

High Efficiency Linear Regulators

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Introduction

Linear voltage regulators continue to enjoy widespread use despite the increasing popularity of switching approaches. Linear regulators are easily implemented, and have much better noise and drift characteristics than switchers. Additionally, they do not radiate RF, function with standard magnetics, are easily frequency compensated, and have fast response. Their largest disadvantage is inefficiency. Excess energy is dissipated as heat. This elegantly simplistic regulation mechanism pays dearly in terms of lost power. Because of this, linear regulators are associated with excessive dissipation, inefficiency, high operating temperatures and large heat sinks. While linears cannot compete with switchers in these areas they can achieve significantly better results than generally supposed. New components and some design techniques permit retention of linear regulator's advantages while improving efficiency.

One way towards improved efficiency is to minimize the input-to-output voltage across the regulator. The smaller this term is, the lower the power loss. The minimum input/output voltage required to support regulation is referred to as the "dropout voltage." Various design techniques and technologies offer different performance capabilities. Appendix A, "Achieving Low Dropout," compares some approaches. Conventional three terminal linear regulators have a 3V dropout, while newer devices feature 1.5V dropout (see Appendix B, "A Low Dropout Regulator Family") at 7.5A, decreasing to 0.05V at 100 μ A.

Regulation from Stable Inputs

Lower dropout voltage results in significant power savings where input voltage is relatively constant. This is normally the case where a linear regulator post-regulates a

switching supply output. Figure 1 shows such an arrangement. The main output ("A") is stabilized by feedback to the switching regulator. Usually, this output supplies most of the power taken from the circuit. Because of this, the amount of energy in the transformer is relatively unaffected by power demands at the "B" and "C" outputs. This results in relatively constant "B" and "C" regulator input voltages. Judicious design allows the regulators to run at or near their dropout voltage, regardless of loading or switcher input voltage. Low dropout regulators thus save considerable power and dissipation.

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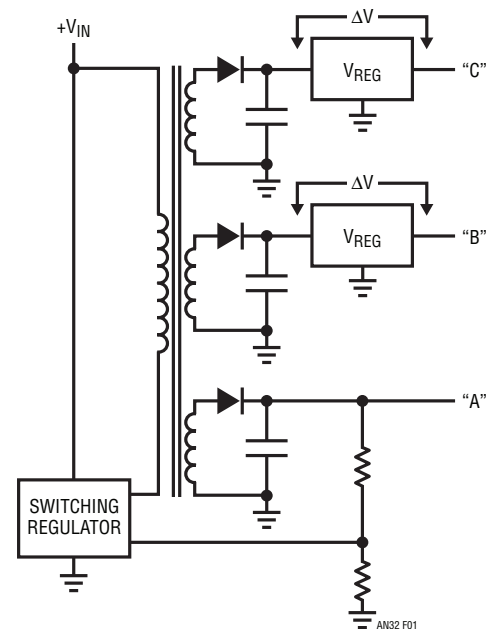


Figure 1. Typical Switching Supply Arrangement Showing Linear Post-Regulators

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Regulation from Unstable Input—AC Line Derived Case

Unfortunately, not all applications furnish a stable input voltage. One of the most common and important situations is also one of the most difficult. Figure 2 diagrams a classic situation where the linear regulator is driven from the AC line via a step-down transformer. A 90VAC (brownout) to 140VAC (high line) line swing causes the regulator to see a proportionate input voltage change. Figure 3 details efficiency under these conditions for standard (LM317) and low dropout (LT[®]1086) type devices. The LT1086's lower dropout improves efficiency. This is particularly evident at 5V output, where dropout is a significant percentage of

the output voltage. The 15V output comparison still favors the low dropout regulator, although efficiency benefit is somewhat reduced. Figure 4 derives resultant regulator power dissipation from Figure 3's data. These plots show that the LT1086 requires less heat sink area to maintain the same die temperature as the LM317.

Both curves show the deleterious effects of poorly controlled input voltages. The low dropout device clearly cuts losses, but input voltage variation degrades obtainable efficiency.

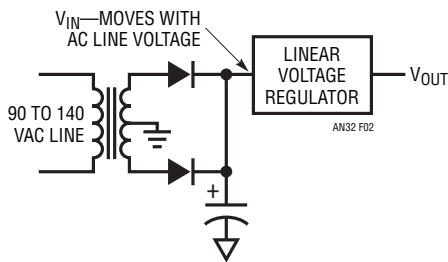
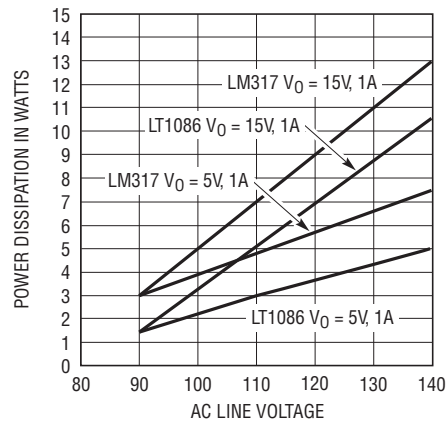
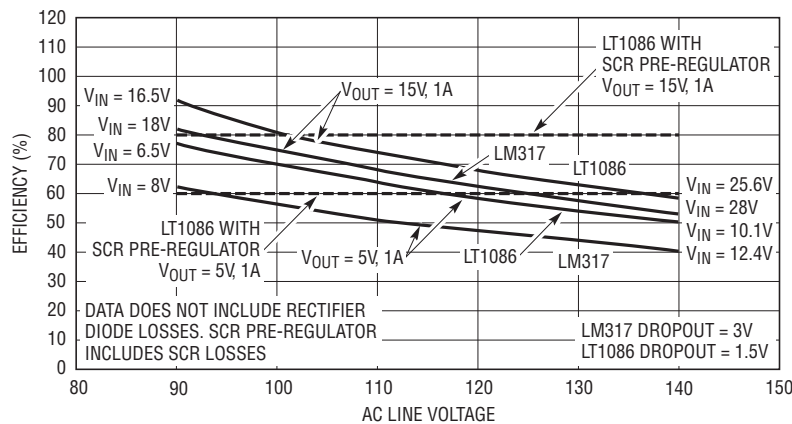


Figure 2. Typical AC Line Driven Linear Regulator



AN32 F04

Figure 4. Power Dissipation for Different Regulators vs AC Line Voltage. Rectifier Diode Losses are not Included



AN32 F03

Figure 3. Efficiency vs AC Line Voltage for LT1086 and LM317 Regulators

SCR Pre-Regulator

Figure 5 shows a way to eliminate regulator input variations, even with wide AC line swings. This circuit, combined with a low dropout regulator, provides high efficiency while retaining all the linear regulators desirable characteristics. This design servo controls the firing point of the SCRs to stabilize the LT1086 input voltage. A1 compares a portion of the LT1086's input voltage to the LT1004 reference. The amplified difference voltage is applied to C1B's negative input. C1B compares this to a line synchronous ramp (Trace B, Figure 6) derived by C1A from the transformers rectified secondary (Trace A is the "sync" point in the figure). C1B's pulse output (Trace C) fires the appropriate

SCR and a path from the main transformer to L1 (Trace D) occurs. The resultant current flow (Trace E), limited by L1, charges the 4700 μ F capacitor. When the transformer output drops low enough the SCR commutates and charging ceases. On the next half-cycle the process repeats, except that the alternate SCR does the work (Traces F and G are the individual SCR currents). The loop phase modulates the SCR's firing point to maintain a constant LT1086 input voltage. A1's 1 μ F capacitor compensates the loop and its output 10k Ω -diode network ensures start-up. The three terminal regulator's current limit protects the circuit from overloads.

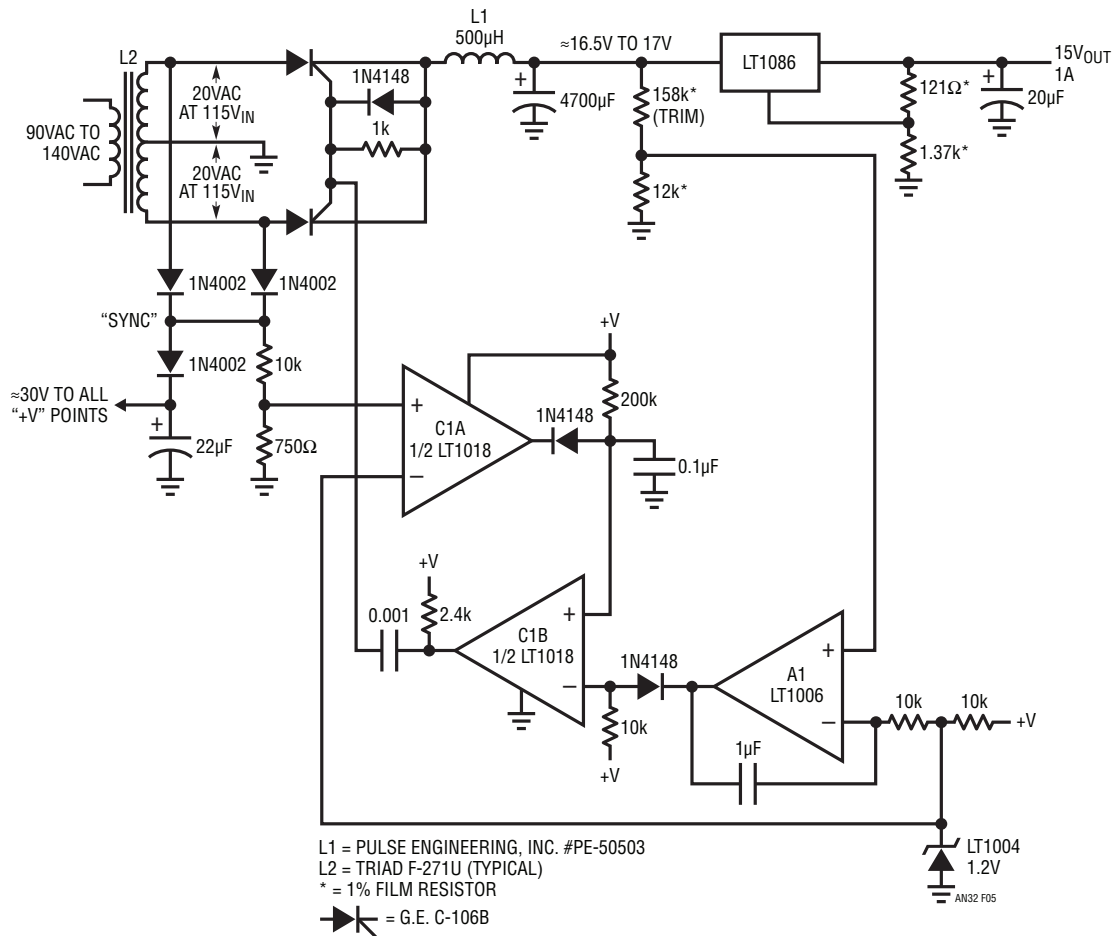


Figure 5. SCR Pre-Regulator

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This circuit has a dramatic impact on LT1086 efficiency versus AC line swing*. Referring back to Figure 3, the data shows good efficiency with no change for 90VAC to 140VAC input variations. This circuit's slow switching preserves the linear regulators low noise. Figure 7 shows slight 120Hz residue with no wideband components.

*The transformer used in a pre-regulator can significantly influence overall efficiency. One way to evaluate power consumption is to measure the actual power taken from the 115VAC line. See Appendix C, "Measuring Power Consumption."

DC Input Pre-Regulator

Figure 8a's circuit is useful where the input is DC, such as an unregulated (or regulated) supply or a battery. This circuit is designed for low losses at high currents. The LT1083 functions in conventional fashion, supplying a regulated output at 7.5A capacity. The remaining components form a switched-mode dissipation regulator. This regulator maintains the LT1083 input just above the dropout voltage under all conditions. When the LT1083 input (Trace A, Figure 9) decays far enough, C1A goes high,

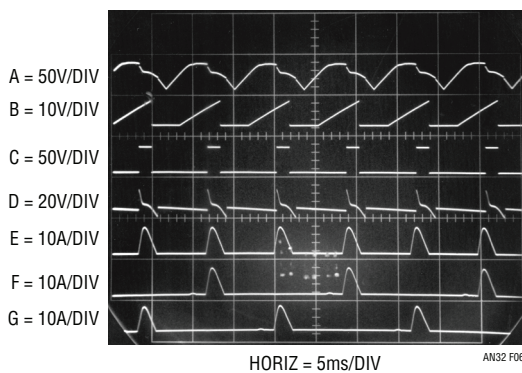


Figure 6. Waveforms for the SCR Pre-Regulator

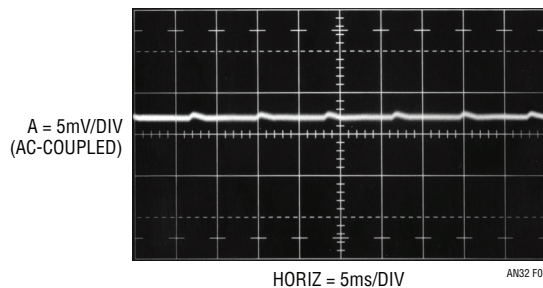


Figure 7. Output Noise for the SCR Pre-Regulated Circuit

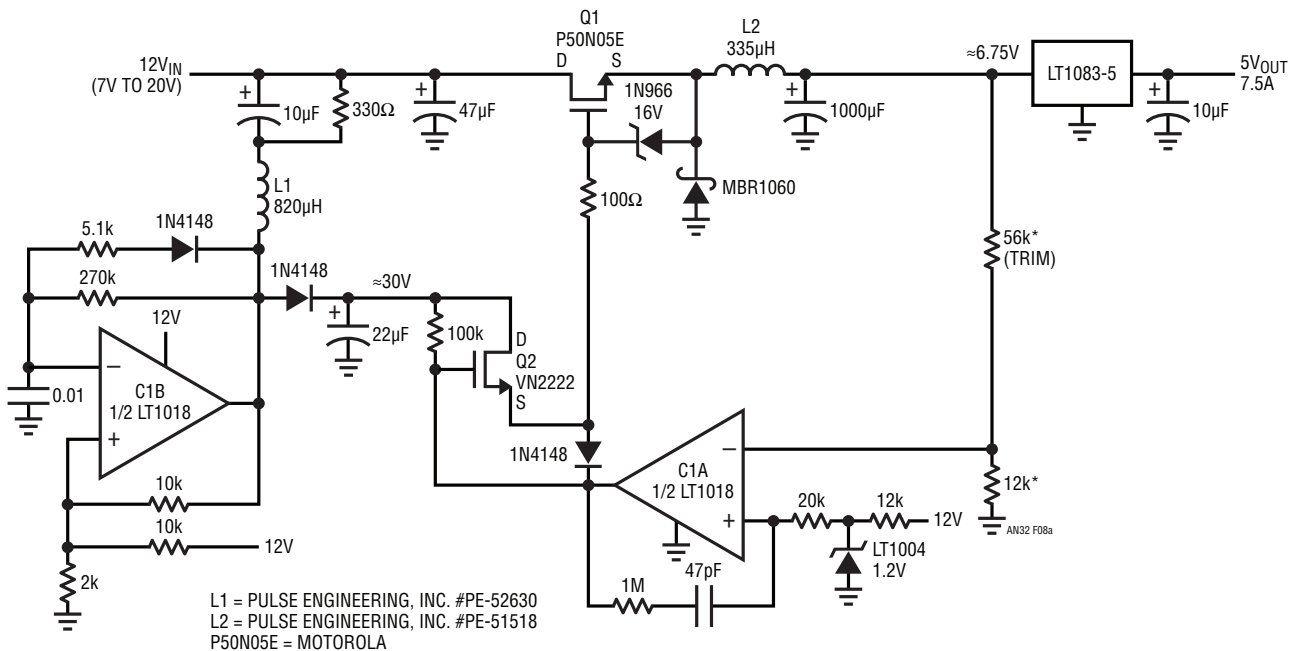


Figure 8a. Pre-Regulated Low Dropout Regulator

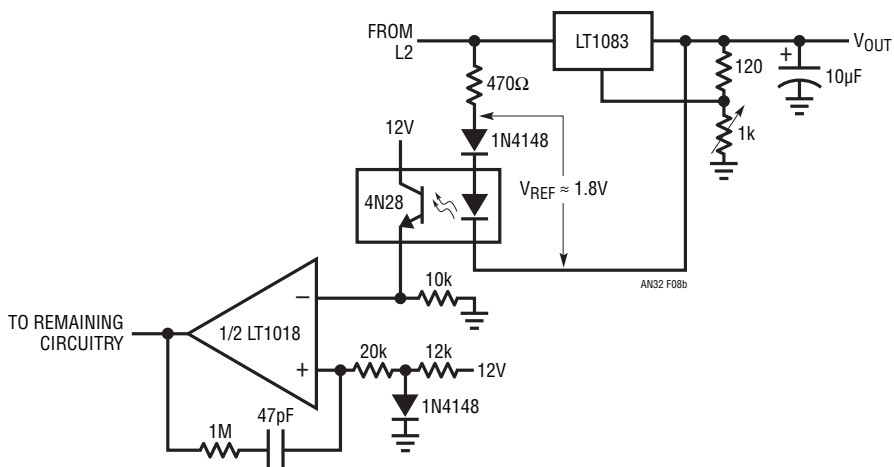


Figure 8b. Differential Sensing for the Pre-Regulator Allows Variable Outputs

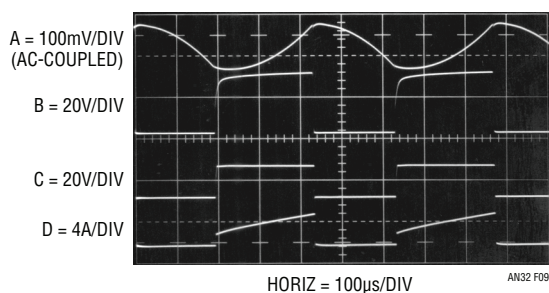


Figure 9. Pre-Regulator Waveforms

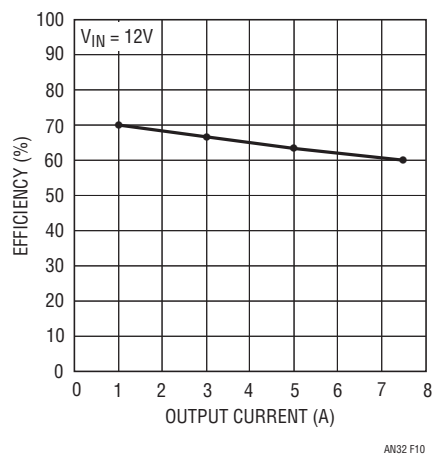


Figure 10. Efficiency vs Output for Figure 8a

allowing Q1's gate (Trace B) to rise. This turns on Q1, and its source (Trace C) drives current (Trace D) into L2 and the 1000μF capacitor, raising regulator input voltage. When the regulator input rises far enough C1A returns low, Q1 cuts off and capacitor charging ceases. The MBR1060 damps L2's flyback spike and the 1M-47pF combination sets loop hysteresis at about 100mV.

Q1, an N-channel MOSFET, has only 0.028Ω of saturation loss but requires 10V of gate-source turn-on bias. C1B, set up as a simple flyback voltage booster, provides about 30V DC boost to Q2. Q2, serving as a high voltage pull-up for C1A, provides voltage overdrive to Q1's gate. This ensures Q1 saturation, despite its source follower connection. The Zener diode clamps excessive gate-source

overdrives. These measures are required because alternatives are unattractive. Low loss P-channel devices are not currently available, and bipolar approaches require large drive currents or have poor saturation. As before, the linear regulator's current limit protects against overloads. Figure 10 plots efficiency for the pre-regulated LT1083 over a range of currents. Results are favorable, and the linear regulator's noise and response advantages are retained.

Figure 8b shows an alternate feedback connection which maintains a fixed small voltage across the LT1083 in applications where variable output is desired. This scheme maintains efficiency as the LT1083's output voltage is varied.

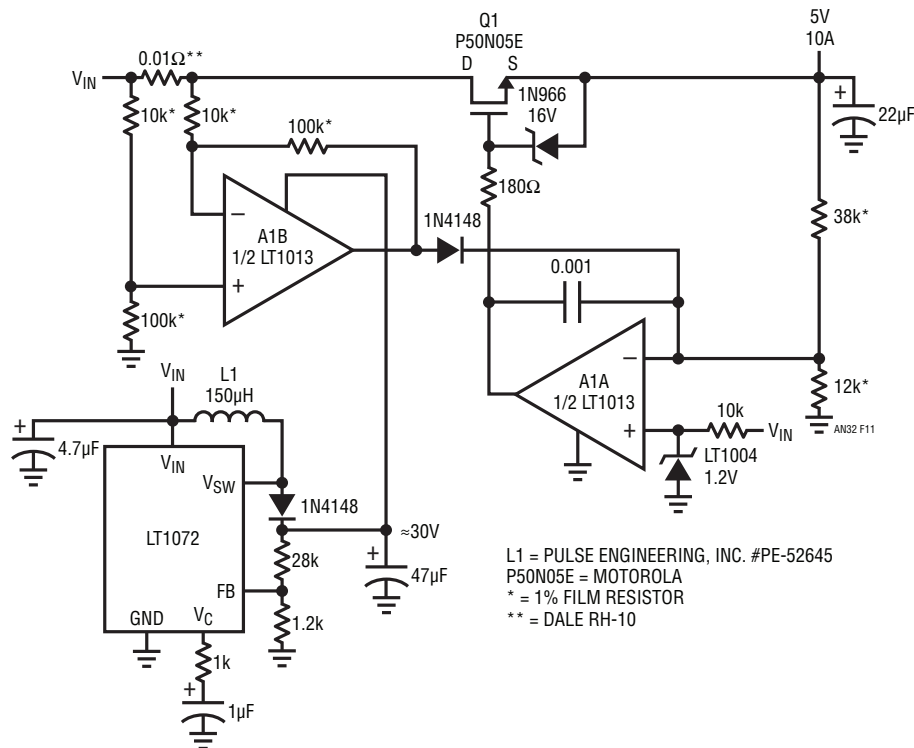


Figure 11. 10A Regulator with 400mV Dropout

10A Regulator with 400mV Dropout

In some circumstances an extremely low dropout regulator may be required. Figure 11 is substantially more complex than a three terminal regulator, but offers 400mV dropout at 10A output. This design borrows Figure 8A's overdriven source follower technique to obtain extremely low saturation resistance. The gate boost voltage is generated by the LT1072 switching regulator, set up as a flyback converter.* This configuration's 30V output powers A1, a dual op amp. A1A compares the regulators output to the LT1004 reference and servo controls Q1's gate to close the loop. The gate voltage overdrive allows Q1 to attain its 0.028Ω saturation, permitting the extremely low dropout noted. The Zener diode clamps excessive gate-source voltage and the 0.001μF capacitor stabilizes the loop. A1B, sensing current

*If boost voltage is already present in the system, significant circuit simplification is possible. See LTC Design Note 32, "A Simple Ultra-Low Dropout Regulator."

across the 0.01Ω shunt, provides current limiting by forcing A1A to swing negatively. The low resistance shunt limits loss to only 100mV at 10A output. Figure 12 plots current limit performance for the regulator. Roll-off is smooth, with no oscillation or undesirable characteristics.

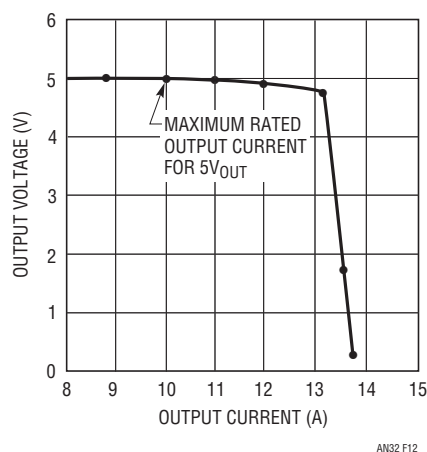
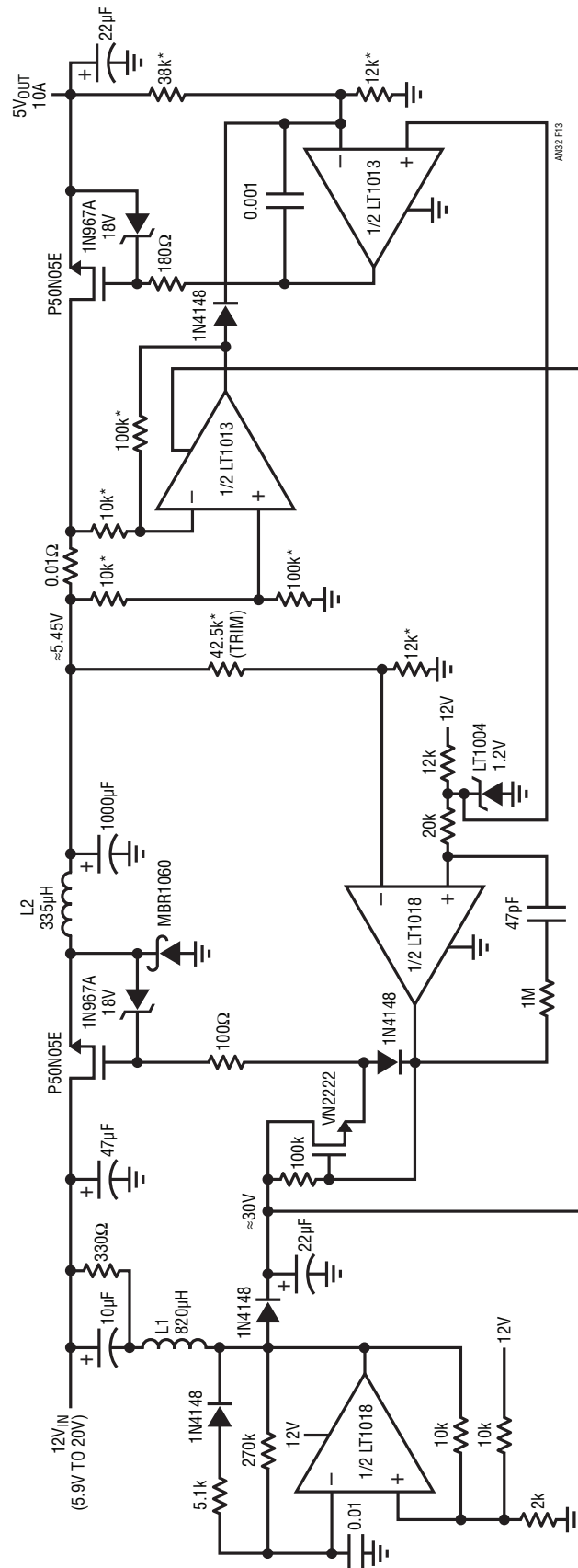


Figure 12. Current Limit Characteristics for the Discrete Regulator



L1 = PULSE ENGINEERING, INC. #PE-52630
 L2 = PULSE ENGINEERING, INC. #PE-51518
 * = 1% FILM RESISTOR
 0.01Ω = DALE RH-10

Figure 13. Ultralow Dropout Linear Regulator with Pre-Regulator

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Ultrahigh Efficiency Linear Regulator

Figure 13 combines the preceding discrete circuits to achieve highly efficient linear regulation at high power. This circuit combines Figure 8a's pre-regulator with Figure 11's discrete low dropout design. Modifications include deletion of the linear regulators boost supply and slight adjustment of the gate-source Zener diode values. Similarly, a single 1.2V reference serves both pre-regulator and linear output regulator. The upward adjustment in the Zener clamp values ensures adequate boost voltage under low voltage input conditions. The pre-regulator's feedback resistors set the linear regulators input voltage just above its 400mV dropout.

This circuit is complex, but performance is impressive. Figure 14 shows efficiency of 86% at 1A output, decreasing to 76% at full load. The losses are approximately evenly distributed between the MOSFETs and the MBR1060 catch diode. Replacing the catch diode with a synchronously switched FET (see Linear Technology AN29, Figure 32) and trimming the linear regulator input to the lowest possible value could improve efficiency by 3% to 5%.

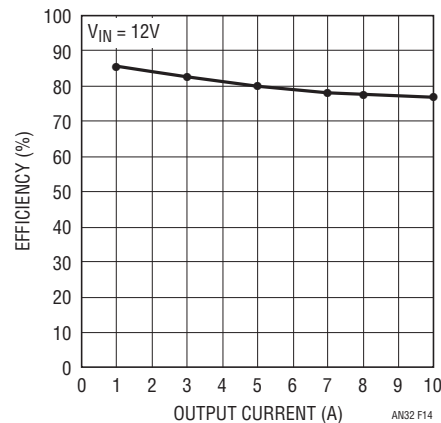


Figure 14. Efficiency vs Output Current for Figure 13

Micropower Pre-Regulated Linear Regulator

Power linear regulators are not the only types which can benefit from the above techniques. Figure 15's pre-regulated micropower linear regulator provides excellent efficiency and low noise. The pre-regulator is similar to Figure 8a. A drop at the pre-regulator's output (Pin 3 of the LT1020 regulator, Trace A, Figure 16) causes the LT1020's comparator to go high. The 74C04 inverter chain switches,

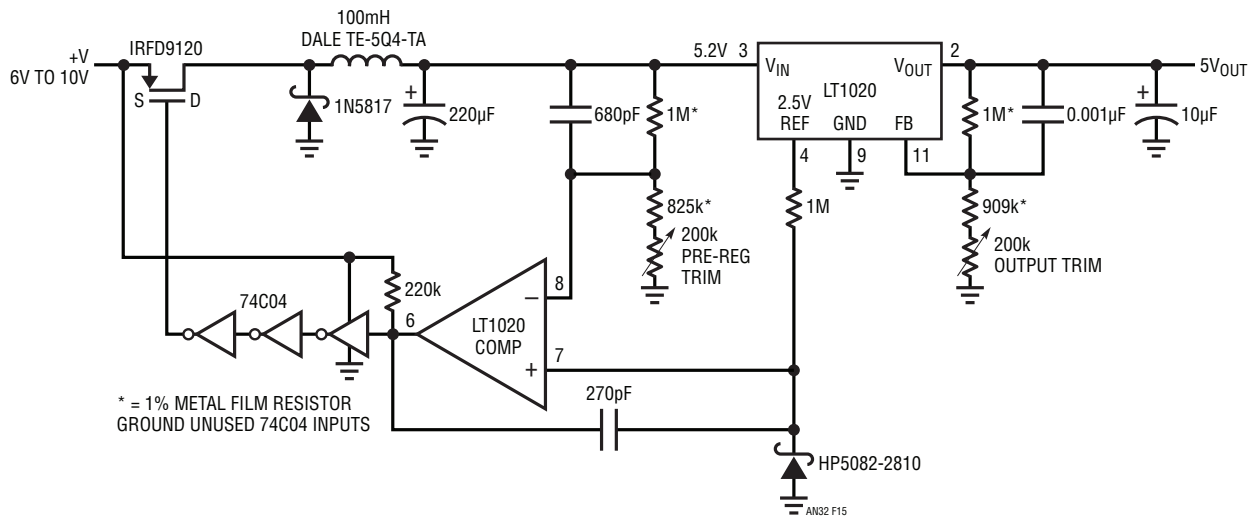


Figure 15. Micropower Pre-Regulated Linear Regulator

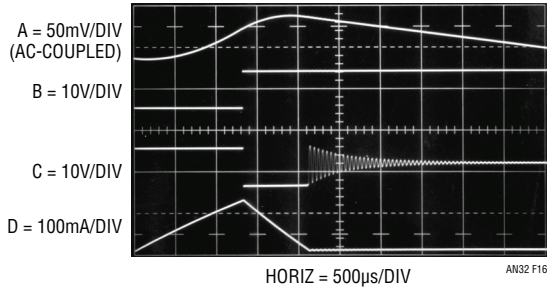


Figure 16. Figure 15's Waveforms

biasing the P-channel MOSFET switch's grid (Trace B). The MOSFET comes on (Trace C), delivering current to the inductor (Trace D). When the voltage at the inductor-220µF junction goes high enough (Trace A), the comparator switches high, turning off MOSFET current flow. This loop regulates the LT1020's input pin at a value set by the resistor divider in the comparator's negative input and the LT1020's 2.5V reference. The 680pF capacitor stabilizes the loop and the 1N5817 is the catch diode. The 270pF capacitor aids comparator switching and the 2810 diode prevents negative overdrives.

The low dropout LT1020 linear regulator smooths the switched output. Output voltage is set with the feedback pin associated divider. A potential problem with this circuit is start-up. The pre-regulator supplies the LT1020's input but relies on the LT1020's internal comparator to function. Because of this, the circuit needs a start-up mechanism. The 74C04 inverters serve this function. When power is applied, the LT1020 sees no input, but the inverters do. The 200k path lifts the first inverter high, causing the chain to switch, biasing the MOSFET and starting the circuit. The inverter's rail-to-rail swing also provides good MOSFET grid drive.

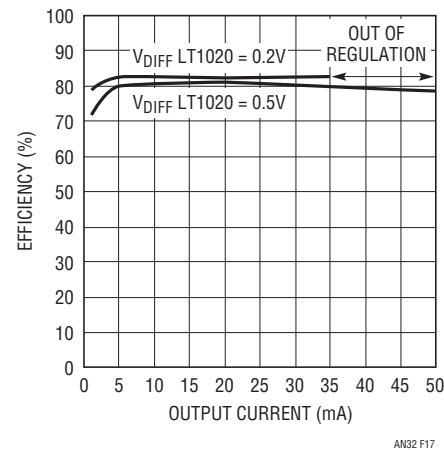


Figure 17. Efficiency vs Output Current for Figure 15

The circuit's low 40µA quiescent current is due to the low LT1020 drain and the MOS elements. Figure 17 plots efficiency versus output current for two LT1020 input-output differential voltages. Efficiency exceeding 80% is possible, with outputs to 50mA available.

References

1. Lambda Electronics, Model LK-343A-FM Manual
2. Grafham, D.R., "Using Low Current SCRs," General Electric AN200.19. Jan. 1967
3. Williams, J., "Performance Enhancement Techniques for Three-Terminal Regulators," Linear Technology Corporation. AN2
4. Williams, J., "Micropower Circuits for Signal Conditioning," Linear Technology Corporation. AN23
5. Williams, J. and Huffman, B., "Some Thoughts on DC-DC Converters," Linear Technology Corporation. AN29
6. Analog Devices, Inc, "Multiplier Application Guide"

Note: This application note was derived from a manuscript originally prepared for publication in EDN magazine.

APPENDIX A

Achieving Low Dropout

Linear regulators almost always use Figure A1a's basic regulating loop. Dropout limitations are set by the pass elements on-impedance limits. The ideal pass element has zero impedance capability between input and output and consumes no drive energy.

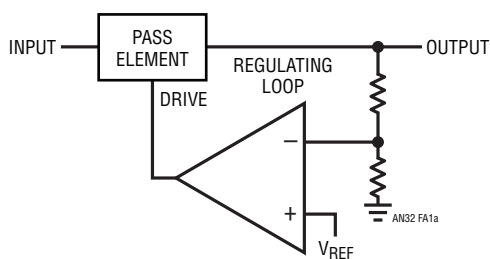


Figure A1a. Basic Regulating Loop

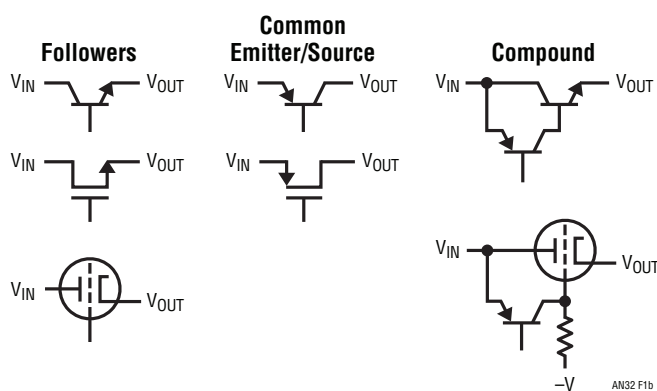


Figure A1b. Linear Regulator with Some Pass Element Candidates

A number of design and technology options offer various trade-offs and advantages. Figure A1b lists some pass element candidates. Followers offer current gain, ease of loop compensation (voltage gain is below unity) and the drive current ends up going to the load. Unfortunately, saturating a follower requires voltage overdriving the input (e.g., base, gate). Since drive is usually derived directly from V_{IN} this is difficult. Practical circuits must either generate the overdrive or obtain it elsewhere. This is not easily done in IC power regulators, but is realizable in discrete circuits (e.g., Figure 11). Without voltage overdrive the saturation loss is set by V_{be} in the bipolar case and channel on-resistance for MOS. MOS channel

on-resistance varies considerably under these conditions, although bipolar losses are more predictable. Note that voltage losses in driver stages (Darlington, etc.) add directly to the dropout voltage. The follower output used in conventional three terminal IC regulators combines with drive stage losses to set dropout at 3V.

Common emitter/source is another pass element option. This configuration removes the V_{be} loss in the bipolar case. The PNP version is easily fully saturated, even in IC form. The trade-off is that the base current never arrives at the load, wasting substantial power. At higher currents, base drive losses can negate a common emitter's saturation advantage. This is particularly the case in IC designs, where high beta, high current PNP transistors are not practical. As in the follower example, Darlington connections exacerbate the problem. At moderate currents PNP common emitters are practical for IC construction. The LT1020/LT1120 uses this approach.

Common source connected P-channel MOSFETs are also candidates. They do not suffer the drive losses of bipolars, but typically require 10V of gate-channel bias to fully saturate. In low voltage applications this usually requires generation of negative potentials. Additionally, P-channel devices have poorer saturation than equivalent size N-channel devices.

The voltage gain of common emitter and source configurations is a loop stability concern, but is manageable.

Compound connections using a PNP driven NPN are a reasonable compromise, particularly for high power (beyond 250mA) IC construction. The trade-off between the PNP V_{ce} saturation term and reduced drive losses over a straight PNP is favorable. Also, the major current flow is through a power NPN, easily realized in monolithic form. This connection has voltage gain, necessitating attention to loop frequency compensation. The LT1083-6 regulators use this pass scheme with an output capacitor providing compensation.

Readers are invited to submit results obtained with our emeritus thermionic friends, shown out of respectful courtesy.

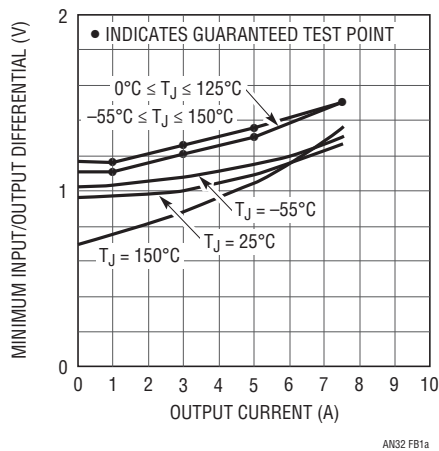
APPENDIX B

A Low Dropout Regulator Family

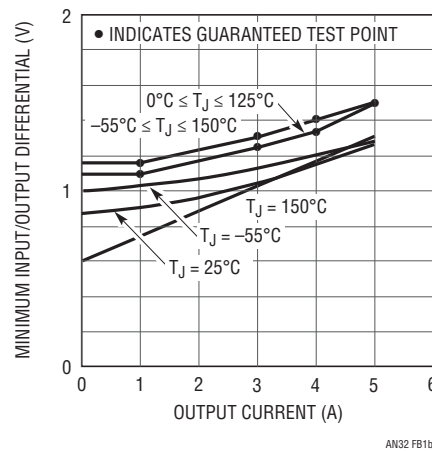
The LT1083-6 series regulators detailed in Figure B1 feature maximum dropout below 1.5V. Output currents range from 1.5A to 7.5A. The curves show dropout is significantly lower at junction temperatures above 25°C. The NPN pass transistor based devices require only 10mA load current for operation, eliminating the large base drive loss characteristic of PNP approaches (see Appendix A for discussion).

In contrast, the LT1020/LT1120 series is optimized for lower power applications. Dropout voltage is about 0.05V at 100µA, rising to only 400mV at 100mA output. Quiescent current is 40µA.

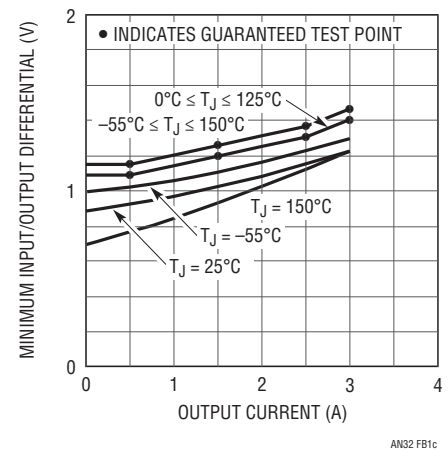
LT1083 Dropout Voltage vs Output Current



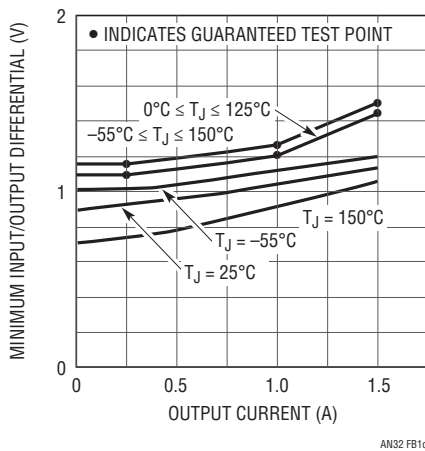
LT1084 Dropout Voltage vs Output Current



LT1085 Dropout Voltage vs Output Current



LT1086 Dropout Voltage vs Output Current



LT1020/LT1120 Dropout Voltage and Supply Current

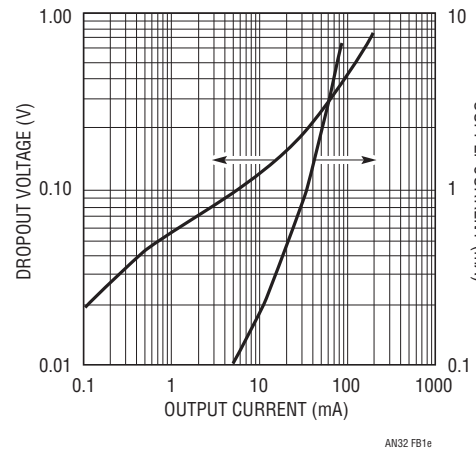


Figure B1. Characteristics of Low Dropout IC Regulators

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APPENDIX C

Measuring Power Consumption

Accurately determining power consumption often necessitates measurement. This is particularly so in AC line driven circuits, where transformer uncertainties or lack of manufacturer's data precludes meaningful estimates. One way to measure AC line originated input power (Watts) is a true, real time computation of E-I product. Figure C1's circuit does this and provides a safe, usable output.

BEFORE PROCEEDING ANY FURTHER, THE READER IS WARNED THAT CAUTION MUST BE USED IN THE CONSTRUCTION, TESTING AND USE OF THIS CIRCUIT. HIGH VOLTAGE, AC LINE-CONNECTED POTENTIALS ARE PRESENT IN THIS CIRCUIT. EXTREME CAUTION MUST BE USED IN WORKING WITH AND MAKING CONNECTIONS TO THIS CIRCUIT. REPEAT: THIS CIRCUIT CONTAINS DANGEROUS, AC LINE-CONNECTED HIGH VOLTAGE POTENTIALS. USE CAUTION.

The AC load to be measured is plugged into the test socket. Current is measured across the 0.01Ω shunt by A1A with additional gain and scaling provided by A1B. The diodes and fuse protect the shunt and amplifier against severe

overloads. Load voltage is derived from the 100k-4k divider. The shunts low value minimizes voltage burden error.

The voltage and current signals are multiplied by a 4-quadrant analog multiplier (AD534) to produce the power product. All of this circuitry floats at AC line potential, making direct monitoring of the multipliers output potentially lethal. Providing a safe, usable output requires a galvanically isolated way to measure the multiplier output. The 286J isolation amplifier does this, and may be considered as a unity-gain amplifier with inputs fully isolated from its output. The 286J also supplies the floating $\pm 15V$ power required for A1 and the AD534. The 286J's output is referred to circuit common (\perp). The 281 oscillator/driver is necessary to operate the 286J (see Analog Devices data sheet for details). The LT1012 and associated components provide a filtered and scaled output. A1B's gain switching provides decade ranging from 20W to 2000W full scale. The signal path's bandwidth permits accurate results, even for nonlinear or discontinuous loads (e.g. SCR choppers). To calibrate this circuit install a known full-scale load, set A1B to the appropriate range, and adjust the trimpot for a correct reading. Typical accuracy is 1%.

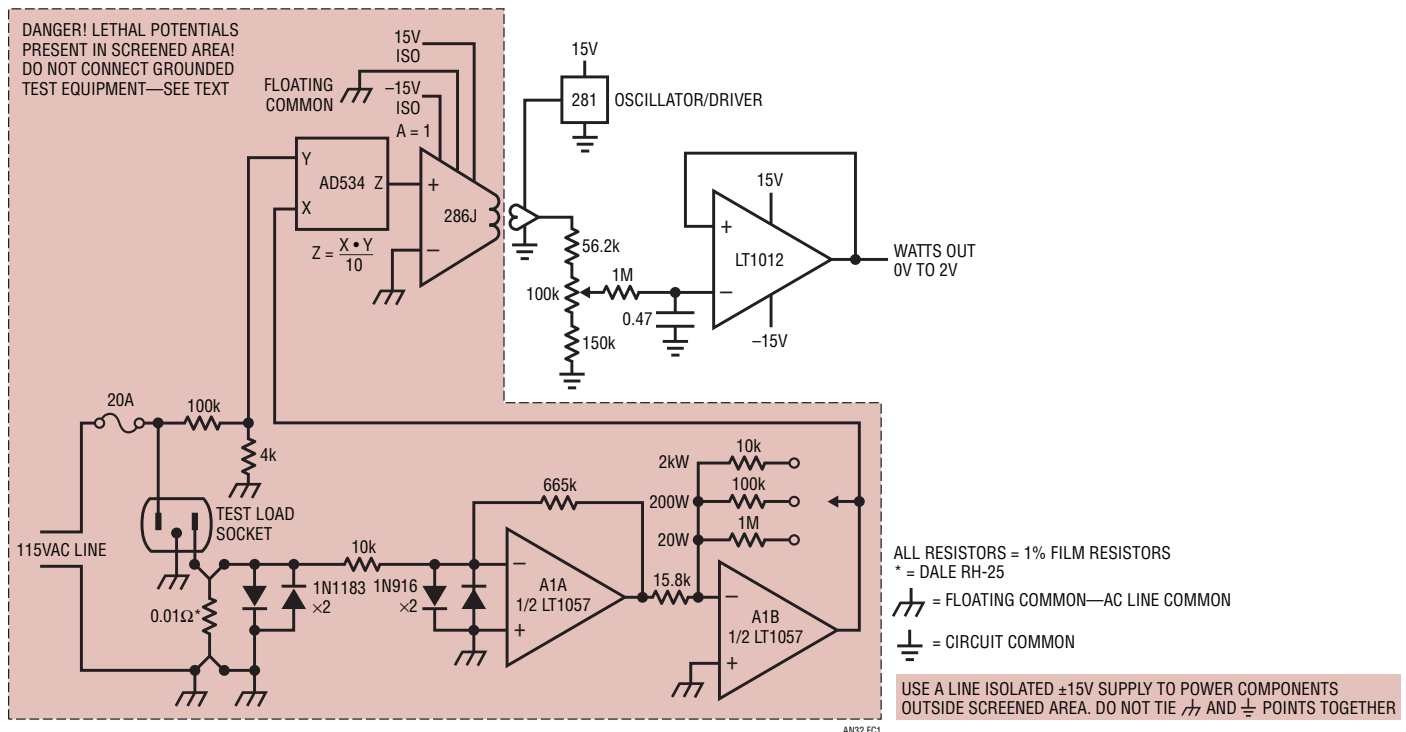


Figure C1. AC Wattmeter **DANGER! Lethal Potentials Present—See Text**