The LM105-An Improved Positive Regulator

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introduction

IC voltage regulators are seeing rapidly increasing usage. The LM100, one of the first, has already been widely accepted. Designed for versatility, this circuit can be used as a linear regulator, a switching regulator, a shunt regulator, or even a current regulator. The output voltage can be set between 2V and 30V with a pair of external resistors, and it works with unregulated input voltages down to 7V. Dissipation limitations of the IC package restrict the output current to less than 20 mA, but external transistors can be added to obtain output currents in excess of 5A. The LM100 and an extensive description of its use in many practical circuits are described in References 1–3.

One complaint about the LM100 has been that it does not have good enough regulation for certain applications. In addition, it becomes difficult to prove that the load regulation is satisfactory under worst-case design conditions. These problems prompted development of the LM105, which is nearly identical to the LM100 except that a gain stage has been added for improved regulation. In the great majority of applications, the LM105 is a plug-in replacement for the LM100.

the improved regulator

The load regulation of the LM100 is about 0.1%, no load to full load, without current limiting. When short circuit protection is added, the regulation begins to degrade as the output current becomes greater than about half the limiting current. This is illustrated in *Figure 1*. The LM105, on the other hand, gives 0.1% regulation up to currents closely approaching the short circuit current. As shown in *Figure 1b*, this is particularly significant at high temperatures.

The current limiting characteristics of a regulator are important for two reasons: First, it is almost mandatory that a regulator be short-circuit protected because the output is distributed to enough places that the probability of it becoming shorted is quite high, Secondly, the sharpness of the limiting characteristics is not improved by the addition of external booster transistors. External transistors can increase the maximum output current, but they do not improve the load regulation at currents approaching the short
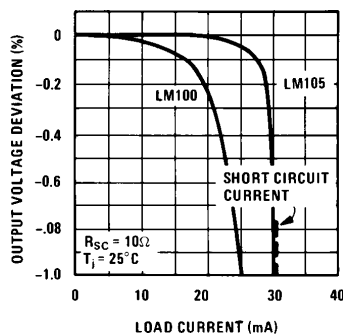
a. $T_j = 25°C$
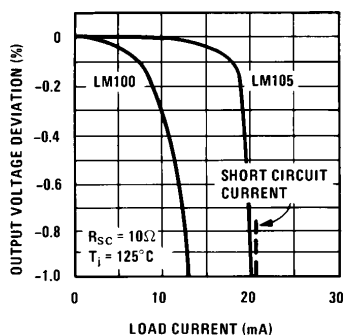
b. $T_j = 125°C$

Figure 1. Comparison between the load regulation of the LM100 and LM105 for equal short circuit currents

circuit current. Thus, it can be seen that the LM105 provides more than ten times better load regulation in practical power supply designs.

Figure 2 shows that the LM105 also provides better line regulation than the LM100. These curves give the percentage change in output voltage for an incremental change in the unregulated input voltage. They show that the line regulation is worst for small differences between the input and output voltages. The LM105 provides about three times better regulation under worst case conditions. Bypassing the internal reference of the regulator makes the ripple rejection of the LM105 almost a factor of ten better than the LM100 over the entire operating range, as shown in the figure. This bypass capacitor also eliminates noise generated in the internal reference zener of the IC.
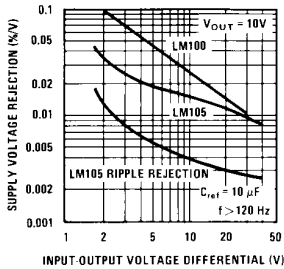

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Figure 2. Comparison between the line regulation characteristics of the LM100 and LM105

The LM105 has also benefited from the use of new IC components developed after the LM100 was designed. These have reduced the internal power consumption so that the LM105 can be specified for input voltages up to 50V and output voltages to 40V. The minimum preload current required by the LM100 is not needed on the LM105.

circuit description

The differences between the LM100 and the LM105 can be seen by comparing the schematic diagrams in *Figures 3* and *4*. Q4 and Q5 have been added to the LM105 to form a common-collector, common-base, common-emitter amplifier, rather than the single common-emitter differential amplifier of the LM100.

In the LM100, generation of the reference voltage starts with zener diode, D1, which is supplied with a fixed current from one of the collectors of Q2. This regulated voltage, which has a positive temperature coefficient, is buffered by
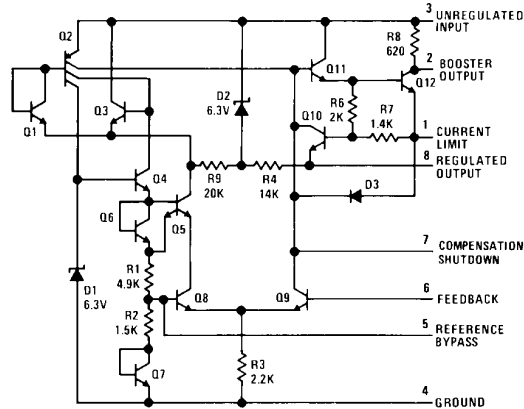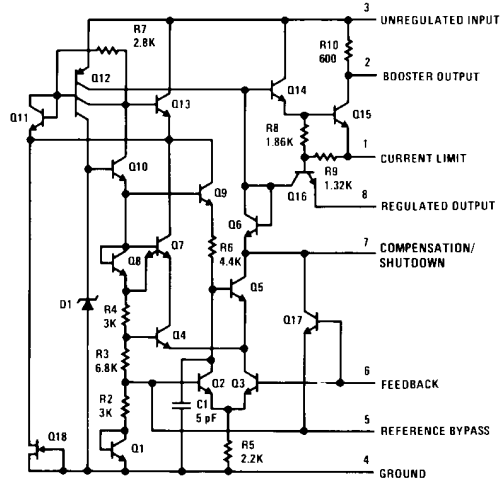

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Figure 4. Schematic diagram of the LM105 regulator

Q4, divided down by R1 and R2 and connected in series with a diode-connected transistor, Q7. The negative temperature coefficient of Q7 cancels out the positive coefficient of the voltage across R2, producing a temperature-compensated 1.8V on the base of Q8. This point is also brought outside the circuit so that an external capacitor can be added to bypass any noise from the zener diode.

Transistors Q8 and Q9 make up the error amplifier of the circuit. A gain of 2000 is obtained from this single stage by using a current source, another collector on Q2, as a collector load. The output of the amplifier is buffered by Q11 and used to drive the series-pass transistor, Q12. The collector of Q12 is brought out so that an external PNP transistor, or PNP—NPN combination, can be added for increased output current.

Current limiting is provided by Q10. When the voltage across an external resistor connected between Pins 1 and 8 becomes high enough to turn on Q10, it removes the base drive from Q11 so the regulator exhibits a constant-current characteristic. Prebiasing the current limit transistor with a portion of the emitter-base voltage of Q12 from R6 and R7 reduces the current limit sense voltage. This increases the

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Figure 3. Schematic diagram of the LM100 regulator

efficiency of the regulator, especially when foldback current limiting is used. With foldback limiting, the voltage dropped across the current sense resistor is about four times larger than the sense voltage.

As for the remaining details, the collector of the amplifier, Q9, is brought out so that external collector-base capacitance can be added to frequency-stabilize the circuit when it is used as a linear regulator. This terminal can also be grounded to shut the regulator off. R9 and R4 are used to start up the regulator, while the rest of the circuitry establishes the proper operating levels for the current source transistor, Q2.

The reference circuitry of the LM105 is the same, except that the current through the reference divider, R2, R3 and R4, has been reduced by a factor of two on the LM105 for reduced power consumption. In the LM105, Q2 and Q3 form an emitter coupled amplifier, with Q3 being the emitter-follower input and Q2 the common-base output amplifier. R6 is the collector load for this stage, which has a voltage gain of about 20. The second stage is a differential amplifier, using Q4 and Q5. Q5 actually provides the gain. Since it has a current source as a collector load, one of the collectors of Q12, the gain is quite high: about 1500. This gives a total gain in the error amplifier of about 30,000 which is ten times higher than the LM100.

It is not obvious from the schematic, but the first stage (Q2 and Q3) and second stage (Q4 and Q5) of the error amplifier are closely balanced when the circuit is operating. This will be true regardless of the absolute value of components and over the operating temperature range. The only thing affecting balance is component matching, which is good in a monolithic integrated circuit, so the error amplifier has good drift characteristics over a wide temperature range.

Frequency compensation is accomplished with an external integrating capacitor around the error amplifier, as with the LM100. This scheme makes the stability insensitive to loading conditions—resistive or reactive—while giving good transient response. However, an internal capacitor, C1, is added to prevent minor-loop oscillations due to the increased gain.

Additional differences between the LM100 and LM105 are that a field-effect transistor, Q18, connected as a current source starts the regulator when power is first applied. Since this current source is connected to ground, rather than the output, the minimum load current before the regulator drops out of operation with large input-output voltage differentials is greatly reduced. This also minimizes power dissipation in the integrated circuit when the difference between the input and output voltage is at the worst-case value. With the LM105 circuit configuration, it was also necessary to add Q17 to eliminate a latch-up mechanism which could exist with lower output-voltage settings. Without Q17, this could occur when Q3 saturated and cut off the second stage amplifiers, Q4 and Q5, causing the output to latch at a voltage nearly equal to the unregulated input.

power limitations

Although it is desirous to put as much of the regulator as possible on the IC chip, there are certain basic limitations. For one, it is not a good idea to put the series pass transistor on the chip. The power that must be dissipated in the pass transistor is too much for practical IC packages. Further, IC's must be rated at a lower maximum operating temperature than power transistors. This means that even with a power package, a more massive heat sink would be required if the pass transistor was included in the IC.

Assuming that these problems could be solved, it is still not advisable to put the pass transistor on the same chip with the reference and control circuitry: changes in the unregulated input voltage or load current produce gross variations in chip temperature. These variations worsen load and line regulation due to temperature interaction with the control and reference circuitry.

To elaborate, it is reasonable to neglect the package problem since it is potentially solvable. The lower, maximum operating temperatures of IC's, however, present a more basic problem. The control circuitry in an IC regulator runs at fairly low currents. As a result, it is more sensitive to leakage currents and other phenomena which degrades the performance of semiconductors at high temperatures. Hence, the maximum operating temperature is limited to 150°C in military temperature range applications. On the other hand, a power transistor operating at high currents may be run at temperatures up to 200°C, because even a 1 mA leakage current would not affect its operation in a properly designed circuit. Even if the pass transistor developed a permanent 1 mA leakage from channeling, operating under these conditions of high stress, it would not affect circuit operation. These conditions would not trouble the pass transistor, but they would most certainly cause complete failure of the control circuitry.

These problems are not eliminated in applications with a lower maximum operating temperature. Integrated circuits are sold for limited temperature range applications at considerably lower cost. This is mainly based on a lower maximum junction temperature. They may be rated so that they do not blow up at higher temperatures, but they are not guaranteed to operate within specifications at these temperatures. Therefore, in applications with a lower maximum ambient temperature, it is necessary to purchase an expensive full temperature range part in order to take advantage of the theoretical maximum operating temperatures of the IC.

Figure 5 makes the point about dissipation limitations more strongly. It gives the maximum short circuit output current for an IC regulator in a TO-5 package, assuming a 25°C temperature rise between the chip and ambient and a quiescent current of 2 mA. Dual-in-line or flat packages give results which are, at best, slightly better, but are usually worse. If the short circuit current is not of prime concern, *Figure 5* can also be used to give the maximum output current as a function of input-output voltage differential, However, the increased dissipation due to the quiescent current flowing at the maximum input voltage must be taken into account. In addition, the input-output differential must be measured with the maximum expected input voltages.
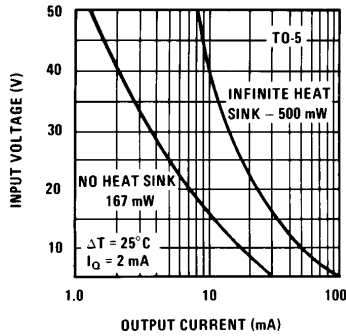
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Figure 5. Dissipation limited short circuit output current for an IC regulator in a TO-5 package

The 25°C temperature rise assumed in arriving at *Figure 5* is not at all unreasonable. With military temperature range parts, this is valid for a maximum junction temperature of 150°C with a 125°C ambient. For low cost parts, marketed for limited temperature range applications, this maximum differential appropriately derates the maximum junction temperature.

In practical designs, the maximum permissible dissipation will always be to the left of the curve shown for an infinite heat sink in *Figure 5*. This curve is realized with the package immersed in circulating acetone, freon or mineral oil. Most heat sinks are not quite as good.

To summarize, power transistors can be run with a temperature differential, junction to ambient, 3 to 5 times as great as an integrated circuit. This means that they can dissipate much more power, even with a smaller heat sink. This, coupled with the fact that low cost, multilead power packages are not available and that there can be thermal interactions between the control circuitry and the pass transistor, strongly suggests that the pass transistors be kept separate from the integrated circuit.

using booster transistors

Figure 6 shows how an external pass transistor is added to the LM105. The addition of an external PNP transistor does not increase the minimum input output voltage differential.
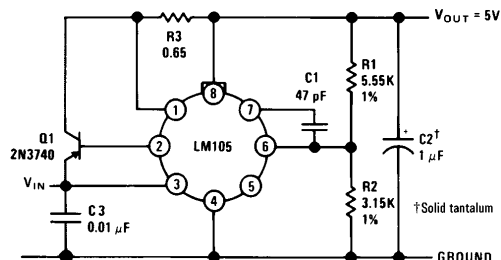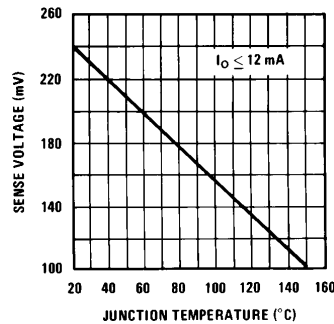

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Figure 6. 0.2A regulator

This would happen if an NPN transistor was used in a compound emitter follower connection with the NPN output transistor of the IC. A single-diffused, wide base transistor like the 2N3740 is recommended because it causes fewer oscillation problems than double-diffused, planar devices. In addition, it seems to be less prone to failure under overload conditions; and low cost devices are available in power packages like the TO-66 or even TO-3.

When the maximum dissipation in the pass transistor is less than about 0.5W, a 2N2905 may be used as a pass transistor. However, it is generally necessary to carefully observe thermal deratings and provide some sort of heat sink.

In the circuit of *Figure 6*, the output voltage is determined by R1 and R2. The resistor values are selected based on a feedback voltage of 1.8V to Pin 6 of the LM105. To keep thermal drift of the output voltage within specifications, the parallel combination of R1 and R2 should be approximately 2K. However, this resistance is not critical. Variations of ±30% will not cause an appreciable degradation of temperature drift.

The 1 μF output capacitor, C2, is required to suppress oscillations in the feedback loop involving the external booster transistor, Q1, and the output transistor of the LM105. C1 compensates the internal regulator circuitry to make the stability independent for all loading conditions. C3 is not normally required if the lead length between the regulator and the output filter of the rectifier is short.

Current limiting is provided by R3. The current limit resistor should be selected so that the maximum voltage drop across it, at full load current, is equal to the voltage given in *Figure 7* at the maximum junction temperature of the IC. This assures a no load to full load regulation better than 0.1% under worst-case conditions.
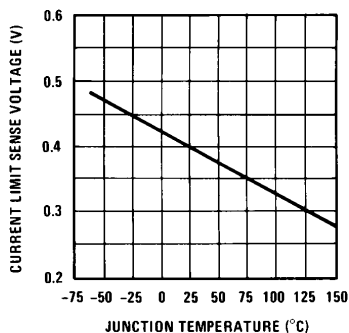

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Figure 7. Maximum voltage drop across current limit resistor at full load for worst case load regulation of 0.1%

The short circuit output current is also determined by R3. *Figure 8* shows the voltage drop across this resistor, when the output is shorted, as a function of junction temperature in the IC.

With the type of current limiting used in *Figure 6*, the dissipation under short circuit conditions can be more than three times the worst-case full load dissipation. Hence, the heat
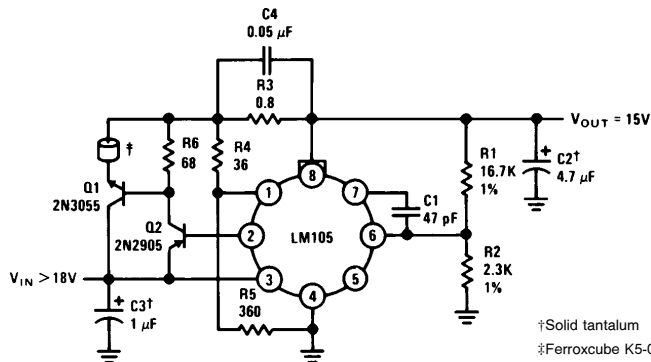
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Figure 8. Voltage drop across current limit resistor required to initiate current limiting

sink for the pass transistor must be designed to accommodate the increased dissipation if the regulator is to survive more than momentarily with a shorted output. It is encouraging to note, however, that the short circuit current will decrease at higher ambient temperatures. This assists in protecting the pass transistor from excessive heating.

foldback current limiting

With high current regulators, the heat sink for the pass transistor must be made quite large in order to handle the power dissipated under worst-case conditions. Making it more than three times larger to withstand short circuits is sometimes inconvenient in the extreme. This problem can be solved with foldback current limiting, which makes the output current under overload conditions decrease below the full load current as the output voltage is pulled down. The short circuit current can be made but a fraction of the full load current.
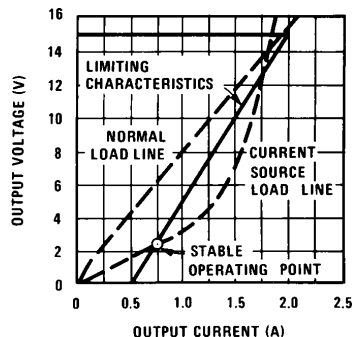
A high current regulator using foldback limiting is shown in *Figure 9*. A second booster transistor, Q1, has been added to provide 2A output current without causing excessive dissipation in the LM105. The resistor across its emitter base junction bleeds off any collector base leakage and establishes a minimum collector current for Q2 to make the circuit easier to stabilize with light loads. The foldback characteristic is produced with R4 and R5. The voltage across R4 bucks out the voltage dropped across the current sense resistor, R3. Therefore, more voltage must be developed across R3 before current limiting is initiated. After the output voltage begins to fall, the bucking voltage is reduced, as it is proportional to the output voltage. With the output shorted,

the current is reduced to a value determined by the current limit resistor and the current limit sense voltage of the LM105.

Figure 10. Limiting characteristics of regulator using foldback current limiting

Figure 10 illustrates the limiting characteristics. The circuit regulates for load currents up to 2A. Heavier loads will cause the output voltage to drop, reducing the available current. With a short on the output, the current is only 0.5A.

In design, the value of R3 is determined from

$$R_3 = \frac{V_{lim}}{I_{SC}}, \qquad (1)$$

where V_{lim} is the current limit sense voltage of the LM105, given in *Figure 8*, and I_{SC} is the design value of short circuit current. R5 is then obtained from

$$R_5 = \frac{V_{OUT} + V_{sense}}{I_{bleed} + I_{bias}}, \qquad (2)$$

where V_{OUT} is the regulated output voltage, V_{sense} is maximum voltage across the current limit resistor for 0.1% regulation as indicated in *Figure 7*, I_{bleed} is the preload current on the regulator output provided by R5 and I_{bias} is the maximum current coming out of Pin 1 of the LM105 under full load conditions. I_{bias} will be equal to 2 mA plus the worst-case base drive for the PNP booster transistor, Q2. I_{bleed} should be made about ten times greater than I_{bias}.

Finally, R4 is given by

$$R_4 = \frac{I_{FL} R_3 - V_{sense}}{I_{bleed}}, \qquad (3)$$

where I_{FL} is the output current of the regulator at full load.

†Solid tantalum
‡Ferroxcube K5-001-00/3B

Figure 9. 2A regulator with foldback current limiting

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It is recommended that a ferrite bead be strung on the emitter of the pass transistor, as shown in *Figure 9*, to suppress oscillations that may show up with certain physical configurations. It is advisable to also include C4 across the current limit resistor.

In some applications, the power dissipated in Q2 becomes too great for a 2N2905 under worst-case conditions. This can be true even if a heat sink is used, as it should be in almost all applications. When dissipation is a problem, the 2N2905 can be replaced with a 2N3740. With a 2N3740, the ferrite bead and C4 are not needed because this transistor has a lower cutoff frequency.

One of the advantages of foldback limiting is that it sharpens the limiting characteristics of the IC. In addition, the maximum output current is less sensitive to variations in the current limit sense voltage of the IC: in this circuit, a 20% change in sense voltage will only affect the trip current by 5%. The temperature sensitivity of the full load current is likewise reduced by a factor of four, while the short circuit current is not.

Even though the voltage dropped across the sense resistor is larger with foldback limiting, the minimum input-output voltage differential of the complete regulator is not increased above the 3V specified for the LM105 as long as this drop is less than 2V. This can be attributed to the low sense voltage of the IC by itself.

Figure 10 shows that foldback limiting can only be used with certain kinds of loads. When the load looks predominantly like a current source, the load line can intersect the foldback characteristic at a point where it will prevent the regulator from coming up to voltage, even without an overload. Fortunately, most solid state circuitry presents a load line which does not intersect. However, the possibility cannot be ignored, and the regulator must be designed with some knowledge of the load.

With foldback limiting, power dissipation in the pass transistor reaches a maximum at some point between full load and short circuited output. This is illustrated in *Figure 11*. However, if the maximum dissipation is calculated with the worst-case input voltage, as it should be, the power peak is not too high.
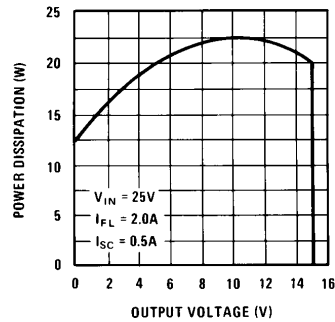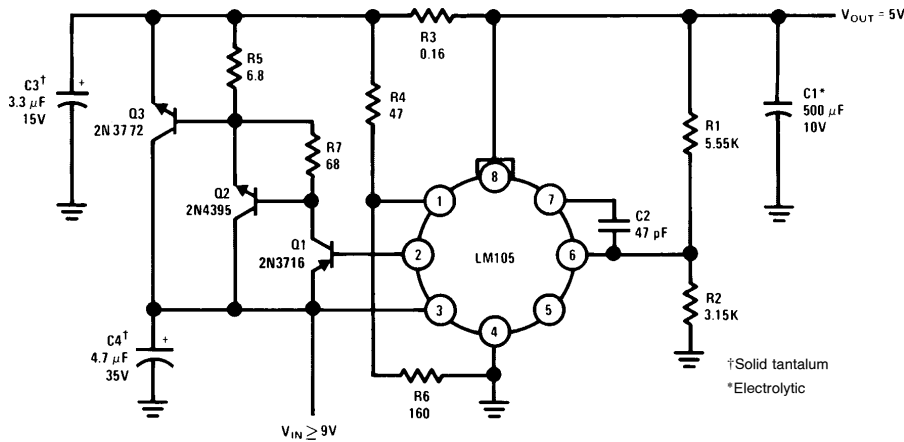

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Figure 11. Power dissipation in series pass transistors under overload conditions in regulator using foldback current limiting

high current regulator

The output current of a regulator using the LM105 as a control element can be increased to any desired level by adding more booster transistors, increasing the effective current gain of the pass transistors. A circuit for a 10A regulator is shown in *Figure 12*. A third NPN transistor has been included to get higher current. A low frequency device is used for Q3 because it seems to better withstand abuse. However, high frequency transistors must be used to drive it. Q2 and Q3 are both double-diffused transistors with good frequency response. This insures that Q3 will present the dominant lag in the feedback loop through the booster transistors, and back around the output transistor of the LM105. This is further insured by the addition of C3.

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Figure 12. 10A regulator with foldback current limiting

The circuit, as shown, has a full load capability of 10A. Foldback limiting is used to give a short circuit output current of 2.5A. The addition of Q3 increases the minimum input-output voltage differential, by 1V, to 4V.

dominant failure mechanisms

By far, the biggest reason for regulator failures is overdissipation in the series pass transistors. This has been borne out by experience with the LM100. Excessive heating in the pass transistors causes them to short out, destroying the IC. This has happened most frequently when PNP booster transistors in a TO-5 can, like the 2N2905, were used. Even with a good heat sink, these transistors cannot dissipate much more than 1W. The maximum dissipation is less in many applications. When a single PNP booster is used and power can be a problem, it is best to go to a transistor like the 2N3740, in a TO-66 power package, using a good heat sink.

Using a compound PNP/NPN booster does not solve all problems. Even when breadboarding with transistors in TO-3 power packages, heat sinks must be used. The TO-3 package is not very good, thermally, without a heat sink. Dissipation in the PNP transistor driving the NPN series pass transistor cannot be ignored either. Dissipation in the driver with worst-case current gain in the pass transistor must be taken into account. In certain cases, this could require that a PNP transistor in a power package be used to drive the NPN pass transistor. In almost all cases, a heat sink is required if a PNP driver transistor in a TO-5 package is selected.

With output currents above 3A, it is good practice to replace a 2N3055 pass transistor with a 2N3772. The 2N3055 is rated for higher currents than 3A, but its current gain falls off rapidly. This is especially true at either high temperatures or low input-output voltage differentials. A 2N3772 will give substantially better performance at high currents, and it makes life much easier for the PNP driver.

The second biggest cause of failures has been the output filter capacitors on power inverters providing unregulated power to the regulator. If these capacitors are operated with excessive ripple across them, and simultaneously near their maximum dc voltage rating, they will sputter. That is, they short momentarily and clear themselves. When they short, the output capacitor of the regulator is discharged back through the reverse biased pass transistors or the control circuitry, frequently causing destruction. This phenomenon is especially prevalent when solid tantalum capacitors are used with high-frequency power inverters. The maximum ripple allowed on these capacitors decreases linearly with frequency.

The solution to this problem is to use capacitors with conservative voltage ratings. In addition, the maximum ripple allowed by the manufacturer at the operating frequency should also be observed.

The problem can be eliminated completely by installing a diode between the input and output of the regulator such that the capacitor on the output is discharged through this diode if the input is shorted. A fast switching diode should be used as ordinary rectifier diodes are not always effective.

Another cause of problems with regulators is severe voltage transients on the unregulated input. Even if these transients do not cause immediate failure in the regulator, they can feed through and destroy the load. If the load shorts out, as is frequently the case, the regulator can be destroyed by subsequent transients.

This problem can be solved by specifying all parts of the regulator to withstand the transient conditions. However, when ultimate reliability is needed, this is not a good solution. Especially since the regulator can withstand the transient, yet severely overstress the circuitry on its output by feeding the transients through. Hence, a more logical recourse is to include circuitry which suppresses the transients. A method of doing this is shown in *Figure 13*. A zener diode, which can handle large peak currents, clamps the input voltage to the regulator while an inductor limits the current through the zener during the transient. The size of the inductor is determined from

$$L = \frac{\Delta V \Delta t}{I} \qquad (4)$$

where ΔV is the voltage by which the input transient exceeds the breakdown voltage of the diode, Δt is the duration of the transient and I is the peak current the zener can handle while still clamping the input voltage to the regulator. As shown, the suppression circuit will clamp 70V, 4 ms transients on the unregulated supply.
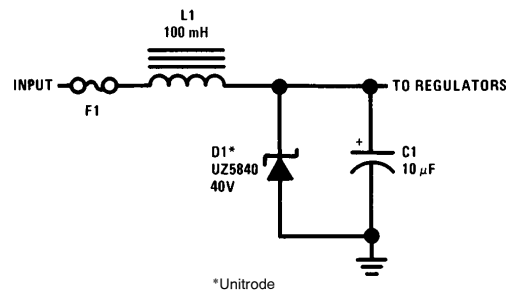

Figure 13. Suppression circuitry to remove large voltage spikes from unregulated supplies

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conclusions

The LM105 is an exact replacement for the LM100 in the majority of applications, providing about ten times better regulation. There are, however, a few differences:

In switching regulator applications,[2] the size of the resistor used to provide positive feedback should be doubled as the impedance seen looking back into the reference bypass terminal is twice that of the LM100 (2 kΩ versus 1 kΩ). In addition, the minimum output voltage of the LM105 is 4.5V, compared with 2V for the LM100. In low voltage regulator applications, the effect of this is obvious. However, it also imposes some limitations on current regulator and shunt regulator designs.[3] Lastly, clamping the compensation terminal (Pin 7) within a diode drop of ground or the output terminal will not guarantee that the regulator is shut off, as it will with the LM100. This restricts the LM105 in the overload shutoff schemes[3] which can be used with the LM100.

Dissipation limitations of practical packages dictate that the output current of an IC regulator be less than 20 mA. However, external booster transistors can be added to get any output current desired. Even with satisfactory packages, considerably larger heat sinks would be needed if the pass transistors were put on the same chip as the reference and control circuitry, because an IC must be run at a lower maximum temperature than a power transistor. In addition, heat dissipated in the pass transistor couples into the low level circuitry and degrades performance. All this suggests that the pass transistor be kept separate from the IC.

Overstressing series pass transistors has been the biggest cause of failures with IC regulators. This not only applies to the transistors within the IC, but also to the external booster transistors. Hence, in designing a regulator, it is of utmost importance to determine the worst-case power dissipation in all the driver and pass transistors. Devices must then be selected which can handle the power. Further, adequate heat sinks must be provided as even power transistors cannot dissipate much power by themselves.

Normally, the highest power dissipation occurs when the output of the regulator is shorted. If this condition requires heat sinks which are so large as to be impractical, foldback current limiting can be used. With foldback limiting, the power dissipated under short circuit conditions can actually be made less than the dissipation at full load.

The LM105 is designed primarily as a positive voltage regulator. A negative regulator, the LM104, which is a functional complement to the LM105, is described in Reference 4.

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