Application Note 35

August 1989

Step-Down Switching Regulators

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A substantial percentage of regulator requirements involve stepping down the primary voltage. Although linear regulators can do this, they cannot achieve the efficiency of switching based approaches[1]. The theory supporting step-down ("buck") switching regulation is well established, and has been exploited for some time. Convenient, easily applied ICs allowing implementation of practical circuits are, however, relatively new. These devices permit broad application of step-down regulation with minimal complexity and low cost. Additionally, more complex functions incorporating step-down regulation become realizable.

Basic Step Down Circuit

Figure 1 is a conceptual voltage step-down or "buck" circuit. When the switch closes the input voltage appears at the inductor. Current flowing through the inductor-capacitor combination builds over time. When the switch opens current flow ceases and the magnetic field around the inductor collapses. Faraday teaches that the voltage induced by the collapsing magnetic field is opposite to the originally applied voltage. As such, the inductor's left side heads negative and is clamped by the diode. The capacitors accumulated charge has no discharge path, and a DC potential appears at the output. This DC potential is lower than the input because the inductor limits current during the switch's on-time. Ideally, there are no dissipative elements in this voltage step-down conversion. Although the output *voltage* is lower than the input, there is no *energy* lost in this voltage-to-current-to-magnetic field-to-current-to-charge-to-voltage conversion. In practice, the circuit elements have losses, but step-down efficiency is still higher than with inherently dissipative (e.g., voltage divider) approaches. Figure 2 feedback controls the basic circuit to regulate output voltage. In this case switch on-time (e.g., inductor charge time) is varied to maintain the output against changes in input or loading.

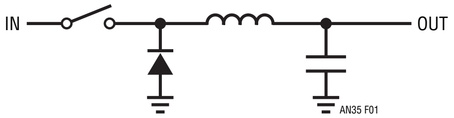

Figure 1. Conceptual Voltage Step-Down ("Buck") Circuit

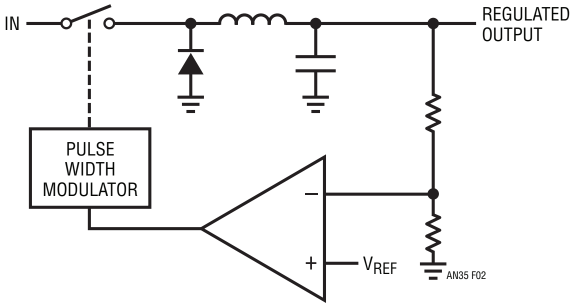

Figure 2. Conceptual Feedback Controlled Step-Down Regulator

Practical Step-Down Switching Regulator

Figure 3, a practical circuit using the LT®1074[2] IC regulator, shows similarities to the conceptual regulator. Some new elements have also appeared. Components at the LT1074's "V_{COMP}" pin control the IC's frequency compensation, stabilizing the feedback loop. The feedback resistors are selected to force the "feedback" pin to the device's internal 2.5V reference value. Figure 4 shows operating waveforms for the regulator at V_{IN} = 28V with a 5V, 1A load.

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Note 1: While linear regulators cannot compete with switchers, they can achieve significantly better efficiencies than generally supposed. See LTC Application Note 32, "High Efficiency Linear Regulators," for details.

Note 2: See Appendix A for details on this device.

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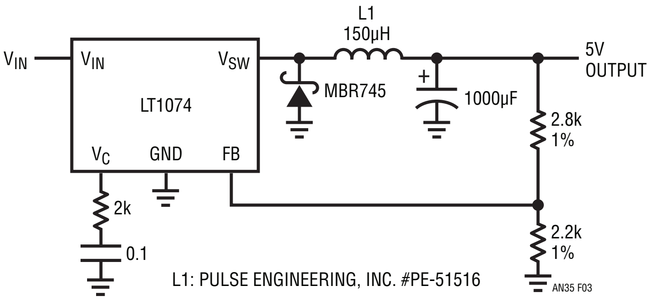

Figure 3. A Practical Step-Down Regulator Using the LT1074

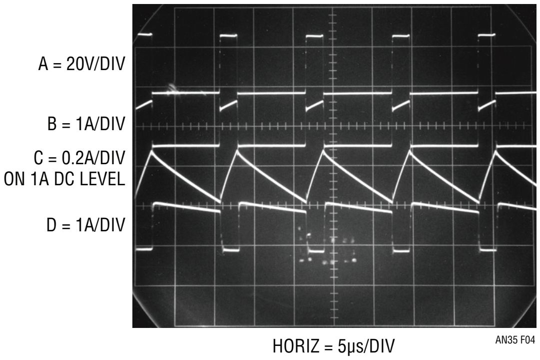

Figure 4. Waveforms for the Step-Down Regulator at V_{IN} = 28V and V_{OUT} = 5V at 1A

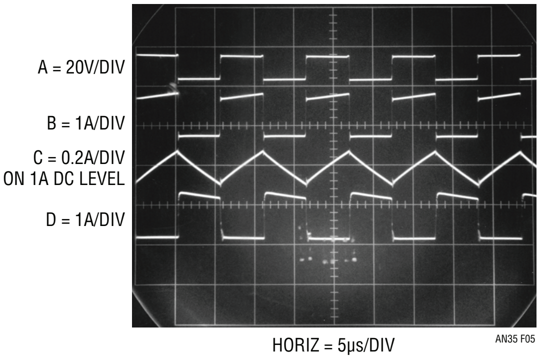

Figure 5. Waveforms for the Step-Down Regulator at V_{IN} = 12V and V_{OUT} = 5V at 1A

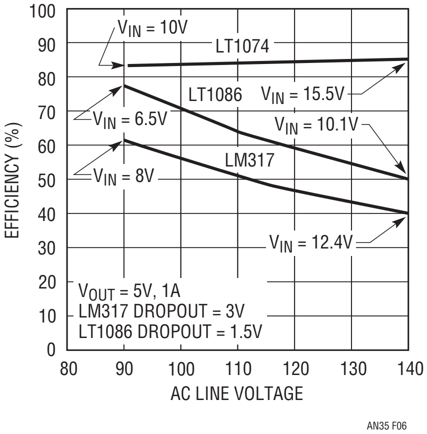

Figure 6. Efficiency vs AC Line Voltage for the LT1074. LT1086 and LM317 Linear Regulators are Shown for Comparison

Trace A is the V_{SW} pin voltage and Trace B is its current. Inductor current[3] appears in Trace C and diode current is Trace D. Examination of the current waveforms allows determination of the V_{SW} and diode path contributions to inductor current. Note that the inductor current's waveform occurs on top of a 1A DC level. Figure 5 shows significant duty cycle changes when V_{IN} is reduced to 12V. The lower input voltage requires longer inductor charge times to maintain the output. The LT1074 controls inductor charge characteristics (see Appendix A for operating details), with resulting waveform shape and time proportioning changes.

Figure 6 compares this circuit's efficiency with linear regulators in a common and important situation. Efficient regulation under varying AC line conditions is a frequent requirement. The figure assumes the AC line has been transformed down to acceptable input voltages. The input voltages shown correspond to the AC line voltages given on the horizontal axis. Efficiency for the LM317 and LT1086 linear regulators suffers over the wide input range.

Note 3: Methods for selecting appropriate inductors are discussed in Appendix B.

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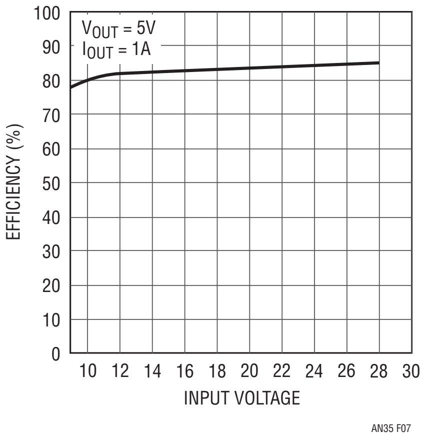

Figure 7. Efficiency Plot for Figure 3. Higher Input Voltages Minimize Effects of Saturation Losses, Resulting in Increased Efficiency

The LT1086 is notably better because its lower dropout voltage cuts dissipation over the range. Switching preregulation[4] can reduce these losses, but cannot equal the LT1074's performance. The plot shows minimum efficiency of 83%, with some improvement over the full AC line excursion. Figure 7 details performance. Efficiency approaches 90% as input voltage rises. This is due to minimization of the effects of fixed diode and LT1074 junction losses as input increases. At low inputs these losses are a higher percentage of available supply, degrading efficiency. Higher inputs make the fixed losses a smaller percentage, improving efficiency. Appendix D presents detail on optimizing circuitry for efficiency.

Dual Output Step-Down Regulator

Figure 8, a logical extension of the basic step-down converter, provides positive and negative outputs. The circuit is essentially identical to Figure 3's basic converter with the addition of a coupled winding to L1. This floating winding's output is rectified, filtered and regulated to a –5V output. The floating bias to the LT1086 positive voltage regulator permits negative outputs by assigning the regulator's output terminal to ground. Negative output power is set by flux pick-up from L1's driven winding. With a 2A load at the +15 output the –5V output can supply over 500mA. Because L1's secondary winding is floating its output may be referred to any point within the breakdown capability of the device. Hence, the secondary output could be 5V or, if stacked on the +15 output, 20V.

Negative Output Regulators

Negative outputs can also be obtained with a simple 2-terminal inductor. Figure 9 demonstrates this by essentially grounding the inductor and steering the catch diodes negative current to the output. A1 facilitates loop closure by providing a scaled inversion of the negative output to the LT1074's feedback pin. The 1% resistors set the scale factor (e.g., output voltage) and the RC network around A1 gives frequency compensation. Waveforms for this circuit are reminiscent of Figure 5, with the exception that diode

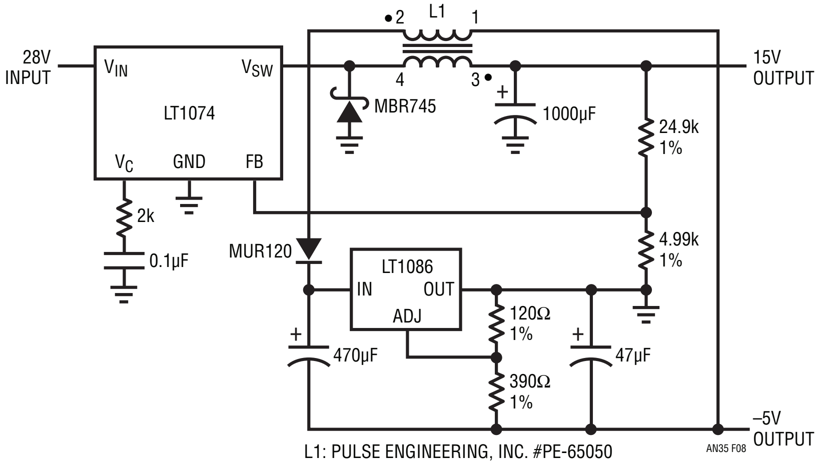

Figure 8. Coupled Inductor Provides Positive and Negative Outputs

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Note 4: See Reference 1.

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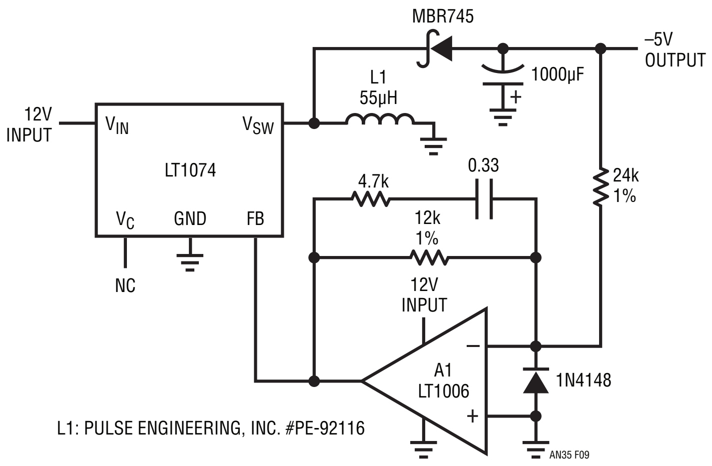

Figure 9. A Negative Output Step-Down Regulator

current (Trace D) is negative. Traces A, B and C are V_{SW} voltage, inductor current and V_{SW} current respectively.

Figure 11, commonly referred to as "Nelson's Circuit," provides the same function as the previous circuit, but eliminates the level-shifting op amp. This design accomplishes the level shift by connecting the LT1074's "ground" pin to the negative output. Feedback is sensed from circuit ground, and the regulator forces its feedback pin 2.5V above its "ground" pin. Circuit ground is common to input and output, making system use easy. Operating waveforms are essentially identical to Figure 10. Advantages of the previous circuit compared to this one are that the LT1074 package can directly contact a grounded heat sink and that control signals may be directly interfaced to the ground referred pins.

The inductor values in both negative output designs are notably lower than in the positive case. This is necessitated by the reduced loop phase margin of these circuits. Higher inductance values, while preferable for limiting peak current, will cause loop instability or outright oscillation.

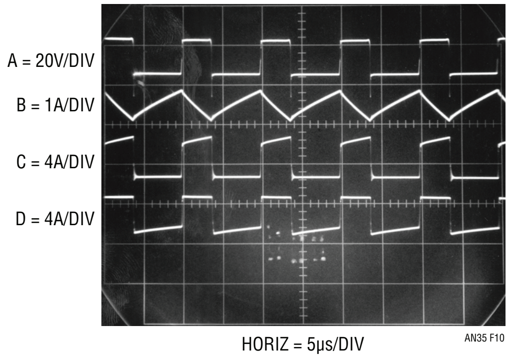

Figure 10. Figure 9's Waveforms

Current-Boosted Step-Down Regulator

Figure 12 shows a way to obtain significantly higher output currents by utilizing efficient energy storage in the LT1074 output inductor. This technique increases the duty cycle over the standard step-down regulator allowing more energy to be stored in the inductor. The increased output current is achieved at the expense of higher output voltage ripple.

The operating waveforms for this circuit are shown in Figure 13. The circuit operating characteristics are similar to that of the step-down regulator (Figure 3). During the V_{SW} (Trace A) "on" time the input voltage is applied to one end of the coupled inductor. Current through the V_{SW} pin (Trace B) ramps up almost instantaneously (since inductor current (Trace F) is present) and then slows as energy is stored in the core. The current proceeds into the inductor (Trace D) and finally is delivered to the load. When the V_{SW} pin goes off, current is no longer available to charge the inductor. The magnetic field collapses, causing the V_{SW} pin voltage to go negative. At this point similarity with the basic regulator vanishes. In this modified version the output current (Trace F) receives a boost as the magnetic field collapses. This results when the energy stored in

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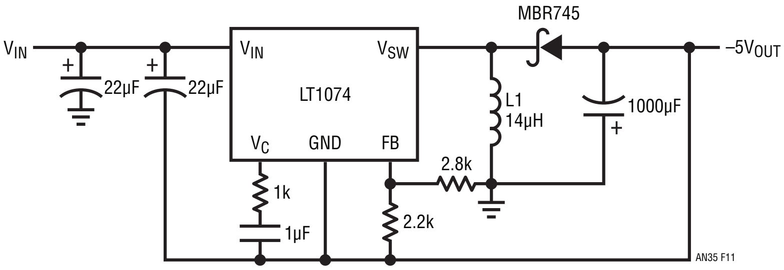
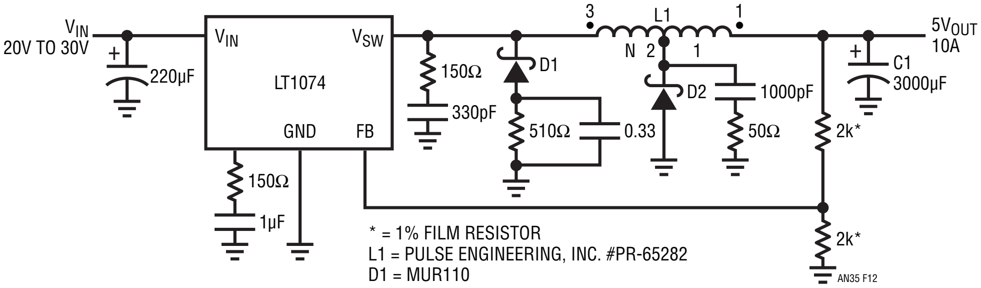


L1 = PULSE ENGINEERING, INC. #PE-51509

Figure 11. Nelson's Circuit…A (Better) Negative Output Step-Down Regulator



* = 1% FILM RESISTOR
L1 = PULSE ENGINEERING, INC. #PR-65282
D1 = MUR110
D2 = 1N5831

Figure 12. "Current Boosted" Step-Down Regulator. Boost Current is Supplied By Energy Stored in the Tapped Inductor

the core is transferred to the output. This current step circulates through C1 and D2 (Trace E), somewhat increasing output voltage ripple. Not all the energy is transferred to the "1" winding. Current (Trace C) will continue to flow in the "N" winding due to leakage inductance. A snubber network suppresses the effects of this leakage inductance. For lowest snubber losses the specified tapped inductor is bifilar wound for maximum coupling.

Post Regulation-Fixed Case

In most instances the LT1074 output will be applied directly to the load. Those cases requiring faster transient response or reduced noise will benefit from linear post regulation. In Figure 14 a 3-terminal regulator follows the LT1074 output. The LT1074 output is set to provide just enough voltage to the LT1084 to maintain regulation. The LT1084's low dropout characteristics combined with a high circuit input voltage minimizes the overall efficiency penalty.

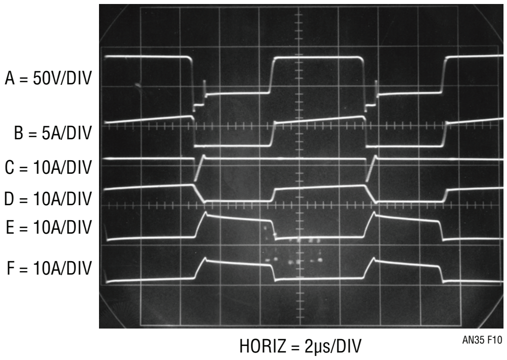


Figure 13. AC Current Flow for the Boosted Regulator

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