

Linear ~~and Switching~~ Voltage Regulator Fundamentals

Abstract

This paper will enable the user to understand the operation of switching and linear voltage regulators. The most commonly used regulating modes will be covered.

For linear regulators, the Standard, Low-Dropout, and Quasi Low-Dropout regulators will be covered (along with circuit examples).

In the switching regulator section, the Buck, Buck-boost, Boost, and Flyback topologies will be detailed. Some examples will be given of products available for the design and implementation of switching converters.

LINEAR VOLTAGE REGULATORS

Introduction

The linear regulator is the basic building block of nearly every power supply used in electronics. The IC linear regulator is so easy to use that it is virtually foolproof, and so inexpensive that it is usually one of the cheapest components in an electronic assembly.

This paper will present information that gives the user greater understanding of how a linear regulator works, and will help to de-mystify regulator specifications and applications.

Some typical circuits will be presented to highlight the commercial regulators that are currently available. The primary focus of the new product examples is in the area of Low-dropout regulators, which offer great advantages over standard regulators in many applications.

Linear Voltage Regulator Operation

Introduction

Every electronic circuit is designed to operate off of some supply voltage, which is usually assumed to be constant. A voltage regulator provides this constant DC output voltage and contains circuitry that continuously holds the output voltage at the design value regardless of changes in load current or input voltage (this assumes that the load current and input voltage are within the specified operating range for the part).

The Basic Linear Regulator

A linear regulator operates by using a voltage-controlled current source to force a fixed voltage to appear at the regulator output terminal (see Figure 1).

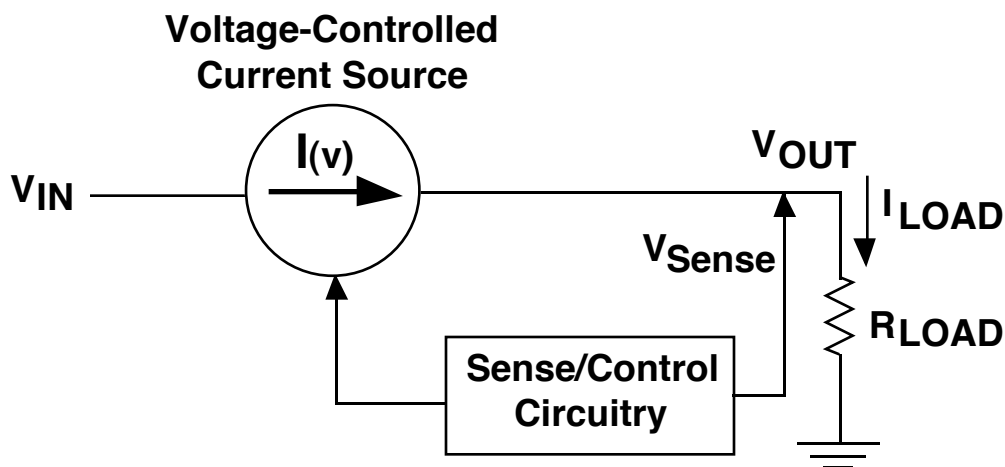


FIGURE 1. LINEAR REGULATOR FUNCTIONAL DIAGRAM

The control circuitry must monitor (sense) the output voltage, and adjust the current source (as required by the load) to hold the output voltage at the desired value. The design limit of the current source defines the maximum load current the regulator can source and still maintain regulation.

The output voltage is controlled using a feedback loop, which requires some type of compensation to assure loop stability. Most linear regulators have built-in compensation, and are completely stable without external components. Some regulators (like Low-Dropout types), do require some external capacitance connected from the output lead to ground to assure regulator stability.

Another characteristic of **any** linear regulator is that it requires a finite amount of time to "correct" the output voltage after a change in load current demand. This "time lag" defines the characteristic called **transient response**, which is a measure of how fast the regulator returns to steady-state conditions after a load change.

Control Loop Operation

The operation of the control loop in a typical linear regulator will be detailed using the simplified schematic diagram in Figure 2 (the function of the control loop is similar in all of the linear regulator types).

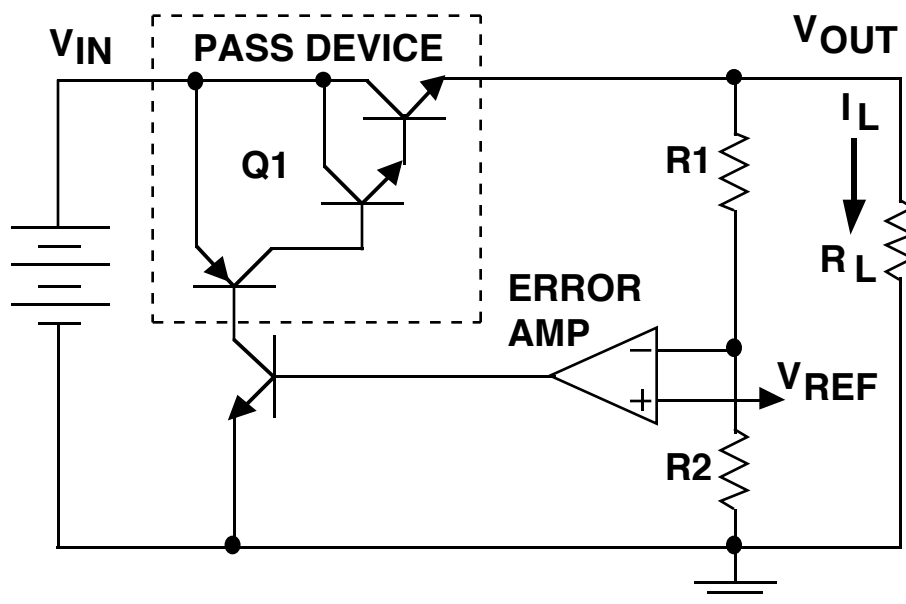


FIGURE 2. DIAGRAM OF A TYPICAL LINEAR REGULATOR

The **pass device (Q1)** in this regulator is made up of an NPN Darlington driven by a PNP transistor (this topology is a **Standard** regulator, as detailed in the following section). The current flowing out the emitter of the pass transistor (which is also the load current I_L) is controlled by **Q2** and the voltage error amplifier. The current through the $R1$, $R2$ resistive divider is assumed to be negligible compared to the load current.

The feedback loop which controls the output voltage is obtained by using $R1$ and $R2$ to "sense" the output voltage, and applying this sensed voltage to the inverting input of the voltage error amplifier. The non-inverting input is tied to a reference voltage, which means the error amplifier will constantly adjust its output voltage (and the current through **Q1**) to force the voltages at its inputs to be equal.

The feedback loop action continuously holds the regulated output at a fixed value which is a multiple of the reference voltage (as set by $R1$ and $R2$), regardless of changes in load current.

It is important to note that a **sudden** increase or decrease in load current demand (a "step" change in load resistance) will cause the output voltage to change until the loop can correct and stabilize to the new level (this is called **transient response**). The output voltage change is sensed through $R1$ and $R2$ and appears as an "error signal" at the input of the error amplifier, causing it to correct the current through **Q1**.

Linear Regulator Types (LDO, Standard, and Quasi-LDO)

There are three basic types of linear regulator designs which will be covered:

Standard (NPN Darlington) Regulator

Low Dropout or LDO Regulator

Quasi LDO Regulator

The single most important difference between these three types is the **dropout voltage**, which is defined as the **minimum voltage drop required across the regulator to maintain output voltage regulation**. A critical point to be considered is that the linear regulator that operates with the smallest voltage across it **dissipates the least internal power and has the highest efficiency**. The **LDO** requires the **least** voltage across it, while the **Standard** regulator requires the **most**.

The second important difference between the regulator types is the **ground pin current** required by the regulator when driving rated load current. The **Standard regulator has the lowest ground pin current**, while the **LDO generally has the highest** (differences between the types is detailed in the following sections). Increased ground pin current is undesirable since it is "wasted" current, in that it must be supplied by the source but does not power the load.

THE STANDARD (NPN) REGULATOR

The first IC voltage regulators made used the NPN Darlington configuration for the pass device, and are designated as the **Standard** regulator (see Figure 3).

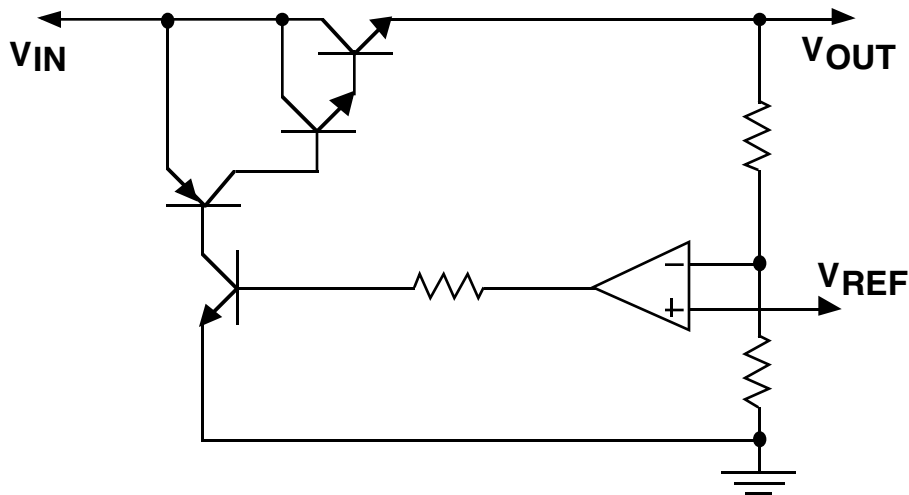


FIGURE 3. STANDARD (NPN) REGULATOR

An important consideration of the Standard regulator is that to maintain output regulation, the pass transistor requires a **minimum** voltage across it given by:

$$V_{D(MIN)} = 2 V_{BE} + V_{CE} \quad (\text{Standard Regulator})$$

Allowing for the -55°C to +150°C temperature range, this minimum voltage requirement is usually set at about **2.5V to 3V** by the manufacturer to guarantee specified performance limits.

The voltage where the output actually falls out of regulation (called the **dropout voltage**) will probably be somewhere between 1.5V and 2.2V for a Standard regulator (it is **dependent on both load current and temperature**). **The dropout voltage of the Standard regulator is the highest (worst)** of the three types.

The ground pin current of the Standard regulator is very low (an LM309 can supply 1A of load current with less than 10 mA of ground pin current). The reason for this is that the **base drive current to the pass transistor (which flows out the ground pin) is equal to the load current divided by the gain of the pass device**. In the Standard regulator, the pass device is a network composed of one PNP and two NPN transistors, which means the total current gain is extremely high (>300).

The result of using a pass device with such high current gain is that very little current is needed to drive the base of the pass transistor, which results in less ground pin current. **The ground pin current of the Standard regulator is the lowest (best)** of the three regulator types.

THE LOW-DROPOUT (LDO) REGULATOR

The Low-dropout (LDO) regulator differs from the Standard regulator in that the pass device of the LDO is made up of only a single PNP transistor (see Figure 4).

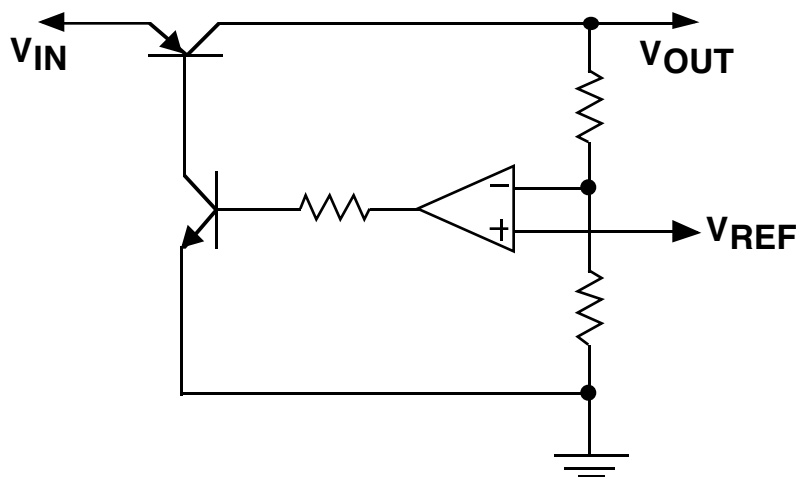


FIGURE 4. LDO REGULATOR

The **minimum** voltage drop required across the LDO regulator to maintain regulation is just the voltage across the PNP transistor:

$$V_{D(MIN)} = V_{CE} \quad (\text{LDO Regulator})$$

The **maximum specified dropout voltage of an LDO regulator is usually about 0.7V to 0.8V at full current**, with typical values around 0.6V. The dropout voltage is directly related to load current, which means that at very low values of load current the dropout voltage may be as little as 50 mV. The **LDO regulator has the lowest (best) dropout voltage specification of the three regulator types**.

The lower dropout voltage is the reason LDO regulators dominate battery-powered applications, since they maximize the utilization of the available input voltage and can operate with higher efficiency. The explosive growth of battery-powered consumer products in recent years has driven development in the LDO regulator product line.

The ground pin current in an LDO regulator is approximately **equal to the load current divided by the gain of the single PNP transistor**. Consequently, the **ground pin current of an LDO is the highest of the three types**.

For example, an **LP2953** LDO regulator delivering its full rated current of 250 mA is specified to have a ground pin current of 28 mA (or less), which translates to a PNP gain of 9 or higher. The **LM2940** (which is a 1A LDO regulator) has a ground pin current specification of 45 mA (max) at full current. This requires a current gain of no less than 22 for the PNP pass transistor at rated current.

THE QUASI LOW-DROPOUT REGULATOR

A variation of the Standard regulator is the quasi-LDO, which uses an NPN and PNP transistor as the pass device (see Figure 5):

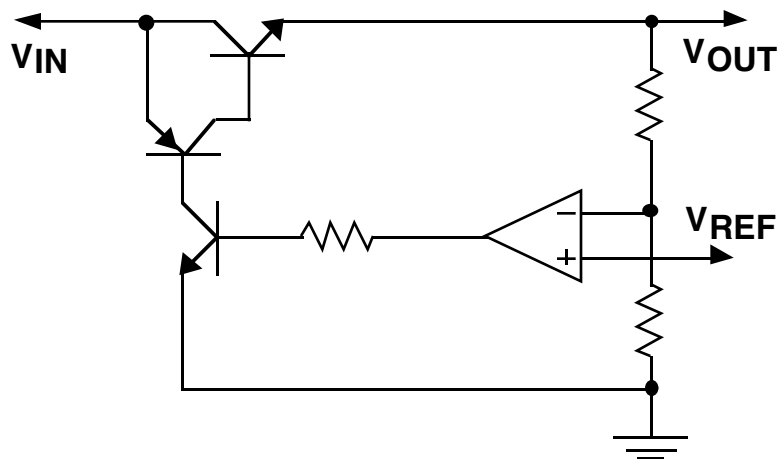


FIGURE 5. QUASI-LDO REGULATOR

The **minimum** voltage drop required across the Quasi-LDO regulator to maintain regulation is given by:

$$V_{D(MIN)} = V_{BE} + V_{CE} \quad (\text{QUASI-LDO Regulator})$$

The dropout voltage for a quasi-LDO delivering rated current is usually specified at about **1.5V(max)**. The actual dropout voltage is temperature and load current dependent, but could never be expected to go lower than about 0.9V (25°C) at even the lightest load. **The dropout voltage for the quasi-LDO is higher than the LDO, but lower than the Standard regulator.**

The ground pin current of the quasi-LDO is fairly low (usually less than 10mA for full rated current) which is as good as the Standard regulator.

SUMMARY

A comparison of the three regulator types¹ is shown in Figure 6.

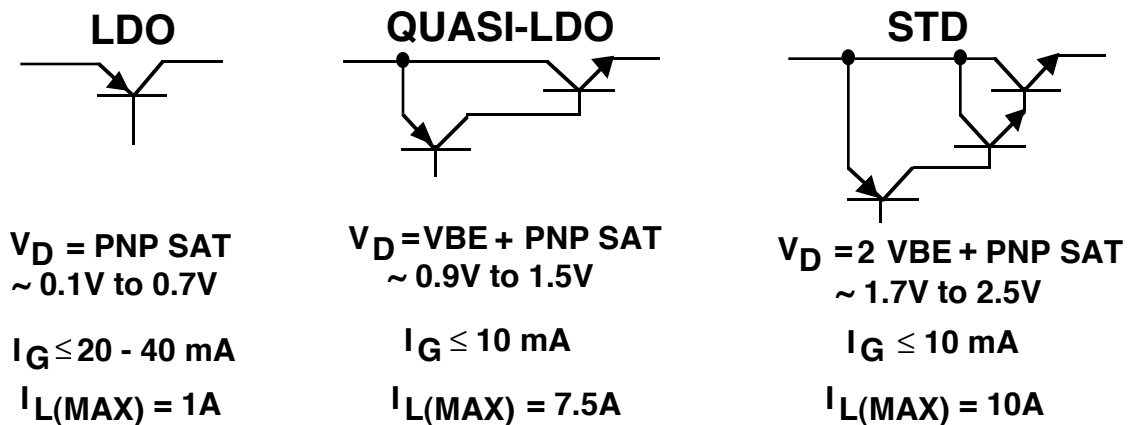


FIGURE 6. REGULATOR TYPE COMPARISON

The Standard regulator is usually best for AC-powered applications, where the low cost and high load current make it the ideal choice. In AC-powered applications, the voltage across the regulator is usually at least 3V or more, so dropout voltage is not critical.

Interestingly, in this type of application (where the voltage drop across the regulator is > 3V) Standard regulators are actually more efficient than LDO types (because the Standard has much less internal power dissipation due to ground pin current).

The LDO regulator is best suited for battery-powered applications, because the lower dropout voltage translates directly into cost savings by reducing the number of battery cells required to provide a regulated output voltage. If the input-output voltage differential is low (like 1V to 2V) the LDO is more efficient than a Standard regulator because of reduced power dissipation resulting from the load current multiplied times the input-output voltage differential.

1. The designations Standard, LDO, and Quasi-LDO as used in this paper are by no means uniform practice throughout the industry. At this time, National Semiconductor makes only the Standard NPN and LDO regulators (no quasi-LDO types), which means all of our LDO regulators use the single PNP device pass transistor and have dropout voltages < 1V. Another major manufacturer makes only the Standard and quasi-LDO regulators, but advertises and sells the quasi-LDO parts as "Low Dropout Regulators". Still another manufacturer (who makes both the quasi-LDO and LDO types) sells the quasi-LDO units as "Low Dropout" and the LDO units as "Very Low Dropout". It is strongly recommended that the designer read the fine print on the data sheet, to find out what the part will actually do (and not rely on advertising descriptions).

Selecting the Best Regulator For Your Application

The best choice for a specific application can be determined by evaluating the requirements such as:

- Maximum Load Current

- Type of Input Voltage Source (Battery or AC)

- Output Voltage Precision (Tolerance)

- Quiescent (Idling) Current

- Special Features (Shutdown Pin, Error Flag, etc.)

MAXIMUM LOAD CURRENT

The maximum current required in an application should be carefully considered when selecting an IC regulator. The load current specification for an IC regulator will be defined as either a **single value** or a value that is **dependent on input-output voltage differential** (this is detailed in the following section on protection circuits).

The regulator selected must be able to provide sufficient current to the load under worst-case operating conditions, if system performance is to be reliable.

INPUT VOLTAGE SOURCE (BATTERY OR AC)

The available input voltage (battery or AC power) will strongly influence which type of regulator is best suited for an application.

Battery: In battery-powered applications, **LDO regulators are usually the best choice** because they utilize the available input voltage more fully (and can operate longer into the discharge cycle of the battery).

For example, a "6V" lead-acid battery (a popular battery type) has a terminal voltage of about 6.3V when fully charged, and about 5.5V at the end-of-discharge point. If a designer wanted to make a regulated 5V supply powered from this battery, **an LDO regulator would be required** (because there is only about 0.5V to 1.3V available for dropout voltage).

AC: If a DC supply is generated from a rectified AC source, the dropout voltage of the regulator is not as critical because additional regulator input voltage is easily obtained by increasing the secondary voltage of the AC transformer (by adding turns to the secondary winding).

In these applications, a standard regulator is **usually** the most economical choice and can also provide more load current. However, in some cases the **additional features** and **better output voltage precision** of some of the new LDO regulators would still make them the best choice.

OUTPUT VOLTAGE PRECISION (TOLERANCE)

Typical linear regulators usually have an output voltage specification that guarantees the regulated output will be within 5% of nominal. This level of accuracy is adequate for most applications.

There are many new regulators which have tighter output tolerances (better than 2% is common), achieved through the use of a laser-trim process. Also, many of the new regulators have separate output specifications that cover room temperature/full operating temperature range, and full-load/light-load conditions.

QUIESCENT (IDLING) CURRENT

The quiescent current that a part draws from the source when idling (either shut down or not delivering significant amounts of load current) can be of critical importance in battery-powered applications.

In some applications, a regulator may spend most of its life shut off (in standby mode) and only supply load current when a main regulator fails. In these cases, the quiescent current determines the battery life.

Many of the new LDO regulators are optimized for low quiescent current (like 75 to 150 μA), and provide significant improvement over typical regulators which draw several milliamps.

SPECIAL FEATURES

Many LDO regulators offer features that allow the designer greater flexibility:

Shutdown: A low-power shutdown pin allows a regulator to be switched off by a logic gate or microcontroller. This feature also allows wiring a regulator for "Snap-ON/Snap-OFF" operation, which will be covered in one of the design examples presented later.

Load-dump Protection: Regulators used in automotive applications need built-in protection against overvoltage transients (load-dump). In these cases the regulator usually shuts down its output during the overvoltage transient, then recovers after it has passed.

Reverse Input Voltage Protection: This prevents damage to the regulator when the input voltage is reversed, essential in applications where the user can accidentally reverse the polarity of the batteries.

Error Flag: This flag is used to alert monitoring or control circuitry that the output has dropped about 5% below its nominal value. It is intended as a "warning flag" that can alert a controller that supply voltage may be low enough to cause erratic operation of the CPU or associated logic circuits.

Protection Circuits Built Into IC Linear Regulators

Linear IC regulators contain built-in protection circuits which make them virtually immune to damage from either excessive load current or high operating temperature. The two protection circuits found in nearly all linear IC regulators are:

Thermal Shutdown

Current Limiting

CHAIN OF COMMAND

The thermal shutdown, current limiter, and voltage error amplifier make up three distinct and separate control loops that have a definite hierarchy (pecking order) which allows one to "override" the other. The order of command (and importance) of the loops is:

- 1) Thermal Limit (IC is regulating junction temperature/power dissipation)
- 2) Current Limit (IC is regulating load current)
- 3) Voltage Control (IC is regulating output voltage)

This hierarchy means that a linear regulator will normally try to operate in "constant voltage" mode, where the voltage error amplifier is regulating the output voltage to a fixed value. However, **this assumes that both the load current and junction temperature are below their limit threshold values.**

If the load current increases to the limiting value, the current limiting circuitry will take control and force the load current to the set limiting value (overriding the voltage error amplifier). The voltage error amplifier can resume control only if the load current is reduced sufficiently to cause the current limiting circuits to release control. This is covered in detail in the "Current Limiting" section.

A rise in die temperature (regardless of cause) approaching the limit threshold (about 160°C) will cause the thermal shutdown to cut drive to the power transistor, thereby reducing load current and internal power dissipation. Note that the thermal limiter can override **both** the current limit circuits and the voltage error amplifier. Thermal shutdown is detailed in the next section.

It is important to understand that a **regulator holds its output voltage fixed only when it is in constant voltage mode.** In **current limiting, the output voltage will be reduced** as required to hold the load current at the set limiting value.

In thermal limiting, the output voltage drops and the load current can be reduced to any value (including zero). **No performance characteristic specifications apply when a part is operating in thermal shutdown mode.**

THERMAL SHUTDOWN

The thermal shutdown circuitry in an IC prevents the junction temperature from rising high enough to damage the part (see Figure 7). This is accomplished by monitoring the die temperature and reducing internal power dissipation to hold the temperature at the limiting value (usually about 160°C).

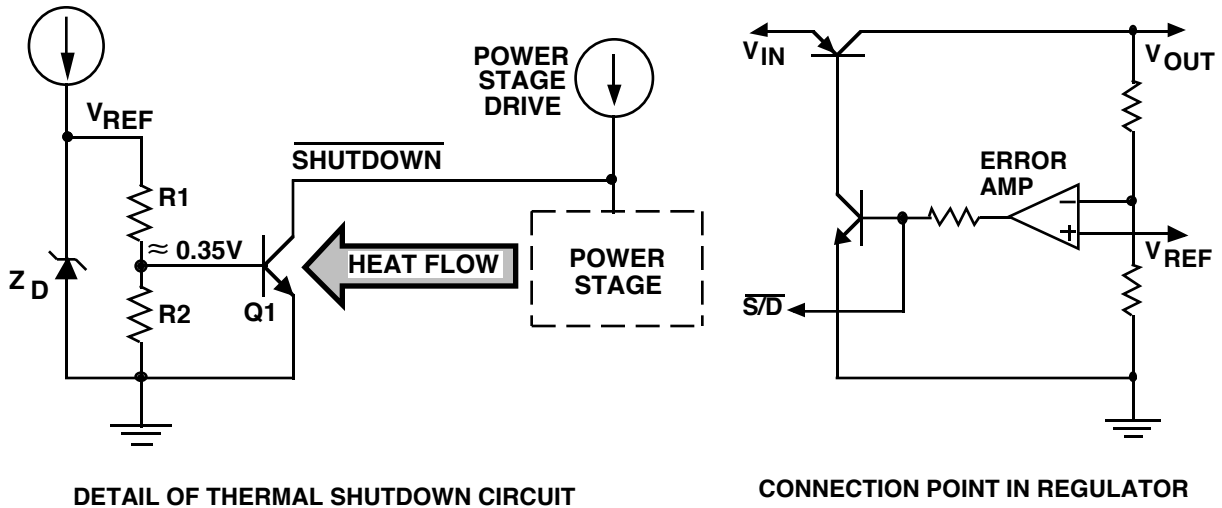


FIGURE 7. THERMAL SHUTDOWN

Circuit Operation:

The temperature sensor (Q1) is located near the power transistor on the die, to assure very close thermal tracking. R1 and R2 hold the base of Q1 at about 0.35V, which corresponds to the turn-on V_{BE} of Q1 at a temperature of about 160°C.

As the die temperature increases, Q1 eventually reaches the turn-on threshold (about 160°C), and starts pulling current away from the current source which supplies drive to the power stage. In this way, the load current is reduced (or cut off entirely) which reduces the internal power dissipation of the regulator.

In cases where thermal limiting occurs, both the output voltage and current will be reduced. When the output voltage drops below its nominal value, the error signal appearing at the voltage error amplifier will cause it to try and correct the regulator output voltage by driving its output high (and sourcing more current to the pass transistor).

The thermal limit circuit can sink all of the current from the error amplifier output, and keep the regulator output voltage/current as low as needed to maintain the junction temperature at 160°C. As shown, the thermal limiter can "override" the voltage control loop when needed to prevent damage to the IC.

CURRENT LIMITING

The function of current limiting circuitry is to prevent damage to the IC when an overload is placed on the output of the regulator (the load impedance is too low). Without current limiting, the regulator would source excessive load current and destroy the pass transistor inside the part.

To prevent this occurrence, the current limit circuit will override the voltage control loop, and cut down the drive to the pass transistor so that the maximum safe current level is not exceeded.

There are two basic types of current limiting circuits most commonly used in linear regulators (detailed in the next sections):

Constant Current Limiting

Voltage-Dependent Current Limiting (sometimes called "Foldback Limiting")

CONSTANT CURRENT LIMITING

The maximum current that a linear regulator can supply to a load is specified on the data sheet. Many regulators (and most LDO regulators) specify only a single value of maximum current. This value is guaranteed for any input/output voltage within the maximum ratings for the part.

For example, the LP2952 is guaranteed to source **at least 250 mA** without going into current limiting, as long as the output is in the 1.25V - 29V range and the input voltage is at least 0.8V above the output.

In Figure 8, a simplified schematic diagram is shown of a circuit that will provide constant current limiting. This is a "discrete" design implementation (the circuitry used in an IC regulator may be slightly different).

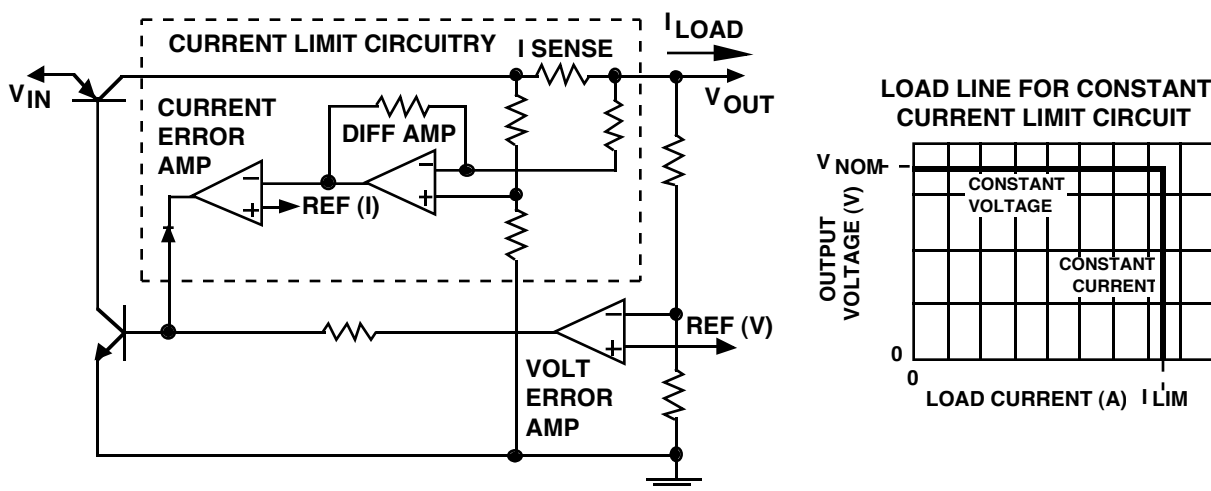


FIGURE 8. CONSTANT CURRENT LIMIT CIRCUIT

Circuit Operation:

The load current is sensed by the "I SENSE" resistor, which develops a voltage that is directly related to the current. This voltage is level shifted (and amplified) by the differential amplifier.

The voltage at the output of the differential amplifier is a ground-referenced signal that is proportional to the load current. This "load current" signal coming from the differential amplifier is applied to the inverting input of the current limit error amplifier, while the non-inverting input is connected to a reference voltage. The value of this reference voltage would be equal to the voltage at the output of the differential amplifier when the regulator is driving maximum current (at the current limit point).

Note that as long as the load current is below the limit threshold, the output of the current error amplifier is high (and the voltage error amplifier keeps the regulator in **constant voltage** mode).

When the load current reaches the limit threshold, the output of the current error amplifier drops low and starts sinking current away from the output of the voltage error amplifier (this puts the regulator in **constant current** mode).

When current limiting occurs, the regulator output voltage will drop below its nominal value, which will be sensed by the voltage error amplifier as an undervoltage condition. The voltage error amplifier will drive its output high in an attempt to raise the output voltage, but the current error amplifier can sink all of the current coming from the voltage error amplifier. Like the thermal limiter, the current limiter overrides the voltage error amplifier to prevent damage to the IC.

The load line shown in Figure 8 illustrates how the output voltage is held constant up to the point where the load current reaches the limit value, where the regulator crosses over into constant current mode. **When operating in constant current mode**, the IC regulates the load current to the "limit" value, which means **the output voltage may be any value down to zero volts**.

It should be made clear that the thermal limiter can always override the current limiter, and **can reduce the output voltage and current to any value necessary to maintain a junction temperature of about 160°C**.

For example, if the **LP2952** (which is rated for **250 mA**) is shorted from the output to ground, a **current will flow from the output which is greater than 250 mA but less than 530 mA** (see "Current Limit specification on the data sheet).

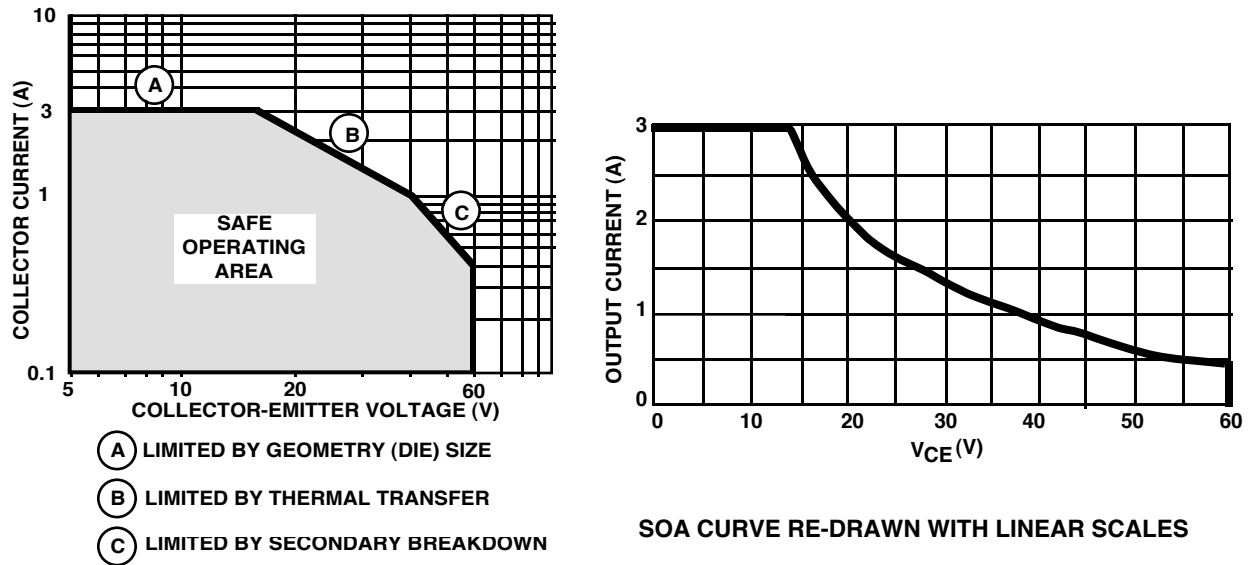
However, if the input voltage is high enough to generate sufficient power to activate the thermal limiter, that current will drop off as the LP2952 regulates its die temperature to about 160°C.

Important: Current limit circuits are (by necessity) very high-speed circuits, and input bypass capacitors on the regulator are always recommended to prevent possible device failure due to interaction with the input source impedance.

VOLTAGE DEPENDENT (FOLDBACK) CURRENT LIMITING

Voltage regulators which are relatively high current ($>1\text{A}$) use a type of current limiting where the maximum allowable value of load current is dependent on the input-output voltage differential across the part.

The reason this is required is due to a characteristic of all transistors called Safe Operating Area (SOA) that limits the amount of current a transistor can safely handle as the voltage increases (see Figure 9).



SOA CURVE FOR 3A/60V NPN TRANSISTOR

FIGURE 9. SOA CURVES FOR 3A/60V NPN TRANSISTOR

The data shown in the SOA curve were taken from a published data sheet for a TIP31A (3A/60V) NPN transistor. The important information on the SOA curve is that the safe **operating current value drops to about 15% of maximum when the voltage across the part (V_{CE}) is at its full rated value.** If the full 3A current rating is to be used, the V_{CE} can not exceed about 14V.

It is important to realize that **the input-output voltage across a linear regulator is also the V_{CE} across its pass transistor.** This means **the load current must be limited in accordance with the SOA curve of the regulator pass transistor.**

The current limit curve for a linear regulator must fit "**under**" the SOA curve for the pass transistor if the device is to survive under all overload conditions. The current limit curve for the LM317 will be detailed later (in Figure 11) to illustrate this. It can be seen the shape of the curve resembles the SOA curve in Figure 9 drawn on linear axes.

CONSTANT CURRENT vs. FOLDBACK LIMITING

Constant current and foldback limiting have different characteristics that have the potential to cause some confusion.

Assuming that the designer wished to test the current limiting, he could use an adjustable power resistor connected to the output of the regulator (see Figure 10). As the resistance is adjusted to lower values (and the load current increases), the point will eventually be reached where current limiting occurs.

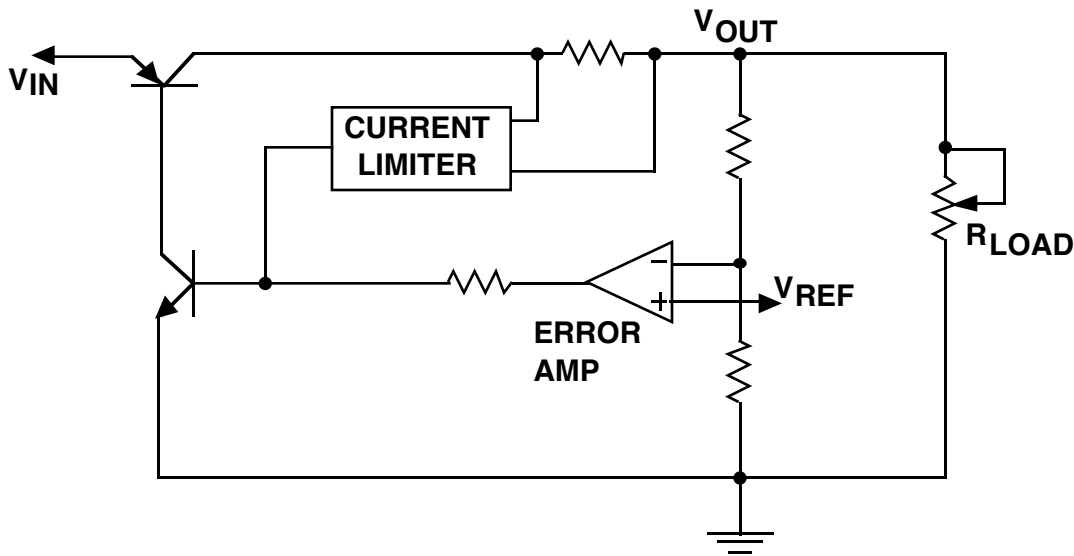


FIGURE 10. CURRENT LIMIT TEST CIRCUIT

Constant Current Limiting: When current limiting first occurs, the output voltage is seen to drop from its nominal value as the regulator goes from constant voltage mode to constant current mode of operation.

As the load resistance is decreased and current limiting occurs, **the amount that the output voltage drops is directly proportional to the decrease in load resistance** (because the load current is held **constant**).

The drop in output voltage can be made to occur gradually, and the output voltage can be moved up and down by adjusting the load resistance.

If the load resistance is increased above the point where the current limiter activated, the regulator will automatically go back into constant voltage mode (the output voltage will be in regulation).

Foldback Limiting: The action of a foldback limiting circuit is different, because it has some "**hysteresis**" built in to it. As the load resistance decreases to the point where limiting occurs, the output voltage can drop suddenly from the nominal voltage to a much lower value.

Returning the load resistance back to the value where limiting started may not restore the output voltage to nominal (the load resistance may have to be increased to a **higher value** to allow the regulator to return to constant voltage operation). This apparent "hysteresis" is due to the shape of the "foldback" current limit curve (see Figure 11).

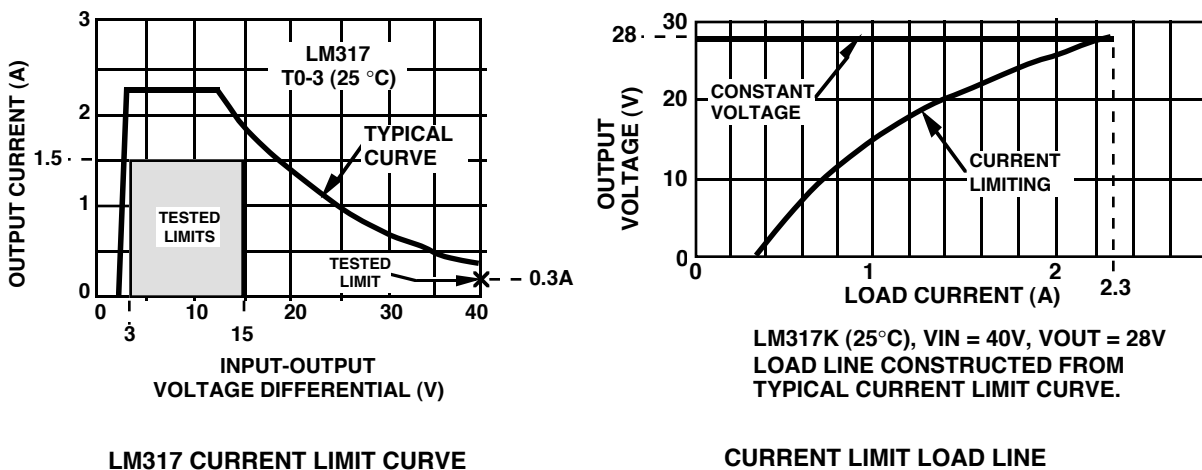


FIGURE 11. FOLDBACK CURRENT LIMIT EXAMPLE

The example shown by the load line was constructed using the typical current limit values, assuming $V_{IN} = 40V$ and $V_{OUT} = 28V$. The shape of the load line explains why the term "**foldback**" is applied, as the load current values are seen to drop with decreasing output voltage.

Explaining how foldback limiting causes hysteresis requires presenting the information in Figure 11 in a slightly different way:

The portion of the load line showing current limiting will be used to generate data points of load resistance that are equivalent to each voltage/current value along the curve (the constant voltage portion is not plotted).

The current limit resistance load line (shown in Figure 12) represents the load resistance values which correspond to the various operating points while the regulator is in the current limiting region of operation.

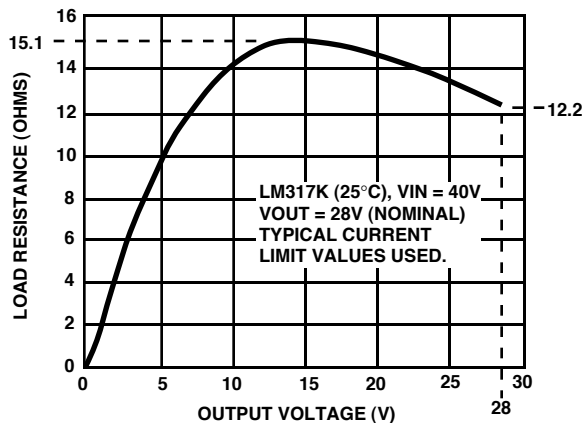
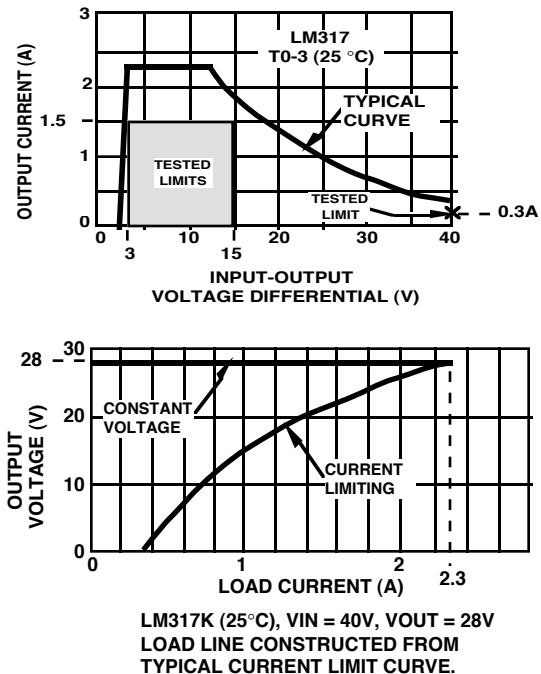


FIGURE 12. RESISTANCE LOAD LINE FOR LM317 EXAMPLE (IN CURRENT LIMITING)



The curve in Figure 12 can explain how foldback limiting can cause a "hysteresis" in the output voltage as the load resistance is decreased. For example:

1) Assume the **output is at 28V** (constant voltage operation) and the **load resistance is set to 14Ω ($I_L = 2A$)**. The load resistance is then gradually **reduced to 12.2Ω** . The load current will then be sufficient to cause current limiting (since this is the value shown on the curve for $V_O = 28V$), and the output voltage will abruptly drop to the point on the load line equal to 12.2Ω . **This point corresponds to an output voltage of about 7V.**

2) In an attempt to restore the output to constant voltage operation ($V_O = 28V$), the load resistance is returned to 14Ω , where it had been operating previously with a 28V output. **Doing this will not return the output to 28V**, rather the operating point will go back up the load line to the first point where 14Ω is seen (at **$V_O = 10V$**).

To get the output back up to 28V, the load resistance has to be increased above 15.1Ω , so the operating point can get "over the bump" in the curve. If the resistance were increased gradually, the output voltage would climb slowly up to about 14V and then "jump" up to 28V.

With the example shown, **there is no value of load resistance that can be placed on the regulator output to force it to operate at output voltages between 14V and 28V**. This is the cause of the "hysteresis" that can be seen in some applications where a regulator with foldback limiting is operated at a load current where the limiting action can be made to occur.

Application Hints for Linear Regulators

Application information will be presented on subjects related to mistakes often made in applying linear regulators.

Output Capacitance Affecting Regulator Loop Stability

The output capacitor used on an LDO linear regulator can make it oscillate if the capacitor is not selected correctly.

CAPACITOR PARASITICS

Every real capacitor contains unwanted parasitic elements which degrade its electrical performance (see Figure 13).

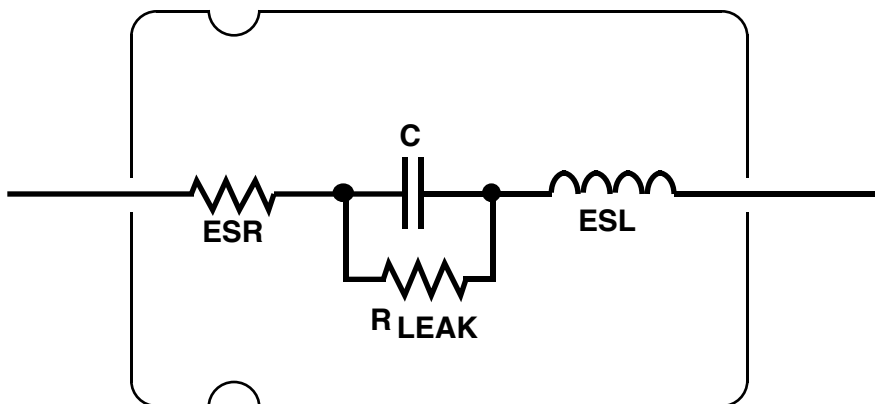


FIGURE 13. MODEL OF A REAL CAPACITOR

The most important elements are the **Equivalent Series Resistance (ESR)** and **Effective Series Inductance (ESL)**.

The **ESL limits a capacitors effectiveness at high frequencies**, and is the primary reason electrolytic capacitors must be bypassed by good RF capacitors in switching regulator applications (ceramic and film types are often used).

The **ESR is the primary cause of regulator loop instability in both linear LDO regulators and switching regulators**. In order to understand this, a brief review of loop theory will be presented to illustrate the effect of ESR on loop response.

REGULATOR LOOP RESPONSE

The loop response of a typical regulator is shown in Figure 14. The most important point to realize is that **for a stable loop, the gain must cross below 0 dB before the phase angle reaches 180°**.

A phase angle of 180° means that the signal being fed back around the loop is actually positive feedback, and will cause oscillations to occur.

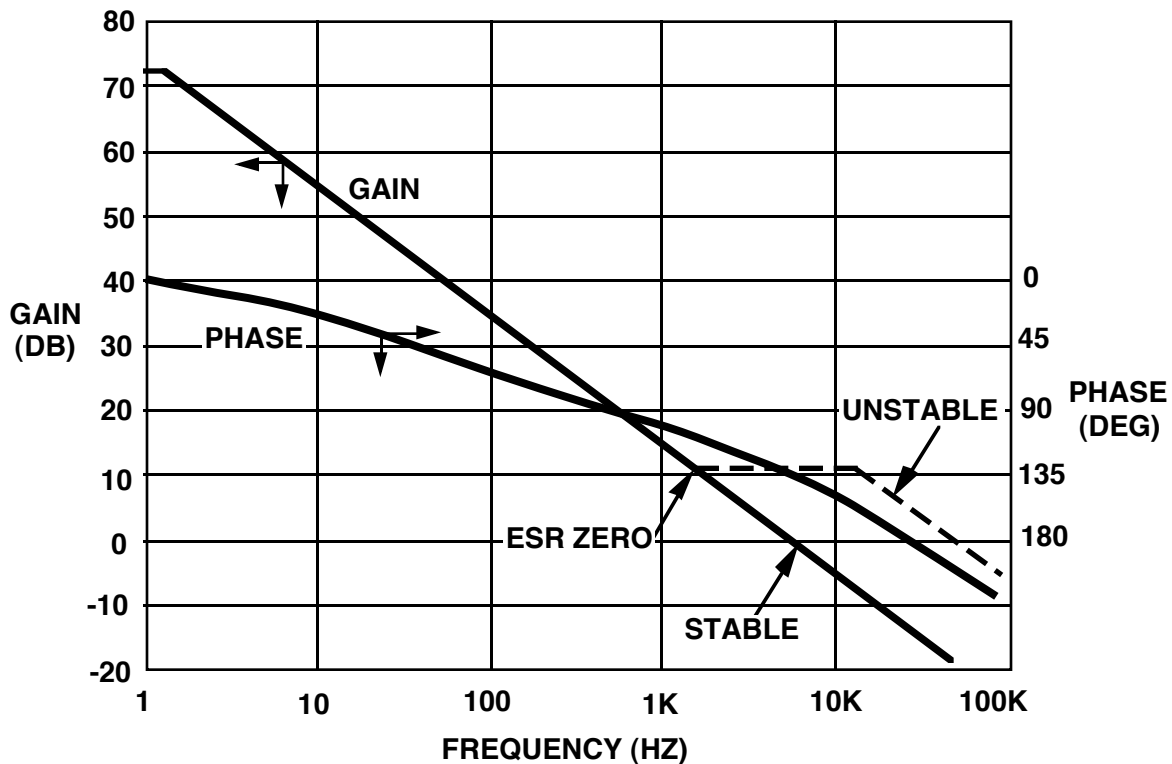


FIGURE 14. LOOP GAIN PLOT

(Note: In reality, a phase margin of 45° is usually required for good stability, which means it is advisable to get a 0 dB crossover before the phase angle reaches 135°).

In an LDO regulator, the output capacitor is required to force the gain to roll off fast enough to meet the stability requirements (a standard NPN regulator is internally compensated, and usually needs **no** output capacitor for stability).

As shown in Figure 14, the ESR of the output capacitor causes an unwanted "zero" in the response, which delays the 0 dB crossover point. **If the ESR is large enough, the "zero frequency" gets low enough to cause regulator instability.**

The stability requirements for a specific regulator will be listed on the data sheet for the part. In some cases, **a range is given which requires that the ESR be within the minimum and maximum limits**. In the newer parts, only a maximum limit must be met (which makes selecting a capacitor much easier).

TEMPERATURE DEPENDENCE OF ESR

Having now established the necessity of controlling the ESR of the output capacitor on an LDO regulator (to keep the regulator from oscillating), we need to point out one very important thing: **ESR is not constant with temperature.**

Figure 15 shows a plot of ESR versus temperature for a typical aluminum electrolytic capacitor. The most important point to observe is how fast the ESR increases at low temperatures.

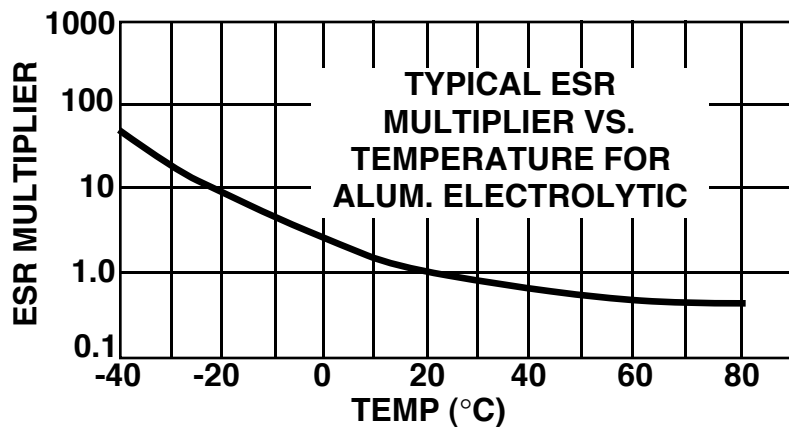


FIGURE 15. ALUMINUM ELECTROLYTIC ESR VS. TEMPERATURE

In cases where an LDO regulator must be operated below about -10°C , it is sometimes not possible to find an aluminum electrolytic capacitor that can maintain an ESR within the acceptable range. Also, it is essential that the capacitor is specified to operate over the full temperature range: **some aluminum electrolytics are not usable below -20°C** (because their electrolyte freezes).

If the regulator has only a **maximum** limit which the ESR must not exceed, the aluminum electrolytic capacitor can be paralleled with a solid tantalum capacitor (which has a much lower ESR).

When two capacitors are in parallel, the effective ESR is the parallel of the two ESR values, which means the tantalum will help suppress the low-temperature ramp up seen in Figure 15. As a good rule, the tantalum should be selected so that its capacitance is about 20% of the aluminum electrolytic.

If the regulator has **both a maximum and minimum limit** (the ESR must stay in a specified range), it may be necessary to use a low value carbon film resistor placed in series with a low ESR capacitor (tantalum, film, or ceramic will work).

The best type of capacitor to use will depend upon how much total capacitance is required.

Load Regulation

The load regulation that a linear regulator **can** deliver is often much better than what is actually seen in the application due to voltage drops occurring along high-current paths. To understand how and why this occurs, we will look at examples of fixed and adjustable linear regulators.

FIXED OUTPUT REGULATORS

A typical application will be examined using an LM7805 three-terminal regulator (see Figure 16).

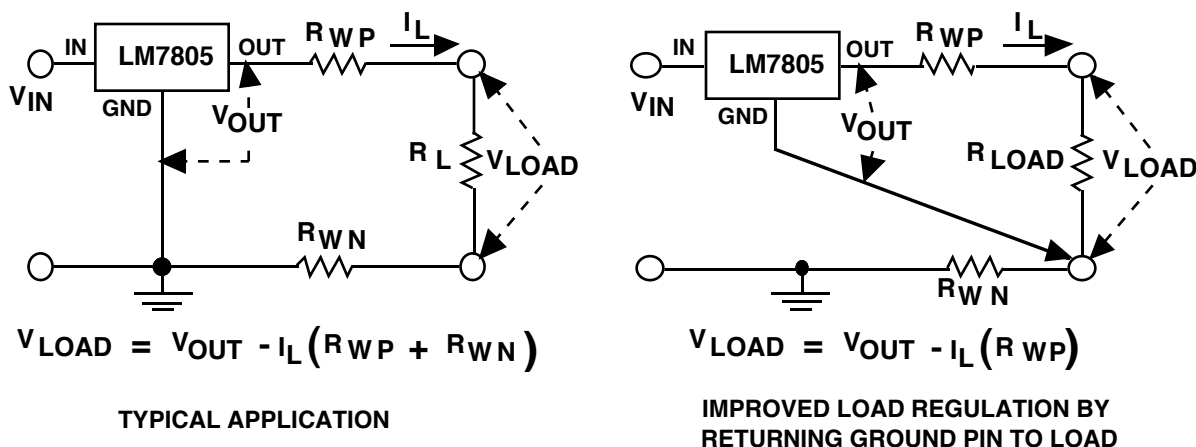


FIGURE 16. LOAD REGULATION EFFECTS DUE TO WIRE DROPS

The user is most interested in the voltage at the load, but the LM7805 is regulating the voltage that appears between its output and ground pins. Any voltage drops that occur between the regulator pins and the load terminals reduce the voltage across the load (and degrade the load regulation).

In the typical application, V_{LOAD} is always less than V_{OUT} by the sum of the voltage drops appearing along the positive PC board trace (or wire) and the negative trace (or wire). The voltage drops along the leads are equal to the resistances (shown as R_{WP} and R_{WN}) multiplied times the load current.

This shows very clearly how trace resistance can cause "voltage errors" to occur at the load terminals, with the amount of "error" being directly related to the load current. In such cases, the regulation seen at the load would be considerably worse than the specification for the IC regulator.

This can be improved in two ways:

- 1) Move the regulator ground lead over and tie it directly to the negative load terminal, so that no other current can flow in this lead and cause voltage drops.
- 2) Minimize the drop in the positive lead by using the maximum possible conductor thickness, and place the IC regulator as near the load as is physically possible.

ADJUSTABLE OUTPUT REGULATORS

Adjustable linear regulators are different from fixed output types because an external resistive divider (along with the internal reference) is used to set the output voltage.

Three-Terminal Regulators

In the three-terminal adjustable regulators (like the **LM317**), the **reference voltage appears between the output pin and the adjust pin** (see Figure 17).

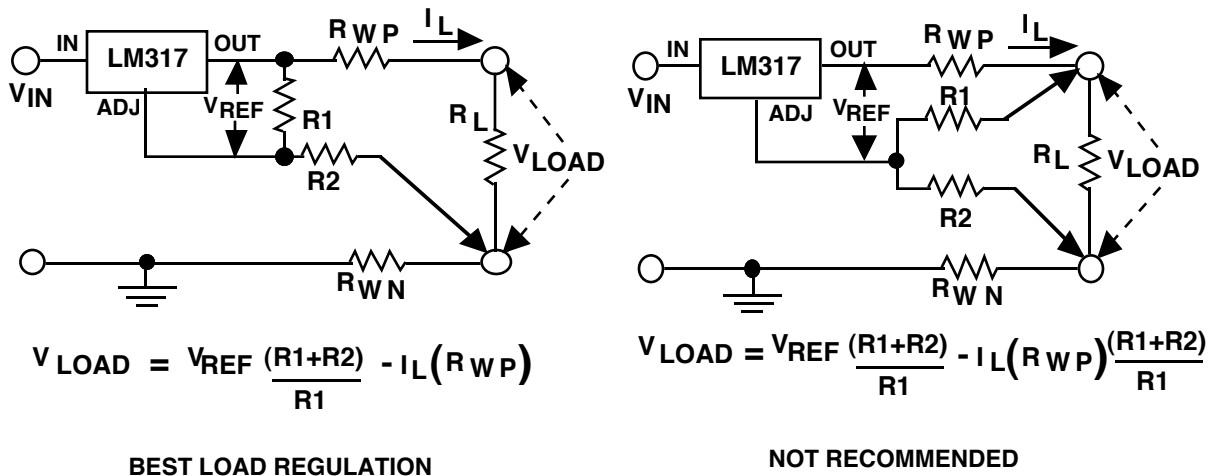


FIGURE 17. LOAD REGULATION EFFECTS USING LM317 REGULATOR

In the circuit for best load regulation, it is shown that the voltage appearing across the load is reduced from the nominal (no load) output voltage by **the voltage drop that results from the positive side trace resistance multiplied times the load current**.

As before, the **best performance** is obtained with the negative (ground) side of the resistive divider tied directly to the negative load terminal. This technique eliminates the drop in the negative high-current output trace (R_{WN}) from causing an additional decrease in V_{LOAD} .

It seems intuitively correct that an additional improvement would be obtained by tying the top side of the divider string to the positive load terminal, but this assumption is **ABSOLUTELY WRONG**.

The voltage V_{REF} is used to force (set) a constant current through both $R1$ and $R2$, and the precision of the output voltage is directly related to the accuracy of this current. If $R1$ is tied to the positive load terminal, the voltage drop across R_{WP} is subtracted from V_{REF} , reducing the current through the divider.

The overall effect of the current change is that the voltage "error" is multiplied by the ratio of $(1 + R2/R1)$, making the load regulation much worse.

Multi-pin Regulators

Adjustable regulators which are not limited to three pins have the advantage of using a ground pin, which allows the elimination of the output voltage error due to voltage drops along the output traces.

An example of such a regulator is the LP2951, a multi-function 250mA LDO regulator that can be adjusted to output voltages from 1.23V to 29V. In Figure 18, we see an LP2951 in a typical application. The voltage error at the load due to trace voltage drops is eliminated in the left-hand figure.

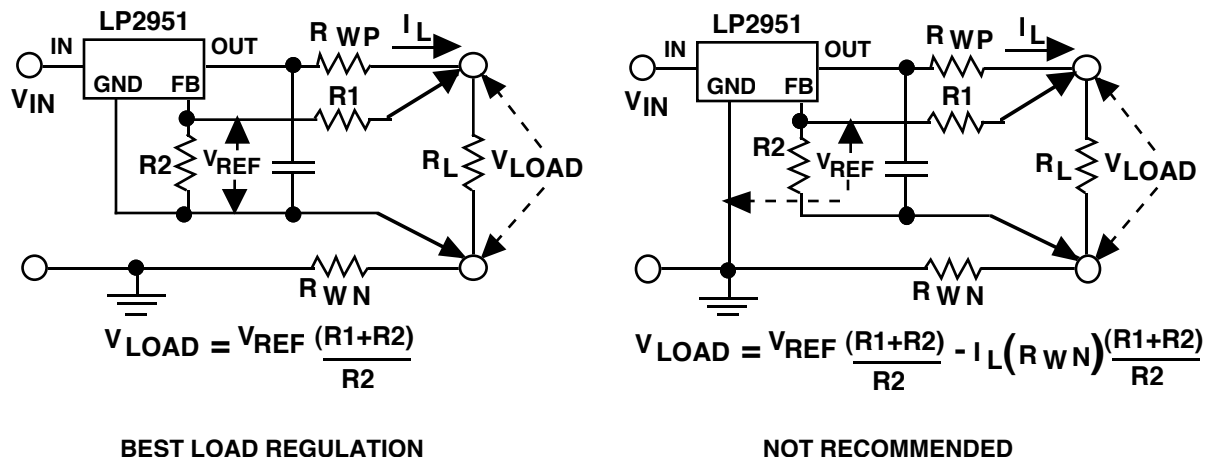


FIGURE 18. ELIMINATING LOAD REGULATION EFFECTS IN THE LP2951 REGULATOR

Note that the reference voltage in the LP2951 is regulated with respect to the ground pin, unlike the three-terminal adjustable regulators which have no ground pin. The discussion of this application is equally applicable to any regulator whose reference is regulated against ground.

In the left-hand figure, the trace voltage errors have been eliminated by tying the sense points of the resistive divider to the load terminals. **Important:** if this remote-sense method is used, the **ground pin must also be tied to the negative load terminal to prevent significant errors in V_{LOAD}** (see the right-hand figure).

If the ground pin and the lower sense point of R2 are separated, the voltage between these two points is multiplied by the ratio of $(1+R1/R2)$ and appears as an error in the voltage V_{LOAD} . Since this error voltage is load current dependent, the voltage V_{LOAD} will also change with load current, resulting in poor load regulation.

For best load regulation, R2 should be located near the regulator with the ground pin tied directly to it. Then a single trace should be run to the negative load terminal, remembering that the trace size should be sufficient to assure a negligible voltage drop will occur along this lead when the part is conducting its maximum ground pin current (ground pin current can be as high as 45 mA in a 1A LDO regulator).

The Carrot in LDO Regulator Ground Pin Current

Many (but not all) LDO regulators have a characteristic in their ground pin current referred to as the "carrot". The carrot is a point in the ground pin current that spikes up as the input voltage is reduced (see Figure 19).

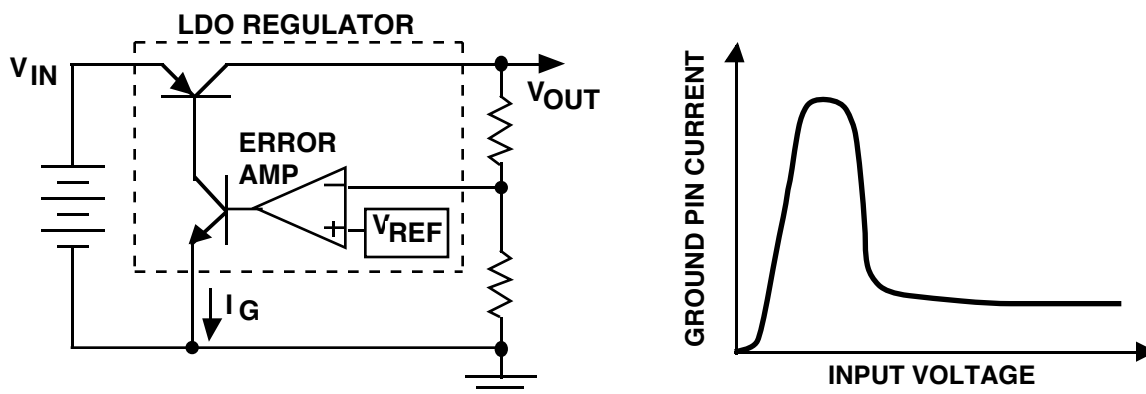


FIGURE 19. LDO REGULATOR WITH "CARROT"

The error amplifier in a regulator always tries to force the output to be the right voltage by adjusting the current through the pass device (in this case, the PNP transistor).

As the input voltage is reduced (and the voltage across the pass transistor decreases) the current gain of the PNP begins to drop. To maintain the correct output voltage, the error amplifier has to drive the base of the PNP harder to supply the same load current. The PNP base drive current leaves the regulator as ground pin current.

As the input voltage drops further, the regulator will approach dropout, causing the error amplifier to drive the PNP base with maximum current (this is the top of the carrot). This value of current may be 3 or 4 times the maximum ground pin current that is required to drive full rated load current with 5V across the pass transistor.

The carrot is recognized as an undesirable characteristic, since the additional ground pin current must be supplied by the source, but does not power the load (it just heats up the regulator).

In the newer LDO regulators, circuitry was built in to prevent this ground pin spike from occurring. For example, the **LP2951** (and all of the products in that family) have only a negligible increase in ground pin current as the input voltage crosses through the range where dropout is occurring.

Application Circuits

Introduction

Application circuits will be introduced which highlight some of the useful features of the new LDO regulators.

Adding External Shutdown Function to a 5V Regulator

The **LP2954** is a new LDO regulator that provides a **precision 5V** output at **load currents up to 250 mA**. The part does not have electronic shutdown built in, but it can be added using a few external components.

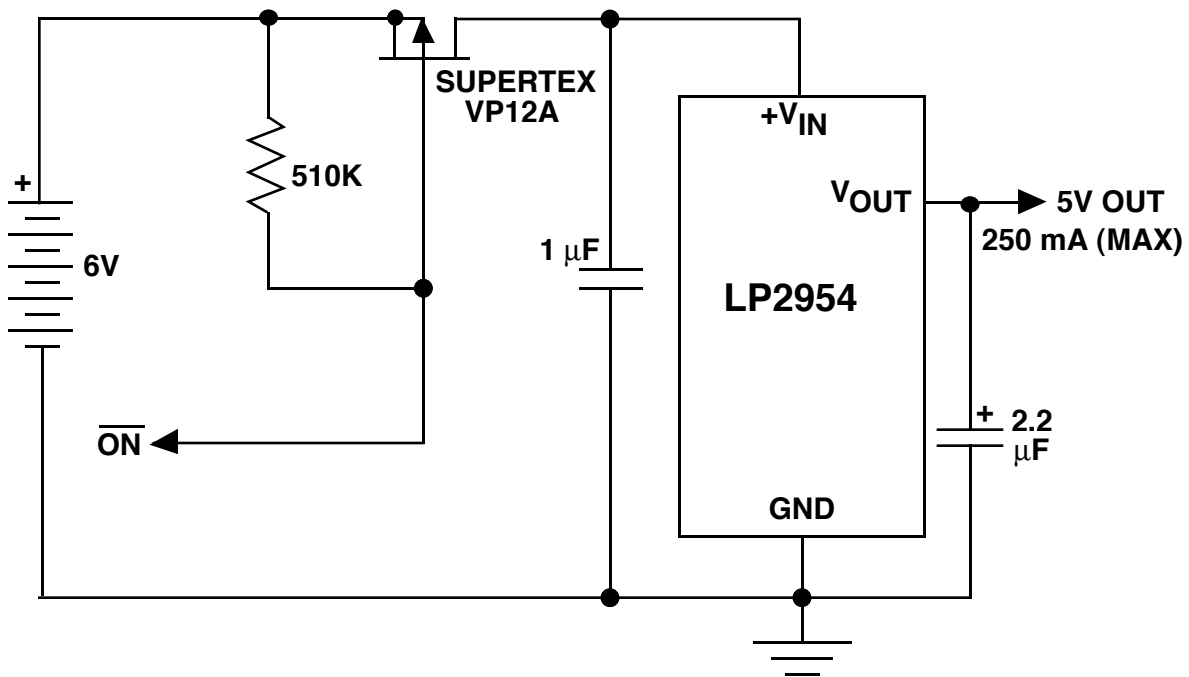


FIGURE 20. PRECISION 5V REGULATOR WITH LOW-POWER SHUTDOWN

A low-power (logic compatible) shutdown can be added by using a P-FET in the input lead as an ON/OFF switch (see Figure 20). If the load current is < 300 mA, there are FET devices available which have very low power losses at these currents. The FET must be a "logic level" type, which means the turn-ON/turn-OFF threshold is between 1V and 3V.

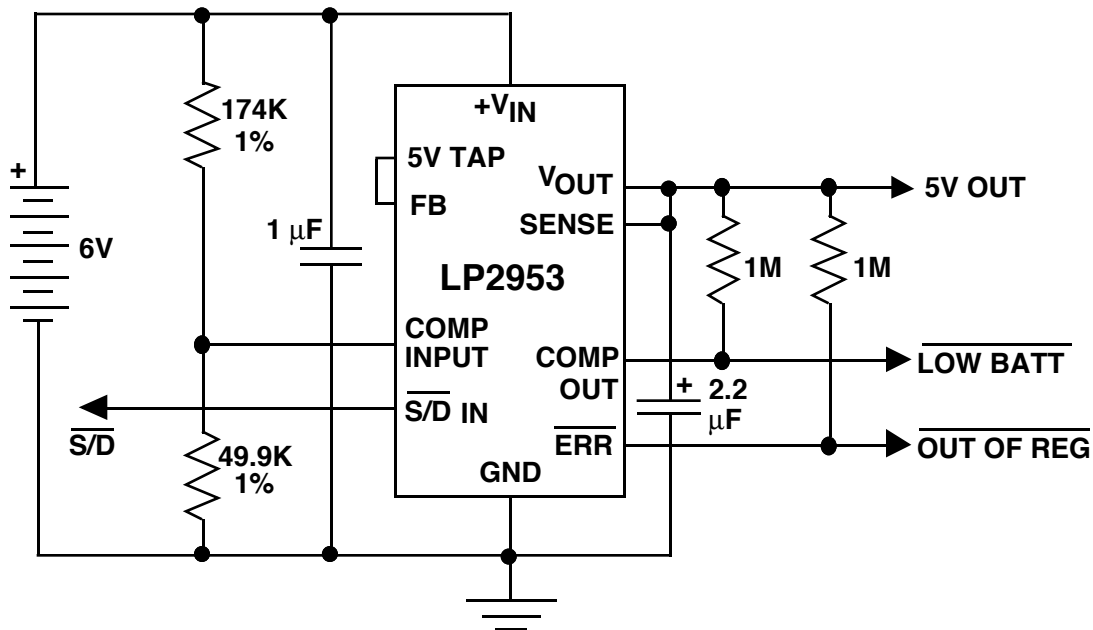
Another advantage of this type of shutdown is that when the FET is off, the only drain current flowing from the battery is the leakage of the FET. This means the quiescent current of the regulator is no longer the determining factor in the standby life of the battery (the leakage of the FET is).

5V REGULATOR FLAGS LOW BATTERY AND LOW OUTPUT

A primary concern for a designer is building in a status flag that warns the system controller of two important conditions:

- 1) Battery Nearing End-of-Life
- 2) 5V Output Has Dropped Out of Regulation

The LP2953 is a multi-function, adjustable-output regulator which can provide 250 mA of load current. It also has a built-in error flag which goes low when the regulated output drops about 5% below its nominal value.



LOW BATT FLAG GOES LOW WHEN BATTERY VOLTAGE FALLS TO 5.5V.

**OUT OF REGULATION FLAG GOES LOW WHEN OUTPUT DROPS 5%
BELOW NOMINAL VALUE (LOAD CURRENT DEPENDENT)**

FIGURE 21. 5V REGULATOR WITH LOW BATTERY FLAG

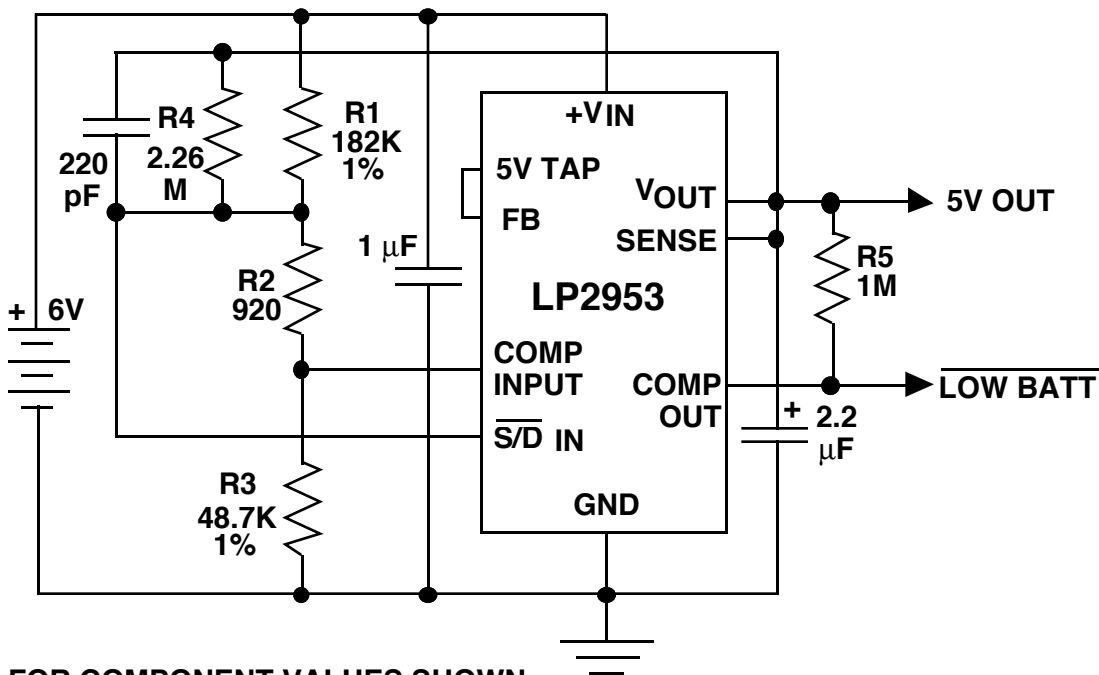
Figure 21 shows an application where the LP2953 is used to provide a precision 5V rail, with the added feature of alerting when the battery is low.

The LP2953 contains an auxiliary comparator, which is used in this application to monitor the input voltage. When the battery voltage discharges down to 5.5V, the output of the comparator goes low (this corresponds to 1.1V/cell, if 5 NI-CAD cells are used).

The LP2953 also provides low-power shutdown, which enables the controller to power down the unit and prevent over-discharge of the battery.

SNAP ON/SNAP OFF OUTPUT PREVENTS μ P ERRORS

Microprocessors can malfunction when their supply voltage drops below 3V. Unfortunately, many of the newer microprocessors remain active (alive) down to voltages as low as 1.5V. This requires that the designer make sure that the supply voltage does not remain in the area where problems can occur for any significant period of time.



**FOR COMPONENT VALUES SHOWN:
OUTPUT SNAPS ON WHEN BATTERY VOLTAGE EQUALS 5.84V
OUTPUT SNAPS OFF WHEN BATTERY VOLTAGE DROPS TO 5.44V
LOW BATTERY FLAG GOES LOW WHEN BATTERY VOLTAGE EQUALS 5.55V**

**FIGURE 22. 5V REGULATOR WITH SNAP-ON/SNAP-OFF
OUTPUT AND LOW BATTERY WARNING FLAG**

Figure 22 shows the LP2953 regulator (adjustable output, 250 mA) wired for snap-ON/snap-OFF output function. The part has a low-power shutdown pin, which is used in the circuit shown to control the output during power-up and power-down.

In this application, the output is "pin-strapped" for 5V using the built-in resistive divider (this means that the guaranteed limits on the data sheet are applicable for output voltage accuracy).

The auxiliary comparator is used in this example to warn of a low battery condition (and alert the user that shutdown is imminent).

CIRCUIT OPERATION:

The resistive divider made up of R1, R2, and R3 controls the voltages applied to the shutdown input and the auxiliary comparator input. Since this divider is tied from the input voltage to ground, the voltages continuously "follow" the input voltage (which reflects the state of charge of the battery).

The battery is assumed to be rechargeable (NI-CAD or Lead-Acid), which means it can be damaged by over discharge. To prevent this, the values of R1, R2, and R3 are selected to force the 5V output to shut off when the battery voltage drops to about 5.44V.

The resistive divider holds the 5V output off until the input voltage rises up to 5.84V (the difference between the turn-ON and turn-OFF point is set by R4).

The output of the auxiliary comparator is used as a warning flag to alert the user that the battery is nearing the point where shutdown is imminent (which allows work to be saved before the automatic shutdown occurs). The warning flag goes low when the battery reaches about 5.55V (which is about 0.1V before the point of shutdown).

The 5V output is always on ($V_O = 5V$) or off ($V_O = 0V$), because intermediate levels are prevented from occurring. This is shown graphically in Figure 23, which is a timing diagram for the circuit.

When the battery voltage is first applied at turn on, the input voltage ramps up as internal capacitances are charged. The regulator is held off until the input reaches 5.84V, at which point it snaps on.

When the battery voltage is removed (turn off) the input voltage decays as the internal capacitances are discharged. The 5V output snaps off when the input gets down to 5.44V. The LP2953 has an internal 50 mA crowbar to bring the output down quickly.

Using this method, the regulator is never allowed to be operational at any input voltages which could cause an output in the range of $0 < V_O < 5V$.

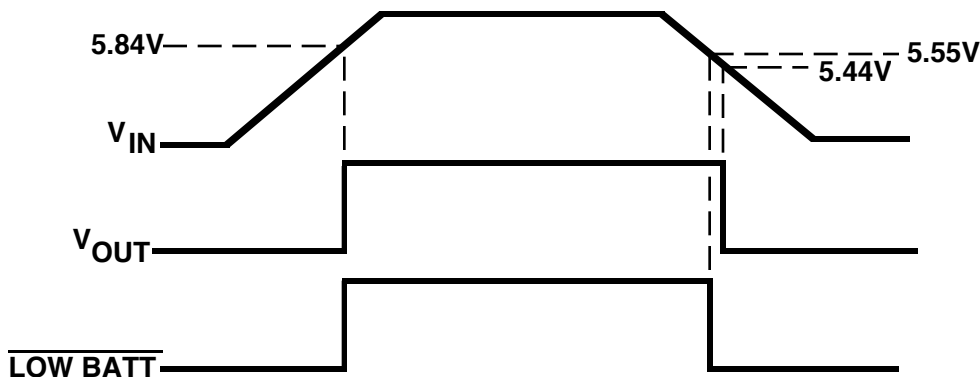


FIGURE 23. SNAP-ON/SNAP-OFF TIMING DIAGRAM

NEGATIVE LDO REGULATORS

In addition to positive output regulators, National Semiconductor also makes negative output LDO regulators:

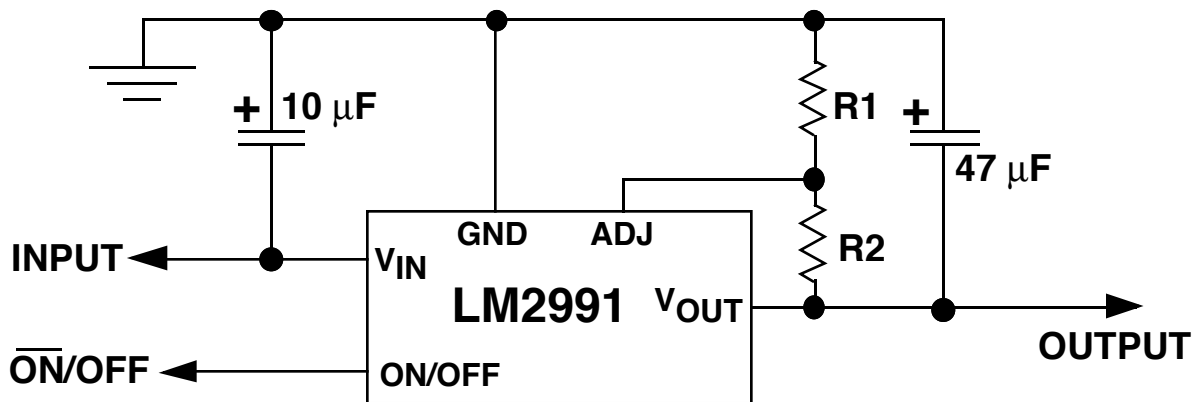
The **LM2990** is a 1A, fixed output regulator in a 3-lead TO-220 package which is offered in -5V, -5.2V, -12V, and -15V voltage options.

The adjustable output version of the LM2990 is the **LM2991** (in the 5-lead TO-220 package) which also has low-power electronic shutdown. An important feature of the LM2991 is that the **shut down is positive-logic compatible** (even though the regulator has negative input/output voltages).

A very big advantage of negative LDO regulators (compared to positive LDO regulators) is that the negative versions use a single NPN power transistor for the pass device. The **higher gain of the NPN in the negative LDO** (compared to the PNP in the positive LDO) **results in much lower ground pin current when driving full load current**.

The LM2940 (a 1A positive LDO regulator) requires a maximum of **45mA** ground pin current to supply 1A of load current. The negative 1A version (LM2990) can drive 1A of load current with **only 5mA of ground pin current**. Note: both specifications apply when the input-output voltage differential is 5V.

The typical application for the LM2991 is shown in Figure 24.



$$V_{OUT} = V_{REF} (1 + R2/R1)$$

FIGURE 24. LM2991 NEGATIVE LDO REGULATOR