

5V to 3.3V Converters for Microprocessor Systems

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Introduction

The new generation of high performance microprocessors are built on dense, low breakdown voltage processes in order to accommodate increased transistor counts. These new processors require high current power at 3.3V, developed from the 5V input used to power the rest of the system. Special techniques are required to ensure proper operation of the microprocessor and good heat dissipation within the computer system.

The 3.3V supply may be either a linear or switching type. For most applications a linear regulator is preferable since it minimizes components and has acceptable efficiency for a whole computer system. In portable computers where high efficiency is paramount because of battery operation, a switching supply is necessary.

This application note contains a collection of 3.3V regulator circuits, each optimized for a 5V input and surface mount technology. The circuits are split into two categories, linear and switching, and further arranged by current capability.

Most of the circuits, with the possible exception of the high current linear regulators, are surface mountable. Where appropriate, part numbers are given for surface mount coils, capacitors, and diodes. Resistors and small capacitors, unless there are special characteristics, are generic and manufacturer's part numbers are not shown.

Both linear and switching regulators are available for the purpose of converting 5V to 3.3V. In general, the linear regulators are the best choice at lower ($\leq 3A$) current levels where their dissipation is minimized, or in line-operated equipment where 66% theoretical efficiency is acceptable. Switchers are favored in higher current and efficiency-conscious applications. Efficiencies in the 90% to 95% range are the norm for switchers described in this application note.

Linear Regulators

Table 1 shows the range of components available for linear regulation of 3.3V with a 5V input. With only 1.7V of headroom, low dropout is essential. Low dropout regulators are available delivering currents from 125mA to 7.5A, allowing almost any microprocessor to be powered with a local 3.3V generation circuit. The first four devices (LT1020, LT1120, LT1121 and LT1129) are PNP micropower low dropout regulators. Since PNP transistors are much larger than monolithic NPNs, higher current regulators use an NPN pass device. The LT1117, LT1086, LT1083 through LT1085, and LT1087 all use NPN pass devices. The NPN structure requires about 1.2V headroom compared to the 400mV to 500mV dropout typical of PNP regulators, and ground current of 5mA or 10mA, independent of output current. Because of this constant quiescent current, the LT1117 and LT1083 family are not suitable for applications requiring micropower standby.

Table 1. 3.3V Linear Regulators

LOAD CURRENT	DEVICE	PASS DEVICE	SHUTDOWN CURRENT	TOLERANCE*
125mA	LT1020	PNP	40 μ A	2.1% (69mV)
125mA	LT1120	PNP	40 μ A	2.1% (69mV)
150mA	LT1121-3.3	PNP	16 μ A	3% (100mV)
700mA	LT1129-3.3	PNP	16 μ A	3% (100mV)
800mA	LT1117-3.3	NPN	–	2% (65mV)
1.5A	LT1086-3.3	NPN	–	1.6% (53mV)
3A	LT1085-3.3	NPN	–	1.6% (53mV)
5A	LT1084	NPN	–	1.9% (61mV)
7.5A	LT1083	NPN	–	1.9% (61mV)
10A	2 \times LT1087	NPN	–	1.9% (61mV)

*Includes line, load, and temperature variations. Adjustable parts also include worst case effect of external 1% resistors.

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Controlling Transient Loads

Microprocessors require the input voltage to be maintained within $\pm 5\%$ under worst case transients. The dynamic nodes internal to the processor are sensitive to voltage. Transients drawn by the processor are so fast that no active loop can respond in time. Adequate reserves of charge must be maintained in a group of capacitors to supply this current until the regulator can respond. This is true for both linear and switching regulators.

Modern power saving processors may draw large transient currents unlike older processors. Many include sleep modes which slow down or stop the processor when it is not in use. The transition from normal operation to sleep mode, or sleep mode to normal operation usually causes a large step in power supply current. The supply current can jump several amps in a matter of nanoseconds—far faster than any regulator can respond. Proper printed circuit layout and bypass capacitors are needed to provide these current transients.

Typical printed circuit board layouts include a power plane and a ground plane which are separate from the rest of the system. Connected to the pins of the processor are small 100nF bypass capacitors, as is common practice in processor layout. These capacitors control the voltage for very fast transients in the 10ns to 100ns time period. Further from the processor is a large reservoir capacitor located at the output of the regulator. This capacitor is typically 100 μ F to 200 μ F and provides the energy reservoir for 100ns to 2 μ s until the control loop in the regulator can correct the output. For longer durations, the control loop in the regulator keeps the output voltage constant.

When the load is released the overshoot must be controlled as well, and the capacitors absorb the energy and limit overshoot from the regulator. The capacitors must be low inductance and connected directly to the power plane close to the processor. Several inches of trace going to a capacitor can be sufficient to cause large transient voltages under changing load conditions because of the inductance in the circuit traces. The power cycling associated with the new processors makes this situation far worse than older processors which operated continuously.

An input bypass capacitor is placed close to the regulator to provide a low source impedance. The input to the

regulator must also provide an energy reservoir. Typically, here again, is a 10 μ F to 100 μ F capacitor that provides the energy at the input of the regulator during a load transient. This capacitor is mandatory since the regulator is usually situated far from the input power supply.

Both the input and output capacitors play a role in the stability of the regulator and help assure adequate transient response. The capacitor values shown in this app note represent the minimum required for stability. Additional capacitance may be necessary to handle load transients. See the design example.

Thermal Design

Heat sinking is an important consideration. For processors drawing 5A, the power dissipated in the regulator can be as high as 8.5W. This amount of power requires adequate heat sinking internal to the computer system.

The general rule for surface mounted components is to maximize the amount of copper connected to the leads of the IC. Flood all open areas, intermediate layers, and the back side of the board with copper. This aids in spreading and radiating the heat. Surface mount components can dissipate up to 2.5W (1.5A output current) using only circuit traces and ground planes totaling 2 or 3 square inches.

For higher output currents a larger heat sink is needed. To compute the thermal resistance of the heat sink it is necessary to know the maximum operating temperature of the regulator, maximum ambient inside the computer enclosure and the air flow over the heat sink. For a power dissipation of 5W (3A output current), maximum junction temperature of 125°C and maximum ambient temperature of 80°C:

$$\theta_{HS} = (T_J - T_A)/P_D - \theta_{JC}$$

$$\theta_{HS} = (125 - 80)/5 - 3$$

$$\theta_{HS} = 6^\circ\text{C/W}$$

where:

P_D = Power Dissipation ($^\circ\text{C}$)

T_J = Maximum Junction Temperature ($^\circ\text{C}$)

T_A = Maximum Ambient Temperature ($^\circ\text{C}$)

θ_{JC} = Junction to Case Thermal Resistance of IC ($^\circ\text{C/W}$)

θ_{HS} = Heat Sink Thermal Resistance ($^\circ\text{C/W}$)

The heat sink for this application must have a thermal resistance of $6^{\circ}\text{C}/\text{W}$ or less. Figure 1 shows the effect of air flow over the surface of a $6^{\circ}\text{C}/\text{W}$ heat sink (Thermalloy 7025B-MT). With no air flow the thermal resistance is dominated by convection currents; this is why the graph stops at approximately 100 feet per minute air flow. A much smaller heat sink could be used in this application if some air flow, such as from the computer's cooling fan, could be guaranteed. At higher output currents and dissipations it is almost always necessary to provide some air flow in order to avoid an unreasonably large heat sink.

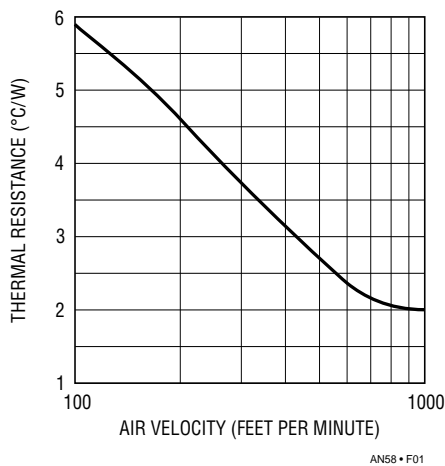


Figure 1. Thermal Resistance vs Air Flow

Selectable 5V and 3.3V

Figure 2 shows a regulator configuration which is pin selectable for 3.3V or 5V output. An external N-channel power MOSFET bypasses the regulator to provide 5V output. When the gate of the MOSFET is grounded by a pin on the microprocessor, the MOSFET turns off and the regulator supplies a 3.3V output. For this type of circuit to operate properly, the regulator must be designed to withstand 5V forced on its output pin without damage. All

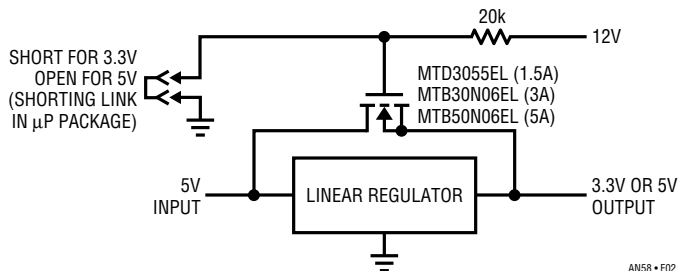


Figure 2. 3.3V Regulator with 5V Bypass Circuit

Linear Technology regulators in the LT1083/4/5/6, LT1117 and LT1121/9 families are designed to withstand over 5V with no problems.

The MOSFET has an on resistance of approximately $30\text{m}\Omega$ when the gate is driven to 12V. There is a 12V power supply available in most systems and a high value resistor can be used to tie the gate of the MOSFET high. If 12V is not available, an LTC1157 high-side driver (Figure 3) can be used to drive the gate of the MOSFET.

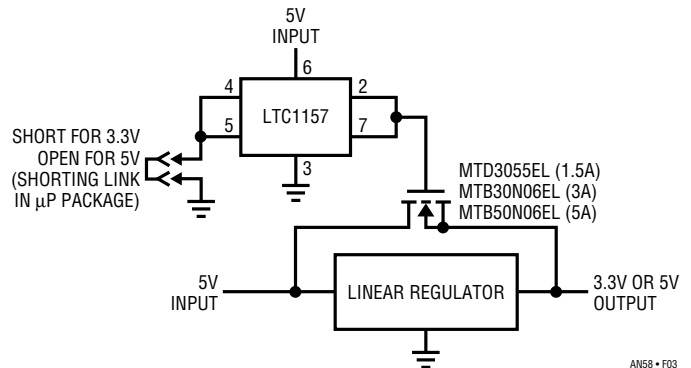


Figure 3. LT1157 Switches Between 5V and 3.3V

Switching Regulators

Properly designed step-down, or buck, switching regulators can provide 5V to 3.3V conversion efficiencies as high as 95%. In a step-down switching regulator, the inductor current flows from the input when the switch is ON and through a diode (or synchronously switching FET) from ground when the switch is OFF. Keys to high efficiency include minimizing quiescent current, using a low resistance power MOSFET switch and in higher current applications, using a synchronous switch to reduce the diode losses. In continuous operation (i.e., the inductor current does not go to zero), the duty cycle for a 5V to 3.3V switching regulator is 66%. This means that the switch is ON for 2/3 of each cycle and OFF for the remaining 1/3.

Table 2 shows four switching regulators suitable for 5V to 3.3V conversion. All of these regulators break the 90% efficiency barrier over a wide range of load currents. High efficiency makes for a compact layout and allows all surface mount solutions at high current since heat sinking is either modest or unnecessary.

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Table 2. 3.3V Switching Regulators

LOAD CURRENT	DEVICE	SYNCHRO-NOUS	SHUTDOWN CURRENT	EFFICIENCY
200mA to 400mA	LTC1174-3.3	No	1 μ A	90%
0.5mA to 2A	LTC1147-3.3	Yes	10 μ A	92%
1A to 5A	LTC1148-3.3	Yes	10 μ A	94%
5A to 20A	LT1158	Yes	2.2mA	91%

The LTC1174, LTC1147 and LTC1148 step-down, high efficiency switching regulators feature Burst Mode™ operation to maintain low quiescent current at light loads (sleep mode) and in the LTC1148, synchronous operation at higher output currents. The LTC1147 and LTC1148 use a constant off-time, current-mode architecture. This results in excellent line and load transient response, constant inductor ripple current and well controlled startup and short-circuit currents.

The LTC1174 and LTC1147 are nonsynchronous converters for applications under 1A. The LTC1148 is fully synchronous for improved efficiency in the 2A to 5A output range. In Figure 17 an LTC1147 is used for 1A output current. This circuit consumes less board space than the LTC1148 circuit of Figure 18, at the cost of 2.5% worse efficiency. The LT1158 is a half-bridge driver designed for 5V to 20A applications. At these current levels multiple paralleled MOSFETs are necessary to maintain high efficiency. The LT1158 is used in Figures 21 and 22.

The compactness of a switching regulator solution is appealing, but not all of the required components shrink as easily as semiconductors and resistors. In particular, coils and high value capacitors present special miniaturization problems. Coil size is limited by practical considerations of core volume, temperature rise, and window area. Very high power densities have been achieved through the use of ferrite cores and materials such as molypermalloy. Unfortunately, the selection of surface mount bobbins for “E” style split cores has lagged behind. This area is the focus of development work but product introductions are slow in coming. A list of surface mount component suppliers can be found in Appendix A of Application Note 54.

Burst Mode™ is a trademark of Linear Technology Corporation

Power Supply Sequencing and Rise Time

New 3.3V microprocessors must interface with 5V logic circuits. As a precaution against damaging logic interfaces, supply turn-on characteristics must be controlled. For example, one specification calls for a maximum difference between the system (5V) supply and the microprocessor (3.3V) supplies of 2.25V. Not all of the circuits shown will meet this specification or have been characterized for input/output differential.

The linear regulators in the LT1083 thru LT1086 family will maintain proper startup and shutdown voltages for mixed supply systems. On turn-on, the output follows the input less the 1.2V dropout voltage until 3.3V is reached on the output. At turn-off, an internal diode insures the 3.3V supply follows the 5V supply down.

Recommended Circuit Design Example

Figure 4 shows a recommended circuit for general purpose 5V to 3.3V conversion in desktop machines. Since the microprocessor draws only a fraction of the total system power, the 66% efficiency of a linear regulator gives acceptable performance. The system requirements are:

$$V_{IN} = 5V \pm 0.25V$$

$$V_{OUT} = 3.3V \pm 0.3V$$

$$I_{OUT} = 3A$$

Transients Loads: 200mA to 3A in 100ns and 3A to 100mA in 100ns

Maximum Circuit Height: 1.5"

Bypass Option: 5V out through low resistance switch if 3.3V processor is not installed.

The LT1085 fullfills these requirements with the output bypassing capacitors shown in Figure 4. The 5V bypass switch, detailed in Figures 2 and 3 can be added as an option. A pin on the 3.3V microprocessor serves as the ground shorting switch to disable the bypass circuit.

Thermal design, as previously discussed, would require a 6°C/W heat sink. The Thermalloy 7025B-MT or Aavid 533402 meet this requirement as well as the 1.5" maximum height requirement.

Regulation, including all combinations of line, load, and temperature, is better than 1.6% (53mV) for the LT1085—well inside the 300mV specification. Figure 5 shows the transient response to a 3A load change. The transient

response should be checked in the finished circuit to verify the layout and capacitor placement.

Figure 6 shows the output voltage tracking as the system is powered up and down. Note that the 5V supply never out runs the 3.3V supply by more than approximately 1.2V, thereby protecting the processor from damage.

Ground current for the LT1085 is just 5mA, even at 3A output current.

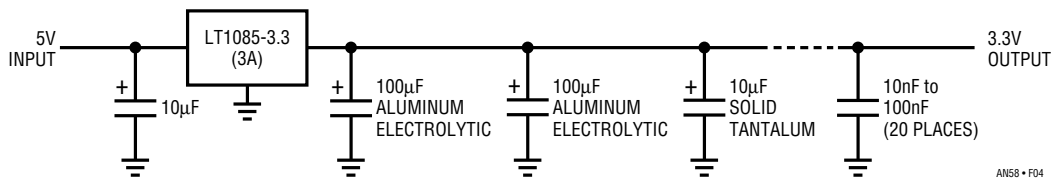


Figure 4. Multiple Bypassing is Necessary in Order to Assure Good Transient Response

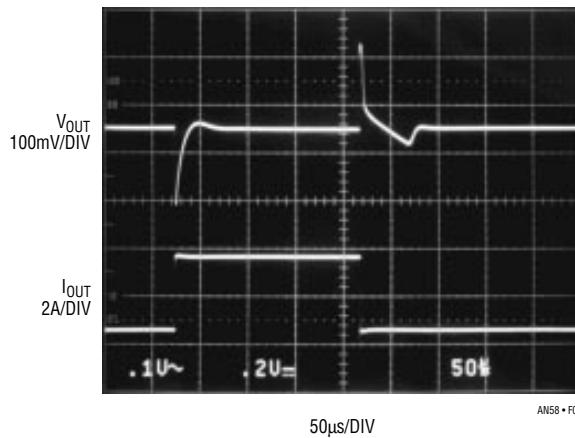
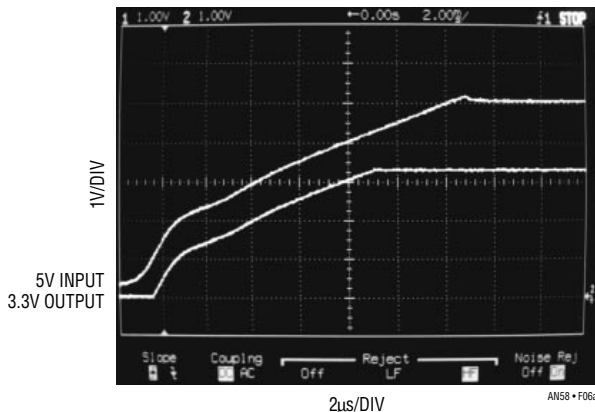
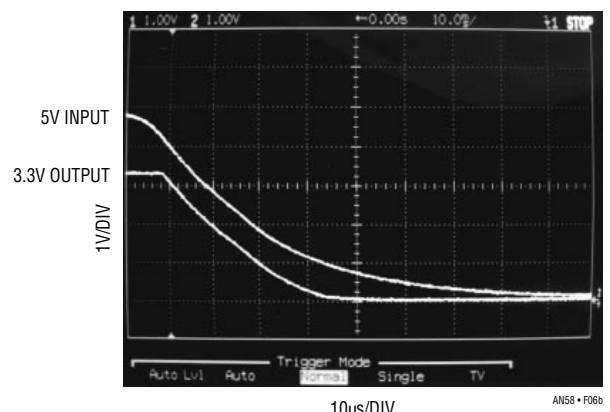


Figure 5. Regulator Transient Response



6A. Power Up



6B. Power Down

Figure 6. 5V/3.3V Tracking at Power Up and Power Down

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CIRCUIT INDEX

Linear Regulators

CURRENT	DEVICE	FIGURE NUMBER	PAGE NUMBER
125mA	LT1020/LT1120	7	AN58-6
150mA	LT1121	8	AN58-6
700mA	LT1129	9	AN58-6
800mA	LT1117	10	AN58-6
1.5A	LT1086	11	AN58-7
3A	LT1085	11	AN58-7
5A	LT1084	12	AN58-7
7.5A	LT1083	12	AN58-7
10A	LT1087	13	AN58-7

Switching Regulators

CURRENT	DEVICE	FIGURE NUMBER	PAGE NUMBER
175mA	LTC1174	14	AN58-7
425mA	LTC1174	15	AN58-8
500mA	LTC1147	16	AN58-8
1A	LTC1147	17	AN58-9
1A	LTC1148	18	AN58-10
2A	LTC1148	19	AN58-11
5A	LTC1148	20	AN58-12
7.5A (10Apk)	LTC1158	21	AN58-13
15A (20Apk)	LTC1158	22	AN58-14

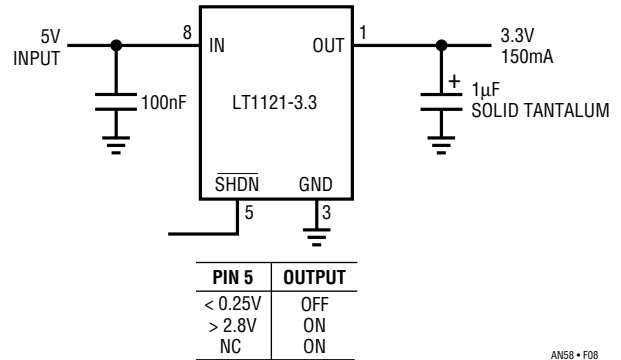
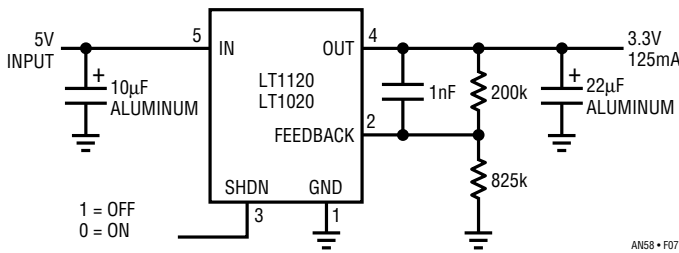


Figure 7. The LT1120 and LT1020 Include On-Chip Comparator Functions. See Their Data Sheets for Details

Figure 8. The Output of the LT1121 Can Be Pulled Up to 5V with No III Effects

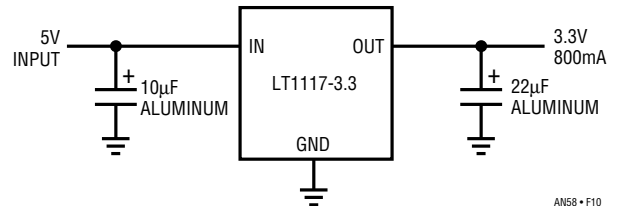
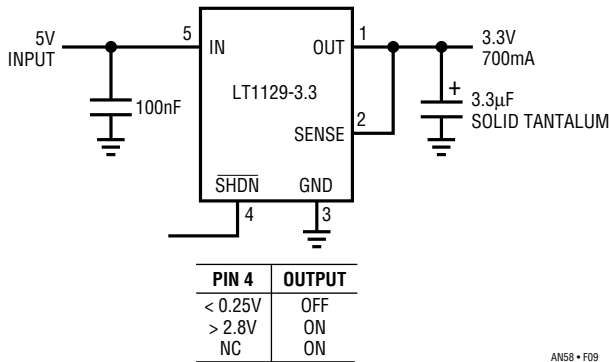


Figure 9. The Output of the LT1129 Can Be Pulled Up to 5V with No III Effects

Figure 10. The LT1117 is Available in a Low Cost, SOT-223 Package

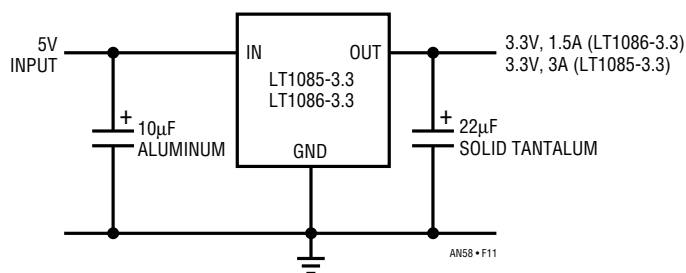


Figure 11. See Figure 4 in the Design Example for Practical Bypassing Values

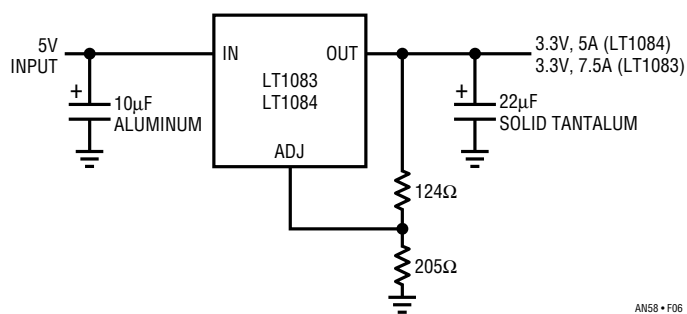


Figure 12. Five Components Deliver Up to 7.5A

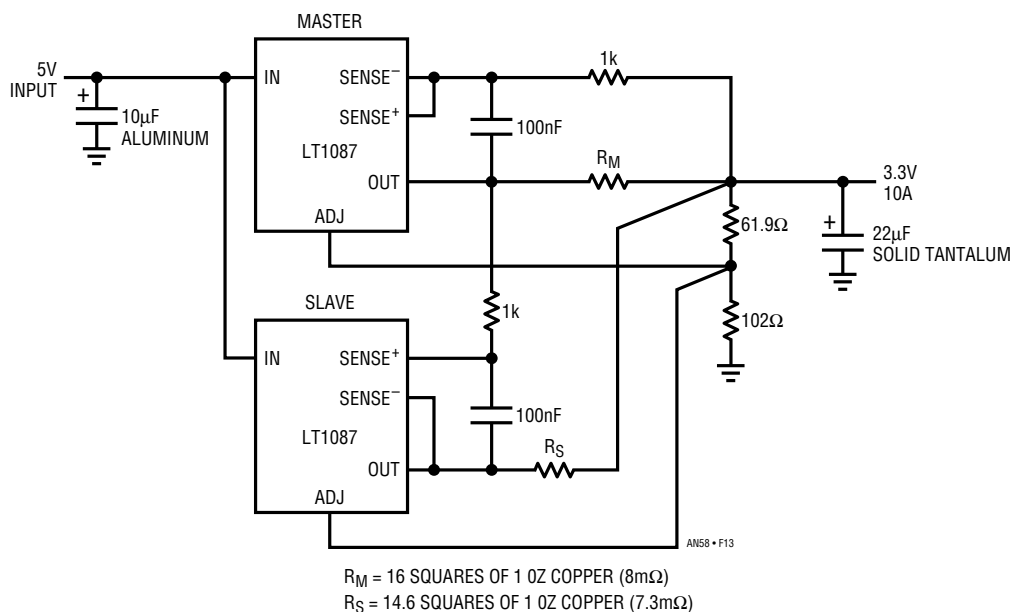
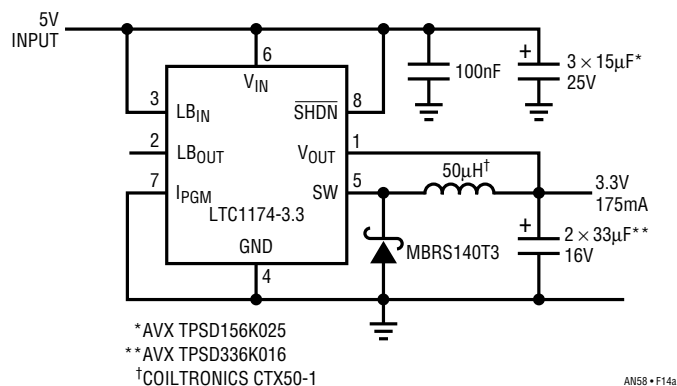
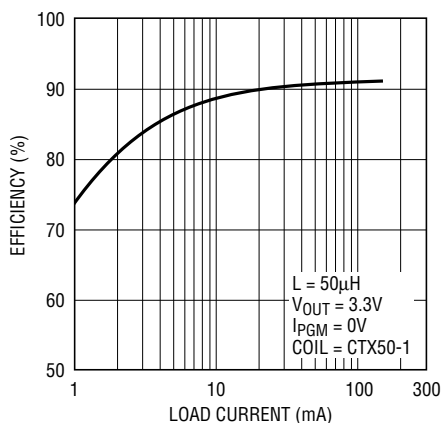


Figure 13. Independently, LT1087s Handle 5A. Their Reference Sense Pins Force Current Sharing for Parallel Operation at 10A



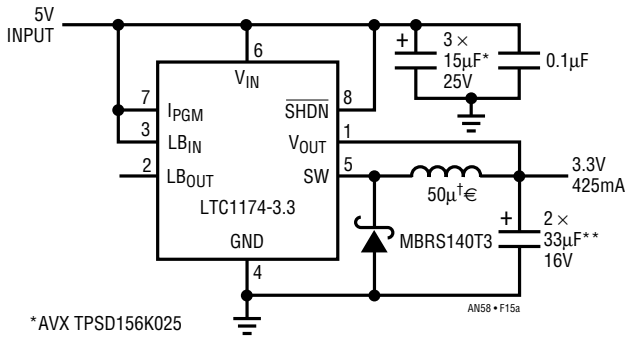
14A.



14B.

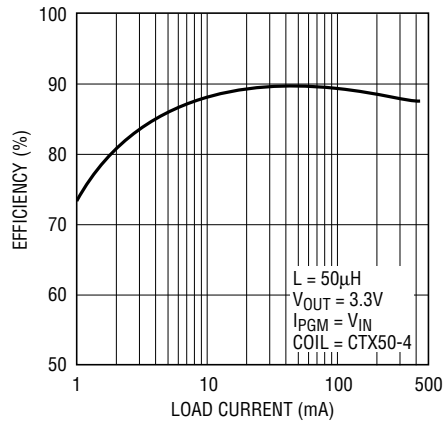
Figure 14. The LTC1174-3.3 Uses Burst Mode™ Operation Throughout its Entire Current Range. Shutdown Current is Just 1µA

Application Note 58



*AVX TPSD156K025
 **AVX TPSD336K016
 †COILTRONICS CTX50-4

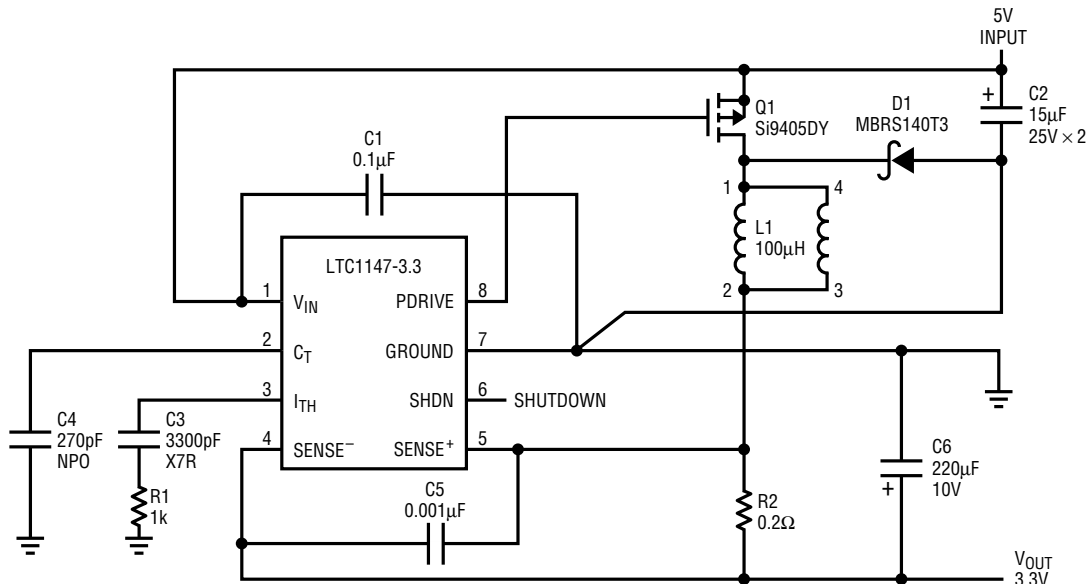
15A.



AN58 • F15b

15B.

Figure 15. Pulling I_{PGM} (Pin 7) High Increases the Internal Current Threshold and Output Current Capability

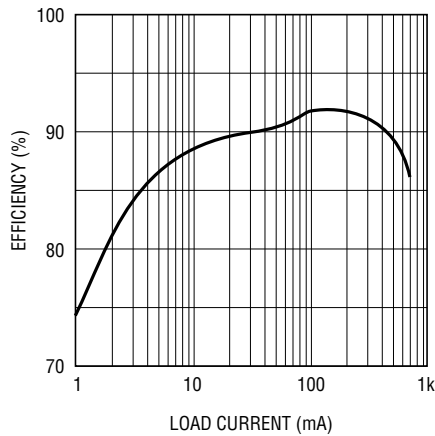


C2: AVX (Ta) TPSD156K025R0200, ESR = 0.200Ω, I_{RMS} = 0.775A
 C6: AVX (Ta) TPSE227K010R0080, ESR = 0.80Ω, I_{RMS} = 1.285A
 Q1: SILICONIX BV_{DSS} = 20V, DCR_{ON} = 0.14Ω, Q_g = 29nC

D1: MOTOROLA
 R2: KRL SP-1/2-A1-0R200, P_D = 0.75W
 L1: COILTRONICS CTX100-4, DCR = 0.175Ω, Kool M μ ® Core

AN58 • F16a

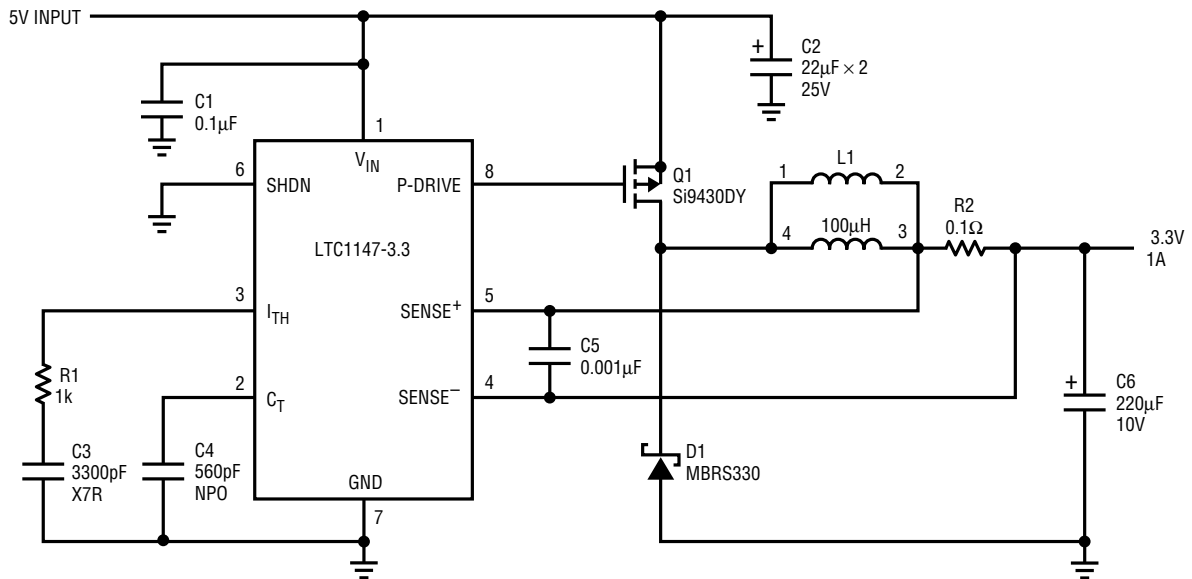
16A.



AN58 • F16b

16B.

Figure 16. Slightly Improved Efficiency Over the Circuit of Figure 15, with Continuous Mode Operation at Higher Loads

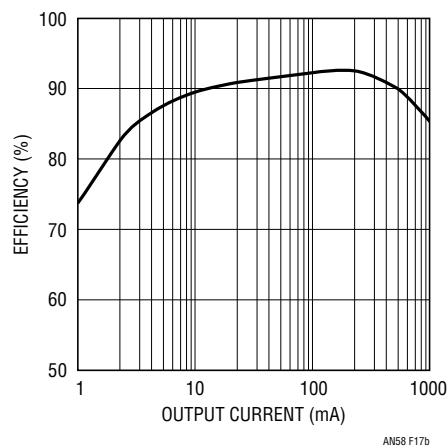


- C2: AVX (Ta) TPSD226K025R0200 ESR = 0.200Ω I_{RMS} = 0.775A
- C6: AVX (Ta) TPSE227K010R0080 ESR = 0.080Ω I_{RMS} = 1.285A
- Q1: SILICONIX BV_{DSS} = 20V DCR_{ON} = 0.100Ω C_{RSS} = 400pF Q_g = 50nC
- D1: MOTOROLA
- R2: KRL SP-1/2-A1-0R100 Pd = 0.75W
- L1: COILTRONICS CTX100-4 DCR = 0.175Ω KOOL M_µ® CORE

QUIESCENT CURRENT = 170µA
 TRANSITION CURRENT (BURST MODE™ OPERATION/CONTINUOUS OPERATION) = 170mA

AN58 F17a

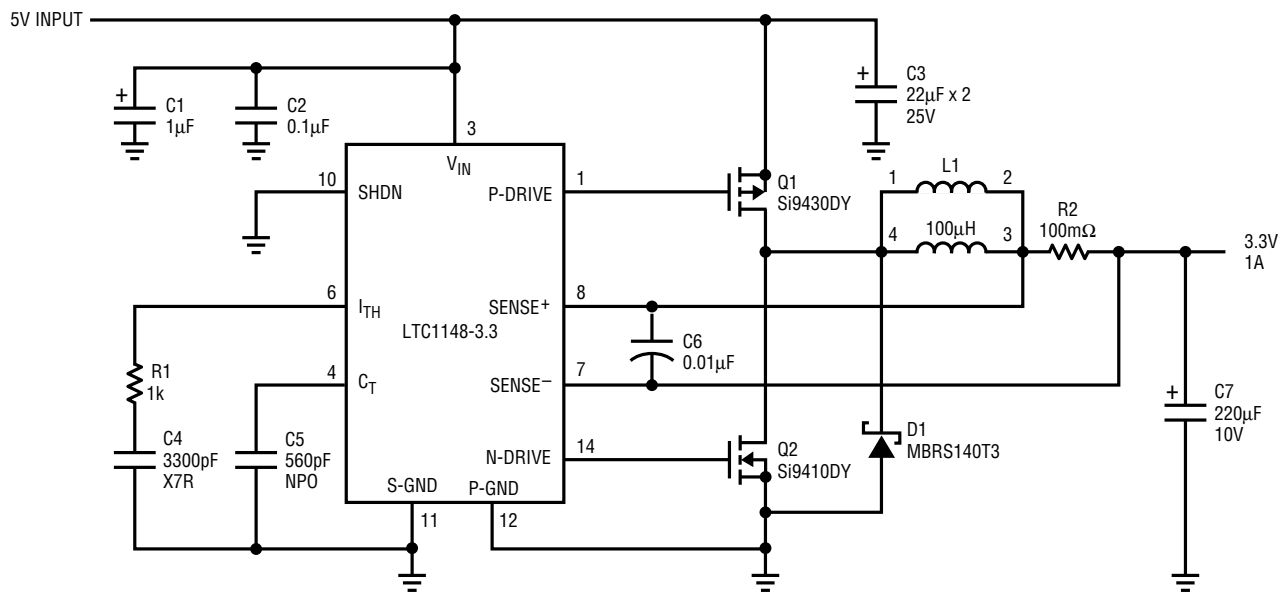
Figure 17A. LTC1147 (5V to 3.3V/1A) Buck Converter with Surface Mount Technology. Shutdown Current is Just 10µA



AN58 F17b

Figure 17B. LTC1147 (5V to 3.3V/1A) Buck Converter Measured Efficiency

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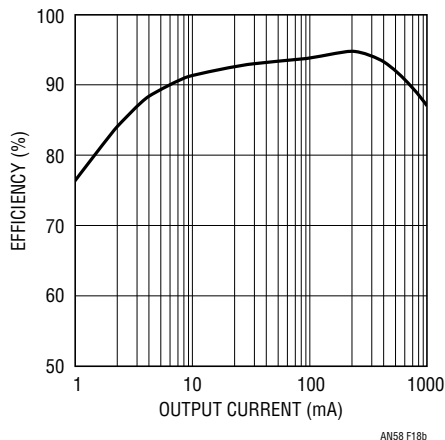
- C1: (Ta)
- C3: AVX (Ta) TPSD226K025R0200 ESR = 0.200Ω I_{RMS} = 0.775A
- C7: AVX (Ta) TPSE227K010R0080 ESR = 0.080Ω I_{RMS} = 1.285A
- Q1: SILICONIX NMOS BV_{DSS} = 20V RDS_{ON} = 0.100Ω C_{RSS} = 400pF Q_g = 50nC
- Q2: SILICONIX NMOS BV_{DSS} = 30V RDS_{ON} = 0.050Ω C_{RSS} = 160pF Q_g = 30nC
- D1: MOTOROLA SCHOTTKY VBR = 40V
- R2: KRL SP-1/2-A1-0R100J Pd = 0.75W
- L1: COILTRONICS CTX100-4 DCR = 0.175Ω KOOL Mµ[®] CORE

QUIESCENT CURRENT = 180µA
 TRANSITION CURRENT (BURST MODE™ OPERATION/CONTINUOUS OPERATION) = 250mA

ALL OTHER CAPACITORS ARE CERAMIC

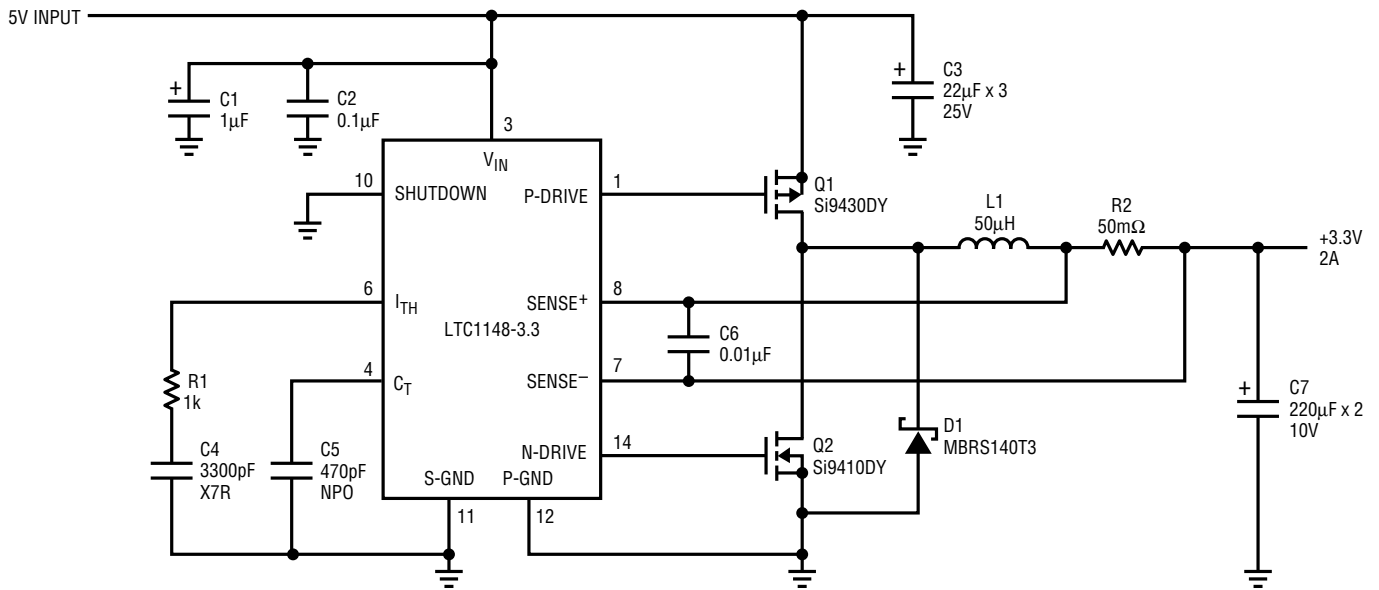
AN58 F18a

Figure 18A. LTC1148 (5V to 3.3V/1A) Fully Synchronous Buck Converter



AN58 F18b

Figure 18B. LTC1148 (5V to 3.3V/1A) Buck Converter Measured Efficiency



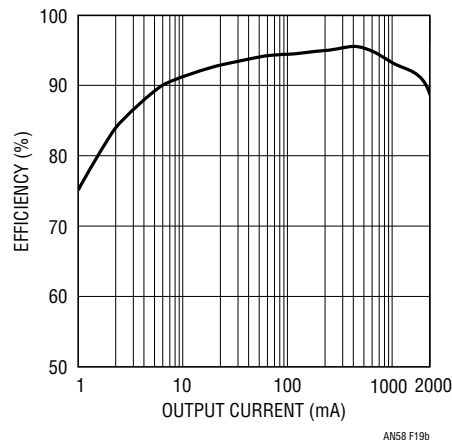
- C1: (Ta)
- C3: AVX (Ta) TPSD226K025R0200 ESR = 0.200Ω I_{RMS} = 0.775A
- C7: AVX (Ta) TPSE227K010R0080 ESR = 0.080Ω I_{RMS} = 1.285A
- Q1: SILICONIX PMOS BV_{DSS} = 20V RDS_{ON} = 0.100Ω C_{RSS} = 400pF Q_g = 50nC
- Q2: SILICONIX NMOS BV_{DSS} = 30V RDS_{ON} = 0.050Ω C_{RSS} = 160pF Q_g = 30nC
- D1: MOTOROLA SCHOTTKY VBR = 40V
- R2: KRL SL-1-C1-0R050J Pd = 1W
- L1: COILTRONICS CTX50-2-MP DCR = 0.032Ω MPP CORE (THROUGH HOLE)

QUIESCENT CURRENT = 180µA
 TRANSITION CURRENT (BURST MODE™ OPERATION/CONTINUOUS OPERATION) = 450mA

ALL OTHER CAPACITORS ARE CERAMIC

AN58 F19a

Figure 19A. LTC1148 (5V to 3.3V/2A) Buck Converter



AN58 F19b

Figure 19B. LTC1148 (5V to 3.3V/2A) Buck Converter Measured Efficiency

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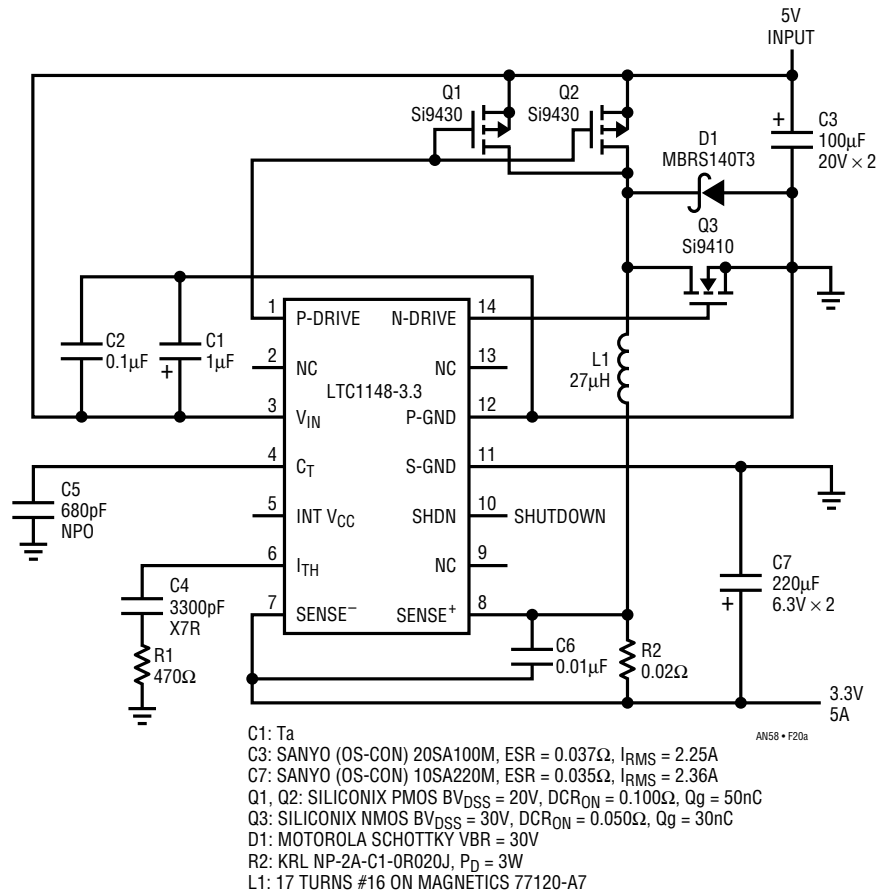


Figure 20A. LTC1148 (5V to 3.3V/5A) Buck Converter. Beyond 5A the LT1158 is a Better Choice

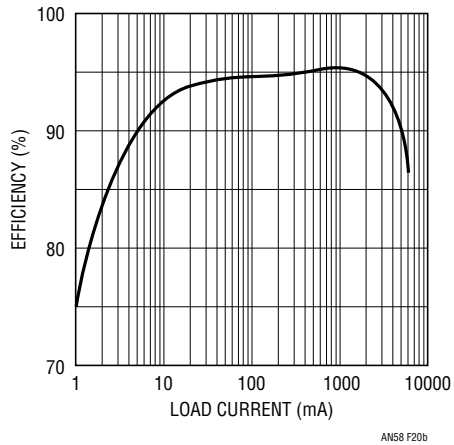


Figure 20B. LTC1148 (5V to 3.3V/5A) Buck Converter Measured Efficiency

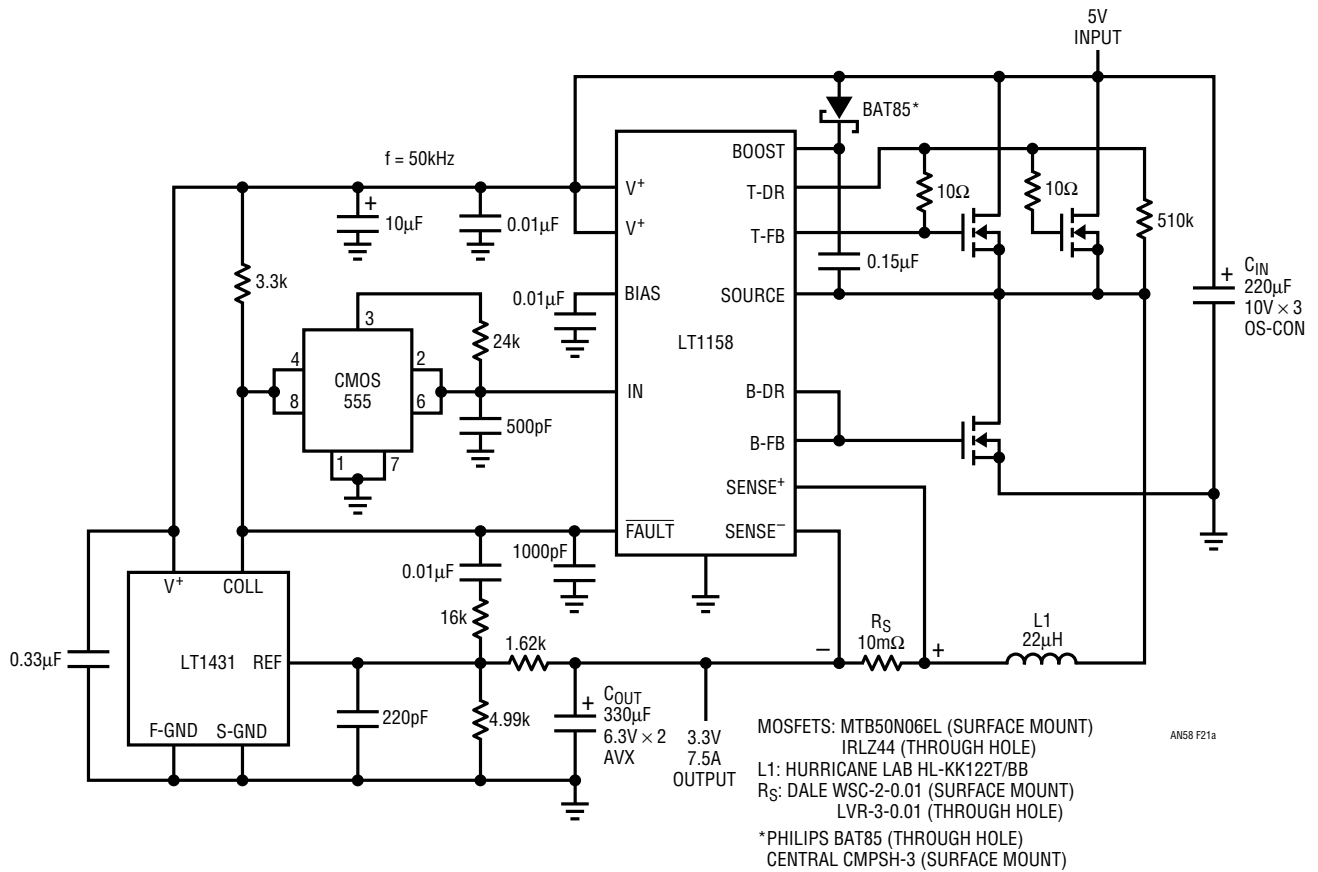


Figure 21A. High Efficiency High Current 5V to 3.3V Switching Regulator
 Output Current = 7.5A Cont. 10A Peak

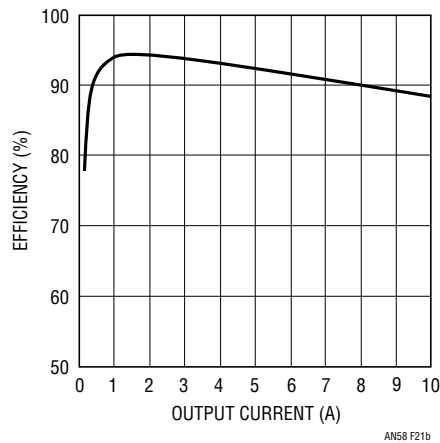


Figure 21B. High Efficiency High Current 5V to 3.3V Switching Regulator

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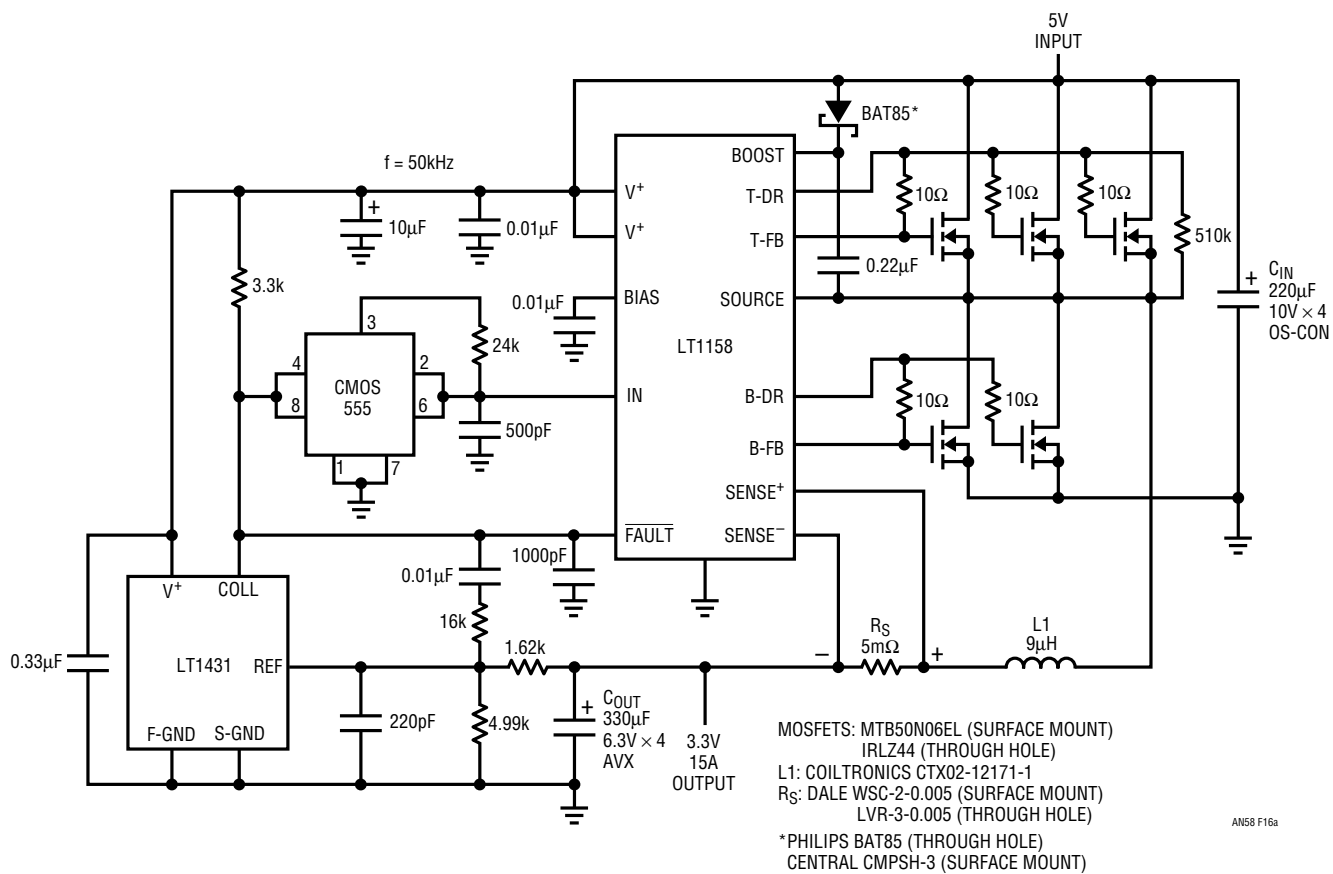


Figure 22A. High Efficiency High Current 5V to 3.3V Switching Regulator
 Output Current = 15A Cont. 20A Peak

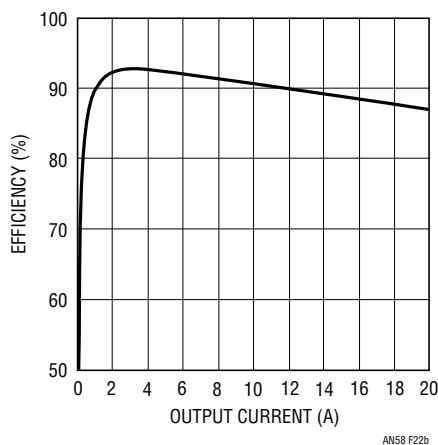


Figure 22B. High Efficiency High Current 5V to 3.3V Switching Regulator

APPENDIX

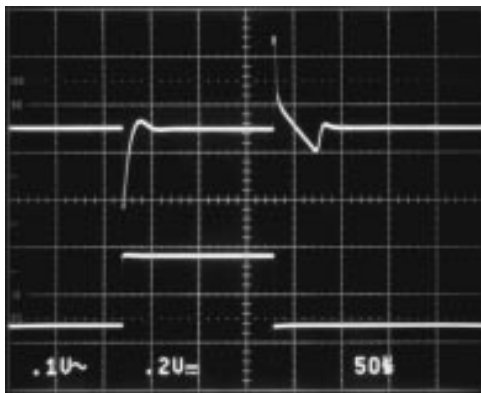
The following photographs illustrate the effect of various types and values of output capacitance on the transient response of the LT1085. The current step for these photographs is equal to the worst case supply current change specified by Intel. This current step occurs when the processor transitions from an idle state to a running state or from a running state to an idle state. The current step illustrated in the photographs is from 100mA to 3A and then from 3A back to 100mA. Both transitions occur in 100ns.

A number of different capacitor types and combinations were used. In each case the capacitors were chosen to limit the output voltage deviation to less than $\pm 5\%$ of 3.3V.

For all photographs:

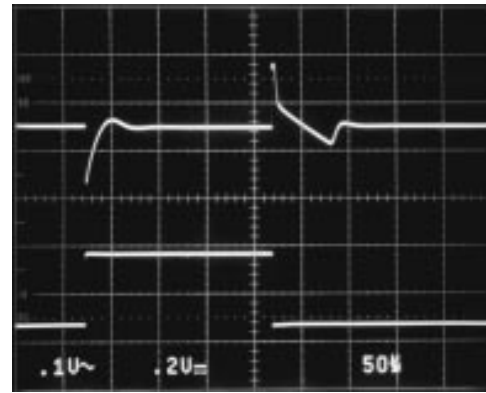
- 1) The top trace is the output variation and the vertical scale is equal to 100mV per division.
- 2) The bottom trace is the output current step at 2A per division. The horizontal scale for all photographs is 50 μ s per division.

**$C_{OUT} = 100\mu\text{F}/10\text{V AVX}$
Tantalum, Surface Mount**



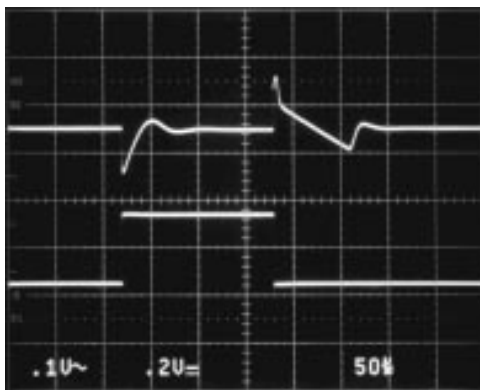
APXA1

**$C_{OUT} = 100\mu\text{F}/10\text{V AVX}$ Tantalum,
Surface Mount in Parallel with $100\mu\text{F}/16\text{V}$
Aluminum Electrolytic**



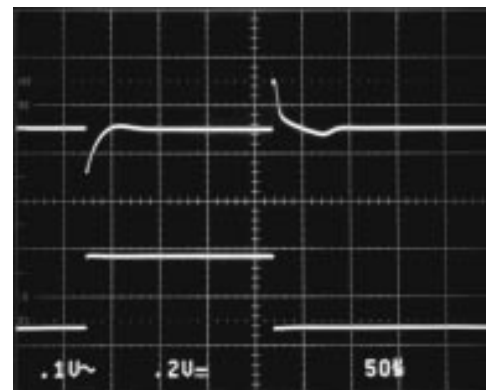
APXA2

**$C_{OUT} = 2\text{-}100\mu\text{F}/10\text{V AVX}$
Tantalum, Surface Mount in Parallel**



APXA3

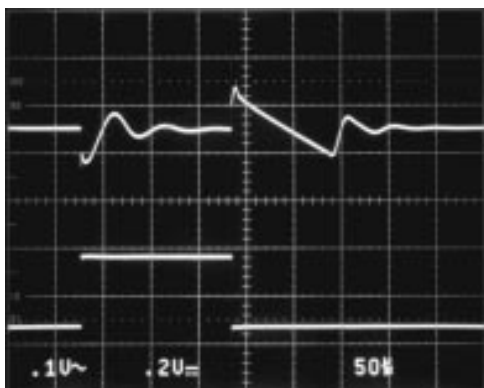
**$C_{OUT} = 100\mu\text{F}/10\text{V AVX}$ Tantalum,
Surface Mount in Parallel with $390\mu\text{F}/16\text{V}$
Aluminum Electrolytic**



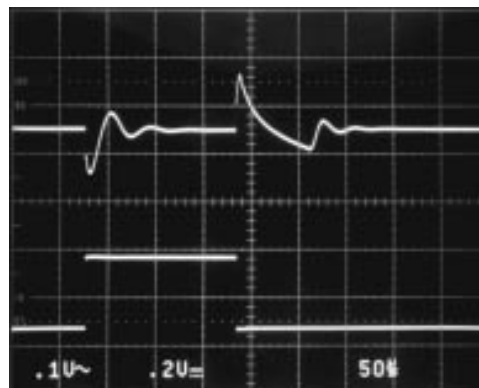
APXA4

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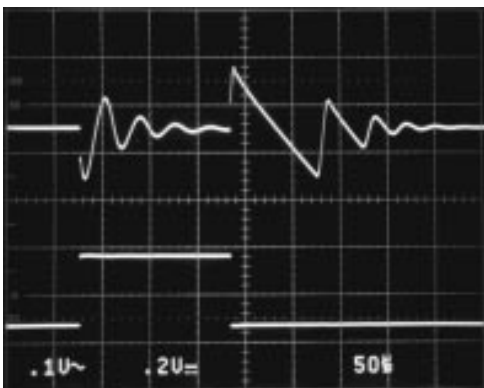
$C_{OUT} = 220\mu\text{F}/10\text{V OS-CON}$



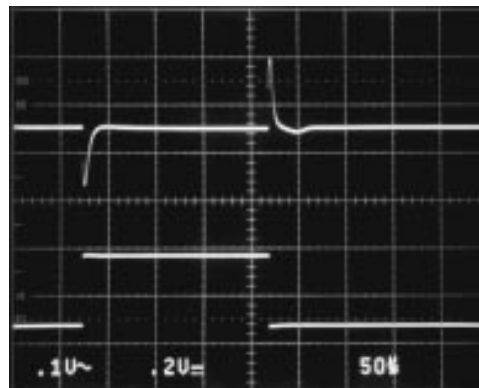
$C_{OUT} = 100\mu\text{F}/16\text{V OS-CON}$ in Parallel with $220\mu\text{F}/16\text{V}$ Aluminum Electrolytic



$C_{OUT} = 100\mu\text{F}/16\text{V OS-CON}$



$C_{OUT} = 22\mu\text{F}/20\text{V OS-CON}$ in Parallel with $390\mu\text{F}/16\text{V}$ Aluminum Electrolytic



$C_{OUT} = 100\mu\text{F}/16\text{V OS-CON}$ in Parallel with $100\mu\text{F}/16\text{V}$ Aluminum Electrolytic

