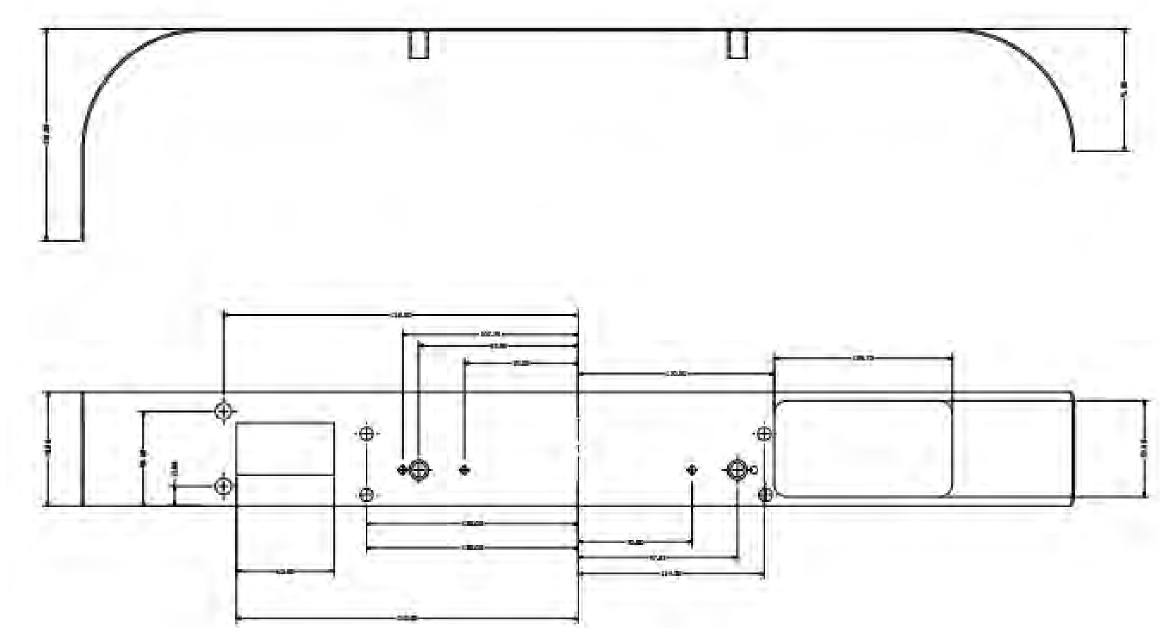
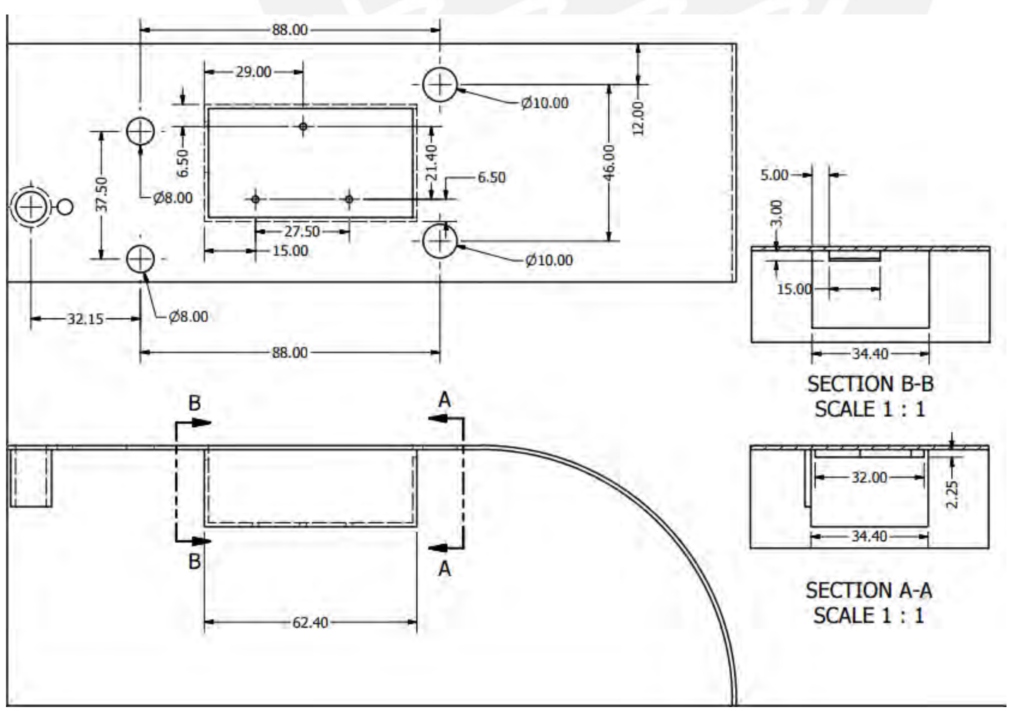
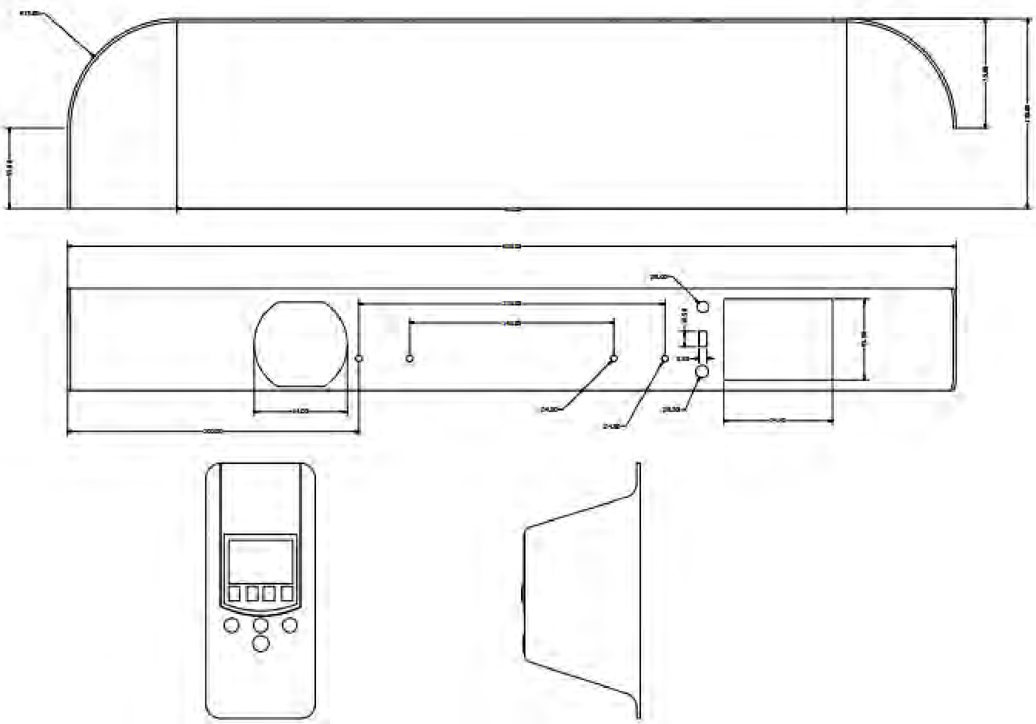
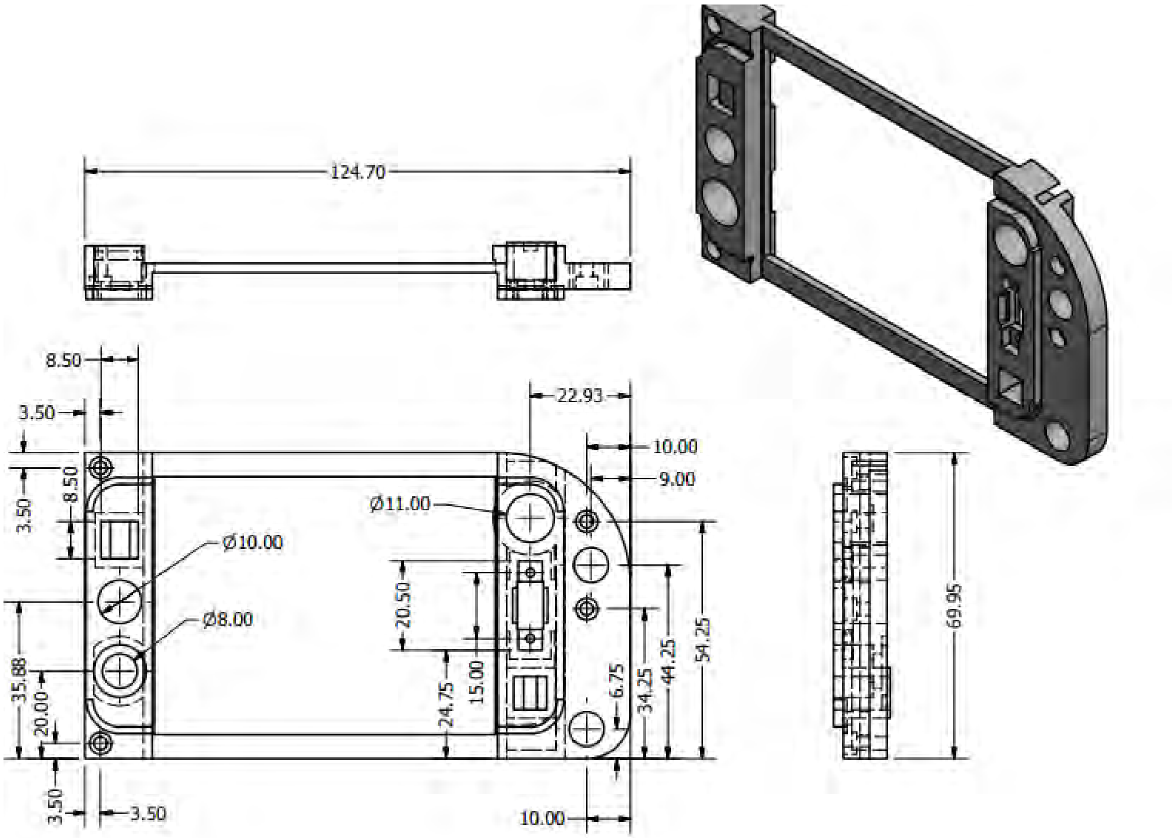
MECANISMO DE ADAPTACIÓN PARA EL SENSOR DE PESO







MÓDULO DE IMPRESIÓN 3D PARA LA PANTALLA GLCD Y LA PCB



CARGOS POR EXCESO DE EQUIPAJE-LAN PERÚ

Cargos por exceso de equipaje

¿Olvidaste tu usuario? ¿Olvidaste tu clave?

Si llevas equipaje con sobrepeso o viajas con tu mascota, infórmate de las normativas antes de tu vuelo. Las mascotas siempre serán consideradas piezas adicionales de equipaje, aunque viajes sin maletas. Para conocer el costo final, revisa la tabla de cargos y valores de cada cargo en esta sección.

23kg **Cargos en ruta entre Ecuador - Miami con franquicia de 1 pieza de equipaje de 23 kg (50 lb)**	**0 kg - 23 kg (0 lb - 50 lb)**	**23 kg - 32 kg (50 lb - 70 lb)**	**32 kg - 45 kg (70 lb - 99 lb)**
Sobrepeso en piezas permitidas	No aplican cargos	1 cargo	2 cargos*
Primera pieza adicional	1 cargos por pieza	2 cargos por pieza	3 cargos por pieza
Segunda pieza adicional	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza
Mascota	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza

32kg 32kg **Cargos en rutas con franquicia de 2 piezas de equipaje de 32 kg (70 lb) cada una**	**0 kg - 23 kg (0 lb - 50 lb)**	**23 kg - 32 kg (50 lb - 70 lb)**	**32 kg - 45 kg (70 lb - 99 lb)**
Sobrepeso en piezas permitidas	No aplican cargos	No aplican cargos	1 cargo*
Pieza adicional	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza
Mascota	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza

23kg 23kg **Cargos en rutas con franquicia de 2 piezas de equipaje de 23 kg (50 lb) cada una**	**0 kg - 23 kg (0 lb - 50 lb)**	**23 kg - 32 kg (50 lb - 70 lb)**	**32 kg - 45 kg (70 lb - 99 lb)**
Sobrepeso en piezas permitidas	No aplican cargos	1 cargo	2 cargos*
Pieza adicional	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza*
Mascota	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza*

+ = 23 kg (50 lb) **Cargos en rutas con franquicia de 2 piezas que entre ambas pesen 23 kg en total**	**0 kg - 23 kg (0 lb - 50 lb)**	**23 kg - 32 kg (50 lb - 70 lb)**	**32 kg - 45 kg (70 lb - 99 lb)**	**45 kg - 65 kg (99 lb - 143 lb)***	**65 kg - 90 kg (143 lb - 198 lb)***
Sobrepeso en piezas permitidas	No aplican cargos	1 cargo	2 cargos*	3 cargos*	4 cargos*
Pieza adicional	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza*	**No se permite****	**No se permite****
Mascota	2 cargos por pieza	3 cargos por pieza	4 cargos por pieza*	**No se permite****	**No se permite****

PATENTES DE MALETAS

(12) **United States Patent**
Truong

(10) **Patent No.: US 7,378,604 B2**
(45) **Date of Patent: May 27, 2008**

(54) **LUGGAGE WITH BUILT-IN WEIGHT MEASUREMENT DEVICE AND METHOD OF USE**

(75) Inventor: **Peter D. Truong**, La Mirada, CA (US)

(73) Assignee: **Ricardo Beverly Hills**, La Mirada, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **11/599,174**

(22) Filed: **Nov. 13, 2006**

(65) **Prior Publication Data**

US 2007/0107947 A1 May 17, 2007

Related U.S. Application Data

(60) Provisional application No. 60/735,341, filed on Nov. 12, 2005.

(51) **Int. Cl.**
G01G 19/58 (2006.01)
A45C 13/00 (2006.01)

(52) **U.S. Cl.** **177/131**; 177/148; 177/245; 190/115; 206/278; 224/576

(58) **Field of Classification Search** 190/115; 177/131, 148, 149, 245; 224/576; 206/278
See application file for complete search history.

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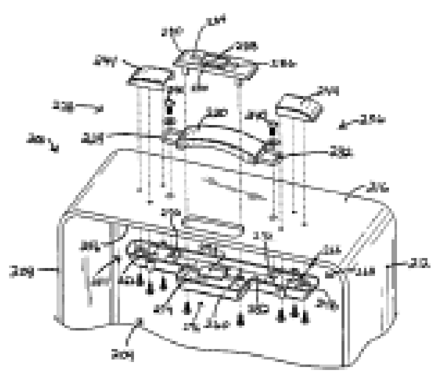
Primary Examiner—Randy W Gibson
(74) *Attorney, Agent, or Firm*—Michael Best & Friedrich LLP

(57) **ABSTRACT**

A weight measurement module operatively coupled to a piece of luggage for determining the weight of the luggage and its contents. The weight measurement module includes one or more load cells, a processor operatively coupled to the one or more load cells, and a display operable to display the weight of the luggage and its contents.

16 Claims, 14 Drawing Sheets

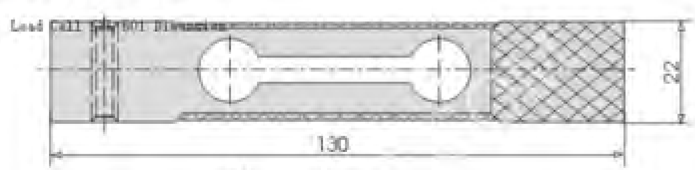


DATOS DE LA CELDA DE CARGA

Specifications

Parameter	Value
Type	Single Point Load Cell
Total Precision	C3 class
Material	Aluminum Alloy
Surface	Anodized Treatment
Protection	IP65
Suggested Platform Size	350 x 350 mm
Applications	Weighing Scales, Retail, Bench & Counting Scales
Rated Load	40 Kg. Max
Rated Output	2.0mV/V+/- 5%
Zero Balance	+/- 1% Full Scale
Input Resistance	405 +/- 6 Ohm
Output Resistance	350 +/- 3 Ohm
Excitation Voltage	5-12V DC
Nonlinearity	0.017% Full Scale
Hysteresis	0.02% Full Scale
Repeatblity	0.01% Full Scale
Creep(30min)	0.015% Full Scale
Operating Temperature	-20 °C to +65 °C
Temperature Effect on Zero	0.017% Full Scale / 10 °C
Temperature Effect on Span	0.014% Full Scale / 10 °C
Insulation Resistance	5000 Mega Ohm(50V DC)
Safe Overload	150% Full Scale
Ultimate Overload	200% Full Scale
Cable	420mm(3mm dia 4 wire shielding cable)

Dimensions



Single and Dual-Supply, Rail-to-Rail, Low Cost Instrumentation Amplifier

Data Sheet **AD623**

FEATURES

- **Easy to use**
- **Rail-to-rail output swing**
- **Input voltage range extends 150 mV below ground (single supply)**
- **Low power, 550 μA maximum supply current**
- **Gain set with one external resistor**
  - **Gain range: 1 to 1000**
- **High accuracy dc performance**
  - **0.10% gain accuracy (G = 1)**
  - **0.35% gain accuracy (G > 1)**
- **Noise: 35 nV/√Hz RTI noise at 1 kHz**
- **Excellent dynamic specifications**
  - **800 kHz bandwidth (G = 1)**
  - **20 μs settling time to 0.01% (G = 10)**

APPLICATIONS

- **Low power medical instrumentation**
- **Transducer interfaces**
- **Thermocouple amplifiers**
- **Industrial process controls**
- **Difference amplifiers**
- **Low power data acquisition**

GENERAL DESCRIPTION

The AD623 is an integrated, single- or dual-supply instrumentation amplifier that delivers rail-to-rail output swing using supply voltages from 3 V to 12 V. The AD623 offers superior user flexibility by allowing single gain set resistor programming and by conforming to the 8-lead industry standard pinout configuration. With no external resistor, the AD623 is configured for unity gain (G = 1), and with an external resistor, the AD623 can be programmed for gains of up to 1000.

The superior accuracy of the AD623 is the result of increasing ac common-mode rejection ratio (CMRR) coincident with increasing gain; line noise harmonics are rejected due to constant CMRR up to 200 Hz. The AD623 has a wide input common-mode range and amplifies signals with common-mode voltages as low as 150 mV below ground. The AD623 maintains superior performance with dual and single polarity power supplies.

Table 1. Low Power Upgrades for the AD623

Part No.	Total V_S (V dc)	Typical I_Q (μA)
AD8235	5.5	30
AD8236	5.5	33
AD8237	5.5	33
AD8226	36	350
AD8227	36	325
AD8420	36	85
AD8422	36	300
AD8426	36	325 (per channel)

FUNCTIONAL BLOCK DIAGRAM

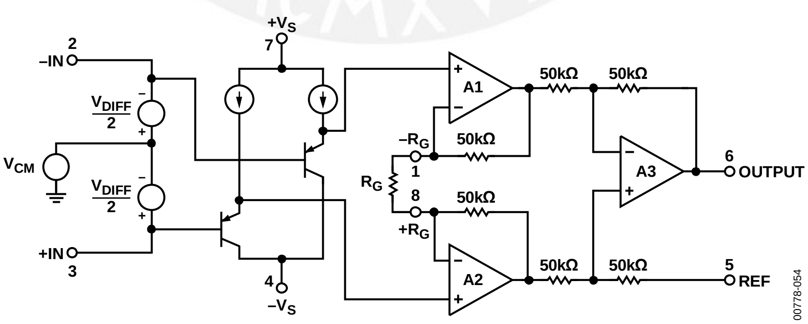


Figure 1.

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AD623* PRODUCT PAGE QUICK LINKS

Last Content Update: 02/23/2017

COMPARABLE PARTS

View a parametric search of comparable parts.

EVALUATION KITS

- AD62x, AD822x, AD842x Series InAmp Evaluation Board

DOCUMENTATION

Application Notes

- AN-1401: Instrumentation Amplifier Common-Mode Range: The Diamond Plot
- AN-244: A User's Guide to I.C. Instrumentation Amplifiers
- AN-245: Instrumentation Amplifiers Solve Unusual Design Problems
- AN-282: Fundamentals of Sampled Data Systems
- AN-589: Ways to Optimize the Performance of a Difference Amplifier
- AN-671: Reducing RFI Rectification Errors in In-Amp Circuits

Data Sheet

- AD623: Single Supply, Rail-to-Rail, Low Cost Instrumentation Amplifier Data Sheet

Technical Books

- A Designer's Guide to Instrumentation Amplifiers, 3rd Edition, 2006

User Guides

- UG-261: Evaluation Boards for the AD62x, AD822x and AD842x Series

TOOLS AND SIMULATIONS

- In-Amp Error Calculator
- AD623 SPICE Macro-Model

REFERENCE MATERIALS

Technical Articles

- Auto-Zero Amplifiers
- High-performance Adder Uses Instrumentation Amplifiers
- Input Filter Prevents Instrumentation-amp RF-Rectification Errors
- Low Power, Low Cost, Wireless ECG Holter Monitor
- Protecting Instrumentation Amplifiers
- The AD8221 - Setting a New Industry Standard for Instrumentation Amplifiers

DESIGN RESOURCES

- AD623 Material Declaration
- PCN-PDN Information
- Quality And Reliability
- Symbols and Footprints

DISCUSSIONS

View all AD623 EngineerZone Discussions.

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SPECIFICATIONS

SINGLE SUPPLY

Typical at 25°C, single supply, $+V_S = 5$ V, $-V_S = 0$ V, and $R_L = 10$ kΩ, unless otherwise noted.

Table 2.

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
GAIN	$G = 1 + (100\ k/R_G)$										
Gain Range		1		1000	1		1000	1		1000	
Gain Error[1]	G1 V_{OUT} = 0.05 V to 3.5 V G > 1 V_{OUT} = 0.05 V to 4.5 V										
G = 1			0.03	0.10		0.03	0.10		0.03	0.05	%
G = 10			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 100			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 1000			0.10	0.35		0.10	0.35		0.10	0.35	%
Nonlinearity	G1 V_{OUT} = 0.05 V to 3.5 V G > 1 V_{OUT} = 0.05 V to 4.5 V										
G = 1 to 1000			50			50			50		ppm
Gain vs. Temperature											
G = 1			5	10		5	10		5	10	ppm/°C
G > 1[1]			50			50			50		ppm/°C
VOLTAGE OFFSET	Total RTI error = $V_{OSI} + V_{OSO}/G$										
Input Offset, V_{OSI}			25	200		200	500		25	100	µV
Over Temperature				350			650			160	µV
Average Temperature Coefficient (Tempco)			0.1	2		0.1	2		0.1	1	µV/°C
Output Offset, V_{OSO}			200	1000		500	2000		200	500	µV
Over Temperature				1500			2600			1100	µV
Average Tempco			2.5	10		2.5	10		2.5	10	µV/°C
Offset Referred to the Input vs. Supply (PSR)											
G = 1		80	100		80	100		80	100		dB
G = 10		100	120		100	120		100	120		dB
G = 100		120	140		120	140		120	140		dB
G = 1000		120	140		120	140		120	140		dB
INPUT CURRENT											
Input Bias Current			17	25		17	25		17	25	nA
Over Temperature				27.5			27.5			27.5	nA
Average Tempco			25			25			25		pA/°C
Input Offset Current			0.25	2		0.25	2		0.25	2	nA
Over Temperature				2.5			2.5			2.5	nA
Average Tempco			5			5			5		pA/°C
INPUT											
Input Impedance											
Differential			2‖2			2‖2			2‖2		GΩ‖pF
Common-Mode			2‖2			2‖2			2‖2		GΩ‖pF
Input Voltage Range[2]	V_S = 3 V to 12 V	$(-V_S) - 0.15$		$(+V_S) - 1.5$	$(-V_S) - 0.15$		$(+V_S) - 1.5$	$(-V_S) - 0.15$		$(+V_S) - 1.5$	V

Parameter	Test Conditions/ Comments	AD623A Min	AD623A Typ	AD623A Max	AD623ARM Min	AD623ARM Typ	AD623ARM Max	AD623B Min	AD623B Typ	AD623B Max	Unit
Common-Mode Rejection at 60 Hz with 1 kΩ Source Imbalance											
G = 1	V_{CM} = 0 V to 3 V	70	80		70	80		77	86		dB
G = 10	V_{CM} = 0 V to 3 V	90	100		90	100		94	100		dB
G = 100	V_{CM} = 0 V to 3 V	105	110		105	110		105	110		dB
G = 1000	V_{CM} = 0 V to 3 V	105	110		105	110		105	110		dB
OUTPUT											
Output Swing	R_L = 10 kΩ	0.01		$(+V_S)$ – 0.5	0.01		$(+V_S)$ – 0.5	0.01		$(+V_S)$ – 0.5	V
	R_L = 100 kΩ	0.01		$(+V_S)$ – 0.15	0.01		$(+V_S)$ – 0.15	0.01		$(+V_S)$ – 0.15	V
DYNAMIC RESPONSE											
Small Signal –3 dB BW											
G = 1			800			800			800		kHz
G = 10			100			100			100		kHz
G = 100			10			10			10		kHz
G = 1000			2			2			2		kHz
Slew Rate			0.3			0.3			0.3		V/µs
Settling Time to 0.01%	V_S = 5 V										
G = 1	Step size: 3.5 V		30			30			30		µs
G = 10	Step size: 4 V, V_{CM} = 1.8 V		20			20			20		µs

[1] Does not include effects of external resistor, R_G.
[2] One input grounded. G = 1.

DUAL SUPPLIES

Typical at 25°C dual supply, V_S = ±5 V, and R_L = 10 kΩ, unless otherwise noted.

Table 3.

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
GAIN	G = 1 + (100 k/R_G)										
Gain Range		1		1000	1		1000	1		1000	
Gain Error[1]	G1 V_{OUT} = −4.8 V to +3.5 V; G > 1 V_{OUT} = 0.05 V to 4.5 V										
G = 1			0.03	0.10		0.03	0.10		0.03	0.05	%
G = 10			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 100			0.10	0.35		0.10	0.35		0.10	0.35	%
G = 1000			0.10	0.35		0.10	0.35		0.10	0.35	%
Nonlinearity	G1 V_{OUT} = −4.8 V to +3.5 V; G > 1 V_{OUT} = −4.8 V to +4.5 V										
G = 1 to 1000			50			50			50		ppm
Gain vs. Temperature											
G = 1			5	10		5	10		5	10	ppm/°C
G > 1[1]			50			50			50		ppm/°C
VOLTAGE OFFSET	Total RTI error = V_{OSI} + V_{OSO}/G										
Input Offset, V_{OSI}			25	200		200	500		25	100	µV
Over Temperature				350			650			160	µV
Average Tempco			0.1	2		0.1	2		0.1	1	µV/°C
Output Offset, V_{OSO}			200	1000		500	2000		200	500	µV
Over Temperature				1500			2600			1100	µV
Average Tempco			2.5	10		2.5	10		2.5	10	µV/°C
Offset Referred to the Input vs. Supply (PSR)											
G = 1		80	100		80	100		80	100		dB
G = 10		100	120		100	120		100	120		dB
G = 100		120	140		120	140		120	140		dB
G = 1000		120	140		120	140		120	140		dB
INPUT CURRENT											
Input Bias Current			17	25		17	25		17	25	nA
Over Temperature				27.5			27.5			27.5	nA
Average Tempco			25			25			25		pA/°C
Input Offset Current			0.25	2		0.25	2		0.25	2	nA
Over Temperature				2.5			2.5			2.5	nA
Average Tempco			5			5			5		pA/°C
INPUT											
Input Impedance											
Differential			2‖2			2‖2			2‖2		GΩ‖pF
Common-Mode			2‖2			2‖2			2‖2		GΩ‖pF
Input Voltage Range[2]	V_S = +2.5 V to ±6 V	(−V_S) − 0.15		(+V_S) − 1.5	(−V_S) − 0.15		(+V_S) − 1.5	(−V_S) − 0.15		(+V_S) − 1.5	V

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Common-Mode Rejection at 60 Hz with 1 kΩ Source Imbalance											
G = 1	V_{CM} = +3.5 V to −5.15 V	70	80		70	80		77	86		dB
G = 10	V_{CM} = +3.5 V to −5.15 V	90	100		90	100		94	100		dB
G = 100	V_{CM} = +3.5 V to −5.15 V	105	110		105	110		105	110		dB
G = 1000	V_{CM} = +3.5 V to −5.15 V	105	110		105	110		105	110		dB
OUTPUT											
Output Swing	R_L = 10 kΩ, V_S = ±5 V	$(-V_S) + 0.2$		$(+V_S) - 0.5$	$(-V_S) + 0.2$		$(+V_S) - 0.5$	$(-V_S) + 0.2$		$(+V_S) - 0.5$	V
	R_L = 100 kΩ	$(-V_S) + 0.05$		$(+V_S) - 0.15$	$(-V_S) + 0.05$		$(+V_S) - 0.15$	$(-V_S) + 0.05$		$(+V_S) - 0.15$	V
DYNAMIC RESPONSE											
Small Signal −3 dB Bandwidth											
G = 1			800			800			800		kHz
G = 10			100			100			100		kHz
G = 100			10			10			10		kHz
G = 1000			2			2			2		kHz
Slew Rate			0.3			0.3			0.3		V/µs
Settling Time to 0.01%	V_S = ±5 V, 5 V step										
G = 1			30			30			30		µs
G = 10			20			20			20		µs

[1] Does not include effects of external resistor, R_G.
[2] One input grounded. G = 1.

ET LUX IN TENEBRIS LUCET MCMXVII

SPECIFICATIONS COMMON TO DUAL AND SINGLE SUPPLIES

Table 4.

Parameter	Test Conditions/ Comments	AD623A			AD623ARM			AD623B			Unit
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
NOISE											
Voltage Noise, 1 kHz	Total RTI noise = $\sqrt{(e_{ni})^2 + (2e_{no}/G)^2}$										
Input, Voltage Noise, e_{ni}			35			35			35		nV/√Hz
Output, Voltage Noise, e_{no}			50			50			50		nV/√Hz
RTI, 0.1 Hz to 10 Hz											
G = 1			3.0			3.0			3.0		µV p-p
G = 1000			1.5			1.5			1.5		µV p-p
Current Noise	f = 1 kHz		100			100			100		fA/√Hz
0.1 Hz to 10 Hz			1.5			1.5			1.5		pA p-p
REFERENCE INPUT											
R_{IN}			100 ± 20%			100 ± 20%			100 ± 20%		kΩ
I_{IN}	V_{IN}+, V_{REF} = 0 V		50	60		50	60		50	60	µA
Voltage Range		$-V_S$		$+V_S$	$-V_S$		$+V_S$	$-V_S$		$+V_S$	V
Gain to Output			1 ± 0.0002			1 ± 0.0002			1 ± 0.0002		V
POWER SUPPLY											
Operating Range	Dual supply	±2.5		±6	±2.5		±6	±2.5		±6	V
	Single supply	2.7		12	2.7		12	2.7		12	V
Quiescent Current	Dual supply		375	550		375	550		375	550	µA
	Single supply		305	480		305	480		305	480	µA
Over Temperature				625			625			625	µA
TEMPERATURE RANGE											
For Specified Performance		−40		+85	−40		+85	−40		+85	°C

ABSOLUTE MAXIMUM RATINGS

Table 5.

Parameter	Rating
Supply Voltage	12 V
Internal Power Dissipation[1]	650 mW
Differential Input Voltage	±6 V
Output Short-Circuit Duration	Indefinite
Storage Temperature Range	−65°C to +125°C
Operating Temperature Range	−40°C to +85°C
Lead Temperature (Soldering, 10 sec)	300°C

[1] Specification is for device in free air:
8-Lead PDIP Package: θ_{JA} = 95°C/W
8-Lead SOIC Package: θ_{JA} = 155°C/W
8-Lead MSOP Package: θ_{JA} = 200°C/W

Stresses at or above those listed under Absolute Maximum Ratings may cause permanent damage to the product. This is a stress rating only; functional operation of the product at these or any other conditions above those indicated in the operational section of this specification is not implied. Operation beyond the maximum operating conditions for extended periods may affect product reliability.

ESD CAUTION

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.

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PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

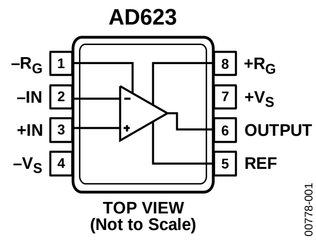

Figure 2. AD623 Pin Configuration

Table 6. Pin Function Descriptions

Pin No.	Mnemonic	Description
1	$-R_G$	Inverting Terminal of External Gain-Setting Resistor, R_G.
2	−IN	Inverting In-Amp Input.
3	+IN	Noninverting In-Amp Input.
4	$-V_S$	Negative Supply Terminal.
5	REF	In-Amp Output Reference Input. The voltage input establishes the common-mode voltage of the output.
6	OUTPUT	In-Amp Output.
7	$+V_S$	Positive Supply Terminal.
8	$+R_G$	Noninverting Terminal of External Gain Setting Resistor, R_G.

TYPICAL PERFORMANCE CHARACTERISTICS

At 25°C, V_S = ±5 V, and R_L = 10 kΩ, unless otherwise noted.

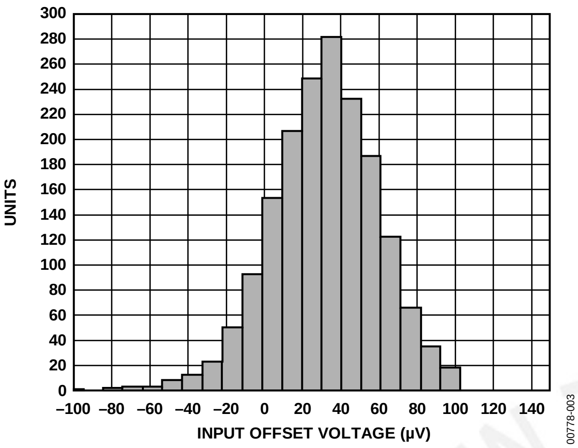

Figure 3. Typical Distribution of Input Offset Voltage, N-8 and R-8 Package Options

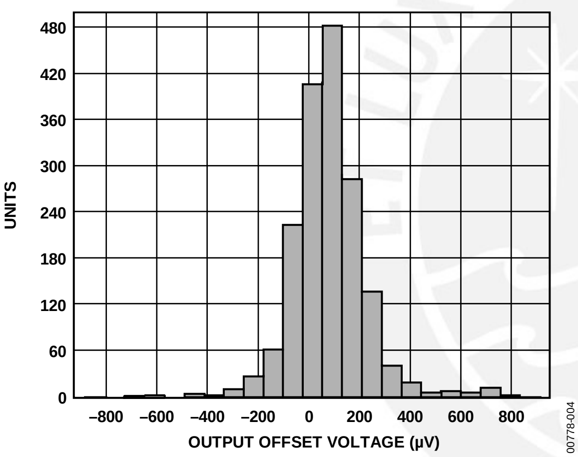

Figure 4. Typical Distribution of Output Offset Voltage, N-8 and R-8 Package Options

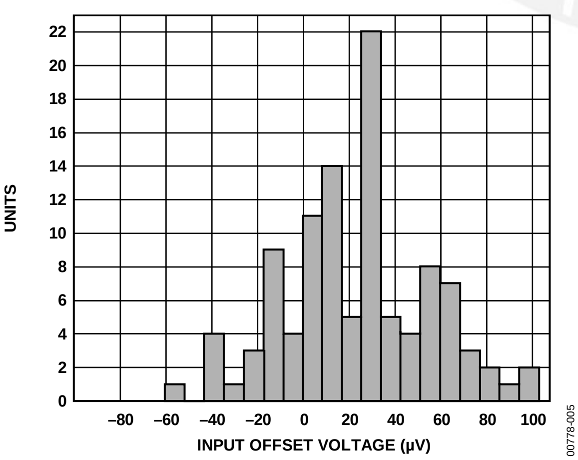

Figure 5. Typical Distribution of Input Offset Voltage, $+V_S$ = 5 V, $-V_S$ = 0 V, V_{REF} = −0.125 V, N-8 and R-8 Package Options

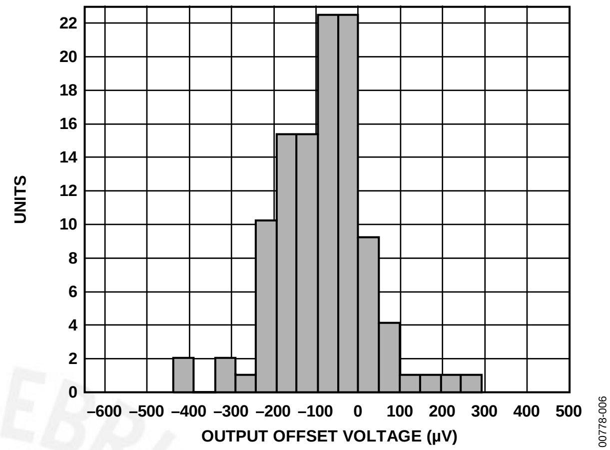

Figure 6. Typical Distribution of Output Offset Voltage, $+V_S$ = 5 V, $-V_S$ = 0 V, V_{REF} = −0.125 V, N-8 and R-8 Package Options

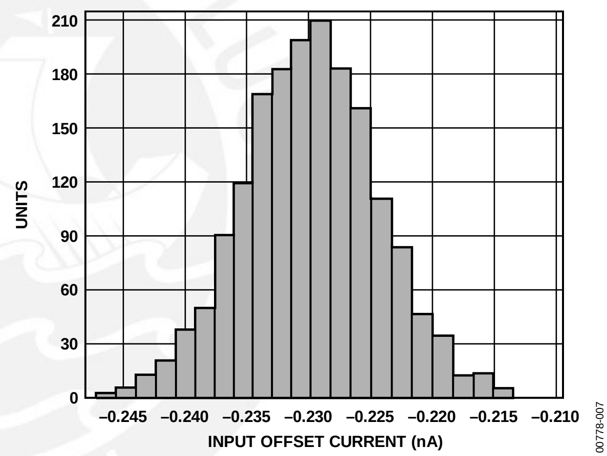

Figure 7. Typical Distribution for Input Offset Current, N-8 and R-8 Package Options

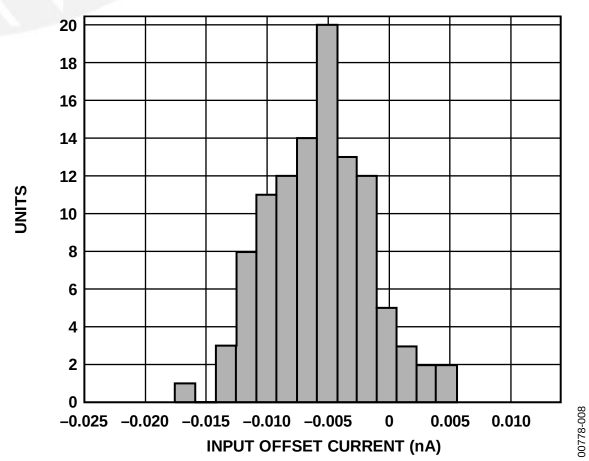

Figure 8. Typical Distribution for Input Offset Current, $+V_S$ = 5 V, $-V_S$ = 0 V, V_{REF} = −0.125 V, N-8 and R-8 Package Options

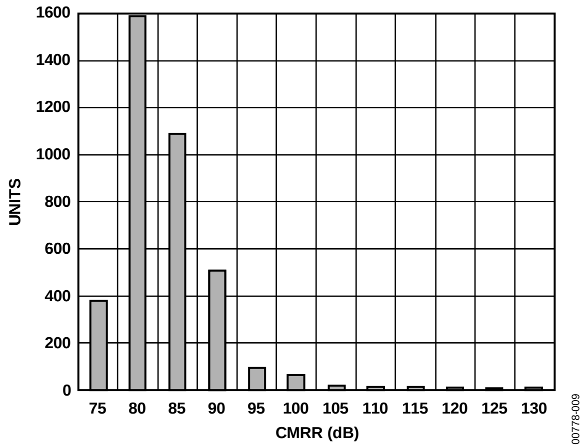

Figure 9. Typical Distribution for CMRR (G = 1)

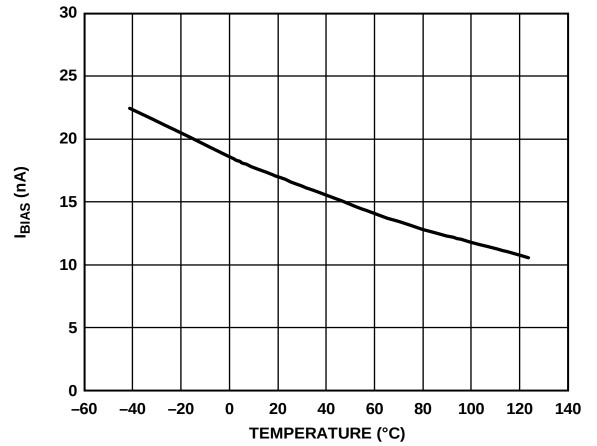

Figure 12. I_{BIAS} vs. Temperature

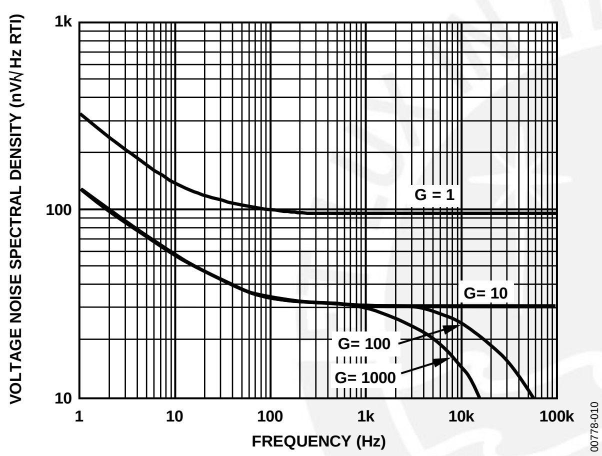

Figure 10. Voltage Noise Spectral Density vs. Frequency

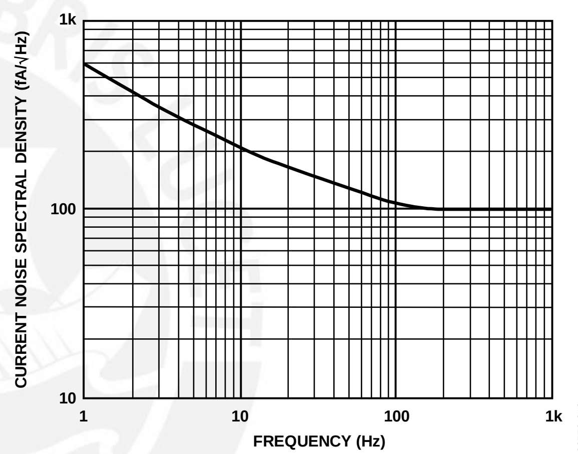

Figure 13. Current Noise Spectral Density vs. Frequency

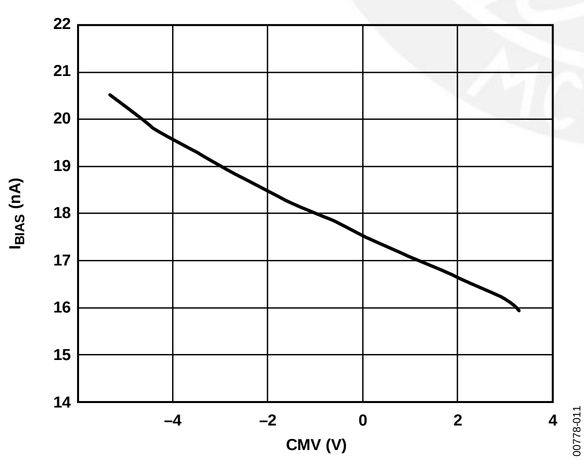

Figure 11. I_{BIAS} vs. CMV

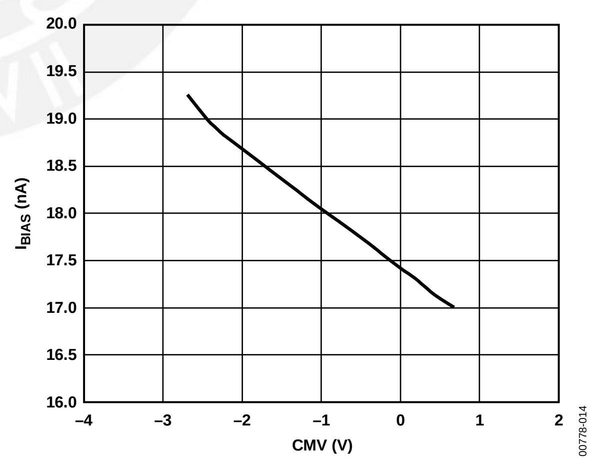

Figure 14. I_{BIAS} vs. CMV, $V_S = \pm 2.5$ V

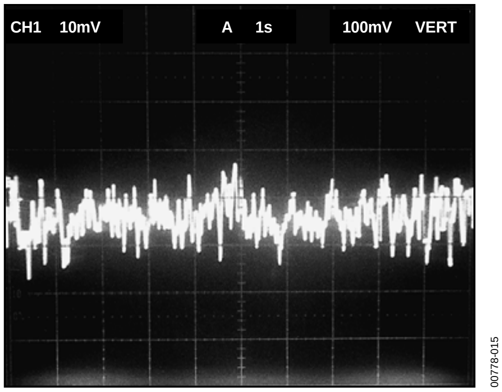

Figure 15. 0.1 Hz to 10 Hz Current Noise (0.71 pA/DIV)

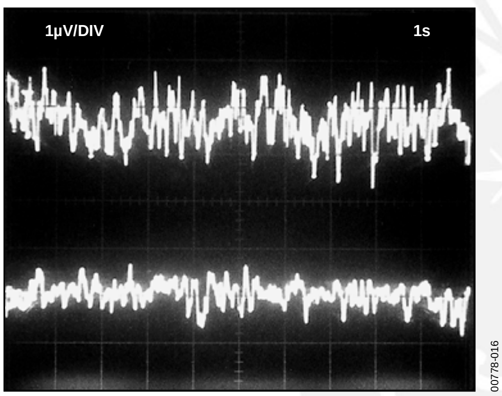

Figure 16. 0.1 Hz to 10 Hz RTI Voltage Noise (1 DIV = 1 μV p-p)

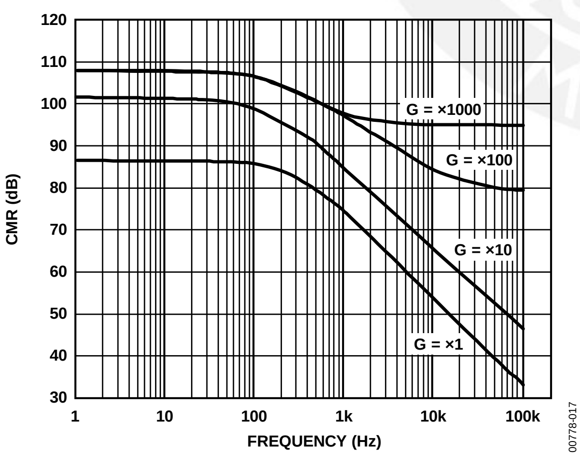

Figure 17. Common-Mode Rejection (CMR) vs. Frequency, $+V_S = 5$ V, $-V_S = 0$ V, $V_{REF} = 2.5$ V, for Various Gain Settings (G)

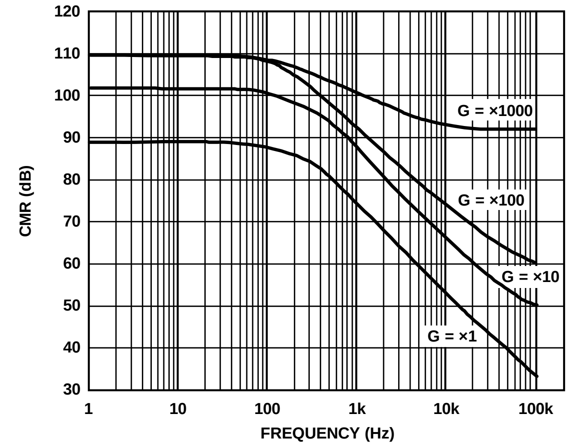

Figure 18. CMR vs. Frequency for Various Gain Settings (G)

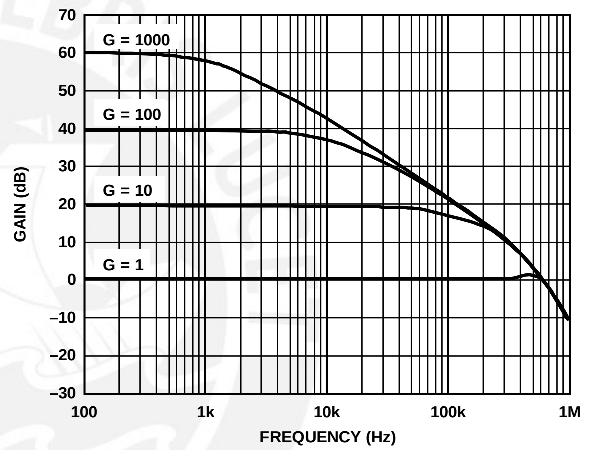

Figure 19. Gain vs. Frequency ($+V_S = 5$ V, $-V_S = 0$ V), $V_{REF} = 2.5$ V, for Various Gain Settings (G)

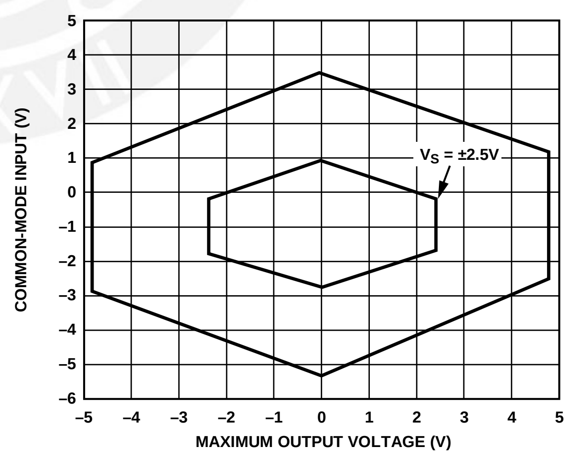

Figure 20. Maximum Output Voltage vs. Common-Mode Input, G = 1, $R_L = 100$ kΩ for Two Supply Voltages

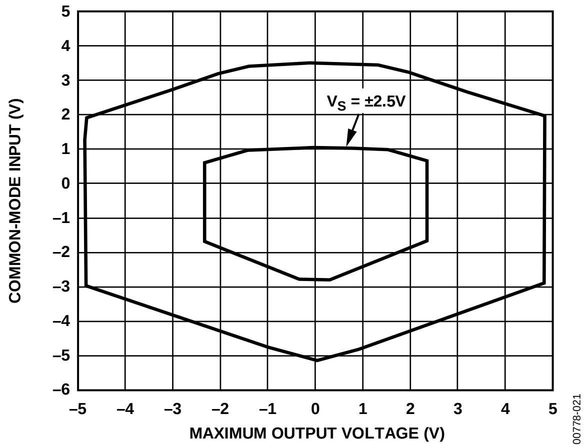

Figure 21. Maximum Output Voltage vs. Common-Mode Input, G ≥ 10, R_L = 100 Ω, for Two Supply Voltages

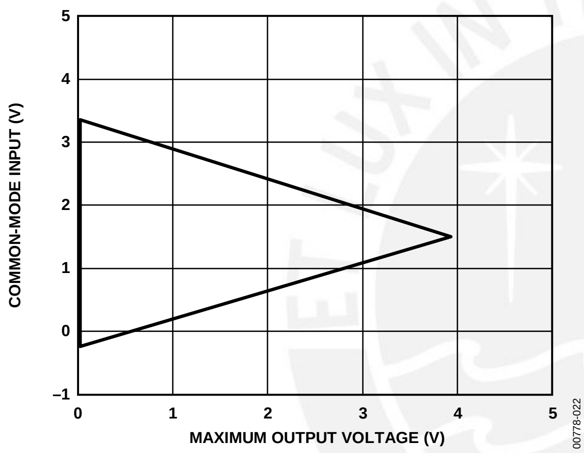

Figure 22. Maximum Output Voltage vs. Common-Mode Input, G = 1, $+V_S$ = 5 V, $−V_S$ = 0 V, R_L = 100 kΩ

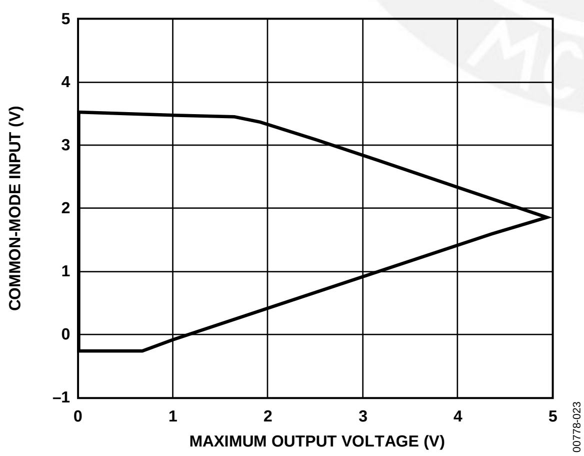

Figure 23. Maximum Output Voltage vs. Common-Mode Input, G ≥ 10, $+V_S$ = 5 V, $−V_S$ = 0 V, R_L = 100 kΩ

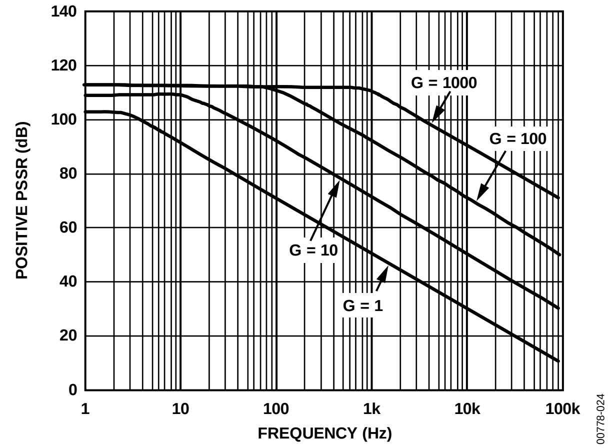

Figure 24. Positive PSRR vs. Frequency

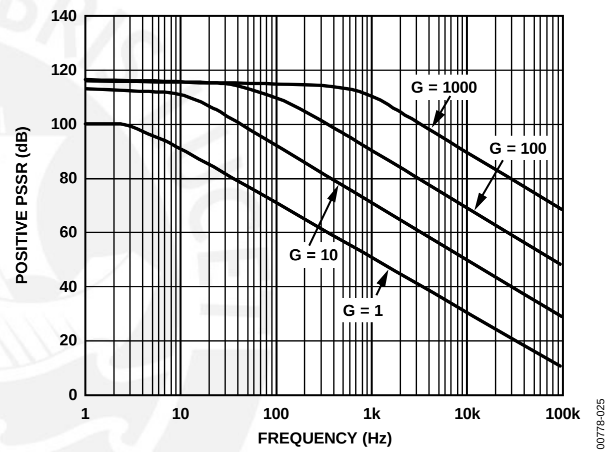

Figure 25. Positive PSRR vs. Frequency, $+V_S$ = 5V, $−V_S$ = 0 V, for Various Gain Settings (G)

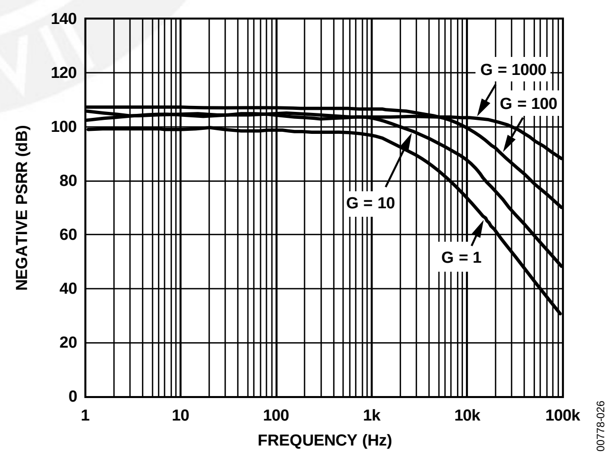

Figure 26. Negative PSRR vs. Frequency for Various Gain Settings (G)

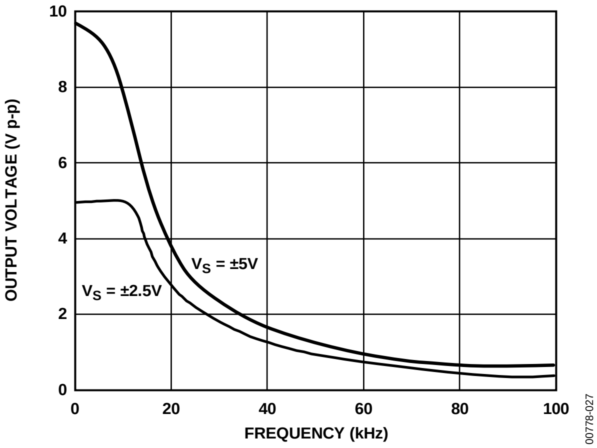

Figure 27. Large Signal Response, G ≤ 10 for Two Supply Voltages

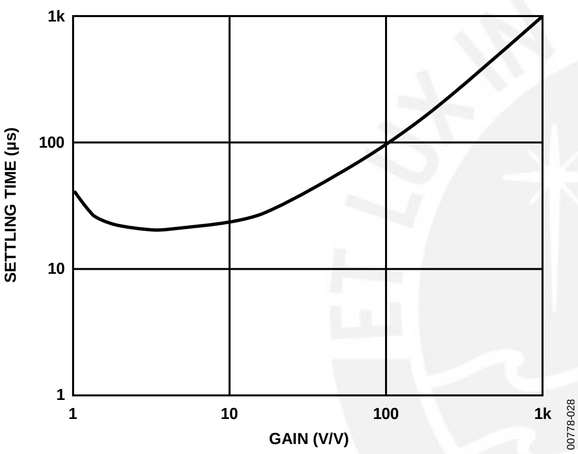

Figure 28. Settling Time to 0.01% vs. Gain, for a 5 V Step at Output, C_L = 100 pF

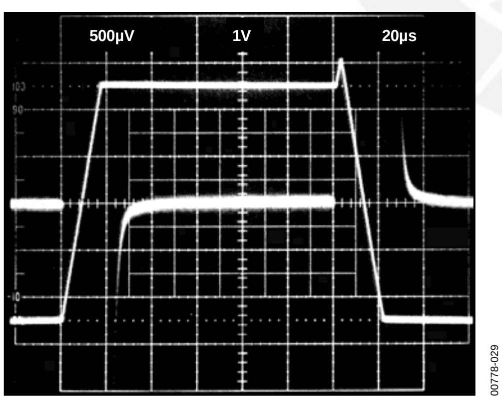

Figure 29. Large Signal Pulse Response and Settling Time, G = −1 (0.250 mV = 0.01%), C_L = 100 pF

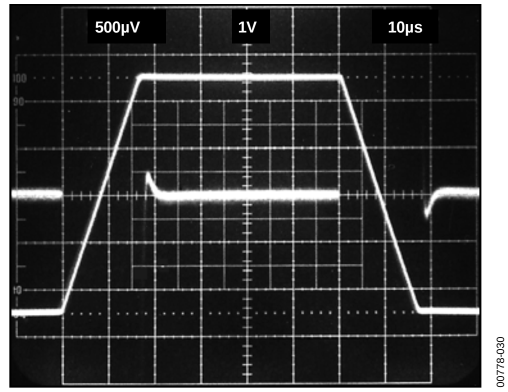

Figure 30. Large Signal Pulse Response and Settling Time, G = −10 (0.250 mV = 0.01%), C_L = 100 pF

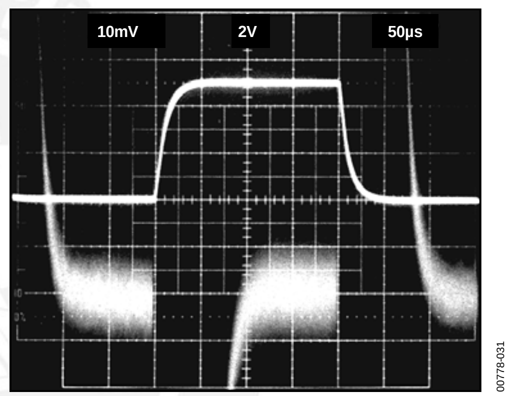

Figure 31. Large Signal Pulse Response and Settling Time, G = 100, C_L = 100 pF

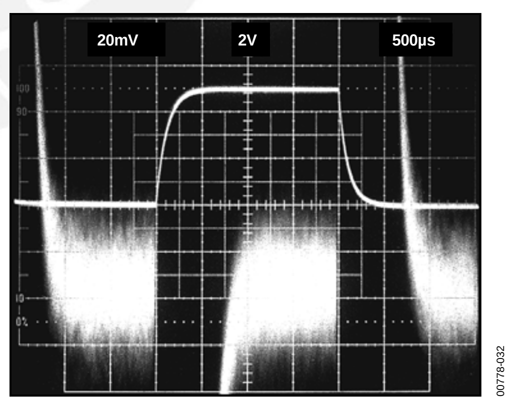

Figure 32. Large Signal Pulse Response and Settling Time, G = −1000 (5 mV = 0.01%), C_L = 100 pF

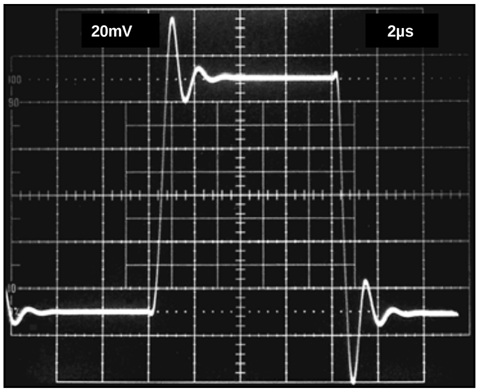

Figure 33. Small Signal Pulse Response, G = 1, R_L = 10 kΩ, C_L = 100 pF

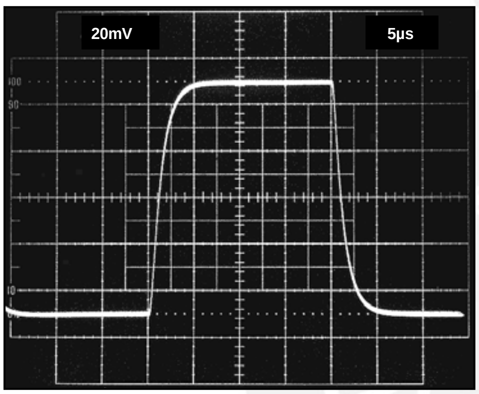

Figure 34. Small Signal Pulse Response, G = 10, R_L = 10 kΩ, C_L = 100 pF

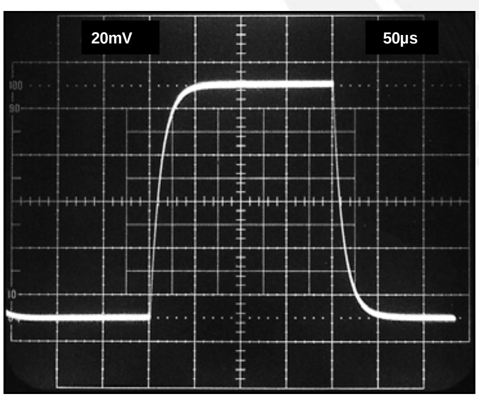

Figure 35. Small Signal Pulse Response, G = 100, R_L = 10 kΩ, C_L = 100 pF

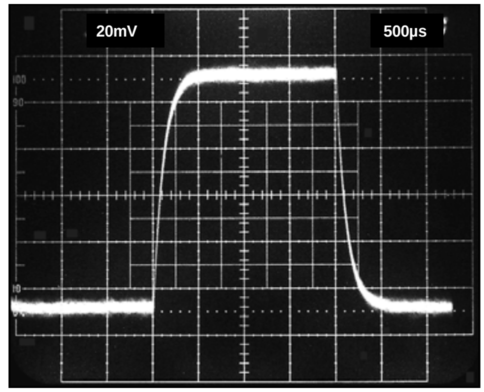

Figure 36. Small Signal Pulse Response, G = 1000, R_L = 10 kΩ, C_L = 100 pF

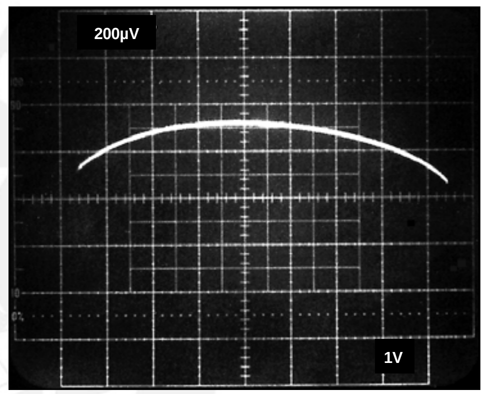

Figure 37. Gain Nonlinearity, G = −1 (50 ppm/DIV)

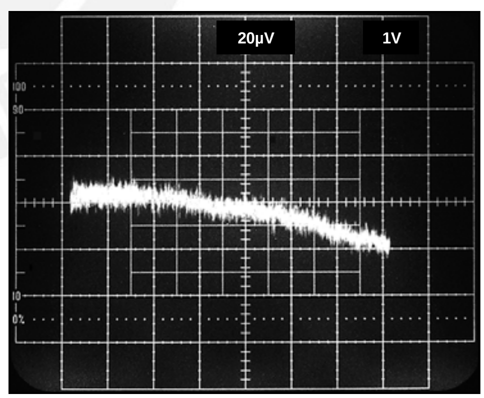

Figure 38. Gain Nonlinearity, G = −10 (6 ppm/DIV)

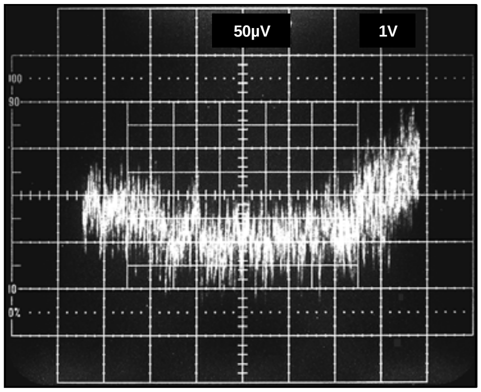

Figure 39. Gain Nonlinearity, G = −100, 15 ppm/DIV

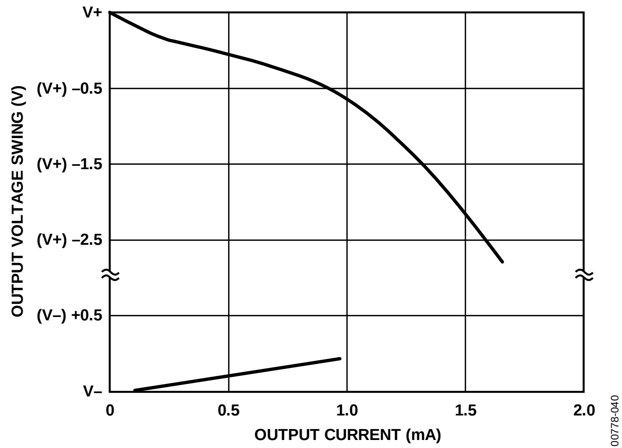

Figure 40. Output Voltage Swing vs. Output Current

THEORY OF OPERATION

The AD623 is an instrumentation amplifier based on a modified classic 3-op-amp approach, to assure single- or dual-supply operation even at common-mode voltages at the negative supply rail. Low voltage offsets, input and output, as well as absolute gain accuracy, and one external resistor to set the gain, make the AD623 one of the most versatile instrumentation amplifiers in its class.

The input signal is applied to PNP transistors acting as voltage buffers and providing a common-mode signal to the input amplifiers (see Figure 41). An absolute value 50 kΩ resistor in each amplifier feedback assures gain programmability.

The differential output is

$$V_O = \left(1 + \frac{100\ \text{k}\Omega}{R_G}\right) V_C$$

The differential voltage is then converted to a single-ended voltage using the output amplifier, which also rejects any common-mode signal at the output of the input amplifiers.

Because the amplifiers can swing to either supply rail, as well as have their common-mode range extended to below the negative supply rail, the range over which the AD623 can operate is further enhanced (see Figure 20 and Figure 21).

The output voltage at Pin 6 is measured with respect to the potential at Pin 5. The impedance of the reference pin is 100 kΩ; therefore, in applications requiring voltage conversion, a small resistor between Pin 5 and Pin 6 is all that is needed.

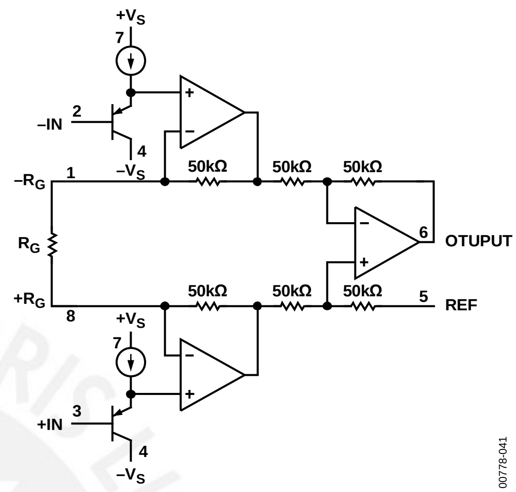

Figure 41. Simplified Schematic

Because of the voltage feedback topology of the internal op amps, the bandwidth of the in-amp decreases with increasing gain. At unity gain, the output amplifier limits the bandwidth.

APPLICATIONS INFORMATION

BASIC CONNECTION

Figure 42 and Figure 43 show the basic connection circuits for the AD623. The $+V_S$ and $-V_S$ terminals are connected to the power supply. The supply can be either bipolar ($V_S = \pm2.5$ V to ±6 V) or single supply ($-V_S = 0$ V, $+V_S = 3.0$ V to 12 V). Capacitively decouple power supplies close to the power pins of the device. For best results, use surface-mount 0.1 µF ceramic chip capacitors and 10 µF electrolytic tantalum capacitors.

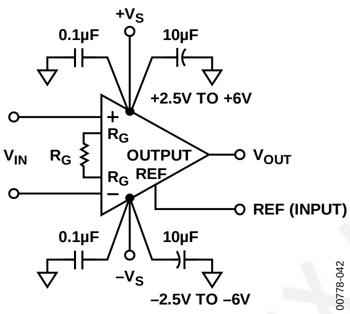

Figure 42. Dual-Supply Basic Connection

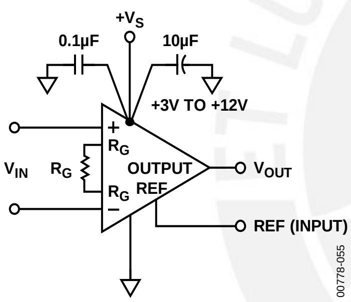

Figure 43. Single-Supply Basic Connection

The input voltage, which can be either single-ended (tie either −IN or +IN to ground) or differential, is amplified by the programmed gain. The output signal appears as the voltage difference between the OUTPUT pin and the externally applied voltage on the REF input. For a ground referenced output, REF must be grounded.

GAIN SELECTION

The gain of the AD623 is programmed by the R_G resistor, or more precisely, by whatever impedance appears between Pin 1 and Pin 8. The AD623 offers accurate gains using 0.1% to 1% tolerance resistors. Table 7 shows the required values of R_G for the various gains. Note that for G = 1, the R_G terminals are unconnected ($R_G = \infty$). For any arbitrary gain, R_G can be calculated by

$$R_G = 100\ \text{k}\Omega/(G - 1)$$

REFERENCE TERMINAL

The reference terminal potential defines the zero output voltage and is especially useful when the load does not share a precise ground with the rest of the system. It provides a direct means of injecting a precise offset to the output. The reference terminal is also useful when bipolar signals are being amplified because it can be used to provide a virtual ground voltage. The voltage on the reference terminal can be varied from $-V_S$ to $+V_S$.

Table 7. Required Values of Gain Resistors

Desired Gain	1% Standard Table Value of R_G	Calculated Gain Using 1% Resistors
2	100 kΩ	2
5	24.9 kΩ	5.02
10	11 kΩ	10.09
20	5.23 kΩ	20.12
33	3.09 kΩ	33.36
40	2.55 kΩ	40.21
50	2.05 kΩ	49.78
65	1.58 kΩ	64.29
100	1.02 kΩ	99.04
200	499 Ω	201.4
500	200 Ω	501
1000	100 Ω	1001

INPUT AND OUTPUT OFFSET VOLTAGE ERROR

The offset voltage (V_{OS}) of the AD623 is attributed to two sources: those originating in the two input stages where the in-amp gain is established, and those originating in the subtractor output stage. The output error is divided by the programmed gain when referred to the input. In practice, the input errors dominate at high gain settings, whereas the output error prevails when the gain is set at or near unity.

The V_{OS} error for any given gain is calculated as follows:

Total Error Referred to Input (RTI)
= Input Error + (Output Error/G)

Total Error Referred to Output (RTO)
= (Input Error × G) + Output Error

The RTI offset errors and noise voltages for different gains are listed in Table 8.

INPUT PROTECTION

Internal supply-referenced clamping diodes allow the input, reference, output, and gain terminals of the AD623 to safely withstand overvoltages of 0.3 V above or below the supplies. This overvoltage protection is true at all gain settings and when cycling power on and off. Overvoltage protection is particularly important because the signal source and amplifier may be powered separately.

If the overvoltage is expected to exceed this value, the current through these diodes must be limited to about 10 mA using external current limiting resistors (see Figure 44). The size of this resistor is defined by the supply voltage and the required overvoltage protection.

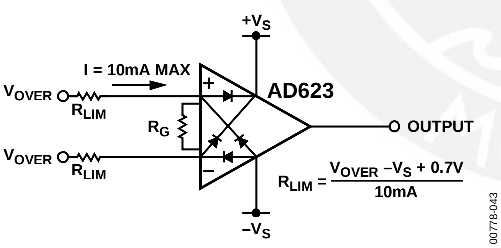

Figure 44. Input Protection

RF INTERFERENCE

All instrumentation amplifiers can rectify high frequency out-of-band signals. Once rectified, these signals appear as dc offset errors at the output. The circuit in Figure 45 provides good RFI suppression without reducing performance within the pass band of the in-amp. Resistor R1 and Capacitor C1 (and likewise, R2 and C2) form a low-pass RC filter that has a −3 dB bandwidth equal to f = 1/(2 π R1C1). Using the component values shown, this filter has a −3 dB bandwidth of approximately 40 kHz. The R1 and R2 resistors were selected to be large enough to isolate the input of the circuit from the capacitors, but not large enough to significantly increase the noise of the circuit. To preserve common-mode rejection in the pass band of the amplifier, the C1 and C2 capacitors must be 5% or better units, or low cost 20% units can be tested and binned to provide closely matched devices.

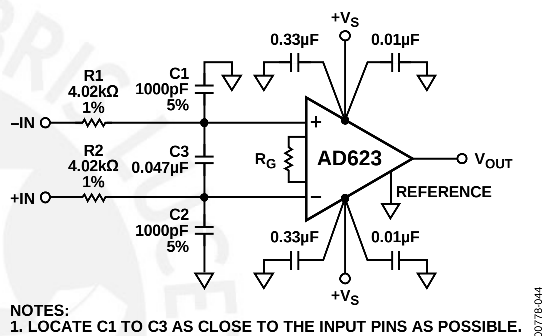

Figure 45. Circuit to Attenuate RF Interference

Capacitor C3 is needed to maintain common-mode rejection at low frequencies. R1/R2 and C1/C2 form a bridge circuit whose output appears across the input pins of the in-amp. Any mismatch between C1 and C2 unbalances the bridge and reduces the common-mode rejection. C3 ensures that any RF signals are common mode (the same on both in-amp inputs) and are not applied differentially. This second low-pass network, R1 + R2 and C3, has a −3 dB frequency equal to 1/(2π(R1 + R2)(C3)). Using a C3 value of 0.047 µF, the −3 dB signal bandwidth of this circuit is approximately 400 Hz. The typical dc offset shift over frequency is less than 1.5 µV, and the RF signal rejection of the circuit is better than 71 dB. The 3 dB signal bandwidth of this circuit can be increased to 900 Hz by reducing R1 and R2 to 2.2 kΩ. The performance is similar to using 4 kΩ resistors, except that the circuitry preceding the in-amp must drive a lower impedance load.

Table 8. RTI Error Sources

	Maximum Total Input Offset Error (µV)		Maximum Total Input Offset Drift (µV/°C)		Total Input Referred Noise (nV/√Hz)	
Gain	AD623A	AD623B	AD623A	AD623B	AD623A	AD623B
1	1200	600	12	11	62	62
2	700	350	7	6	45	45
5	400	200	4	3	38	38
10	300	150	3	2	35	35
20	250	125	2.5	1.5	35	35
50	220	110	2.2	1.2	35	35
100	210	105	2.1	1.1	35	35
1000	200	100	2	1	35	35

The circuit in Figure 45 must be built using a printed circuit board (PCB) with a ground plane on both sides. All component leads must be as short as possible. The R1 and R2 resistors can be common 1% metal film units; however, the C1 and C2 capacitors must be ±5% tolerance devices to avoid degrading the common-mode rejection of the circuit. Either the traditional 5% silver mica units or Panasonic ±2% PPS film capacitors are recommended.

In many applications, shielded cables are used to minimize noise; for best CMR over frequency, the shield must be properly driven. Figure 46 shows an active guard driver that is configured to improve ac common-mode rejection by bootstrapping the capacitances of input cable shields, thus minimizing the capacitance mismatch between the inputs.

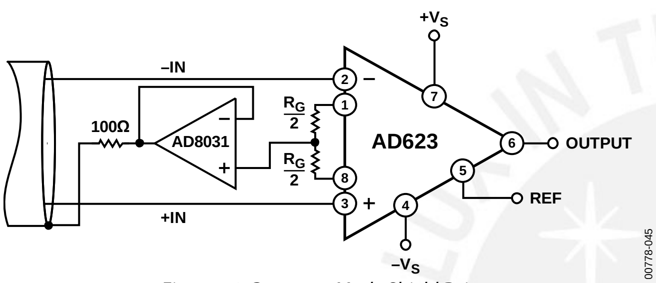

Figure 46. Common-Mode Shield Driver

GROUNDING

Because the AD623 output voltage is developed with respect to the potential on the reference terminal, many grounding problems can be solved by simply tying the REF pin to the appropriate local ground. The REF pin must, however, be tied to a low impedance point for optimal CMR.

The use of ground planes is recommended to minimize the impedance of ground returns (and hence the size of dc errors). To isolate low level analog signals from a noisy digital environment, many data acquisition components have separate analog and digital ground returns (see Figure 47). All ground pins from mixed signal components, such as analog-to-digital converters (ADCs), must be returned through the high quality analog ground plane. Maximum isolation between analog and digital is achieved by connecting the ground planes back at the supplies. The digital return currents from the ADC that flow in the analog ground plane, in general, have a negligible effect on noise performance.

If there is only a single power supply available, it must be shared by both digital and analog circuitry. Figure 48 shows how to minimize interference between the digital and analog circuitry. As in the previous case, use separate analog and digital ground planes (reasonably thick traces can be used as an alternative to a digital ground plane). These ground planes must be connected at the ground pin of the power supply. Run separate traces from the power supply to the supply pins of the digital and analog circuits. Ideally, each device has its own power supply trace, but these can be shared by a number of devices, as long as a single trace is not used to route current to both digital and analog circuitry.

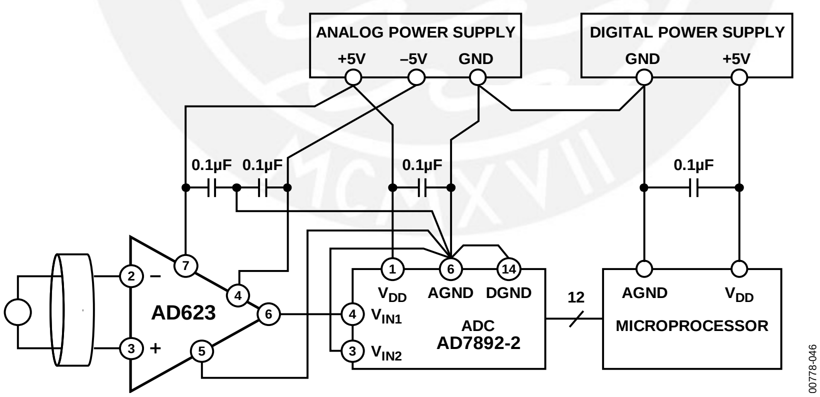

Figure 47. Optimal Grounding Practice for a Bipolar Supply Environment with Separate Analog and Digital Supplies

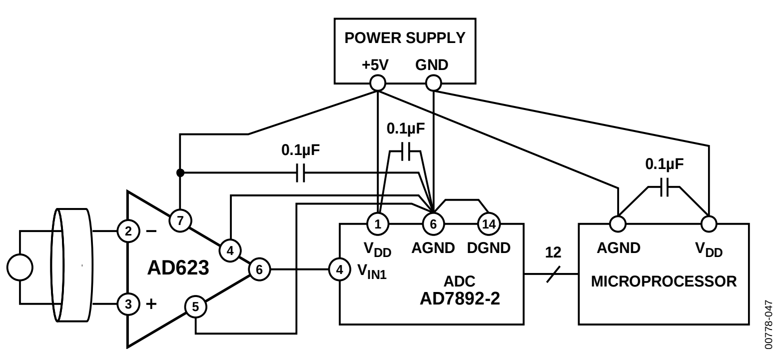

Figure 48. Optimal Ground Practice in a Single-Supply Environment

Ground Returns for Input Bias Currents

Input bias currents are those dc currents that must flow to bias the input transistors of an amplifier. These are usually transistor base currents. When amplifying floating input sources, such as transformers or ac-coupled sources, there must be a direct dc path into each input so that the bias current can flow. Figure 49, Figure 50, and Figure 51 show how a bias current path can be provided for the cases of transformer coupling, thermocouple, and capacitive ac coupling. In dc-coupled resistive bridge applications, providing this path is generally not necessary because the bias current simply flows from the bridge supply through the bridge into the amplifier. However, if the impedances that the two inputs see are large and differ by a large amount (>10 kΩ), the offset current of the input stage causes dc errors proportional with the input offset voltage of the amplifier.

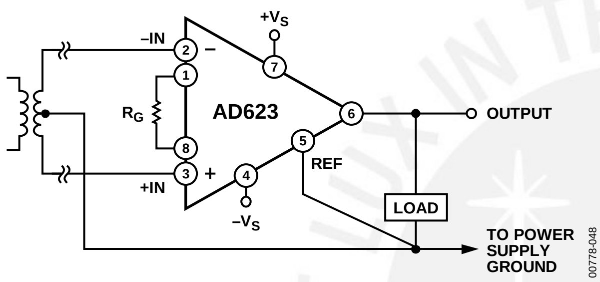

Figure 49. Ground Returns for Bias Currents with Transformer-Coupled Inputs

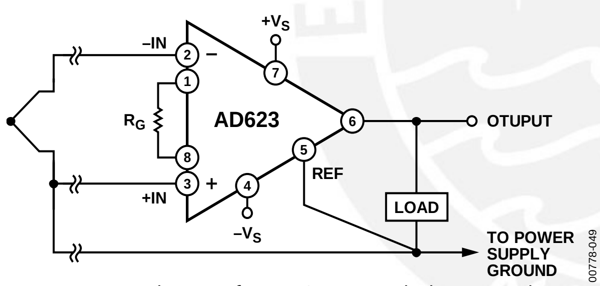

Figure 50. Ground Returns for Bias Currents with Thermocouple Inputs

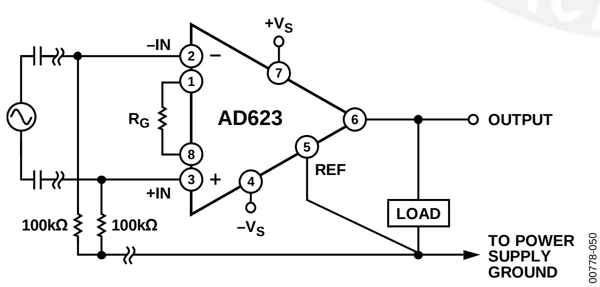

Figure 51. Ground Returns for Bias Currents with AC-Coupled Inputs

Output Buffering

The AD623 is designed to drive loads of 10 kΩ or greater. If the load is less than this value, the output of the AD623 must be buffered with a precision single-supply op amp, such as the OP113. This op amp can swing from 0 V to 4 V on its output while driving a load as small as 600 Ω. Table 9 summarizes the performance of some buffer op amps.

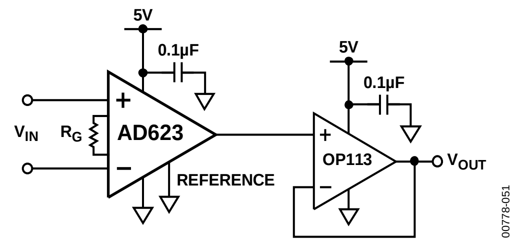

Figure 52. Output Buffering

Table 9. Buffering Options

Op Amp	Description
OP113	Single-supply, high output current
OP191	Rail-to-rail input and output, low supply current

Single-Supply Data Acquisition System

Interfacing bipolar signals to single-supply ADCs presents a challenge. The bipolar signal must be mapped into the input range of the ADC. Figure 53 shows how this translation can be achieved.

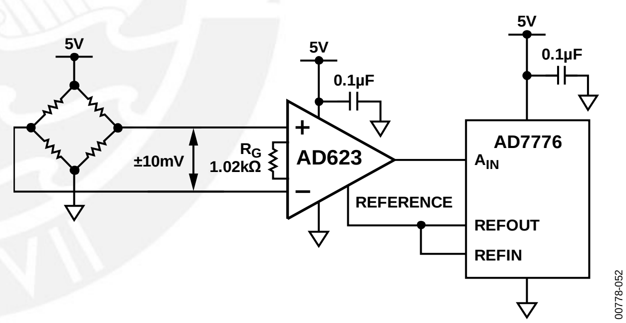

Figure 53. A Single-Supply Data Acquisition System

The bridge circuit is excited by a 5 V supply. The full-scale output voltage from the bridge (±10 mV) therefore has a common-mode level of 2.5 V. The AD623 removes the common-mode component and amplifies the input signal by a factor of 100 (R_{GAIN} = 1.02 kΩ), which results in an output signal of ±1 V. To prevent this signal from running into the ground rail of the AD623, the voltage on the REF pin must be raised to at least 1 V. In this example, the 2 V reference voltage from the AD7776 ADC biases the output voltage of the AD623 to 2 V ± 1 V, which corresponds to the input range of the ADC.

Amplifying Signals with Low Common-Mode Voltage

Because the common-mode input range of the AD623 extends 0.1 V below ground, it is possible to measure small differential signals which have low or no common-mode component. Figure 54 shows a thermocouple application where one side of the J-type thermocouple is grounded.

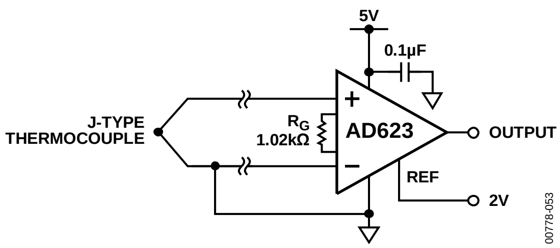

Figure 54. Amplifying Bipolar Signals with Low Common-Mode Voltage

Over a temperature range of −200°C to +200°C, the J-type thermocouple delivers a voltage ranging from −7.890 mV to +10.777 mV. A programmed gain on the AD623 of 100 (R_G = 1.02 kΩ) and a voltage on the REF pin of 2 V result in the output voltage ranging from 1.110 V to 3.077 V relative to ground.

INPUT DIFFERENTIAL AND COMMON-MODE RANGE vs. SUPPLY AND GAIN

Figure 55 shows a simplified block diagram of the AD623. The voltages at the outputs of Amplifier A1 and Amplifier A2 are given by

$$V_{A2} = V_{CM} + V_{DIFF}/2 + 0.6\ V + V_{DIFF} \times R_F/R_G$$
$$= V_{CM} + 0.6\ V + V_{DIFF} \times Gain/2$$

$$V_{A1} = V_{CM} - V_{DIFF}/2 + 0.6\ V + V_{DIFF} \times R_F/R_G$$
$$= V_{CM} + 0.6\ V - V_{DIFF} \times Gain/2$$

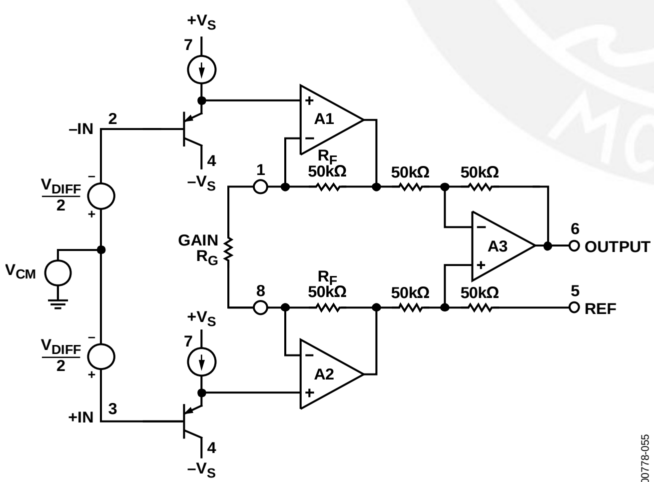

Figure 55. Simplified Block Diagram

The voltages on these internal nodes are critical in determining whether the output voltage is clipped. The V_{A1} and V_{A2} voltages can swing from approximately 10 mV above the negative supply (V− or ground) to within approximately 100 mV of the positive rail before clipping occurs. Based on this and from the previous equations, the maximum and minimum input common-mode voltages are given by the following equations:

$$V_{CMMAX} = V+ - 0.7\ \text{V} - V_{DIFF} \times Gain/2$$

$$V_{CMMIN} = V- - 0.590\ \text{V} + V_{DIFF} \times Gain/2$$

These equations can be rearranged to give the maximum possible differential voltage (positive or negative) for a particular common-mode voltage, gain, and power supply. Because the signals on A1 and A2 can clip on either rail, the maximum differential voltage is the lesser of the two equations.

$$|V_{DIFFMAX}| = 2\ (V+ - 0.7\ \text{V} - V_{CM})/Gain$$

$$|V_{DIFFMAX}| = 2\ (V_{CM} - V- + 0.590\ \text{V})/Gain$$

However, the range on the differential input voltage range is also constrained by the output swing. Therefore, the range of V_{DIFF} may need to be lower according the following equation:

$$Input\ Range \leq Available\ Output\ Swing/Gain$$

For a bipolar input voltage with a common-mode voltage that is roughly half way between the rails, $V_{DIFFMAX}$ is half the value that the previous equations yield because the REF pin is at midsupply. Note that the available output swing is given for different supply conditions in the Specifications section.

The equations can be rearranged to give the maximum gain for a fixed set of input conditions. The maximum gain is the lesser of the two equations.

$$Gain_{MAX} = 2\ (V+ - 0.7\ \text{V} - V_{CM})/V_{DIFF}$$

$$Gain_{MAX} = 2\ (V_{CM} - \text{V}- + 0.590\ V)/V_{DIFF}$$

Again, it is recommended that the resulting gain times the input range is less than the available output swing. If this is not the case, the maximum gain is given by

$$Gain_{MAX} = Available\ Output\ Swing/Input\ Range$$

Also for bipolar inputs (that is, input range = 2 V_{DIFF}), the maximum gain is half the value yielded by the previous equations because the REF pin must be at midsupply.

The maximum gain and resulting output swing for different input conditions is given in Table 10. Output voltages are referenced to the voltage on the REF pin.

For the purposes of computation, it is necessary to break down the input voltage into its differential and common-mode components. Therefore, when one of the inputs is grounded or at a fixed voltage, the common-mode voltage changes as the differential voltage changes. Take the case of the thermocouple amplifier in Figure 54. The inverting input on the AD623 is grounded; therefore, when the input voltage is −10 mV, the voltage on the noninverting input is −10 mV. For the purpose of the signal swing calculations, this input voltage must be composed of a common-mode voltage of −5 mV (that is, (+IN + −IN)/2) and a differential input voltage of −10 mV (that is, +IN − −IN).

Table 10. Maximum Attainable Gain and Resulting Output Swing for Different Input Conditions

V_{CM}	V_{DIFF}	REF Pin	Supply Voltages	Maximum Gain	Closest 1% Gain Resistor	Resulting Gain	Output Swing
0 V	±10 mV	2.5 V	+5 V	118	866 Ω	116	±1.2 V
0 V	±100 mV	2.5 V	+5 V	11.8	9.31 kΩ	11.7	±1.1 V
0 V	±10 mV	0 V	±5 V	490	205 Ω	488	±4.8 V
0 V	±100 mV	0 V	±5 V	49	2.1 kΩ	48.61	±4.8 V
0 V	±1 V	0 V	±5 V	4.9	26.1 kΩ	4.83	±4.8 V
2.5 V	±10 mV	2.5 V	+5 V	242	422 Ω	238	±2.3 V
2.5 V	±100 mV	2.5 V	+5 V	24.2	4.32 kΩ	24.1	±2.4 V
2.5 V	±1 V	2.5 V	+5 V	2.42	71.5 kΩ	2.4	±2.4 V
1.5 V	±10 mV	1.5 V	+3 V	142	715 Ω	141	±1.4 V
1.5 V	±100 mV	1.5 V	+3 V	14.2	7.68 kΩ	14	±1.4 V
0 V	±10 mV	1.5 V	+3 V	118	866 Ω	116	±1.1 V
0 V	±100 mV	1.5 V	+3 V	11.8	9.31 kΩ	11.74	±1.1 V

ADDITIONAL INFORMATION

For an updated design of the AD623, see the AD8223.

For a selection guide to all Analog Devices instrumentation amplifiers, see the Instrumentation Amplifiers page on the Analog Devices website at www.analog.com.

For additional information on in-amps, refer to the following:

MT-061. *Instrumentation Amplifier (In-Amp) Basics.* Analog Devices, Inc.

MT-070. *In-Amp Input RFI Protection.* Analog Devices, Inc.

Counts, Lew and Charles Kitchen. *A Designer's Guide to Instrumentation Amplifiers.* 3rd edition. Analog Devices, Inc., 2006.

EVALUATION BOARD

GENERAL DESCRIPTION

The EVAL-INAMP-62RZ can be used to evaluate the AD620, AD621, AD622, AD623, AD627, AD8223, and AD8225 instrumentation amplifiers. In addition to the basic in-amp connection, circuit options enable the user to adjust the offset voltage, apply an output reference, or provide shield drivers with user supplied components. The board is shipped with an assortment of instrumentation amplifier ICs in the legacy SOIC pinout, such as the AD620, AD621, AD622, AD623, AD8223, and AD8225. The board also has an alternative footprint for a through-hole, 8-lead PDIP.

Figure 56 shows a photograph of the evaluation boards for all Analog Devices instrumentation amplifiers. For additional information, see the EVAL-INAMP user guide (UG-261).

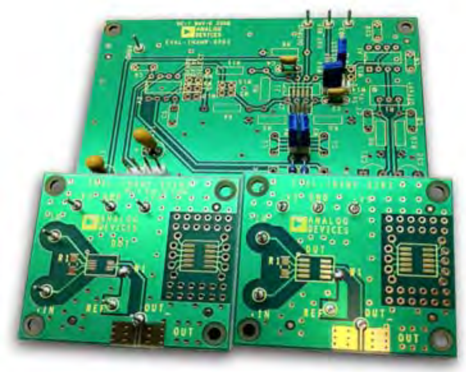

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Figure 56. Evaluation Boards for Analog Devices In-Amps

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OUTLINE DIMENSIONS

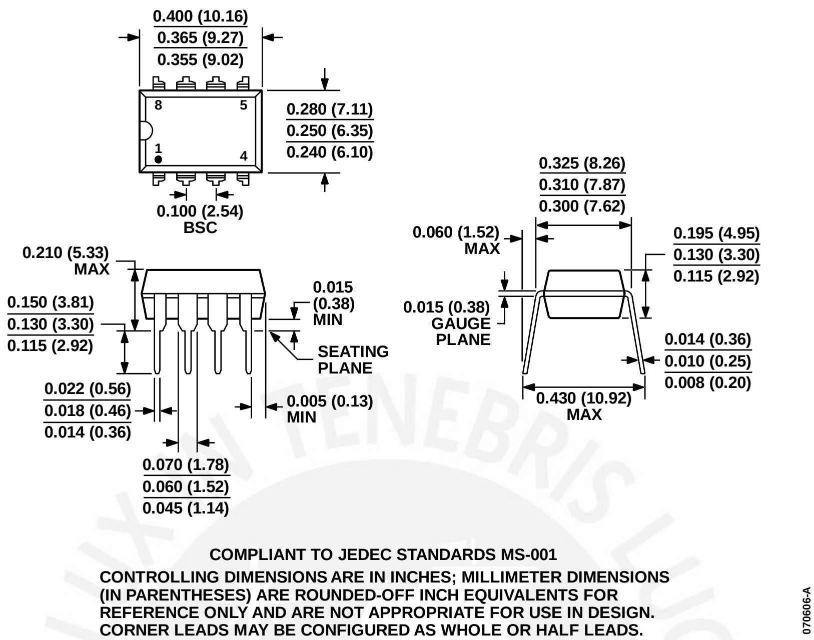

Figure 57. 8-Lead Plastic Dual In-Line Package [PDIP]
Narrow Body (N-8)
Dimensions shown in inches and (millimeters)

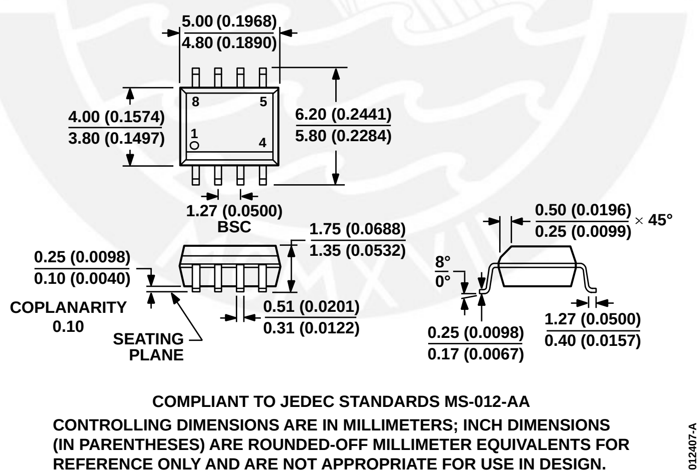

Figure 58. 8-Lead Standard Small Outline Package [SOIC_N]
Narrow Body (R-8)
Dimensions shown in millimeters and (inches)

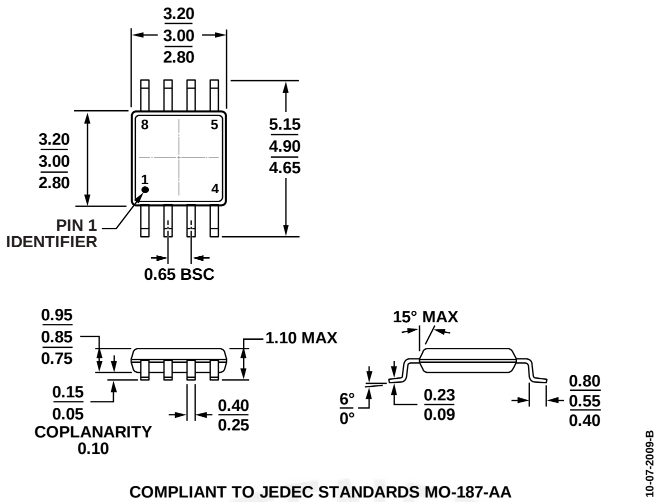

Figure 59. 8-Lead Mini Small Outline Package [MSOP] (RM-8) Dimensions shown in millimeters

ORDERING GUIDE

Model[1]	Temperature Range	Package Description	Package Option	Branding
AD623ANZ	−40°C to +85°C	8-Lead Plastic Dual In-Line Package [PDIP]	N-8	
AD623AR	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N]	R-8	
AD623AR-REEL7	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N], 7" Tape and Reel	R-8	
AD623ARZ	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N]	R-8	
AD623ARZ-R7	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N], 7" Tape and Reel	R-8	
AD623ARZ-RL	−40°C to +85°C	8-Lead SOIC, 13" Tape and Reel	R-8	
AD623ARMZ	−40°C to +85°C	8-Lead Mini Small Outline Package [MSOP]	RM-8	J0A
AD623ARMZ-REEL	−40°C to +85°C	8-Lead Mini Small Outline Package [MSOP], 13" Tape and Reel	RM-8	J0A
AD623ARMZ-REEL7	−40°C to +85°C	8-Lead Mini Small Outline Package [MSOP], 7" Tape and Reel	RM-8	J0A
AD623BNZ	−40°C to +85°C	8-Lead Plastic Dual In-Line Package [PDIP]	N-8	
AD623BRZ	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N]	R-8	
AD623BRZ-R7	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N], 7" Tape and Reel	R-8	
AD623BRZ-RL	−40°C to +85°C	8-Lead Standard Small Outline Package [SOIC_N], 13" Tape and Reel	R-8	
EVAL-INAMP-62RZ		Evaluation Board		

[1] Z = RoHS Compliant Part.

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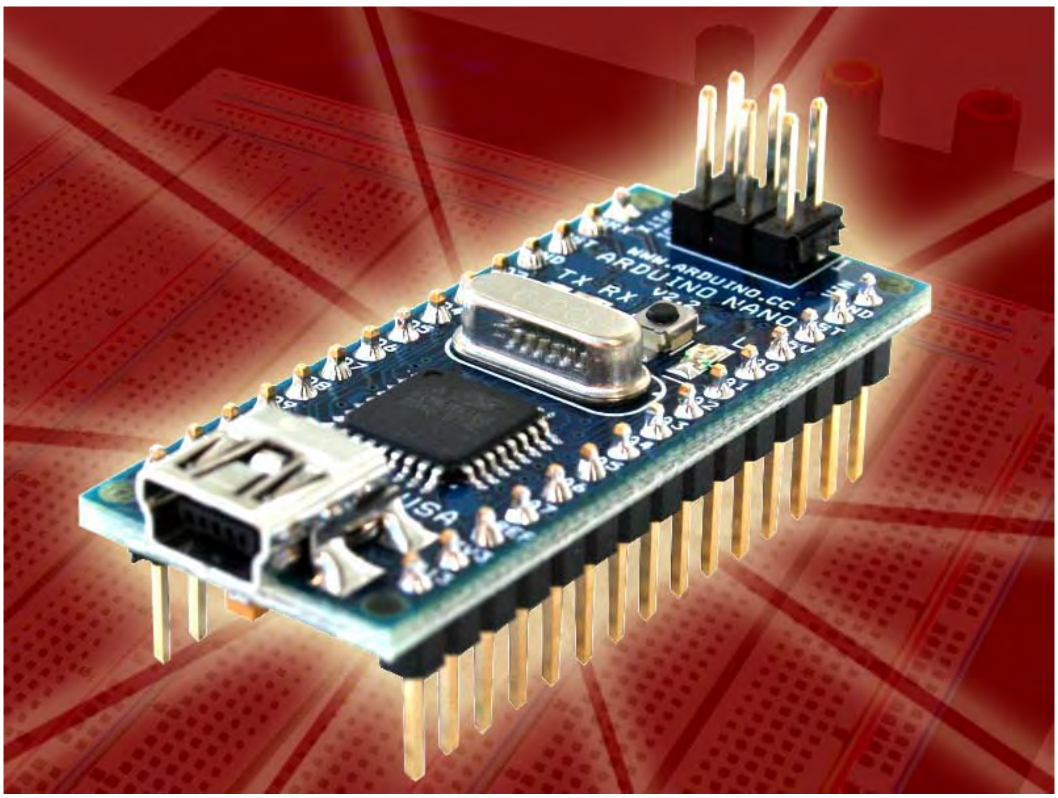
Arduino Nano *(V2.3)*

User Manual



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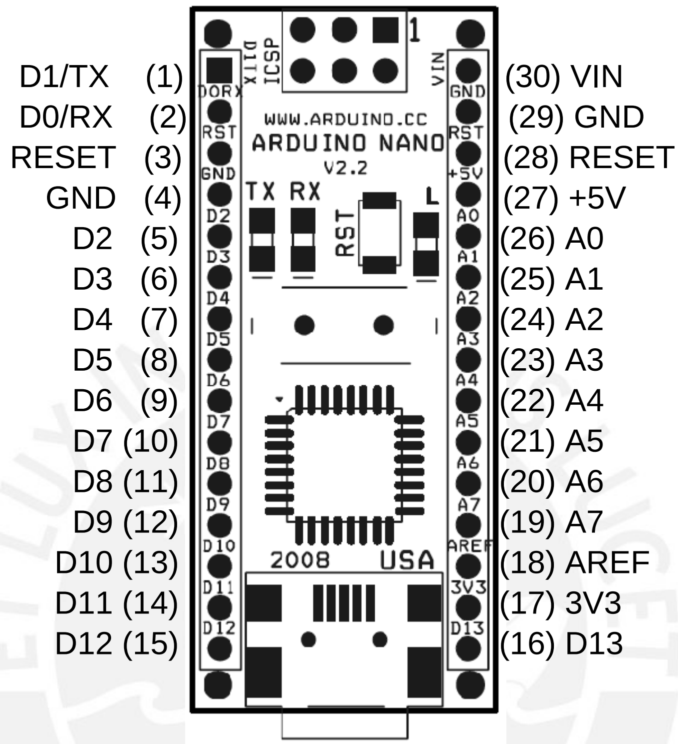
More information:

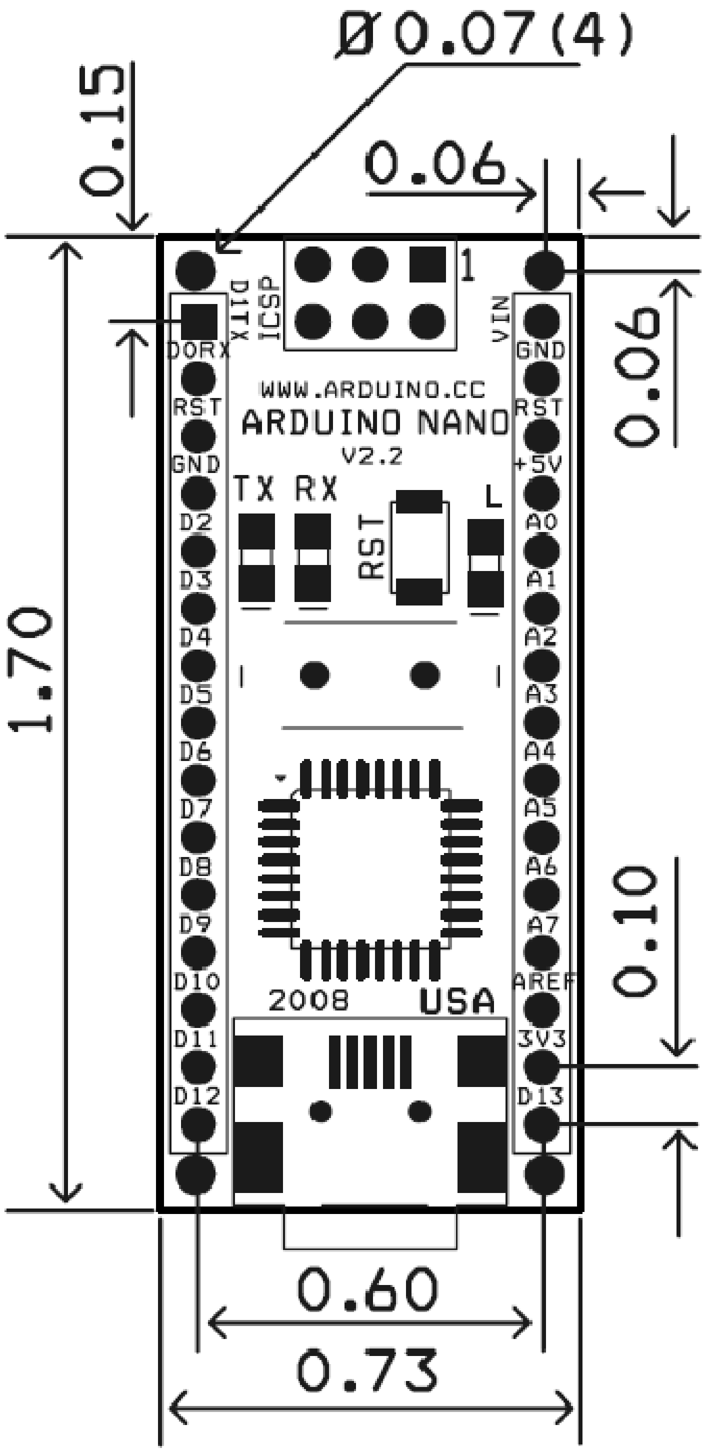
www.arduino.cc Rev. 2.3

Arduino Nano Pin Layout



Pin No.	Name	Type	Description
1-2, 5-16	D0-D13	I/O	Digital input/output port 0 to 13
3, 28	RESET	Input	Reset (active low)
4, 29	GND	PWR	Supply ground
17	3V3	Output	+3.3V output (from FTDI)
18	AREF	Input	ADC reference
19-26	A7-A0	Input	Analog input channel 0 to 7
27	+5V	Output or Input	+5V output (from on-board regulator) or +5V (input from external power supply)
30	VIN	PWR	Supply voltage

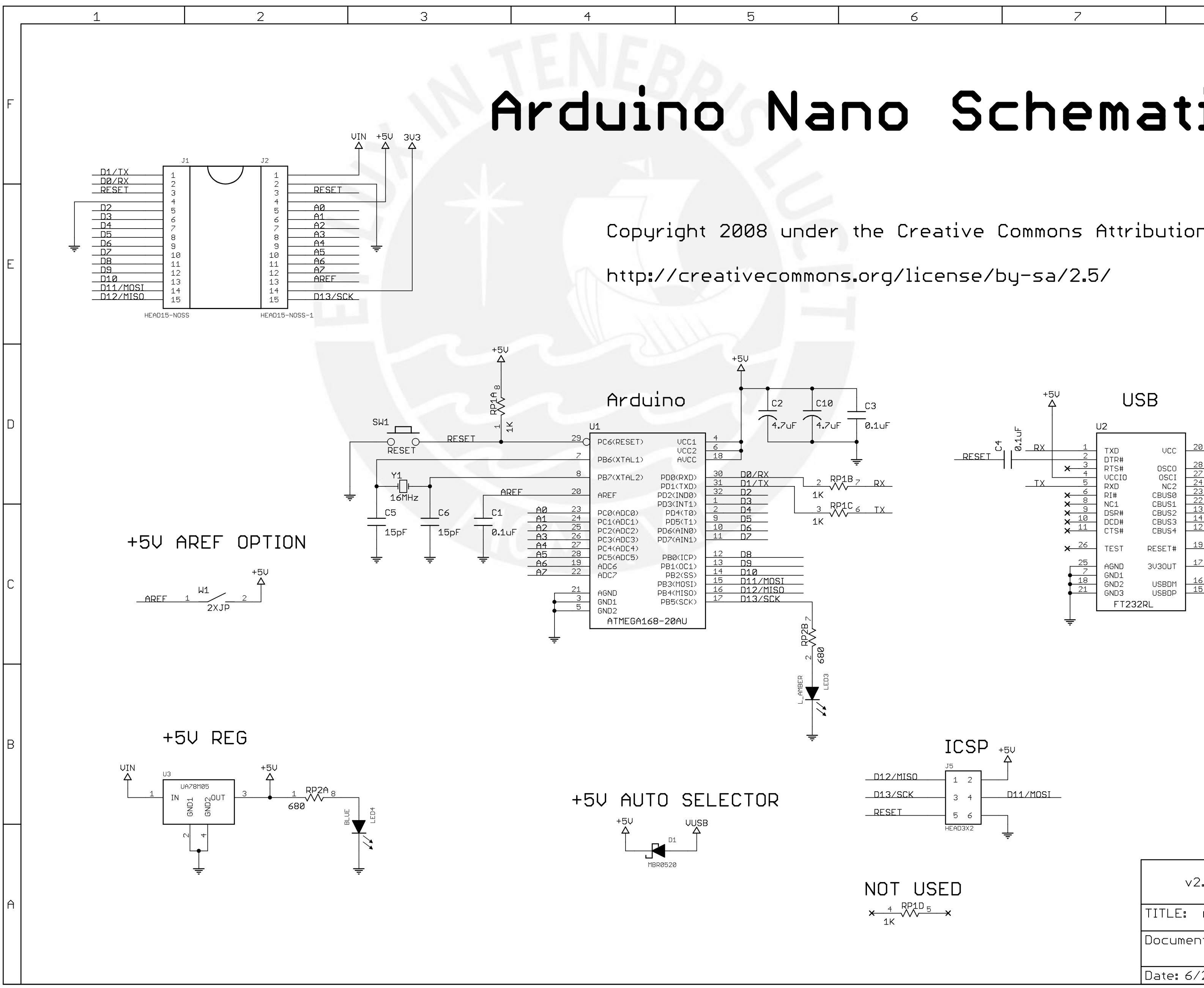
Arduino Nano Mechanical Drawing



ALL DIMENTIONS ARE IN INCHES

Arduino Nano Bill of Material

Item Number	Qty.	Ref. Dest.	Description	Mfg. P/N	MFG	Vendo
1	5	C1,C3,C4,C7,C9	Capacitor, 0.1uF 50V 10% Ceramic X7R 0805	C0805C104K5RACTU	Kemet	80-C0805
2	3	C2,C8,C10	Capacitor, 4.7uF 10V 10% Tantalum Case A	T491A475K010AT	Kemet	80-T491A
3	2	C5,C6	Capacitor, 18pF 50V 5% Ceramic NOP/COG 0805	C0805C180J5GACTU	Kemet	80-C0805
4	1	D1	Diode, Schottky 0.5A 20V	MBR0520LT1G	ONSemi	863-MBR
5	1	J1,J2	Headers, 36PS 1 Row	68000-136HLF	FCI	649-6800
6	1	J4	Connector, Mini-B Recept Rt. Angle	67503-1020	Molex	538-675
7	1	J5	Headers, 72PS 2 Rows	67996-272HLF	FCI	649-6799
8	1	LD1	LED, Super Bright RED 100mcd 640nm 120degree 0805	APT2012SRCPRV	Kingbright	604-APT20
9	1	LD2	LED, Super Bright GREEN 50mcd 570nm 110degree 0805	APHCM2012CGCK-F01	Kingbright	604-APHCM
10	1	LD3	LED, Super Bright ORANGE 160mcd 601nm 110degree 0805	APHCM2012SECK-F01	Kingbright	04-APHCM
11	1	LD4	LED, Super Bright BLUE 80mcd 470nm 110degree 0805	LTST-C170TBKT	Lite-On Inc	160-157
12	1	R1	Resistor Pack, 1K +/-5% 62.5mW 4RES SMD	YC164-JR-071KL	Yageo	YC164J-1
13	1	R2	Resistor Pack, 680 +/-5% 62.5mW 4RES SMD	YC164-JR-07680RL	Yageo	YC164J-6
14	1	SW1	Switch, Momentary Tact SPST 150gf 3.0x2.5mm	B3U-1000P	Omron	SW102
15	1	U1	IC, Microcontroller RISC 16kB Flash, 0.5kB EEPROM, 23 I/O Pins	ATmega168-20AU	Atmel	556-ATMEG
16	1	U2	IC, USB to SERIAL UART 28 Pins SSOP	FT232RL	FTDI	895-FT
17	1	U3	IC, Voltage regulator 5V, 500mA SOT-223	UA78M05CDCYRG3	TI	595-UA78M
18	1	Y1	Cystal, 16MHz +/-20ppm HC-49/US Low Profile	ABL-16.000MHZ-B2	Abracon	815-AB



Arduino Nano Schemati
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http://creativecommons.org/license/by-sa/2.5/
Arduino
USB
+5V AREF OPTION
+5V REG
+5V AUTO SELECTOR
ICSP
NOT USED
ATMEGA168-20AU
FT232RL
UA78M05
MBR0520
HEAD15-NOSS
HEAD15-NOSS-1
HEAD3X2
TITLE:
Document
Date: 6/

HC Serial Bluetooth Products

User Instructional Manual

1 Introduction

HC serial Bluetooth products consist of Bluetooth serial interface module and Bluetooth adapter, such as:

(1) Bluetooth serial interface module:

Industrial level: HC-03, HC-04(HC-04-M, HC-04-S)

Civil level: HC-05, HC-06(HC-06-M, HC-06-S)

HC-05-D, HC-06-D (with baseboard, for test and evaluation)

(2) Bluetooth adapter:

HC-M4

HC-M6

This document mainly introduces Bluetooth serial module. Bluetooth serial module is used for converting serial port to Bluetooth. These modules have two modes: master and slaver device. The device named after even number is defined to be master or slaver when out of factory and can’t be changed to the other mode. But for the device named after odd number, users can set the work mode (master or slaver) of the device by AT commands.

HC-04 specifically includes:

Master device: HC-04-M, M=master

Slave device: HC-04-S, S=slaver

The default situation of HC-04 is slave mode. If you need master mode, please state it clearly or place an order for HC-O4-M directly.The naming rule of HC-06 is same.

When HC-03 and HC-05 are out of factory, one part of parameters are set for activating the device. The work mode is not set, since user can set the mode of HC-03, HC-05 as they want.

The main function of Bluetooth serial module is replacing the serial port line, such as:

1. There are two MCUs want to communicate with each other. One connects to Bluetooth master device while the other one connects to slave device. Their connection can be built once the pair is made. This Bluetooth connection is equivalently liked to a serial port line connection including RXD, TXD

signals. And they can use the Bluetooth serial module to communicate with each other.

2. When MCU has Bluetooth salve module, it can communicate with Bluetooth adapter of computers and smart phones. Then there is a virtual communicable serial port line between MCU and computer or smart phone.

3. The Bluetooth devices in the market mostly are salve devices, such as Bluetooth printer, Bluetooth GPS. So, we can use master module to make pair and communicate with them.

Bluetooth Serial module's operation doesn't need drive, and can communicate with the other Bluetooth device who has the serial. But communication between two Bluetooth modules requires at least two conditions:

(1) The communication must be between master and slave.

(2) The password must be correct.

However, the two conditions are not sufficient conditions. There are also some other conditions basing on different device model. Detailed information is provided in the following chapters.

In the following chapters, we will repeatedly refer to Linvor's (Formerly known as Guangzhou HC Information Technology Co., Ltd.) material and photos.

2 Selection of the Module

The Bluetooth serial module named even number is compatible with each other; The salve module is also compatible with each other. In other word, the function of HC-04 and HC-06, HC-03 and HC-05 are mutually compatible with each other. HC-04 and HC-06 are former version that user can't reset the work mode (master or slave). And only a few AT commands and functions can be used, like reset the name of Bluetooth (only the slaver), reset the password, reset the baud rate and check the version number. The command set of HC-03 and HC-05 are more flexible than HC-04 and HC-06's. Generally, the Bluetooth of HC-03/HC-05 is recommended for the user.

Here are the main factory parameters of HC-05 and HC-06. Pay attention to the differences:

HC-05	HC-06
Master and slave mode can be switched	Master and slave mode can't be switched
Bluetooth name: HC-05	Bluetooth name: linvor
Password:1234	Password:1234

Master role: have no function to remember the last paired salve device. It can be made paired to any slave device. In other words, just set AT+CMODE=1 when out of factory. If you want HC-05 to remember the last paired slave device address like HC-06, you can set AT+CMODE=0 after paired with the other device. Please refer the command set of HC-05 for the details.	Master role: have paired memory to remember last slave device and only make pair with that device unless KEY (PIN26) is triggered by high level. The default connected PIN26 is low level.
Pairing: The master device can not only make pair with the specified Bluetooth address, like cell-phone, computer adapter, slave device, but also can search and make pair with the slave device automatically. Typical method: On some specific conditions, master device and slave device can make pair with each other automatically. (This is the default method.)	Pairing: Master device search and make pair with the slave device automatically. Typical method: On some specific conditions, master and slave device can make pair with each other automatically.
Multi-device communication: There is only point to point communication for modules, but the adapter can communicate with multi-modules.	Multi-device communication: There is only point to point communication for modules, but the adapter can communicate with multi-modules.
AT Mode 1: After power on, it can enter the AT mode by triggering PIN34 with high level. Then the baud rate for setting AT command is equal to the baud rate in communication, for example: 9600. AT mode 2: First set the PIN34 as high level, or while on powering the module set the PIN34 to be high level, the Baud rate used here is 38400 bps. Notice: All AT commands can be operated only	AT Mode: Before paired, it is at the AT mode. After paired it's at transparent communication.

when the PIN34 is at high level. Only part of the AT commands can be used if PIN34 doesn't keep the high level after entering to the AT mode. Through this kind of designing, set permissions for the module is left to the user's external control circuit, that makes the application of HC-05 is very flexible.	
During the process of communication, the module can enter to AT mode by setting PIN34 to be high level. By releasing PIN34, the module can go back to communication mode in which user can inquire some information dynamically. For example, to inquire the pairing is finished or not.	During the communication mode, the module can't enter to the AT mode.
Default communication baud rate: 9600, 4800-1.3M are settable.	Default communication baud rate: 9600, 1200-1.3M are settable.
KEY: PIN34, for entering to the AT mode.	KEY: PIN26, for master abandons memory.
LED1: PIN31, indicator of Bluetooth mode. Slow flicker (1Hz) represents entering to the AT mode2, while fast flicker(2Hz) represents entering to the AT mode1 or during the communication pairing. Double flicker per second represents pairing is finished, the module is communicable. LED2: PIN32, before pairing is at low level, after the pairing is at high level. The using method of master and slaver's indicator is the same. Notice: The PIN of LED1 and LED2 are connected with LED+.	LED: The flicker frequency of slave device is 102ms. If master device already has the memory of slave device, the flicker frequency during the pairing is 110ms/s. If not, or master has emptied the memory, then the flicker frequency is 750m/s. After pairing, no matter it's a master or slave device, the LED PIN is at high level. Notice: The LED PIN connects to LED+ PIN.
Consumption: During the pairing, the current is	Consumption: During the pairing, the current is

fluctuant in the range of 30-40mA. The mean current is about 25mA. After paring, no matter processing communication or not, the current is 8mA. There is no sleep mode. This parameter is same for all the Bluetooth modules.	fluctuant in the range of 30-40 m. The mean current is about 25mA. After paring, no matter processing communication or not, the current is 8mA. There is no sleep mode. This parameter is same for all the Bluetooth modules.
Reset: PIN11, active if it’s input low level. It can be suspended in using.	Reset: PIN11, active if it’s input low level. It can be suspended in using.
Level: Civil	Level: Civil

The table above that includes main parameters of two serial modules is a reference for user selection.

HC-03/HC-05 serial product is recommended.

3. Information of Package

The PIN definitions of HC-03, HC-04, HC-05 and HC-06 are kind of different, but the package size is the same: 28mm * 15mm * 2.35mm.

The following figure 1 is a picture of HC-06 and its main PINs. Figure 2 is a picture of HC-05 and its main PINs. Figure 3 is a comparative picture with one coin. Figure 4 is their package size information. When user designs the circuit, you can visit the website of Guangzhou HC Information Technology Co., Ltd. (www.wavesen.com) to download the package library of protle version.

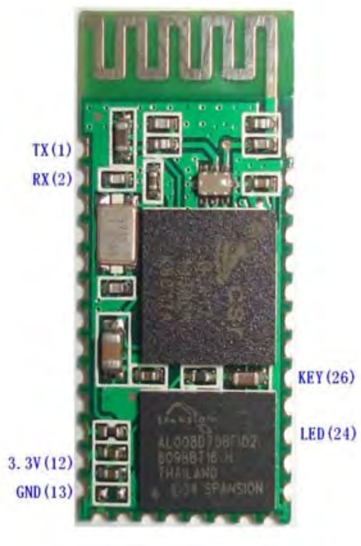


Figure 1 HC-06

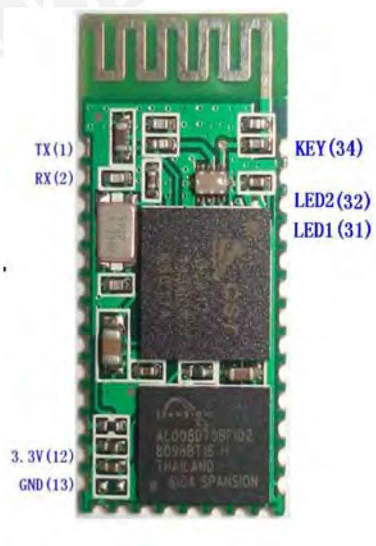


Figure 2 HC-05

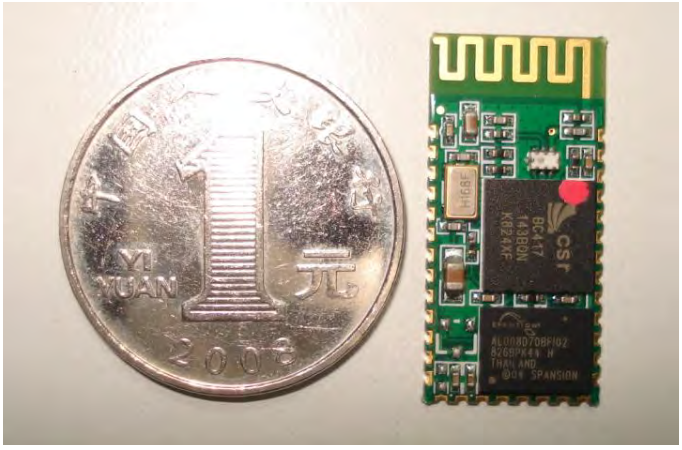
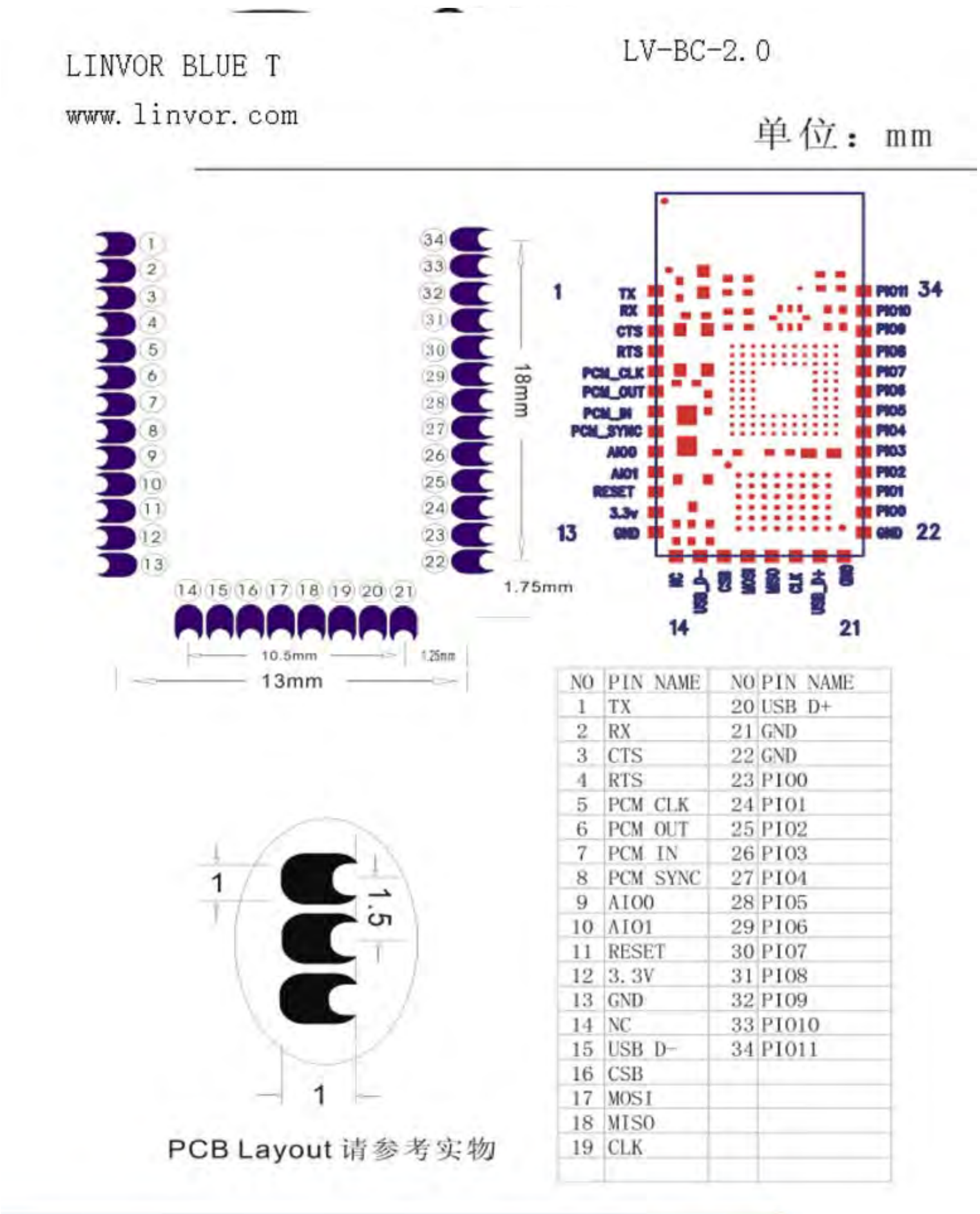


Figure 3 Comparative picture with one coin



NO	PIN NAME	NO	PIN NAME
1	TX	20	USB D+
2	RX	21	GND
3	CTS	22	GND
4	RTS	23	PIO0
5	PCM CLK	24	PIO1
6	PCM OUT	25	PIO2
7	PCM IN	26	PIO3
8	PCM SYNC	27	PIO4
9	AIO0	28	PIO5
10	AIO1	29	PIO6
11	RESET	30	PIO7
12	3.3V	31	PIO8
13	GND	32	PIO9
14	NC	33	PIO10
15	USB D-	34	PIO11
16	CSB		
17	MOSI		
18	MISO		
19	CLK		

Figure 4 Package size information

4. The Using and Testing Method of HC-06 for the First Time

This chapter will introduce the using method of HC-06 in detail. User can test the module according to this chapter when he or she uses the module at the first time.

PINs description:

PIN1	UART_TXD , TTL/CMOS level, UART Data output
PIN2	UART_RXD, TTL/COMS level, s UART Data input
PIN11	RESET, the reset PIN of module, inputting low level can reset the module, when the module is in using, this PIN can connect to air.
PIN12	VCC, voltage supply for logic, the standard voltage is 3.3V, and can work at 3.0-4.2V
PIN13	GND
PIN22	GND
PIN24	LED, working mode indicator Slave device: Before paired, this PIN outputs the period of 102ms square wave. After paired, this PIN outputs high level. Master device: On the condition of having no memory of pairing with a slave device, this PIN outputs the period of 110ms square wave. On the condition of having the memory of pairing with a slave device, this PIN outputs the period of 750ms square wave. After paired, this PIN outputs high level.
PIN26	For master device, this PIN is used for emptying information about pairing. After emptying, master device will search slaver randomly, then remember the address of the new got slave device. In the next power on, master device will only search this address.

(1) The circuit 1 (connect the module to 3.3V serial port of MCU) is showed by figure 5.

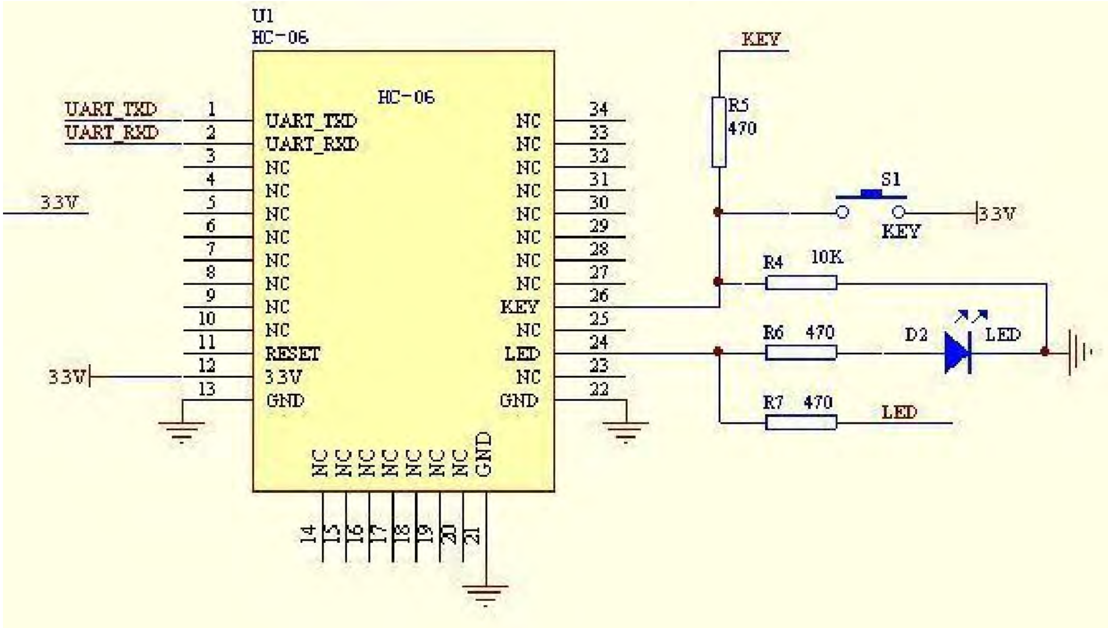


Figure 5 The circuit 1

In principle, HC-06 can work when UART_TXD, UART_RXD, VCC and GND are connected. However, for better testing results, connecting LED and KEY are recommended (when testing the master).

Where, the 3.3V TXD of MCU connects to HC-06's UART_RXD, the 3.3V RXD of MCU connects to HC-06's UART_TXD, and 3.3V power and GND should be connected. Then the minimum system is finished.

Note that, the PIN2:UART_RXD of Bluetooth module has no pull-up resistor. If the MCU TXD doesn't have pull-up function, then user should add a pull-up resistor to the UART_RXD. It may be easy to be ignored.

If there are two MCU which connect to master and slave device respectively, then before paired(LED will flicker) user can send AT commands by serial port when the system is power on. Please refer to HC-04 and HC-06's data sheet for detailed commands. In the last chapter, the command set will be introduced. Please pay attention to that the command of HC-04/HC-06 doesn't have terminator. For example, consider the call command, sending out AT is already enough, need not add the CRLF (carriage return line feed).

If the LED is constant lighting, it indicates the pairing is finished. The two MCUs can communicate with each other by serial port. User can think there is a serial port line between two MCUs.

(2) The circuit 2 (connect the module to 5V serial port of MCU) is showed by figure 6.

Figure 6 is the block diagram of Bluetooth baseboard. This kind of circuit can amplify Bluetooth module's operating voltage to 3.1-6.5V. In this diagram, the J1 port can not only be connected with MCU system of 3.3V and 5V, but also can be connected with computer serial port.

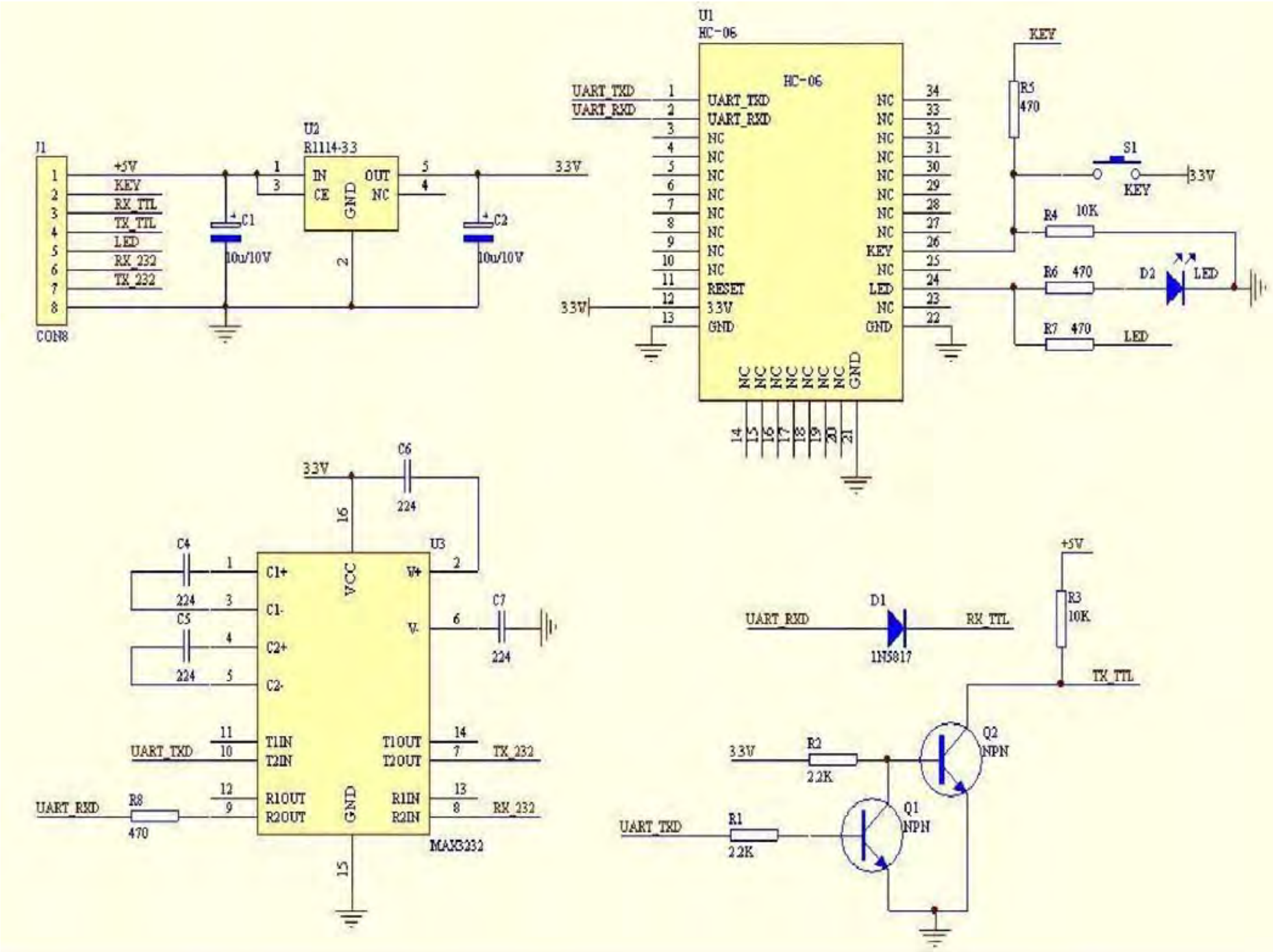


Figure 6 The circuit 2

(3) AT command test

Before paired, the mode of HC-04 and HC-06 are AT mode.

On the condition of 9600N81, OK will be received when user send the two letters AT. Please refer to the last chapter of datasheet for other commands of HC-06. Please pay attention to that sending out AT is already enough, need not add the CRLF (carriage return line feed).

The command set of Version V1.4 doesn't include parity. The version V1.5 and its later version have parity function. Moreover, there are three more commands of V1.5 than V1.4. They are:

No parity (default)　　　AT+PN

Odd parity AT+PO

Even parity AT+PE

Do not let the sending frequency of AT command of HC-06 exceed 1Hz, because the command of HC-06 end or not is determined by the time interval.

(4) Pairing with adapter

User can refer to the download center of the company's website for "The Introduction of IVT" that introduces the Bluetooth module makes pair with computer adapter. That document taking HC-06-D for example introduces how the serial module makes pair with the adapter. That method is like to make pair with cell-phone. But the difference is that cell-phone need a third-party communication software to help. It's liked the kind of PC serial helper of and the hyper terminal. A software named "PDA serial helper" provided by our company is suitable for WM system. It has been proven that this serial module is supported by many smart phone systems' Bluetooth, such as, sybian, android, windows mobile and etc.

(5) Pairing introduction

HC-06 master device has no memory before the first use. If the password is correct, the mater device will make pair with the slave device automatically in the first use. In the following use, the master device will remember the Bluetooth address of the last paired device and search it. The searching won't stop until the device is found. If master device's PIN26 is input high level, the device will lose the memory. In that occasion, it'll search the proper slave device like the first use. Based on this function, the master device can be set to make pair with the specified address or any address by user.

(6) Reset new password introduction

User can set a new password for the HC-06 through AT+PINxxxx command. But the new password will become active after discharged all the energy of the module. If the module still has any energy, the old one is still active. In the test, for discharging all the system energy and activating the new password, we can connect the power supply PIN with GND about 20 seconds after the power is cut off. Generally, shutting down the device for 30 minutes also can discharge the energy, if there is no peripheral circuit helps discharge energy. User should make the proper way according to the specific situation.

(7) Name introduction

If the device has no name, it's better that user doesn't try to change the master device name. The name should be limited in 20 characters.

Summary: The character of HC-06: 1 not many command 2 easy for application 3 low price. It's good for some specific application. HC-04 is very similar with HC-06. Their only one difference is HC-04 is for industry, HC-06 is for civil. Except this, they don't have difference.

The following reference about HC-04 and HC-06 can be downloaded from company website www.wavesen.com:

HC-06 datasheet .pdf	(the command set introduction is included)
HC-04 datasheet .pdf	(the command set introduction is included)
IVT BlueSoleil-2.6	(IVT Bluetooth drive test version)
Bluetooth FAQ.pdf	
HC-04-D(HD-06-D)datasheet(English).pdf	
HC-06-AT command software (test version)	(some commands in V1.5 is not supported by V1.4)
PCB package of Bluetooth key modules	(PCB package lib in protel)
IVT software manual.pdf	(introduce how to operate the modern and make pair with Bluetooth module)
PDA serial test helper.exe	(serial helper used for WM system)

5 manual for the first use of HC-05

This chapter will introduce how to test and use the HC-05 if it's the first time for user to operate it.

(1) PINs description

PIN1	UART_TXD, Bluetooth serial signal sending PIN, can connect with MCU's RXD PIN
PIN2	UART_RXD, Bluetooth serial signal receiving PIN, can connect with the MCU's TXD PIN, there is no pull-up resistor in this PIN. But It needs to be added an eternal pull-up resistor.
PIN11	RESET, the reset PIN of module, inputting low level can reset the module, when the module is in using, this PIN can connect to air.
PIN12	VCC, voltage supply for logic, the standard voltage is 3.3V, and can work at 3.0-4.2V
PIN13	GND

PIN31	LED1, indicator of work mode. Has 3 modes: When the module is supplied power and PIN34 is input high level, PIN31 output 1Hz square wave to make the LED flicker slowly. It indicates that the module is at the AT mode, and the baud rate is 38400; When the module is supplied power and PIN34 is input low level, PIN31 output 2Hz square wave to make the LED flicker quickly. It indicates the module is at the pairable mode. If PIN34 is input high level, then the module will enter to AT mode, but the output of PIN31 is still 2Hz square wave. After the pairing, PIN31 output 2Hz square ware. Note: if PIN34 keep high level, all the commands in the AT command set can be in application. Otherwise, if just excite PIN34 with high level but not keep, only some command can be used. More information has provided at chapter 2.
PIN32	Output terminal. Before paired, it output low level. Once the pair is finished, it output high level.
PIN34	Mode switch input. If it is input low level, the module is at paired or communication mode. If it's input high level, the module will enter to AT mode. Even though the module is at communication, the module can enter to the AT mode if PIN34 is input high level. Then it will go back to the communication mode if PIN34 is input low level again.

(2) Application circuit 1 (connect to the 3.3V system)

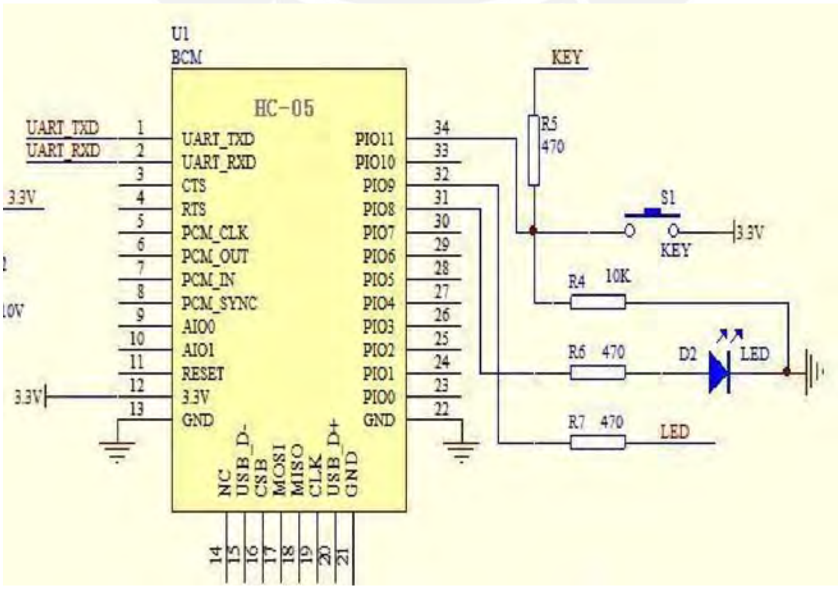


Figure 7 Application 1

(3) Application circuit 2 (connect to 5V serial system or PC serial)

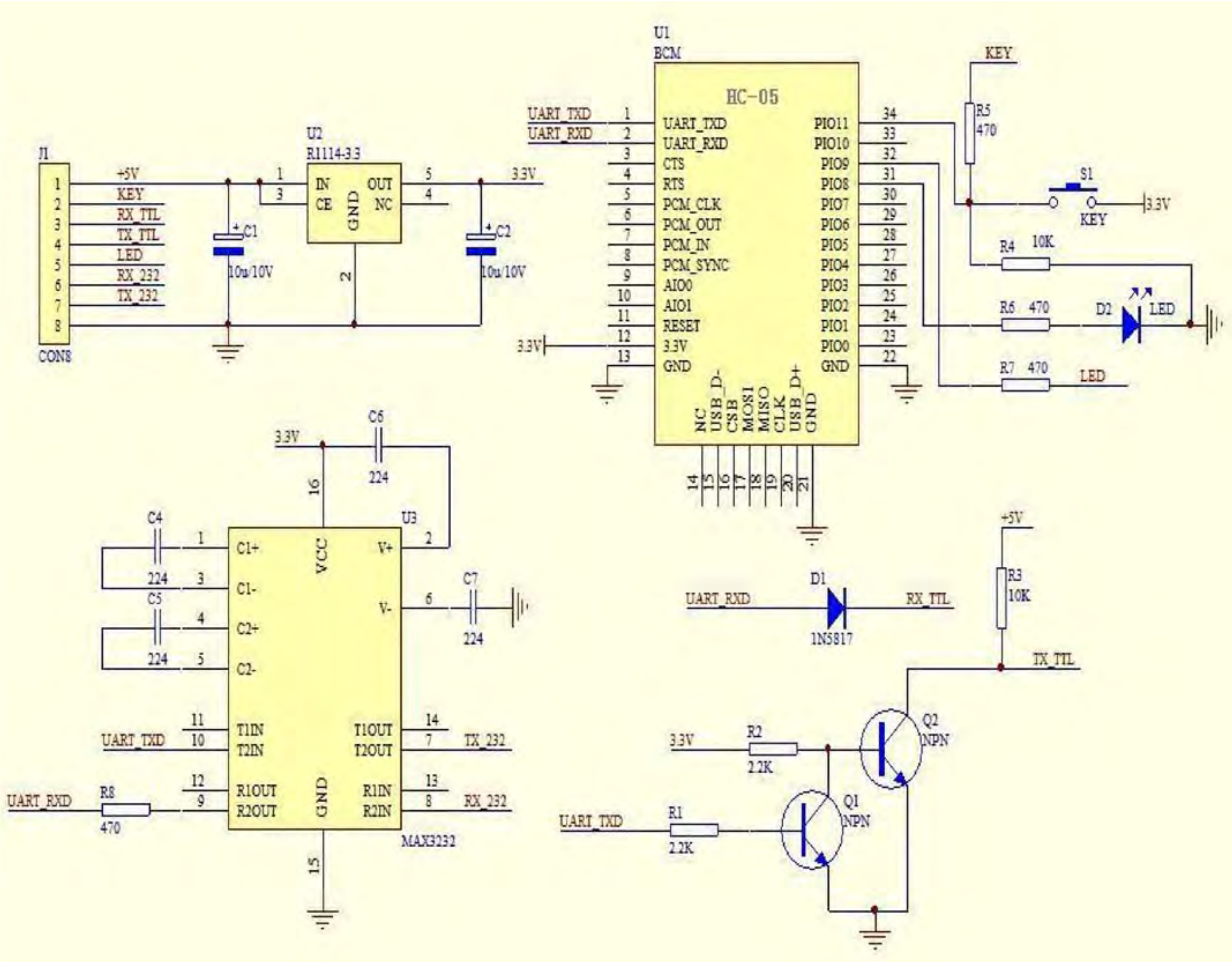


Figure 8 Application circuit 2

(4) AT command test

This chapter introduces some common commands in use. The detail introduction about HC-05 command is in HC-0305 AT command set.

Enter to AT mode:

Way1: Supply power to module and input high level to PIN34 at the same time, the module will enter to AT mode with the baud rate-38400.

Way2: In the first step, supply power to module; In the second step, input high level to PIN34. Then the module will enter to AT mode with the baud rate-9600. Way1 is recommended.

Command structure: all command should end up with “\r\n” (Hex: 0X0D X0A) as the terminator. If the serial helper is installed, user just need enter “ENTER” key at the end of command.

Reset the master-slave role command:

AT+ROLE=0 ----Set the module to be salve mode. The default mode is salve.

AT+ROLE=1 ----Set the module to be master mode.

Set memory command:

AT+CMODE=1

Set the module to make pair with the other random Bluetooth module (Not specified address). The default is this mode.

AT+CMODE=1

Set the module to make pair with the other Bluetooth module (specified address). If set the module to make pair with random one first, then set the module to make pair with the Bluetooth module has specified address. Then the module will search the last paired module until the module is found.

Reset the password command

AT+PSWD=XXXX

Set the module pair password. The password must be 4-bits.

Reset the baud rate

AT+UART== <Param>,<Param2>,<Param3>.

More information is provided at HC-0305 command set

Example:

AT+UART=9600,0,0 ----set the baud rate to be 9600N81

Reset the Bluetooth name

AT+NAME=XXXXX

Summary:

HC-05 has many functions and covers all functions of HC-06. The above commands are the most common ones. Besides this, HC-05 leaves lots of space for user. So HC-05 is better than HC-06 and recommended. HC-03 is similar with HC-05. The above introduction also suits HC-03

The following reference about HC-03 and HC-05 can be downloaded from company website www.wavesen.com:

HC-03 datasheet .pdf (the command set introduction is included)

HC-05 datasheet .pdf (the command set introduction is included)

IVT BlueSoleil-2.6 (IVT Bluetooth drive test version)

Bluetooth FAQ.pdf

PCB package of Bluetooth key modules (PCB package lib in protel)

IVT software manual.pdf (introduce how to operate the modern and make pair with Bluetooth module)

PDA serial test helper.exe (serial helper used for WM system)

HC-03/05 Bluetooth serial command set.pdf

6. Ordering information

The website of Guangzhou HC Information Technology Co., Ltd is www.wavesen.com The contact information is provided at the company website.

Order Way: If you want our product, you can give order to the production center of our company directly or order it in Taobao. There is a link to Taobao in our company website.

Package: 50 pieces chips in an anti-static blister package. The weight of a module is about 0.9g. The weight of a package is about 50g.

Please provide the product's model when you order:

HC-04-M HC-04 master module

HC-04-S HC-04 slave module

HC-06-M HC-06 master module

HC-06-S HC-06 slave module

HC-03

HC-05 HC-03/05 can be preset to be master module or slave module.

LM2598 SIMPLE SWITCHER® Power Converter 150-kHz 1-A Step-Down Voltage Regulator, With Features

1 Features

- 3.3-V, 5-V, 12-V, and Adjustable Output Versions
- Adjustable Version Output Voltage Range, 1.2-V to 37-V ±4% Max Over Line and Load Conditions
- 1-A Output Current
- Available in 7-Pin TO-220 and DDPAK (Surface Mount) Package
- Input Voltage Range Up to 40 V
- Excellent Line and Load Regulation Specifications
- 150 kHz Fixed Frequency Internal Oscillator
- Shutdown/Soft-start
- Out of Regulation Error Flag
- Error Output Delay
- Low Power Standby Mode, I_Q, Typically 85 μA
- High Efficiency
- Uses Readily Available Standard Inductors
- Thermal Shutdown and Current Limit Protection

2 Applications

- Simple High-Efficiency Step-down (Buck) Regulator
- Efficient Preregulator for Linear Regulators
- On-Card Switching Regulators
- Positive to Negative Converter

3 Description

The LM2598 series of regulators are monolithic integrated circuits that provide all the active functions for a step-down (buck) switching regulator, capable of driving a 1-A load with excellent line and load regulation. These devices are available in fixed output voltages of 3.3 V, 5 V, 12 V, and an adjustable output version.

The LM2598 is a member of the LM259x family.

Requiring a minimum number of external components, these regulators are simple to use and include internal frequency compensation, improved line and load specifications, fixed-frequency oscillator, Shutdown/Soft-start, error flag delay and error flag output.

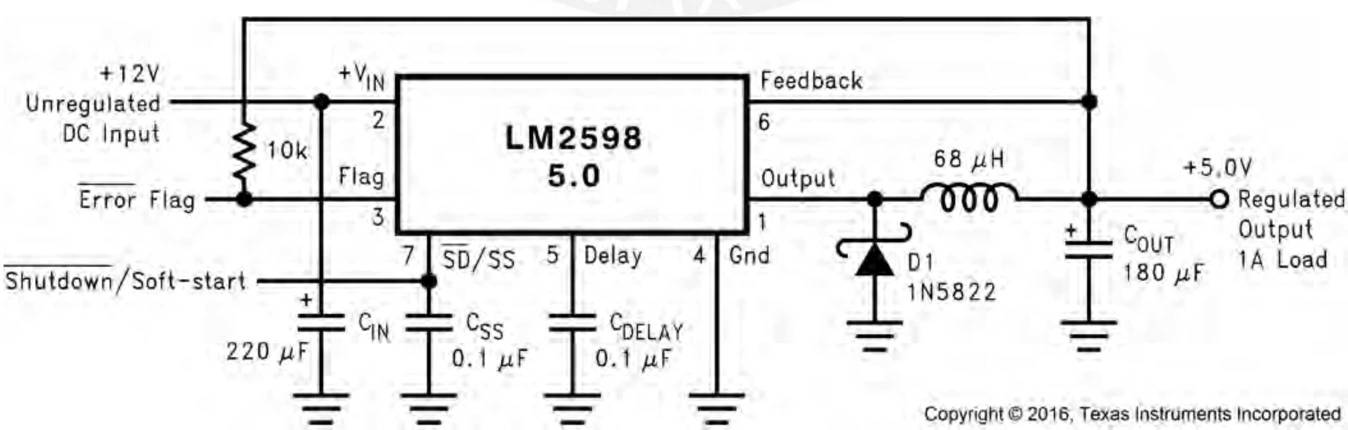
The LM2598 series operates at a switching frequency of 150 kHz, thus allowing smaller sized filter components than what would be required with lower-frequency switching regulators. Available in a standard 7-lead TO-220 package with several different lead bend options, and a 7-lead DDPAK surface mount package. Typically, for output voltages less than 12 V, and ambient temperatures less than 50°C, no heat sink is required.

Device Information(1)

PART NUMBER	PACKAGE	BODY SIZE (NOM)
LM2598	TO-220 (7)	14.986 mm × 10.16 mm
	TO-263 (7)	10.10 mm × 8.89 mm

(1) For all available packages, see the orderable addendum at the end of the data sheet.

Typical Application



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Fixed output voltage versions

An IMPORTANT NOTICE at the end of this data sheet addresses availability, warranty, changes, use in safety-critical applications, intellectual property matters and other important disclaimers. PRODUCTION DATA.

Table of Contents

4 Revision History

NOTE: Page numbers for previous revisions may differ from page numbers in the current version.

Changes from Revision C (April 2013) to Revision D — **Page**

- Added *ESD Ratings* table, *Feature Description* section, *Device Functional Modes*, *Application and Implementation* section, *Power Supply Recommendations* section, *Layout* section, *Device and Documentation Support* section, and *Mechanical, Packaging, and Orderable Information* section. 1
- Removed all references to design software *Switchers Made Simple* 1

Changes from Revision B (April 2013) to Revision C — **Page**

- Changed layout of National Semiconductor Data Sheet to TI format 38

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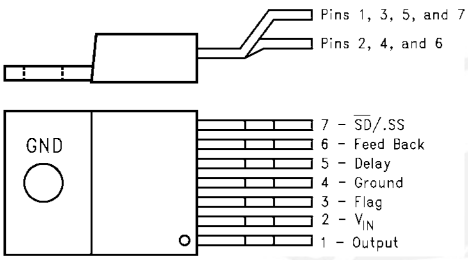
5 Description (continued)

A standard series of inductors (both through hole and surface mount types) are available from several different manufacturers optimized for use with the LM2598. This feature greatly simplifies the design of switch-mode power supplies.

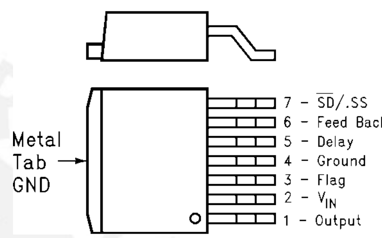
Other features include a specified ±4% tolerance on output voltage under all conditions of input voltage and output load conditions, and ±15% on the oscillator frequency. External shutdown is included, featuring typically 85-µA standby current. Self-protection features include a two stage current limit for the output switch and an overtemperature shutdown for complete protection under fault conditions.

6 Pin Configuration and Functions

NDZ Package
7-Pin TO-220
Top View



KTW Package
7-Pin TO-263
Top View



Pin Functions

PIN		I/O	DESCRIPTION
NO.	NAME		
1	Output	O	Internal switch. The voltage at this pin switches between approximately ($+V_{IN} – V_{SAT}$) and approximately –0.5 V, with a duty cycle of V_{OUT} / V_{IN}. To minimize coupling to sensitive circuitry, the PCB copper area connected to this pin must be kept to a minimum.
2	$+V_{IN}$	I	This is the positive input supply for the IC switching regulator. A suitable input bypass capacitor must be present at this pin to minimize voltage transients and to supply the switching currents required by the regulator.
3	Error Flag	O	Open collector output that provides a low signal (flag transistor ON) when the regulated output voltage drops more than 5% from the nominal output voltage. On start up, Error Flag is low until V_{OUT} reaches 95% of the nominal output voltage and a delay time determined by the Delay pin capacitor. This signal can be used as a reset to a microprocessor on power-up. (1)
4	Ground	—	Circuit ground.
5	Delay	O	At power-up, this pin can be used to provide a time delay between the time the regulated output voltage reaches 95% of the nominal output voltage, and the time the error flag output goes high. (1)
6	Feedback	I	Senses the regulated output voltage to complete the feedback loop.
7	$\overline{\text{Shutdown}}$/Soft-start	I	This dual function pin provides the following features: (a) Allows the switching regulator circuit to be shut down using logic level signals thus dropping the total input supply current to approximately 80 µA. (b) Adding a capacitor to this pin provides a soft-start feature which minimizes start-up current and provides a controlled ramp up of the output voltage. (1)

(1) If any of the above three features ($\overline{\text{Shutdown}}$/Soft-start, Error Flag, or Delay) are not used, the respective pins must be left open.

7 Specifications

7.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)(1)(2)

			MIN	MAX	UNIT
Maximum supply voltage, V_{IN}				45	V
$\overline{SD}$/SS pin input voltage(3)				6	V
Delay pin voltage(3)				1.5	V
Flag pin voltage			–0.3	45	V
Feedback pin voltage			–0.3	25	V
Output voltage to ground (steady state)				–1	V
Power dissipation			Internally limited		
Lead temperature	KTW package	Vapor phase (60 s)		215	°C
		Infrared (10 s)		245	°C
	NDZ package (soldering, 10 s)			260	°C
Maximum junction temperature				150	°C
Storage temperature, T_{stg}			–65	150	°C

(1) Stresses beyond those listed under *Absolute Maximum Ratings* may cause permanent damage to the device. These are stress ratings only, which do not imply functional operation of the device at these or any other conditions beyond those indicated under *Recommended Operating Conditions*. Exposure to absolute-maximum-rated conditions for extended periods may affect device reliability.
(2) If Military/Aerospace specified devices are required, please contact the Texas Instruments Sales Office/Distributors for availability and specifications.
(3) Voltage internally clamped. If clamp voltage is exceeded, limit current to a maximum of 1 mA.

7.2 ESD Ratings

			VALUE	UNIT
$V_{(ESD)}$	Electrostatic discharge	Human-body model (HBM), per ANSI/ESDA/JEDEC JS-001(1)(2)	±2000	V

(1) JEDEC document JEP155 states that 500-V HBM allows safe manufacturing with a standard ESD control process.
(2) The human body model is a 100-pF capacitor discharged through a 1.5k resistor into each pin.

7.3 Recommended Operating Conditions

	MIN	MAX	UNIT
Supply voltage	4.5	40	V
Temperature	–25	125	°C

7.4 Thermal Information

THERMAL METRIC(1)			LM2598		UNIT
			KTW (TO-263)	NDZ (TO-220)	
			7 PINS	7 PINS	
$R_{\theta JA}$	Junction-to-ambient thermal resistance(2)(3)	See(4)	—	50	°C/W
		See(5)	50	—	
		See(6)	30	—	
		See(7)	20	—	
$R_{\theta JC(top)}$	Junction-to-case (top) thermal resistance		2	2	°C/W

(1) For more information about traditional and new thermal metrics, see the *Semiconductor and IC Package Thermal Metrics* application report, SPRA953.
(2) The package thermal impedance is calculated in accordance to JESD 51-7.
(3) Thermal Resistances were simulated on a 4 -layer, JEDEC board.
(4) Junction to ambient thermal resistance (no external heat sink) for the package mounted TO-220 package mounted vertically, with the leads soldered to a printed circuit board with (1 oz.) copper area of approximately 1 in^2.
(5) Junction to ambient thermal resistance with the TO-263 package tab soldered to a single sided printed circuit board with 0.5 in^2 of (1 oz.) copper area.
(6) Junction to ambient thermal resistance with the TO-263 package tab soldered to a single sided printed circuit board with 2.5 in^2 of (1 oz.) copper area.
(7) Junction to ambient thermal resistance with the TO-263 package tab soldered to a double sided printed circuit board with 3 in^2 of (1 oz.) copper area on the LM2598S side of the board, and approximately 16 in^2 of copper on the other side of the PCB.

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7.5 Electrical Characteristics – 3.3-V Version

Specifications are for T_J = 25°C, unless otherwise specified.

PARAMETER		TEST CONDITIONS		MIN(1)	TYP(2)	MAX (1)	UNIT
SYSTEM PARAMETERS(3) (see Figure 42 and Figure 45 for test circuits)							
V_{OUT}	Output voltage	4.75 V ≤ V_{IN} ≤ 40 V, 0.1 A ≤ I_{LOAD} ≤ 1 A	T_J = 25°C	3.168	3.3	3.432	V
			Over full operating temperature range	3.135		3.465	
η	Efficiency	V_{IN} = 12 V, I_{LOAD} = 1 A			78%		

(1) All room temperature limits are 100% production tested. All limits at temperature extremes are specified via correlation using standard Statistical Quality Control (SQC) methods. All limits are used to calculate Average Outgoing Quality Level (AOQL).
(2) Typical numbers are at 25°C and represent the most likely norm.
(3) External components such as the catch diode, inductor, input and output capacitors can affect switching regulator system performance. When the LM2598 is used as shown in the Figure 42 and Figure 45, system performance is as shown in system parameters of *Electrical Characteristics*.

7.6 Electrical Characteristics – 5-V Version

Specifications are for T_J = 25°C, unless otherwise specified.

PARAMETER		TEST CONDITIONS		MIN(1)	TYP(2)	MAX(1)	UNIT
SYSTEM PARAMETERS(3) (see Figure 42 and Figure 45 for test circuits)							
V_{OUT}	Output voltage	7 V ≤ V_{IN} ≤ 40 V, 0.1 A ≤ I_{LOAD} ≤ 1 A	T_J = 25°C	4.8	5	5.2	V
			Over full operating temperature range	4.75		5.25	
η	Efficiency	V_{IN} = 12 V, I_{LOAD} = 1 A			82%		

(1) All room temperature limits are 100% production tested. All limits at temperature extremes are specified via correlation using standard Statistical Quality Control (SQC) methods. All limits are used to calculate Average Outgoing Quality Level (AOQL).
(2) Typical numbers are at 25°C and represent the most likely norm.
(3) External components such as the catch diode, inductor, input and output capacitors can affect switching regulator system performance. When the LM2598 is used as shown in the Figure 42 and Figure 45, system performance is as shown in system parameters of *Electrical Characteristics*.

7.7 Electrical Characteristics – 12-V Version

Specifications are for T_J = 25°C, unless otherwise specified.

PARAMETER		TEST CONDITIONS		MIN(1)	TYP(2)	MAX(1)	UNIT
SYSTEM PARAMETERS(3) (see Figure 42 and Figure 45 for test circuits)							
V_{OUT}	Output voltage	15 V ≤ V_{IN} ≤ 40 V, 0.1 A ≤ I_{LOAD} ≤ 1 A	T_J = 25°C	11.52	12	12.48	V
			Over full operating temperature range	11.4		12.6	
η	Efficiency	V_{IN} = 25 V, I_{LOAD} = 1 A			90%		

(1) All room temperature limits are 100% production tested. All limits at temperature extremes are specified via correlation using standard Statistical Quality Control (SQC) methods. All limits are used to calculate Average Outgoing Quality Level (AOQL).
(2) Typical numbers are at 25°C and represent the most likely norm.
(3) External components such as the catch diode, inductor, input and output capacitors can affect switching regulator system performance. When the LM2598 is used as shown in the Figure 42 and Figure 45, system performance is as shown in system parameters of *Electrical Characteristics*.

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7.8 Electrical Characteristics – Adjustable Voltage Version

Specifications are for T_J = 25°C, unless otherwise specified.

PARAMETER		TEST CONDITIONS		MIN [1]	TYP [2]	MAX [1]	UNIT
SYSTEM PARAMETERS [3] (see Figure 42 and Figure 45 for test circuits)							
V_{FB}	Feedback voltage	4.5 V ≤ V_{IN} ≤ 40 V, 0.1 A ≤ I_{LOAD} ≤ 1 A			1.23		V
		V_{OUT} programmed for 3 V, circuit of Figure 42 and Figure 45	T_J = 25°C	1.193		1.267	
			Over full operating temperature range	1.18		1.28	
η	Efficiency	V_{IN} = 12 V, V_{OUT} = 3 V, I_{LOAD} = 1 A			78%		

(1) All room temperature limits are 100% production tested. All limits at temperature extremes are specified via correlation using standard Statistical Quality Control (SQC) methods. All limits are used to calculate Average Outgoing Quality Level (AOQL).
(2) Typical numbers are at 25°C and represent the most likely norm.
(3) External components such as the catch diode, inductor, input and output capacitors can affect switching regulator system performance. When the LM2598 is used as shown in the Figure 42 and Figure 45, system performance is as shown in system parameters of *Electrical Characteristics*.

7.9 Electrical Characteristics – All Output Voltage Versions

Specifications are for T_J = 25°C unless otherwise noted. Unless otherwise specified, V_{IN} = 12 V for the 3.3-V, 5-V, and Adjustable version and V_{IN} = 24 V for the 12-V version. I_{LOAD} = 500 mA

PARAMETER		TEST CONDITIONS		MIN [1]	TYP [2]	MAX [1]	UNIT
DEVICE PARAMETERS							
I_b	Feedback bias current	Adjustable version only, V_{FB} = 1.3 V	T_J = 25°C		10	50	nA
			Over full operating temperature range			100	
f_O	Oscillator frequency	See [3]	T_J = 25°C	127	150	173	kHz
			Over full operating temperature range	110		173	
V_{SAT}	Saturation voltage	I_{OUT} = 1 A [4][5]	T_J = 25°C		1	1.2	V
			Over full operating temperature range			1.3	
DC	Max duty cycle (ON)	See [5]			100%		
	Minimum duty cycle (OFF)	See [6]			0%		
I_{CL}	Current limit	Peak current [4][5]	T_J = 25°C	1.2	1.5	2.4	A
			Over full operating temperature range	1.15		2.6	
I_L	Output leakage current	Output = 0 V, see [4][6][7]				50	μA
		Output = –1 V			2	15	mA
I_Q	Operating quiescent current	$\overline{SD}$/SS pin open [6]			5	10	mA
I_{STBY}	Current standby quiescent	$\overline{SD}$/SS pin = 0 V [7]	T_J = 25°C		85	200	μA
			Over full operating temperature range			250	

(1) All room temperature limits are 100% production tested. All limits at temperature extremes are specified via correlation using standard Statistical Quality Control (SQC) methods. All limits are used to calculate Average Outgoing Quality Level (AOQL).
(2) Typical numbers are at 25°C and represent the most likely norm.
(3) The switching frequency is reduced when the second stage current limit is activated. The amount of reduction is determined by the severity of current overload.
(4) No diode, inductor or capacitor connected to output pin.
(5) Feedback pin removed from output and connected to 0 V to force the output transistor switch ON.
(6) Feedback pin removed from output and connected to 12 V for the 3.3-V, 5-V, and the Adjustable version, and 15 V for the 12-V version, to force the output transistor switch OFF.
(7) V_{IN} = 40 V.

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Electrical Characteristics – All Output Voltage Versions (continued)

Specifications are for T_J = 25°C unless otherwise noted. Unless otherwise specified, V_{IN} = 12 V for the 3.3-V, 5-V, and Adjustable version and V_{IN} = 24 V for the 12-V version. I_{LOAD} = 500 mA

PARAMETER		TEST CONDITIONS		MIN (1)	TYP (2)	MAX (1)	UNIT
SHUTDOWN AND SOFT-START CONTROL (see Figure 42 and Figure 45 for test circuits)							
V_{SD}	Shutdown threshold voltage	T_J = 25°C			1.3		V
		Low, (Shutdown Mode), over full operating temperature range				0.6	
		High, (Soft-start Mode), over full operating temperature range		2			
V_{SS}	Soft-start voltage	V_{OUT} = 20% of nominal output voltage			2		V
		V_{OUT} = 100% of nominal output voltage			3		
I_{SD}	Shutdown current	$V_{\overline{SHUTDOWN}}$ = 0.5 V			5	10	µA
I_{SS}	Soft-start current	$V_{Soft\text{-}start}$ = 2.5 V			1.6	5	µA
FLAG AND DELAY CONTROL (see Figure 42 and Figure 45 for test circuits)							
	Regulator dropout detector threshold voltage	Low (Flag ON)		92%	96%	98%	
VF_{SAT}	Voltage flag output saturation	I_{SINK} = 3 mA			0.3		V
		V_{DELAY} = 0.5 V	T_J = 25°C			0.7	V
			Over full operating temperature range			1	
IF_L	Flag output leakage current	V_{FLAG} = 40 V			0.3		µA
	Voltage delay pin threshold				1.25		V
		Low (Flag ON)		1.21			V
		High (Flag OFF) and V_{OUT} Regulated				1.29	
	Delay pin source current	V_{DELAY} = 0.5 V			3	6	µA
	Delay pin saturation	Low (Flag ON)	T_J = 25°C		55	350	mV
			Over full operating temperature range			400	

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7.10 Typical Characteristics

Circuit of Figure 45

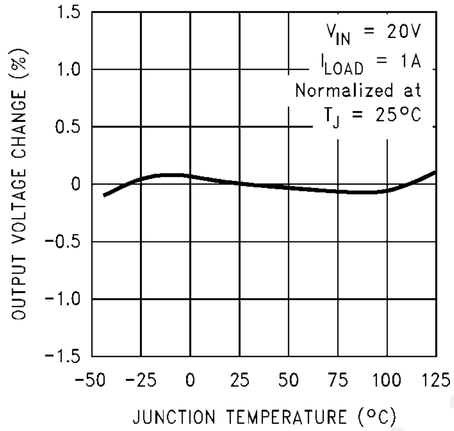

Figure 1. Normalized Output Voltage

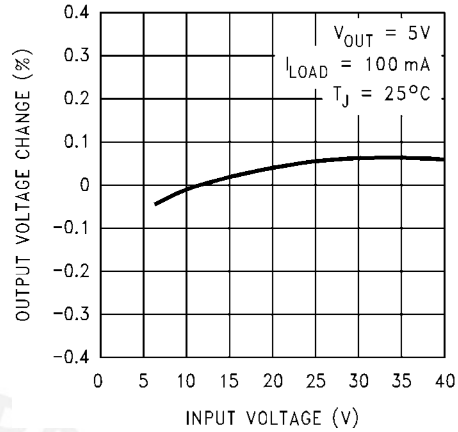

Figure 2. Line Regulation

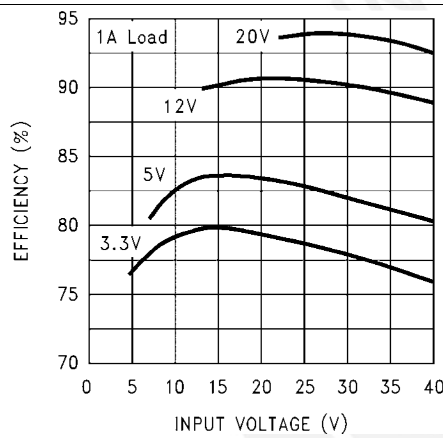

Figure 3. Efficiency

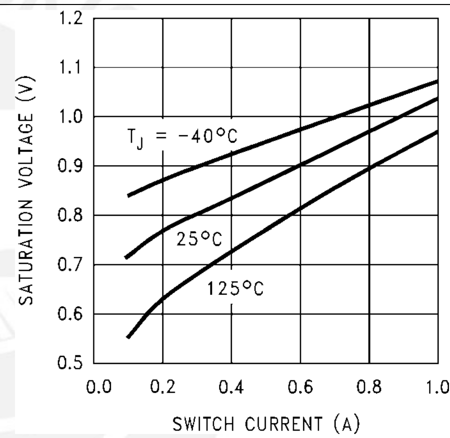

Figure 4. Switch Saturation Voltage

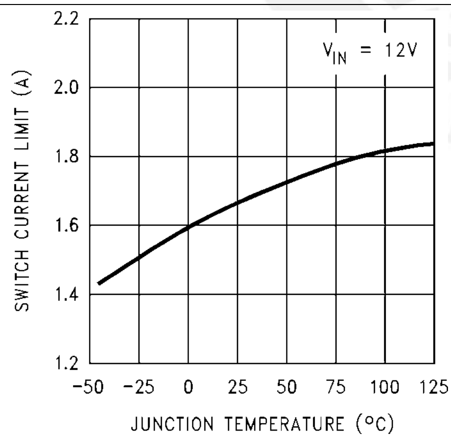

Figure 5. Switch Current Limit

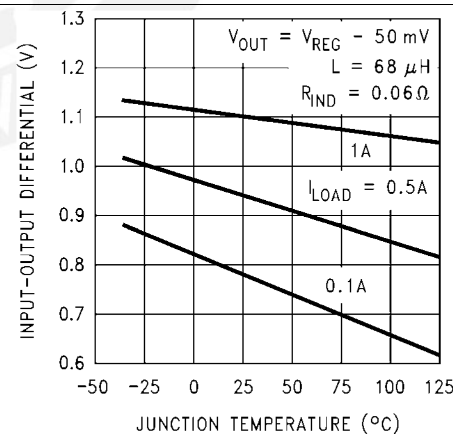

Figure 6. Dropout Voltage

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Typical Characteristics (continued)

Circuit of Figure 45

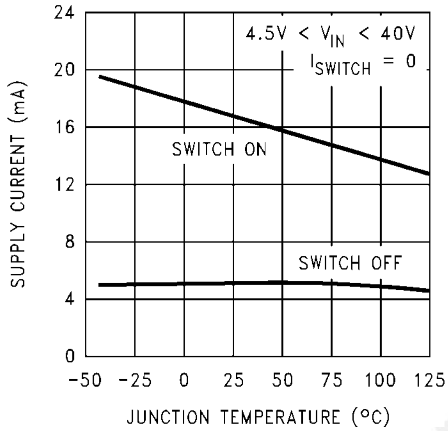

Figure 7. Operating Quiescent Current

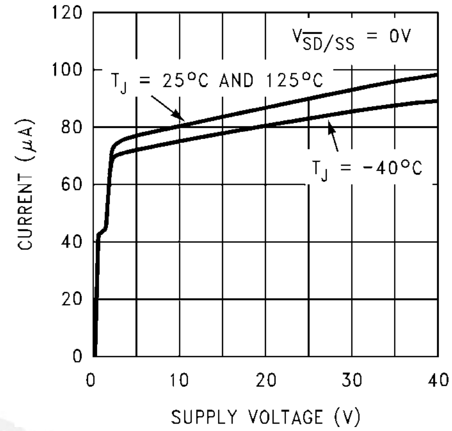

Figure 8. Shutdown Quiescent Current

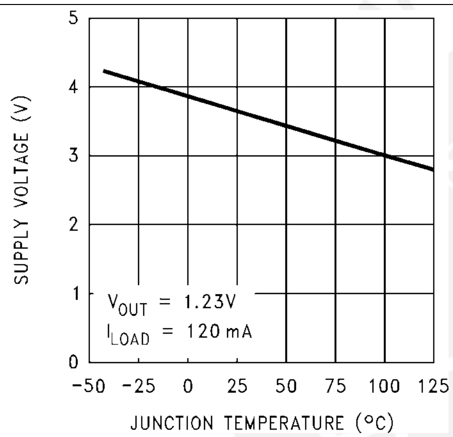

Figure 9. Minimum Operating Supply Voltage

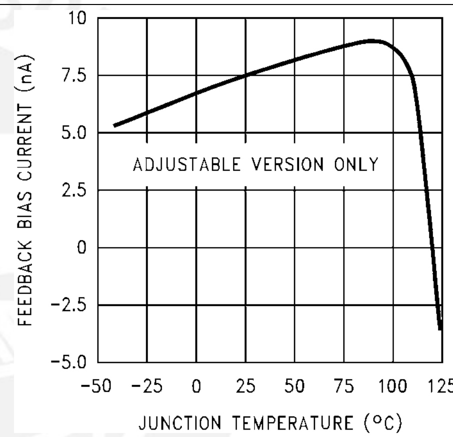

Figure 10. Feedback Pin Bias Current

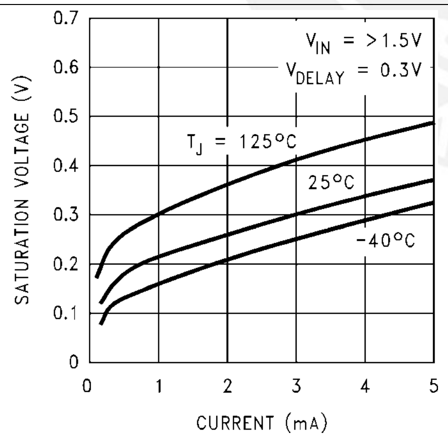

Figure 11. Flag Saturation Voltage

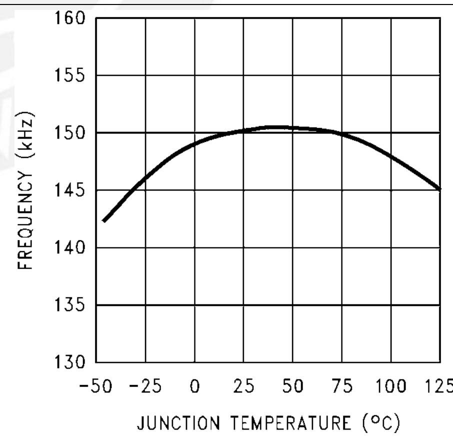

Figure 12. Switching Frequency

Typical Characteristics (continued)

Circuit of Figure 45

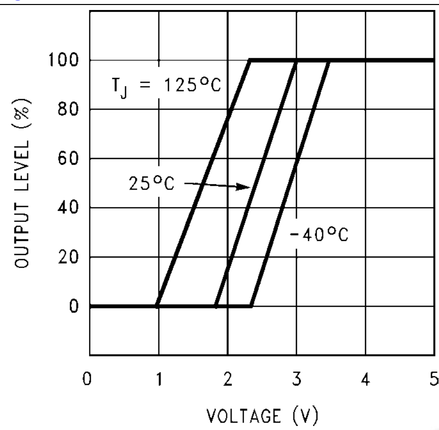

Figure 13. Soft-start

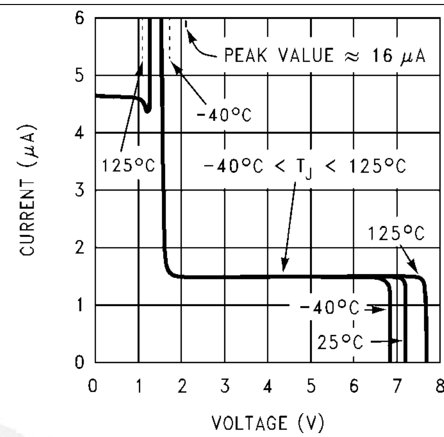

Figure 14. Shutdown/Soft-start Current

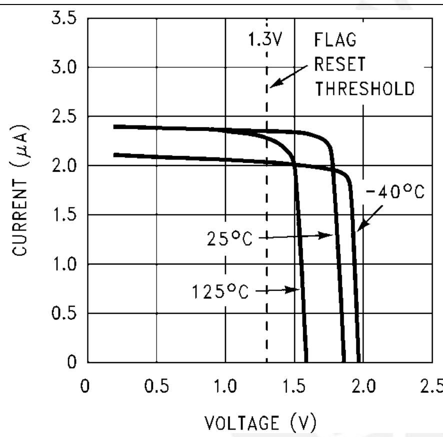

Figure 15. Delay Pin Current

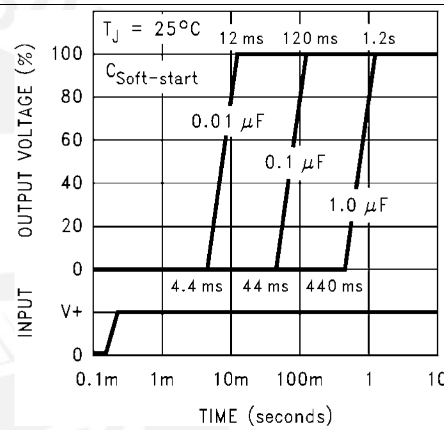

Figure 16. Soft-start Response

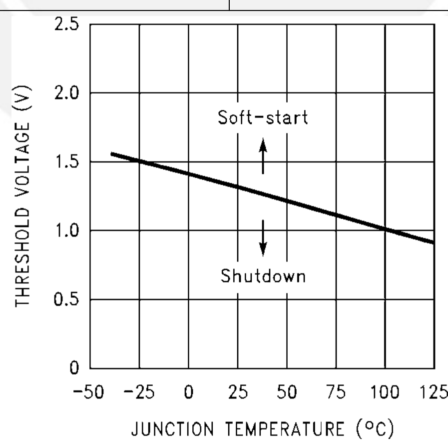

Figure 17. Shutdown and Soft-start Threshold Voltage

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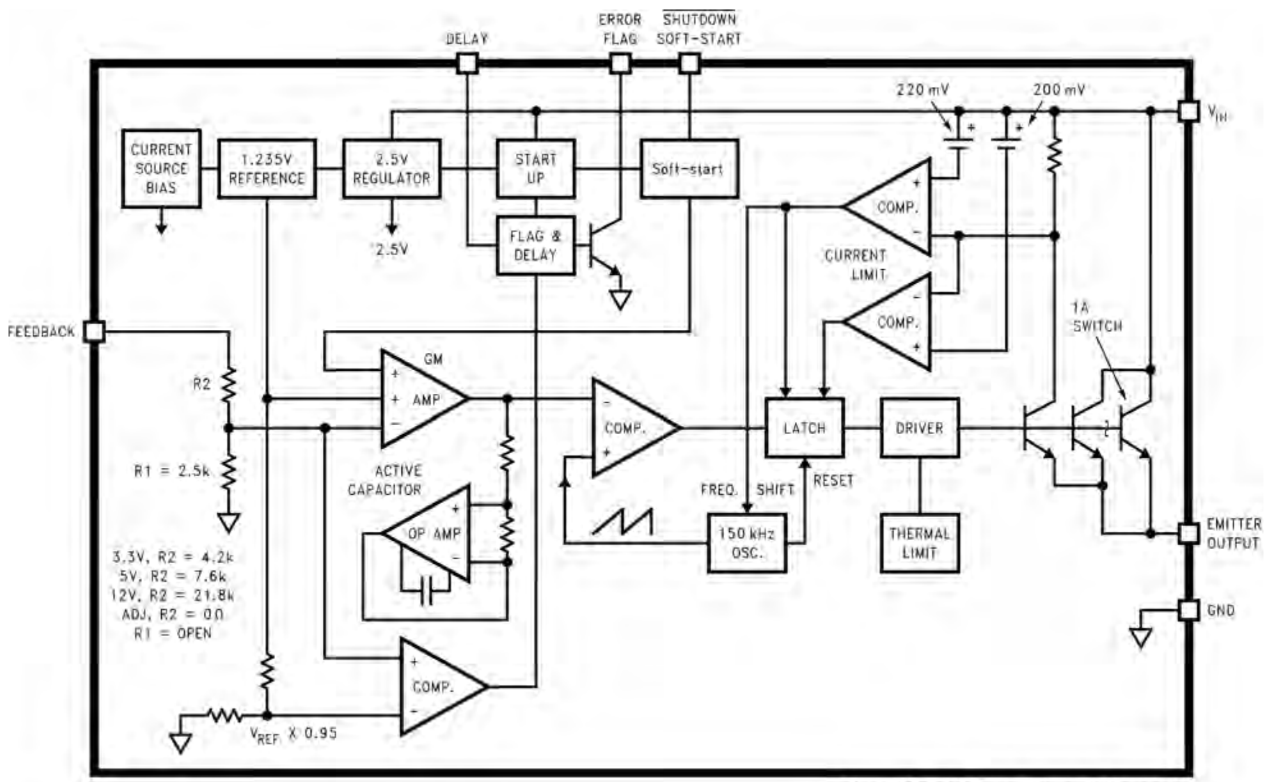
8 Detailed Description

8.1 Overview

The LM2598 SIMPLE SWITCHER® regulator is an easy-to-use, nonsynchronous, step-down DC-DC converter with a wide input voltage range up to 40 V. The regulator is capable of delivering up to 1-A DC load current with excellent line and load regulation. These devices are available in fixed output voltages of 3.3-V, 5-V, 12-V and an adjustable output version. The family requires few external components, and the pin arrangement was designed for simple, optimum PCB layout.

8.2 Functional Block Diagram



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8.3 Feature Description

8.3.1 SHUTDOWN and Soft-Start

The circuit shown in Figure 20 is a standard buck regulator with 24-V_{IN}, 12-V_{OUT}, 280-mA load, and using a 0.068-µF soft-start capacitor. The photo in Figure 18 and Figure 19 show the effects of Soft-start on the output voltage, the input current, with, and without a soft-start capacitor. Figure 18 also shows the error flag output going high when the output voltage reaches 95% of the nominal output voltage. The reduced input current required at start-up is very evident when comparing the two photos. The Soft-start feature reduces the start-up current from 1 A down to 240 mA, and delays and slows down the output voltage rise time.

This reduction in start-up current is useful in situations where the input power source is limited in the amount of current it can deliver. In some applications Soft-start can be used to replace undervoltage lockout or delayed start-up functions.

If a very slow output voltage ramp is desired, the Soft-start capacitor can be made much larger. Many seconds or even minutes are possible.

If only the shutdown feature is required, the Soft-start capacitor can be eliminated.

Feature Description (continued)

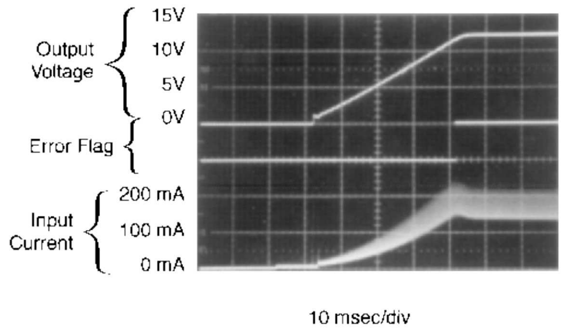

Figure 18. Output Voltage, Input Current, and Error Flag Signal at Start-Up With Soft-start

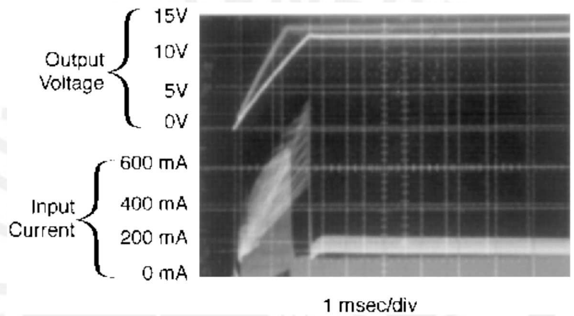

Figure 19. Output Voltage and Input Current at Start-Up Without Soft-start

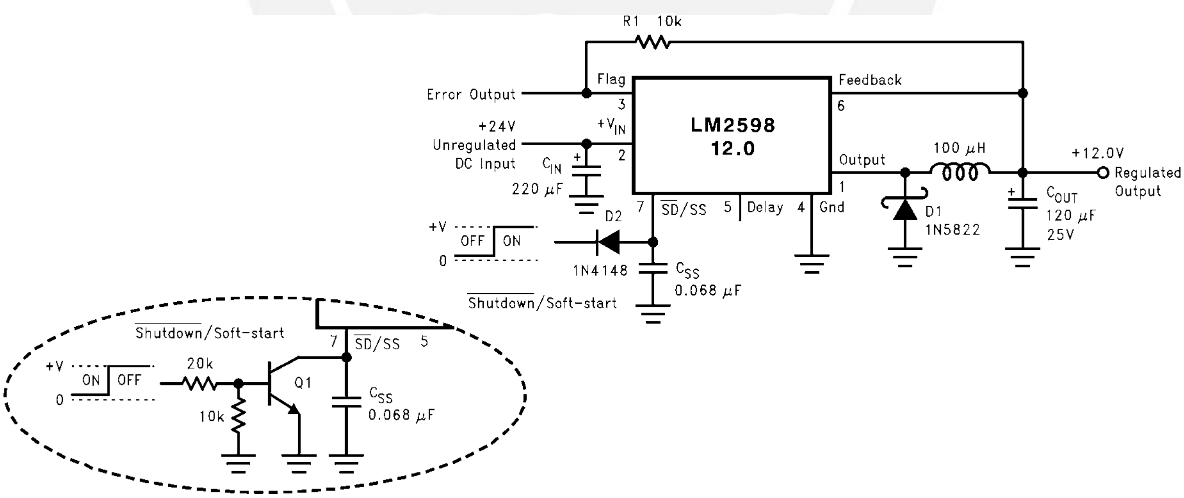

Figure 20. Typical Circuit Using Shutdown/Soft-start and Error Flag Features

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Feature Description (continued)

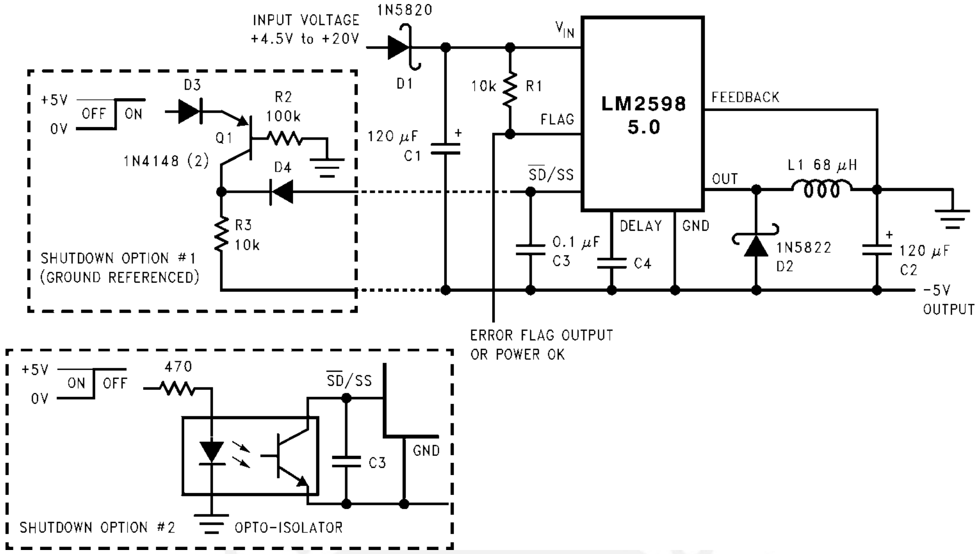

Figure 21. Inverting –5-V Regulator With Shutdown and Soft-start

8.3.2 Inverting Regulator

The circuit in Figure 21 converts a positive input voltage to a negative output voltage with a common ground. The circuit operates by bootstrapping the regulators ground pin to the negative output voltage, then grounding the feedback pin, the regulator senses the inverted output voltage and regulates it.

This example uses the LM2598-5 to generate a –5-V output, but other output voltages are possible by selecting other output voltage versions, including the adjustable version. Because this regulator topology can produce an output voltage that is either greater than or less than the input voltage, the maximum output current greatly depends on both the input and output voltage. The curve shown in Figure 22 provides a guide as to the amount of output load current possible for the different input and output voltage conditions.

The maximum voltage appearing across the regulator is the absolute sum of the input and output voltage, and this must be limited to a maximum of 40 V. In this example, when converting 20 V to –5 V, the regulator would see 25 V between the input pin and ground pin. The LM2598 has a maximum input voltage rating of 40 V.

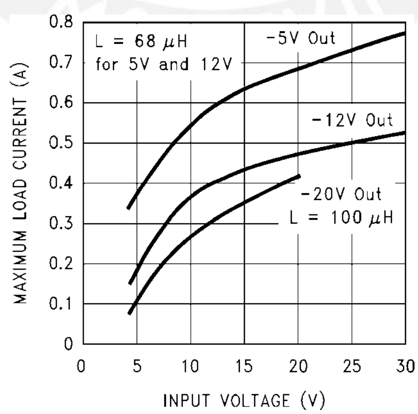

Figure 22. Maximum Load Current for Inverting Regulator Circuit

Feature Description (continued)

An additional diode is required in this regulator configuration. Diode D1 is used to isolate input voltage ripple or noise from coupling through the C_{IN} capacitor to the output, under light or no load conditions. Also, this diode isolation changes the topology to closely resemble a buck configuration thus providing good closed loop stability. A Schottky diode is recommended for low input voltages, (because of its lower voltage drop) but for higher input voltages, a 1N5400 diode could be used.

Because of differences in the operation of the inverting regulator, the standard design procedure is not used to select the inductor value. In the majority of designs, a 68-μH, 1.5-A inductor is the best choice. Capacitor selection can also be narrowed down to just a few values. Using the values shown in Figure 21 provides good results in the majority of inverting designs.

This type of inverting regulator can require relatively large amounts of input current when starting up, even with light loads. Input currents as high as the LM2598 current limit (approximately 1.5 A) are required for 2 ms or more, until the output reaches its nominal output voltage. The actual time depends on the output voltage and the size of the output capacitor. Input power sources that are current limited or sources that can not deliver these currents without getting loaded down, may not work correctly. Because of the relatively high start-up currents required by the inverting topology, the soft-start feature shown in Figure 21 is recommended.

Also shown in Figure 21 are several shutdown methods for the inverting configuration. With the inverting configuration, some level shifting is required, because the ground pin of the regulator is no longer at ground, but is now at the negative output voltage. The shutdown methods shown accept ground referenced shutdown signals.

8.3.3 Undervoltage Lockout

Some applications require the regulator to remain off until the input voltage reaches a predetermined voltage. Figure 23 shows an undervoltage lockout feature applied to a buck regulator, while Figure 24 and Figure 25 are for the inverting types (only the circuitry pertaining to the undervoltage lockout is shown). Figure 23 uses a Zener diode to establish the threshold voltage when the switcher begins operating. When the input voltage is less than the Zener voltage, resistors R1 and R2 hold the Shutdown or Soft-start pin low, keeping the regulator in the shutdown mode. As the input voltage exceeds the Zener voltage, the Zener conducts, pulling the Shutdown/Soft-start pin high, allowing the regulator to begin switching. The threshold voltage for the undervoltage lockout feature is approximately 1.5 V greater than the Zener voltage.

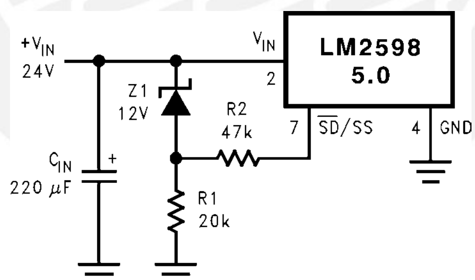

Figure 23. Undervoltage Lockout for a Buck Regulator

Figure 24 and Figure 25 apply the same feature to an inverting circuit. Figure 24 features a constant threshold voltage for turnon and turnoff (Zener voltage plus approximately 1 V). Because the SD/SS pin has an internal 7-V zener clamp, R2 is required to limit the current into this pin to approximately 1 mA when Q1 is on. If hysteresis is required, the circuit in Figure 25 has a turnon voltage which is different than the turnoff voltage. The amount of hysteresis is approximately equal to the value of the output voltage.

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Feature Description (continued)

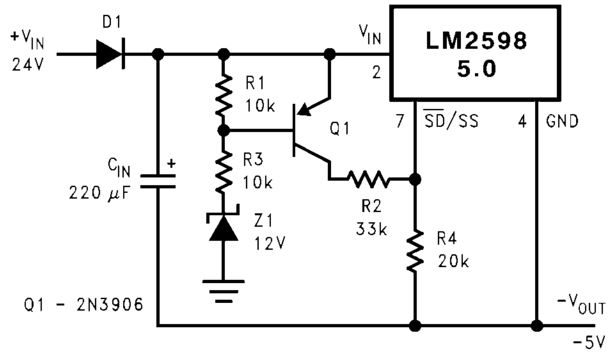

Figure 24. Undervoltage Lockout Without Hysteresis for an Inverting Regulator

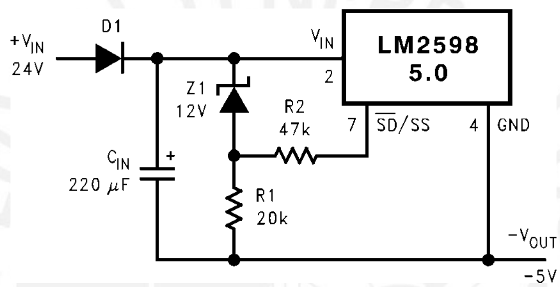

Figure 25. Undervoltage Lockout With Hysteresis for an Inverting Regulator

8.3.4 Negative Voltage Charge Pump

Occasionally a low current negative voltage is required for biasing parts of a circuit. A simple method of generating a negative voltage using a charge pump technique and the switching waveform present at the OUT pin, is shown in Figure 26. This unregulated negative voltage is approximately equal to the positive input voltage (minus a few volts), and can supply up to a 200 mA of output current. There is a requirement however, that there be a minimum load of several hundred mA on the regulated positive output for the charge pump to work correctly. Also, resistor R1 is required to limit the charging current of C1 to some value less than the LM2598 current limit (typically 1.5 A).

This method of generating a negative output voltage without an additional inductor can be used with other members of the Simple Switcher Family, using either the buck or boost topology.

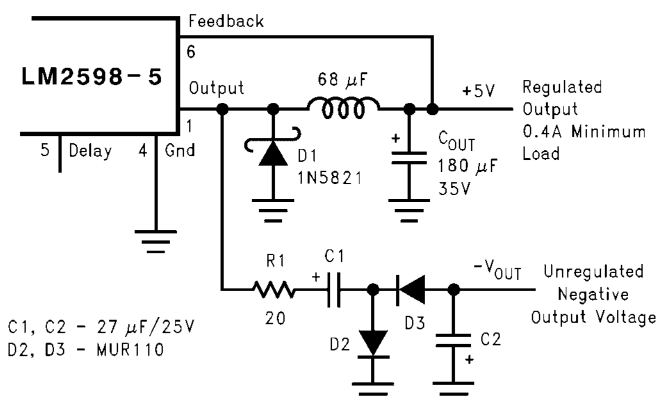

Figure 26. Charge Pump for Generating a Low Current, Negative Output Voltage

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8.4 Device Functional Modes

8.4.1 Discontinuous Mode Operation

The selection guide chooses inductor values suitable for continuous mode operation, but for low current applications or high input voltages, a discontinuous mode design may be a better choice. Discontinuous mode would use an inductor that would be physically smaller, and would require only one half to one third the inductance value required for a continuous mode design. The peak switch and inductor currents is higher in a discontinuous design, but at these low load currents (200 mA and below), the maximum switch current is still less than the switch current limit.

Discontinuous operation can have voltage waveforms that are considerably different than a continuous design. The output pin (switch) waveform can have some damped sinusoidal ringing present (see Figure 46) This ringing is normal for discontinuous operation, and is not caused by feedback loop instabilities. In discontinuous operation, there is a period of time where neither the switch nor the diode are conducting, and the inductor current has dropped to zero. During this time, a small amount of energy can circulate between the inductor and the switch or diode parasitic capacitance causing this characteristic ringing. Normally this ringing is not a problem, unless the amplitude becomes great enough to exceed the input voltage, and even then, there is very little energy present to cause damage.

Different inductor types or core materials produce different amounts of this characteristic ringing. Ferrite core inductors have very little core loss and therefore produce the most ringing. The higher core loss of powdered iron inductors produce less ringing. If desired, a series RC could be placed in parallel with the inductor to dampen the ringing.

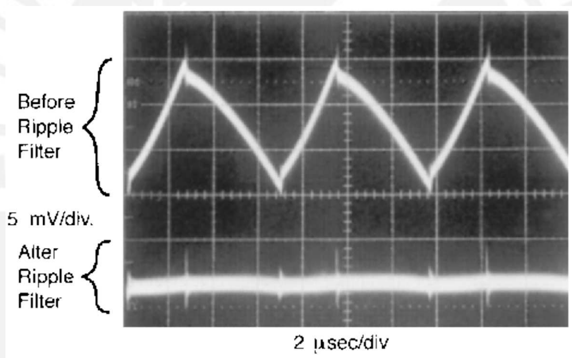

Figure 27. Post Ripple Filter Waveform

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9 Application and Implementation

NOTE

Information in the following applications sections is not part of the TI component specification, and TI does not warrant its accuracy or completeness. TI's customers are responsible for determining suitability of components for their purposes. Customers should validate and test their design implementation to confirm system functionality.

9.1 Application Information

9.1.1 Soft-Start Capacitor (C_{SS})

A capacitor on this pin provides the regulator with a Soft-start feature (slow start-up). When the DC input voltage is first applied to the regulator, or when the Shutdown/Soft-start pin is allowed to go high, a constant current (approximately 5 μA begins charging this capacitor). As the capacitor voltage rises, the regulator goes through four operating regions (See the bottom curve in Figure 28).

1. Regulator in shutdown: When the $\overline{SD}$/SS pin voltage is between 0 V and 1.3 V, the regulator is in shutdown, the output voltage is zero, and the IC quiescent current is approximately 85 μA.
2. Regulator ON, but the output voltage is zero: With the $\overline{SD}$/SS pin voltage between approximately 1.3 V and 1.8 V, the internal regulator circuitry is operating, the quiescent current rises to approximately 5 mA, but the output voltage is still zero. Also, as the 1.3-V threshold is exceeded, the Soft-start capacitor charging current decreases from 5 μA down to approximately 1.6 μA. This decreases the slope of capacitor voltage ramp.
3. Soft-start region: When the $\overline{SD}$/SS pin voltage is between 1.8 V and 2.8 V at 25°C, the regulator is in a Soft-start condition. The switch (Pin 1) duty cycle initially starts out very low, with narrow pulses and gradually get wider as the capacitor $\overline{SD}$/SS pin ramps up towards 2.8 V. As the duty cycle increases, the output voltage also increases at a controlled ramp up. See the center curve in Figure 28. The input supply current requirement also starts out at a low level for the narrow pulses and ramp up in a controlled manner. This is a very useful feature in some switcher topologies that require large start-up currents (such as the inverting configuration) which can load down the input power supply.

   Note: The lower curve shown in Figure 28 shows the Soft-start region from 0% to 100%. This is not the duty cycle percentage, but the output voltage percentage. Also, the Soft-start voltage range has a negative temperature coefficient associated with it.
4. Normal operation: Above 2.8 V, the circuit operates as a standard pulse width modulated switching regulator. The capacitor continues to charge up until it reaches the internal clamp voltage of approximately 7 V. If this pin is driven from a voltage source, the current must be limited to about 1 mA.

If the part is operated with an input voltage at or below the internal soft-start clamp voltage of approximately 7 V, the voltage on the $\overline{SD}$/SS pin tracks the input voltage and can be disturbed by a step in the voltage. To maintain proper function under these conditions, it is strongly recommended that the $\overline{SD}$/SS pin be clamped externally between the 3-V maximum soft-start threshold and the 4.5-V minimum input voltage. Figure 30 is an example of an external approximately 3.7-V clamp that prevents a line-step related glitch but does not interfere with the soft-start behavior of the device.

Application Information (continued)

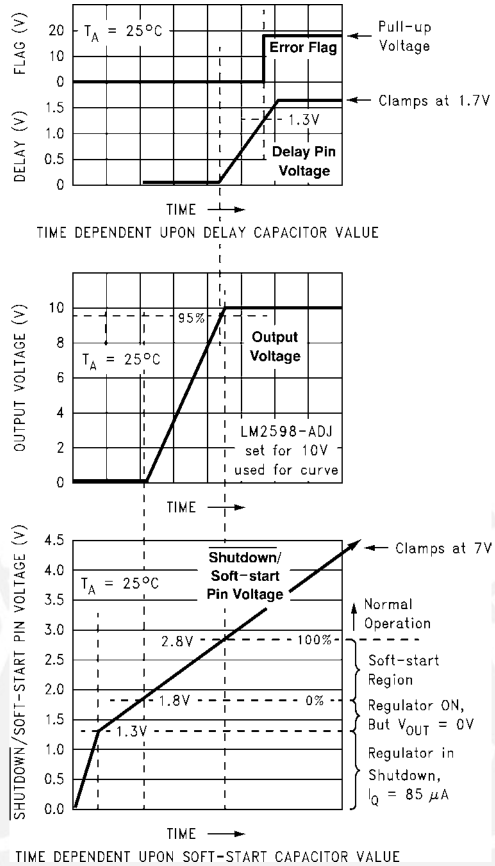

Figure 28. Soft-start, Delay, Error, Output

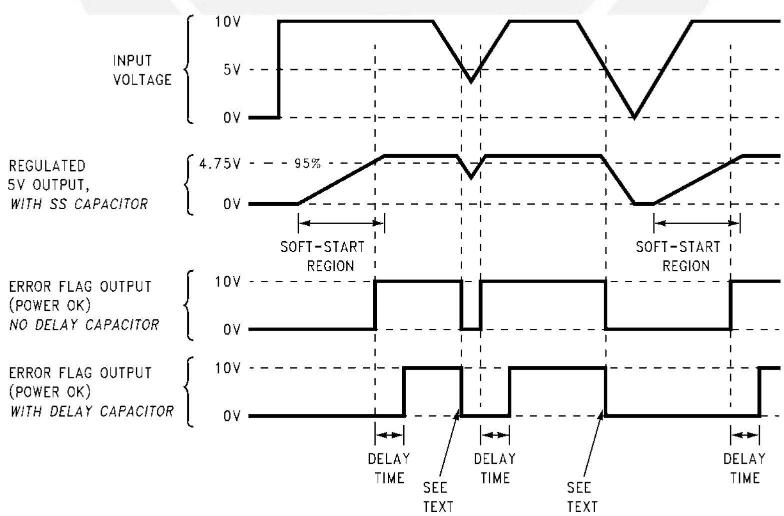

Figure 29. Timing Diagram for 5-V Output

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Application Information (continued)

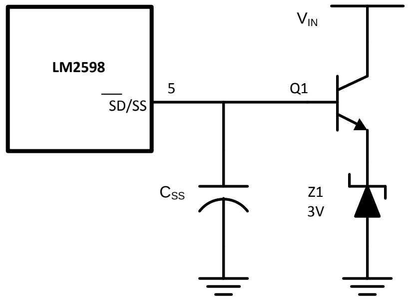

Figure 30. External 3.7-V Soft-Start Clamp

9.1.2 Delay Capacitor (C_{DELAY})

Provides delay for the error flag output. See the upper curve in Figure 28, and also refer to timing diagrams in Figure 29. A capacitor on this pin provides a time delay between the time the regulated output voltage (when it is increasing in value) reaches 95% of the nominal output voltage, and the time the error flag output goes high. A 3-μA constant current from the delay pin charges the delay capacitor resulting in a voltage ramp. When this voltage reaches a threshold of approximately 1.3 V, the open collector error flag output (or power OK) goes high. This signal can be used to indicate that the regulated output has reached the correct voltage and has stabilized.

If, for any reason, the regulated output voltage drops by 5% or more, the error output flag (Pin 3) immediately goes low (internal transistor turns on). The delay capacitor provides very little delay if the regulated output is dropping out of regulation. The delay time for an output that is decreasing is approximately a 1000 times less than the delay for the rising output. For a 0.1-μF delay capacitor, the delay time would be approximately 50 ms when the output is rising and passes through the 95% threshold, but the delay for the output dropping would only be approximately 50 μs.

The error flag output, $R_{Pull\ Up}$ (or power OK), is the collector of a NPN transistor, with the emitter internally grounded. To use the error flag, a pullup resistor to a positive voltage is required. The error flag transistor is rated up to a maximum of 45 V and can sink approximately 3 mA. If the error flag is not used, it can be left open.

9.1.3 Feedforward Capacitor (C_{FF})

NOTE

Adjustable output voltage version only

Figure 45 shows a feedfoward capacitor across R2 which is used when the output voltage is greater than 10 V or then C_{OUT} has a very low ESR. This capacitor adds lead compensation to the feedback loop and increases the phase margin for better loop stability.

If the output ripple is large (> 5% of the nominal output voltage), this ripple can be coupled to the feedback pin through the feedforward capacitor and cause the error comparator to trigger the error flag. In this situation, adding a resistor, R_{FF}, in series with the feedforward capacitor, approximately 3 times R1, attenuates the ripple voltage at the feedback pin.

9.1.4 Input Capacitor (C_{IN})

A low ESR aluminum or tantalum bypass capacitor is required between the input pin and ground pin. The capacitor must be located near the regulator using short leads. This capacitor prevents large voltage transients from appearing at the input, and provides the instantaneous current required each time the switch turns on.

The important parameters for the Input capacitor are the voltage rating and the RMS current rating. Because of the relatively high RMS currents flowing in a buck regulator's input capacitor, this capacitor must be chosen for its RMS current rating rather than its capacitance or voltage ratings, although the capacitance value and voltage rating are directly related to the RMS current rating.

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Application Information (continued)

The RMS current rating of a capacitor could be viewed as a capacitor's power rating. The RMS current flowing through the capacitors internal ESR produces power which causes the internal temperature of the capacitor to rise. The RMS current rating of a capacitor is determined by the amount of current required to raise the internal temperature approximately 10°C above an ambient temperature of 105°C. The ability of the capacitor to dissipate this heat to the surrounding air determines the amount of current the capacitor can safely sustain. Capacitors that are physically large and have a large surface area typically has higher RMS current ratings. For a given capacitor value, a higher voltage electrolytic capacitor is physically larger than a lower voltage capacitor, and thus be able to dissipate more heat to the surrounding air, and therefore has a higher RMS current rating.

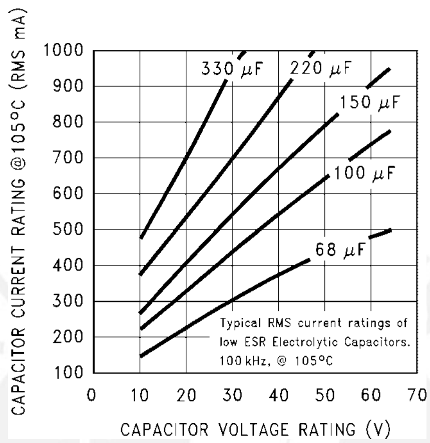

Figure 31. RMS Current Ratings for Low ESR Electrolytic Capacitors (Typical)

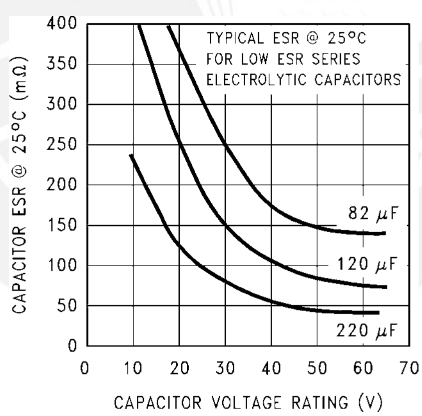

Figure 32. Capacitor ESR vs Capacitor Voltage Rating (Typical Low ESR Electrolytic Capacitor)

The consequences of operating an electrolytic capacitor above the RMS current rating is a shortened operating life. The higher temperature speeds up the evaporation of the capacitor's electrolyte, resulting in eventual failure.

Selecting an input capacitor requires consulting the manufacturers data sheet for maximum allowable RMS ripple current. For a maximum ambient temperature of 40°C, a general guideline would be to select a capacitor with a ripple current rating of approximately 50% of the DC load current. For ambient temperatures up to 70°C, a current rating of 75% of the DC load current would be a good choice for a conservative design. The capacitor voltage rating must be at least 1.25 times greater than the maximum input voltage, and often a much higher voltage capacitor is required to satisfy the RMS current requirements.

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Application Information (continued)

Figure 31 shows the relationship between an electrolytic capacitor value, its voltage rating, and the RMS current it is rated for. These curves were obtained from the Nichicon *PL* series of low-ESR, high-reliability electrolytic capacitors designed for switching regulator applications. Other capacitor manufacturers offer similar types of capacitors, but always check the capacitor data sheet.

Standard electrolytic capacitors typically have much higher ESR numbers, lower RMS current ratings and typically have a shorter operating lifetime.

Because of their small size and excellent performance, surface mount solid tantalum capacitors are often used for input bypassing, but several precautions must be observed. A small percentage of solid tantalum capacitors can short if the inrush current rating is exceeded. This can happen at turnon when the input voltage is suddenly applied, and of course, higher input voltages produce higher inrush currents. Several capacitor manufacturers do a 100% surge current testing on their products to minimize this potential problem. If high turnon currents are expected, it may be necessary to limit this current by adding either some resistance or inductance before the tantalum capacitor, or select a higher voltage capacitor. As with aluminum electrolytic capacitors, the RMS ripple current rating must be sized to the load current.

9.1.5 Output Capacitor (C_{OUT})

An output capacitor is required to filter the output and provide regulator loop stability. Low impedance or low ESR Electrolytic or solid tantalum capacitors designed for switching regulator applications must be used. When selecting an output capacitor, the important capacitor parameters are; the 100-kHz Equivalent Series Resistance (ESR), the RMS ripple current rating, voltage rating, and capacitance value. For the output capacitor, the ESR value is the most important parameter.

The output capacitor requires an ESR value that has an upper and lower limit. For low output ripple voltage, a low ESR value is required. This value is determined by the maximum allowable output ripple voltage, typically 1% to 2% of the output voltage. But if the selected capacitor's ESR is extremely low, there is a possibility of an unstable feedback loop, resulting in an oscillation at the output. Using the capacitors listed in the tables, or similar types, provides design solutions under all conditions.

If very low output ripple voltage (less than 15 mV) is required, see *Output Voltage Ripple and Transients* for a post ripple filter.

An aluminum electrolytic capacitor's ESR value is related to the capacitance value and its voltage rating. In most cases, higher voltage electrolytic capacitors have lower ESR values (see Figure 32). Often, capacitors with much higher voltage ratings may be required to provide the low ESR values required for low output ripple voltage.

The output capacitor for many different switcher designs often can be satisfied with only three or four different capacitor values and several different voltage ratings. See Figure 38 and Table 1 for typical capacitor values, voltage ratings, and manufacturers capacitor types.

Electrolytic capacitors are not recommended for temperatures below –25°C. The ESR rises dramatically at cold temperatures and typically rises 3X at –25°C and as much as 10X at –40°C. See curve shown in Figure 33.

Solid tantalum capacitors have a much better ESR specifications for cold temperatures and are recommended for temperatures below –25°C.

Application Information (continued)

Table 1. Output Capacitor and Feedforward Capacitor Selection Table

OUTPUT VOLTAGE (V)	THROUGH-HOLE ELECTROLYTIC			SURFACE-MOUNT TANTALUM		
	PANASONIC HFQ SERIES (µF/V)	NICHICON PL SERIES (µF/V)	FEEDFORWARD CAPACITOR	AVX TPS SERIES (µF/V)	SPRAGUE 595D SERIES (µF/V)	FEEDFORWARD CAPACITOR
1.2	330/50	330/50	0	330/6.3	330/6.3	0
4	220/25	220/25	4.7 nF	220/10	220/10	4.7 nF
6	220/25	220/25	3.3 nF	220/10	220/10	3.3 nF
9	180/25	180/25	1.5 nF	100/16	180/16	1.5 nF
12	120/25	120/25	1.5 nF	68/20	120/20	1.5 nF
15	120/25	120/25	1.5 nF	68/20	100/20	1.5 nF
24	82/35	82/35	1 nF	33/25	33/35	220 pF
28	82/50	82/50	1 nF	10/35	33/35	220 pF

9.1.6 Catch Diode

Buck regulators require a diode to provide a return path for the inductor current when the switch turns off. This must be a fast diode and must be located close to the LM2598 using short leads and short printed circuit traces.

Because of their very fast switching speed and low forward voltage drop, Schottky diodes provide the best performance, especially in low output voltage applications (5 V and lower). Ultra-fast recovery, or high-efficiency rectifiers are also a good choice, but some types with an abrupt turnoff characteristic may cause instability or EMI problems. Ultra-fast recovery diodes typically have reverse recovery times of 50 ns or less. Rectifiers such as the 1N5400 series are much too slow and must not be used.

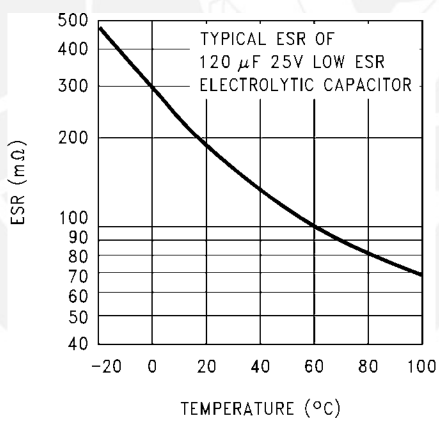

Figure 33. Capacitor ESR Change vs Temperature

9.1.7 Inductor Selection

All switching regulators have two basic modes of operation; continuous and discontinuous. The difference between the two types relates to the inductor current, whether it is flowing continuously, or if it drops to zero for a period of time in the normal switching cycle. Each mode has distinctively different operating characteristics, which can affect the regulators performance and requirements. Most switcher designs operate in the discontinuous mode when the load current is low.

The LM2598 (or any of the Simple Switcher family) can be used for both continuous or discontinuous modes of operation.

In many cases the preferred mode of operation is the continuous mode. This mode offers greater output power, lower peak switch, inductor and diode currents, and can have lower output ripple voltage. However, the continuous mode requires larger inductor values to keep the inductor current flowing continuously, especially at low output load currents or high input voltages.

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To simplify the inductor selection process, an inductor selection guide (nomograph) was designed (see Table 1 through Figure 37). This guide assumes that the regulator is operating in the continuous mode, and selects an inductor that allows a peak-to-peak inductor ripple current to be a certain percentage of the maximum design load current. This peak-to-peak inductor ripple current percentage is not fixed, but is allowed to change as different design load currents are selected. (See Figure 34.)

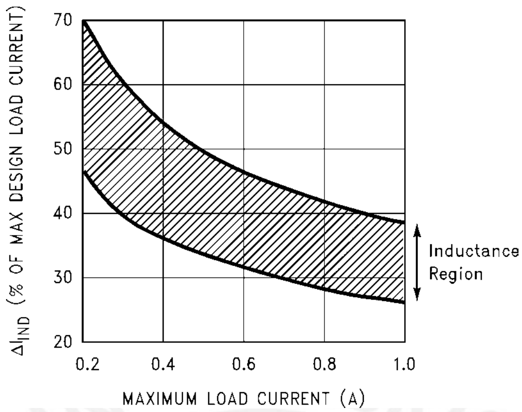

Figure 34. (ΔI_{IND}) Peak-to-Peak Inductor Ripple Current (as a Percentage of the Load Current) vs Load Current

By allowing the percentage of inductor ripple current to increase for low load currents, the inductor value and size can be kept relatively low.

When operating in the continuous mode, the inductor current waveform ranges from a triangular to a sawtooth type of waveform (depending on the input voltage), with the average value of this current waveform equal to the DC output load current.

Inductors are available in different styles such as pot core, toroid, E-core, bobbin core, and so forth, as well as different core materials, such as ferrites and powdered iron. The least expensive, the bobbin, rod or stick core, consists of wire wound on a ferrite bobbin. This type of construction makes for an inexpensive inductor; however, because the magnetic flux is not completely contained within the core, it generates more Electro-Magnetic Interference (EMl). This magnetic flux can induce voltages into nearby printed circuit traces, thus causing problems with both the switching regulator operation and nearby sensitive circuitry, and can give incorrect scope readings because of induced voltages in the scope probe. Also see*Open Core Inductors*.

When multiple switching regulators are located on the same PCB, open core magnetics can cause interference between two or more of the regulator circuits, especially at high currents. A torroid or E-core inductor (closed magnetic structure) must be used in these situations.

The inductors listed in the selection chart include ferrite E-core construction for Schott, ferrite bobbin core for Renco and Coilcraft, and powdered iron toroid for Pulse Engineering.

Exceeding an inductor's maximum current rating may cause the inductor to overheat because of the copper wire losses, or the core may saturate. If the inductor begins to saturate, the inductance decreases rapidly and the inductor begins to look mainly resistive (the DC resistance of the winding). This can cause the switch current to rise very rapidly and force the switch into a cycle-by-cycle current limit, thus reducing the DC output load current. This can also result in overheating of the inductor or the LM2598. Different inductor types have different saturation characteristics, and this must be kept in mind when selecting an inductor.

The inductor manufacturer's data sheets include current and energy limits to avoid inductor saturation.

For continuous mode operation, see the inductor selection graphs in Figure 35 through Figure 38.

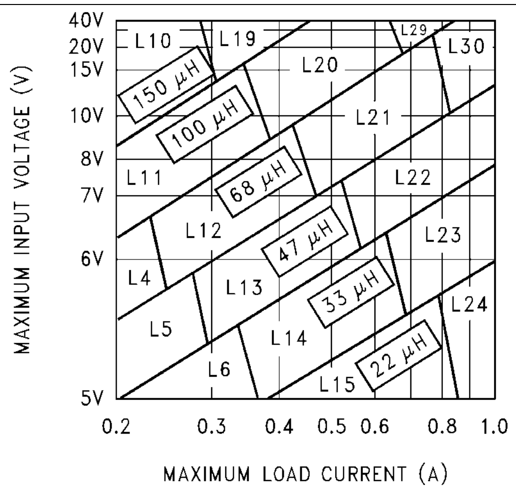

Figure 35. LM2598-3.3

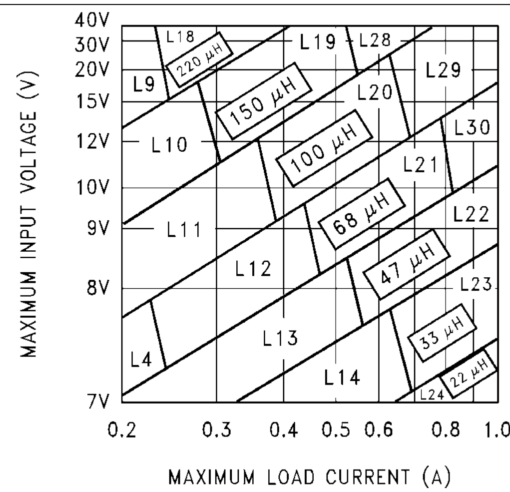

Figure 36. LM2598-5.0

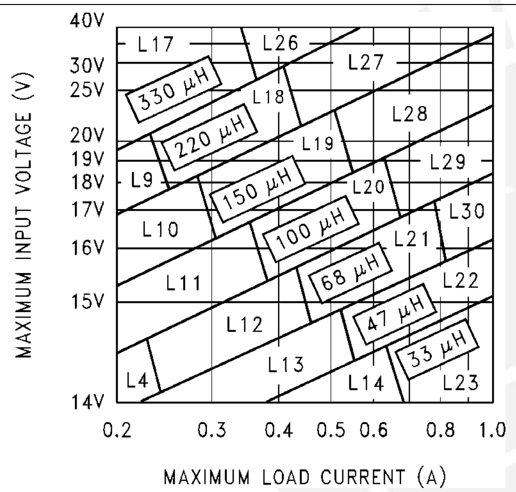

Figure 37. LM2598-12

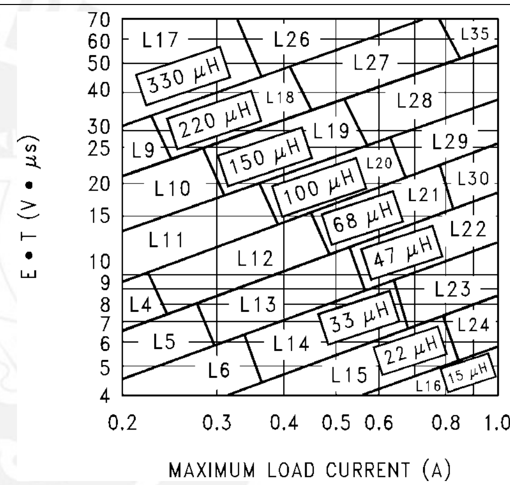

Figure 38. LM2598-ADJ

Table 2. Inductor Manufacturers Part Numbers

	INDUCTANCE (µH)	CURRENT (A)	SCHOTTKY		RENCO		PULSE ENGINEERING		COILCRAFT
			THROUGH HOLE	SURFACE MOUNT	THROUGH HOLE	SURFACE MOUNT	THROUGH HOLE	SURFACE MOUNT	SURFACE MOUNT
L4	68	0.32	67143940	67144310	RL-1284-68-43	RL1500-68	PE-53804	PE-53804-S	DO1608-68
L5	47	0.37	67148310	67148420	RL-1284-47-43	RL1500-47	PE-53805	PE-53805-S	DO1608-473
L6	33	0.44	67148320	67148430	RL-1284-33-43	RL1500-33	PE-53806	PE-53806-S	DO1608-333
L9	220	0.32	67143960	67144330	RL-5470-3	RL1500-220	PE-53809	PE-53809-S	DO3308-224
L10	150	0.39	67143970	67144340	RL-5470-4	RL1500-150	PE-53810	PE-53810-S	DO3308-154
L11	100	0.48	67143980	67144350	RL-5470-5	RL1500-100	PE-53811	PE-53811-S	DO3308-104
L12	68	0.58	67143990	67144360	RL-5470-6	RL1500-68	PE-53812	PE-53812-S	DO3308-683
L13	47	0.7	67144000	67144380	RL-5470-7	RL1500-47	PE-53813	PE-53813-S	DO3308-473
L14	33	0.83	67148340	67148450	RL-1284-33-43	RL1500-33	PE-53814	PE-53814-S	DO3308-333
L15	22	0.99	67148350	67148460	RL-1284-22-43	RL1500-22	PE-53815	PE-53815-S	DO3308-223
L16	15	1.24	67148360	67148470	RL-1284-15-43	RL1500-15	PE-53816	PE-53816-S	DO3308-153
L17	330	0.42	67144030	67144410	RL-5471-1	RL1500-330	PE-53817	PE-53817-S	DO3316-334
L18	220	0.55	67144040	67144420	RL-5471-2	RL1500-220	PE-53818	PE-53818-S	DO3316-224
L19	150	0.66	67144050	67144430	RL-5471-3	RL1500-150	PE-53819	PE-53819-S	DO3316-154
L20	100	0.82	67144060	67144440	RL-5471-4	RL1500-100	PE-53820	PE-53820-S	DO3316-104
L21	68	0.99	67144070	67144450	RL-5471-5	RL1500-68	PE-53821	PE-53821-S	DO3316-683

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Table 2. Inductor Manufacturers Part Numbers (continued)

	INDUCTANCE (µH)	CURRENT (A)	SCHOTTKY		RENCO		PULSE ENGINEERING		COILCRAFT
			THROUGH HOLE	SURFACE MOUNT	THROUGH HOLE	SURFACE MOUNT	THROUGH HOLE	SURFACE MOUNT	SURFACE MOUNT
L22	47	1.17	67144080	67144460	RL-5471-6	—	PE-53822	PE-53822-S	DO3316-473
L23	33	1.4	67144090	67144470	RL-5471-7	—	PE-53823	PE-53823-S	DO3316-333
L24	22	1.7	67148370	67144480	RL-1283-22-43	—	PE-53824	PE-53824-S	DO3316-223
L26	330	0.8	67144100	67144480	RL-5471-1	—	PE-53826	PE-53826-S	DO5022P-334
L27	220	1	67144110	67144490	RL-5471-2	—	PE-53827	PE-53827-S	DO5022P-224
L28	150	1.2	67144120	67144500	RL-5471-3	—	PE-53828	PE-53828-S	DO5022P-154
L29	100	1.47	67144130	67144510	RL-5471-4	—	PE-53829	PE-53829-S	DO5022P-104
L30	68	1.78	67144140	67144520	RL-5471-5	—	PE-53830	PE-53830-S	DO5022P-683
L35	47	2.15	67144170	—	RL-5473-1	—	PE-53935	PE-53935-S	—

9.1.8 Output Voltage Ripple and Transients

The output voltage of a switching power supply operating in the continuous mode contains a sawtooth ripple voltage at the switcher frequency, and may also contain short voltage spikes at the peaks of the sawtooth waveform.

The output ripple voltage is a function of the inductor sawtooth ripple current and the ESR of the output capacitor. A typical output ripple voltage can range from approximately 0.5% to 3% of the output voltage. To obtain low ripple voltage, the ESR of the output capacitor must be low; however, caution must be exercised when using extremely low ESR capacitors because they can affect the loop stability, resulting in oscillation problems. If very low output ripple voltage is required (less than 20 mV), TI recommends a post ripple filter (see Figure 45). The inductance required is typically between 1 µH and 5 µH, with low DC resistance, to maintain good load regulation. A low ESR output filter capacitor is also required to assure good dynamic load response and ripple reduction. The ESR of this capacitor may be as low as desired, because it is out of the regulator feedback loop. Figure 27 shows a typical output ripple voltage, with and without a post ripple filter.

When observing output ripple with a scope, it is essential that a short, low inductance scope probe ground connection be used. Most scope probe manufacturers provide a special probe terminator which is soldered onto the regulator board, preferably at the output capacitor. This provides a very short scope ground, thus eliminating the problems associated with the 3 inch ground lead normally provided with the probe, and provides a much cleaner and more accurate picture of the ripple voltage waveform.

The voltage spikes are caused by the fast switching action of the output switch, the diode, the parasitic inductance of the output filter capacitor, and its associated wiring. To minimize these voltage spikes, the output capacitor must be designed for switching regulator applications, and the lead lengths must be kept very short. Wiring inductance, stray capacitance, as well as the scope probe used to evaluate these transients, all contribute to the amplitude of these spikes.

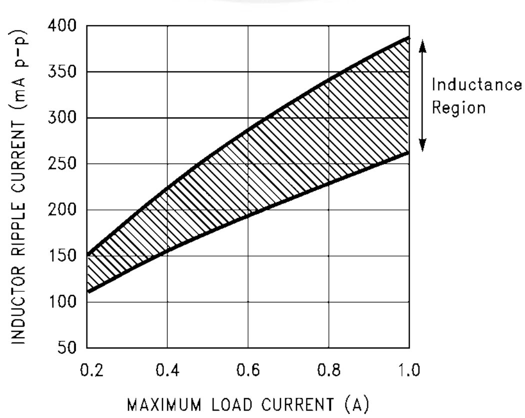

Figure 39. Peak-to-Peak Inductor Ripple Current vs Load Current

When a switching regulator is operating in the continuous mode, the inductor current waveform ranges from a triangular to a sawtooth type of waveform (depending on the input voltage). For a given input and output voltage, the peak-to-peak amplitude of this inductor current waveform remains constant. As the load current increases or decreases, the entire sawtooth current waveform also rises and falls. The average value (or the center) of this current waveform is equal to the DC load current.

If the load current drops to a low enough level, the bottom of the sawtooth current waveform reaches zero, and the switcher smoothly changes from a continuous to a discontinuous mode of operation. Most switcher designs (regardless how large the inductor value is) is forced to run discontinuous if the output is lightly loaded. This is a perfectly acceptable mode of operation.

In a switching regulator design, knowing the value of the peak-to-peak inductor ripple current (ΔI_{IND}) can be useful for determining a number of other circuit parameters. Parameters such as, peak inductor or peak switch current, minimum load current before the circuit becomes discontinuous, output ripple voltage and output capacitor ESR can all be calculated from the peak-to-peak ΔI_{IND}. When the inductor nomographs shown in Figure 35 through Figure 38 are used to select an inductor value, the peak-to-peak inductor ripple current can immediately be determined. Figure 39 shows the range of (ΔI_{IND}) that can be expected for different load currents. Figure 39 also shows how the peak-to-peak inductor ripple current (ΔI_{IND}) changes as the designer goes from the lower border to the upper border (for a given load current) within an inductance region. The upper border represents a higher input voltage, while the lower border represents a lower input voltage (see Inductor Selection Guides).

These curves are only correct for continuous mode operation, and only if the inductor selection guides are used to select the inductor value

Consider the following example:

V_{OUT} = 5 V, maximum load current of 800 mA

V_{IN} = 12 V, nominal, varying between 10 V and 14 V.

The selection guide in Figure 36 shows that the vertical line for a 0.8-A load current and the horizontal line for the 12-V input voltage intersect approximately midway between the upper and lower borders of the 68-µH inductance region. A 68-µH inductor allows a peak-to-peak inductor current (ΔI_{IND}) to a percentage of the maximum load current. Referring to Figure 39, follow the 0.8-A line approximately midway into the inductance region, and read the peak-to-peak inductor ripple current (ΔI_{IND}) on the left hand axis (approximately 300-mA p-p).

As the input voltage increases to 14 V, it approaches the upper border of the inductance region, and the inductor ripple current increases. Figure 39 shows that for a load current of 0.8 A, the peak-to-peak inductor ripple current (ΔI_{IND}) is 300 mA with 12-V in, and can range from 340 mA at the upper border (14-V in) to 225 mA at the lower border (10-V in).

Once the ΔI_{IND} value is known, the following formulas can be used to calculate additional information about the switching regulator circuit.

1. Peak Inductor or peak switch current $= \left(I_{LOAD} + \frac{\Delta I_{IND}}{2}\right) = \left(0.8A + \frac{0.3}{2}\right) = 0.95A$
2. Minimum load current before the circuit becomes discontinuous $= \frac{\Delta I_{IND}}{2} = \frac{0.3}{2} = 0.15A$
3. Output Ripple Voltage = (ΔI_{IND}) × (ESR of C_{OUT}) = 0.3 A × 0.16 Ω = 48 mV_{p-p}
4. ESR of C_{OUT} $= \frac{\text{Output Ripple Voltage } (\Delta V_{OUT})}{\Delta I_{IND}}$ $= \frac{0.048V}{0.30A} = 0.16\Omega$

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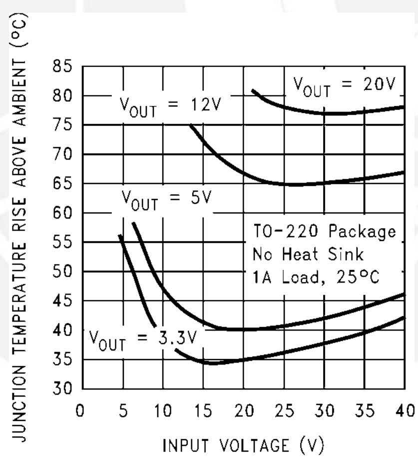
9.1.9 Open Core Inductors

Another possible source of increased output ripple voltage or unstable operation is from an open core inductor. Ferrite bobbin or stick inductors have magnetic lines of flux flowing through the air from one end of the bobbin to the other end. These magnetic lines of flux induce a voltage into any wire or PCB copper trace that comes within the magnetic field of the inductor. The strength of the magnetic field, the orientation and location of the PC copper trace to the magnetic field, and the distance between the copper trace and the inductor determine the amount of voltage generated in the copper trace. Another way of looking at this inductive coupling is to consider the PCB copper trace as one turn of a transformer (secondary) with the inductor winding as the primary. Many millivolts can be generated in a copper trace located near an open core inductor, which can cause stability problems or high output ripple voltage problems.

If unstable operation is seen, and an open core inductor is used, it is possible that the location of the inductor with respect to other PC traces may be the problem. To determine if this is the problem, temporarily raise the inductor away from the board by several inches and then check circuit operation. If the circuit now operates correctly, then the magnetic flux from the open core inductor is causing the problem. Substituting a closed-core inductor such as a torroid or E-core correct the problem, or re-arranging the PC layout may be necessary. Magnetic flux cutting the IC device ground trace, feedback trace, or the positive or negative traces of the output capacitor must be minimized.

Sometimes, placing a trace directly beneath a bobbin inductor provides good results, provided it is exactly in the center of the inductor (because the induced voltages cancel themselves out). However, problems could arise if the trace is off center. If flux problems are present, even the direction of the inductor winding can make a difference in some circuits.

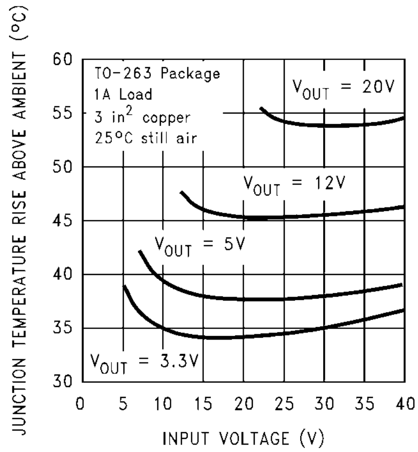
This discussion on open core inductors is not to frighten users, but to alert them on what kind of problems to watch out for when using them. Open core bobbin or *stick* inductors are an inexpensive, simple way of making a compact, efficient inductor, and they are used by the millions in many different applications.



Circuit Data for Temperature Rise Curve TO-220 Package (T)

Capacitors	Through hole electrolytic
Inductor	Through hole, Schott, 68 μH
Diode	Through hole, 3-A, 40-V, Schottky
Printed-circuit board	3 square inches single sided 2 oz. copper (0.0028″)

Figure 40. Junction Temperature Rise, TO-220



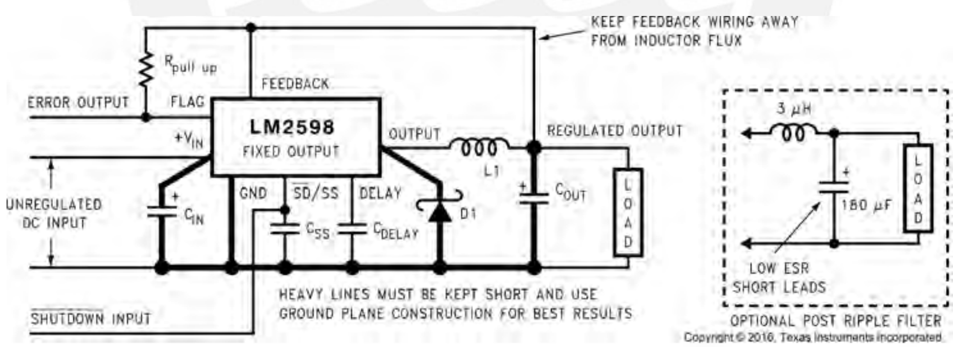
Circuit Data for Temperature Rise Curve DDPAK Package (S)

Capacitors	Surface mount tantalum, molded *D* size
Inductor	Surface mount, Schott, 68 µH
Diode	Surface mount, 3-A, 40-V, Schottky
Printed-circuit board	3 square inches single sided 2 oz. copper (0.0028″)

Figure 41. Junction Temperature Rise, DDPAK

9.2 Typical Application

9.2.1 LM2598 Fixed Output Series Buck Regulator



Component Values shown are for V_{IN} = 15 V, V_{OUT} = 5 V, I_{LOAD} = 1 A.
120-µF, 50-V, Aluminum Electrolytic Nichicon *PL Series*
120-µF, 35-V Aluminum Electrolytic, Nichicon *PL Series*
3-A, 40-V Schottky Rectifier, 1N5822
68-µH, L30
Typical Values
*C_{SS}: — 0.1 µF
C_{DELAY}: — 0.1 µF
$R_{Pull\ Up}$: — 4.7k

Figure 42. Fixed Output Voltage Version

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Typical Application (continued)

9.2.1.1 Design Requirements

Table 3 lists the design parameters of this application example.

Table 3. Design Parameters

PARAMETERS	EXAMPLE VALUE
Regulated output voltage (3.3 V, 5 V or 12 V), V_{OUT}	5 V
Maximum DC input voltage, V_{IN}(max)	12 V
Maximum load current, I_{LOAD}(max)	1 A

9.2.1.2 Detailed Design Procedure

9.2.1.2.1 Inductor Selection (L1)

1. Select the correct inductor value selection guide from Figure 35, Figure 36, or Figure 37 (Output voltages of 3.3 V, 5 V, or 12 V respectively.) Use the inductor selection guide for the 5-V version shown in Figure 36.
2. From the inductor value selection guide, identify the inductance region intersected by the maximum input voltage line and the maximum load current line. Each region is identified by an inductance value and an inductor code (LXX). From the inductor value selection guide shown in Figure 36, the inductance region intersected by the 12-V horizontal line and the 1-A vertical line is 68 μH, and the inductor code is L30.
3. Select an appropriate inductor from the four manufacturer's part numbers listed in Table 2. The inductance value required is 68 μH. See row L30 of Table 2 and choose an inductor part number from any of the four manufacturers shown. (In most instance, both through hole and surface mount inductors are available.)

9.2.1.2.2 Output Capacitor Selection (C_{OUT})

1. In the majority of applications, low ESR (Equivalent Series Resistance) electrolytic capacitors between 47 μF and 330 μF and low ESR solid tantalum capacitors between 56 μF and 270 μF provide the best results. This capacitor must be located close to the IC using short capacitor leads and short copper traces. Do not use capacitors larger than 330 μF.

   For additional information, see section on output capacitors in *Output Capacitor (C_{OUT})* section.
2. To simplify the capacitor selection procedure, see Figure 38 for quick design component selection. This table contains different input voltages, output voltages, and load currents, and lists various inductors and output capacitors that provide the best design solutions.

   From Figure 38, locate the 5-V output voltage section. In the load current column, choose the load current line that is closest to the current required for the application; for this example, use the 1-A line. In the maximum input voltage column, select the line that covers the input voltage required for the application; in this example, use the 15-V line. The rest of this line shows the recommended inductors and capacitors that provide the best overall performance.

   The capacitor list contains both through hole electrolytic and surface mount tantalum capacitors from four different capacitor manufacturers. TI recommends using both the manufacturers and the manufacturer's series that are listed in Figure 38.

   In this example aluminum electrolytic capacitors from several different manufacturers are available with the range of ESR numbers required.
   - 220-μF, 25-V Panasonic HFQ Series
   - 220 μF, 25-V Nichicon PL Series

Table 4. LM2598 Fixed Voltage Quick Design Component Selection Table

CONDITIONS			INDUCTOR		OUTPUT CAPACITOR			
					THROUGH-HOLE ELECTROLYTIC		SURFACE-MOUNT TANTALUM	
OUTPUT VOLTAGE (V)	LOAD CURRENT (A)	MAX INPUT VOLTAGE (V)	INDUCTANCE (µH)	INDUCTOR (#)	PANASONIC HFQ SERIES (µF/V)	NICHICON PL SERIES (µF/V)	AVX TPS SERIES (µF/V)	SPRAGUE 595D SERIES (µF/V)
3.3	1	5	22	L24	330/16	330/16	220/10	330/10
		7	33	L23	270/25	270/25	220/10	270/10
		10	47	L31	220/25	220/35	220/10	220/10
		40	68	L30	180/35	220/35	220/10	180/10
		6	47	L13	220/25	220/16	220/16	220/10
	0.5	10	68	L21	150/35	150/25	100/16	150/16
		40	100	L20	150/35	82/35	100/16	100/20
5	1	8	33	L28	330/16	330/16	220/10	270/10
		10	47	L31	220/25	220/25	220/10	220/10
		15	68	L30	180/35	180/35	220/10	150/16
		40	100	L29	180/35	120/35	100/16	120/16
		9	68	L21	180/16	180/16	220/10	150/16
	0.5	20	150	L19	120/25	120/25	100/16	100/20
		40	150	L19	100/25	100/25	68/20	68/25
12	1	15	47	L31	220/25	220/25	68/20	120/20
		18	68	L30	180/35	120/25	68/20	120/20
		30	150	L36	82/25	82/25	68/20	100/20
		40	220	L35	82/25	82/25	68/20	68/25
		15	68	L21	180/25	180/25	68/20	120/20
	0.5	20	150	L19	82/25	82/25	68/20	100/20
		40	330	L26	56/25	56/25	68/20	68/25

3. The capacitor voltage rating for electrolytic capacitors must be at least 1.5 times greater than the output voltage, and often much higher voltage ratings are required to satisfy the low ESR requirements for low output ripple voltage

   For a 5-V output, a capacitor voltage rating at least 7.5 V or more is required. But, in this example, even a low ESR, switching grade, 220-µF, 10-V aluminum electrolytic capacitor would exhibit approximately 225 mΩ of ESR (see the curve in Figure 32 for the ESR vs voltage rating). This amount of ESR would result in relatively high output ripple voltage. To reduce the ripple to 1% of the output voltage, or less, a capacitor with a higher voltage rating (lower ESR) must be selected. A 16-V or 25-V capacitor reduces the ripple voltage by approximately half.

9.2.1.2.3 Catch Diode Selection (D1)

1. The catch diode current rating must be at least 1.3 times greater than the maximum load current. Also, if the power supply design must withstand a continuous output short, the diode must have a current rating equal to the maximum current limit of the LM2598. The most stressful condition for this diode is an overload or shorted output condition. See Table 5. In this example, a 3-A, 20-V, 1N5820 Schottky diode provides the best performance, and does not overstressed even for a shorted output.

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Table 5. Diode Selection Table

VR	1-A DIODES				3-A DIODES			
	SURFACE MOUNT		THROUGH HOLE		SURFACE MOUNT		THROUGH HOLE	
	SCHOTTKY	ULTRA FAST RECOVERY	SCHOTTKY	ULTRA FAST RECOVERY	SCHOTTKY	ULTRA FAST RECOVERY	SCHOTTKY	ULTRA FAST RECOVERY
20 V	SK12	All of these diodes are rated to at least 50 V.	1N5817	All of these diodes are rated to at least 50 V.		All of these diodes are rated to at least 50 V.	IN5820	All of these diodes are rated to at least 50 V.
			SR102		SK32		SR302	
							MBR320	
30 V	SK13		1N5818				1N5821	
	MBRS130		SR103		SK33		MBR330	
			11DQ03				31DQ03	
40 V	SK14						1N5822	
	MBRS140		1N5819		SK34		SR304	
	10BQ040		SR104		MBRS340		MBR340	
	10MQ040	MURS120	11DQ04	MUR120	30WQ04	MURS320	31DQ04	MUR320
50 V or more	MBRS160	10BF10	SR105		SK35	30WF10	SR305	30WF10
	10BQ050		MBR150		MBRS360		MBR350	
	10MQ060		11DQ05		30WQ05		31DQ05	

2. The reverse voltage rating of the diode must be at least 1.25 times the maximum input voltage.
3. This diode must be fast (short reverse recovery time) and must be located close to the LM2598 using short leads and short printed circuit traces. Because of their fast switching speed and low forward voltage drop, Schottky diodes provide the best performance and efficiency, and must be the first choice, especially in low output voltage applications. Ultra-fast recovery, or high-efficiency rectifiers also provide good results. Ultra-fast recovery diodes typically have reverse recovery times of 50 ns or less. Rectifiers such as the 1N5400 must not be used because they are too slow.

9.2.1.2.4 Input Capacitor (C_{IN})

A low ESR aluminum or tantalum bypass capacitor is required between the input pin and ground to prevent large voltage transients from appearing at the input. In addition, the RMS current rating of the input capacitor must be selected to be at least ½ the DC load current. The capacitor manufacturers data sheet must be checked to assure that this current rating is not exceeded. Figure 31 shows typical RMS current ratings for several different aluminum electrolytic capacitor values.

This capacitor must be located close to the IC using short leads and the voltage rating must be approximately 1.5 times the maximum input voltage.

If solid tantalum input capacitors are used, TI recommends they be surge current tested by the manufacturer.

Use caution when using ceramic capacitors for input bypassing, because it may cause severe ringing at the V_{IN} pin.

The important parameters for the Input capacitor are the input voltage rating and the RMS current rating. With a nominal input voltage of 12 V, an aluminum electrolytic capacitor with a voltage rating greater than 18 V (1.5 × V_{IN}) is necessary. The next higher capacitor voltage rating is 25 V.

The RMS current rating requirement for the input capacitor in a buck regulator is approximately ½ the DC load current. In this example, with a 1-A load, a capacitor with a RMS current rating of at least 500 mA is required. Figure 31 shows curves that can be used to select an appropriate input capacitor. From the curves, locate the 25-V line and note which capacitor values have RMS current ratings greater than 500 mA. Either a 180-µF or 220-µF, 25-V capacitor could be used.

For a through-hole design, a 220-µF, 25-V electrolytic capacitor (Panasonic HFQ series or Nichicon PL series or equivalent) would be adequate. Other types or other manufacturers' capacitors can be used provided the RMS ripple current ratings are adequate.

For surface-mount designs, solid tantalum capacitors are recommended. The TPS series available from AVX, and the 593D series from Sprague are both surge current tested.

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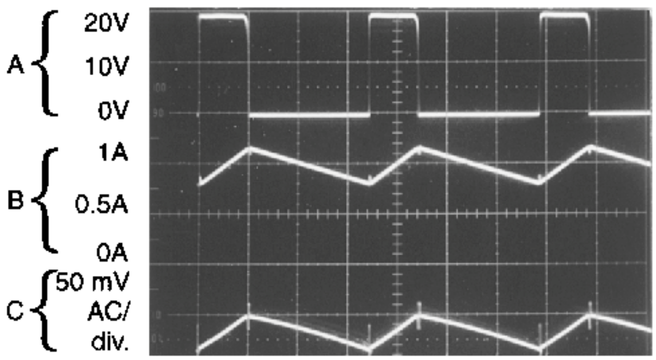
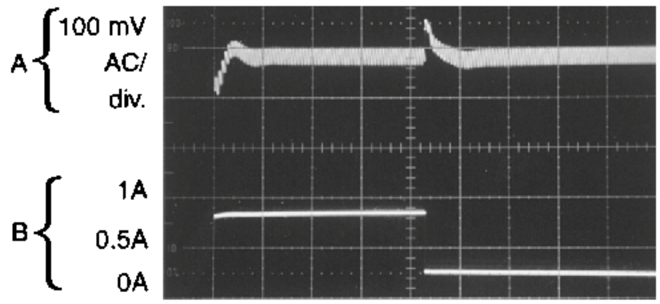
9.2.1.3 Application Curves



Continuous Mode Switching Waveforms
V_{IN} = 20 V, V_{OUT} = 5 V, I_{LOAD} = 1 A, L = 68 μH,
C_{OUT} = 120 μF, C_{OUT} ESR = 100 mΩ
A: Output Pin Voltage, 10 V/div.
B: Inductor Current 0.5 A/div.
C: Output Ripple Voltage, 50 mV/div.

Figure 43. Horizontal Time Base: 2 μs/div



Load Transient Response for Continuous Mode
V_{IN} = 20 V, V_{OUT} = 5 V, I_{LOAD} = 250 mA to 750 mA,
L = 68 μH, C_{OUT} = 120 μF, C_{OUT} ESR = 100 mΩ
A: Output Voltage, 100 mV/div. (AC)
B: 250-mA to 750-mA Load Pulse

Figure 44. Horizontal Time Base: 100 μs/div

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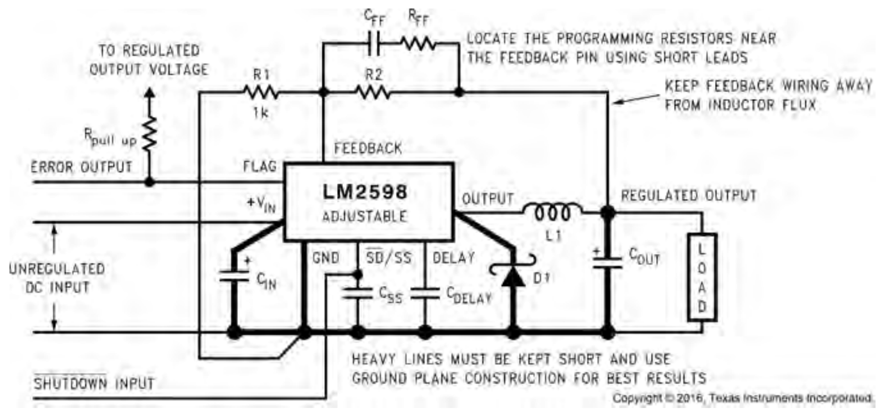
9.2.2 LM2598 Adjustable Output Series Buck Regulator



$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right)$$

where V_{REF} = 1.23 V

$$R_2 = R_1\left(\frac{V_{OUT}}{V_{REF}} - 1\right)$$

Select R_1 to be approximately 1 kΩ, use a 1% resistor for best stability.
Component Values shown are for V_{IN} = 20 V,
V_{OUT} = 10 V, I_{LOAD} = 1 A.
C_{IN} — 120 µF, 35-V, Aluminum Electrolytic Nichicon *PL Series*
C_{OUT} — 120 µF, 35-V Aluminum Electrolytic, Nichicon *PL Series*
D1 —3-A, 40-V Schottky Rectifier, 1N5822
L1 —100 µH, L29
R_1 —1 kΩ, 1%
R_2 —7.1 kΩ, 1%
C_{FF} — 3.3 nF, See *Feedforward Capacitor (C_{FF})*
R_{FF} — 3 kΩ, See *Feedforward Capacitor (C_{FF})*
Typical Values
C_{SS}—0.1 µF
C_{DELAY}—0.1 µF
$R_{PULL\ UP}$—4.7 kΩ

Figure 45. Adjustable Output Voltage Version

9.2.2.1 Design Requirements

Table 6 lists the design parameters for this application example.

Table 6. Design Parameters

PARAMETERS	EXAMPLE VALUE
Regulated output voltage (3.3 V, 5 V or 12 V), V_{OUT}	20 V
Maximum DC input voltage, V_{IN}(max)	28 V
Maximum load current, I_{LOAD}(max)	1 A
Switching frequency, F	Fixed at a nominal 150 kHz

9.2.2.2 Detailed Design Procedure

9.2.2.2.1 Programming Output Voltage

Select R_1 and R_2, as shown in Figure 45.

Use Equation 1 to select the appropriate resistor values.

$$V_{OUT} = V_{REF}\left(1 + \frac{R_2}{R_1}\right) \quad \text{where } V_{REF} = 1.23\text{V} \tag{1}$$

Select a value for R_1 with Equation 2 between 240 Ω and 1.5 kΩ. The lower resistor values minimize noise pickup in the sensitive feedback pin. (For the lowest temperature coefficient and the best stability with time, use 1% metal film resistors.)

$$R_2 = R_1 \left(\frac{V_{OUT}}{V_{REF}} - 1 \right) \quad (2)$$

Select R_1 with Equation 3 to be 1 kΩ, 1%. Solve for R_2.

$$R_2 = R_1 \left(\frac{V_{OUT}}{V_{REF}} - 1 \right) = 1k \left(\frac{20V}{1.23V} - 1 \right) \quad (3)$$

R_2 = 1k (16.26 – 1) = 15.26k, closest 1% value is 15.4 kΩ.

R_2 = 15.4 kΩ.

9.2.2.2.2 Inductor Selection (L1)

1. Calculate the inductor Volt • microsecond constant E • T (V • µs) with Equation 4.

   $$E \bullet T = (V_{IN} - V_{OUT} - V_{SAT}) \bullet \frac{V_{OUT} + V_D}{V_{IN} - V_{SAT} + V_D} \bullet \frac{1000}{150\ kHz} (V \bullet \mu s)$$

   where
   - V_{SAT} = internal switch saturation voltage = 1 V
   - V_D = diode forward voltage drop = 0.5 V (4)

   Calculate the inductor Volt • microsecond constant (E • T) with Equation 5.

   $$E \bullet T = (28 - 20 - 1) \bullet \frac{20 + 0.5}{28 - 1 + 0.5} \bullet \frac{1000}{150} (V \bullet \mu s)$$

   $$E \bullet T = (7) \bullet \frac{20.5}{27.6} \bullet 6.67\ (V \bullet \mu s) = 34.8\ (V \bullet \mu s) \quad (5)$$

2. Use the E • T value from the previous formula and match it with the E • T number on the vertical axis of the see the inductor selection graphs in Figure 35 through Figure 38.

   E • T = 34.8 (V • µs)

3. On the horizontal axis, select the maximum load current.

   I_{LOAD}(max) = 1 A

4. Identify the inductance region intersected by the E • T value and the Maximum Load Current value. Each region is identified by an inductance value and an inductor code (LXX).

   From the inductor selection graphs in Figure 35 through Figure 38, the inductance region intersected by the 35 (V • µs) horizontal line and the 1-A vertical line is 100 µH, and the inductor code is L29.

5. Select an appropriate inductor from the four manufacturer's part numbers listed in Table 2.

   From the table in Table 2, locate line L29, and select an inductor part number from the list of manufacturers' part numbers.

9.2.2.2.3 Output Capacitor Selection (C_{OUT})

1. In the majority of applications, low ESR electrolytic or solid tantalum capacitors between 82 µF and 220 µF provide the best results. This capacitor must be located close to the IC using short capacitor leads and short copper traces. Do not use capacitors larger than 220 µF. For additional information, see *Output Capacitor (C_{OUT})*.

2. To simplify the capacitor selection procedure, see Table 1 for a quick design guide. This table contains different output voltages, and lists various output capacitors that provide the best design solutions.

   From Table 1, locate the output voltage column. From that column, locate the output voltage closest to the output voltage in your application. In this example, select the 24-V line. Under the *Output Capacitor (C_{OUT})* section, select a capacitor from the list of through hole electrolytic or surface mount tantalum types from four different capacitor manufacturers. TI recommends that both the manufacturers and the manufacturers series that are listed in Table 1 be used.

   In this example, through hole aluminum electrolytic capacitors from several different manufacturers are available:

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  - 82-µF, 35-V Panasonic HFQ Series
  - 82-µF, 35-V Nichicon PL Series

3. The capacitor voltage rating must be at least 1.5 times greater than the output voltage, and often much higher voltage ratings are required to satisfy the low ESR requirements required for low output ripple voltage.

   For a 20-V output, a capacitor rating of at least 30 V or more is required. In this example, either a 35-V or 50-V capacitor would work. A 35-V rating was chosen although a 50-V rating could also be used if a lower output ripple voltage is required.

   Other manufacturers or other types of capacitors may also be used, provided the capacitor specifications (especially the 100 kHz ESR) closely match the types listed in Table 1. Refer to the capacitor manufacturers data sheet for this information.

9.2.2.2.4 Feedforward Capacitor (C_{FF})

For output voltages greater than approximately 10 V, an additional capacitor is required (use Equation 6; see Figure 45). The compensation capacitor is typically between 50 pF and 10 nF, and is wired in parallel with the output voltage setting resistor, R_2. It provides additional stability for high output voltages, low input or output voltages, or very low ESR output capacitors, such as solid tantalum capacitors.

$$C_{FF} = \frac{1}{31 \times 10^3 \times R_2} \tag{6}$$

This capacitor type can be ceramic, plastic, silver mica, etc. (Because of the unstable characteristics of ceramic capacitors made with Z5U material, they are not recommended.)

The table shown in Table 1 contains feedforward capacitor values for various output voltages. In this example, a 1-nF capacitor is required.

9.2.2.2.5 Catch Diode Selection (D1)

1. The catch diode current rating must be at least 1.3 times greater than the maximum load current. Also, if the power supply design must withstand a continuous output short, the diode must have a current rating equal to the maximum current limit of the LM2598. The most stressful condition for this diode is an overload or shorted output condition.

   See Table 5. Schottky diodes provide the best performance, and in this example a 3-A, 40-V, 1N5822 Schottky diode is a good choice. The 3-A diode rating is more than adequate and does not overstressed even for a shorted output.
2. The reverse voltage rating of the diode must be at least 1.25 times the maximum input voltage.
3. This diode must be fast (short reverse recovery time) and must be placed close to the LM2598 using short leads and short printed circuit traces. Because of their fast switching speed and low forward voltage drop, Schottky diodes provide the best performance and efficiency, and must be the first choice, especially in low output voltage applications. Ultra-fast recovery or high-efficiency rectifiers are also good choices, but some types with an abrupt turnoff characteristic may cause instability or EMI problems. Ultra-fast recovery diodes typically have reverse recovery times of 50 ns or less. Rectifiers such as the 1N4001 series must not be used because they are too slow.

9.2.2.2.6 Input Capacitor (C_{IN})

A low ESR aluminum or tantalum bypass capacitor is required between the input pin and ground to prevent large voltage transients from appearing at the input. In addition, the RMS current rating of the input capacitor must be selected to be at least ½ the DC load current. The capacitor manufacturers data sheet must be checked to assure that this current rating is not exceeded. Figure 31 shows typical RMS current ratings for several different aluminum electrolytic capacitor values.

This capacitor must be located close to the IC using short leads and the voltage rating must be approximately 1.5 times the maximum input voltage.

If solid tantalum input capacitors are used, it is recomended that they be surge current tested by the manufacturer.

Use caution when using a high dielectric constant ceramic capacitor for input bypassing, because it may cause severe ringing at the V_{IN} pin.

The important parameters for the input capacitor are the input voltage rating and the RMS current rating. With a nominal input voltage of 28 V, an aluminum electrolytic aluminum electrolytic capacitor with a voltage rating greater than 42 V (1.5 × V_{IN}) is required. Because the the next higher capacitor voltage rating is 50 V, a 50-V capacitor must be used. The capacitor voltage rating of (1.5 × V_{IN}) is a conservative guideline, and can be modified somewhat if desired.

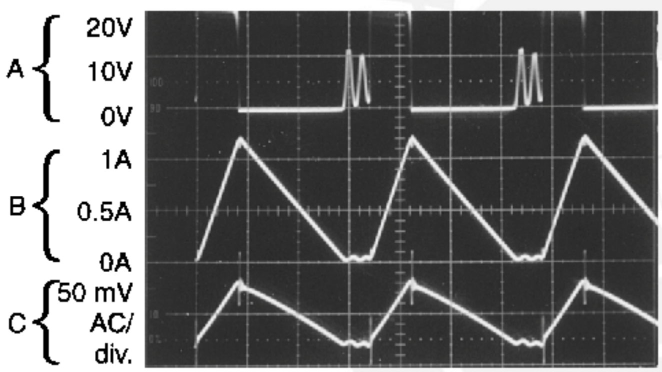
The RMS current rating requirement for the input capacitor of a buck regulator is approximately ½ the DC load current. In this example, with a 1-A load, a capacitor with a RMS current rating of at least 500 mA is required.

Figure 31 shows curves that can be used to select an appropriate input capacitor. From the curves, locate the 50-V line and note which capacitor values have RMS current ratings greater than 500 mA. Either a 100-µF or 120-µF, 50-V capacitor could be used.

For a through-hole design, a 120-µF, 50-V electrolytic capacitor (Panasonic HFQ series or Nichicon PL series or equivalent) would be adequate. Other types or other manufacturers' capacitors can be used provided the RMS ripple current ratings are adequate.

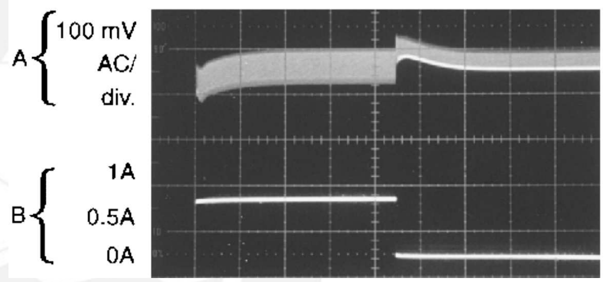
For surface-mount designs, solid tantalum capacitors can be used, but caution must be exercised with regard to the capacitor surge current rating (see *Input Capacitor (C_{IN})*). The TPS series available from AVX, and the 593D series from Sprague are both surge current tested.

9.2.2.3 Application Curves



Discontinuous Mode Switching Waveforms
V_{IN} = 20 V,V_{OUT} = 5 V, I_{LOAD} = 600 mA, L = 22 µH,
C_{OUT} = 220 µF,C_{OUT} ESR = 50 mΩ
A: Output Pin Voltage, 10 V/div.
B: Inductor Current 0.5 A/div.
C: Output Ripple Voltage, 50 mV/div.

Figure 46. Horizontal Time Base: 2 µs/div



Load Transient Response for Discontinuous Mode
V_{IN} = 20 V, V_{OUT} = 5 V, I_{LOAD} = 250 mA to 750 mA,
L = 22 µH, C_{OUT} = 220 µF, C_{OUT} ESR = 50 mΩ
A: Output Voltage, 100 mV/div. (AC)
B: 250-mA to 750-mA Load Pulse

Figure 47. Horizontal Time Base: 200 µs/div

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10 Power Supply Recommendations

The LM2598 is designed to operate from an input voltage supply up to 40 V. This input supply must be well regulated and able to withstand maximum input current and maintain a stable voltage.

11 Layout

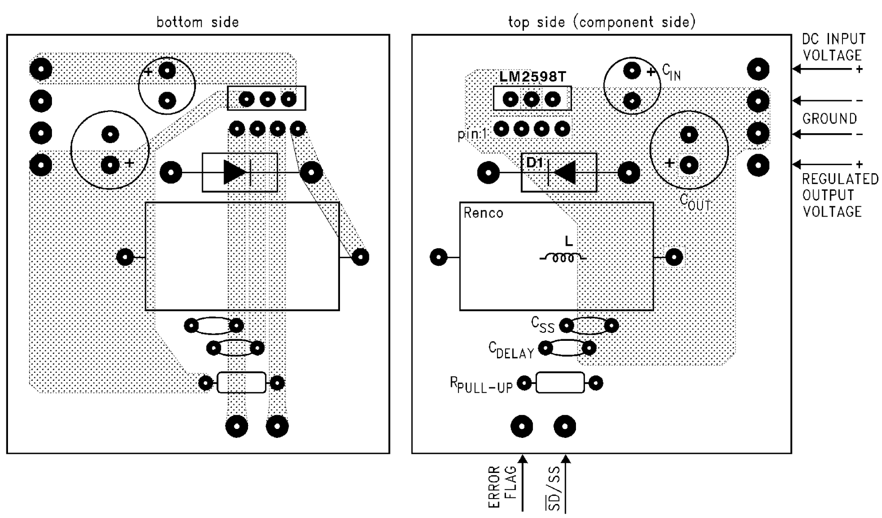
11.1 Layout Guidelines

As in any switching regulator, layout is very important. Rapidly switching currents associated with wiring inductance can generate voltage transients which can cause problems. For minimal inductance and ground loops, the wires indicated by heavy lines must be wide printed circuit traces and must be kept as short as possible. For best results, external components must be placed as close to the switcher IC as possible using ground plane construction or single point grounding.

If open core inductors are used, take special care regarding the location and positioning of this type of inductor. Allowing the inductor flux to intersect sensitive feedback, IC groundpath and C_{OUT} wiring can cause problems.

When using the adjustable version, special care must be taken as to the location of the feedback resistors and the associated wiring. Physically place both resistors near the IC, and route the wiring away from the inductor, especially an open core type of inductor (see *Open Core Inductors* for more information).

11.2 Layout Examples



C_{IN}—150-µF, 50-V Aluminum Electrolytic, Panasonic *HFQ series*

C_{OUT}—120-µF, 25-V Aluminum Electrolytic, Panasonic *HFQ series*

D1 — 3-A, 40-V Schottky Rectifier, 1N5822

L1 — 68-µH, L30, Renco, Through hole

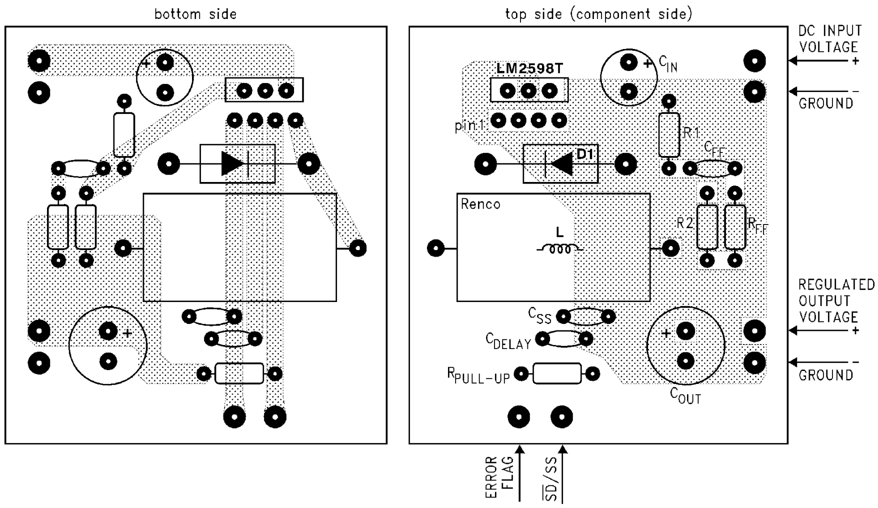
$R_{PULL-UP}$ — 10 kΩ

C_{DELAY} — 0.1 µF

$C_{\overline{SD}/SS}$ — 0.1 µF

Figure 48. Typical Through-Hole PCB Layout, Fixed Output (1x Size), Double-Sided, Through-Hole Plated

Layout Examples (continued)



C_{IN} — 150-µF, 50-V, Aluminum Electrolytic, Panasonic *HFQ series*

C_{OUT} — 120-µF, 25-V Aluminum Electrolytic, Panasonic *HFQ series*

D1 — 3-A, 40-V Schottky Rectifier, 1N5822

L1 — 68-µH, L30, Renco, Through hole

R1 — 1 kΩ, 1%

R2—Use formula in Design Procedure

C_{FF}—See *Feedforward Capacitor (C_{FF})*.

R_{FF}—See *Feedforward Capacitor (C_{FF})*.

$R_{PULL\text{-}UP}$—10 kΩ

C_{DELAY} — 0.1-µF

$C_{\overline{SD}/SS}$ — 0.1 µF

Figure 49. Typical Through-Hole PCB Layout, Adjustable Output (1x Size), Double-Sided, Through-Hole Plated

11.3 Thermal Considerations

The LM2598 is available in two packages: a 7-pin TO-220 (T) and a 7-pin surface mount DDPAK (S).

The TO-220 package can be used without a heat sink for ambient temperatures up to approximately 50°C (depending on the output voltage and load current). Figure 40 shows the LM2598T junction temperature rises above ambient temperature for different input and output voltages. The data for these curves was taken with the LM2598T (TO-220 package) operating as a switching regulator in an ambient temperature of 25°C (still air). These temperature rise numbers are all approximate and there are many factors that can affect these temperatures. Higher ambient temperatures require some heat sinking, either to the PCB or a small external heat sink.

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Thermal Considerations (continued)

The DDPAK surface mount package tab is designed to be soldered to the copper on a printed-circuit board (PCB). The copper and the board are the heat sink for this package and the other heat producing components, such as the catch diode and inductor. The PCB copper area that the package is soldered to must be at least 0.4 in^2, and ideally must have 2 or more square inches of 2 oz. (0.0028) in) copper. Additional copper area improves the thermal characteristics, but with copper areas greater than approximately 3 in^2, only small improvements in heat dissipation are realized. If further thermal improvements are required, TI recommends double-sided or multilayer PCB with large copper areas.

Figure 41 shows the LM2598S (DDPAK package) junction temperature rise above ambient temperature with a 1-A load for various input and output voltages. This data was taken with the circuit operating as a buck switching regulator with all components mounted on a PCB to simulate the junction temperature under actual operating conditions. This curve can be used for a quick check for the approximate junction temperature for various conditions, but be aware that there are many factors that can affect the junction temperature.

For the best thermal performance, wide copper traces and generous amounts of PCB copper must be used in the board layout. (One exception to this is the output (switch) pin, which must not have large areas of copper.) Large areas of copper provide the best transfer of heat (lower thermal resistance) to the surrounding air, and moving air lowers the thermal resistance even further.

Package thermal resistance and junction temperature rise numbers are all approximate, and there are many factors that affect these numbers. Some of these factors include board size, shape, thickness, position, location, and even board temperature. Other factors are trace width, total printed-circuit copper area, copper thickness, single- or double-sided multilayer board, and the amount of solder on the board. The effectiveness of the PCB to dissipate heat also depends on the size, quantity, and spacing of other components on the board, as well as whether the surrounding air is still or moving. Furthermore, some of these components such as the catch diode adds heat to the PCB and the heat can vary as the input voltage changes. For the inductor, depending on the physical size, type of core material, and the DC resistance, it could either act as a heat sink taking heat away from the board, or it could add heat to the board.

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12 Device and Documentation Support

12.1 Community Resources

The following links connect to TI community resources. Linked contents are provided "AS IS" by the respective contributors. They do not constitute TI specifications and do not necessarily reflect TI's views; see TI's Terms of Use.

TI E2E™ Online Community ***TI's Engineer-to-Engineer (E2E) Community.*** Created to foster collaboration among engineers. At e2e.ti.com, you can ask questions, share knowledge, explore ideas and help solve problems with fellow engineers.

Design Support ***TI's Design Support*** Quickly find helpful E2E forums along with design support tools and contact information for technical support.

12.2 Trademarks

E2E is a trademark of Texas Instruments.
SIMPLE SWITCHER is a registered trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

12.3 Electrostatic Discharge Caution

These devices have limited built-in ESD protection. The leads should be shorted together or the device placed in conductive foam during storage or handling to prevent electrostatic damage to the MOS gates.

12.4 Glossary

SLYZ022 — *TI Glossary*.

This glossary lists and explains terms, acronyms, and definitions.

13 Mechanical, Packaging, and Orderable Information

The following pages include mechanical, packaging, and orderable information. This information is the most current data available for the designated devices. This data is subject to change without notice and revision of this document. For browser-based versions of this data sheet, refer to the left-hand navigation.

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PACKAGING INFORMATION

Orderable Device	Status (1)	Package Type	Package Drawing	Pins	Package Qty	Eco Plan (2)	Lead/Ball Finish (6)	MSL Peak Temp (3)	Op Temp (°C)	Device Marking (4/5)	Samples
LM2598S-12/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	45	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -12 P+	Samples
LM2598S-3.3/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	45	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -3.3 P+	Samples
LM2598S-5.0	NRND	DDPAK/ TO-263	KTW	7	45	TBD	Call TI	Call TI	-40 to 125	LM2598S -5.0 P+	
LM2598S-5.0/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	45	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -5.0 P+	Samples
LM2598S-ADJ/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	45	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -ADJ P+	Samples
LM2598SX-12/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	500	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -12 P+	Samples
LM2598SX-3.3/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	500	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -3.3 P+	Samples
LM2598SX-5.0	NRND	DDPAK/ TO-263	KTW	7	500	TBD	Call TI	Call TI	-40 to 125	LM2598S -5.0 P+	
LM2598SX-5.0/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	500	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -5.0 P+	Samples
LM2598SX-ADJ/NOPB	ACTIVE	DDPAK/ TO-263	KTW	7	500	Pb-Free (RoHS Exempt)	CU SN	Level-3-245C-168 HR	-40 to 125	LM2598S -ADJ P+	Samples
LM2598T-12/NOPB	ACTIVE	TO-220	NDZ	7	45	Green (RoHS & no Sb/Br)	CU SN	Level-1-NA-UNLIM	-40 to 125	LM2598T -12 P+	Samples
LM2598T-3.3/NOPB	ACTIVE	TO-220	NDZ	7	45	Green (RoHS & no Sb/Br)	CU SN	Level-1-NA-UNLIM	-40 to 125	LM2598T -3.3 P+	Samples
LM2598T-5.0/NOPB	ACTIVE	TO-220	NDZ	7	45	Green (RoHS & no Sb/Br)	CU SN	Level-1-NA-UNLIM	-40 to 125	LM2598T -5.0 P+	Samples
LM2598T-ADJ/NOPB	ACTIVE	TO-220	NDZ	7	45	Green (RoHS & no Sb/Br)	CU SN	Level-1-NA-UNLIM	-40 to 125	LM2598T -ADJ P+	Samples

(1) The marketing status values are defined as follows:
ACTIVE: Product device recommended for new designs.
LIFEBUY: TI has announced that the device will be discontinued, and a lifetime-buy period is in effect.
NRND: Not recommended for new designs. Device is in production to support existing customers, but TI does not recommend using this part in a new design.
PREVIEW: Device has been announced but is not in production. Samples may or may not be available.
OBSOLETE: TI has discontinued the production of the device.

[2] Eco Plan - The planned eco-friendly classification: Pb-Free (RoHS), Pb-Free (RoHS Exempt), or Green (RoHS & no Sb/Br) - please check http://www.ti.com/productcontent for the latest availability information and additional product content details.
TBD: The Pb-Free/Green conversion plan has not been defined.
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Pb-Free (RoHS Exempt): This component has a RoHS exemption for either 1) lead-based flip-chip solder bumps used between the die and package, or 2) lead-based die adhesive used between the die and leadframe. The component is otherwise considered Pb-Free (RoHS compatible) as defined above.
Green (RoHS & no Sb/Br): TI defines "Green" to mean Pb-Free (RoHS compatible), and free of Bromine (Br) and Antimony (Sb) based flame retardants (Br or Sb do not exceed 0.1% by weight in homogeneous material)

[3] MSL, Peak Temp. - The Moisture Sensitivity Level rating according to the JEDEC industry standard classifications, and peak solder temperature.

[4] There may be additional marking, which relates to the logo, the lot trace code information, or the environmental category on the device.

[5] Multiple Device Markings will be inside parentheses. Only one Device Marking contained in parentheses and separated by a "~" will appear on a device. If a line is indented then it is a continuation of the previous line and the two combined represent the entire Device Marking for that device.

[6] Lead/Ball Finish - Orderable Devices may have multiple material finish options. Finish options are separated by a vertical ruled line. Lead/Ball Finish values may wrap to two lines if the finish value exceeds the maximum column width.

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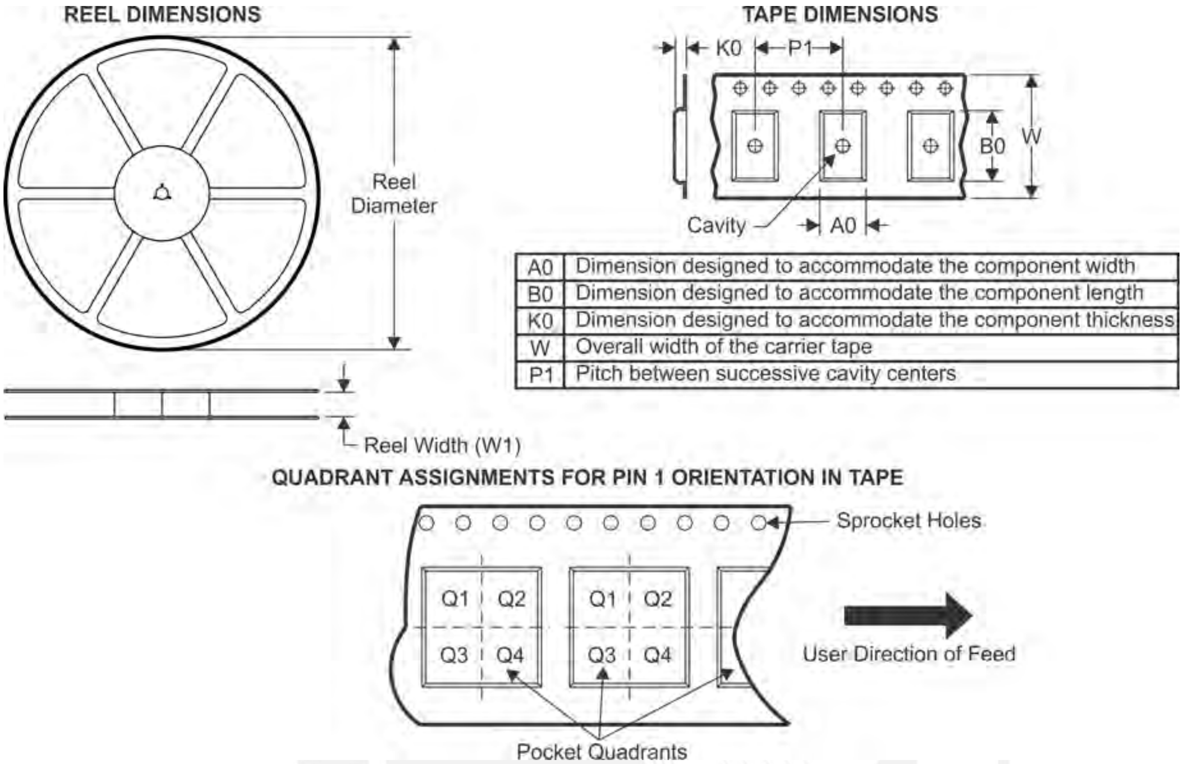
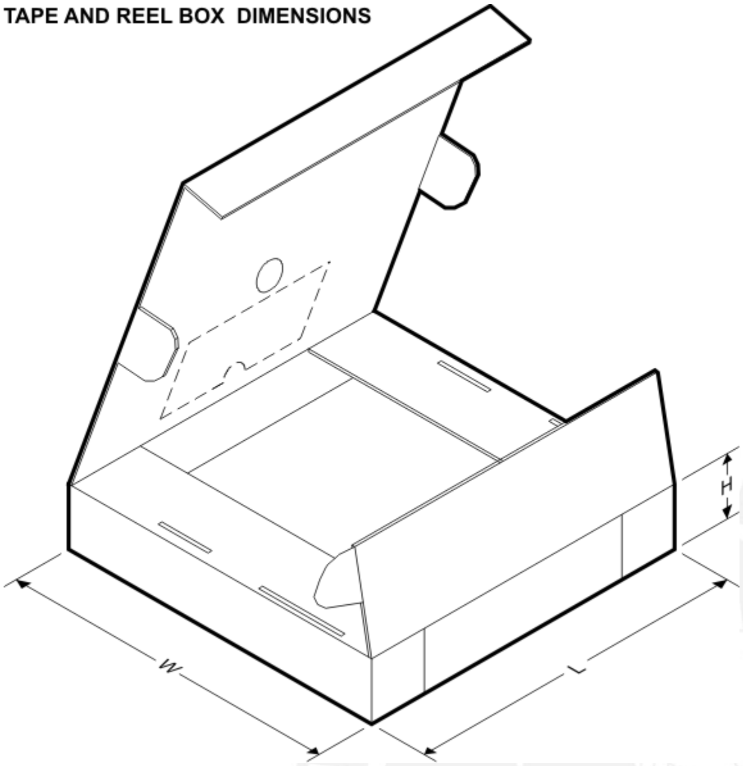


*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Reel Diameter (mm)	Reel Width W1 (mm)	A0 (mm)	B0 (mm)	K0 (mm)	P1 (mm)	W (mm)	Pin1 Quadrant
LM2598SX-12/NOPB	DDPAK/ TO-263	KTW	7	500	330.0	24.4	10.75	14.85	5.0	16.0	24.0	Q2
LM2598SX-3.3/NOPB	DDPAK/ TO-263	KTW	7	500	330.0	24.4	10.75	14.85	5.0	16.0	24.0	Q2
LM2598SX-5.0	DDPAK/ TO-263	KTW	7	500	330.0	24.4	10.75	14.85	5.0	16.0	24.0	Q2
LM2598SX-5.0/NOPB	DDPAK/ TO-263	KTW	7	500	330.0	24.4	10.75	14.85	5.0	16.0	24.0	Q2
LM2598SX-ADJ/NOPB	DDPAK/ TO-263	KTW	7	500	330.0	24.4	10.75	14.85	5.0	16.0	24.0	Q2

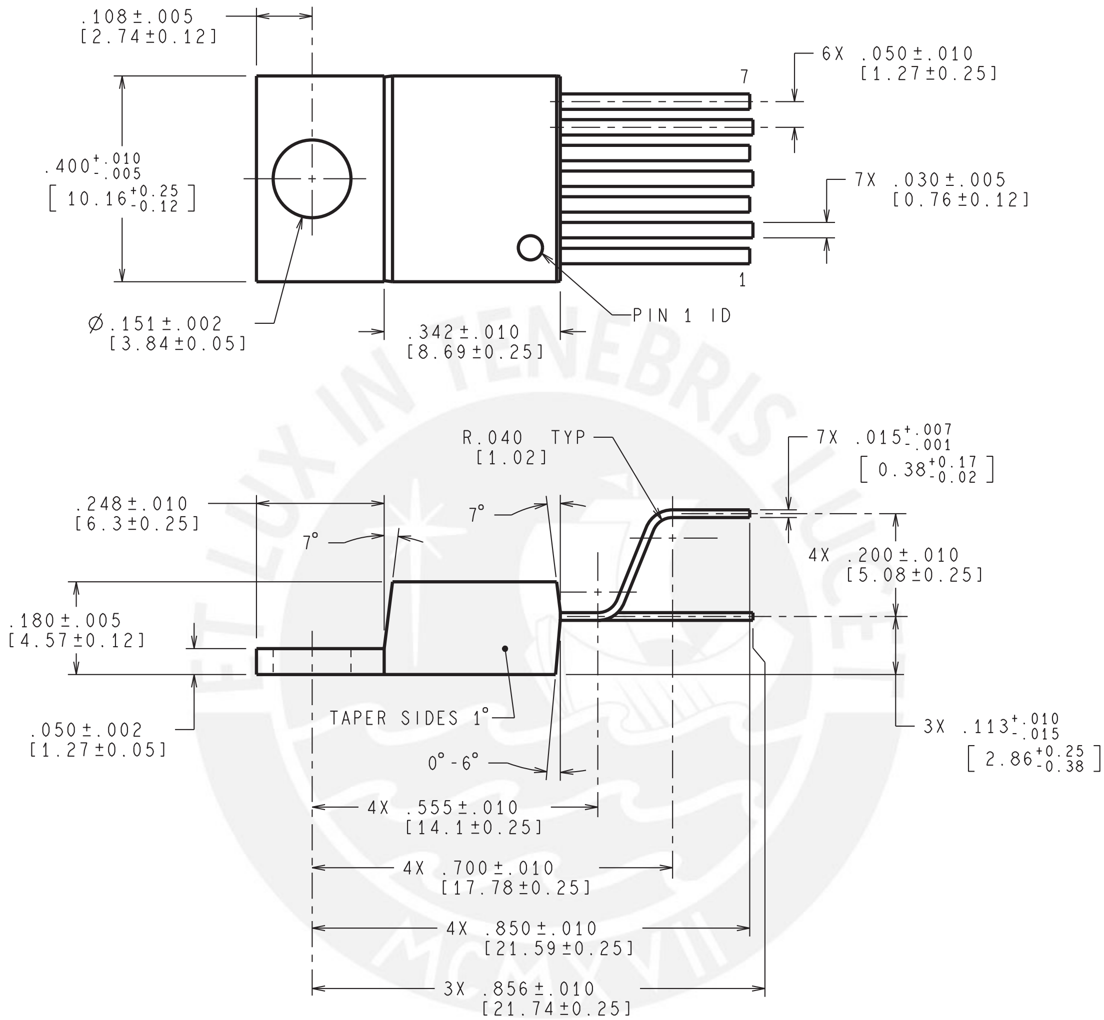
TAPE AND REEL BOX DIMENSIONS



*All dimensions are nominal

Device	Package Type	Package Drawing	Pins	SPQ	Length (mm)	Width (mm)	Height (mm)
LM2598SX-12/NOPB	DDPAK/TO-263	KTW	7	500	367.0	367.0	45.0
LM2598SX-3.3/NOPB	DDPAK/TO-263	KTW	7	500	367.0	367.0	45.0
LM2598SX-5.0	DDPAK/TO-263	KTW	7	500	367.0	367.0	45.0
LM2598SX-5.0/NOPB	DDPAK/TO-263	KTW	7	500	367.0	367.0	45.0
LM2598SX-ADJ/NOPB	DDPAK/TO-263	KTW	7	500	367.0	367.0	45.0

NDZ0007B



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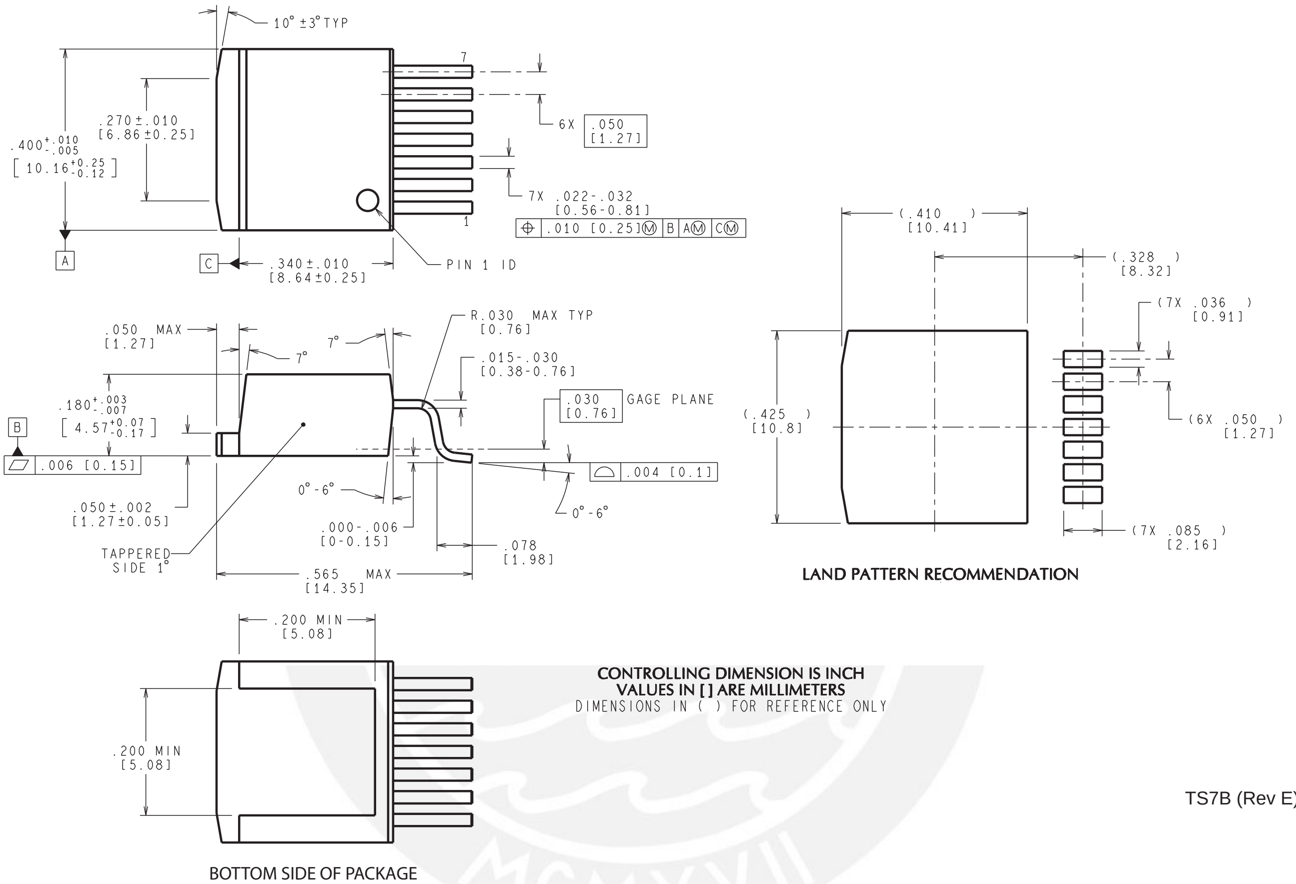

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2N7000G

Small Signal MOSFET
200 mAmps, 60 Volts
N−Channel TO−92

Features

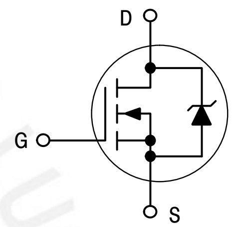
- AEC Qualified
- PPAP Capable
- This is a Pb−Free Device*

ON Semiconductor®

http://onsemi.com

200 mAMPS
60 VOLTS
$R_{DS(on)}$ = 5 Ω

N−Channel



MAXIMUM RATINGS

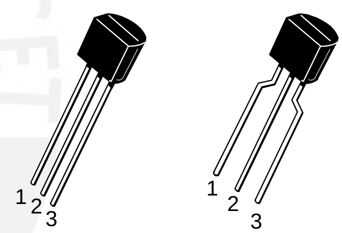
Rating	Symbol	Value	Unit
Drain Source Voltage	V_{DSS}	60	Vdc
Drain−Gate Voltage (R_{GS} = 1.0 MΩ)	V_{DGR}	60	Vdc
Gate−Source Voltage − Continuous − Non−repetitive ($t_p \le 50$ μs)	V_{GS} V_{GSM}	±20 ±40	Vdc Vpk
Drain Current − Continuous − Pulsed	I_D I_{DM}	200 500	mAdc
Total Power Dissipation @ T_C = 25°C Derate above 25°C	P_D	350 2.8	mW mW/°C
Operating and Storage Temperature Range	T_J, T_{stg}	−55 to +150	°C

THERMAL CHARACTERISTICS

Characteristic	Symbol	Max	Unit
Thermal Resistance, Junction−to−Ambient	$R_{\theta JA}$	357	°C/W
Maximum Lead Temperature for Soldering Purposes, 1/16″ from case for 10 seconds	T_L	300	°C

Stresses exceeding Maximum Ratings may damage the device. Maximum Ratings are stress ratings only. Functional operation above the Recommended Operating Conditions is not implied. Extended exposure to stresses above the Recommended Operating Conditions may affect device reliability.

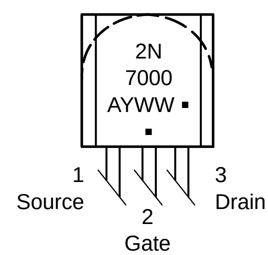
TO−92
CASE 29
STYLE 22



STRAIGHT LEAD
BULK PACK

BENT LEAD
TAPE & REEL
AMMO PACK

MARKING DIAGRAM AND PIN ASSIGNMENT



A = Assembly Location
Y = Year
WW = Work Week
▪ = Pb−Free Package
(Note: Microdot may be in either location)

ORDERING INFORMATION

See detailed ordering and shipping information in the package dimensions section on page 2 of this data sheet.

*For additional information on our Pb−Free strategy and soldering details, please download the ON Semiconductor Soldering and Mounting Techniques Reference Manual, SOLDERRM/D.

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April, 2011 − Rev. 8
Publication Order Number:
2N7000/D

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted)

Characteristic	Symbol	Min	Max	Unit
OFF CHARACTERISTICS				
Drain−Source Breakdown Voltage (V_{GS} = 0, I_D = 10 μAdc)	$V_{(BR)DSS}$	60	–	Vdc
Zero Gate Voltage Drain Current (V_{DS} = 48 Vdc, V_{GS} = 0) (V_{DS} = 48 Vdc, V_{GS} = 0, T_J = 125°C)	I_{DSS}	– –	1.0 1.0	μAdc mAdc
Gate−Body Leakage Current, Forward (V_{GSF} = 15 Vdc, V_{DS} = 0)	I_{GSSF}	–	−10	nAdc
ON CHARACTERISTICS (Note 1)				
Gate Threshold Voltage (V_{DS} = V_{GS}, I_D = 1.0 mAdc)	$V_{GS(th)}$	0.8	3.0	Vdc
Static Drain−Source On−Resistance (V_{GS} = 10 Vdc, I_D = 0.5 Adc) (V_{GS} = 4.5 Vdc, I_D = 75 mAdc)	$r_{DS(on)}$	– –	5.0 6.0	Ω
Drain−Source On−Voltage (V_{GS} = 10 Vdc, I_D = 0.5 Adc) (V_{GS} = 4.5 Vdc, I_D = 75 mAdc)	$V_{DS(on)}$	– –	2.5 0.45	Vdc
On−State Drain Current (V_{GS} = 4.5 Vdc, V_{DS} = 10 Vdc)	$I_{d(on)}$	75	–	mAdc
Forward Transconductance (V_{DS} = 10 Vdc, I_D = 200 mAdc)	g_{fs}	100	–	μmhos
DYNAMIC CHARACTERISTICS				
Input Capacitance (V_{DS} = 25 V, V_{GS} = 0, f = 1.0 MHz)	C_{iss}	–	60	pF
Output Capacitance (V_{DS} = 25 V, V_{GS} = 0, f = 1.0 MHz)	C_{oss}	–	25	
Reverse Transfer Capacitance (V_{DS} = 25 V, V_{GS} = 0, f = 1.0 MHz)	C_{rss}	–	5.0	
SWITCHING CHARACTERISTICS (Note 1)				
Turn−On Delay Time (V_{DD} = 15 V, I_D = 500 mA, R_G = 25 Ω, R_L = 30 Ω, V_{gen} = 10 V)	t_{on}	–	10	ns
Turn−Off Delay Time (V_{DD} = 15 V, I_D = 500 mA, R_G = 25 Ω, R_L = 30 Ω, V_{gen} = 10 V)	t_{off}	–	10	

1. Pulse Test: Pulse Width ≤ 300 μs, Duty Cycle ≤ 2.0%.

ORDERING INFORMATION

Device	Package	Shipping†
2N7000G	TO−92 (Pb−Free)	1000 Units / Bulk
2N7000RLRAG	TO−92 (Pb−Free)	2000 Tape & Reel

†For information on tape and reel specifications, including part orientation and tape sizes, please refer to our Tape and Reel Packaging Specifications Brochure, BRD8011/D.

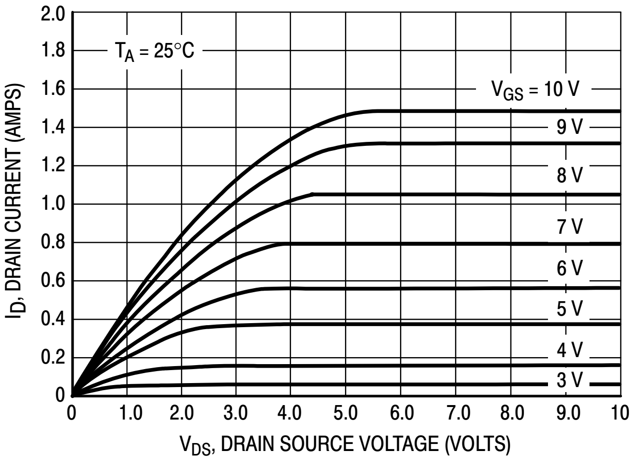


Figure 1. Ohmic Region

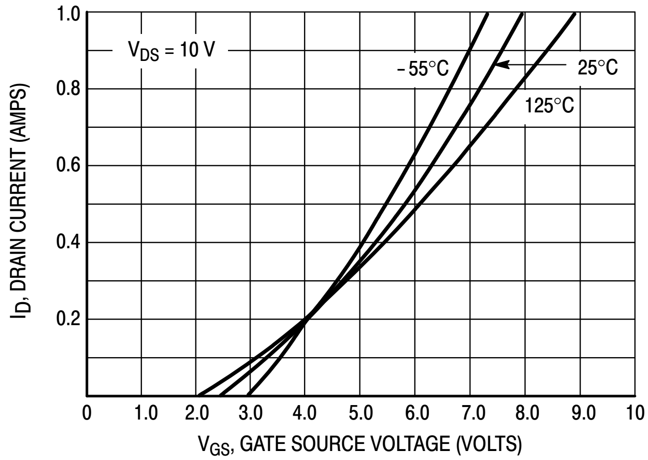


Figure 2. Transfer Characteristics

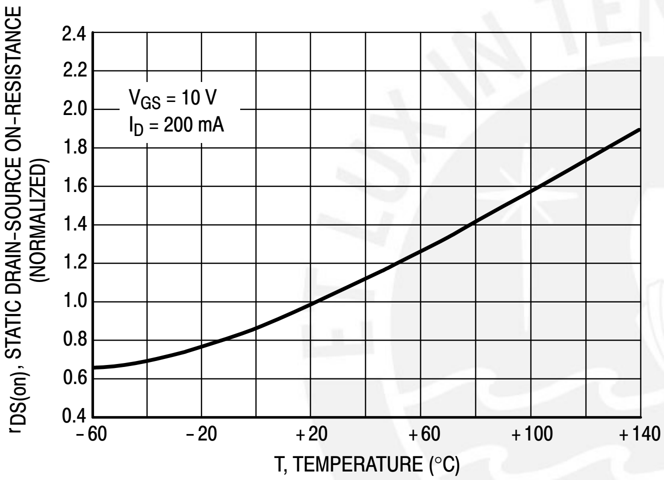


Figure 3. Temperature versus Static Drain−Source On−Resistance

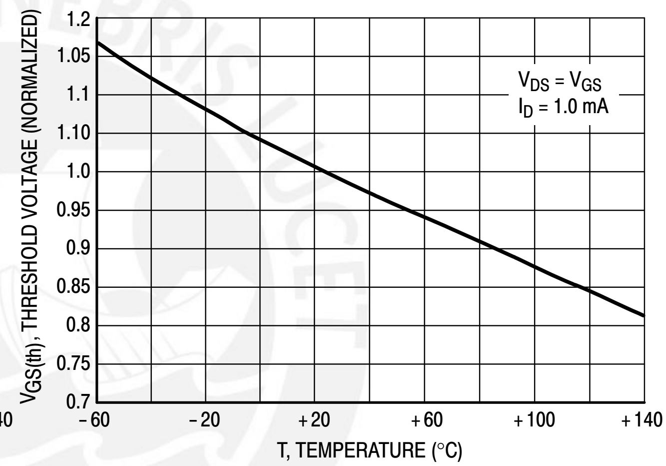
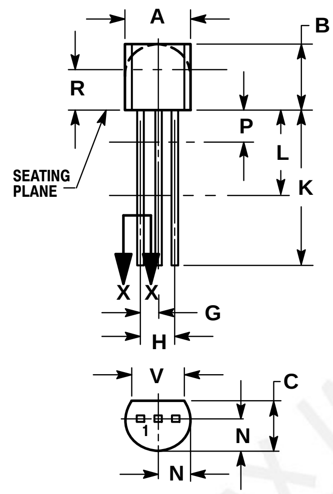


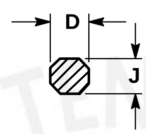
Figure 4. Temperature versus Gate Threshold Voltage

PACKAGE DIMENSIONS

TO−92 (TO−226)
CASE 29−11
ISSUE AM



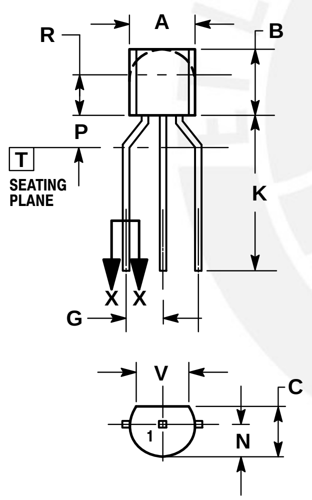
STRAIGHT LEAD
BULK PACK



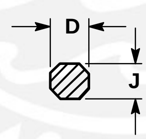
SECTION X−X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ANSI Y14.5M, 1982.
2. CONTROLLING DIMENSION: INCH.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	INCHES		MILLIMETERS	
DIM	MIN	MAX	MIN	MAX
A	0.175	0.205	4.45	5.20
B	0.170	0.210	4.32	5.33
C	0.125	0.165	3.18	4.19
D	0.016	0.021	0.407	0.533
G	0.045	0.055	1.15	1.39
H	0.095	0.105	2.42	2.66
J	0.015	0.020	0.39	0.50
K	0.500	---	12.70	---
L	0.250	---	6.35	---
N	0.080	0.105	2.04	2.66
P	---	0.100	---	2.54
R	0.115	---	2.93	---
V	0.135	---	3.43	---



BENT LEAD
TAPE & REEL
AMMO PACK



SECTION X−X

NOTES:
1. DIMENSIONING AND TOLERANCING PER ASME Y14.5M, 1994.
2. CONTROLLING DIMENSION: MILLIMETERS.
3. CONTOUR OF PACKAGE BEYOND DIMENSION R IS UNCONTROLLED.
4. LEAD DIMENSION IS UNCONTROLLED IN P AND BEYOND DIMENSION K MINIMUM.

	MILLIMETERS	
DIM	MIN	MAX
A	4.45	5.20
B	4.32	5.33
C	3.18	4.19
D	0.40	0.54
G	2.40	2.80
J	0.39	0.50
K	12.70	---
N	2.04	2.66
P	1.50	4.00
R	2.93	---
V	3.43	---

STYLE 22:
PIN 1. SOURCE
2. GATE
3. DRAIN

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