Monolithic Power Systems

General Description

The MP1591 is a high voltage step down converter ideal for cigarette lighter battery chargers. It's wide 6.5 to 32V (Max = 36V) input voltage range covers the automotive battery requirements. It achieves 2A continuous output for quick charge capability.

Current mode operation provides fast transient response and eases loop stabilization. Fault protection includes cycle-by-cycle current limiting and thermal shutdown. In shutdown mode the converter draws only 20µA of supply current.

The MP1591 requires a minimum number of readily available external components to complete a 2A step-down DC/DC converter solution.

Ordering Information

Part Number ∗	Package	Temperature
MP1591DS	SOIC8	-40 to + 85C
MP1591DN	SOIC8 w/ Heat Slug	-40 to + 85C
EV0042	MP1591DN Evaluation Board	

∗ For Tape & Reel use suffix - Z (e.g. MP1591DS-Z)

Features

- Wide 6.5 to 32V Operating Input Range
  - 36V Maximum
- 2A Output Current
- 120mΩ Internal Power MOSFET Switch
- Stable with Low ESR Output Ceramic Capacitors
- Up to 95% Efficiency
- 20µA Shutdown Mode
- Fixed 300KHz frequency
- Thermal Shutdown
- Cycle-by-Cycle Over Current Protection
- Output Adjustable From 1.22 to 21V
- Under Voltage Lockout
- Reference Voltage Output
- Available in 8 pin SOIC Package
- **Evaluation Board Available**

Applications

- Cigarette Lighter PDA and Cell Phone Battery Chargers
- Distributed Power Systems
- Automotive Aftermarket Electronics

Figure 1: Typical Application
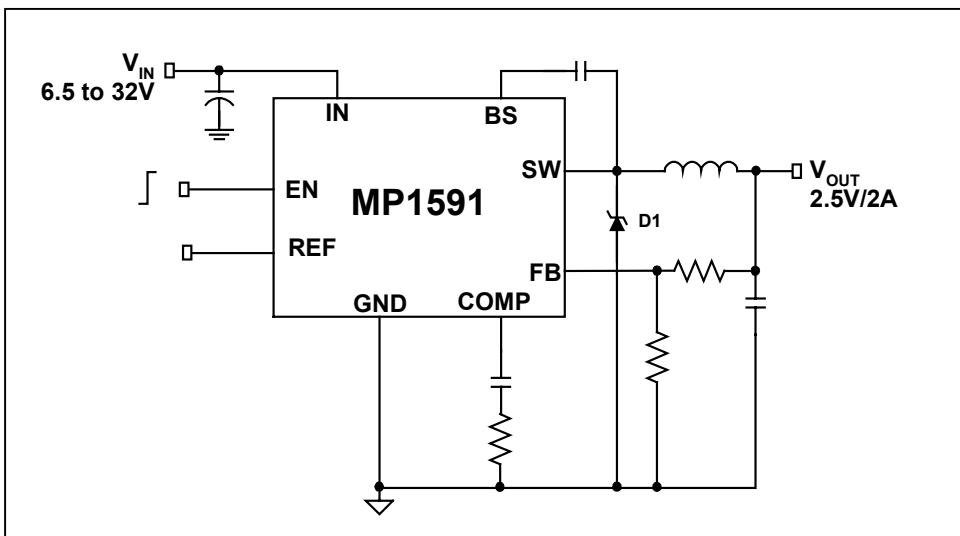
Absolute Maximum Ratings (Note 1)

IN Supply Voltage	-0.3V to 36V
SW Voltage	-1V to V_{IN}+0.3V
BS Voltage	V_{SW}-0.3V to V_{SW}+6V
All Other Pins	-0.3V to 6V
Junction Temperature	125°C
Lead Temperature	260°C
Storage Temperature	-65°C to 150°C

Recommended Operating Conditions (Note 2)

Input Voltage	6.5V to 32V
Operating Temperature	-40°C to +85°C

Package Thermal Characteristics (Note 3)

Thermal Resistance, θ_{JA}	90°C/W
Thermal Resistance, θ_{JA} (w/ Heat Slug)	50°C/W

Electrical Characteristics (Unless otherwise specified V_{IN}=12V, T_A=25°C)

Parameters	Condition	Min	Typ	Max	Units
Shutdown Supply Current	V_{EN} = 0V		20	35	µA
Supply current	V_{EN} = 5V; V_{FB} =1.4V		1.0	1.2	mA
Feedback Voltage	6.5V ≤ V_{IN} ≤ 32V; V_{COMP} < 2V	1.198	1.222	1.246	V
Error Amplifier Voltage Gain			400		V/V
Error Amplifier Transconductance	ΔI_C = ±10 µA	400	700	1000	µS
High-Side Switch On Resistance (Note 4)			120		mΩ
Low-Side Switch On Resistance (Note 4)			8.5		Ω
High-Side Switch Leakage Current	V_{EN}=0V; V_{SW}=0V		0	10	µA
Current Limit		2.3	4.2	5.9	A
Current Sense to COMP Transconductance			3.5		A/V
Oscillation Frequency		268	300	342	KHz
Short Circuit Oscillation Frequency	V_{FB} = 0V		43		KHz
Maximum Duty Cycle (Note 4)	V_{FB} = 1.0V		90		%
Minimum Duty Cycle (Note 4)	V_{FB} = 1.5V			0	%
EN Threshold Voltage		0.8	1.2	1.6	V
Enable Pull Up Current	V_{EN} = 0V		1.8		µA
Under Voltage Lockout Threshold	V_{IN} Rising	2.4	2.55	2.7	V
Under Voltage Lockout Threshold Hysteresis			250		mV
Thermal Shutdown (Note 4)			160		°C
REF Voltage	I_{REF} = 0		5.0		V
REF Load Regulation (Note 4)	ΔI_{REF} = 0 to 1mA		100		mV
REF Line Regulation (Note 4)	I_{REF} = 100µA, V_{IN} = 6.5 to 32V		30		mV

Notes:

1. Exceeding these ratings may damage the device.
2. The device is not guaranteed to function outside its operating rating.
3. Measured on approximately 1" square of 1 oz. copper.
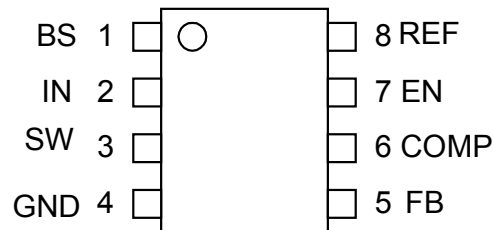4. Guaranteed by design; not production tested

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Pin Description

```
        BS  1  ┌──○──┐  8 REF
        IN  2  │     │  7 EN
        SW  3  │     │  6 COMP
       GND  4  └─────┘  5 FB
```

Table 1: Pin Designators

Pin#	Name	Description
1	BS	High-Side Gate Drive Boost Input. BS supplies the drive for the high-side N-channel MOSFET switch. Connect a 10nF or greater capacitor from SW to BS to power the high-side switch.
2	IN	Power Input. IN supplies the power to the IC, as well as the step-down converter switches. Drive IN with a 6.5V to 32V power source. Bypass IN to GND with a suitably large capacitor to eliminate noise on the input to the IC. See *Input Capacitor*.
3	SW	Power Switching Output. SW is the switching node that supplies power to the output. Connect the output LC filter from SW to the output load. Note that a capacitor is required from SW to BS to power the high-side switch.
4	GND	Ground
5	FB	Feedback Input. FB senses the output voltage to regulate that voltage. Drive FB with a resistive voltage divider from the output voltage. The feedback threshold is 1.222V. See *Setting the Output Voltage*.
6	COMP	Compensation Node. COMP is used to compensate the regulation control loop. Connect a series RC network from COMP to GND to compensate the regulation control loop. In some cases, an additional capacitor from COMP to GND is required. See *Compensation*
7	EN	Enable Input. EN is a digital input that turns the regulator on or off. Drive EN high to turn on the regulator, drive EN low to turn it off. For automatic startup, leave EN unconnected.
8	REF	Reference Output. REF is the 5V reference voltage output. REF can supply up to 1mA to external circuitry. If used bypass REF to GND with 10nF or greater capacitor. Leave REF unconnected if not used.

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Figure 2: Functional Block
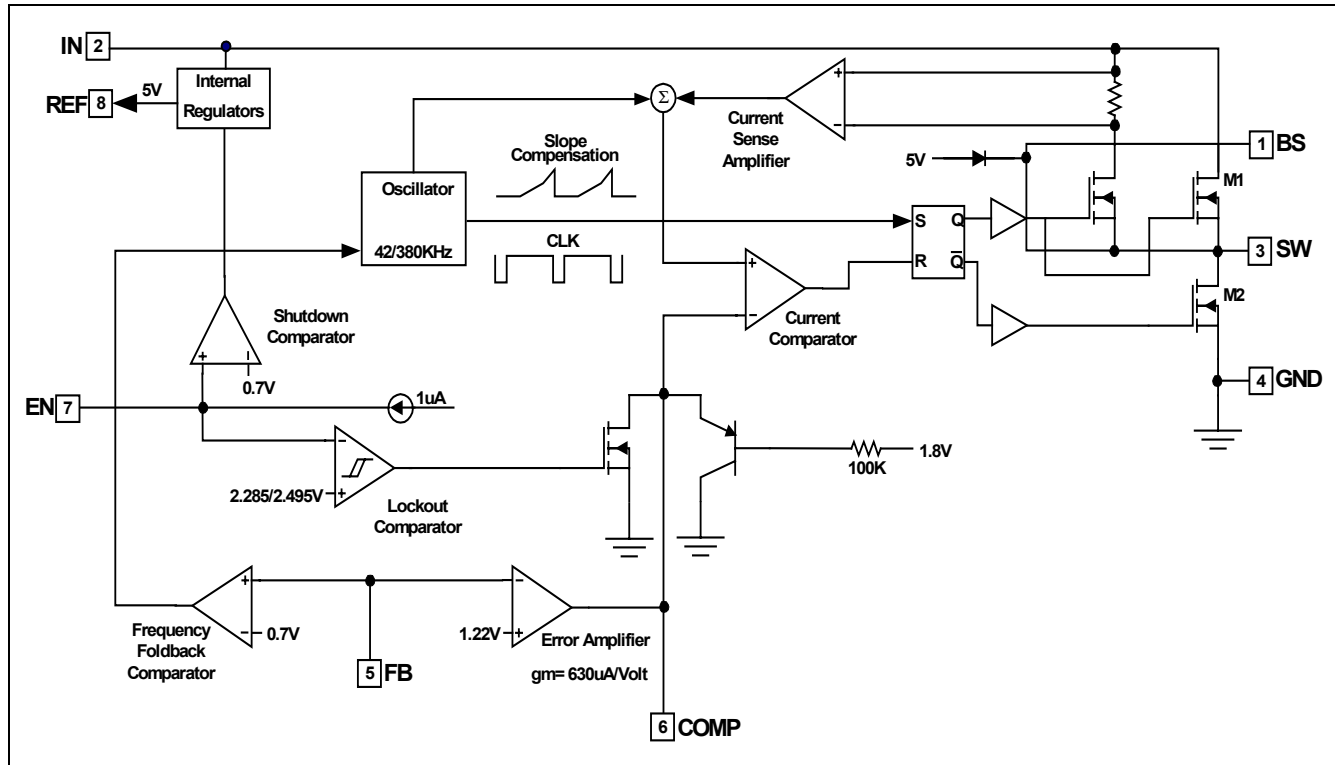
Functional Description

The MP1591 is a current mode step-down regulator. It regulates input voltages from 6.5V to 32V down to an output voltage as low as 1.222V, and is able to supply up to 2A of load current.

The MP1591 uses current-mode control to regulate the output voltage. The output voltage is measured at FB through a resistive voltage divider and amplified through the internal error amplifier. The output current of the transconductance error amplifier is presented at COMP where a network compensates the regulation control system.

The voltage at COMP is compared to the switch current measured internally to control the output voltage. The converter uses an internal N-Channel MOSFET switch to step-down the input voltage to the regulated output voltage. Since the MOSFET requires a gate voltage greater than the input voltage, a boost capacitor connected between SW and BS drives the gate. The capacitor is internally charged while SW is low. An internal 10Ω switch from SW to GND is used to insure that SW is pulled to GND, when the switch is off, to fully charge the BS capacitor.

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Setting the Output Voltage

The output voltage is set using a resistive voltage divider from the output voltage to FB. The voltage divider divides the output voltage down by the ratio:

$$V_{FB} = V_{OUT} * R2 / (R1 + R2)$$

Thus the output voltage is:

$$V_{OUT} = 1.222 * (R1 + R2) / R2$$

A typical value for R2 can be as high as 100KΩ, but 10KΩ is recommended.

Using that value, R1 is determined by:

$$R1 \approx= 8.18 * (V_{OUT} - 1.222) \text{ K}\Omega$$

For example, for a 3.3V output voltage, R2 is 10KΩ, and R1 is 17KΩ.

Inductor (L1)

The inductor is required to supply constant current to the output load while being driven by the switched input voltage. A larger value inductor results in less ripple current that results in lower output ripple voltage. However, the larger value inductor has a larger physical size, higher series resistance, and/or lower saturation current. Choose an inductor that does not saturate under the worst-case load conditions. A good rule to use, for determining the inductance, is to allow the peak-to-peak ripple current in the inductor to be approximately 30% of the maximum load current. Also, make sure that the peak inductor current (the load current plus half the peak-to-peak inductor ripple current) is below the 2.3A minimum current limit.

The inductance value can be calculated by the equation:

$$L1 = (V_{OUT}) * (V_{IN}-V_{OUT}) / (V_{IN} * f * \Delta I)$$

Where V_{OUT} is the output voltage, V_{IN} is the input voltage, f is the switching frequency, and ΔI is the peak-to-peak inductor ripple current. Table 2 lists a number of suitable inductors from various manufacturers.

Table 2: Inductor Selection Guide

Vendor/ Model	Core Type	Core Material	Package Dimensions (mm)		
			W	L	H
Sumida					
CR75	Open	Ferrite	7.0	7.8	5.5
CDH74	Open	Ferrite	7.3	8.0	5.2
CDRH5D28	Shielded	Ferrite	5.5	5.7	5.5
CDRH5D28	Shielded	Ferrite	5.5	5.7	5.5
CDRH6D28	Shielded	Ferrite	6.7	6.7	3.0
CDRH104R	Shielded	Ferrite	10.1	10.0	3.0
Toko					
D53LC Type A	Shielded	Ferrite	5.0	5.0	3.0
D75C	Shielded	Ferrite	7.6	7.6	5.1
D104C	Shielded	Ferrite	10.0	10.0	4.3
D10FL	Open	Ferrite	9.7	11.5	4.0
Coilcraft					
DO3308	Open	Ferrite	9.4	13.0	3.0
DO3316	Open	Ferrite	9.4	13.0	5.1

Input Capacitor (C1)

The input current to the step-down converter is discontinuous, and so a capacitor is required to supply the AC current to the step-down converter while maintaining the DC input voltage. A low ESR capacitor is required to keep the noise at the IC to a minimum. Ceramic capacitors are preferred, but tantalum or low ESR electrolytic capacitors may also suffice.

The input capacitor value should be greater than 10µF. The capacitor can be electrolytic, tantalum or ceramic. However since it absorbs the input switching current it requires an adequate ripple current rating. Its RMS current rating should be greater than approximately 1/2 of the DC load current.

For insuring stable operation C1 should be placed as close to the IC as possible. Alternately a smaller high quality ceramic 0.1µF capacitor may be placed closer to the IC and a larger capacitor placed further away. If using this technique, it is recommended that the larger capacitor be a tantalum or electrolytic type. All ceramic capacitors should be placed close to the MP1591.

Output Capacitor (C5)

The output capacitor is required to maintain the DC output voltage. Low ESR capacitors are preferred to keep the output voltage ripple low. The characteristics of the output capacitor also affect the stability of the regulation control system. Ceramic, tantalum, or low ESR electrolytic capacitors are recommended. In the case of ceramic capacitors, the impedance at the switching frequency is dominated by the capacitance, and so the output voltage ripple is mostly independent of the ESR. The output voltage ripple is estimated to be:

$$V_{RIPPLE} \sim= 1.4 * V_{IN} * (f_{LC}/f_{SW})^2$$

Where V_{RIPPLE} is the output ripple voltage, V_{IN} is the input voltage, f_{LC} is the resonant frequency of the LC filter, f_{SW} is the switching frequency.

In the case of tantalum or low-ESR electrolytic capacitors, the ESR dominates the impedance at the switching frequency, and so the output ripple is calculated as:

$$V_{RIPPLE} \sim= \Delta I * R_{ESR}$$

Where V_{RIPPLE} is the output voltage ripple, ΔI is the inductor ripple current, and R_{ESR} is the equivalent series resistance of the output capacitors.

Output Rectifier Diode (D1)

The output rectifier diode supplies the current to the inductor when the high-side switch is off. To reduce losses due to the diode forward voltage and recovery times, use a Schottky rectifier.

Table 3 provides some recommended Schottky rectifiers based on the maximum input voltage and current rating.

Table 3: Diode Selection Guide

V_{IN} (Max)	2A Load Current		3A Load Current	
	Part Number	Vendor	Part Number	Vendor
15V	30BQ15	4		
20V	B220	1	B320	1
	SK23	6	SK33	1, 6
	SR22	6	SS32	3
30V	20BQ030	4	B330	1
	B230	1	B340L	1
	SK23	6	MBRD330	4, 5
	SR23	3, 6	SK33	1, 6
	SS23	2, 3	SS33	2, 3
36V	21DQ04	4	B340L	1
	MBRS240L	5	MBRS340	4
	SK24	6	SK34	1, 6
	SS24	2, 3	SS34	2, 3

Table 4 lists manufacturer's websites.

Table 4: Schottky Diode Manufacturers

#	Vendor	Web Site
1	Diodes, Inc.	www.diodes.com
2	Fairchild Semiconductor	www.fairchildsemi.com
3	General Semiconductor	www.gensemi.com
4	International Rectifier	www.irf.com
5	On Semiconductor	www.onsemi.com
6	Pan Jit International	www.panjit.com.tw

Choose a rectifier whose maximum reverse voltage rating is greater than the maximum input voltage, and who's current rating is greater than the maximum load current.

Compensation

The system stability is controlled through the COMP pin. COMP is the output of the internal transconductance error amplifier. A series capacitor-resistor combination sets a pole-zero combination to control the characteristics of the control system.

The DC loop gain is:

$$A_{VDC} = (V_{REF} / V_{OUT}) * A_{VEA} * G_{CS} * R_{LOAD}$$

Where:
- V_{REF} is the feedback threshold voltage, 1.222V
- V_{OUT} is the desired output regulation voltage
- A_{VEA} is the transconductance error amplifier voltage gain, 400 V/V
- G_{CS} is the current sense gain, (roughly the output current divided by the voltage at COMP), 3.5 A/V
- R_{LOAD} is the load resistance (V_{OUT} / I_{OUT} where I_{OUT} is the output load current)

The system has 2 poles of importance, one is due to the compensation capacitor (C4), and the other is due to the output capacitor (C5). These are:

$$f_{P1} = G_{MEA} / (2\pi * A_{VEA} * C4)$$

Where f_{P1} is the first pole, and G_{MEA} is the error amplifier transconductance (770µS).

And
$$f_{P2} = 1 / (2\pi * R_{LOAD} * C5)$$

The system has one zero of importance, due to the compensation capacitor (C4) and the compensation resistor (R3).
The zero is:

$$f_{Z1} = 1 / (2\pi * R3 * C4)$$

If large value capacitors with relatively high equivalent-series-resistance (ESR) are used,

the zero due to the capacitance and ESR of the output capacitor can be compensated by a third pole set by R3 and C3. The pole is:

$$f_{P3} = 1 / (2\pi * R3 * C3)$$

The system crossover frequency, f_C, (the frequency where the loop gain drops to 1, or 0dB) is important. A good rule of thumb is to set the crossover frequency to approximately 1/5 of the switching frequency. In this case, the switching frequency is 300KHz, so use a crossover frequency of 40KHz. Lower crossover frequencies result in slower response and worse transient load recovery. Higher crossover frequencies can result in instability.

Choosing the Compensation Components

The values of the compensation components given in Table 5 yield a stable control loop for the output voltage and capacitor given. To optimize the compensation components that are not listed in Table 5, use the following procedure.

Table 5: Compensation Values for Typical Output Voltage/Capacitor Combinations

V_{OUT}	C5	R3	C3	C4
2.5V	22µF Ceramic	4.2KΩ	None	3.9nF
3.3V	22µF Ceramic	5.6KΩ	None	2.7nF
5V	22µF Ceramic	8.2KΩ	None	1.8nF
12V	22µF Ceramic	10KΩ	None	3.3nF
2.5V	47µF SP-Cap	9.1KΩ	None	1.8nF
3.3V	47µF SP-Cap	10KΩ	None	1.8nF
5V	47µF SP-Cap	10KΩ	None	2.7nF
12V	47µF SP-Cap	10KΩ	None	6.8nF
2.5V	560µF/6.3V, AL 30mΩ ESR	10KΩ	1.5nF	18nF
3.3V	560µF/6.3V, AL 30mΩ ESR	10KΩ	1.5nF	22nF
5V	470µF/10V, AL 30mΩ ESR	10KΩ	1.5nF	27nF
12V	220µF/25V, AL 30mΩ ESR	10KΩ	None	33nF

Note: "AL" = Electrolytic

Choose the compensation resistor to set the desired crossover frequency. Determine the value by the following equation:

$$R3 = 2\pi * C5 * V_{OUT} * f_C / (G_{EA} * G_{CS} * V_{REF})$$

Putting in the know constants and setting the crossover frequency to the desired 40kHz:

$$R3 \approx 7.7 \times 10^7 * C5 * V_{OUT}$$

The value of R3 is limited to 10KΩ to prevent output overshoot at startup, so if the value calculated for R3 is greater than 10KΩ, use 10KΩ. In this case, the actual crossover frequency is less than the desired 40KHz, and is calculated by:

$$f_C = R3 * G_{EA} * G_{CS} * V_{REF} / (2\pi * C5 * V_{OUT})$$

or

$$f_C \approx 5.2 / (C_{OUT} * V_{OUT})$$

Choose the compensation capacitor to set the zero to ¼ of the crossover frequency. Determine the value by the following equation:

$$C4 = 2 / (\pi * R3 * f_C) \approx 1.59 \times 10^{-5} / R3$$

if R3 is less than 10KΩ, or

$$C4 \approx 1.22 \times 10^{-5} * C_{OUT} * V_{OUT}$$

if R3 = 10KΩ

Determine if the second compensation capacitor, C3 is required. It is required if the ESR zero of the output capacitor happens at less than four times the crossover frequency. Or:

$$8\pi * C5 * R_{ESR} * f_C \geq 1$$

where R_{ESR} is the equivalent series resistance of the output capacitor.

If this is the case, then add the second compensation resistor. Determine the value by the equation:

$$C3 = C5 * R_{ESR(max)} / R3$$

Where $R_{ESR(MAX)}$ is the maximum ESR of the output capacitor.

Example:

V_{OUT} = 5V, C5 = 22µF Ceramic (ESR = 10mΩ)

R3 ≈ 6.78×10^7 (22x10^{-6}) (5) = 7458Ω

Use the nearest standard value of 7.5KΩ.

C4 ≈ 1.59×10^{-5} / 7.5K = 2.12nF

Use the nearest standard value of 2.2nF.

$8\pi * C5 * R_{ESR} f_C$ = 0.22 which is less than 1, therefore no second compensation capacitor (C3) is required.

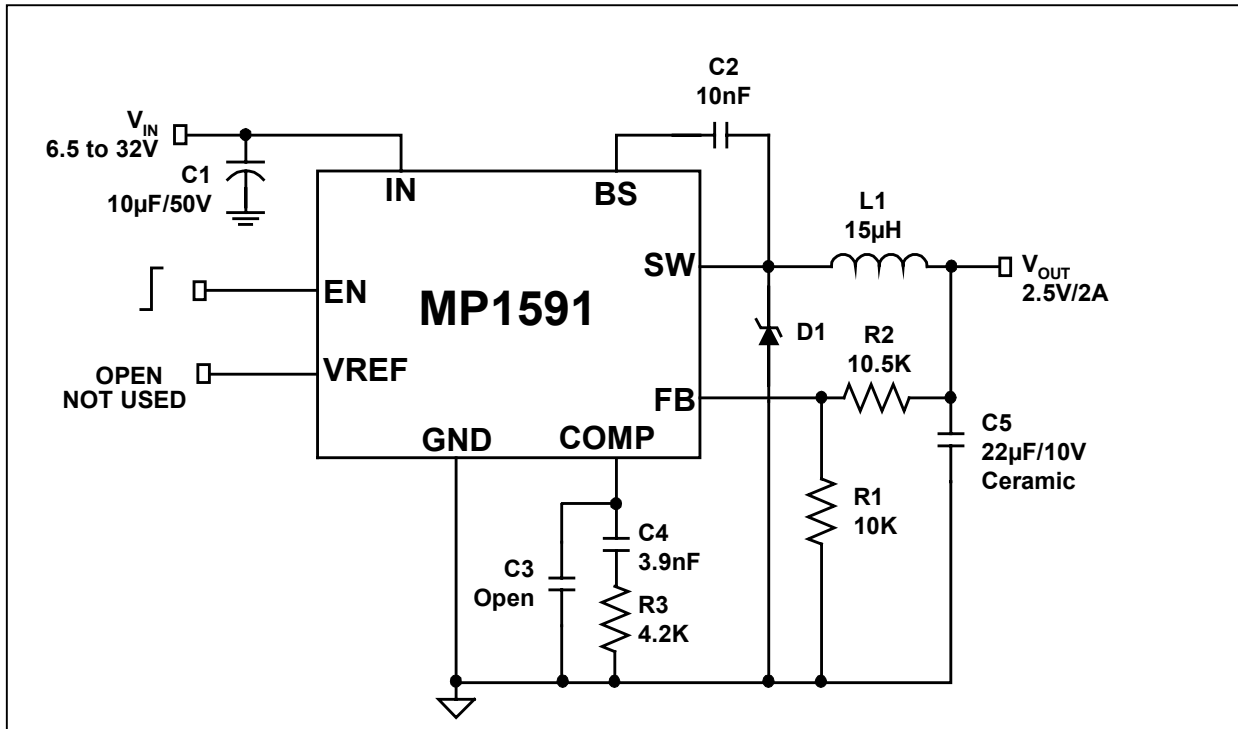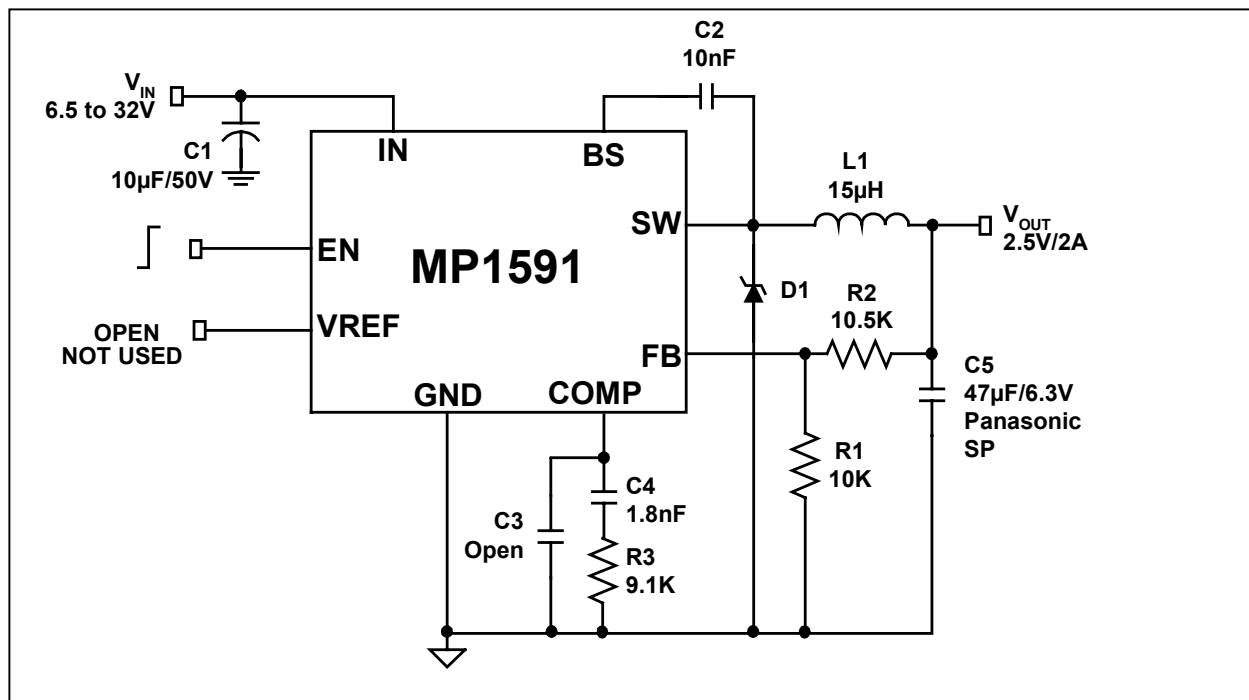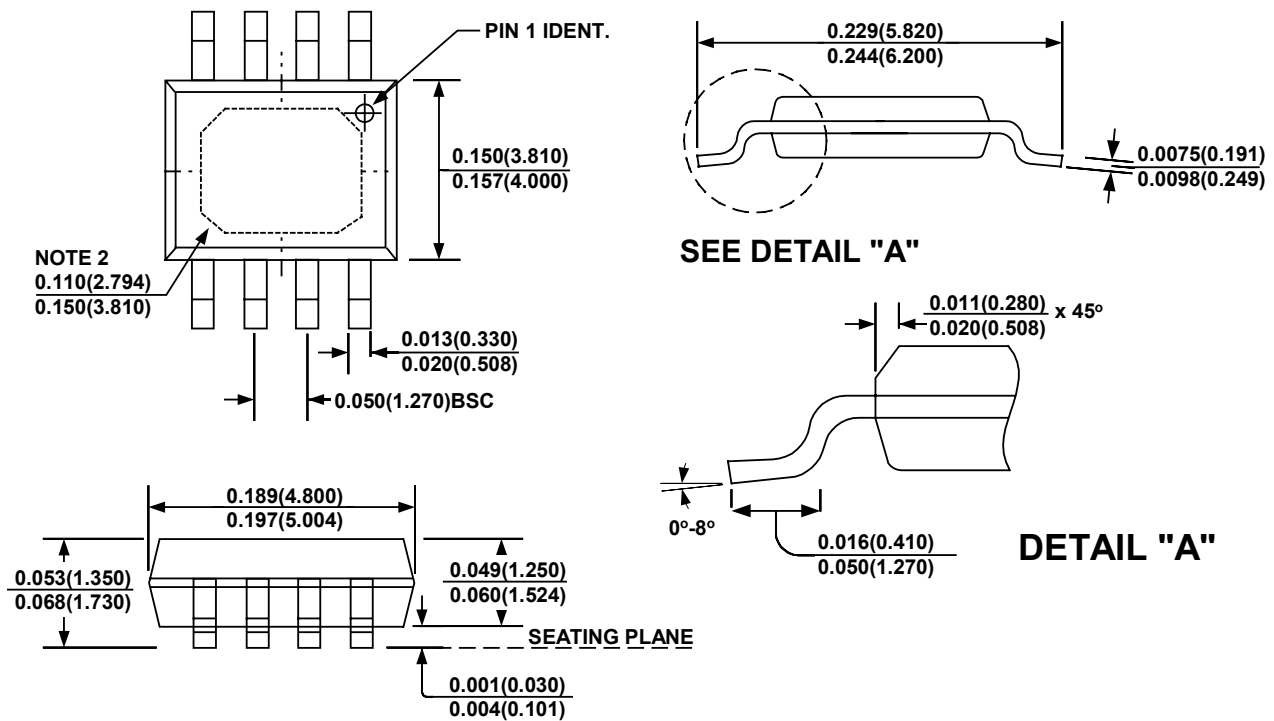**Figure 3: MP1591 with Murata 22µF/10V Ceramic Output Capacitor**

Figure 4: MP1591 with Panasonic 47µF/6.3V Special Polymer Output Capacitor

Monolithic Power Systems

Packaging

SOIC8
(with or without Heat Slug)

PIN 1 IDENT.

0.229(5.820)
0.244(6.200)

0.150(3.810)
0.157(4.000)

0.0075(0.191)
0.0098(0.249)

SEE DETAIL "A"

NOTE 2
0.110(2.794)
0.150(3.810)

0.013(0.330)
0.020(0.508)

0.050(1.270)BSC

0.011(0.280) x 45°
0.020(0.508)

DETAIL "A"

0°-8°

0.016(0.410)
0.050(1.270)

0.189(4.800)
0.197(5.004)

0.053(1.350)
0.068(1.730)

0.049(1.250)
0.060(1.524)

SEATING PLANE

0.001(0.030)
0.004(0.101)

NOTE:
1) Control dimension is in inches. Dimension in bracket is millimeters.
2) Heat Slug Option Only (N Package)

MP1591 Rev 1.1
02/26/03
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