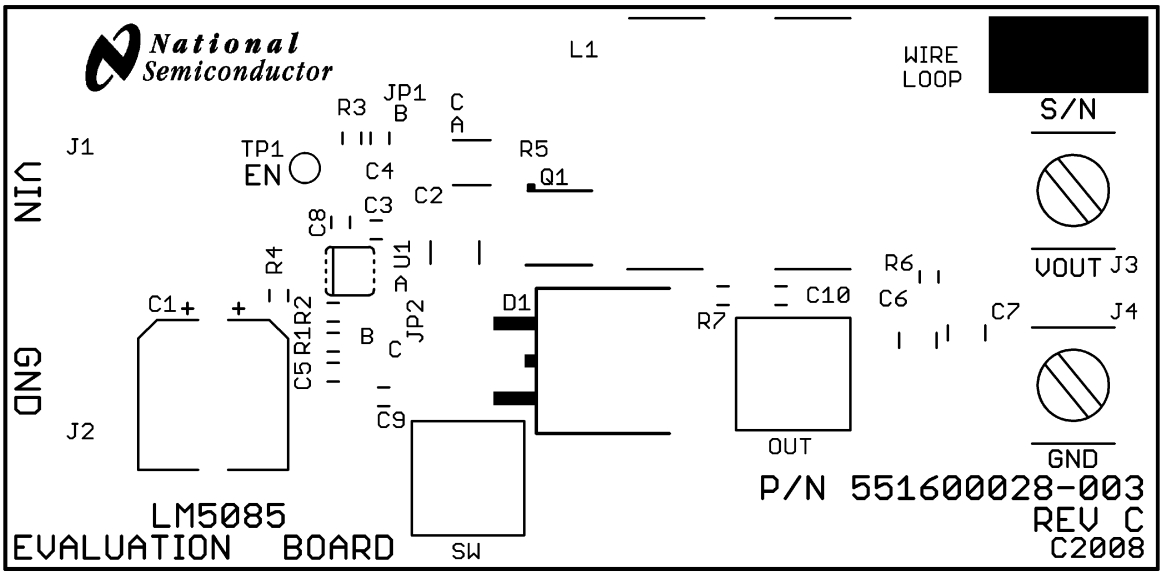


Figure 17. Board Silkscreen

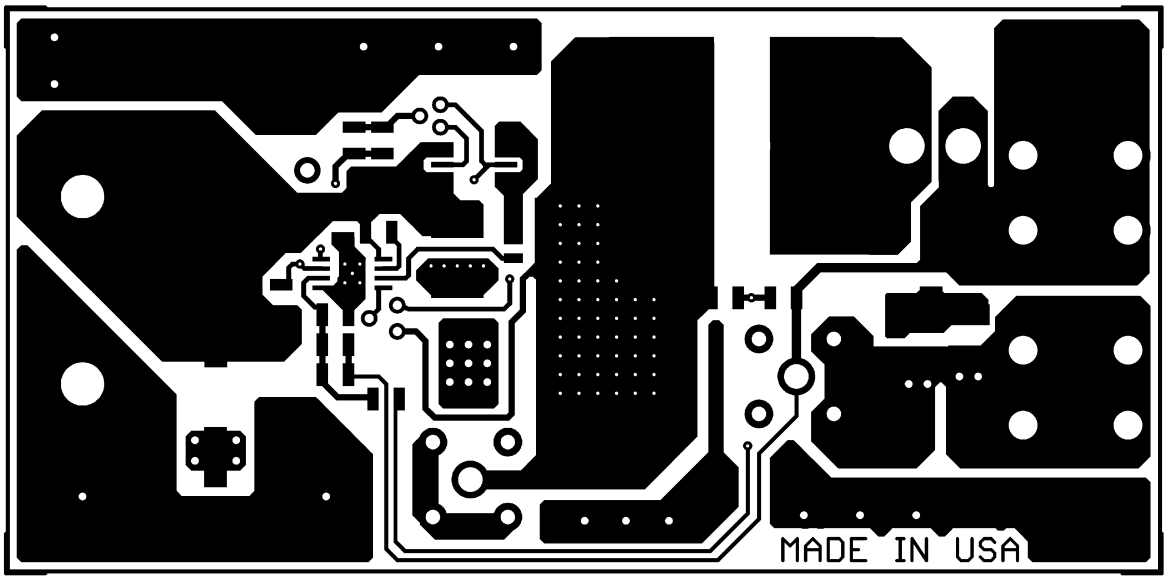


Figure 18. Board Top Layer

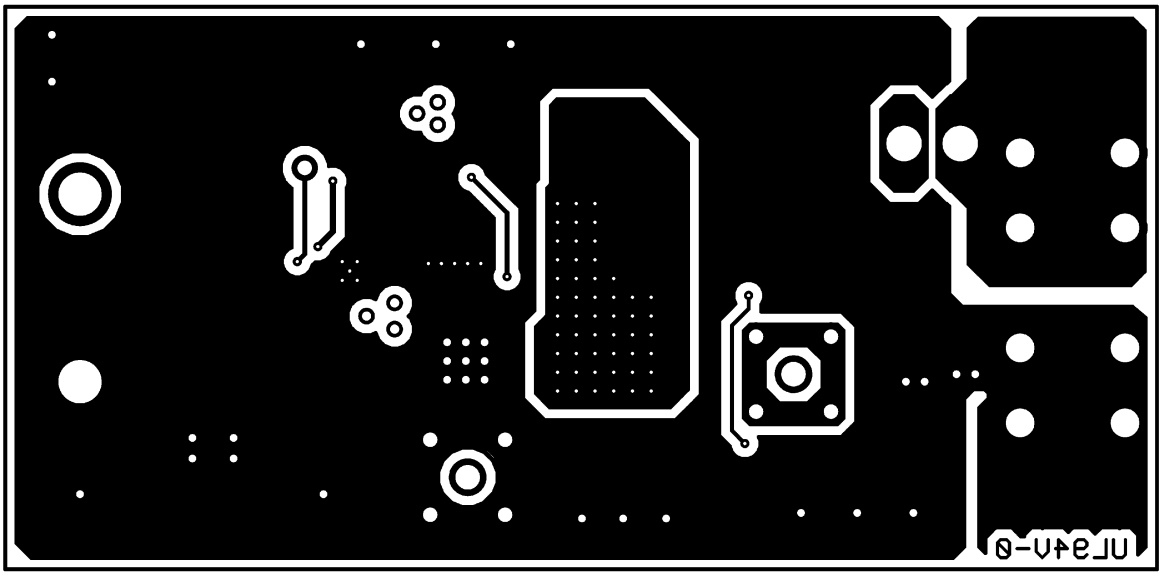


Figure 19. Board Bottom Layer (Viewed From Top)

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