

**LM2940,LM2990,LM2991,LM309,LM317,LP2951,  
LP2952,LP2953,LP2954**

*Linear and Switching Voltage Regulator Fundamental Part 1*



Literature Number: SNVA558

# 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).

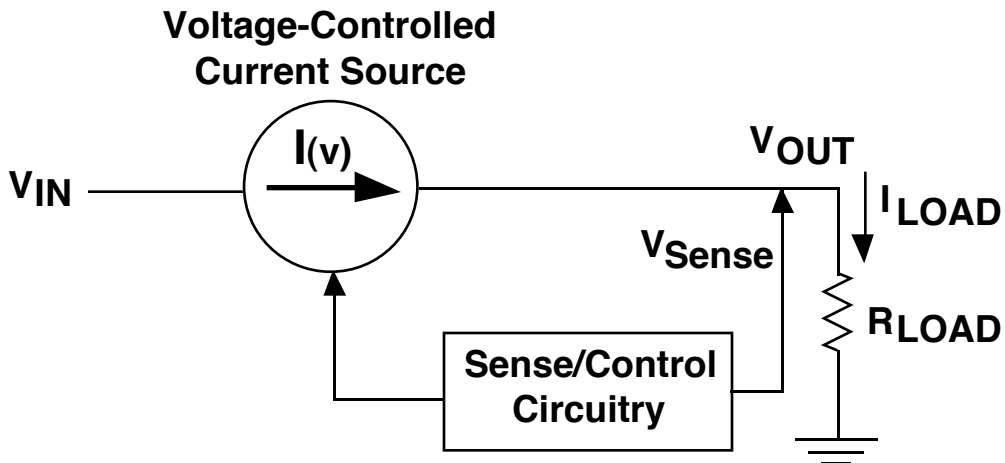


FIGURE 1. LINEAR REGULATOR FUNCTIONAL DIAGRAM

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).

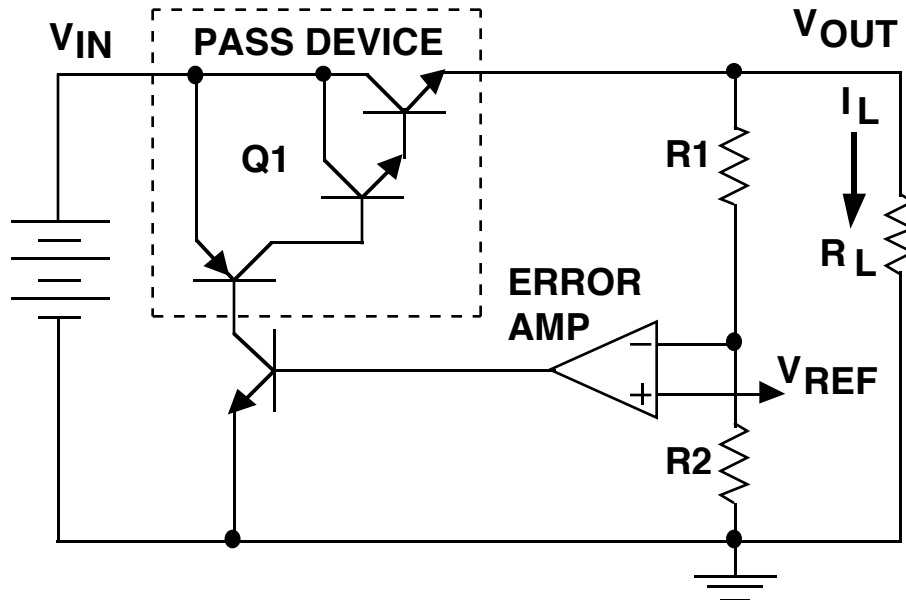


FIGURE 2. DIAGRAM OF A TYPICAL LINEAR REGULATOR

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).

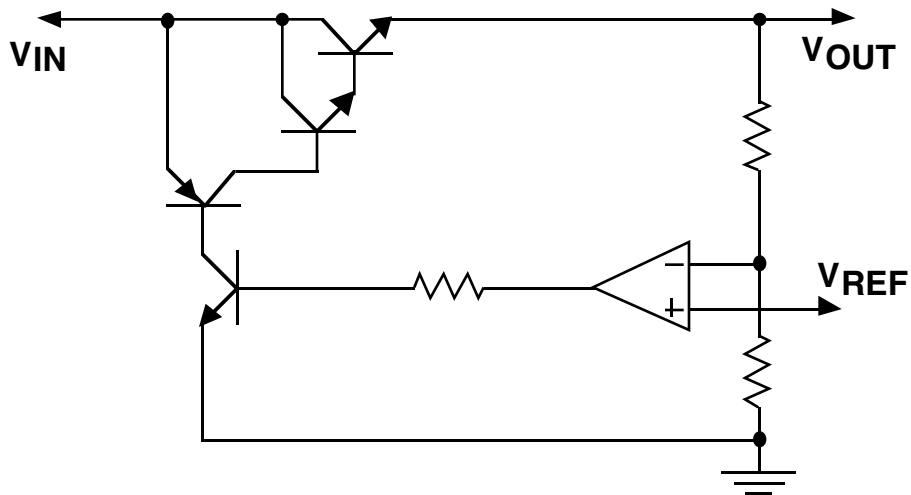


FIGURE 3. STANDARD (NPN) REGULATOR

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).

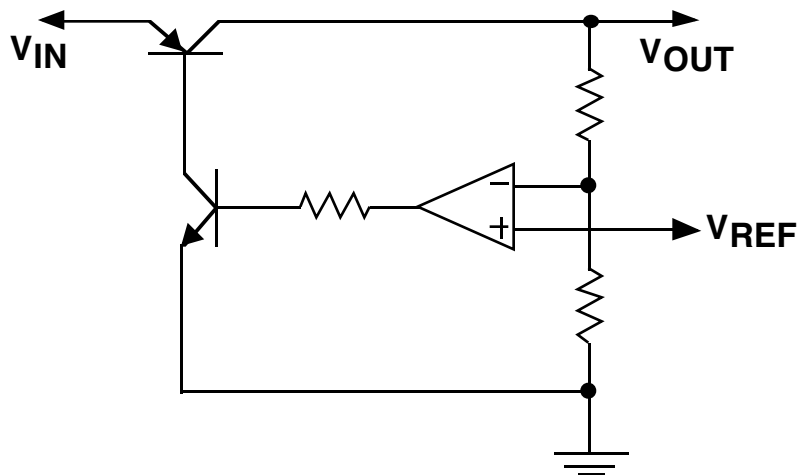


FIGURE 4. LDO REGULATOR

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):

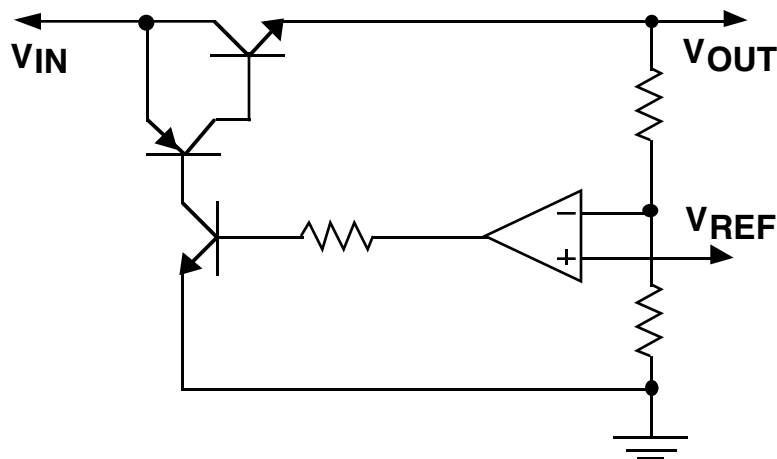


FIGURE 5. QUASI-LDO REGULATOR

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 types<sup>1</sup> is shown in Figure 6.

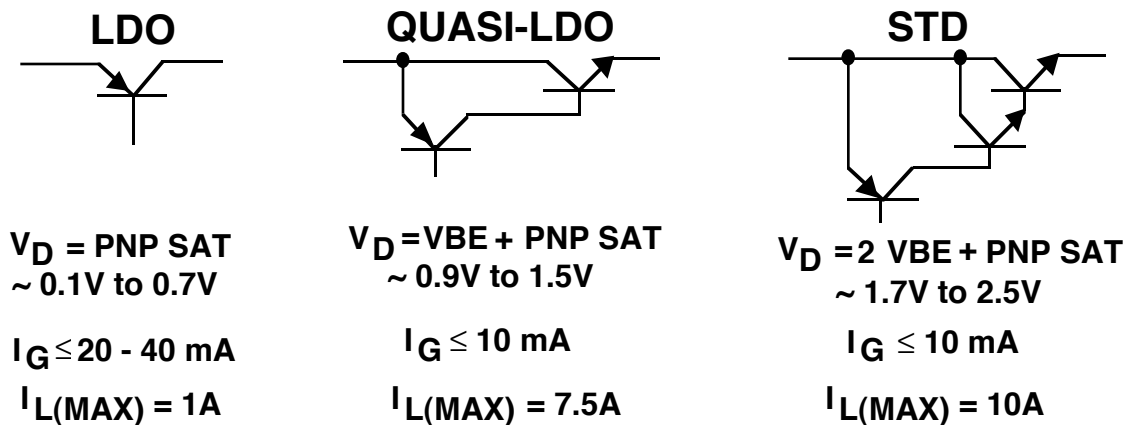


FIGURE 6. REGULATOR TYPE COMPARISON

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  $\mu\text{A}$ ), 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).

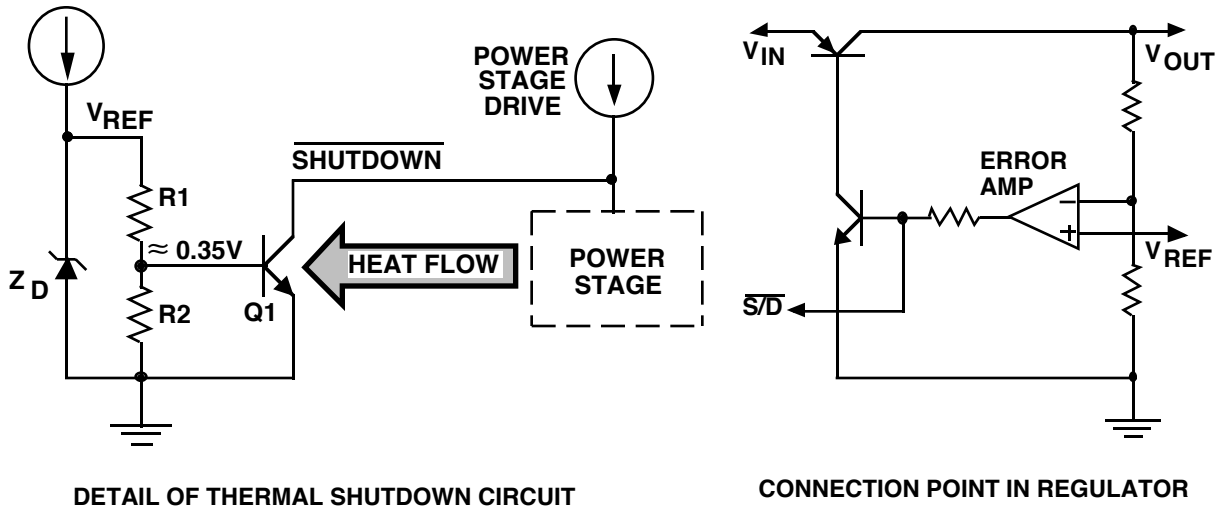


FIGURE 7. THERMAL SHUTDOWN

### 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).

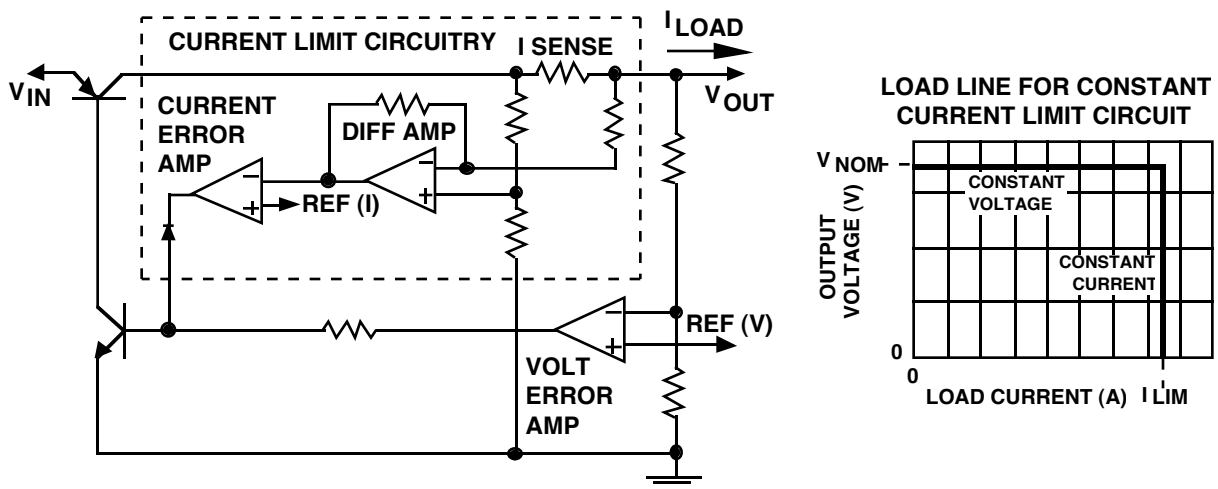


FIGURE 8. CONSTANT CURRENT LIMIT CIRCUIT

### 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 (>1A) 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).

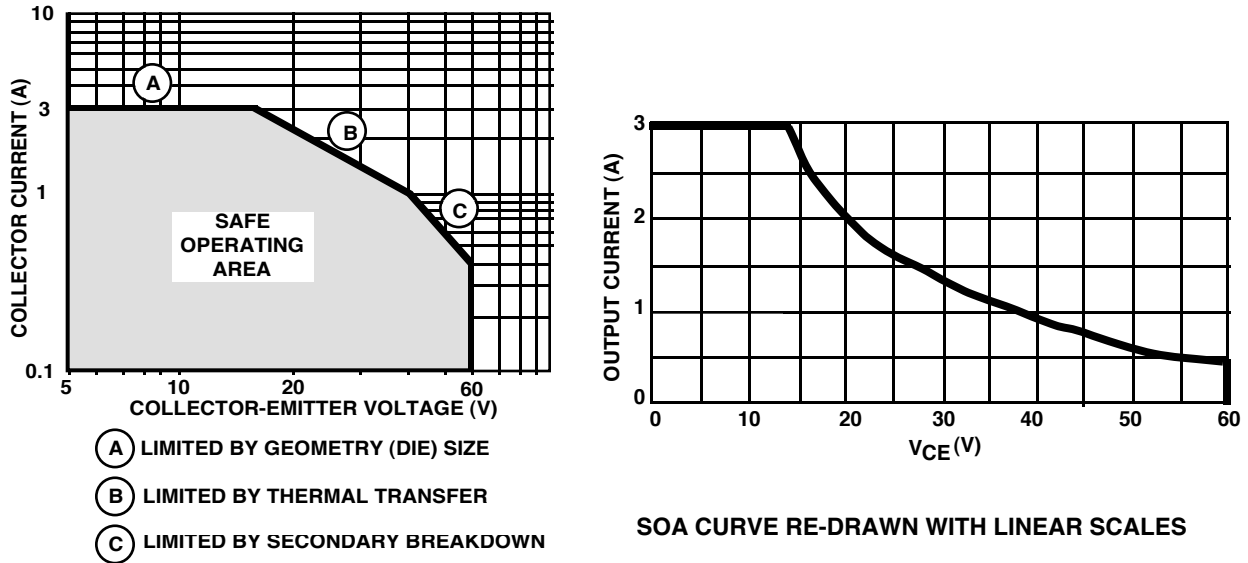


FIGURE 9. SOA CURVES FOR 3A/60V NPN TRANSISTOR

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.

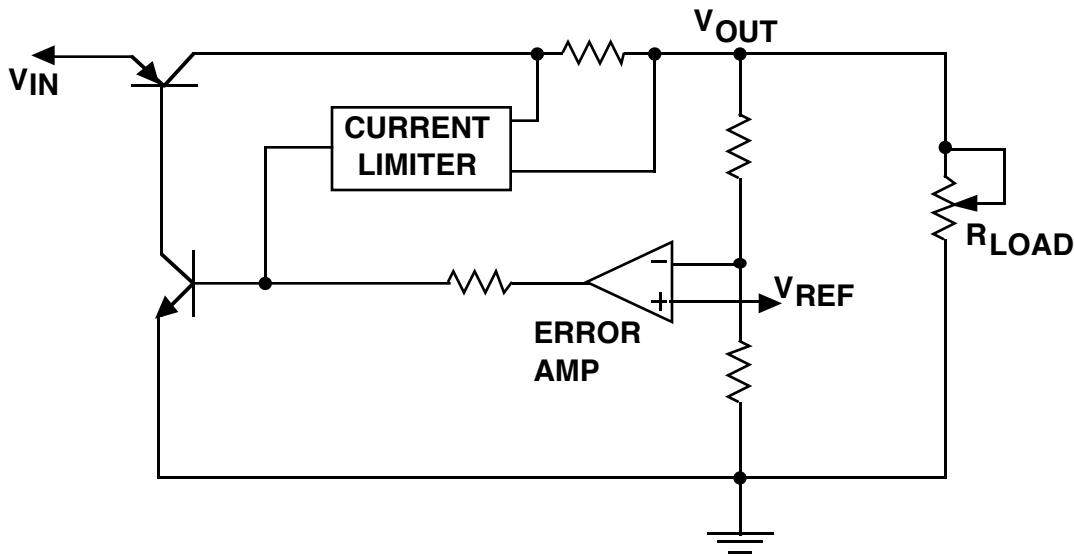


FIGURE 10. CURRENT LIMIT TEST CIRCUIT

**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**).

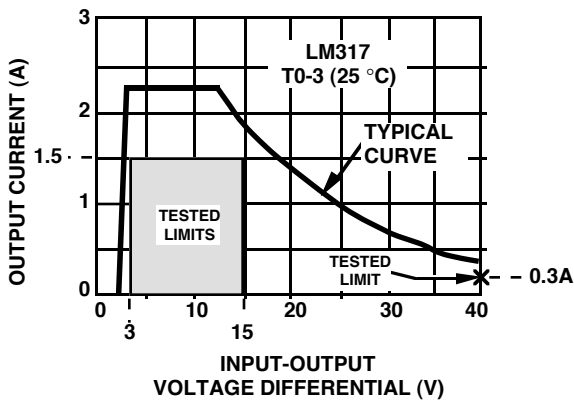
The drop in output voltage can be made to occur gradually, and the output voltage can be moved up and down by adjusting the load resistance.

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).

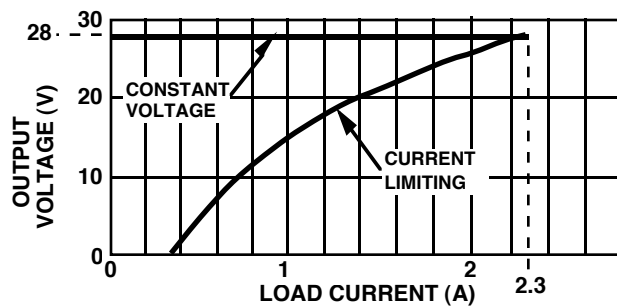


**Foldback Limiting:** The action of a foldback limiting circuit is different, because it has some "hysteresis" built in to it. As the load resistance decreases to the point where limiting occurs, the output voltage can drop suddenly from the nominal voltage to a much lower value.

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).



LM317 CURRENT LIMIT CURVE



LM317K (25°C),  $V_{IN} = 40V$ ,  $V_{OUT} = 28V$   
LOAD LINE CONSTRUCTED FROM  
TYPICAL CURRENT LIMIT CURVE.

CURRENT LIMIT LOAD LINE

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.

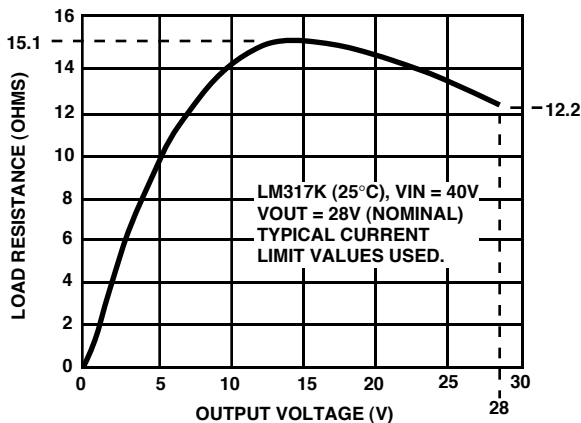
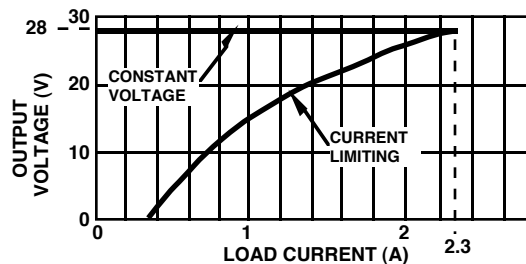
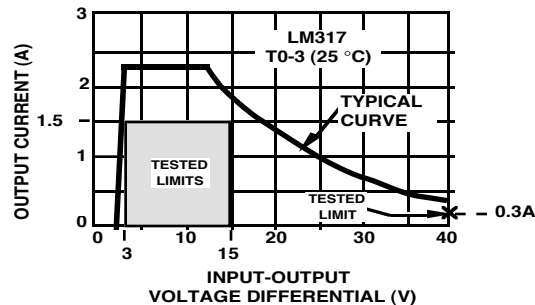


FIGURE 12. RESISTANCE LOAD LINE FOR LM317 EXAMPLE (IN CURRENT LIMITING)



LM317K (25°C), VIN = 40V, VOUT = 28V  
LOAD LINE CONSTRUCTED FROM TYPICAL CURRENT LIMIT CURVE.

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 (IL = 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 VO = 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 (VO = 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 **VO = 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).

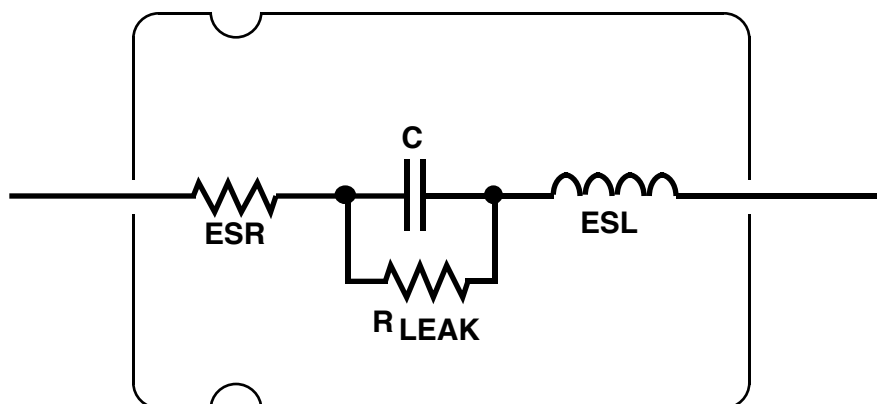


FIGURE 13. MODEL OF A REAL CAPACITOR

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.

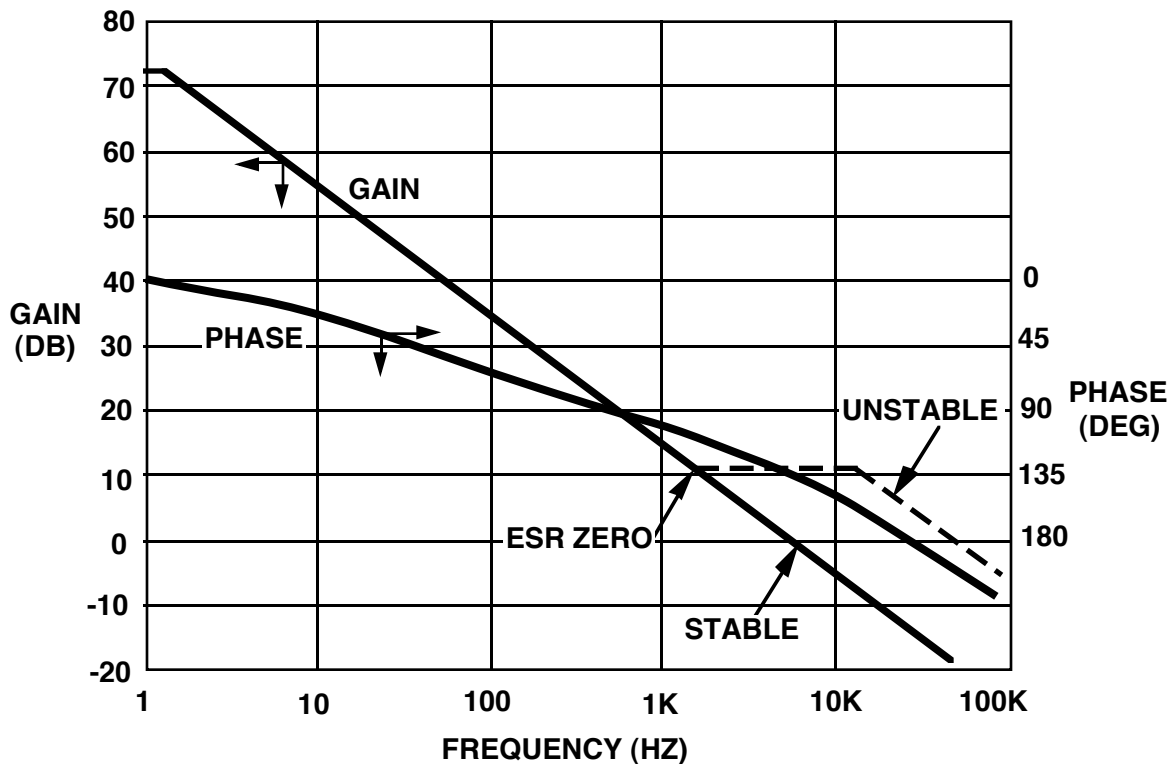


FIGURE 14. LOOP GAIN PLOT

(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.

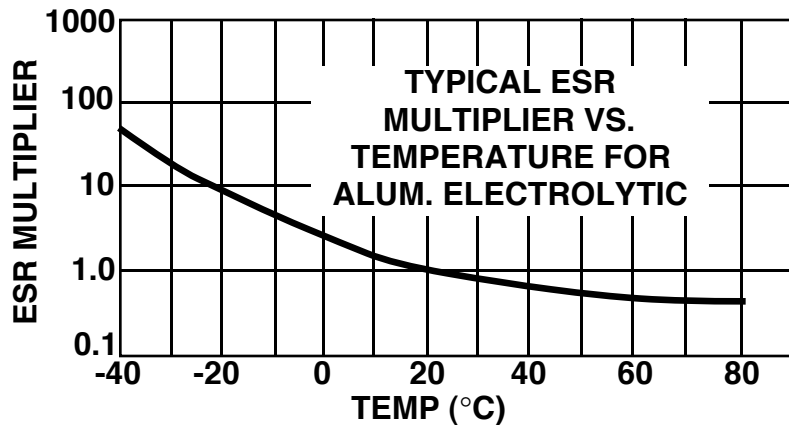


FIGURE 15. ALUMINUM ELECTROLYTIC ESR VS. TEMPERATURE

In cases where an LDO regulator must be operated below about  $-10\text{ }^{\circ}\text{C}$ , 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  $-20\text{ }^{\circ}\text{C}$**  (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).

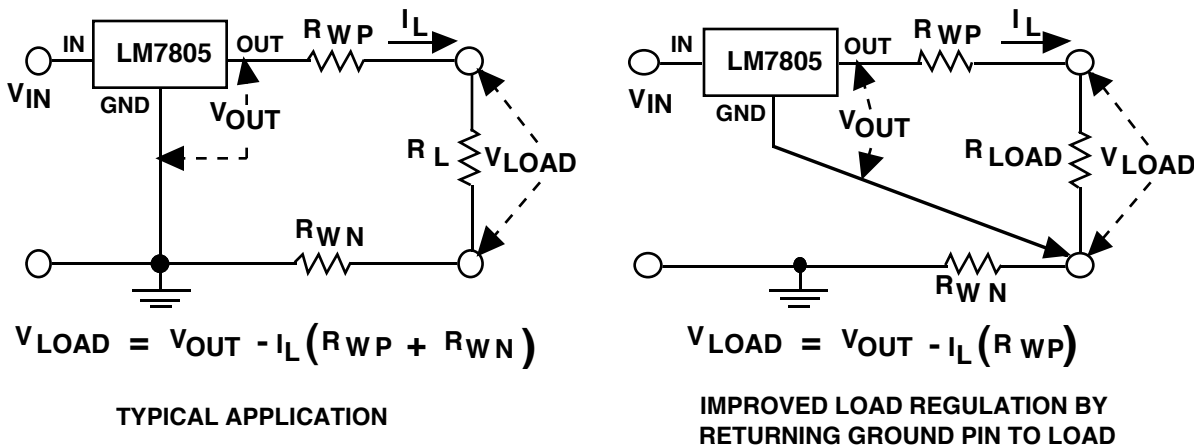


FIGURE 16. LOAD REGULATION EFFECTS DUE TO WIRE DROPS

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).

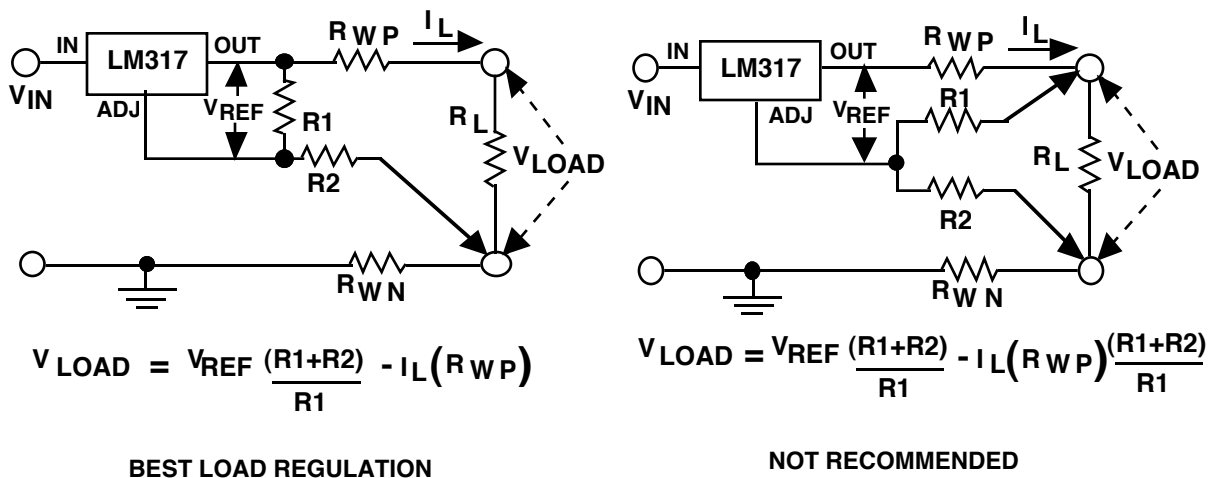


FIGURE 17. LOAD REGULATION EFFECTS USING LM317 REGULATOR

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**.

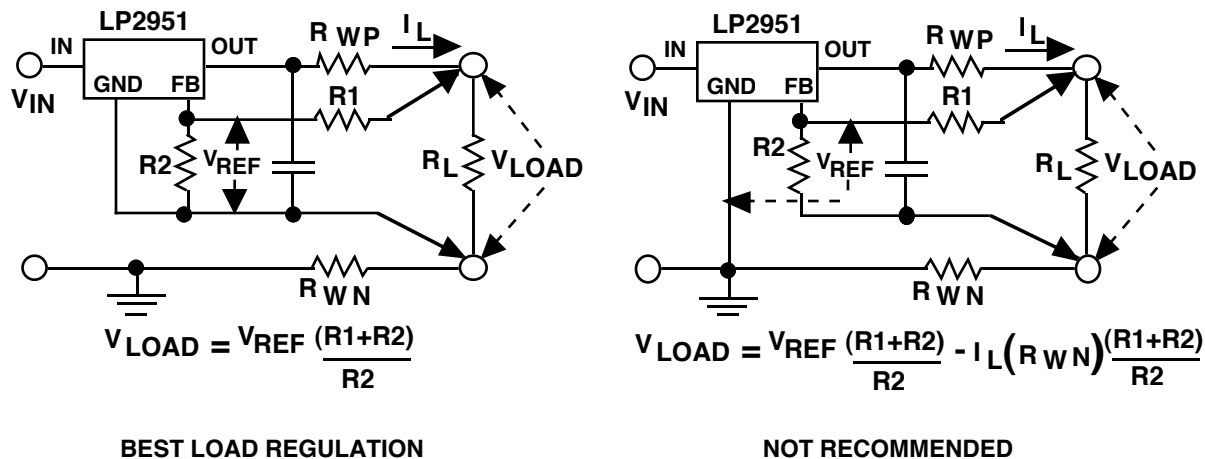
The voltage  $V_{REF}$  is used to force (set) a constant current through both  $R1$  and  $R2$ , and the precision of the output voltage is directly related to the accuracy of this current. If  $R1$  is tied to the positive load terminal, the voltage drop across  $R_{WP}$  is subtracted from  $V_{REF}$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

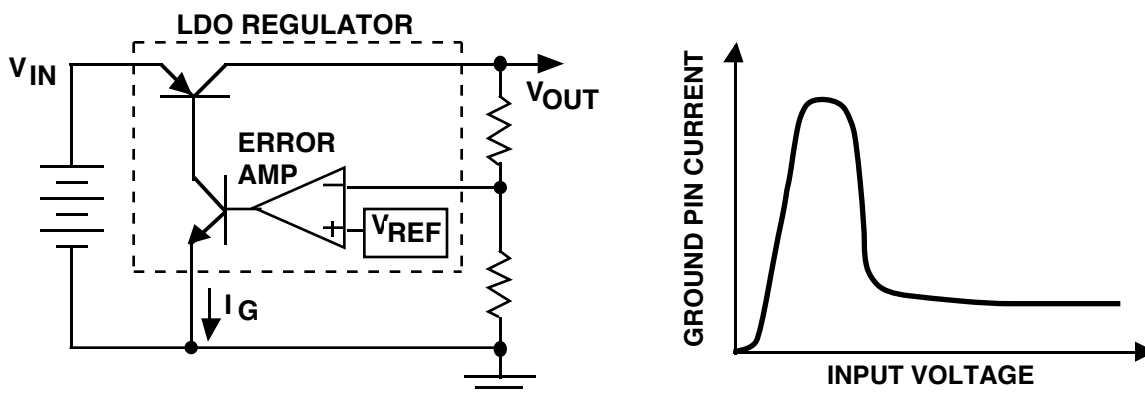


FIGURE 19. LDO REGULATOR WITH "CARROT"

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.

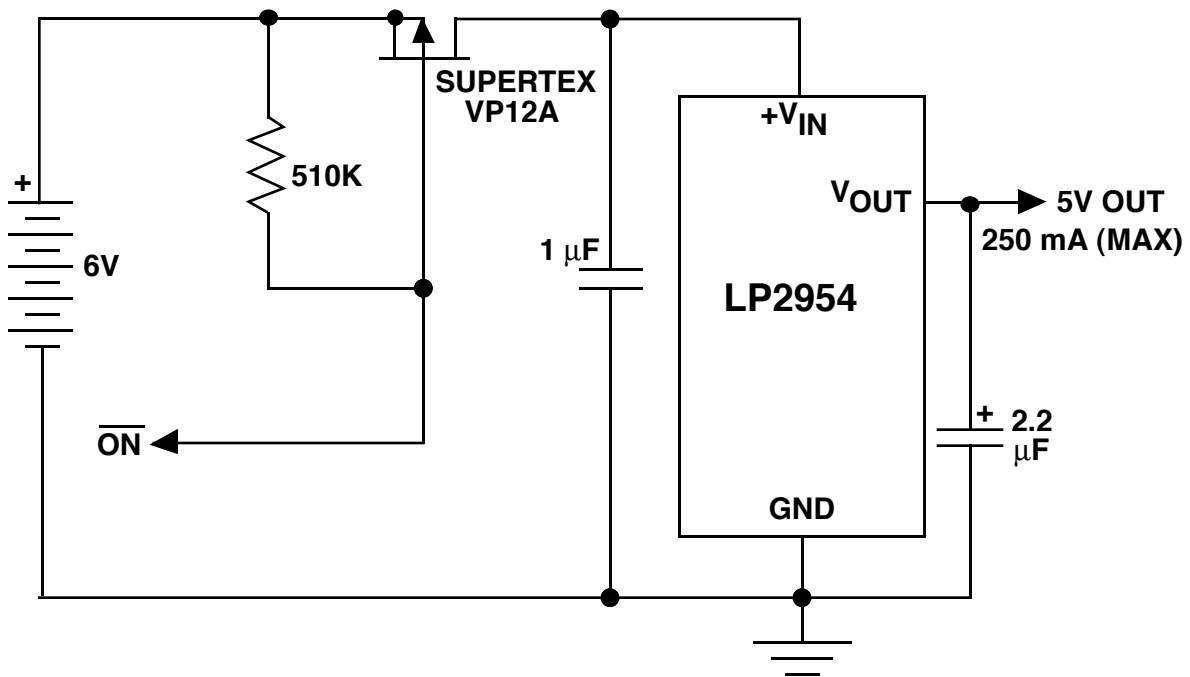


FIGURE 20. PRECISION 5V REGULATOR WITH LOW-POWER SHUTDOWN

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.

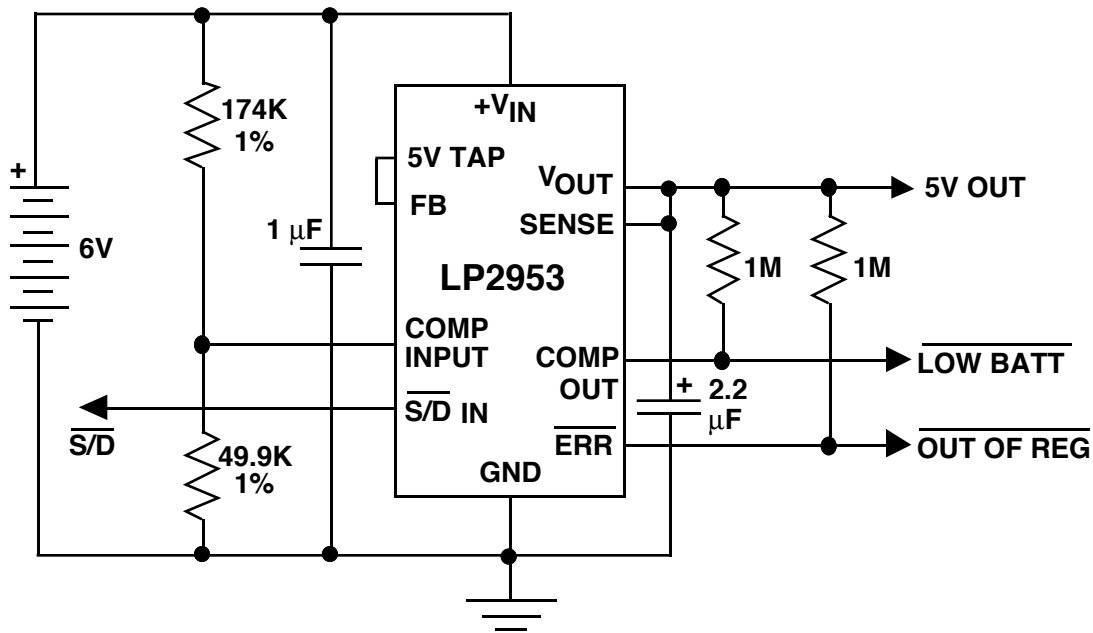
Another advantage of this type of shutdown is that when the FET is off, the only drain current flowing from the battery is the leakage of the FET. This means the quiescent current of the regulator is no longer the determining factor in the standby life of the battery (the leakage of the FET is).

## 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**

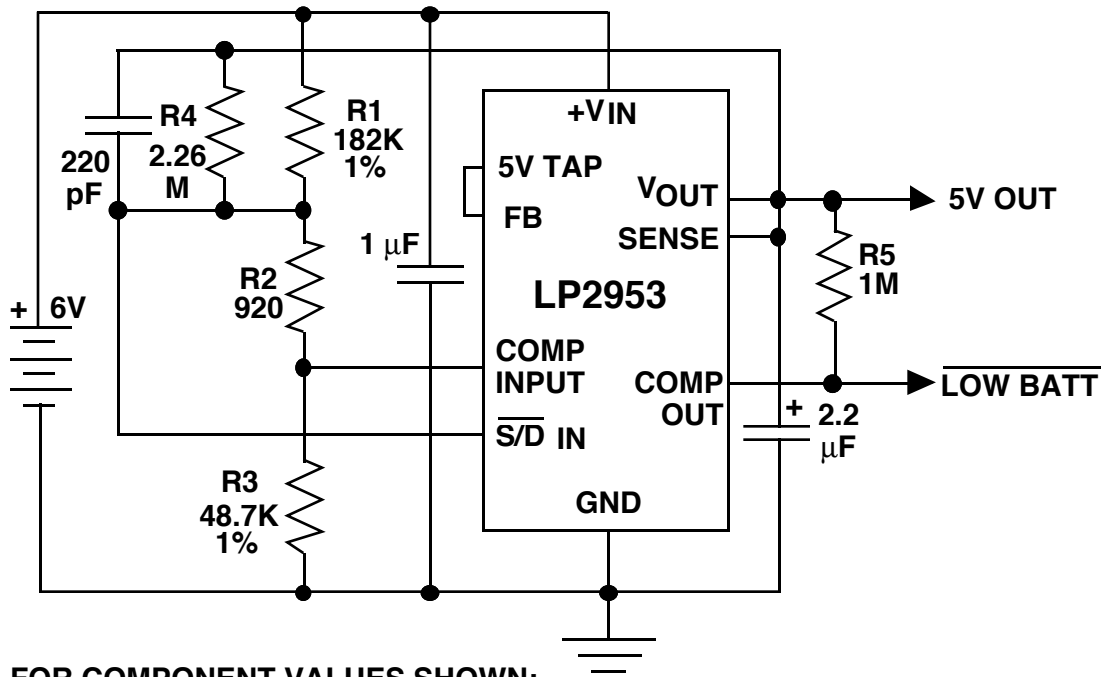
Figure 21 shows an application where the LP2953 is used to provide a precision 5V rail, with the added feature of alerting when the battery is low.

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 $\mu$ 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  $0 < V_O < 5V$ .

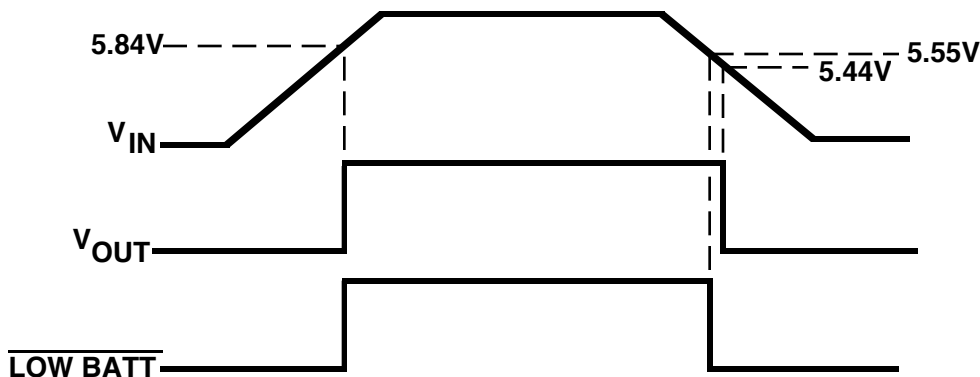


FIGURE 23. SNAP-ON/SNAP-OFF TIMING DIAGRAM

## NEGATIVE LDO REGULATORS

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

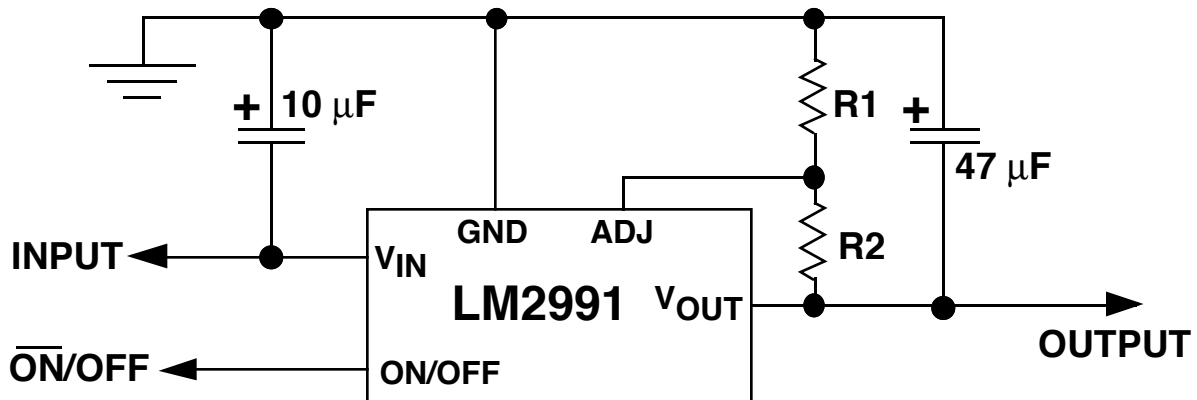
The **LM2990** is a 1A, fixed output regulator in a 3-lead TO-220 package which is offered in -5V, -5.2V, -12V, and -15V voltage options.

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 uses 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

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# SWITCHING REGULATORS

## Introduction

The switching regulator is increasing in popularity because it offers the advantages of higher power conversion efficiency and increased design flexibility (multiple output voltages of different polarities can be generated from a single input voltage).

This paper will detail the operating principles of the four most commonly used switching converter types:

Buck: used to reduce a DC voltage to a lower DC voltage.

Boost: provides an output voltage that is higher than the input.

Buck-Boost (invert): an output voltage is generated opposite in polarity to the input.

Flyback: an output voltage that is less than or greater than the input can be generated, as well as multiple outputs.

Also, some multiple-transistor converter topologies will be presented:

Push-Pull: A two-transistor converter that is especially efficient at low input voltages.

Half-Bridge: A two-transistor converter used in many off-line applications.

Full-Bridge: A four-transistor converter (usually used in off-line designs) that can generate the highest output power of all the types listed.

Application information will be provided along with circuit examples that illustrate some applications of Buck, Boost, and Flyback regulators.

## Switching Fundamentals

Before beginning explanations of converter theory, some basic elements of power conversion will be presented:

### THE LAW OF INDUCTANCE

If a voltage is forced across an inductor, a current will flow through that inductor (and this current will vary with time). Note that the **current flowing in an inductor will be time-varying even if the forcing voltage is constant.**

It is equally correct to say that if a time-varying current is forced to flow in an inductor, a voltage across the inductor will result.

The fundamental law that defines the relationship between the voltage and current in an inductor is given by the equation:

$$v = L (di/dt)$$



Two important characteristics of an inductor that follow directly from the law of inductance are:

- 1) A voltage across an inductor results **only** from a **current that changes with time**. A **steady (DC) current flowing in an inductor causes no voltage across it** (except for the tiny voltage drop across the copper used in the windings).
- 2) A **current flowing in an inductor can not change value instantly** (in zero time), as this would require infinite voltage to force it to happen. However, **the faster the current is changed in an inductor, the larger the resulting voltage will be**.

Note: Unlike the current flowing in the inductor, the **voltage across it can change instantly** (in zero time).

The principles of inductance are illustrated by the information contained in Figure 25.

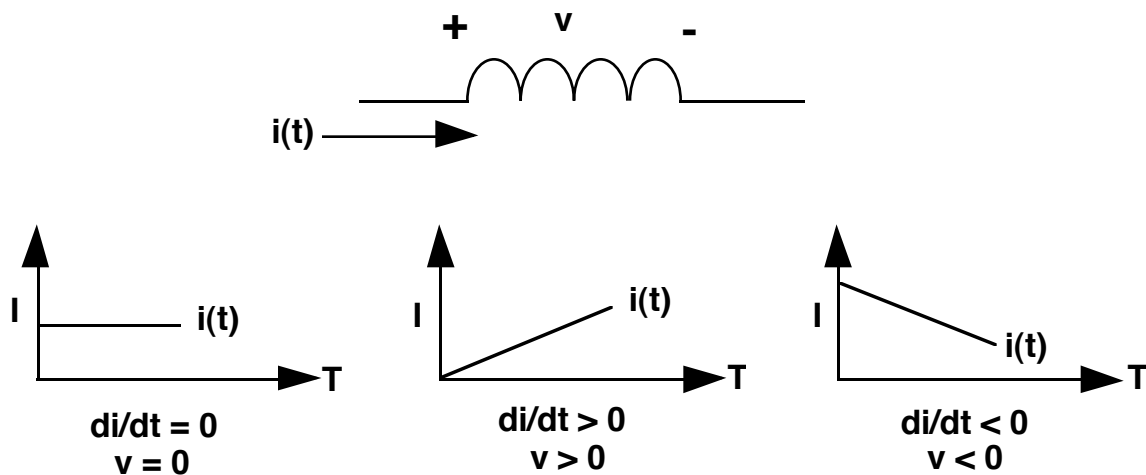


FIGURE 25. INDUCTOR VOLTAGE/CURRENT RELATIONSHIP

The important parameter is the  $di/dt$  term, which is simply a measure of how the current changes with time. When the current is plotted versus time, the **value of  $di/dt$  is defined as the slope of the current plot at any given point**.

The graph on the left shows that current which is constant with time has a  $di/dt$  value of zero, and results in no voltage across the inductor.

The center graph shows that a current which is increasing with time has a positive  $di/dt$  value, resulting in a positive inductor voltage.

Current that decreases with time (shown in the right-hand graph) gives a negative value for  $di/dt$  and inductor voltage.

It is important to note that a **linear current ramp in an inductor** (either up or down) **occurs only when it has a constant voltage across it**.

## TRANSFORMER OPERATION

A transformer is a device that has two or more magnetically-coupled windings. The basic operation is shown in Figure 26.

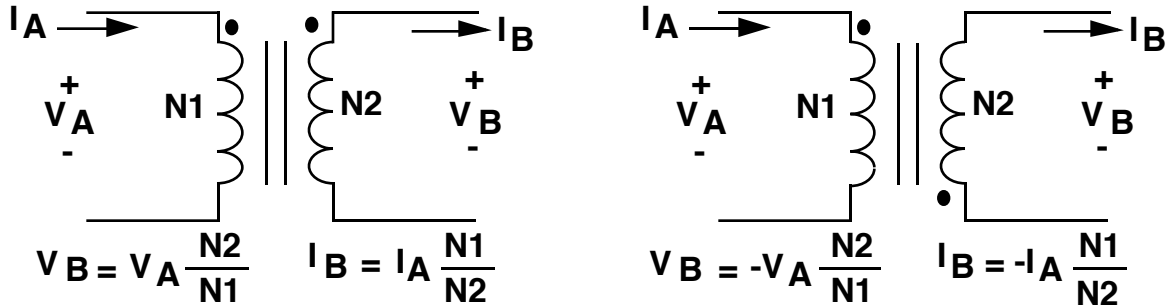


FIGURE 26. TRANSFORMER THEORY

The action of a transformer is such that a time-varying (AC) voltage or current is transformed to a higher or lower value, as set by the transformer turns ratio. The transformer does not add power, so it follows that the power ( $V \times I$ ) on either side must be constant. That is the reason that the **winding with more turns has higher voltage but lower current**, while the **winding with less turns has lower voltage but higher current**.

The **dot on a transformer winding identifies its polarity** with respect to another winding, and **reversing the dot results in inverting the polarity**.

Example of Transformer Operation:

An excellent example of how a transformer works can be found under the hood of your car, where a transformer is used to generate the 40 kV that fires your cars spark plugs (see Figure 27).

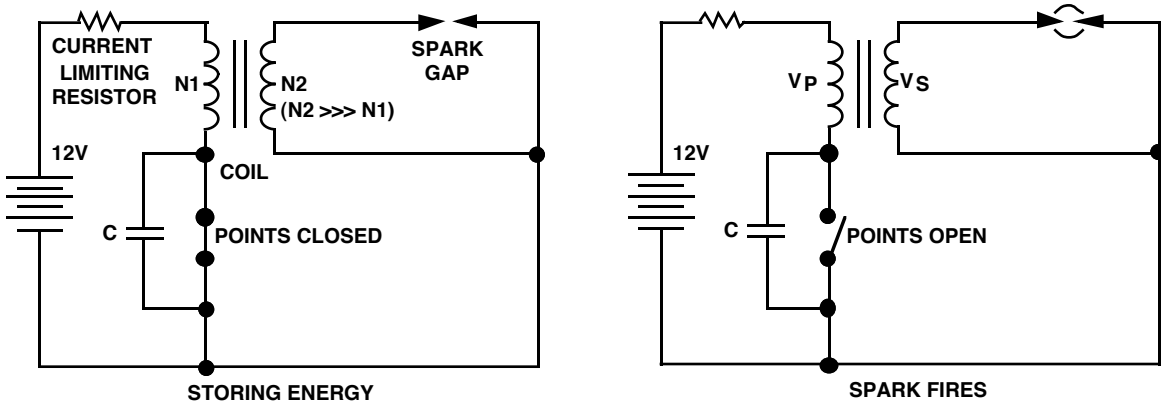


FIGURE 27. SPARK FIRING CIRCUIT

The "coil" used to generate the spark voltage is actually a transformer, with a very high secondary-to-primary turns ratio.

When the points first close, current starts to flow in the primary winding and eventually reaches the final value set by the 12V battery and the current limiting resistor. At this time, the current flow is a fixed DC value, which means no voltage is generated across either winding of the transformer.

When the points open, the current in the primary winding collapses very quickly, causing a large voltage to appear across this winding. This voltage on the primary is magnetically coupled to (and stepped up by) the secondary winding, generating a voltage of 30 kV - 40 kV on the secondary side.

As explained previously, the law of inductance says that it is not possible to instantly break the current flowing in an inductor (because an infinite voltage would be required to make it happen).

This principle is what causes the arcing across the contacts used in switches that are in circuits with highly inductive loads. When the switch just begins to open, the high voltage generated allows electrons to jump the air gap so that the current flow does not actually stop instantly. Placing a capacitor across the contacts helps to reduce this arcing effect.

In the automobile ignition, a capacitor is placed across the points to minimize damage due to arcing when the points "break" the current flowing in the low-voltage coil winding (in car manuals, this capacitor is referred to as a "condenser").

### PULSE WIDTH MODULATION (PWM)

All of the switching converters that will be covered in this paper use a form of output voltage regulation known as **Pulse Width Modulation (PWM)**. Put simply, the feedback loop adjusts (corrects) the output voltage by changing the ON time of the switching element in the converter.

As an example of how PWM works, we will examine the result of applying a series of square wave pulses to an L-C filter (see Figure 28).

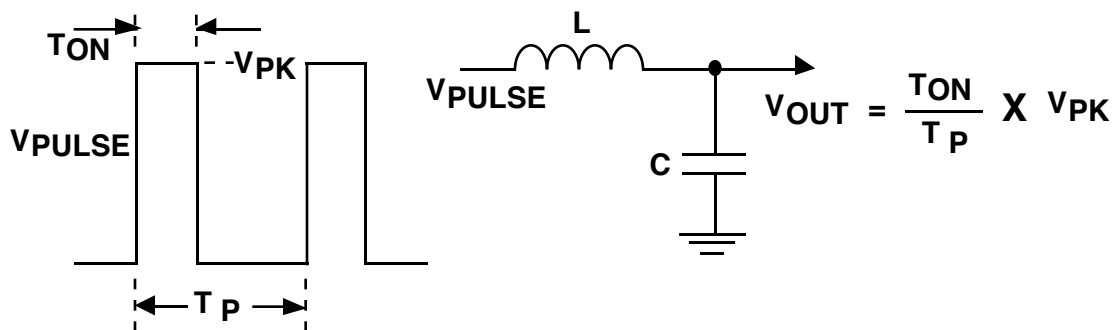


FIGURE 28. BASIC PRINCIPLES OF PWM

The series of square wave pulses is filtered and provides a **DC output voltage that is equal to the peak pulse amplitude multiplied times the duty cycle** (duty cycle is defined as the switch ON time divided by the total period).

This relationship explains how the output voltage can be directly controlled by changing the ON time of the switch.

## Switching Converter Topologies

The most commonly used DC-DC converter circuits will now be presented along with the basic principles of operation.

### BUCK REGULATOR

The most commonly used switching converter is the Buck, which is used to down-convert a DC voltage to a lower DC voltage of the same polarity. This is essential in systems that use distributed power rails (like 24V to 48V), which must be locally converted to 15V, 12V or 5V with very little power loss.

The Buck converter uses a transistor as a switch that alternately connects and disconnects the input voltage to an inductor (see Figure 29).

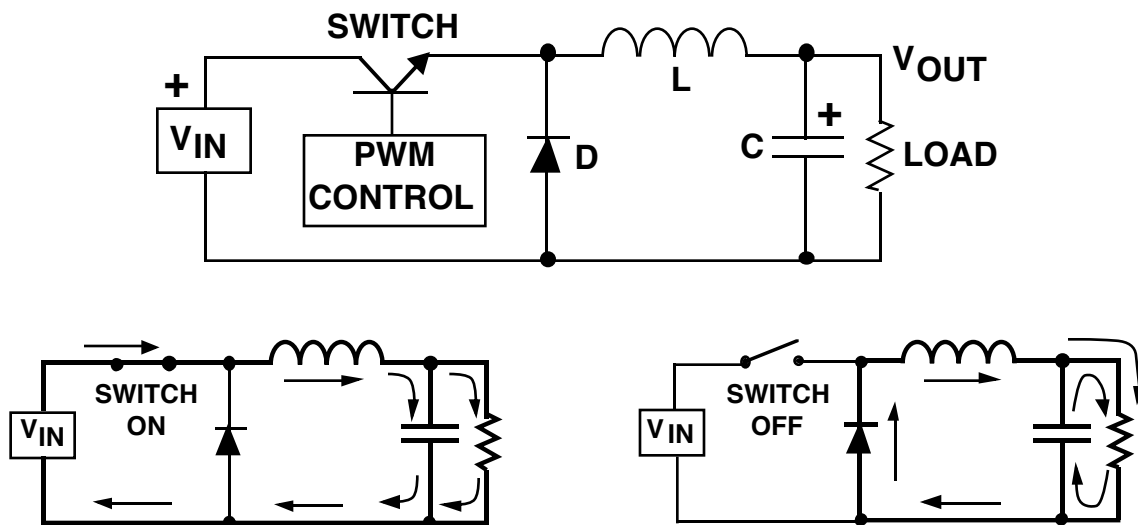


FIGURE 29. BUCK REGULATOR

The lower diagrams show the current flow paths (shown as the heavy lines) when the switch is on and off.

When the switch turns on, the input voltage is connected to the inductor. The difference between the input and output voltages is then forced across the inductor, causing current through the inductor to increase.

During the **on time**, the inductor current flows into both the load and the output capacitor (the capacitor **charges** during this time).

When the switch is turned off, the input voltage applied to the inductor is removed. However, since the current in an inductor can not change instantly, the voltage across the inductor will adjust to hold the current constant.

The input end of the inductor is forced negative in voltage by the decreasing current, eventually reaching the point where the diode is turned on. The inductor current then flows through the load and back through the diode.

The capacitor discharges into the load during the off time, contributing to the total current being supplied to the load (the total load current during the switch off time is the sum of the inductor and capacitor current).

The shape of the current flowing in the inductor is similar to Figure 30.

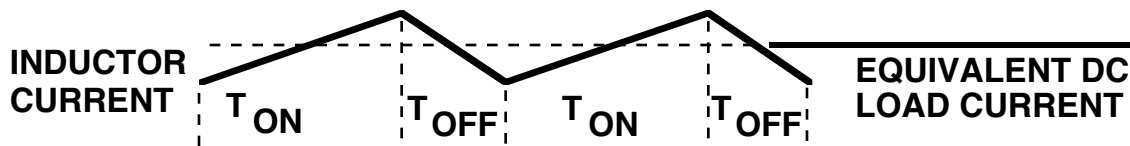


FIGURE 30. BUCK REGULATOR INDUCTOR CURRENT

As explained, the current through the inductor ramps up when the switch is on, and ramps down when the switch is off. The DC load current from the regulated output is the average value of the inductor current.

The peak-to-peak difference in the inductor current waveform is referred to as the **inductor ripple current**, and the inductor is typically selected large enough to keep this ripple current less than 20% to 30% of the rated DC current.

### CONTINUOUS vs. DISCONTINUOUS OPERATION

In most Buck regulator applications, the inductor current never drops to zero during full-load operation (this is defined as **continuous mode operation**). Overall performance is usually better using continuous mode, and it allows maximum output power to be obtained from a given input voltage and switch current rating.

In applications where the maximum load current is fairly low, it can be advantageous to design for discontinuous mode operation. In these cases, operating in discontinuous mode can result in a smaller overall converter size (because a smaller inductor can be used).

Discontinuous mode operation at lower load current values is generally harmless, and **even converters designed for continuous mode operation at full load will become discontinuous as the load current is decreased** (usually causing no problems).

## BOOST REGULATOR

The Boost regulator takes a DC input voltage and produces a DC output voltage that is higher in value than the input (but of the same polarity). The Boost regulator is shown in Figure 31, along with details showing the path of current flow during the switch on and off time.

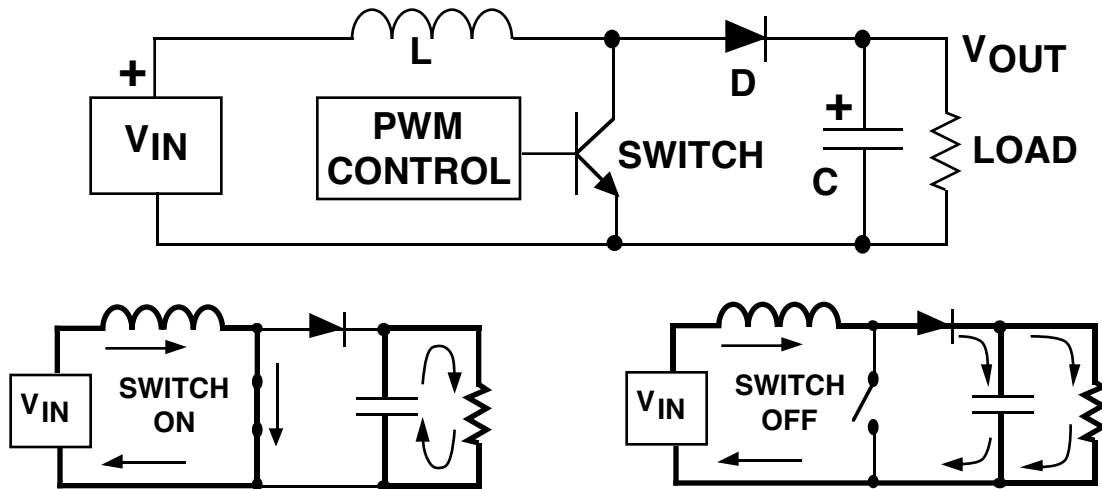


FIGURE 31. BOOST REGULATOR

Whenever the switch is on, the input voltage is forced across the inductor which causes the current through it to increase (ramp up).

When the switch is off, the decreasing inductor current forces the "switch" end of the inductor to swing positive. This forward biases the diode, allowing the capacitor to charge up to a voltage that is higher than the input voltage.

During steady-state operation, the inductor current flows into both the output capacitor and the load during the switch off time. When the switch is on, the load current is supplied only by the capacitor.

### OUTPUT CURRENT AND LOAD POWER

An important design consideration in the Boost regulator is that the **output load current and the switch current are not equal**, and the **maximum available load current is always less than the current rating of the switch transistor**.

It should be noted that the **maximum total power available for conversion in any regulator** is equal to the **input voltage multiplied times the maximum average input current** (which is **less than** the current rating of the switch transistor).

Since the output voltage of the Boost is **higher than the input voltage**, it follows that the **output current must be lower than the input current**.

## BUCK-BOOST (INVERTING) REGULATOR

The Buck-Boost or Inverting regulator takes a DC input voltage and produces a DC output voltage that is opposite in polarity to the input. The negative output voltage can be either larger or smaller in magnitude than the input voltage.

The Inverting regulator is shown in Figure 32.

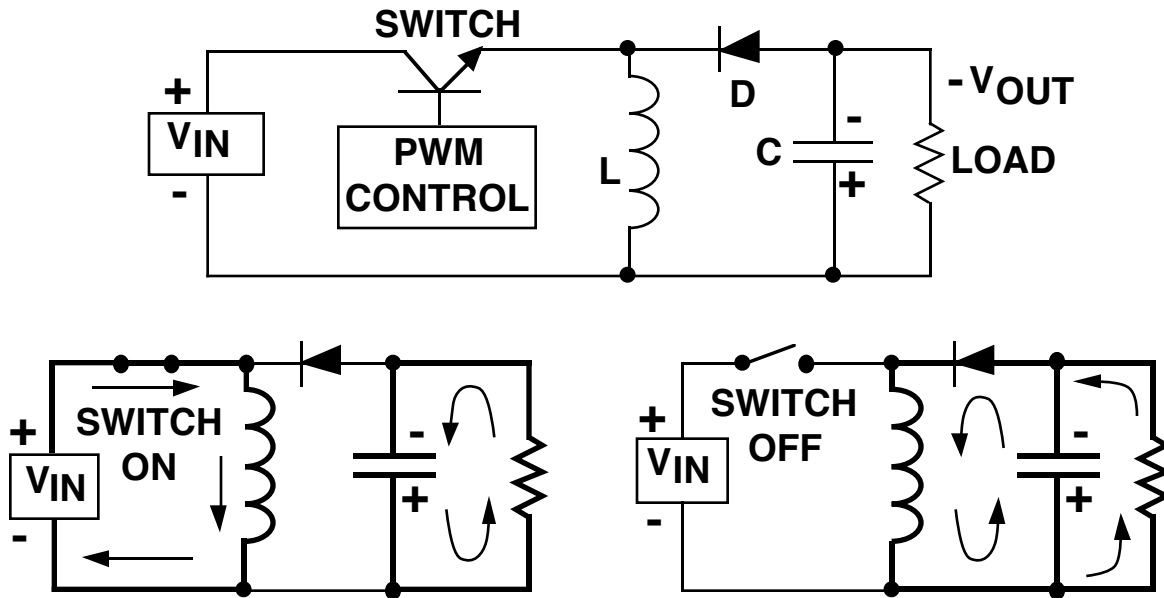


FIGURE 32. BUCK-BOOST (INVERTING) REGULATOR

When the switch is on, the input voltage is forced across the inductor, causing an increasing current flow through it. During the on time, the discharge of the output capacitor is the only source of load current.

This requires that the charge lost from the output capacitor during the on time be replenished during the off time.

When the switch turns off, the decreasing current flow in the inductor causes the voltage at the diode end to swing negative. This action turns on the diode, allowing the current in the inductor to supply **both the output capacitor and the load**.

As shown, **the load current is supplied by inductor when the switch is off, and by the output capacitor when the switch is on.**

## FLYBACK REGULATOR

The Flyback is the most versatile of all the topologies, allowing the designer to create one or more output voltages, some of which may be opposite in polarity.

Flyback converters have gained popularity in battery-powered systems, where a single voltage must be converted into the required system voltages (for example, +5V, +12V and -12V) with very high power conversion efficiency.

The basic single-output flyback converter is shown in Figure 33.

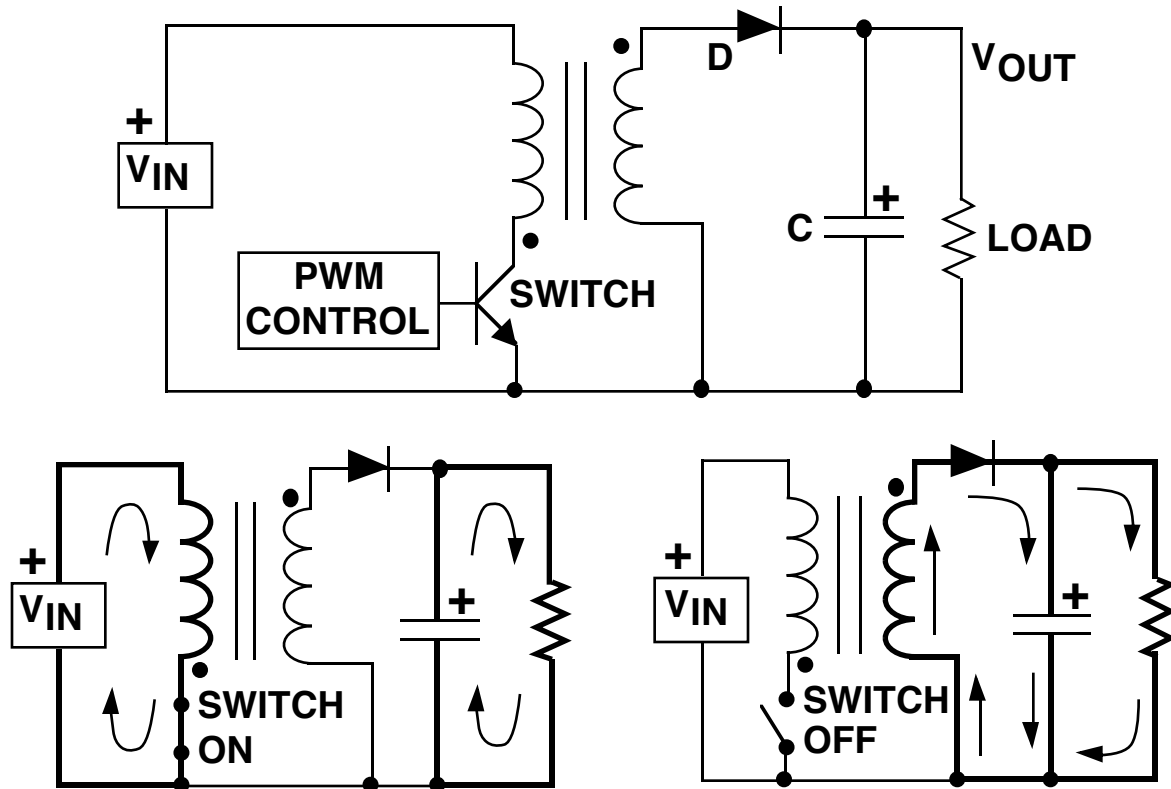


FIGURE 33. SINGLE-OUTPUT FLYBACK REGULATOR

The most important feature of the Flyback regulator is the transformer phasing, as shown by the dots on the primary and secondary windings.

When the switch is on, the input voltage is forced across the transformer primary which causes an increasing flow of current through it.

Note that the **polarity of the voltage on the primary is dot-negative** (more negative at the dotted end), causing a voltage with the same polarity to appear at the transformer secondary (the magnitude of the secondary voltage is set by the transformer secondary-to-primary turns ratio).



The dot-negative voltage appearing across the secondary winding turns off the diode, preventing current flow in the secondary winding during the switch on time. During this time, the load current must be supplied by the output capacitor alone.

When the switch turns off, the decreasing current flow in the primary causes the voltage at the dot end to swing positive. At the same time, the primary voltage is reflected to the secondary with the same polarity. The dot-positive voltage occurring across the secondary winding turns on the diode, allowing current to flow into both the load and the output capacitor. The output capacitor charge lost to the load during the switch on time is replenished during the switch off time.

Flyback converters operate in either **continuous mode** (where the secondary current is always  $>0$ ) or **discontinuous mode** (where the secondary current falls to zero on each cycle).

### GENERATING MULTIPLE OUTPUTS

Another big advantage of a Flyback is the capability of providing multiple outputs (see Figure 34). In such applications, one of the outputs (usually the highest current) is selected to provide PWM feedback to the control loop, **which means this output is directly regulated**.

The other secondary winding(s) are **indirectly regulated**, as their pulse widths will follow the regulated winding. The load regulation on the unregulated secondaries is not great (typically 5 - 10%), but is adequate for many applications.

If tighter regulation is needed on the lower current secondaries, an LDO post-regulator is an excellent solution. The secondary voltage is set about 1V above the desired output voltage, and the LDO provides excellent output regulation with very little loss of efficiency.

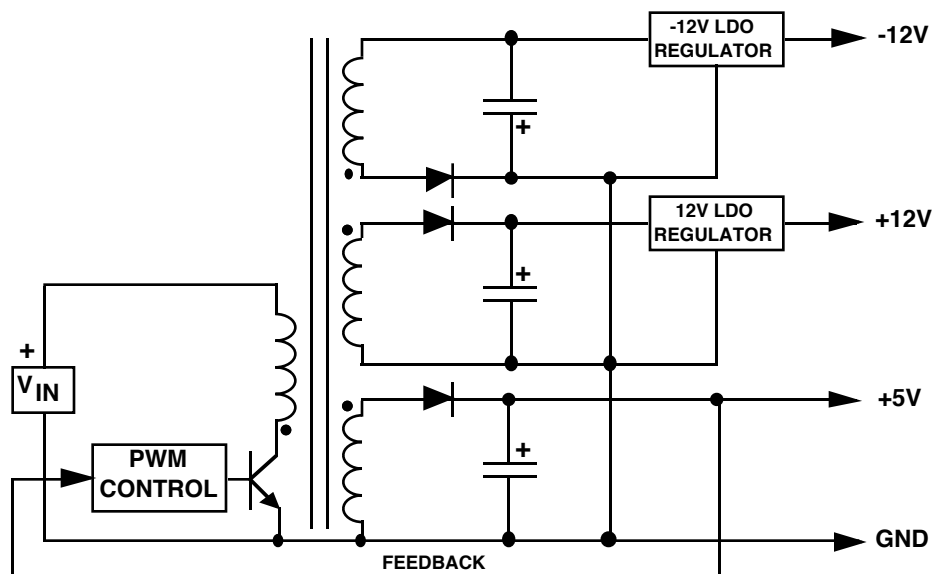


FIGURE 34. TYPICAL MULTIPLE-OUTPUT FLYBACK

## PUSH-PULL CONVERTER

The Push-Pull converter uses two transistors to perform DC-DC conversion (see Figure 35).

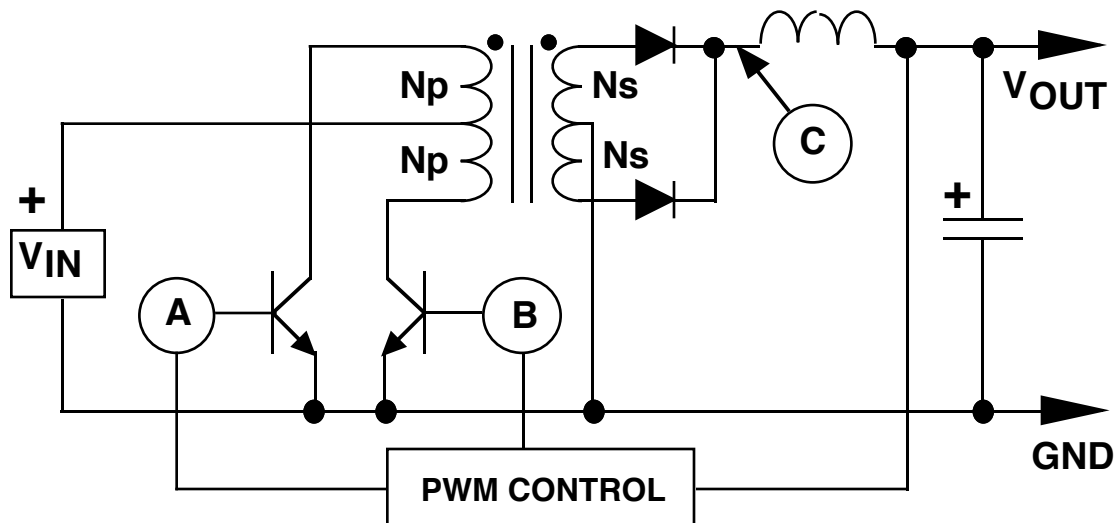


FIGURE 35. PUSH-PULL CONVERTER

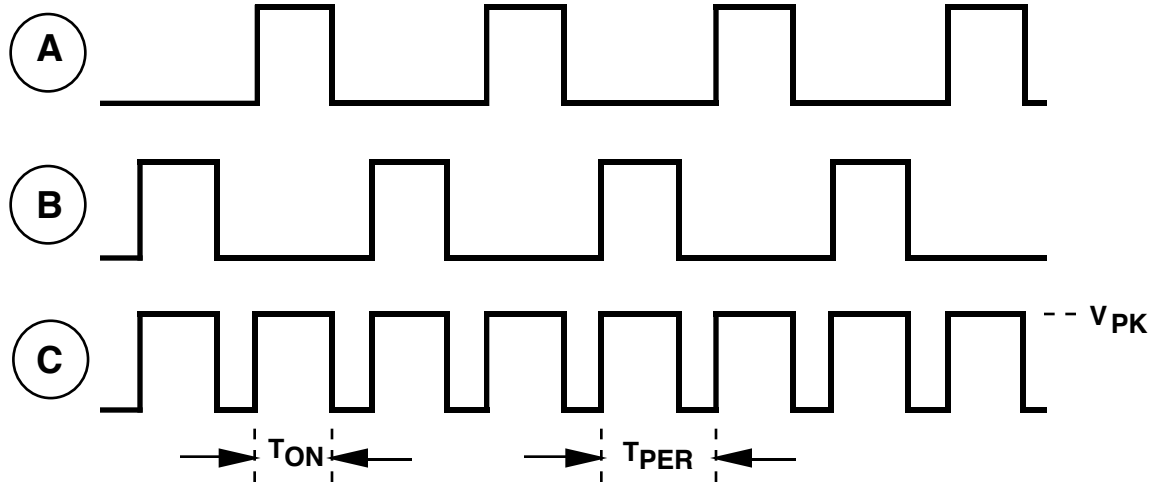
The converter operates by turning on each transistor on alternate cycles (the two transistors are **never** on at the same time). **Transformer secondary current flows at the same time as primary current** (when either of the switches is on).

For example, when transistor "A" is turned on, the input voltage is forced across the upper primary winding with dot-negative polarity. On the secondary side, a dot-negative voltage will appear across the winding which turns on the bottom diode. This allows current to flow into the inductor to supply both the output capacitor and the load.

When transistor "B" is on, the input voltage is forced across the lower primary winding with dot-positive polarity. The same voltage polarity on the secondary turns on the top diode, and current flows into the output capacitor and the load.

An important characteristic of a Push-Pull converter is that the switch transistors have to be able to stand off more than twice the input voltage: when one transistor is on (and the input voltage is forced across one primary winding) the same magnitude voltage is induced across the other primary winding, but it is "floating" on top of the input voltage. This puts the collector of the turned-off transistor at **twice** the input voltage with respect to ground.

The "double input voltage" rating requirement of the switch transistors means the Push-Pull converter is best suited for lower input voltage applications. It has been widely used in converters operating in 12V and 24V battery-powered systems.



**FIGURE 36. TIMING DIAGRAM FOR PUSH-PULL CONVERTER**

Figure 36 shows a timing diagram which details the relationship of the input and output pulses.

It is important to note that frequency of the secondary side voltage pulses is twice the frequency of operation of the PWM controller driving the two transistors. For example, if the PWM control chip was set up to operate at 50 kHz on the primary side, the frequency of the secondary pulses would be 100 kHz.

The DC output voltage is given by the equation:

$$V_{OUT} = V_{PK} \times (T_{ON} / T_{PER})$$

The peak amplitude of the secondary pulses ( $V_{PK}$ ) is given by:

$$V_{PK} = (V_{IN} - V_{SWITCH}) \times (N_S / N_P) - V_{RECT}$$

This highlights why the Push-Pull converter is well-suited for low voltage converters. The voltage forced across each primary winding (which provides the power for conversion) is the full input voltage minus only the saturation voltage of the switch.

If MOS-FET power switches are used, the voltage drop across the switches can be made extremely small, resulting in very high utilization of the available input voltage.

Another advantage of the Push-Pull converter is that it can also generate multiple output voltages (by adding more secondary windings), some of which may be negative in polarity. This allows a power supply operated from a single battery to provide all of the voltages necessary for system operation.

A disadvantage of Push-Pull converters is that they require very good matching of the switch transistors to prevent unequal on times, since this will result in saturation of the transformer core (and failure of the converter).

## HALF-BRIDGE CONVERTER

The Half-Bridge is a two-transistor converter frequently used in high-power designs. It is well-suited for applications requiring load power in the range of 500W to 1500W, and is almost always operated directly from the AC line.

Off-line operation means that no large 60 Hz power transformer is used, eliminating the heaviest and costliest component of a typical transformer-powered supply. All of the transformers in the Half-Bridge used for power conversion operate at the switching frequency (typically 50 kHz or higher) which means they can be very small and efficient.

A very important advantage of the Half-Bridge is **input-to-output isolation** (the regulated DC output is electrically isolated from the AC line). But, this means that all of the PWM control circuitry must be referenced to the DC output ground.

The voltage to run the control circuits is usually generated from a DC rail that is powered by a small 60 Hz transformer feeding a three-terminal regulator. In some designs requiring extremely high efficiency, the switcher output takes over and provides internal power after the start-up period.

The switch transistor drive circuitry must be isolated from the transistors, requiring the use of base drive transformers. The added complexity of the base drive circuitry is a disadvantage of using the Half-Bridge design.

If a 230 VAC line voltage is rectified by a full-wave bridge and filtered by a capacitor, an unregulated DC voltage of about 300V will be available for DC-DC conversion. If 115 VAC is used, a voltage doubler circuit is typically used to generate the 300V rail.

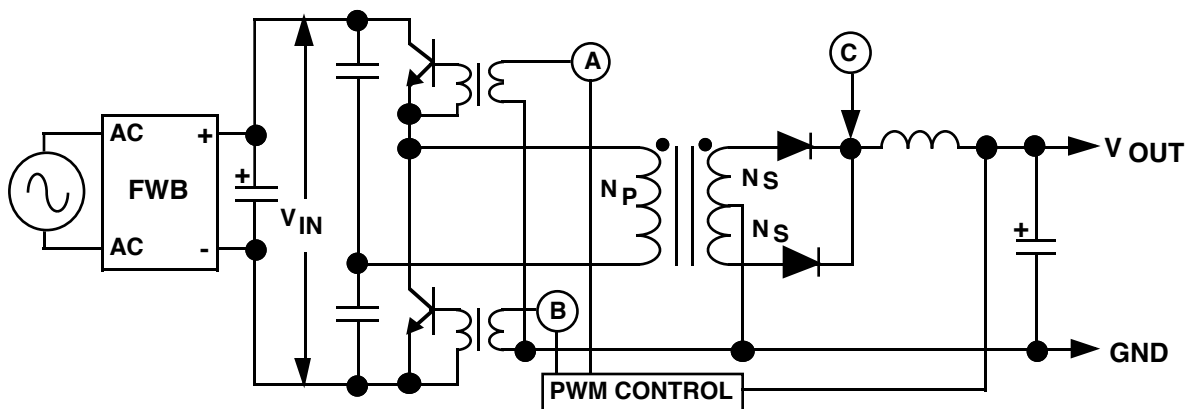


FIGURE 37. HALF-BRIDGE CONVERTER

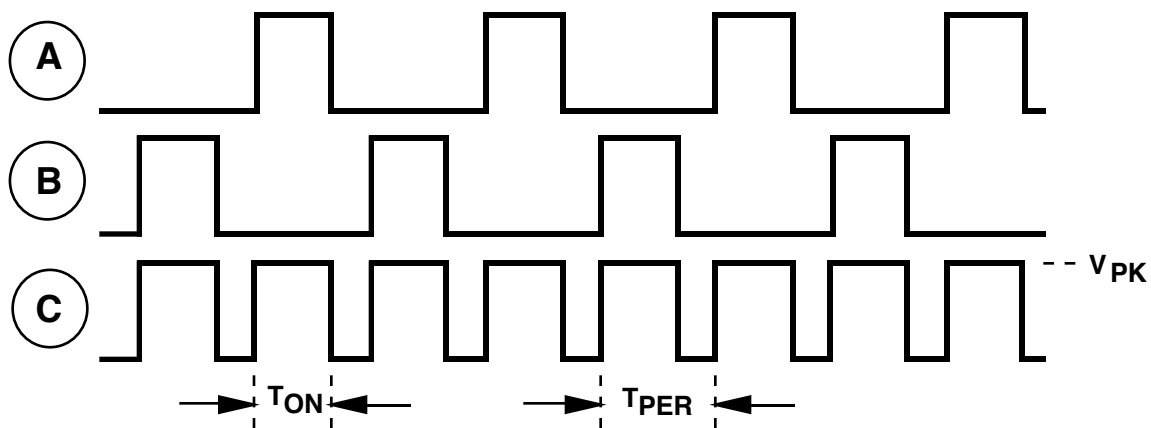
The basic Half-bridge converter is shown in Figure 37. A capacitive divider is tied directly across the unregulated DC input voltage, providing a reference voltage of  $1/2V_{IN}$  for one end of the transformer primary winding. The other end of the primary is actively driven up and down as the transistors alternately turn on and off.

The switch transistors force one-half of the input voltage across the primary winding during the switch on time, reversing polarity as the transistors alternate. The switching transistors are **never** on at the same time, or they would be destroyed (since they are tied directly across  $V_{IN}$ ). The timing diagram for the Half-Bridge converter is shown in Figure 38 (it is the same as the Push-Pull).

When the "A" transistor is on, a dot-positive voltage is forced across the primary winding and reflected on the secondary side (with the magnitude being set by the transformer turns ratio). The dot-positive secondary voltage turns on the upper rectifier diode, supplying current to both the output capacitor and the load.

When the "A" transistor turns off and the "B" transistor turns on, the polarity of the primary voltage is reversed. The secondary voltage polarity is also reversed, turning on the lower diode (which supplies current to the output capacitor and the load).

In a Half-Bridge converter, **primary and secondary current flow in the transformer at the same time** (when either transistor is on), supplying the load current and charging the output capacitor. The output capacitor discharges into the load **only during the time when both transistors are off**.



**FIGURE 38. TIMING DIAGRAM FOR HALF-BRIDGE CONVERTER**

It can be seen that the voltage pulses on the transformer secondary side (applied to the L-C filter) are occurring at twice the frequency of the PWM converter which supplies the drive pulses for the switching transistors.

The output voltage is again given by:

$$V_{OUT} = V_{PK} \times (T_{ON} / T_{PER})$$

The peak amplitude of the secondary pulses ( $V_{PK}$ ) is given by:

$$V_{PK} = (1/2 V_{IN} - V_{SWITCH}) \times (N_S / N_P) - V_{RECT}$$

## FULL-BRIDGE CONVERTER

The Full-Bridge converter requires a total of four switching transistors to perform DC-DC conversion. The full bridge is most often seen in applications that are powered directly from the AC line, providing load power of 1 kW to 3 kW.

Operating off-line, the Full Bridge converter typically uses about 300V of unregulated DC voltage for power conversion (the voltage that is obtained when a standard 230 VAC line is rectified and filtered).

An important feature of this design is the isolation from the AC line provided by the switching transformer. The PWM control circuitry is referenced to the the output ground, requiring a dedicated voltage rail (usually powered from a small 60 Hz transformer) to run the control circuits.

The base drive voltages for the switch transistors (which are provided by the PWM chip) have to be transformer-coupled because of the required isolation.

Figure 39 shows a simplified schematic diagram of a Full-Bridge converter.

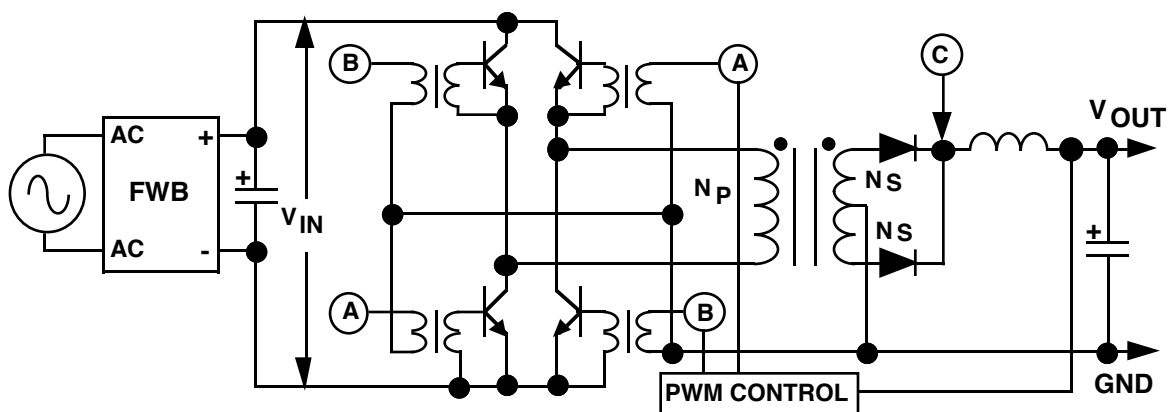


FIGURE 39. FULL BRIDGE CONVERTER

The transformer primary is driven by the **full voltage  $V_{IN}$**  when either of the transistor sets ("A" set or "B" set) turns on. The full input voltage utilization means the **Full-Bridge can produce the most load power of all the converter types**. The timing diagram is identical to the Half-Bridge, as shown in Figure 38.

Primary and secondary current flows in the transformer during the switch on times, while the output capacitor discharges into the load when both transistors are off.

The equation for the output voltage is (see Figure 38):

$$V_{OUT} = V_{PK} \times (T_{ON} / T_{PER})$$

The peak voltage of the transformer secondary pulses ( $V_{PK}$ ) is given by:

$$V_{PK} = (V_{IN} - 2V_{SWITCH}) \times (N_S / N_P) - V_{RECT}$$

# Application Hints For Switching Regulators

Application information will be provided on topics which will enhance the designers ability to maximize switching regulator performance.

## Capacitor Parasitics Affecting Switching Regulator Performance

All capacitors contain parasitic elements which make their performance less than ideal (see Figure 40).

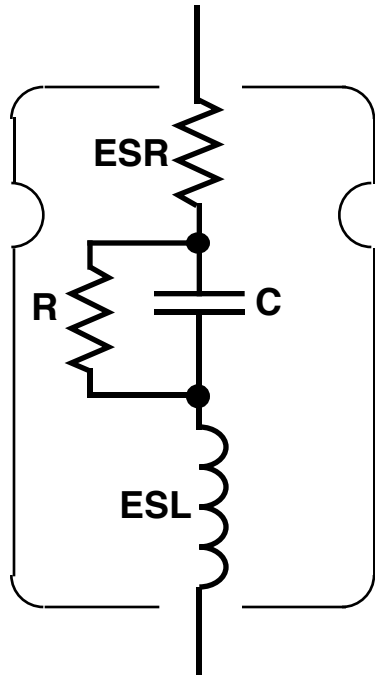


FIGURE 40.  
CAPACITOR PARASITICS

### Summary of Effects of Parasitics:

**ESR:** The ESR (**Equivalent Series Resistance**) causes internal heating due to power dissipation as the ripple current flows into and out of the capacitor. The capacitor can fail if ripple current exceeds maximum ratings.

**Excessive output voltage ripple will result from high ESR, and regulator loop instability is also possible.** ESR is highly dependent on temperature, increasing very quickly at temperatures below about 10 °C.

**ESL:** The ESL (**Effective Series Inductance**) limits the high frequency effectiveness of the capacitor. High ESL is the reason electrolytic capacitors need to be bypassed by film or ceramic capacitors to provide good high-frequency performance.

The ESR, ESL and C within the capacitor form a resonant circuit, whose frequency of resonance should be as high as possible. Switching regulators generate ripple voltages on their outputs with very high frequency (>10 MHz) components, which can cause ringing on the output voltage if the capacitor resonant frequency is low enough to be near these frequencies.

## INPUT CAPACITORS

All of the switching converters in this paper (and the vast majority in use) operate as DC-DC converters that "chop" a DC input voltage at a very high frequency. As the converter switches, it has to draw current pulses from the input source. The **source impedance is extremely important**, as even a small amount of inductance can cause significant ringing and spiking on the voltage at the input of the converter.

The best practice is to **always provide adequate capacitive bypass as near as possible to the switching converter input**. For best results, an electrolytic is used with a film capacitor (and possibly a ceramic capacitor) in parallel for optimum high frequency bypassing.

## OUTPUT CAPACITOR ESR EFFECTS

The primary function of the output capacitor in a switching regulator is filtering. As the converter operates, current must flow into and out of the output filter capacitor.

The ESR of the output capacitor directly affects the performance of the switching regulator. ESR is specified by the manufacturer on good quality capacitors, **but be certain that it is specified at the frequency of intended operation.**

General-purpose electrolytics usually only specify ESR at 120 Hz, but capacitors intended for high-frequency switching applications will have the ESR guaranteed at high frequency (like 20 kHz to 100 kHz).

Some ESR dependent parameters are:

Ripple Voltage: In most cases, **the majority of the output ripple voltage results from the ESR of the output capacitor.** If the ESR increases (as it will at low operating temperatures) the output ripple voltage will increase accordingly.

Efficiency: As the switching current flows into and out of the capacitor (through the ESR), power is dissipated internally. This "wasted" power reduces overall regulator efficiency, and **can also cause the capacitor to fail if the ripple current exceeds the maximum allowable specification for the capacitor.**

Loop Stability: The ESR of the output capacitor can affect regulator loop stability. Products such as the LM2575 and LM2577 are compensated for stability assuming the ESR of the output capacitor will stay within a specified range.

Keeping the ESR within the "stable" range is not always simple in designs that must operate over a wide temperature range. **The ESR of a typical aluminum electrolytic may increase by 40X as the temperature drops from 25°C to -40°C.**

In these cases, an aluminum electrolytic must be paralleled by another type of capacitor with a flatter ESR curve (like Tantalum or Film) so that the effective ESR (which is the parallel value of the two ESR's) stays within the allowable range.

Note: if operation **below -40°C** is necessary, aluminum electrolytics are probably not feasible for use.

## BYPASS CAPACITORS

High-frequency bypass capacitors are always recommended on the supply pins of IC devices, but if the devices are used in assemblies near switching converters **bypass capacitors are absolutely required.**

The components which perform the high-speed switching (transistors and rectifiers) generate significant EMI that easily radiates into PC board traces and wire leads.

To assure proper circuit operation, all IC supply pins must be bypassed to a clean, low-inductance ground (for details on grounding, see next section).



## Proper Grounding

The "ground" in a circuit is supposed to be at one potential, but in real life it is not. When ground currents flow through traces which have non-zero resistance, voltage differences will result at different points along the ground path.

In DC or low-frequency circuits, "ground management" is comparatively simple: the only parameter of critical importance is the **DC resistance of a conductor**, since that defines the voltage drop across it for a given current. In high-frequency circuits, it is the **inductance** of a trace or conductor that is much more important.

In switching converters, peak currents flow in high-frequency ( $> 50$  kHz) pulses, which can cause severe problems if trace inductance is high. Much of the "ringing" and "spiking" seen on voltage waveforms in switching converters is the result of high current being switched through parasitic trace (or wire) inductance.

Current switching at high frequencies tends to flow near the surface of a conductor (this is called "skin effect"), which means that ground traces must be very wide on a PC board to avoid problems. It is usually best (when possible) to use one side of the PC board as a **ground plane**.

Figure 41 illustrates an example of a terrible layout:

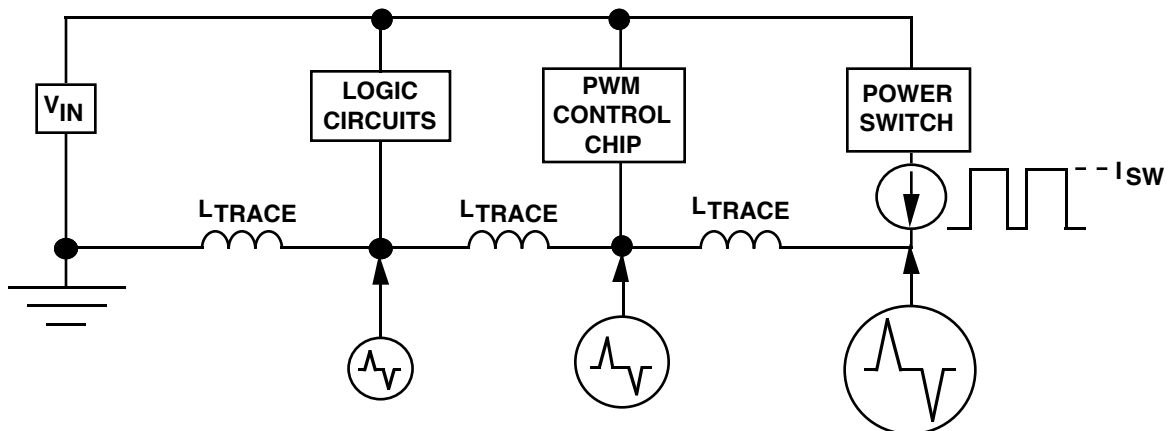


FIGURE 41. EXAMPLE OF POOR GROUNDING

The layout shown has the high-power switch return current passing through a trace that also provides the return for the PWM chip and the logic circuits. The switching current pulses flowing through the trace will cause a voltage spike (positive and negative) to occur as a result of the rising and falling edge of the switch current. This voltage spike follows directly from the  $v = L (di/dt)$  law of inductance.

It is important to note that the **magnitude of the spike will be different at all points along the trace**, being largest near the power switch. Taking the ground symbol as a point of reference, this shows how all three circuits would be bouncing up and down with respect to ground. More important, **they would also be moving with respect to each other**.

Mis-operation often occurs when sensitive parts of the circuit "rattle" up and down due to ground switching currents. This can induce noise into the reference used to set the output voltage, resulting in excessive output ripple.

Very often, regulators that suffer from ground noise problems appear to be unstable, and break into oscillations as the load current is increased (which increases ground currents).

A much better layout is shown in Figure 42.

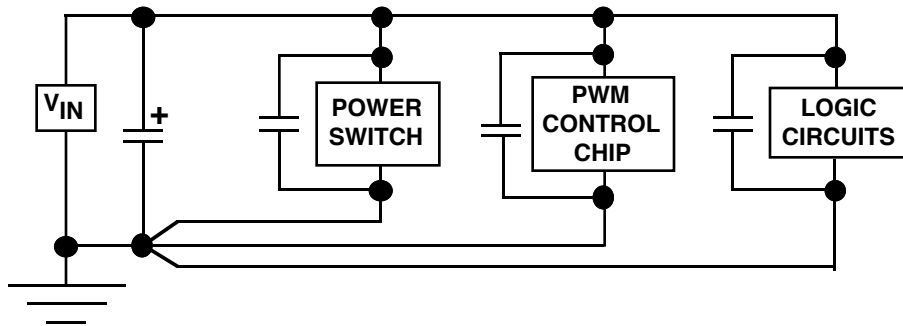


FIGURE 42. EXAMPLE OF GOOD GROUNDING

A big improvement is made by using **single-point grounding**. A good high-frequency electrolytic capacitor (like solid Tantalum) is used near the input voltage source to provide a good ground point.

All of the individual circuit elements are returned to this point **using separate ground traces**. This prevents high current ground pulses from bouncing the logic circuits up and down.

Another important improvement is that **the power switch** (which has the highest ground pin current) **is located as close as possible to the input capacitor**. This minimizes the trace inductance along its ground path.

It should also be pointed out that all of the individual circuit blocks have "local" bypass capacitors tied directly across them. The purpose of this capacitor is RF bypass, so it must be a ceramic or film capacitor (or both).

A good value for bypassing logic devices would be 0.01  $\mu\text{F}$  ceramic capacitor(s), distributed as required.

If the circuit to be bypassed generates large current pulses (like the power switch), **more capacitance is required**. A good choice would be an aluminum electrolytic bypassed with a film and ceramic capacitor. Exact size depends on peak current, but the more capacitance used, the better the result.

## Transformer/Inductor Cores and Radiated Noise

The type of core used in an inductor or transformer directly affects its cost, size, and radiated noise characteristics. Electrical noise radiated by a transformer is extremely important, as it may require shielding to prevent erratic operation of sensitive circuits located near the switching regulator.

The most commonly used core types will be presented, listing the advantages and disadvantages of each.

The important consideration in evaluating the electrical noise that an inductor or transformer is likely to generate is the **magnetic flux path**. In Figure 43, the **slug core** and **toroidal core** types are compared.

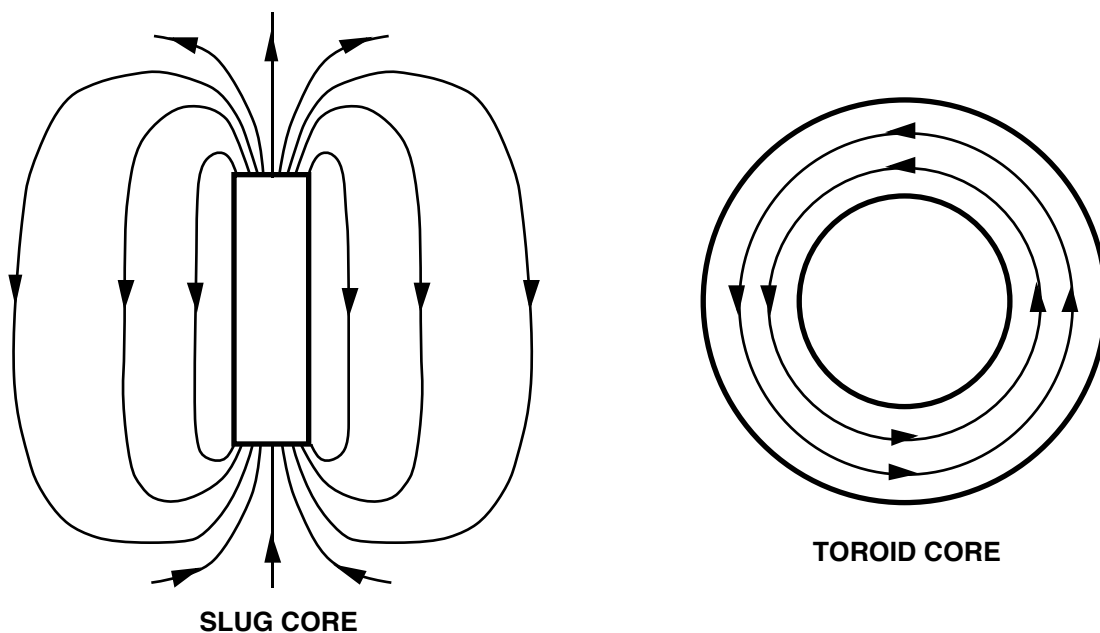


FIGURE 43. FLUX PATHS IN SLUG AND TOROID CORES

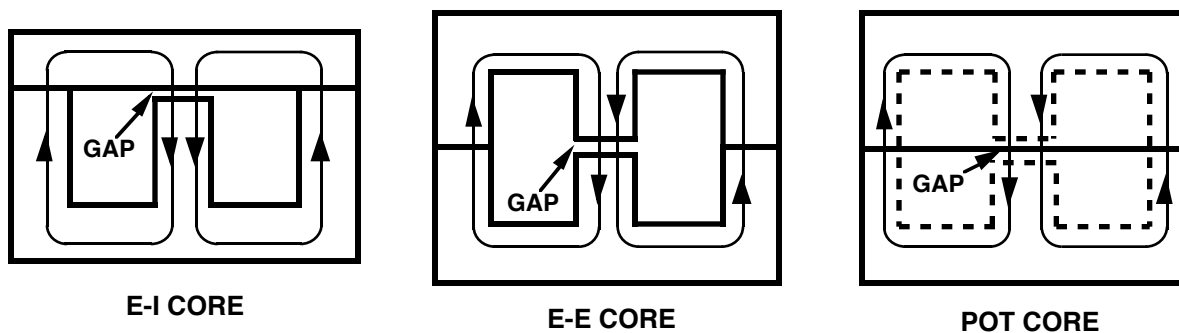
The flux in the slug core leaves one end, travels through the air, and returns to the other end. The **slug core is the highest (worst) for radiated flux noise**. In most cases, the slug core device will give the smallest, cheapest component for a given inductor size (it is very cheap to manufacture).

The magnetic flux path in the toroid is **completely contained within the core**. For this reason it has the **lowest (best) radiated flux noise**. Toroid core components are typically larger and more expensive compared to other core types. Winding a toroid is fairly difficult (and requires special equipment), driving up the finished cost of the manufactured transformer.

There is another class of cores commonly used in magnetic design which have radiated flux properties that are much better than the slug core, but not as good as the toroid. These cores are two-piece assemblies, and are assembled by gluing the core pieces together around the bobbin that holds the winding(s).

The cores shown are frequently "gapped" to prevent saturation of the Ferrite core material. The air gap is installed by grinding away a small amount of the core (the gap may be only a few thousandths of an inch).

Figure 44 shows the popular E-I, E-E and Pot cores often used in switching regulator transformers. The cores show the locations where an air gap is placed (if required), but the bobbins/windings are omitted for clarity.



**FIGURE 44. FLUX PATHS IN E-I, E-E AND POT CORES**

The air gap can emit flux noise because there is a high flux density in the vicinity of the gap, as the flux passing through the core has to jump the air gap to reach the other core piece.

The E-E and E-I cores are fairly cheap and easy to manufacture, and are very common in switching applications up to about 1 kW. There is a wide variety of sizes and shapes available, made from different Ferrite "blends" optimized for excellent switching performance. The radiated flux from this type of core is still reasonably low, and can usually be managed by good board layout.

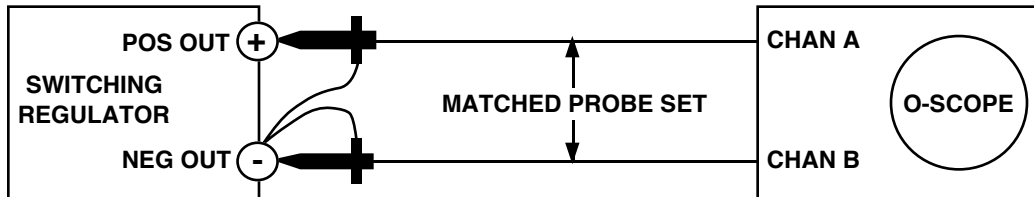
The Pot core (which is difficult to accurately show in a single view drawing), benefits from the shielding effect of the core sides (which are not gapped). This tends to keep the radiated flux contained better than an E-E or E-I core, making the Pot core second best only to the toroid core in minimizing flux noise.

Pot cores are typically more expensive than E-E or E-I cores of comparable power rating, but they have the advantage of being less noisy. Pot core transformers are much easier to manufacture than toroid transformers because the windings are placed on a standard bobbin and then the core is assembled around it.

## Measuring Output Ripple Voltage

The ripple appearing on the output of the switching regulator can be important to the circuits under power. Getting an accurate measurement of the output ripple voltage is not always simple.

If the output voltage waveform is measured using an oscilloscope, an accurate result can only be obtained using a **differential** measurement method (see Figure 45).



NOTE: INVERT CHANNEL B AND ADD TO CHANNEL A TO REMOVE COMMON-MODE SIGNAL

FIGURE 45. DIFFERENTIAL OUTPUT RIPPLE MEASUREMENT

The differential measurement shown uses the second channel of the oscilloscope to "cancel out" the signal that is common to both channels (by inverting the B channel signal and adding it to the A channel).

The reason this method must be used is because the fast-switching components in a switching regulator generate voltage spikes that have significant energy at very high frequencies. These signals can be picked up very easily by "antennas" as small as the 3" ground lead on the scope probe.

Assuming the probes are reasonably well matched, the B channel probe will pick up the same radiated signal as the A channel probe, which allows this "common-mode" signal to be eliminated by adding the inverted channel B signal to channel A.

It is often necessary to measure the RMS output ripple voltage, and this is usually done with some type of digital voltmeter. If the reading obtained is to be meaningful, the following must be considered:

- 1) **The meter must be true-RMS reading**, since the waveforms to be measured are very non-sinusoidal.
- 2) **The 3dB bandwidth of the meter should be at least 3X the bandwidth of the measured signal** (the output voltage ripple frequency will typically be > 100 kHz).
- 3) **Subtract the "noise floor" from the measurement.** Connect both meter leads to the negative regulator output and record this value. Move the positive meter lead to positive regulator output and record this value. **The actual RMS ripple voltage is the difference between these two readings.**

## Measuring Regulator Efficiency of DC-DC Converters

The **efficiency** ( $\eta$ ) of a switching regulator is defined as:

$$\eta = P_{LOAD} / P_{TOTAL}$$

In determining converter efficiency, the first thing that must be measured is the total consumed power ( $P_{TOTAL}$ ). Assuming a DC input voltage,  $P_{TOTAL}$  is defined as the **total power drawn from the source**, which is **equal to**:

$$P_{TOTAL} = V_{IN} \times I_{IN} (AVE)$$

It must be noted that the input current value used in the calculation must be the **average value** of the waveform (**the input current will not be DC or sinusoidal**).

Because the total power dissipated must be constant from input to output,  $P_{TOTAL}$  is also **equal to the load power plus the internal regulator power losses**:

$$P_{TOTAL} = P_{LOAD} + P_{LOSSES}$$

Measuring (or calculating) the power to the load is very simple, since the output voltage and current are both DC. The load power is found by:

$$P_{LOAD} = V_{OUT} \times I_{LOAD}$$

Measuring the input power drawn from the source is not simple. Although the **input voltage to the regulator is DC**, the **current drawn at the input of a switching regulator is not**. If a typical "clip-on" current meter is used to measure the input current, the taken data will be essentially meaningless.

The average input current to the regulator can be measured with reasonable accuracy by using a wide-bandwidth current probe connected to an oscilloscope.

The average value of input current can be closely estimated by drawing a horizontal line that divides the waveform in such a way that the **area of the figure above the line will equal the "missing" area below the line** (see Figure 46). In this way, the "average" current shown is equivalent to the value of DC current that would produce the same input power.

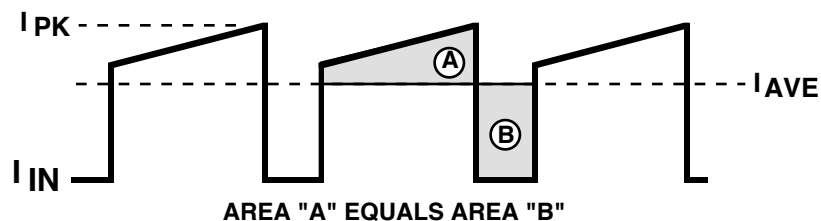


FIGURE 46. AVERAGE VALUE OF TYPICAL INPUT CURRENT WAVEFORM

If more exact measurements are needed, it is possible to **force** the current in the line going to the input of the DC-DC converter to be DC by using an L-C filter between the power source and the input of the converter (see Figure 47).

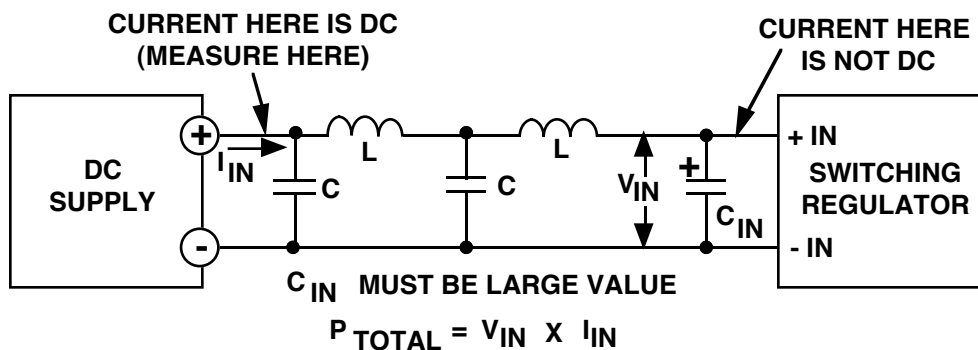


FIGURE 47. L-C FILTER USED IN DC INPUT CURRENT MEASUREMENT

If the L-C filter components are adequate, the current coming from the output of the DC power supply will be DC current (**with no high-frequency switching component**) which means it can be accurately measured with a cheap clip-on ammeter and digital volt meter.

It is essential that a large, low-ESR capacitor be placed at C<sub>IN</sub> to support the input of the switching converter. The L-C filter that the converter sees looking back into the source presents a high impedance for switching current, which means C<sub>IN</sub> is necessary to provide the switching current required at the input of the converter.

### Measuring Regulator Efficiency of Off-Line Converters

Off-Line converters are powered directly from the AC line, by using a bridge rectifier and capacitive filter to generate an unregulated DC voltage for conversion (see Figures 37 and 38).

Measuring the total power drawn from the AC source is fairly difficult because of the **power factor**. If **both the voltage and current are sinusoidal, power factor is defined as the cosine of the phase angle between the voltage and current waveforms.**

The capacitive-input filter in an off-line converter causes the input current to be **very non-sinusoidal**. The current flows in narrow, high-amplitude pulses (called Haversine pulses) which requires that the power factor be re-defined in such cases.

For capacitive-input filter converters, power factor is defined as:

$$\text{P.F.} = P_{\text{REAL}} / P_{\text{APPARENT}}$$

The **real power drawn from the source** ( $P_{REAL}$ ) is the power (in **Watts**) which equals the **sum of the load power and regulator internal losses**.

The **apparent power** ( $P_{APPARENT}$ ) is equal to the **RMS input current times the RMS input voltage**. Re-written, the importance of power factor is shown

$$I_{IN} (RMS) = P_{REAL} / ( V_{IN} (RMS) \times PF )$$

The RMS input current that the AC line must supply (for a given **real power** in Watts) increases directly as the power factor reduces from unity. Power factor for single-phase AC-powered converters is typically about 0.6. If three-phase power is used, the power factor is about 0.9.

If the efficiency of an off-line converter is to be measured, power analyzers are available which will measure and display input voltage, input power, and power factor. These are fairly expensive, so they may not be available to the designer.

Another method which will give good results is to measure the power **after the rectifier bridge and input capacitor** (where the voltage and current are DC). This method is shown in Figure 48.

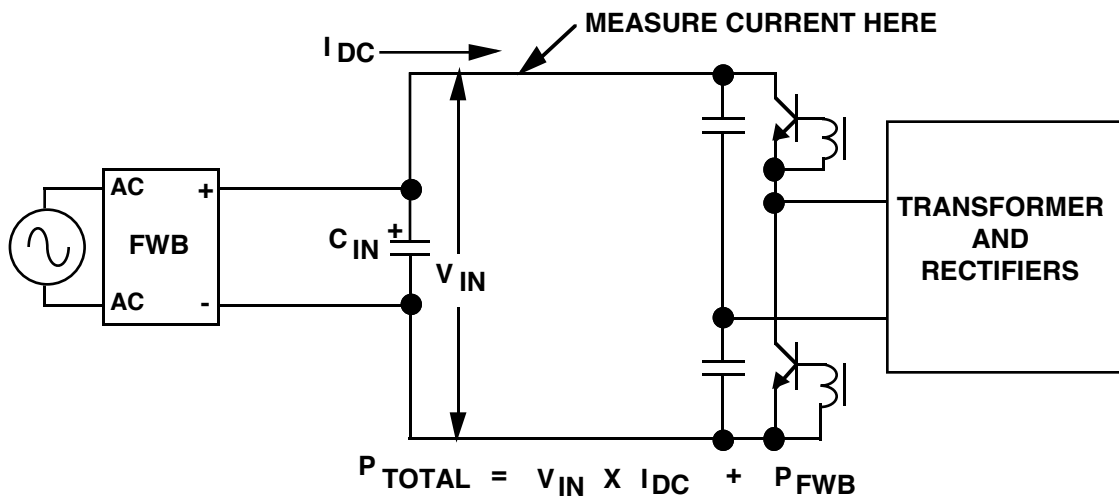


FIGURE 48. MEASURING INPUT POWER IN OFF-LINE CONVERTER

The current flowing from  $C_{IN}$  to the converter should be very nearly DC, and the average value can be readily measured or approximated (see previous section).

The total power drawn from the AC source is the sum of the power supplied by  $C_{IN}$  (which is  $V_{IN} \times I_{DC}$ ) and the power dissipated in the input bridge rectifier. The power in the bridge rectifier is easily estimated, and is actually negligible in most off-line designs.



# Application Circuits

## Introduction

Application circuits will be detailed which will demonstrate some examples of switching regulator designs.

## LM2577: A Complete Flyback/Boost Regulator IC

The LM2577 is an IC developed as part of the **SIMPLE SWITCHER™** product family. It is a **current-mode control** switching regulator, with a built-in NPN switch rated for 3A switch current and 65V breakdown voltage.

The most commonly used applications are for Flyback or Boost regulators (see Figure 49). In the Boost regulator, the output is always greater than the input. In the Flyback, the output may be greater than, less than, or equal to the input voltage.

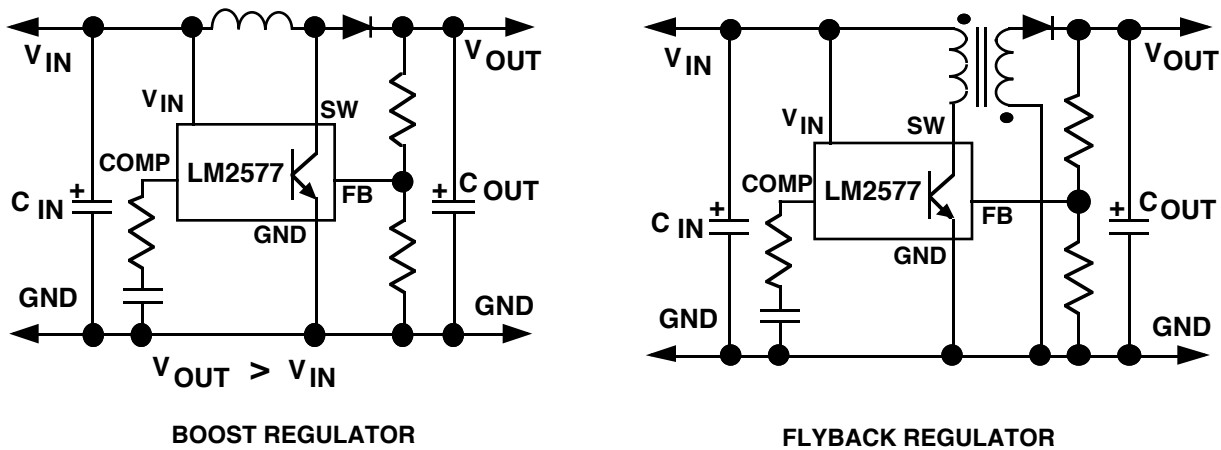


FIGURE 49. BASIC APPLICATION CIRCUITS FOR THE LM2577

The theory of operation of the Flyback and Boost Converters has been previously covered, and will not be repeated here.

The LM2577 is targeted for applications with load power requirements up to a maximum of about 25 Watts, and can be used to implement Boost or Flyback regulators (with multiple output voltages available if Flyback is selected).

The **SIMPLE SWITCHER** product family is supported by design-aid software titled "Switchers Made Simple", which allows finished designs to be generated directly from the computer.

The next sections will show the LM2577 being used in circuits which are more advanced than the typical applications (these circuits were generated as solutions for specific customer requirements).

## Increasing Available Load Power in an LM2577 Boost Regulator

One of the most frequently requested circuits is a method to squeeze more power out of a boost converter. The maximum load power available at the output is directly related to the input power available to the DC-DC converter.

When the input voltage is a low value (like 5V), this greatly reduces the amount of power that can be drawn from the source (because the maximum input current is limited by what the switch can handle). In the case of the LM2577, the maximum switch current is 3A (peak).

Increased load power can be obtained with the LM2577 by paralleling two devices (see Figure 50). Because current-mode control is used in the LM2577, the two converters will automatically share the load current demand.

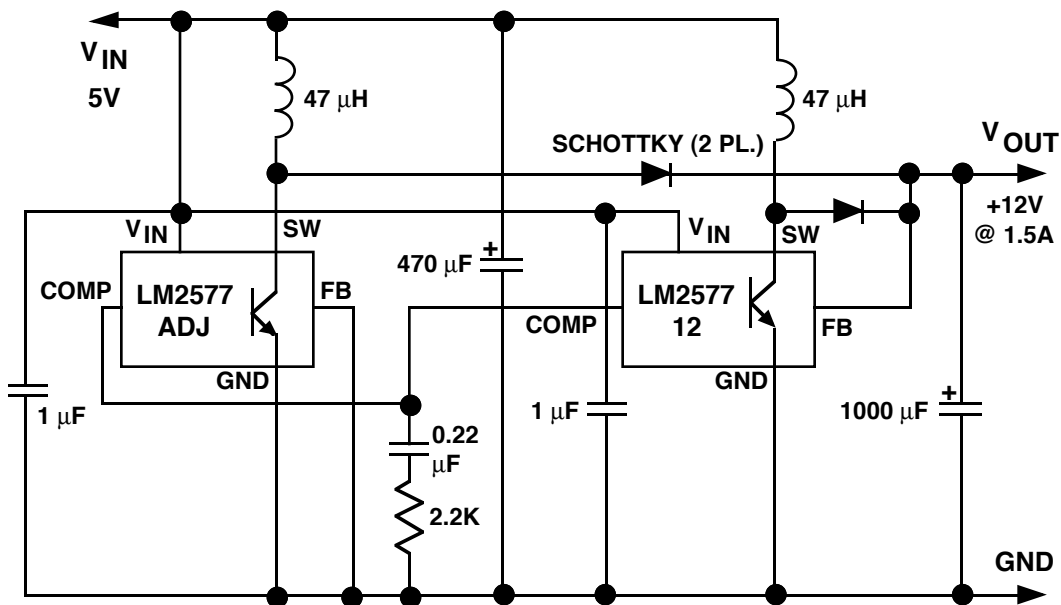


FIGURE 50. DUAL LM2577 BOOST CIRCUIT

The right-hand regulator (which is a fixed 12V version) is the master that sets the duty cycle of both regulators (tying the **Compensation** pins together forces the duty cycles to track).

The master regulator has direct feedback from the output, while the other regulator has its Feedback pin grounded. Grounding the Feedback pin makes the regulator attempt to run "wide open" (at maximum duty cycle), but the master regulator controls the voltage at **both** Compensation pins, which adjusts the pulse widths as required to hold the output voltage at 12V.

## LM2577 Negative Buck Regulator

The LM2577 can be used in a Buck regulator configuration that takes a **negative input voltage** and produces a **regulated negative output voltage** (see Figure 51).

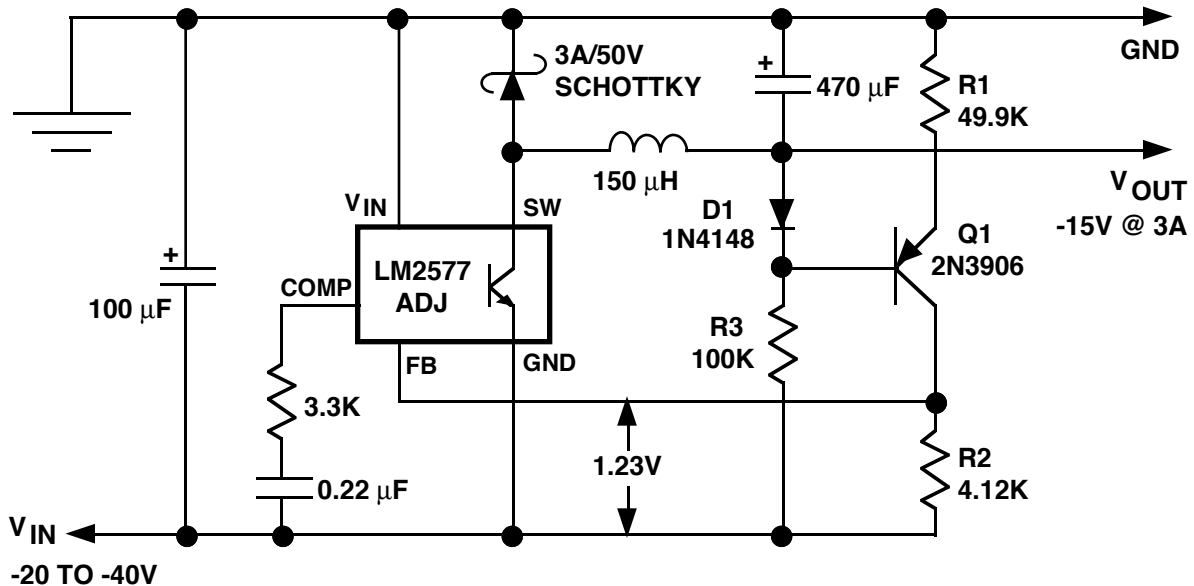


FIGURE 51. NEGATIVE BUCK REGULATOR

The LM2577 is referenced to the negative input, which means the feedback signal coming from the regulated output must be DC level shifted. R1, D1, and Q1 form a current source that sets a current through R2 that is directly proportional to the output voltage (D1 is included to cancel out the  $V_{BE}$  of Q1).

Neglecting the base current error of Q1, the current through R2 is equal to:

$$I_{R2} = V_{OUT} / R1 \quad (\text{which is } 300 \mu\text{A} \text{ for this example.})$$

The voltage across R2 provides the 1.23V feedback signal which the LM2577 requires for its feedback loop.

The operation of the power converter is similar to what was previously described for the Buck regulator:

When the switch is ON, current flows from ground through the load, into the regulator output, through the inductor, and down through the switch to return to the negative input. The output capacitor also charges during the switch ON time.

When the switch turns OFF, the voltage at the diode end of the inductor flies positive until the Schottky diode turns on (this allows the inductor current to continue to flow through the load during the OFF time). The output capacitor also discharges through the load during the OFF time, providing part of the load current.

## LM2577 Three-Output, Isolated Flyback Regulator

Many applications require electrical isolation between the input and output terminals of the power supply (for example, **medical monitoring instruments** require isolation to assure patient safety).

Figure 52 shows an example of a three-output Flyback regulator<sup>2</sup> built using the LM2577 that has electrical isolation between the input and output voltages.

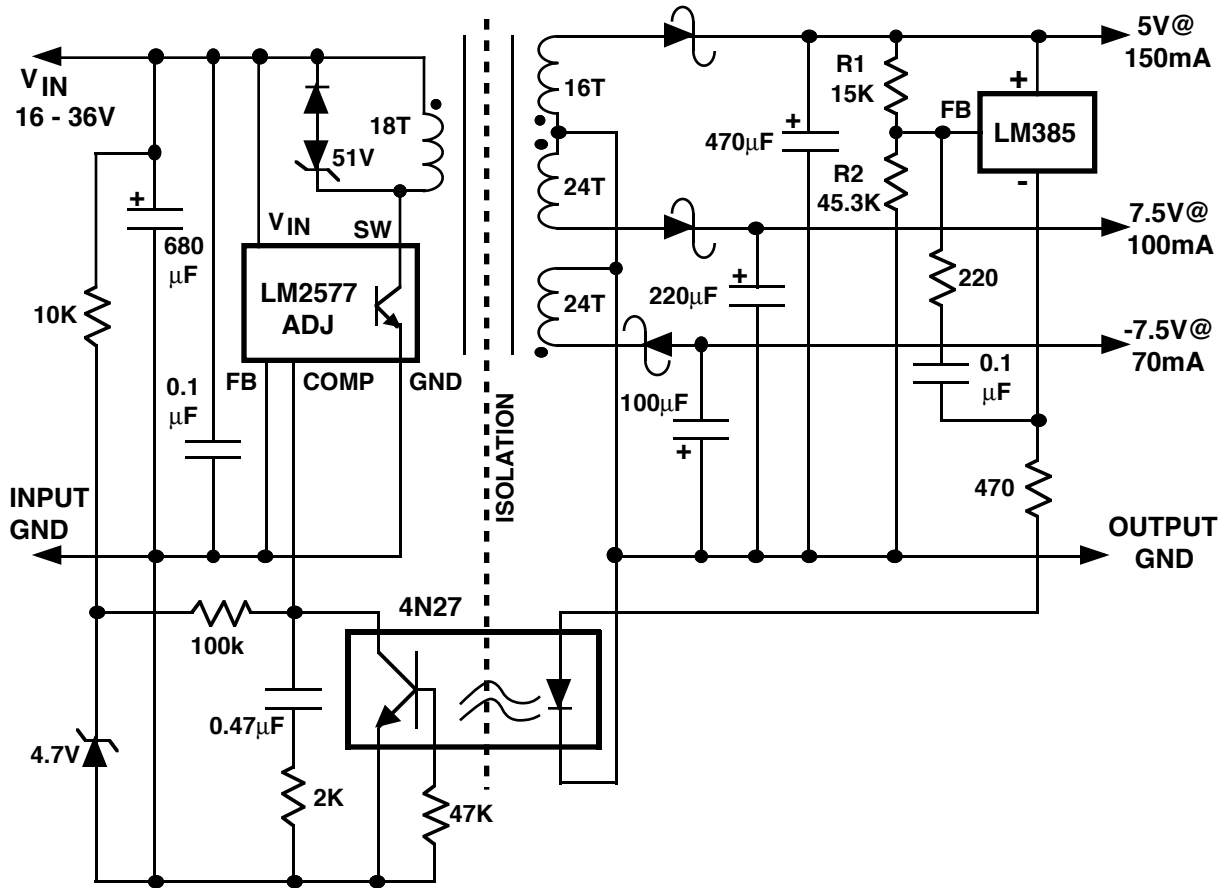


FIGURE 52. THREE-OUTPUT ISOLATED FLYBACK REGULATOR

Three output voltages are obtained from three separate transformer secondary windings, with voltage feedback being taken from the 5V output.

To maintain electrical isolation, the feedback path uses a 4N27 opto-coupler to transfer the feedback signal across the isolation barrier.

The 5V output is regulated using an LM385 adjustable reference, whose voltage is set by R1 and R2. The LM385 operates by forcing a 1.24V reference voltage between the positive terminal and the feedback pin, so the set voltage across the LM385 is given by:

$$V_{REF} = 1.24 \times (R2/R1 + 1)$$

For the values shown in this example, the voltage will be 5V.

The function of the LM385 in the circuit can be described as an "ideal" Zener diode, because the current flowing through the LM385 is very small until the voltage at its positive terminal reaches 5V with respect to ground. At that point, it tries to regulate its positive terminal to 5V by conducting current (which flows out of the negative terminal of the LM385 and through the 470Ω resistor into the diode side of the opto-coupler).

When the LM385 starts conducting current through the opto-coupler diode, the collector of the transistor in the opto-coupler pulls down on the compensation pin of the LM2577, which reduces the duty cycle (pulse widths) of the switching converter. In this way, a negative feedback loop is established which holds the output at 5V.

The feedback signal from the collector of the opto-coupler is fed into the compensation pin (not the feedback pin) of the LM2577 in order to bypass the internal error amplifier of the LM2577. The gain of the LM385 is so high that using the error amplifier inside the loop would make it difficult to stabilize (and is not necessary for good performance).

Test data taken with the input voltage set to 26V and all outputs fully loaded showed the frequency response of the control loop had a 0dB crossover point of 1kHz with a phase margin of 90°.

The 7.5V and -7.5V outputs are not directly regulated, which means their voltages are set by the pulse width of the regulated (5V) winding. As a result, the load regulation of these two outputs is not quite as good as the 5V output.

Summary of test performance data:

Output Voltages	Line Regulation (@ Full Load)	Load Regulation (VIN=26V)	Output Ripple Voltage (25°C)
5V	0.2%	0.04% (30mA - 150mA)	50mV
7.5V	0.3%	3% (20mA - 100mA)	50mV
-7.5V	0.3%	2% (12mA - 70mA)	50mV

# LM2575 and LM2576 Buck Regulators

The LM2575 and LM2576 products are Buck regulators developed as part of the **SIMPLE SWITCHER™** product family.

The LM2575 is rated for 1A of continuous load current, while the LM2576 can supply 3A. The maximum input voltage for the parts is 40V (60V for the "HV" versions), with both adjustable and fixed output voltages available. Both parts are included in the "Switchers Made Simple" design software.

The basic Buck regulator application circuit is shown in Figure 53.

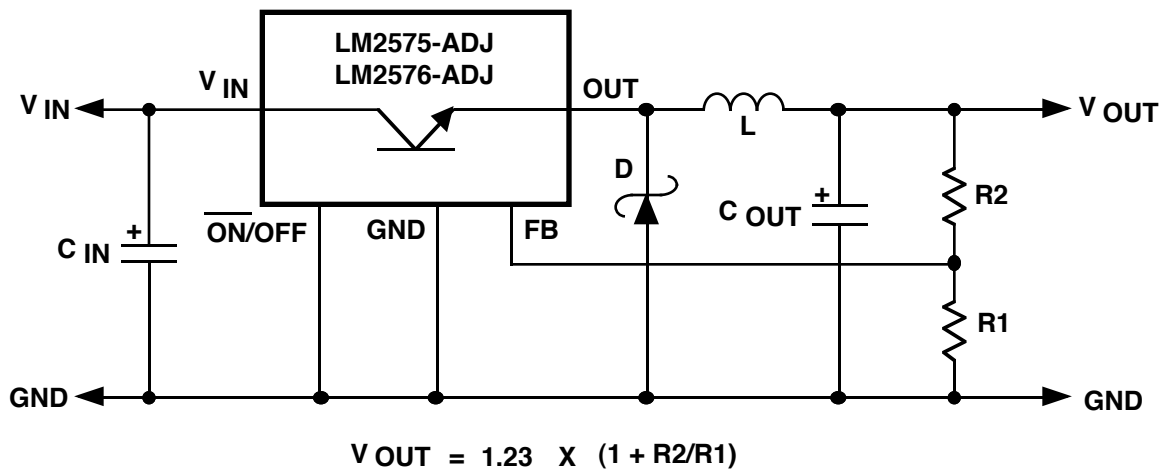


FIGURE 53. LM2575 AND LM2576 BUCK REGULATOR APPLICATION

The LM2575 and LM2576 can also be used in an inverting (Buck-Boost) configuration which allows a positive input voltage to be converted to a negative regulated output voltage (see Figure 54).

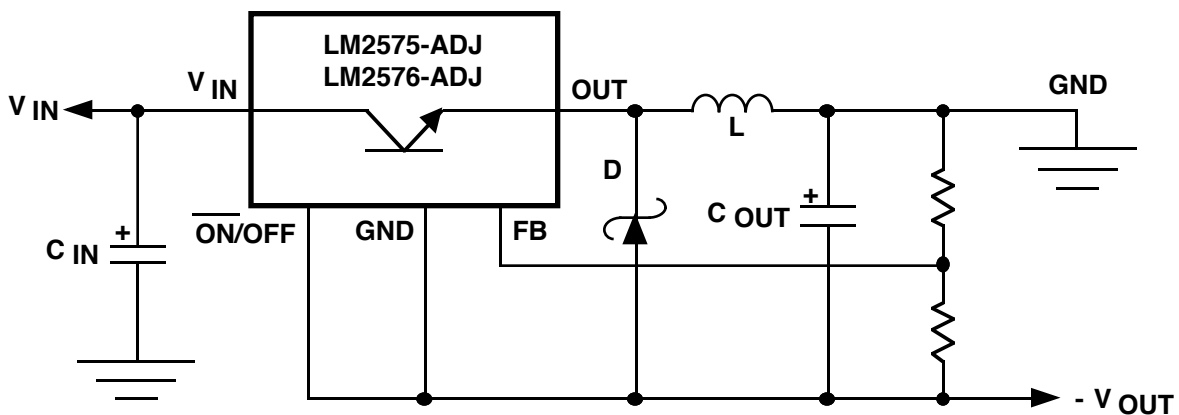


FIGURE 54. LM2575 AND LM2576 INVERTING APPLICATION

## Low Dropout, High Efficiency 5V/3A Buck Regulator

A circuit was developed which provides a 5V/3A regulated output voltage with very high efficiency and very low dropout voltage (see Figure 55). The customer required that the circuit be able to operate with an input voltage range of 6V to 12V, allowing **only 1V of dropout** at the lowest input voltage.

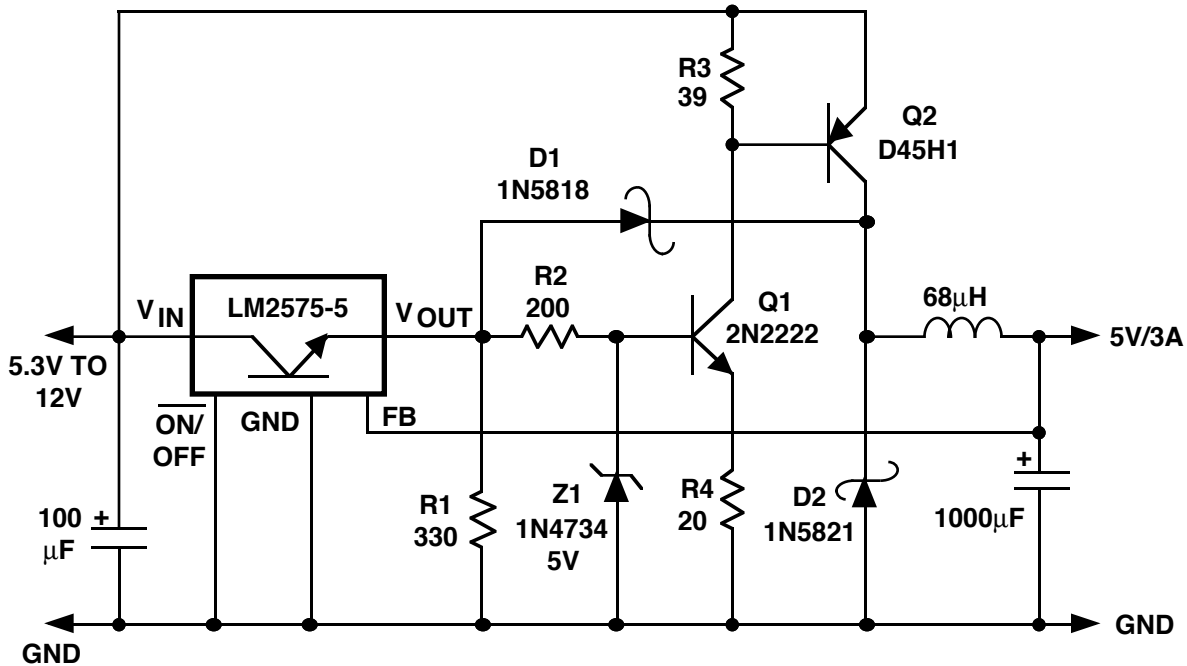


FIGURE 55. LOW-DROPOUT 5V/3A REGULATOR

An unusual feature of this circuit is that it can stay in regulation with **only 300 mV across the regulator**. Also, the **efficiency is highest (89%) at the lowest input voltage** (buck converters are typically more efficient at higher input voltages).

The low (<300mV) dropout voltage is achieved by using an external PNP power transistor (Q2) as the main switching transistor (the other transistors in the circuit are drivers for Q2). With components values shown, **Q2 has a saturation voltage of 200mV @ 3A**, which allows the 300 mV input-output differential requirement for the regulator to be met.

The switch inside the LM2575 drives the base of Q1 through R2. Note that the maximum collector current of Q1 (and the maximum base drive available for Q2) is limited by Z1 and R4. When Z1 clamps at 5V, the maximum current through Q1 is:

$$I_{Q1} (\text{MAX}) = (5 - V_{BE}) / R4 = 215\text{mA}$$

The maximum Q1 current (215mA) limits the amount of base drive available to Q2, forcing the collector current of Q2 to "beta limit" as the output is overloaded (this means the maximum collector current of Q2 will be limited by the gain of the transistor and the base drive provided). Although this is not a precise current limiter, it is adequate to protect Q2 from damage during an overload placed on the output.

If the regulator output is **shorted to ground**, the output short-circuit current flows from the output of the LM2575 (through D1 and the inductor), **which means the regulator short-circuit current is limited to the value set internally to the LM2575 (which is about 2A)**.

Note also that when the regulator output is shorted to ground, the cathode of D1 will also be near ground. This allows D1 to clamp off the base drive to Q1 off, preventing current flow in the switch transistor Q2.

If the input voltage does not exceed 8V, R2 and Z1 are not required in the circuit.

This circuit was tested with 6V input and was **able to deliver more than 4A of load current with 5V out**. Other test data taken are:

<b>Measured Performance Data:</b>	
<u>Line Regulation:</u>	
5.3V to 12V @ 1A	32mV
5.3V to 12V @ 3A	45mV
<u>Load Regulation:</u>	
0.3A to 3A @ 5.3V Input	10mV
0.3A to 3A @ 12V Input	17mV
<u>Efficiency @ 3A Load:</u>	
VIN = 5.3V	89%
VIN = 12V	80%
<u>Output Ripple Voltage:</u>	
VIN = 7.2V, IL = 3A	35 mV(p-p)



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