AT9933

Hysteretic Boost-Buck (Ćuk) LED Driver IC

Features

- Constant Current LED Driver
- Steps Input Voltage Up or Down
- Low Electromagnetic Interference (EMI)
- Variable Frequency Operation
- Internal 75V Linear Regulator
- Input and Output Current Sensing
- Input Current Limit
- Enable and Pulse-width Modulation (PWM) Dimming
- Ambient Temperature Rating of up to 125°C

Applications

- LED Lighting Applications

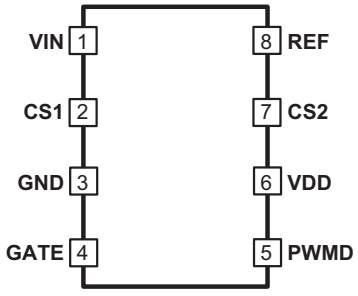
General Description

The AT9933 is a variable frequency PWM controller IC, designed to control an LED lamp driver using a low-noise boost-buck (Ćuk) topology. It uses patent-pending Hysteretic Current-mode control to regulate both the input and the output currents. This enables superior input surge immunity without the necessity for complex loop compensation. Input current control enables current limiting during Startup, Input Undervoltage and Output Overload conditions. The AT9933 provides a low-frequency PWM dimming input that can accept an external control signal with a duty cycle of 0%–100% and a high dimming ratio.

This AT9933-based LED driver is ideal for LED lamps. The part is rated for up to 125°C ambient temperatures.

Package Type

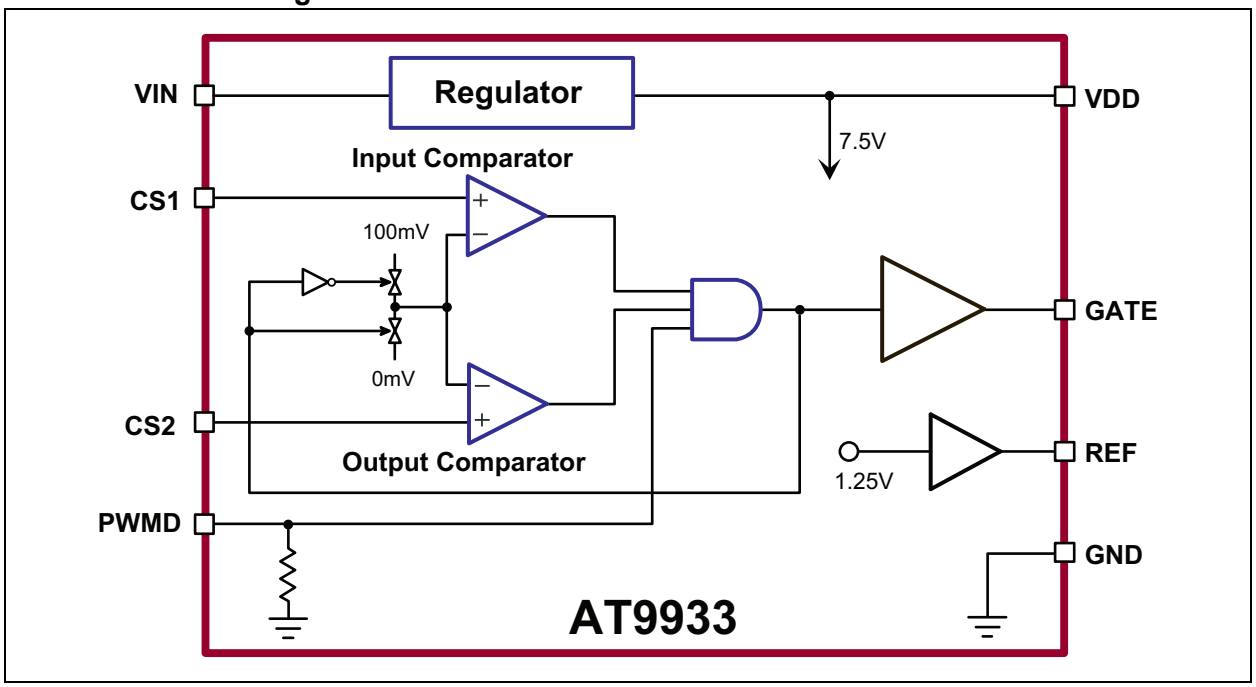
8-lead SOIC
(Top View)



See Table 2-1 for pin information.

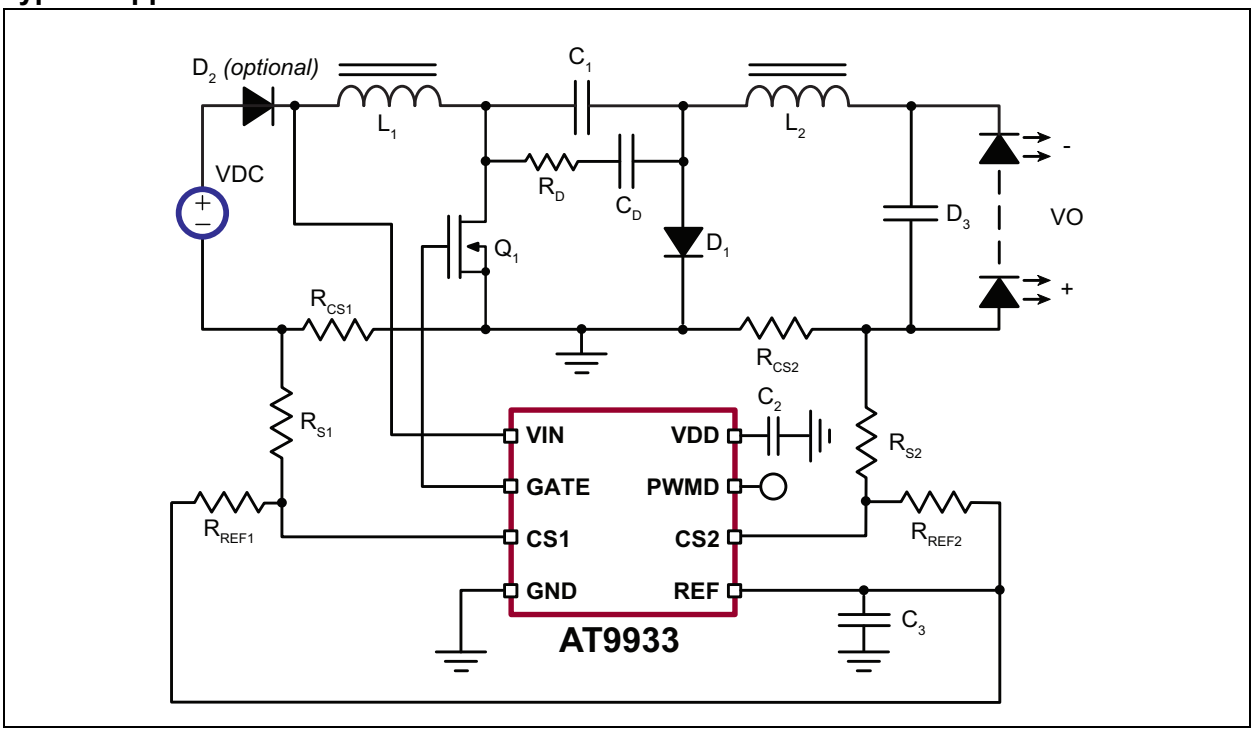
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Functional Block Diagram



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Typical Application Circuit



1.0 ELECTRICAL CHARACTERISTICS

Absolute Maximum Ratings†

V_{IN} to GND .....–0.5V to +75V
CS1, CS2, PWMD and GATE to GND .....–0.3V to V_{DD} +0.3V
$V_{DD(MAX)}$ .....+12V
Operating Temperature Range..... –40°C to +125°C
Junction Temperature..... +150°C
Storage Temperature Range ..... –65°C to +150°C
Continuous Power Dissipation (T_A = +25°C):
8-lead SOIC ..... 700 mW

† Notice: Stresses above those listed under “Absolute Maximum Ratings” may cause permanent damage to the device. This is a stress rating only, and functional operation of the device at those or any other conditions above those indicated in the operational sections of this specification is not intended. Exposure to maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

Electrical Specifications: Specifications are at T_A = 25°C, V_{IN} = Open and V_{DD} = 7.5V unless otherwise noted.

Parameter	Sym.	Min.	Typ.	Max.	Unit	Conditions
INPUT						
Input DC Supply Voltage Range	V_{INDC}	**Note 3**	—	75	V	DC input voltage (**Note 1** and **Note 2**)
Shutdown Mode Supply Current	I_{INSD}	—	0.5	1	mA	PWMD connected to GND, V_{IN} = 12V (**Note 2**)
INTERNAL REGULATOR						
Internally Regulated Voltage	V_{DD}	7	7.5	9	V	V_{IN} = 8V–75V, $I_{DD(EXT)}$ = 0, 500 pF capacitor at GATE, PWMD = GND (**Note 1**)
V_{DD} Undervoltage Lockout Threshold	UVLO	6.35	6.7	7.05	V	V_{DD} rising (**Note 1**)
V_{DD} Undervoltage Lock-out Hysteresis	ΔUVLO	—	500	—	mV	
REFERENCE						
REF Pin Voltage 0°C < T_A < +85°C	V_{REF}	1.212	1.25	1.288	V	REF bypassed with a 0.1 µF capacitor to GND, I_{REF} = 0, PWMD = 5V
REF Pin Voltage –40°C < T_A < +125°C		1.187	1.25	1.312		
Line Regulation of Reference Voltage	$V_{REFLINE}$	0	—	20	mV	REF bypassed with a 0.1 µF capacitor to GND, I_{REF} = 0, V_{DD} = 7V–9V, PWMD = 5V
Reference Output Current Range	I_{REF}	–0.01	—	500	µA	REF bypassed with a 0.1 µF capacitor to GND, I_{REF} = 0, V_{DD} = 7V–9V, PWMD = 5V
Load Regulation of Reference Voltage	$V_{REFLOAD}$	0	—	10	mV	REF bypassed with a 0.1 µF capacitor to GND, I_{REF} = 0 µA–500 µA, PWMD = 5V
PWM DIMMING						
PWMD Input Low Voltage	$V_{PWMD(LO)}$	—	—	0.8	V	V_{DD} = 7V–9V (**Note 1**)
PWMD Input High Voltage	$V_{PWMD(HI)}$	2	—	—	V	V_{DD} = 7V–9V (**Note 1**)

Note 1: Specifications apply over the full operating ambient temperature range of –40ºC < T_A < +125ºC.
2: Also limited by package power dissipation limit, whichever is lower
3: Depends on the current drawn by the part. See **Section 4.0 “Application Information”**

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ELECTRICAL CHARACTERISTICS (CONTINUED)

Electrical Specifications: Specifications are at T_A = 25°C, V_{IN} = Open and V_{DD} = 7.5V unless otherwise noted.						
Parameter	**Sym.**	**Min.**	**Typ.**	**Max.**	**Unit**	**Conditions**
PWMD Pull-down Resistance	R_{PWMD}	50	100	150	kΩ	V_{PWMD} = 5V
GATE DRIVER						
GATE Short Circuit Current	I_{SOURCE}	0.165	—	—	A	V_{GATE} = 0V
GATE Sinking Current	I_{SINK}	0.165	—	—	A	V_{GATE} = V_{DD}
GATE Output Rise Time	T_{RISE}	—	30	50	ns	C_{GATE} = 500 pF
GATE Output Fall Time	T_{FALL}	—	30	50	ns	C_{GATE} = 500 pF
INPUT CURRENT SENSE COMPARATOR						
Voltage required to turn on GATE	$V_{TURNON1}$	85	100	115	mV	C_{S2} = 200 mV, C_{S1} increasing, GATE goes LOW to HIGH (**Note 1**)
Voltage required to turn off GATE	$V_{TURN-OFF1}$	–15	0	15	mV	C_{S2} = 200 mV, C_{S1} decreasing, GATE goes HIGH to LOW (**Note 1**)
Delay to Output (Turn-on)	$T_{D1,ON}$	—	150	250	ns	C_{S2} = 200 mV, C_{S1} = 50 mV to +200 mV step
Delay to Output (Turn-off)	$T_{D1,OFF}$	—	150	250	ns	C_{S2} = 200 mV, C_{S1} = 50 mV to –100 mV step
OUTPUT CURRENT SENSE COMPARATOR						
Voltage required to turn on GATE	$V_{TURNON2}$	85	100	115	mV	C_{S1} = 200 mV, C_{S2} increasing, GATE goes LOW to HIGH (**Note 1**)
Voltage required to turn off GATE	$V_{TURN-OFF2}$	–15	0	15	mV	C_{S1} = 200 mV, C_{S2} decreasing, GATE goes HIGH to LOW (**Note 1**)
Delay to Output (Turn-on)	$T_{D2,ON}$	—	150	250	ns	C_{S1} = 200 mV, C_{S2} = 50 mV to +200 mV step
Delay to Output (Turn-off)	$T_{D2,OFF}$	—	150	250	ns	C_{S1} = 200 mV, C_{S2} = 50 mV to –100 mV step

Note 1: Specifications apply over the full operating ambient temperature range of –40ºC < T_A < +125ºC.

2: Also limited by package power dissipation limit, whichever is lower

3: Depends on the current drawn by the part. See **Section 4.0 "Application Information"**

TEMPERATURE SPECIFICATIONS

Parameter	**Sym.**	**Min.**	**Typ.**	**Max.**	**Unit**	**Conditions**
TEMPERATURE RANGE						
Operating Temperature	T_A	–40	—	+125	°C	
Junction Temperature	T_J	—	—	+150	°C	
Storage Temperature	T_S	–65	—	+150	°C	
PACKAGE THERMAL RESISTANCE						
8-lead SOIC	θ_{JA}	—	+101	—	°C/W	**Note 1**

Note 1: Mounted on a FR-4 board, 25 mm x 25 mm x 1.57 mm

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2.0 PIN DESCRIPTION

The details on the pins of AT9933 are listed on Table 2-1. Refer to **Package Type** for the location of the pins.

TABLE 2-1: PIN FUNCTION TABLE

Pin Number	Pin Name	Description
1	VIN	This pin is the input of an 8V–75V voltage regulator.
2	CS1	This pin is used to sense the input and output currents of the boost-buck converter. It is a non-inverting input of the internal comparator.
3	GND	This is the ground return for all the internal circuitry. This pin must be electrically connected to the ground of the power train.
4	GATE	This pin is the output gate driver for an external N-channel power Metal-oxide Semiconductor Field-effect Transistor (MOSFET).
5	PWMD	When this pin is left open or pulled to GND, the gate driver is disabled. Pulling the pin to a voltage greater than 2V will enable the gate driver output.
6	VDD	This is a power supply pin for all internal circuits. It must be bypassed to GND with a low-ESR capacitor greater than 0.1 µF.
7	CS2	This pin is used to sense the input and output currents of the boost-buck converter. It is a non-inverting input of the internal comparator.
8	REF	This pin provides accurate reference voltage. It must be bypassed with a 0.01 µF–0.1 µF capacitor to GND.

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3.0 DETAILED DESCRIPTION

3.1 Power Topology

The AT9933 is optimized to drive a Continuous Conduction Mode (CCM) boost-buck DC/DC converter topology commonly referred to as Ćuk converter. (Refer to **Typical Application Circuit**.) This power converter topology offers numerous advantages useful for driving high-brightness light-emitting diodes (HB LED). These advantages include step-up or step-down voltage conversion ratio and low input and output current ripple. The output load is decoupled from the input voltage with a capacitor, making the driver inherently failure-safe for the output load.

The AT9933 offers a simple and effective control technique for a boost-buck LED driver. It uses two Hysteretic mode controllers—one for the input and one for the output. The outputs of these two hysteretic comparators are ANDED and used to drive the external FET. This control scheme gives accurate current control and constant output current in the presence of input voltage transients without the need for complicated loop design.

3.2 Input Voltage Regulator

The AT9933 can be powered directly from its V_{IN} pin that can withstand a maximum voltage of up to 75V. When a voltage is applied to the V_{IN} pin, the AT9933 seeks to regulate a constant 7.5V (typical) at the V_{DD} pin. The regulator also has a built-in undervoltage lockout which shuts off the IC when the voltage at the V_{DD} pin falls below the UVLO threshold.

The V_{DD} pin must be bypassed by a low-ESR capacitor (≥0.1 µF) to provide a low-impedance path for the high frequency current of the output gate driver.

The input current drawn from the V_{IN} pin is the sum of the 1 mA current drawn by the internal circuit and the current drawn by the gate driver, which in turn depends on the switching frequency and the gate charge of the external FET. Refer to Equation 3-1.

EQUATION 3-1:

$$I_{IN} = 1mA + Q_G \times f_S$$

In the above equation, f_S is the switching frequency, and Q_G is the gate charge of the external FET which can be obtained from the data sheet of the FET.

3.3 Minimum Input Voltage at V_{IN} Pin

The minimum input voltage at which the converter will start and stop depends on the minimum voltage drop required for the linear regulator. The internal linear regulator will control the voltage at the V_{DD} pin when V_{IN} is between 8V and 75V. However, when the V_{IN} is less than 8V, the converter will still function as long as the V_{DD} is greater than the undervoltage lockout. Thus, under certain conditions, the converter will be able to start at V_{IN} voltages of less than 8V. The start/stop voltages at the V_{IN} pin can be determined using the maximum voltage drop across the linear regulator as a function of the current drawn. The data for ambient temperatures 25ºC and 125ºC are shown in Figure 3-1 below:

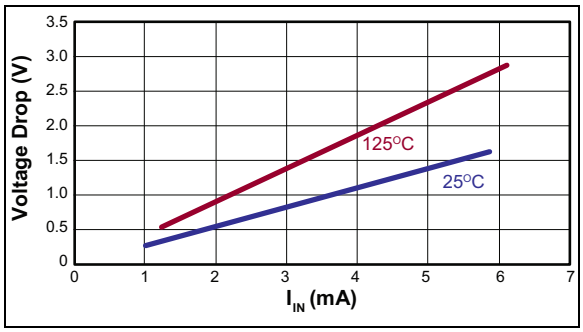


FIGURE 3-1: *Maximum Voltage Drop vs. Input Current.*

Assume an ambient temperature of 125°C. Provided that the IC is driving a 15 nC gate charge FET at 300 kHz, the total input current is estimated to be 5.5 mA (using Equation 3-1). At this input current, the maximum voltage drop from Figure 3-1 can be approximately estimated to be V_{DROP} = 2.7V. However, before the IC starts switching, the current drawn will be 1 mA. At this current level, the voltage drop is approximately V_{DROP1} = 0.5V. Thus, the start/stop V_{IN} voltages can be computed as shown in Equation 3-2 and Equation 3-3:

EQUATION 3-2:

$$\begin{aligned} V_{IN-START} &= UVLO_{MAX} + V_{DROP1} \\ &= 6.95V + 0.5V \\ &= 7.45V \end{aligned}$$

EQUATION 3-3:

$$\begin{aligned} V_{IN-STOP} &= UVLO_{MAX} - \Delta UVLO + V_{DROP} \\ &= 6.95V - 0.5V + 2.7V \\ &= 9.15V \end{aligned}$$

Note: Since the gate driver draws too much current in this situation, $V_{IN-START}$ is less than $V_{IN-STOP}$. The control IC will oscillate between on and off if the input voltage is between the start and stop voltages. In these circumstances, it is recommended that the input voltage be kept higher than $V_{IN-STOP}$. The IC will operate normally if the input voltage is kept higher than 9.2V.

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In case of input transients that reduce the input voltage below 8V (e.g. Cold Crank condition in an automotive system), the V_{IN} pin of the AT9933 can be connected to the MOSFET drain through a switching diode using a small (1 nF) capacitor between V_{IN} and GND as long as the drain voltage does not exceed 75V. Since the drain of the FET is at a voltage equal to the sum of the input and output voltages, the IC will still be operational when the input goes below 8V. Therefore, a larger capacitor is needed at the V_{DD} pin to supply power to the IC when the MOSFET is switched on.

In this case, $V_{DD\ UVLO}$ cannot be relied upon to turn off the IC at low input voltages when input current levels can get too large. In such cases, the input current limit must be chosen to ensure that the input current is set to a safe level.

3.4 Reference

An internally trimmed voltage reference of 1.25V is provided at the REF pin. The reference can supply a maximum output current of 500 µA to drive external resistor dividers.

This reference can be used to set the current thresholds of the two comparators as shown in the **Typical Application Circuit** section.

3.5 Current Comparators

The AT9933 features two identical comparators with a built-in 100 mV hysteresis. When the GATE is low, the inverting terminal is connected to 100 mV, but when the GATE is high, it is connected to GND. One comparator is used for the input current control and the other for the output current control.

The input side hysteretic controller is in operation during Start-up, Overload and Input Undervoltage conditions. This ensures that the input current never exceeds the designed value. During normal operation, the input current is less than the programmed current. Therefore, the output of the input side comparator will be high. The output of the AND gate will then be dictated by the output current controller.

The output side hysteretic comparator controls the external MOSFET during Steady state operation of the circuit. This comparator turns the MOSFET on and off based on the LED current.

3.6 PWM Dimming

PWM Dimming can be achieved by applying a TTL-compatible square wave signal to the PWM pin. When the PWMD pin is pulled high, the gate driver is enabled and the circuit operates normally. When the PWMD pin is left open or connected to GND, the gate driver is disabled and the external MOSFET turns off. The signal at the PWMD pin inhibits the driver only and the IC need not go through the entire start-up cycle each time, ensuring a quick response time for the output current. The recommended PWM dimming frequency range is from 100 Hz to a few kilohertz.

The flying capacitor in the Ćuk converter (C1) is initially charged to the input voltage VDC (through diodes D_1 and D_2). When the circuit is turned on and reaches Steady state, the voltage across C1 will be VDC+VO. In the absence of diode D_2, when the circuit is turned off, capacitor C_1 will discharge through the LEDs and the input voltage source VDC. Thus, during PWM dimming, if capacitor C_1 has to be charged and discharged each cycle, the transient response of the circuit will be limited. By adding diode D_2, the voltage across capacitor C_1 is held at VDC+VO even when the circuit is turned off, enabling the circuit to return quickly to its Steady state (and bypassing the start-up stage) upon being enabled.

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4.0 APPLICATION INFORMATION

4.1 Overvoltage Protection

Overvoltage protection can be added by splitting the output side resistor R_{S2} into two components and adding a Zener diode D_3. (Refer to Figure 4-1 below.) When there is an Open LED condition, the diode D_3 will clamp the output voltage and the Zener diode current will be regulated by the sum of R_{S2A} and R_{CS2}.

4.2 Damping Circuit

The Ćuk converter is inherently unstable when the output current is being controlled. An uncontrolled input current will lead to an undamped oscillation between L_1 and C_1, causing excessively high voltages across capacitor C_1. To prevent these oscillations, a damping circuit consisting of R_D and C_D is applied across the capacitor C_1. This damping circuit will stabilize the circuit and help in the proper operation of the converter.

4.3 Design and Operation of the Boost-buck Converter

For details on the design for a boost-buck converter using the AT9933 and the calculation of the damping components, refer to Application Notes *AN-H51* and *AN-H58*.

4.4 Design Example

The choice of the resistor dividers to set the input and output current levels is illustrated by means of the design example given below.

The parameters of the power circuit are:

$$V_{IN,MIN} = 9.01V$$
$$V_{IN,MAX} = 16V$$
$$V_O = 28V$$
$$I_O = 0.35A$$
$$f_{S,MIN} = 300kHz$$

Using these parameters, the values of the power stage inductors and capacitor can be computed. (See figures below.) Refer to Application Note *AN-H51* for more details.

$$L_1 = 82\mu H$$
$$L_2 = 150\mu H$$
$$C_1 = 0.22\mu F$$

The input and output currents for this design are:

$$I_{IN,MAX} = 1.6A$$
$$\Delta I_{IN} = 0.21A$$
$$I_O = 350mA$$
$$\Delta I_O = 87.5mA$$

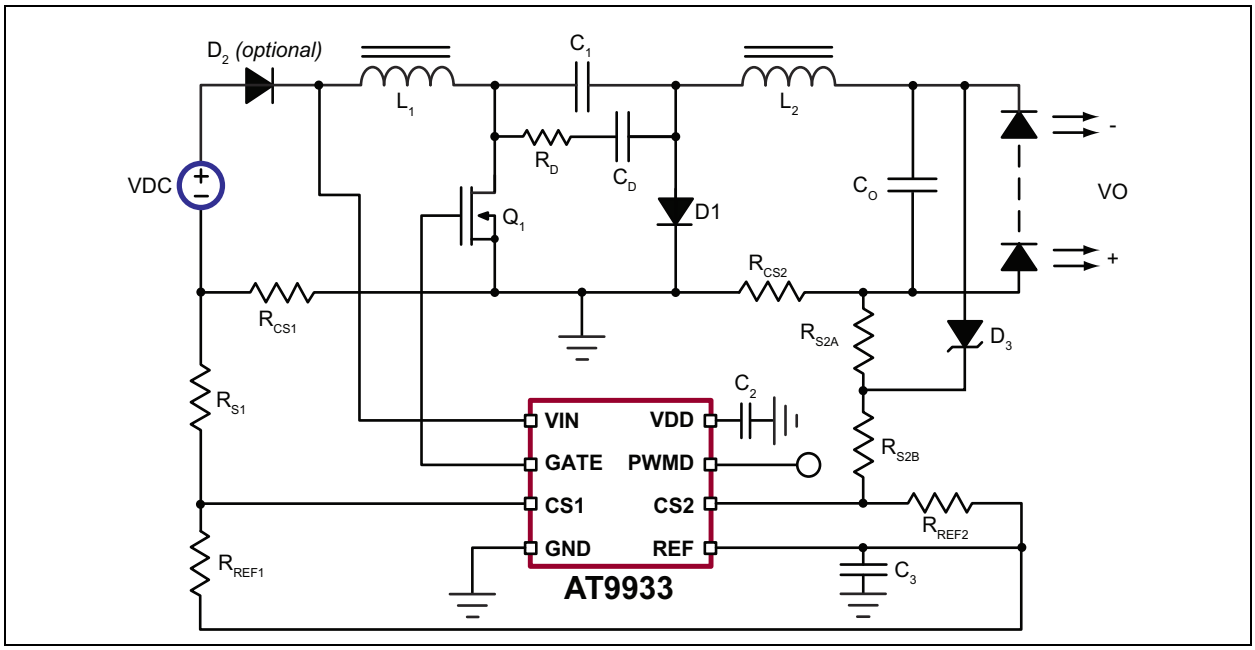


FIGURE 4-1: *Design Example Circuit.*

4.5 Current Limits

The current sense resistor R_{CS2}, combined with the other resistors R_{S2} and R_{REF2}, determines the output current limits.

The resistors can be chosen using Equation 4-1 and Equation 4-2.

EQUATION 4-1:

$$I \times R_{CS} = 1.2V \times \left(\frac{R_S}{R_{REF}}\right) - 0.05V$$

Where I is the current (either I_O or I_{IN}) and ΔI is the peak-to-peak ripple in the current (either ΔI_O or ΔI_{IN}).

EQUATION 4-2:

$$\Delta I \times R_{CS} = 0.1V \times \left(\frac{R_S}{R_{REF}}\right) + 0.1V$$

Where I is the current (either I_O or I_{IN}) and ΔI is the peak-to-peak ripple in the current (either ΔI_O or ΔI_{IN}).

For the input side, the current level used in the equations should be larger than the maximum input current, so that it does not interfere with the normal operation of the circuit. The peak input current can be computed as shown in Equation 4-3.

EQUATION 4-3:

$$I_{IN,PK} = I_{IN,MAX} + \left(\frac{\Delta I_{IN}}{2}\right) = 1.706A$$

Assuming a 30% peak-to-peak ripple when the converter is in Input Current Limit mode, the minimum value of the input current is calculated as seen in Equation 4-4.

EQUATION 4-4:

$$I_{LIM,MIN} = 0.85 \times I_{IN,LIM}$$

Setting

$$I_{LIM,MIN} = 1.05 \times I_{IN,PK}$$

The current level to limit the converter can then be computed. See equation Equation 4-5.

EQUATION 4-5:

$$I_{IN,LIM} = \left(\frac{1.05}{0.85}\right) \times I_{IN,PK} = 2.1A$$

Using I_O = 350 mA and ΔI_O = 87.5 mA in Equation 4-1 and Equation 4-2, R_{CS2} = 1.78Ω and R_{S2}/R_{REF2} = 0.5625.

Before the design of the output side is complete, overvoltage protection has to be included in the design. For this application, choose a 33V Zener diode. This is the voltage at which the output will clamp in case of an Open LED condition. For a 350 mW diode, the maximum current rating at 33V works out to about 10 mA. Using a 2.5 mA current level during Open LED conditions, and assuming the same R_{S2}/R_{REF2} ratio, the Zener current limiting resistor can be determined as illustrated in Equation 4-6.

EQUATION 4-6:

$$R_{CS} + R_{S2A} = 120\Omega$$

Choose the following values for the resistors:

$R_{CS2} = 1.65\Omega$, 1/4W, 1%

$R_{REF2} = 10\ k\Omega$, 1/8W, 1%

$R_{S2A} = 100\Omega$, 1/8W, 1%

$R_{S2B} = 5.23\ k\Omega$, 1/8W, 1%

The current sense resistor needs to be at least a 1/4W, 1% resistor.

Similarly, using I_{IN} = 2.1A and ΔI_{IN} = 0.3 x I_{IN} = 0.63 in Equation 4-1 and Equation 4-2, the following values can be determined:

$$\frac{R_{S1}}{R_{REF1}} = 0.442$$

$$R_{CS1} = 0.228\Omega$$

$$P_{RCS1} = I^2_{IN,LIM} \times R_{CS1} = 1W$$

Choose the following values for the resistors:

R_{CS1} = parallel combination of three 0.68Ω, 1/2W, 5% resistors

$R_{REF1} = 10k\Omega$, 1/8W, 1%

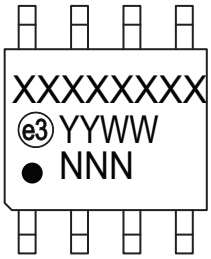
$R_{S1} = 4.42k\Omega$, 1/8W, 1%

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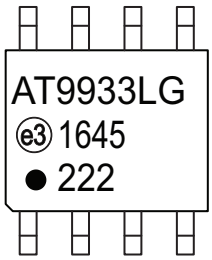
5.0 PACKAGING INFORMATION

5.1 Package Marking Information

8-lead SOIC



Example

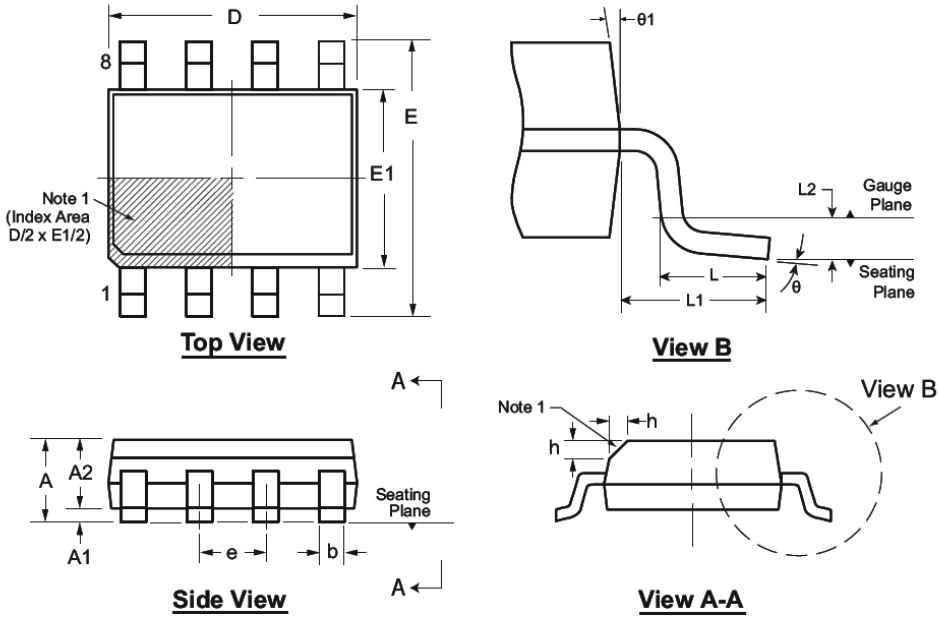


Legend:	XX...X	Product Code or Customer-specific information
	Y	Year code (last digit of calendar year)
	YY	Year code (last 2 digits of calendar year)
	WW	Week code (week of January 1 is week ‘01’)
	NNN	Alphanumeric traceability code
	(e3)	Pb-free JEDEC® designator for Matte Tin (Sn)
	*	This package is Pb-free. The Pb-free JEDEC designator ((e3)) can be found on the outer packaging for this package.

Note: In the event the full Microchip part number cannot be marked on one line, it will be carried over to the next line, thus limiting the number of available characters for product code or customer-specific information. Package may or not include the corporate logo.

8-Lead SOIC (Narrow Body) Package Outline (LG/TG)

4.90x3.90mm body, 1.75mm height (max), 1.27mm pitch



Note: For the most current package drawings, see the Microchip Packaging Specification at www.microchip.com/packaging.

Note:

1. *This chamfer feature is optional. A Pin 1 identifier must be located in the index area indicated. The Pin 1 identifier can be: a molded mark/identifier; an embedded metal marker; or a printed indicator.*

Symbol		A	A1	A2	b	D	E	E1	e	h	L	L1	L2	θ	θ1
Dimension (mm)	MIN	1.35*	0.10	1.25	0.31	4.80*	5.80*	3.80*	1.27 BSC	0.25	0.40	1.04 REF	0.25 BSC	0°	5°
	NOM	-	-	-	-	4.90	6.00	3.90		-	-			-	-
	MAX	1.75	0.25	1.65*	0.51	5.00*	6.20*	4.00*		0.50	1.27			8°	15°

JEDEC Registration MS-012, Variation AA, Issue E, Sept. 2005.

** This dimension is not specified in the JEDEC drawing.*

Drawings are not to scale.

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APPENDIX A: REVISION HISTORY

Revision A (October 2016)

- Converted Supertex Doc# DSFP-AT9933 to Microchip DS20005597A
- Changed the quantity of the 8-lead SOIC package from 3000/Reel to 3300/Reel
- Made minor text changes throughout the document

PRODUCT IDENTIFICATION SYSTEM

To order or obtain information, e.g., on pricing or delivery, contact your local Microchip representative or sales office.

PART NO.	XX	-	X	-	X
Device	Package Options		Environmental		Media Type

Device:	AT9933	=	Hysteretic Boost-Buck (Ćuk) LED Driver IC
Package:	LG	=	8-lead SOIC
Environmental:	G	=	Lead (Pb)-free/RoHS-compliant Package
Media Type:	(blank)	=	3300/Reel for an LG Package

Example:

a) AT9933LG-G: Hysteretic Boost-buck (Ćuk) LED Driver IC, 8-lead SOICPackage, 3300/Reel

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- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
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ISBN: 978-1-5224-0995-3

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06/23/16

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