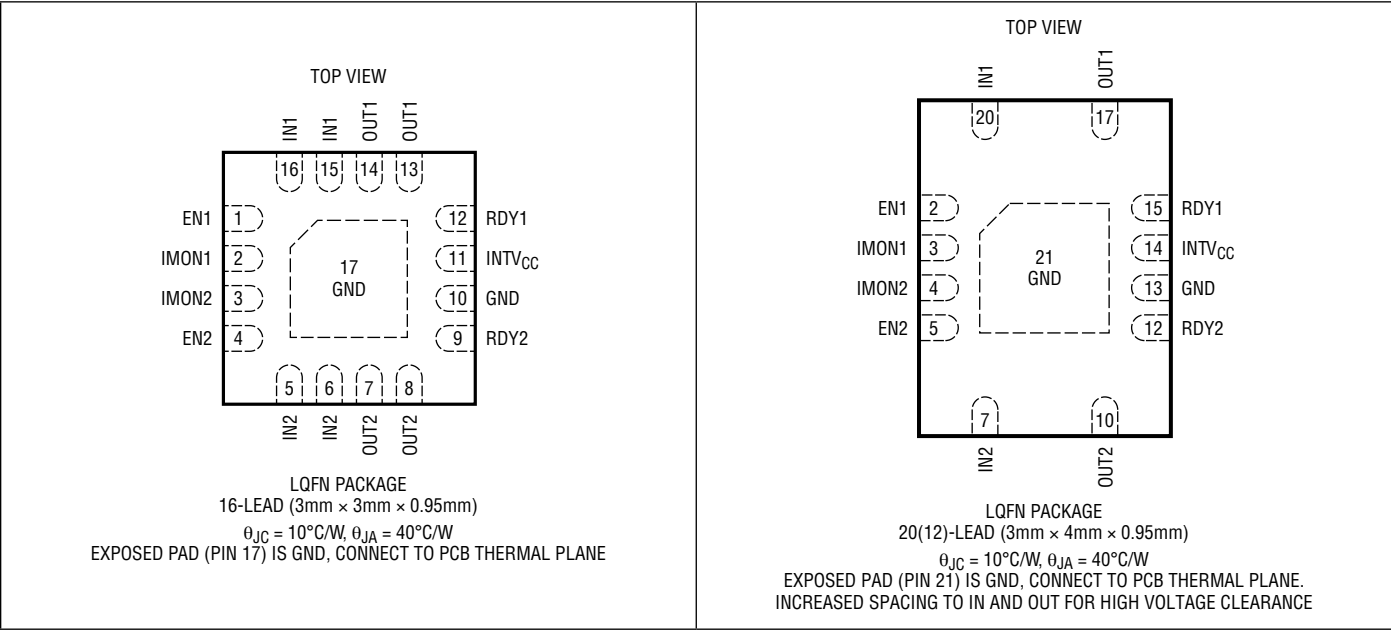




ABSOLUTE MAXIMUM RATINGS (Notes 1, 2, 3, 4)

Input Voltages		Input Currents	
IN1, IN2.....	–0.3V to 72V	IN1, IN2.....	3A
EN1, EN2 (Note 5).....	–0.3V to 5.5V	Output Currents	
Output Voltages		OUT1, OUT2.....	–3A
OUT1, OUT2.....	–0.3V to 72V	RDY1, RDY2	10mA
RDY1, RDY2.....	–0.3V to 5.5V	IMON1, IMON2.....	–1mA
IMON1, IMON2.....	–0.3V to 2.7V	Operating Junction Temperature Range	
INTV _{CC}	–0.3V to 5.5V	LTC4249A	–40°C to 125°C
		Storage Temperature Range	–65°C to 150°C

PIN CONFIGURATION



ORDER INFORMATION

TRAY	PART MARKING	PACKAGE DESCRIPTION	FAULT RESPONSE	TEMPERATURE RANGE
LTC4249AV-1#PBF	LHMZ	16-Lead (3mm × 3mm × 0.95mm) LQFN Package	Latch Off	–40°C to 125°C
LTC4249AV2-1#PBF	4249	20(12)-Lead (3mm × 4mm × 0.95mm) LQFN Package	Latch Off	–40°C to 125°C

Contact the factory for parts specified with wider operating temperature ranges.

ELECTRICAL CHARACTERISTICS The ● denotes specifications that apply over the full operating temperature range, otherwise specifications are at $T_A = 25^\circ\text{C}$. $V_{IN1} = V_{IN2} = 52\text{V}$ and $R_{IMON} = 10\text{k}\Omega$ unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
Channel Inputs (IN1, IN2)							
V_{IN1}	IN1 Operating Range		●	6		65	V
V_{IN2}	IN2 Operating Range	$V_{IN1} \geq 6\text{V}$	●	1.5		65	V
I_{MAX}	IN1, IN2 Maximum Steady State ECB Current				1.2		A
I_{IN1}	IN1 Input Supply Current	$I_{OUT1} = I_{OUT2} = 0\text{A}$; $EN1 = EN2 = 3.3\text{V}$ $I_{OUT1} = I_{OUT2} = 0\text{A}$; $EN1 = EN2 = \text{GND}$	● ●		1 0.6	1.5 0.8	mA mA
I_{IN2}	IN2 Input Supply Current	$I_{OUT2} = 0\text{A}$, $EN2 = 3.3\text{V}$ $I_{OUT2} = 0\text{A}$, $EN2 = \text{GND}$	● ●		20 0.5	28 3	μA μA
R_{ON}	ECB On-Resistance	$I_{OUT} = -1\text{A}$	●	50	75	150	$\text{m}\Omega$
R_{ONM}	ECB Channel to Channel R_{ON} Matching	$I_{OUT} = -1\text{A}$	●		± 1	± 4	%
Channel Outputs (OUT1, OUT2)							
I_{CL}	ECB Turn-On Inrush Current	$C_{OUT} = 100\mu\text{F}$	●	-0.8	-1	-1.2	A
t_{CL}	Inrush Current Limited Operating Time		●	8	10	12	ms
V_{SC}	Short-Circuit Comparator Threshold		●	1.14	1.2	1.26	V
t_{SC}	Short-Circuit Evaluation Delay	EN rising to short-circuit fault	●	240	300	360	μs
Current Monitor and Electronic Circuit Breaker (ECB) Thresholds (IMON1, IMON2)							
G_{IMON}	IMON Gain	$I_{OUT} = -30\text{mA}$ to -1.2A	●	95	100	105	$\mu\text{A}/\text{A}$
I_{OC}	IMON Offset Current	$I_{OUT} = -30\text{mA}$				± 1	μA
V_{IMON}	IMON Output Voltage	$I_{OUT} = -1\text{A}$	●	950	1000	1050	mV
I_{ACC}	IMON Output Current Accuracy	$I_{OUT} = -1\text{A}$ $I_{OUT} = -1\text{A}$, $T_A = 25^\circ\text{C}$	●			± 5 ± 2	% %
V_{ECB1}	V_{IMON} at Primary ECB Threshold		●	1.17	1.20	1.23	V
V_{ACC1}	Primary ECB Accuracy		●			± 2.5	%
V_{ECB2}	V_{IMON} at Secondary ECB Threshold		●	2.28	2.40	2.52	V
V_{ACC2}	Secondary ECB Accuracy		●			± 5	%
t_{OC1}	ECB Response Time to Primary OC	Step I_{OUT} from -1.15A to -1.25A ; measure time from step to RDY Low	●	30	50	70	μs
t_{OC2}	ECB Response Time to Secondary OC	Step I_{OUT} from -0.5A to -2.5A ; measure time from step to RDY Low $T_A > 0^\circ\text{C}$ $T_A < 0^\circ\text{C}$			2 4	4 18	μs μs
Enable Inputs (EN1, EN2)							
V_{ENTH}	EN Rising Threshold		●	780	800	820	mV
V_{ENHYS}	EN Threshold Hysteresis	EN Falling			35		mV
t_{ENMIN}	Minimum EN Input Pulse Width		●	10			μs

ELECTRICAL CHARACTERISTICS The ● denotes specifications that apply over the full operating temperature range, otherwise specifications are at $T_A = 25^\circ\text{C}$. $V_{IN1} = V_{IN2} = 52\text{V}$ and $R_{IMON} = 10\text{k}\Omega$ unless otherwise specified.

SYMBOL	PARAMETER	CONDITIONS		MIN	TYP	MAX	UNITS
Ready Outputs (RDY1 and RDY2)							
V_{OL}	Output Low Voltage	$I_{RDY} = 3\text{mA}$	●		50	150	mV
I_{OH}	Open-Drain Output High Leakage Current	$RDY = 5\text{V}$	●			1	μA
t_{COOL}	ECB Cool-Down Time after Fault		●	0.8	1	1.2	s
INTV_{CC} Output							
V_{CCOR}	INTV _{CC} Operating Range	Decoupled with $0.1\mu\text{F}$ to GND	●	3.7	4.2	4.7	V

Note 1: Stresses beyond those listed under Absolute Maximum Ratings may cause permanent damage to the device. Exposure to any Absolute Maximum Rating condition for extended periods may affect device reliability and lifetime.

Note 2: All currents into pins are positive; all voltages are referenced to GND unless otherwise noted.

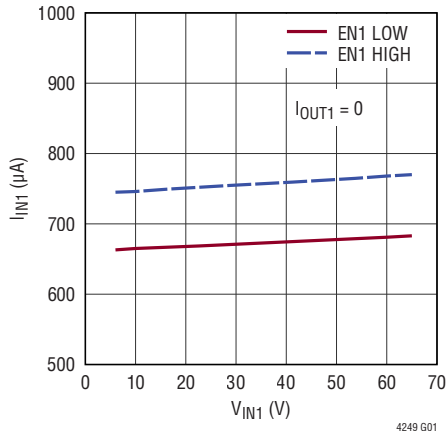
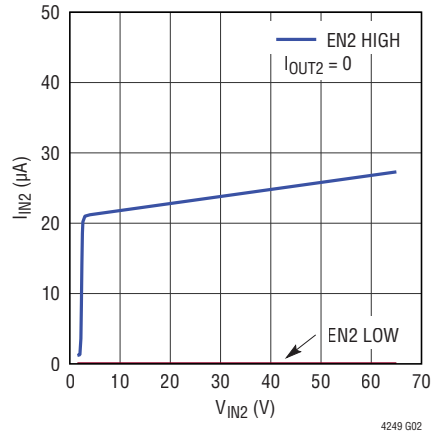
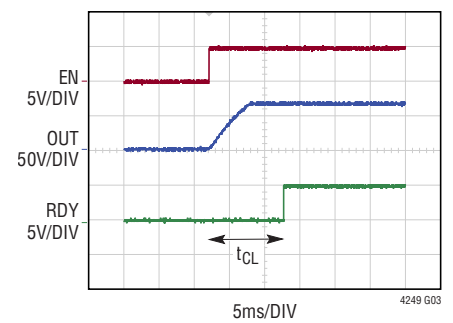
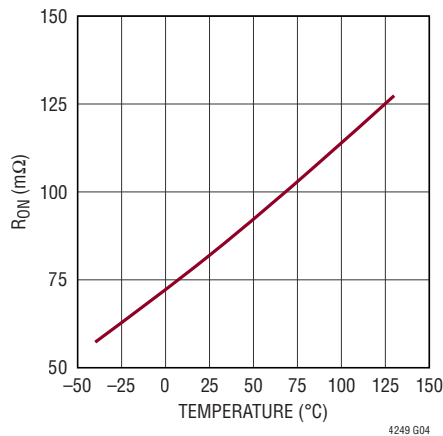
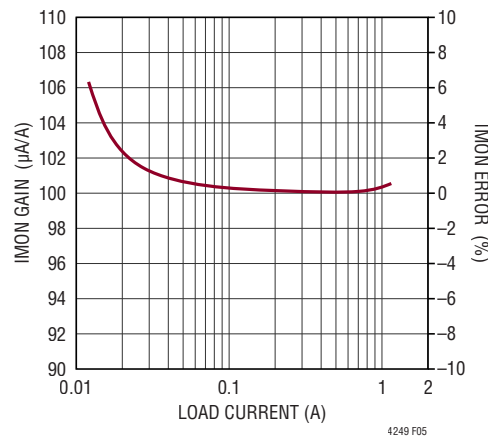
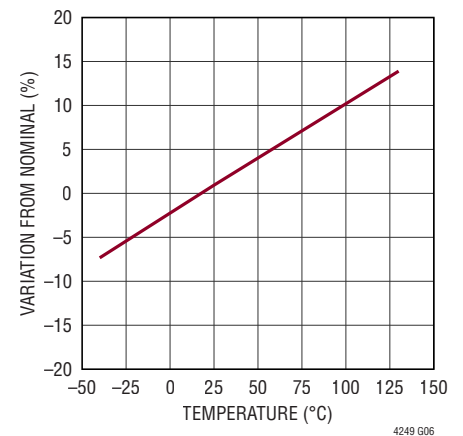
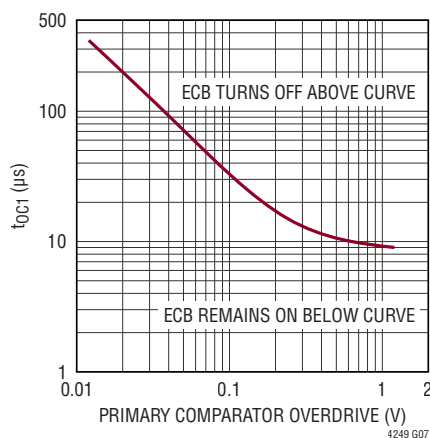
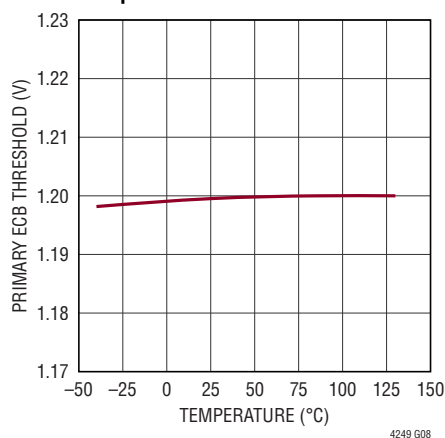
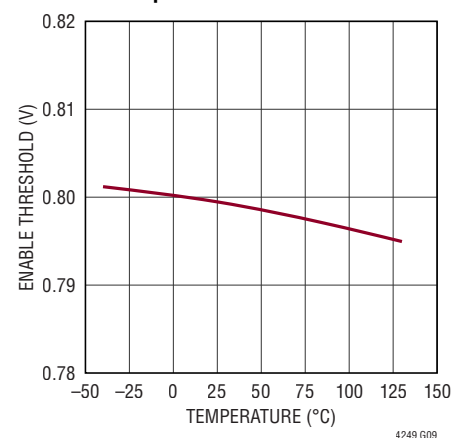
Note 3: The LTC4249 is tested under pulsed load conditions such that $T_J \approx T_A$. The junction temperature (T_J in $^\circ\text{C}$) is calculated from the ambient temperature (T_A in $^\circ\text{C}$) and power dissipation (P_D in Watts) according to the formula:

$$T_J = T_A + (P_D \cdot \theta_{JA}).$$

Note 4: The LTC4249 includes overtemperature protection that is intended to protect the device during momentary overload conditions. Junction temperature will exceed 150°C when overtemperature protection is active. Continuous operation above the specified maximum operating junction temperature may impair device reliability.

Note 5: These pins can be pulled below -0.3V through a resistor that limits the current below 1mA .

TYPICAL PERFORMANCE CHARACTERISTICS

IN1 Current vs IN1 Voltage

IN2 Current vs IN2 Voltage

OUT Charging 100μF (IN = 65V)

On-Resistance vs Temperature

IMON Gain and Error

Timing Variation vs Temperature
 t_{CL} , t_{SC} , t_{COOL}

Primary Comparator Response vs Overdrive

Primary ECB Threshold vs Temperature

EN Threshold and Pull-Up Current vs Temperature


PIN FUNCTIONS

EN1, EN2: Enable Inputs. Pulling EN high turns on the ECB and connects IN to OUT. Pulling EN low turns off the ECB and disconnects IN from OUT. Toggling EN resets the ECB when in a latched off condition.

Exposed Pad: Exposed thermal pad. The exposed pad is internally connected to ground and provides an optimal path for heat removal. Connect the exposed pad to a PCB ground plane for enhanced thermal performance.

GND: Device Ground.

IMON1, IMON2: Analog Current Monitor Outputs. A resistor from IMON to GND converts the scaled down output current to a voltage. The ECB turns off if the voltage on IMON exceeds 1.20V (primary OC threshold).

In the case of severe overcurrent, the ECB quickly turns off if the voltage on IMON exceeds 2.4V (fast secondary OC threshold).

The IMON outputs do not source current when RDY is low.

Connect IMON to ground if unused. Use caution when grounding IMON because the primary and secondary OC comparators will not function. However, short-circuit ($OUT < 1.2V$) and overtemperature conditions are still detected and turn off the ECB.

IN1, IN2: ECB Inputs. Both circuit breakers operate independently. However, IN1 is used to bias an internal low voltage bias supply rail. Therefore, IN2 cannot be used without $IN1 \geq 6V$. A special 5V ONLY application is discussed in the Applications Information section.

A 1 μF (or greater) bypass capacitor is recommended. A low impedance layout should be used between the input power supply and the IN1, IN2 inputs. Trace inductance should be kept below 400nH to minimize dissipated energy after short-circuit events.

INTV_{CC}: Internal Operating Supply. INTV_{CC} is used to bias internal circuitry. INTV_{CC} is generated by an internal regulator from IN1. A 0.01 μF (or greater) bypass capacitor is recommended.

INTV_{CC} should not be driven or loaded with external circuitry. However, a special 5V ONLY application is discussed in the Applications Information section.

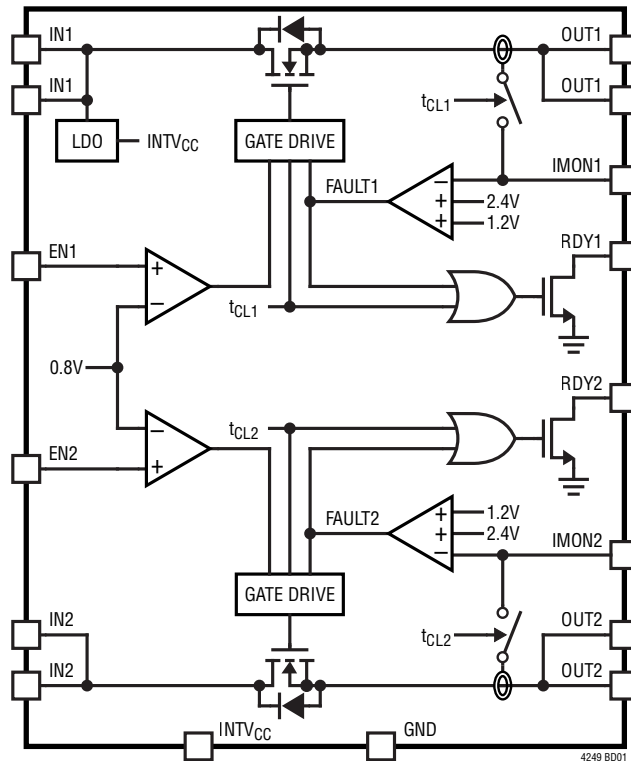
OUT1, OUT2: ECB Outputs. When enabled, OUT is connected to IN through a high voltage N-channel MOSFET. Maximum recommended steady state current is 1.2A per channel. ECBs may be paralleled for higher current loads. See Applications Information for more details.

A low impedance layout should be used between the load and the OUT1, OUT2 outputs. Trace inductance should be kept below 400nH to minimize dissipated energy after short-circuit events. Maximum capacitance at OUT is limited to 100 μF .

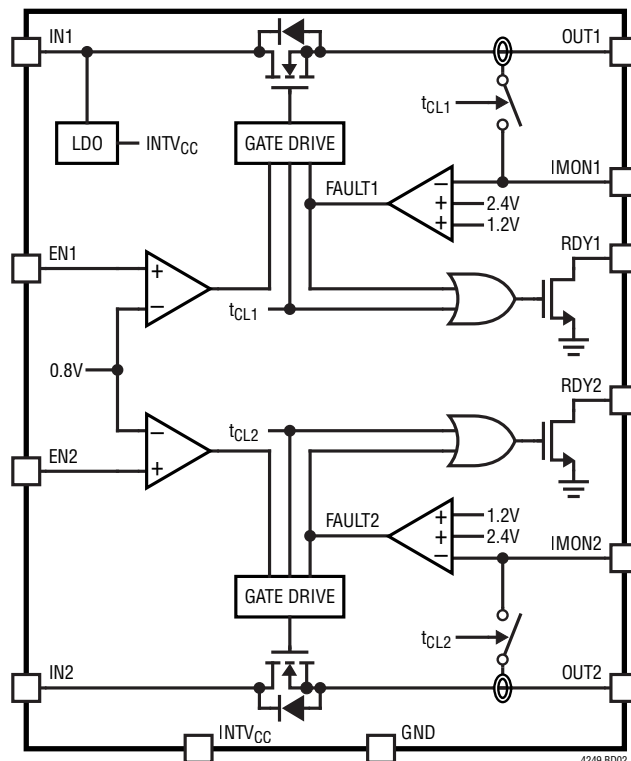
RDY1, RDY2: Ready Outputs. RDY pulls low when EN is low or after an ECB fault. After a channel is enabled, RDY outputs remain low until the current limited operating phase is complete (10ms nominal). After the current limited operating phase, RDY outputs release and may be used to enable subsequent functions. For example, RF Power Amplifier gate bias may be applied after RDY is released.

Leave RDY open or connected to ground if unused.

BLOCK DIAGRAMS



3mm × 3mm Package



3mm × 4mm Package

OPERATION

The LTC4249 is a two channel 65V electronic circuit breaker (ECB) with current monitoring outputs. Circuit breaker input IN1 has a 6V to 65V voltage input range and provides internal operating bias for the LTC4249. IN2 input range is 1.5V to 65V when IN1 is biased. Load circuits typically connect to OUT. The circuit breakers close when EN is high and open when EN is low. The ready (RDY) outputs pull low when the ECBs are off and are released when ECBs are on.

When RDY is released, an accurate scaled replica of the output load current is sourced from the IMON outputs. A resistor connected from IMON to GND converts the scaled current to a voltage. If the IMON voltage exceeds 1.2V, an overcurrent fault is deemed to exist; the ECB turns off and RDY pulls low.

Each enable input is compared to an internal 0.8V reference to enable or disable its respective channel. While a standard GPIO can be used to drive these inputs, the precision reference allows an external resistive divider to be used as an adjustable UVLO (undervoltage lockout) based on the applied input voltage. If the applied voltage falls below the EN falling threshold, the circuit breaker turns off. See the Applications Information for examples.

When initially enabled, the ECB enters a current limited operating phase, limiting inrush current without the

need for external components. During the current limited operating phase, OUT is charged with a 1A current source for 10ms. Maximum allowable OUT capacitance is 100 μ F. If OUT fails to charge beyond 1.2V in the first 300 μ s after enable, the output is deemed shorted and the circuit breaker turns off. At the successful conclusion of the current limited operating phase, the ECB enters low R_{ON} operation (75m Ω typical).

At this point, the analog current monitor function begins to source current to the IMON output. The 5% accurate current monitor produces 100 μ A/A of output load current, useful for closed loop load bias control or monitoring (see Applications Information for details). Internally, two comparators with different thresholds sense the voltage developed on the IMON output. The primary threshold comparator has a 1.2V threshold. It contains built-in filtering to remove glitches which could cause chatter near the primary threshold. The filter characteristic is shown in the Applications Information. The secondary comparator has a 2.4V threshold with a 2 μ s response time, to quickly open the ECB in situations with large overcurrent.

Overcurrent ($V_{IMON} > 1.2V$) or short-circuit ($OUT < 1.2V$) faults latch the circuit breaker off. Toggling EN clears the latch and turns the circuit breaker on. After an overtemperature fault, both channels turn off. The enables must be toggled in order to turn the respective ECBs back on.

APPLICATIONS INFORMATION

The LTC4249 finds great utility in RF Power Amplifier (PA) and industrial safety applications. Massive MIMO arrays with defective elements can be automatically isolated from a common power bus, preventing unwanted bus loading. The LTC4249 provides two 65V electronic circuit breakers with built-in protection and current monitoring circuitry. Enable (EN) inputs and ready (RDY) outputs make bias sequencing applications painless.

Short-circuit protection and automatic inrush control requires no external components. Overcurrent (OC) threshold accuracy ($\pm 5\%$) minimizes over-design of input power supplies.

Precise enable input and current monitor thresholds allow undervoltage (UV), overvoltage (OV), overcurrent (OC) and short-circuit (SC) detection and protection. Back-to-back connections of the ECBs permit reverse OC protection and isolation applications. Each OC threshold is configured with a single resistor.

ECB channels may be paralleled for load current sharing. A skipped lead package option is available for high voltage spacing requirements. An integrated backside thermal pad for printed circuit board design allows high ambient temperature and high current applications.

Enabling an ECB Channel

An input logic signal from a controller may be used to enable a circuit breaker channel. The EN input threshold is 0.8V, which accommodates low-voltage logic operation and/or resistively configured undervoltage lockout. Figure 1 shows a simplified enable application using a microcontroller open-drain output and an opto-isolator. The ECBs turn on when the switches release pull down on the EN inputs. The resistors at the EN inputs provide pull-up capability and keep the maximum voltage at EN below the absolute maximum of 5.5V.

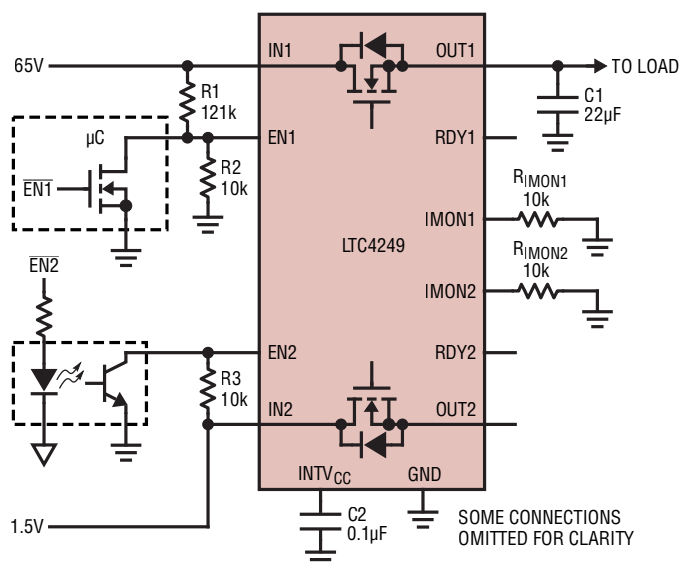


Figure 1. Switch Based Enable

Because the EN input threshold is $\pm 2.5\%$ accurate over temperature, a resistive divider can be connected to EN and a power supply, to form a voltage based enable with undervoltage (UV) lockout. If the monitored voltage is too low, the ECB channel is disabled.

Figure 2 demonstrates a voltage based enable using external 1% tolerance resistors. The desired UV threshold is 10.8V. The application assumes that the monitored supply is nominally 12V.

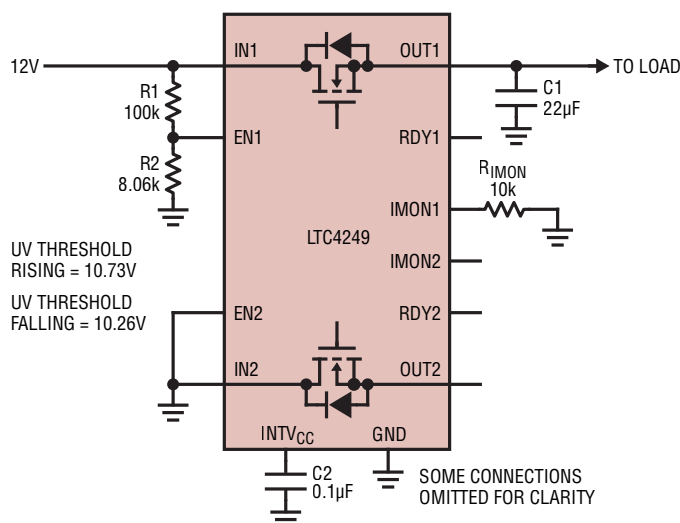


Figure 2. Voltage Based Enable with Undervoltage Lockout and Hysteresis

APPLICATIONS INFORMATION

With an internal 0.8V EN threshold, and a desired 10.8V UV threshold, R1 may be easily determined by specifying the desired resistive divider load current. Picking 100μA as a starting point, the relationship for R1 is:

$$R1 = \frac{10.8V - 0.8V}{100\mu A} = 100k\Omega$$

R2 is determined by dividing the 0.8V EN threshold by the divider load current:

$$R2 = \frac{0.8V}{100\mu A} = 8k\Omega$$

The closest standard 1% resistor is 8.06k. The resistor difference will not cause much error in the UV threshold (10.73V).

To prevent ECB chattering due to a noisy monitored voltage, the 0.8V EN threshold has 35mV falling hysteresis. The supply referred hysteresis is simply related to the resistive divider gain:

$$\begin{aligned} \text{Falling Hysteresis} &= 35mV \cdot \left(1 + \frac{R1}{R2}\right) \\ &= 469mV \end{aligned}$$

Therefore, for the application in Figure 2, after the monitored supply rises above 10.73V, the falling UV threshold drops to 10.26V. If the monitored supply is below the configured UV threshold the ECB channel is turned off.

Automatic Inrush Control

The LTC4249 is designed to control the inrush current upon enabling an ECB channel. For the first 10ms, output loads are charged at 1A. Maximum capacitive load is 100μF. At 100μF, the output charges at 10V/ms. When operating at the maximum input supply of 65V, a 100μF capacitor charges in 6.5ms, and is safely below the 10ms charge time. Figure 3 demonstrates output charging at maximum operating voltage and capacitive load.

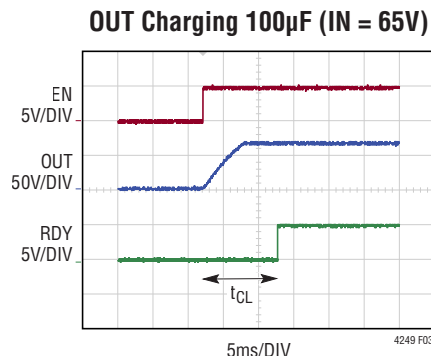


Figure 3. Output Charging at Initial Turn-On

Attempting to charge a large capacitance quickly requires large currents. Without inrush control, the safe operating area of the ECB would be exceeded. Furthermore, without inrush control, voltage sag on the input supply could be severe, causing brown-outs or system resets.

All LTC4249 applications require that the ECB output be fully charged ($V_{OUT} \approx V_{IN}$) within 10ms. After the 10ms current limited operating phase (t_{CL}), the ECB turns on fully to its rated 75mΩ on-resistance. At this point, over-current protection becomes active and the RDY output is released.

Voltage or Capacitance Start-Up Derating at High Ambient Temperature

The LTC4249 is designed to prevent operation outside its Safe Operating Area (SOA). Maximum power dissipation occurs when starting both ECB channels simultaneously. During the inrush portion of operation, with an ambient temperature above 90°C, junction temperature may briefly exceed the thermal shutdown threshold above 150°C, depending on input voltage and output capacitance. Exceeding the thermal shutdown threshold causes the ECBs to safely latch off. Toggling the enable inputs allows the ECBs to turn back on.

Figure 4 shows the allowable operating time at a given power dissipation before reaching thermal shutdown. Operating to the left of the curves prevents thermal shutdown. After inrush, typical power dissipation drops below 0.5W, which keeps the junction temperature far below thermal shutdown.

APPLICATIONS INFORMATION

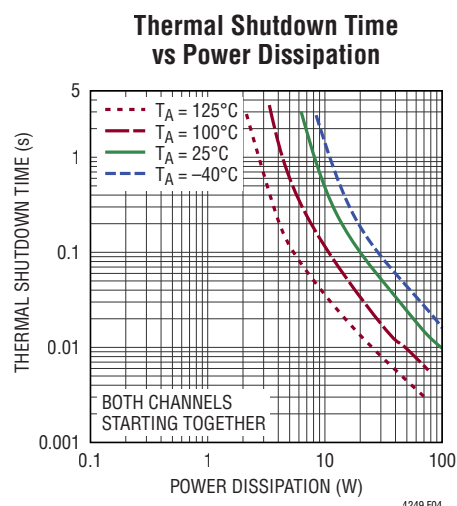


Figure 4. Thermal Shutdown Time vs Power Dissipation

Figure 5 provides temperature derating information for input voltage and output capacitance during the inrush portion of operation. If the output capacitance is 47 μ F (or less), 65V operation is possible at any allowed ambient temperature. At 100 μ F, input voltage should be reduced by $-375\text{mV}/^\circ\text{C}$, starting at 90°C ambient. Connecting the exposed back pad to a ground plane is recommended for heat removal.

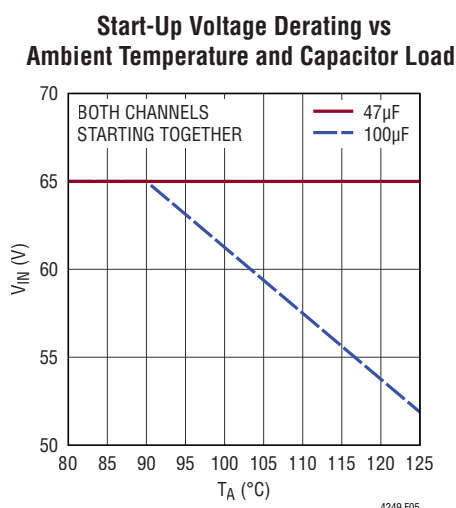


Figure 5. High Temperature Start-Up Derating

Short-Circuit Protection

During the first 300 μ s of the 10ms current limited operating phase, the OUT voltage is monitored for voltage rise.

If the OUT voltage does not exceed 1.2V at the 300 μ s time point, OUT is considered shorted and the ECB turns off.

At the conclusion of the 10ms current limited operating phase, the short-circuit logic is inverted. If OUT should fall below 1.2V, OUT is again considered shorted and the ECB turns off. The short-circuit comparator response time is typically 2 μ s for 50mV overdrive.

An important applications consideration under a short-circuit event is the amount of inductance between the ECB outputs and the load. An antenna array with multiple RF PAs could have inches of trace inductance between the ECB channel outputs and each PA. It is recommended to keep load path inductance below 400nH.

When the ECB is on and the load end is shorted through an inductance as shown in Figure 6, the ECB current increases rapidly. Peak current is a function of the output voltage, trace inductance and the time to turn off the ECB. The secondary OC and short-circuit comparators have limited bandwidth (about 2 μ s response time) and are not sufficiently fast enough to limit the current build up to typical OC setpoints under an inductive hard short. However, the ECB controller itself does have limited current compliance, allowing the OUT voltage to fall, keeping the ECB inside its safe operating area. After reaching peak current, the ECB dissipates the inductor energy and turns off. The integrated protections eliminate the need for large high-power and high-voltage Schottky diodes at the OUT pin.

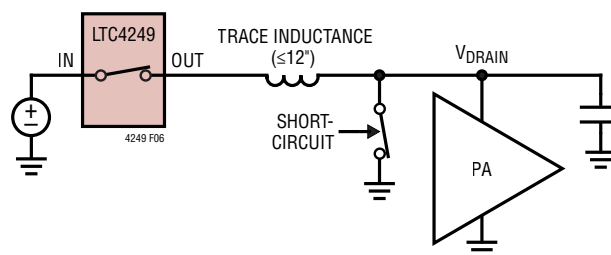


Figure 6. Load Short with Inductance

The input voltage side of the ECB should also have low inductance. For array applications, a large low impedance layout is recommended for input voltage distribution. It is recommended to keep the input supply path inductance below 400nH. A 1 μ F (or greater) bypass capacitor placed close to the IN inputs and ground is recommended.

Rev. 0

APPLICATIONS INFORMATION

Applying the RDY Output

The RDY open-drain output is released and allowed to pull high when the ECB is fully turned on and OUT is “ready” for application. In a RF PA circuit, with OUT connected to the PA drain, RDY may be used to enable PA gate bias. RDY pulls low when EN is low and/or when fault events such as overcurrent, short-circuit or thermal shutdown conditions have occurred.

Figure 7 shows a typical RDY response to EN and subsequent overcurrent fault. RDY may be pulled up as high as 5.5V, by an external source. Resistors in the range of 1k to 10k are recommended. RDY may also be used to enable other downstream loads such as DC-DC converters.

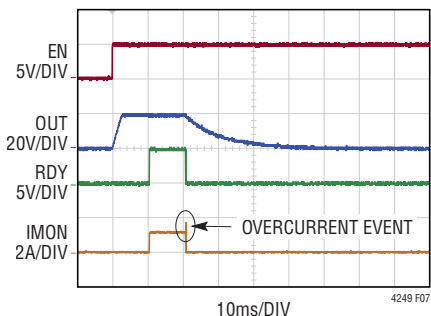


Figure 7. Typical RDY Response

Configuring Overcurrent (OC) Thresholds

Overcurrent thresholds are easily configured with a single resistor (R_{IMON}) from IMON to GND. IMON sources $100\mu A/A$ of ECB current. The primary (filtered) OC voltage threshold at the IMON output is 1.2V. R_{IMON} is simply determined from:

$$R_{IMON} = \frac{1.2V}{I_{ECB}} \cdot 10,000$$

where I_{ECB} is the desired circuit breaker threshold in amperes. For a 1.2A circuit breaker threshold, R_{IMON} is $10k\Omega$. Larger values of R_{IMON} yield lower circuit breaker thresholds. The secondary (fast) OC threshold is always twice the configured primary OC threshold.

The primary OC threshold is filtered to remove small fluctuations which allows the ECB to operate at currents near the OC threshold. In order to trip the primary OC comparator, the 1.2V threshold must be overdriven with requisite magnitude and duration. The typical overdrive versus time characteristic for the primary OC comparator is shown in Figure 8.

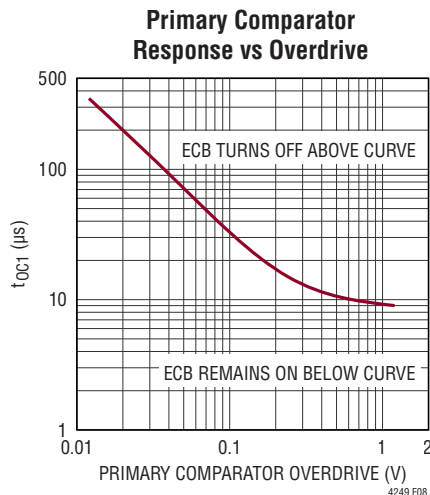


Figure 8. Primary OC Comparator Filter Characteristic

The secondary OC threshold comparator does not have added filtering and has a $2\mu s$ (typical) response time when the 2.4V IMON threshold has been exceeded.

External filtering of the IMON output voltage to achieve added ECB delay or noise rejection can be performed by adding a capacitor C_{IMON} in parallel with R_{IMON} . A pole will be formed by the RC combination.

Monitoring ECB Current

The IMON output current provides an accurate scaled replica ($100\mu A/A$) of the OUT current. The IMON output current is 5% accurate (30mA to 1.2A) over temperature (Figure 9). Note that excellent accuracy is maintained even at ECB currents below 30mA. The IMON accuracy reduces the need to over design the input power supply current capability due to the low variability in ECB threshold.

APPLICATIONS INFORMATION

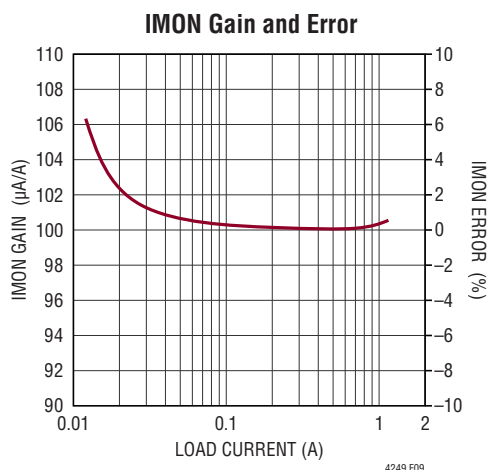


Figure 9. Typical IMON Gain vs Load Current

The IMON output has the bandwidth to follow ECB currents to approximately 50kHz. The bandwidth is a function of load capacitance at OUT and any capacitance at the IMON output. Figure 10 shows how the IMON output voltage follows a step change in ECB current from 0.5A to 1A. OUT capacitance is 100μF and no explicit capacitance was added to IMON.

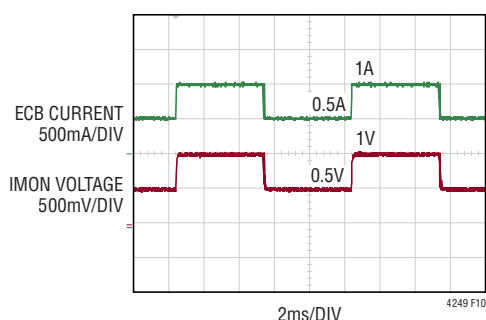


Figure 10. IMON Step Response ($C_{OUT} = 100\mu F$, $R_{IMON} = 10k\Omega$)

In applications where ECB current information must be captured, the scaled ECB current history can be stored in external memory by digitizing the IMON voltage with an analog to digital converter.

Load Current Servo Control

In RF PA applications, the IMON voltage may be compared to a reference and a control loop can servo the PA gate bias to control drain bias current. The front-page application schematic demonstrates how PA BIAS current can be

controlled by a DAC. PA V_{GG} threshold variations due to process and temperature are overcome with servo control, making individual bias trims obsolete.

In the front-page application, the input supply (28V) at IN1 passes to the RF PA V_{DD} when the voltage at EN1 exceeds 0.8V. Resistors R1 and R2 are chosen to provide an under-voltage (UV) threshold of 24.88V and 1.09V of falling hysteresis. Below threshold, RDY1 is low and the op amp is in shutdown. With the op amp in shutdown, the RF PA V_{GG} is pulled to the negative potential (–5V) through ROFF and the PA is off.

When the 28V input exceeds the UV threshold, the PA V_{DD} voltage ramps to the IN1 potential. RDY1 pulls high after 10ms and the op amp becomes active. At this point, the op amp drives the RF PA V_{GG} to the potential that forces the PA BIAS current to track the controlling input at the op amp non-inverting terminal. For example, if the controlling input is 1V, the PA V_{GG} bias moves to force the PA BIAS current to 1A.

If the PA BIAS current exceeds 1.2A, the ECB disconnects the V_{DD} bias and the RDY1 output pulls low. With RDY1 low, the op amp is in shutdown and the PA V_{GG} bias pulls to the negative rail.

For most closed loop applications, loop stability is achieved with integrating capacitor C_F . In situations where C_{OUT} is greater than 10μF, an additional resistor/capacitor combination may be needed for lead-lag compensation. A generalized compensation methodology is described below.

Loop Analysis

The front page schematic loop elements are extracted and shown in Figure 11. Various important quantities are defined here:

- V_C : the controlling input at the non-inverting terminal of the op amp
- R_{ON} : the ECB on-resistance (75mΩ)
- C_{OUT} : the PA V_{DD} drain capacitance (10μF)
- GM: the LTC4249 current monitor transconductance (1.33 mA/V)

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- R_M : the IMON sense and overcurrent setpoint resistor (10k Ω)
- C_F : the feedback capacitance used to provide a stable loop (330pF)
- R_G : resistance to limit op amp overshoot due to PA input capacitance (100 Ω)
- C_G : PA input capacitance (150pF)

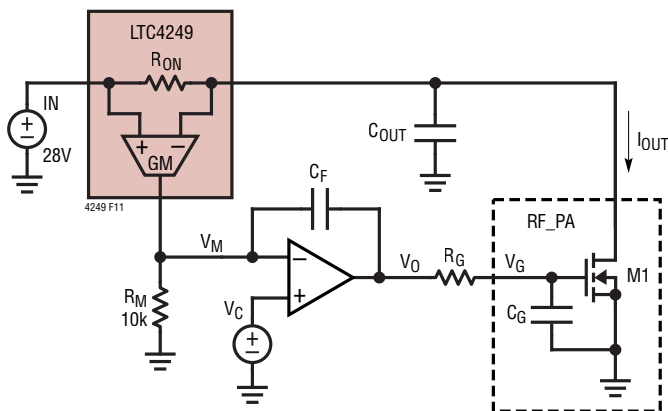


Figure 11. PA Servo Loop Components

It is important to understand how the loop components affect stability and the closed loop response I_{OUT}/V_C .

The LTC4249 current monitor GM and R_M components may be converted to a Thevenin equivalent. C_F is temporarily removed for analysis. GM_{PA} is the PA transconductance. The loop is transformed to a block diagram equivalent in Figure 12, where $A(s)$ is the op amp open loop transfer function and the canonical $G(s)$ and $H(s)$ blocks are outlined.

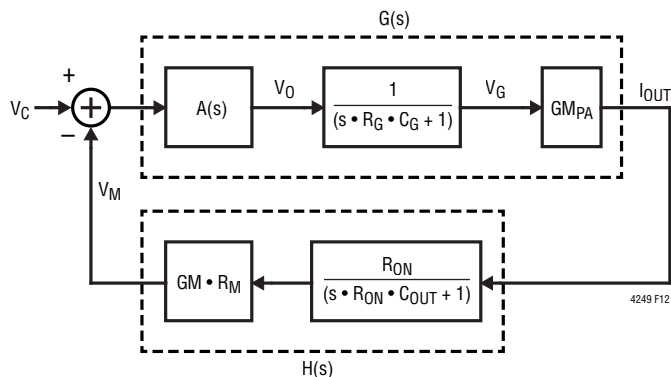


Figure 12. Servo Loop Block Diagram without C_F

Figure 13 shows the magnitude and phase of the uncompensated loop gain $G(s)H(s)$. It is easy to see inadequate phase margin ($\sim 0^\circ$) at the crossover frequency. The region near crossover consists of multiple deleterious poles including contributions from $R_{ON} \cdot C_{OUT}$, $R_G \cdot C_G$ and high frequency op amp poles.

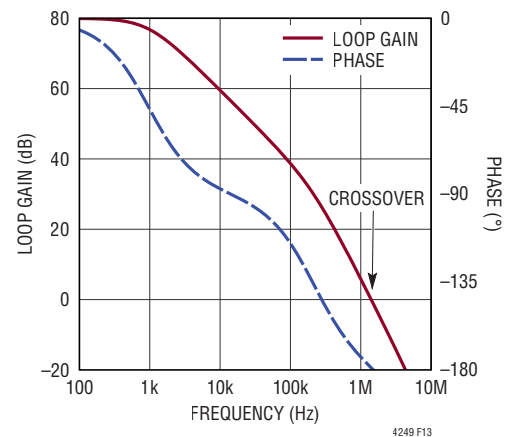


Figure 13. Uncompensated Loop Gain and Phase

Crossing the system over at a lower frequency can help achieve loop stability. This is easily done by adding feedback elements around the op amp. If we add a generalized feedback impedance Z_F around the op amp, the loop can be stabilized and sensitivity to the op amp transfer function can be eliminated. Figure 14 shows the block diagram with Z_F added.

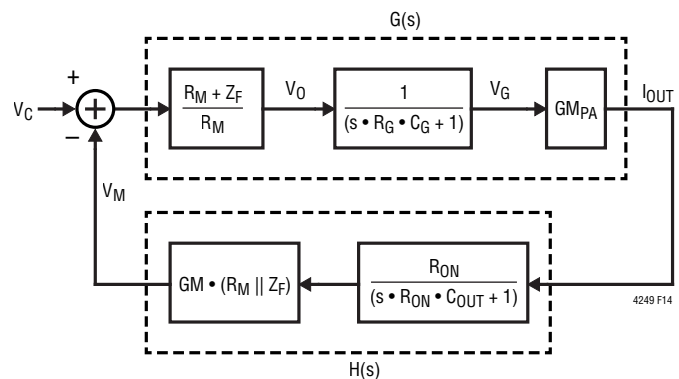


Figure 14. Servo Loop Block Diagram with Generalized Impedance Z_F around Op Amp

With $Z_F = 1/sC_F$, the crossover frequency is lower (~ 10 kHz) and phase margin improves to almost 90° as

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shown in Figure 15. Step response as shown on the front page is clean with a rise time of about 10 μ s.

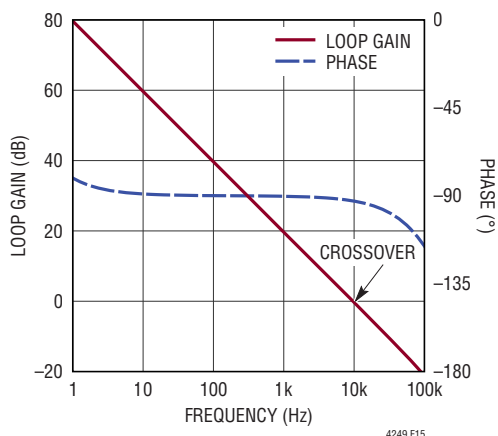


Figure 15. Compensated Loop Gain and Phase
($Z_F = 1/sC_F$, $C_F = 330\text{pF}$)

When C_{OUT} is large (closer to 100 μ F), phase margin may be lower compared to the 10 μ F example. With large C_{OUT} , another loop term should be considered for its phase margin impact. During step changes in load current, the LTC4249 current monitor output lags load current briefly. Transport lag results in phase erosion that is a function of frequency but does not impact the loop gain magnitude. The phase erosion is equal to $360^\circ \cdot f \cdot T$, where $T \approx 2\mu\text{s}$. At the crossover frequency $f = 10\text{kHz}$, phase margin loss due to transport lag is -7.2° .

In a low phase margin situation, a lead-lag network may be required to control the step response. Adding a resistor (R_Z) in series with C_F provides a leading zero and a small capacitor (C_P) around R_Z provides a lagging pole to restore high frequency roll-off (Figure 16). For analysis purposes, simply condense the compensation network around the op amp into a Z_F impedance and use the model in Figure 14 to obtain the new loop gain and phase (add the transport lag loss term to the phase as needed).

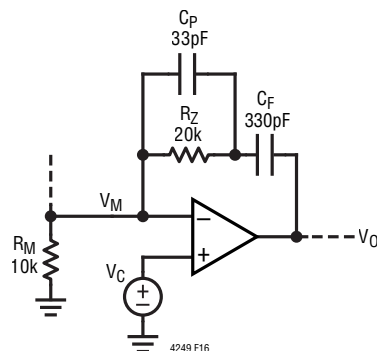


Figure 16. Lead-Lag Network Example

RF PA Bias Sequencing

Some RF PAs have a strict bias sequence order. Use the LTC4249 EN inputs, RDY outputs and IMON outputs to simplify the sequencing process. A recommended bias sequence during power up is the following:

- 1) Start with the PA V_{DD} near ground. To achieve this, begin with EN low (ECB off, OUT near ground). Drive the PA V_{GG} to a suitably negative voltage to guarantee PA BIAS current = 0. RDY should be pulling low at this time.
- 2) Raise EN above threshold (0.8V). The LTC4249 enters its current limited operating phase and charges the OUT capacitance with 1A. After 300 μ s, OUT is checked for voltage above 1.2V. If it is less, the channel output is deemed to be "shorted" and the corresponding ECB shuts off. Assuming no short, the LTC4249 completes current limited operating phase after 10ms and begins low R_{ON} operation. RDY is now released and may be pulled high. OUT voltage should now be close to I_N .
- 3) After RDY release, increase PA V_{GG} voltage until desired BIAS current is achieved. BIAS current may be inferred from the voltage at the IMON output.
- 4) Apply RFIN signal.

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The recommended bias sequence during power down is the following:

- 1) Remove RFIN signal.
- 2) Decrease PA V_{GG} voltage to bring PA BIAS current to zero. BIAS current may be inferred from the voltage at the IMON output.
- 3) Pull EN below threshold (OUT disconnects from IN, RDY pulls low).

Current Sharing

Some applications may require operation and OC sensing above 1.2A load current. Operation up to 2.4A is possible by simply paralleling the two ECB channels (Figure 17). The two channels will share load current to typically 1%, governed by R_{ON} matching.

If either channel exceeds 1.2A, the respective ECB shuts off. This action throws the load current to the remaining channel causing the second channel to shut off as well. Multiple LTC4249s may be paralleled for even more current. The efficacy of that approach depends on device to device R_{ON} matching (typically $\pm 2\%$, but is not guaranteed), and is slightly worse than the $\pm 1\%$ channel matching specification.

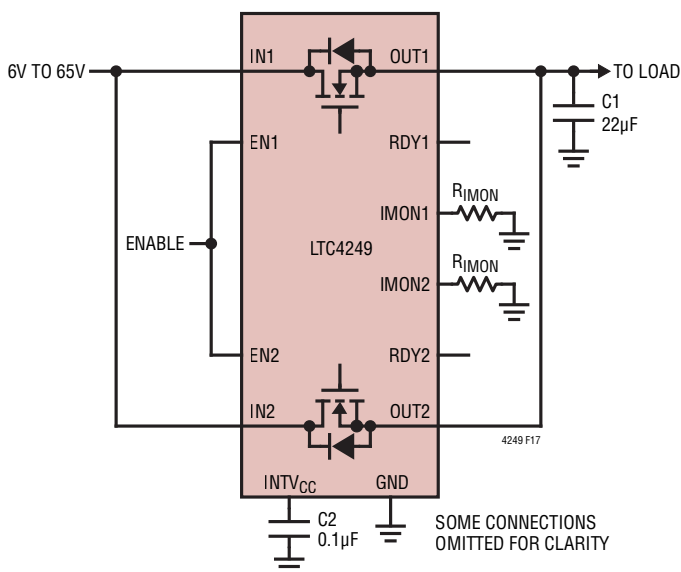


Figure 17. Current Sharing for Applications above 1.2A

Output Overcurrent and Overvoltage

Circuit breaker action may also be achieved based on over-voltage at the OUT node by the addition of a single resistor R_{OV} (Figure 18) between OUT and IMON. Calculating resistor R_{OV} depends on whether the load has current sink or resistive properties. In this application, the OC and OV thresholds become dependent and resistor calculation is a multi-step procedure.

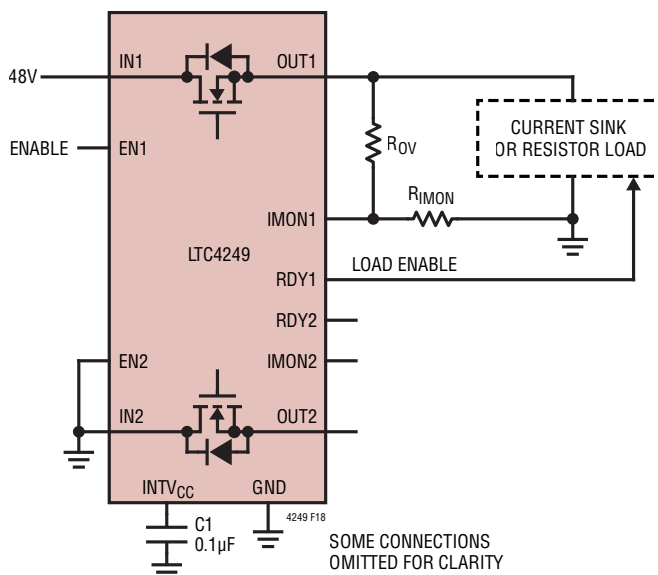


Figure 18. OV/OC Circuit Breaker with One Additional Resistor

The nominal OUT1 voltage (V_{OUT}) in Figure 18 is ~48V with a desired OV threshold (V_{OV}) of 56.2V. For a current sink load (I_{OUT}) operating nominally at 650mA and a desired overcurrent threshold (I_{OC}) of 732mA, R_{OV} is found from:

$$R_{OV} = \frac{V_{OUT} - 1.2V}{\left(\left(\frac{1.2V}{R_{IMON}} \right) - (I_{OC} \bullet G_{IMON}) \right)}$$

where $G_{IMON} = 100\mu A/A$ and $R_{IMON} = 10k\Omega$. Plugging in $I_{OC} = 732mA$ yields $R_{OV} = 1M\Omega$. With R_{OV} at $1M\Omega$ and $I_{OUT} = 650mA$, V_{OV} is determined from:

$$V_{OV} = \left(\left(\frac{1.2V}{R_{IMON}} \right) - (I_{OUT} \bullet G_{IMON}) \right) \bullet R_{OV} + 1.2V$$

with a result of $V_{OV} = 56.2V$.

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When the load is resistive, the calculation for R_{OV} is unchanged. For $V_{OUT} = 48V$ and $I_{OC} = 732mA$, R_{OV} remains $1M\Omega$. However, the calculation for OV threshold must include an additional contribution from IMON output current due to the excess voltage over the resistive load:

$$V_{OV} = 1.2V \cdot \frac{\left(\frac{1}{R_{IMON}} + \frac{1}{R_{OV}} \right)}{\left(\frac{I_{OUT} \cdot G_{IMON}}{V_{OUT}} + \frac{1}{R_{OV}} \right)}$$

where I_{OUT} is the nominal load of 650mA yielding a result of $V_{OV} = 51.48V$. To regain a higher OV threshold, R_{OV} must increase, which will cause I_{OC} to increase. For example, if R_{OV} is increased to $1.21M\Omega$, V_{OV} becomes 55.48V and I_{OC} increases to 813mA.

Reverse Current Circuit Breaker

In applications where the ECB output (load side) could be pulled above the input, such as a power mux circuit, the risk of forward biasing the ECB body diode and conducting current to the input exists. To overcome that possibility, the two LTC4249 channels can be connected back to back as shown in Figure 19. The back to back connection places the two ECB body diodes in opposite directions and prevents current from the load connection at IN2 back to IN1, when the ECBs are off.

When the channels are turned on, however, current can still pass through the ECBs in both directions. Fortunately, due to the reverse connection of channel 2, current from IN2 to OUT2 is still reported at I_{MON2} because channel 2

is operating normally if IN2 rises above OUT2. With an appropriate choice of R_{IMON2} , an accurate “reverse current” threshold can be chosen to shut off channel 2 and prevent excess current from the load connection at IN2 back to IN1. Channel 1 operates as usual and turns off due to excess forward current, configured by R_{IMON1} .

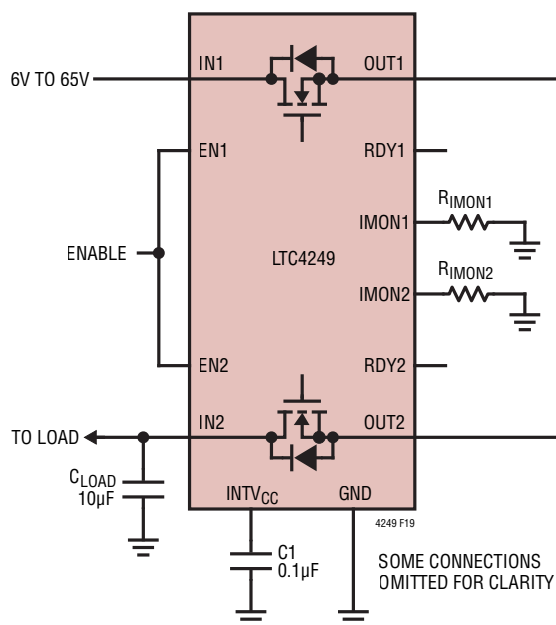


Figure 19. Back to Back Connection for Load Isolation and Forward/Reverse Current Circuit Breaker

Load Switch with Isolation

Building from Figure 19, a load switch with reverse isolation is possible by duplicating the application and providing enable inputs to preferentially select the input supply (V1 or V2) that is delivered to the load (Figure 20).

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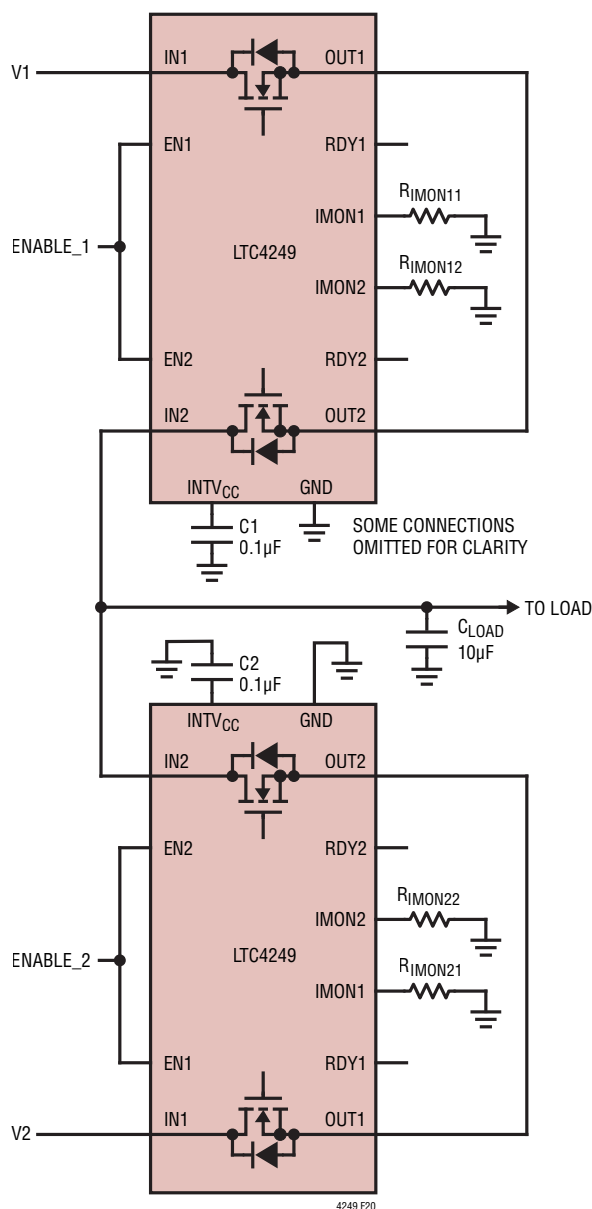


Figure 20. Load Switch Application

High Voltage Spacing Considerations

In applications where creepage and clearance standards up to 65V must be met, a 12-Lead 3mm × 4mm LQFN package is available for ordering. The IN1, OUT1, IN2 and OUT2 leads are all adequately spaced to all other leads including the exposed thermal pad.

Thermal Considerations

The exposed thermal pad is internally connected to ground and provides an optimal path for heat removal. In applications where the ambient temperature is above 90°C, connect the exposed pad to 2 inch² of 1oz PCB copper to limit junction heating when operating at maximum current capability of 1.2A per channel (2.4A total).

At high ambient temperatures, a heat removal path is also important during the 10ms current limited operating phase, where the pulsed power can cause brief but large temperature rise.

Under extreme thermal conditions an integrated thermal switch activates to turn off both channels. The breakers remain off for typically 1 second and until the respective enable inputs are toggled.

Industrial Applications

Many of the individual applications discussed thus far can be combined in clever ways to solve system problems. Industrial applications often require the need for circuit breakers. The back page shows an industrial application utilizing the LTC4249 capabilities to provide undervoltage (UV), overvoltage (OV), overcurrent (OC) and reverse current protection for a 15V system with a nominal 50mA resistive load current. The resistor values are calculated to provide the following thresholds:

UV Threshold: 12V

0V Threshold: 16.9V

Forward OC Primary Threshold: 193mA

Reverse OC Primary Threshold: 1.2A

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During initial turn-on, the load capacitance charges through ECB1 and the body diode of ECB2. RDY1 enables ECB2 after the ECB1 10ms current limited turn phase is complete. ECB2 then turns on and shunts the body diode path.

Special “5V ONLY” Application

Under most circumstances, the minimum IN1 voltage required for operation is 6V. However, a very narrow application for IN1 = 5V is possible provided a few conditions are met. First, the IN1 supply voltage must be tightly regulated to $\pm 5\%$ (4.75V to 5.25V). Second, IN1 must be connected to the INTV_{CC} output (Figure 21). OUT1, when ECB1 is on, is therefore constrained to the IN1 limitation. IN2 may be operated normally over its full range.

This application is tested in production and has been qualified over temperature. Note that while the electrical table does not extend IN1 below 6V, this application is supported with respect to all other electrical table entries except for V_{CCOR}, V_{ECB2}, V_{ACC2} and t_{OC2}. Above 1.8A, the secondary overcurrent comparators may experience increased threshold or delay. The primary overcurrent comparators however, conform to data sheet specifications over their full range (1.2A), ensuring ECB shutoff under overcurrent conditions.

Operation beyond these special constraints is not recommended and operation is not guaranteed.

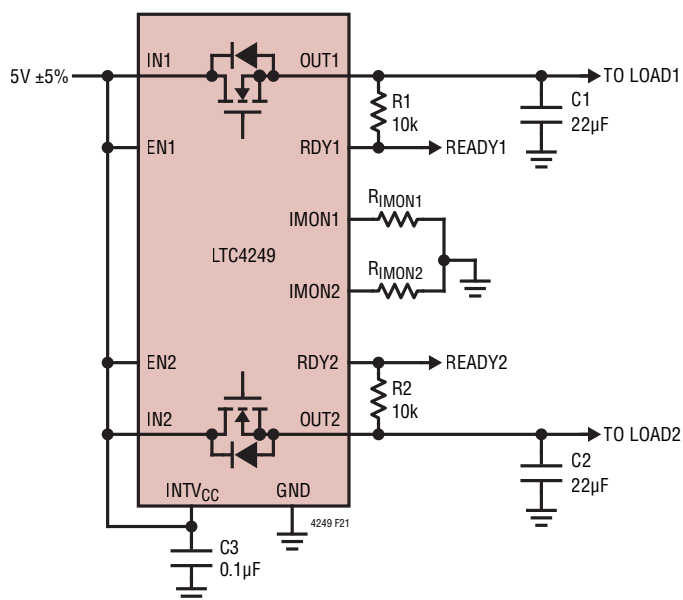
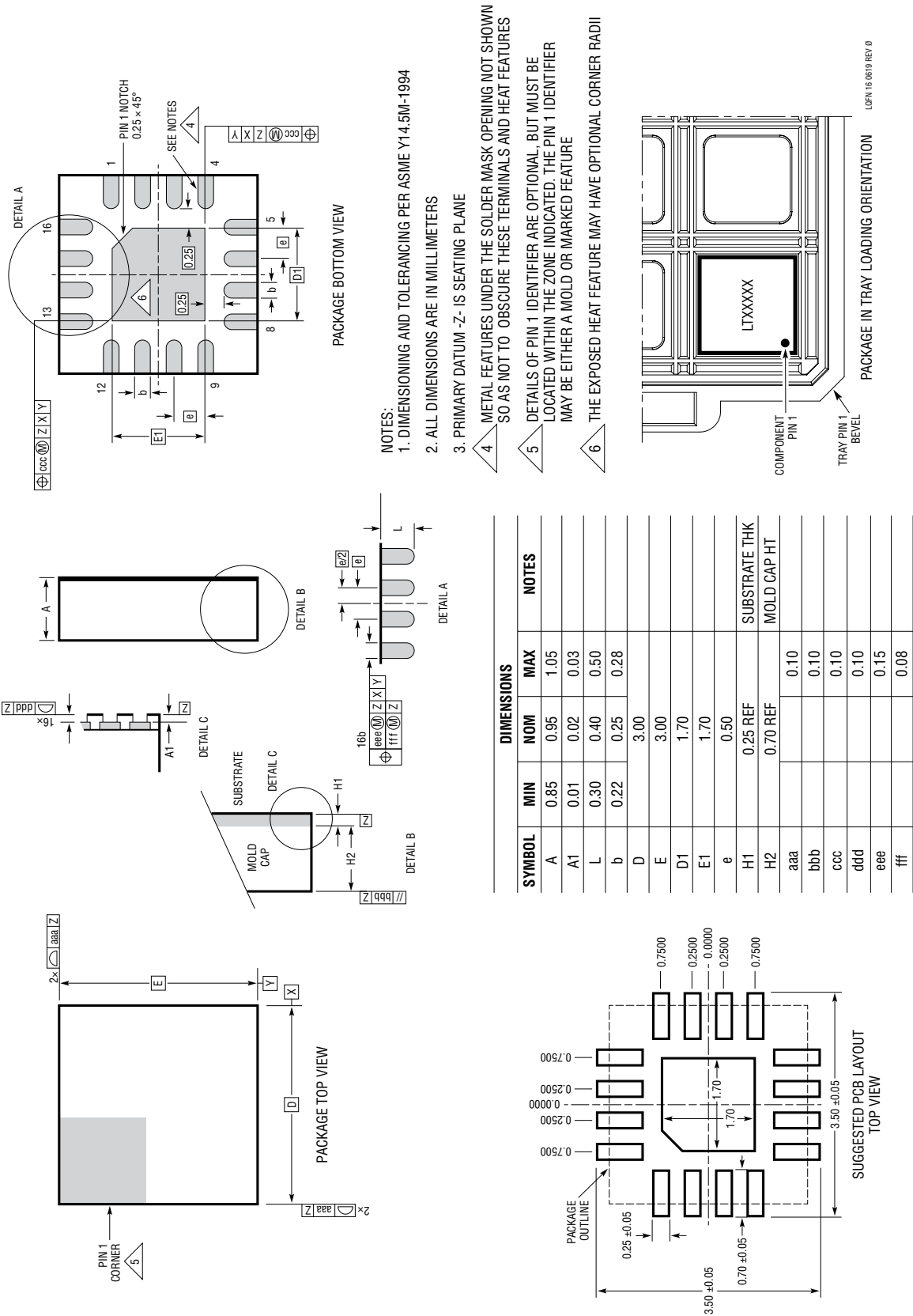


Figure 21. Special “5V ONLY” Application

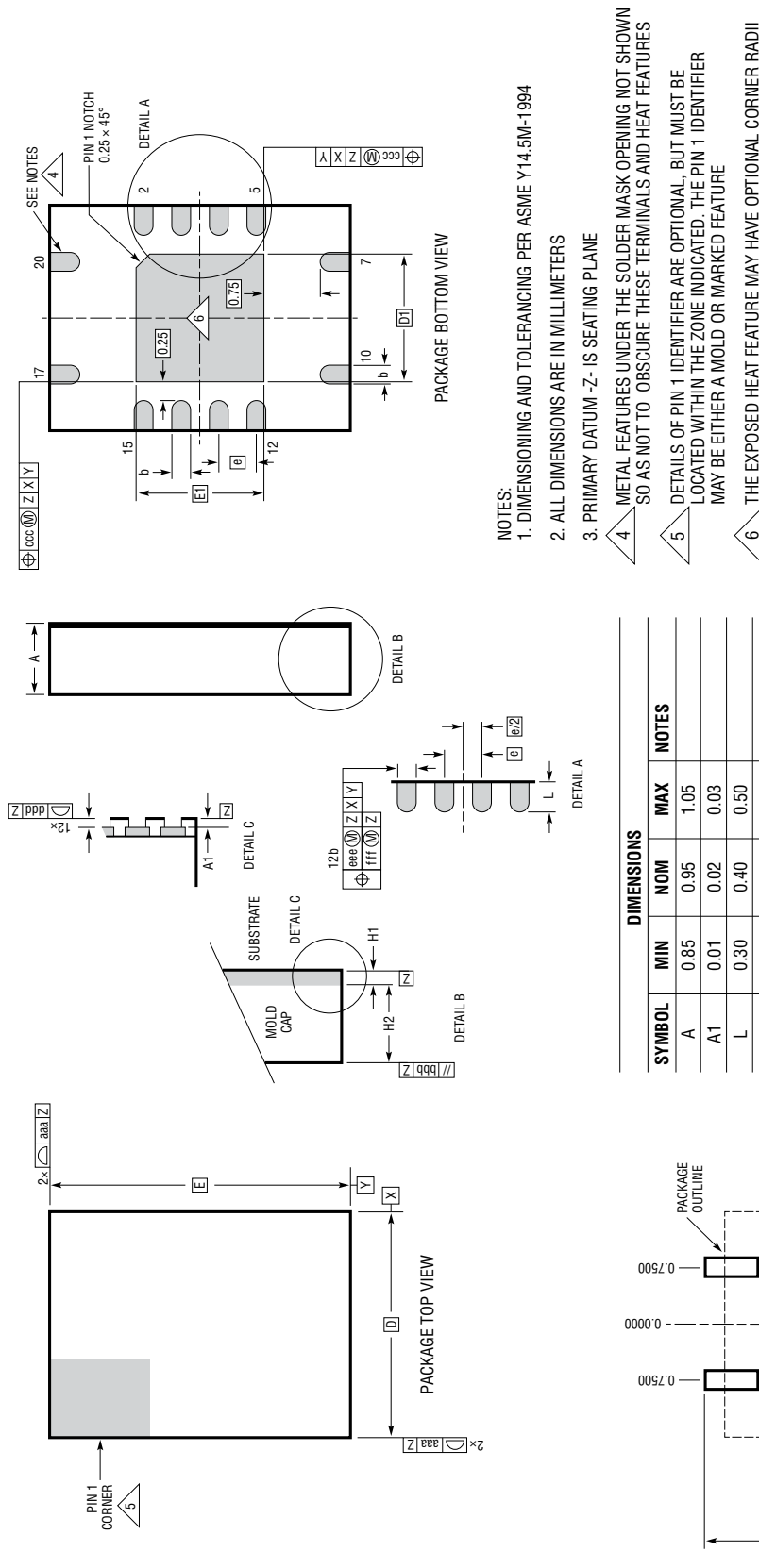
PACKAGE DESCRIPTION

LQFN Package
16-Lead (3mm × 3mm × 0.95mm)
(Reference LTC DWG # 05-08-1443 Rev 0)



PACKAGE DESCRIPTION

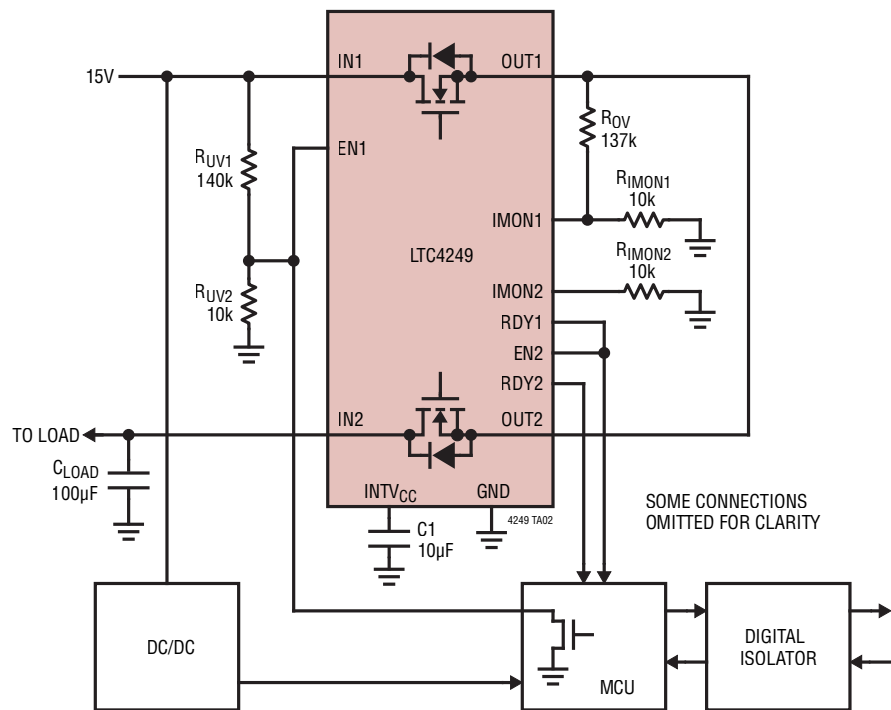
LQFN Package
20 (12)-Lead (3mm × 4mm × 0.95mm)
 (Reference LTC DWG # 05-08-1441 Rev 0)



LQFN 20(12) 0619 REV 0

TYPICAL APPLICATION

ECB For Industrial Application with UV, OV, OC and Reverse Current Protection



RELATED PARTS

PART NUMBER	DESCRIPTION	COMMENTS
LTC4368	LTC4367 + Bidirectional Circuit Breaker	±50mV or 50mV/–3mV Circuit Breaker Thresholds; MSOP-10, DFN-10 Packages
LTC4367	100V Overvoltage, Undervoltage and Reverse Supply Protection Controller	Wide Operating Range: 2.5V to 60V, Protection Range: –40V to 100V, No TVS Required for Most Applications
LTC4365	Overvoltage, Undervoltage and Reverse Supply Protection Controller	Wide Operating Range: 2.5V to 34V, Protection Range: –40V to 60V, No TVS Required for Most Applications
LTC4366	High Voltage Surge Stopper	9V to >500V Operation, 8-Pin TSOT and 3mm × 2mm DFN Packages
LTC4364	Surge Stopper with Ideal Diode	4V to 80V Operation, –40V Reverse Input, –20V Reverse Output
LT4363	High Voltage Surge Stopper with Current Limit	Wide Operating Range: 4V to 80V, Reverse Protection to –60V, Adjustable Output Clamp Voltage
LTC4361	Overvoltage/Overcurrent Protection Controllers	5.8V Overvoltage Threshold, 85V Absolute Maximum
LTC4380	8µA I _Q Surge Stopper	4V to 72V Operation, Pin Selectable Clamp Voltage