DC/DC Converters with Linear Regulators

Linear regulators (or voltage regulators) act as a series-variable power resistor when they are connected between an unregulated voltage source and a load. Linear regulators are used to provide voltage stability (regulation) for the load. However do not confuse linear regulators with switching regulators, which are switching circuits designed around a PWM energy-storing element, such as an inductor or capacitor, to step up or step down a voltage source. Switching regulators offer higher efficiency than linear regulators, but they also feature higher voltage ripple. When a low ripple is required, the ripple of a switching regulator can be reduced by a linear regulator.

The output ripple of a standard DC/DC converter is between 0.5% and 1% of its nominal output voltage. For applications that require a lower output ripple, linear regulators can be used to reduce a converter's output ripple or noise down to a few mV (millivolts) or even microvolts.

Through a negative feedback loop, the linear regulator monitors its output voltage at the load and adjusts the value of the variable power resistor in order to keep its output constant from any line (V_{IN}) or load variation.

Figure 1 shows a block diagram of a typical flyback DC/DC converter. At its output, C_{O1} provides coarse output filtering and energy storage, while L_O with C_{O2} (a low pass filter) performs the fine output filtering.

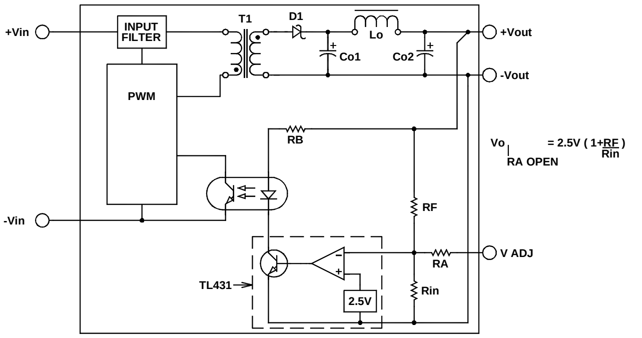

FIGURE 1. Block diagram of a typical flyback DC/DC converter

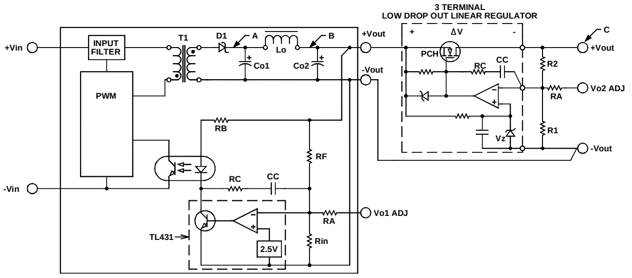

FIGURE 2. Converter from Figure 1 followed by low dropout linear regulator

Figure 2 shows the converter from Figure 1 followed by a low dropout linear regulator. It should be obvious that the output of the linear regulator is lower than the output of the converter by at least the dropout voltage of the linear regulator. In Figure 2, both DC/DC converters have an output adjust terminal and either one can be used to set the required voltages of V_{O1}, V_{O2} for proper operation of the system.

Under steady state conditions (constant line and load), one can adjust V_{O1} to be $V_{O1} = V_{O2} + \Delta V$. At room temperature the system will operate fine, but it may run out of regulation over its operating temperature if the temperature coefficient of the reference voltage in the converter and that of the linear regulator do not track.

Under load transients, the system may also go out of regulation especially when the output of the converter is set higher to provide the minimum dropout voltage for the regulator. Linear regulators offer very fast transient response to switching load, but the same is not true for all isolated DC/DC converters.

The transient response of a 50% to 100% to 50% load step can range from 100µS to 300µS for a typical DC/DC converter, while a linear regulator with the same load transient ranges from 1µS to 5µS even when the load switches from no load to full load.

When the response time difference is greater than one order of magnitude between the two devices, one may try one of the following:

1) Use a converter designed with a current mode PWM that offers faster response times of 50µS to 75µS;

2) Use big capacitors at the output of the slow converter;

3) Increase the output voltage of the converter, which will increase the input voltage to the linear regulator, but reduce the overall efficiency;

4) Use a switching regulator in place of a DC/DC converter if isolation is not required between input and output. Nowadays switching regulators can offer response times of a few nanoseconds even at a full load step;

5) Use a converter with an onboard linear regulator, such as Beta Dyne's series of Low-Noise 10W & 15W DC/DC Converters, for the reasons outlined below (the interested reader can refer to US Patent 5,777,519: High Efficiency Power Amplifier for more information).

As described above, the interface of a DC/DC converter and a linear regulator is not as straightforward as it may appear at first glance. Previous generation converters with linear regulators were designed with a DC chopper at the front end and the linear regulator was used at the output for line and load regulation, and to dissipate a lot of power at high line. The input voltage range was only ±10% of V_{IN} Nominal, and efficiency was 60% to 70% at nominal line and much lower at high line, which lowered the converters' power density, operating temperature and reliability.

Converters designed with PWM or PFM at the front end offer higher efficiency, wide input voltage range, relatively higher ripple and higher cost. In our Low-Noise series of converters, we employ a single voltage reference for both the converter and regulator to eliminate the potential reference TC mismatch. For the load transient mismatch, the loop compensation of the converter is optimized and the dropout voltage is set for worst-case over/under shoot of the converter, i.e. no load to full load step. As can be seen in Figure 4, the output of the linear regulator (waveform #4) is constant even under no load to full load step.

The output of the converter (see Figure 3B) takes 2mS to return to within 1% of V_{OUT} and has ±160mV overshoot. The dropout voltage is set for 220mV or V_{O1}; in Figure 2, it is set for 5.220mV. Therefore the actual dropout voltage for this regulator is 220 – 160 = 60mV@2A (see Figure 4, waveform #3). Even with 220mV as ΔV, the power dissipated at the P channel MOSFET is 0.44W and the regulator's efficiency is (P_O/P_{IN}) * 100 = (10 / 10.44) * 100 = 95.8%.

It should be noted that the transient response of V_{O1} in Figure 2 or waveform #2 in Figure 4 becomes waveform #5 in Figure 4 when a 50% load step is used with 50% constant load (50% FL to 100% FL to 50% FL). Under this loading condition, we could have set ΔV for 60mV and improved the regulator's efficiency by 3% ((10 / 10.12 * 100) = 98.8%).

To maintain a constant efficiency even when the customer needs to set the output of the converter at different voltages, the preset dropout voltage must be constant over the V_{OUT} adjust range while one terminal is used to adjust the outputs of both the converter and regulator.

Beta Dyne's Low-Noise series of converters utilize a patented circuit to eliminate all potential problems associated with the interfacing of a DC/DC converter with a linear regulator, as well as, to maximize efficiency and minimize noise resulting in a complete solution for customers. The internal linear regulators in the Low-Noise 10W series are designed with discrete components that reduce the power density of converters and increase their cost.

As seen in Figures 3 & 4, the linear regulator of a 10W $5V_{OUT}$@2A converter offers 2mV to 5mV of output ripple but also reduces the output noise by approximately 12dB. The linear regulator acts as a low pass filter and will not attenuate any common-mode noise between the converter's input and output. Please note that all the snubbers in the experimental converter were removed and that no high frequency ceramic capacitors were installed across the converter's output terminals.

Figure 3D shows the results of using a 6.8µF capacitor to lower the noise floor by 10dB (compare Figure 3C without the 6.8µF to Figure 3D with the 6.8µF capacitor).

Much greater power can be saved if a smart power supply is designed to supply a power amplifier. Let's assume for a moment that a 60W power amplifier is used to drive an 8Ω speaker and a dual ±24V power supply is needed for $\pm V_{CC}$.

In Figure 5, the volume control pot is used to adjust the power output. For $12V_{OUT}$, $P_{OUT} = V^2/R$ = 18W. The power dissipated in the amplifier is 18W, thus 30% of the available power is wasted in the power amplifier, which would require cooling either through forced convection or a large heat sink.

The same amplifier will operate without a heat sink if the smart power supply was designed to deliver $V_O + \Delta V$ Minimum. A smart power supply is designed to follow the needed output voltage as shown in Figure 5. If we set the output of the power supply to be V_{OUT} + 2V, the dissipated power is 2 * I_O = 2 * 1.5A = 3W, a reduction in the power dissipation by a factor of 6.

Some may say that it is not possible to have an adjustable power source with 10KHz to 20KHz bandwidth; I say it's not even needed. A 10Hz to 100Hz is needed only because the smart power supply will adjust itself for a DC output. A peak detector or RMS converter can be used to set the required DC output. To demonstrate that an adjustable power source is possible, Beta Dyne offers the upcoming Low-Noise 35W Adjustable DC/DC Converter series with a linear regulator at their output. The oscillogram in Figure 6 shows the two outputs are offset by 10V because the ΔV for the linear regulator is set for 1.5V and the two outputs with 20V/cm gain on the oscilloscope coincide.

The same converter is used for the oscillogram in Figure 7. When the common output pin is used for a ground reference, a dual output supply is created. Due to the input-to-output isolation, any output terminals can be used as ground reference resulting in a 10V to 100V, ±50V, or -10V to -100V adjustable output. The flat portion around 0V indicates that the output control circuit saturates at 2V. Smart power sources can be used to drive a wide variety of devices, including DC motors and heaters.

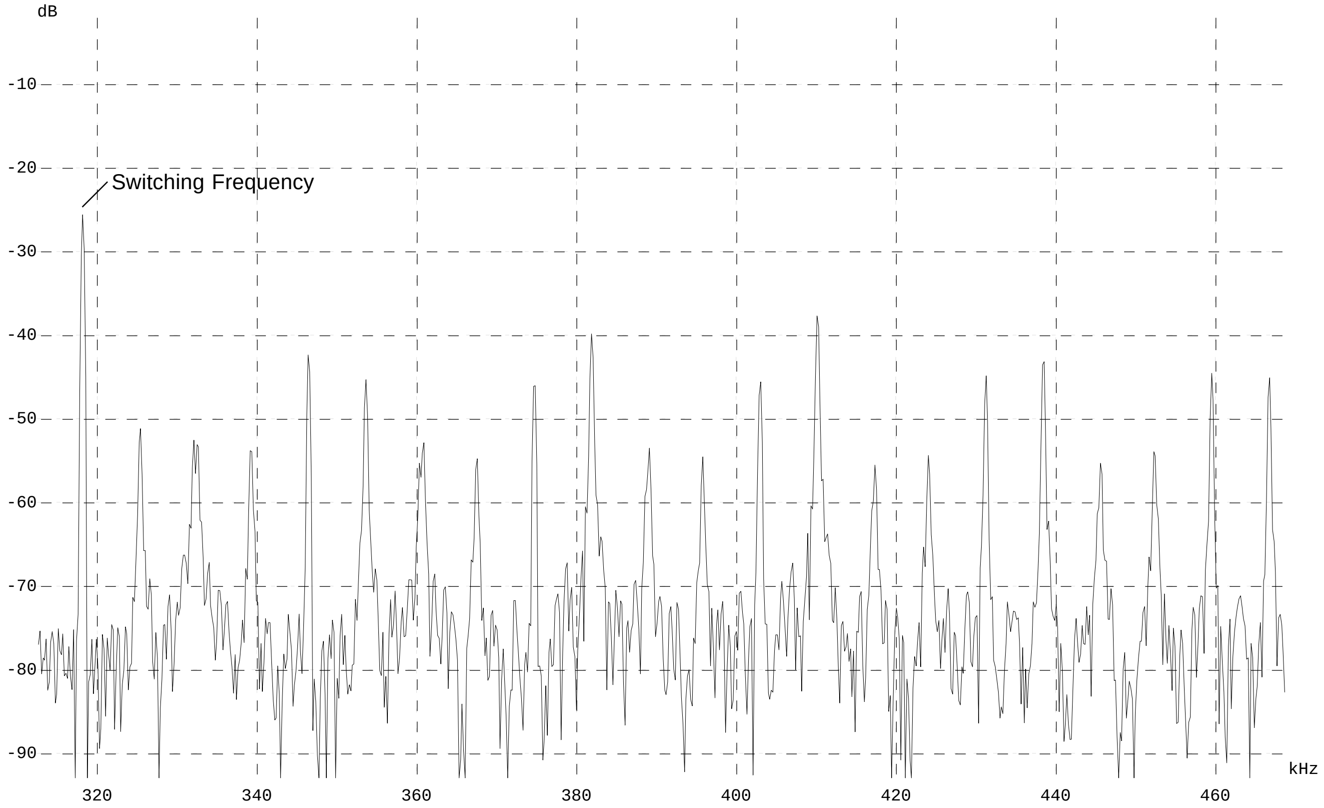

FIGURE 3A. Spectrum of V_{OUT} at Point A in Figure 2

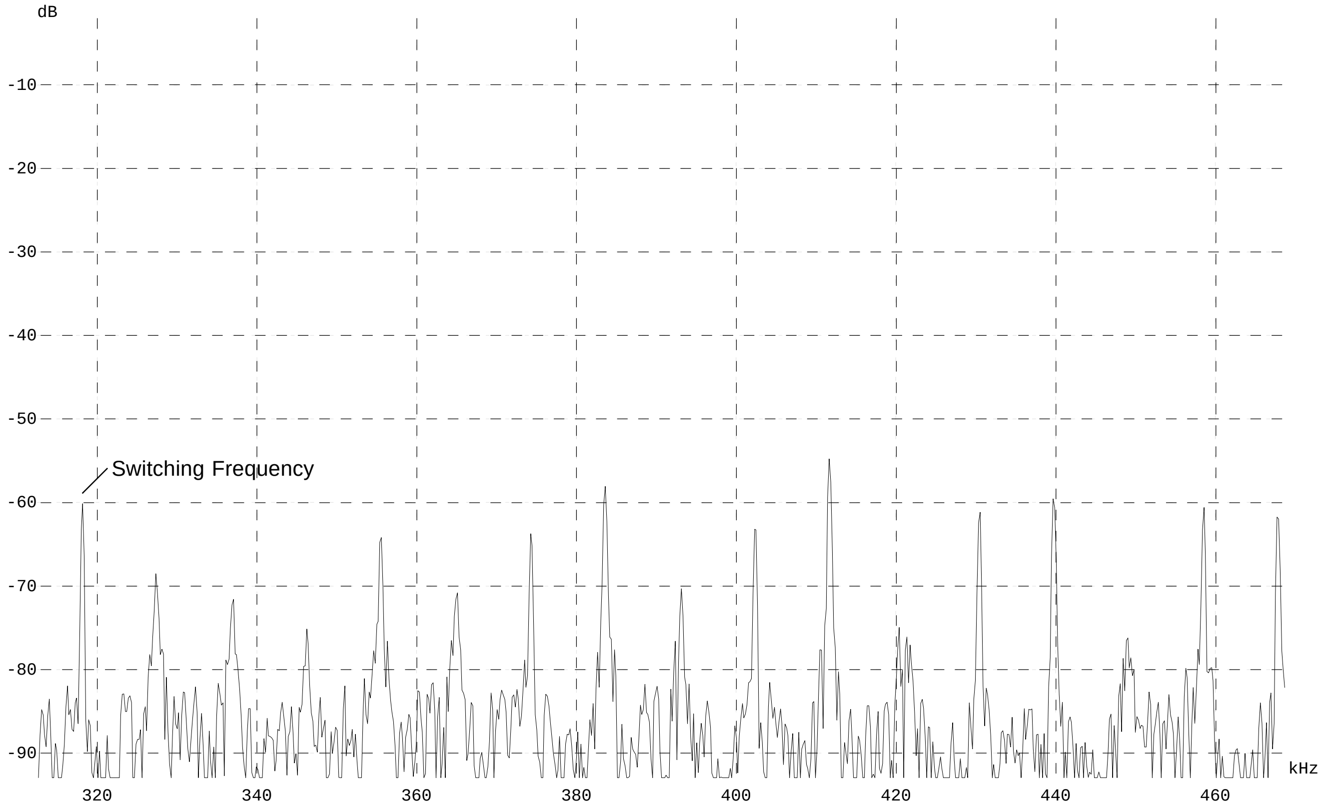

FIGURE 3b. Spectrum of V_{OUT} at Point B in Figure 2

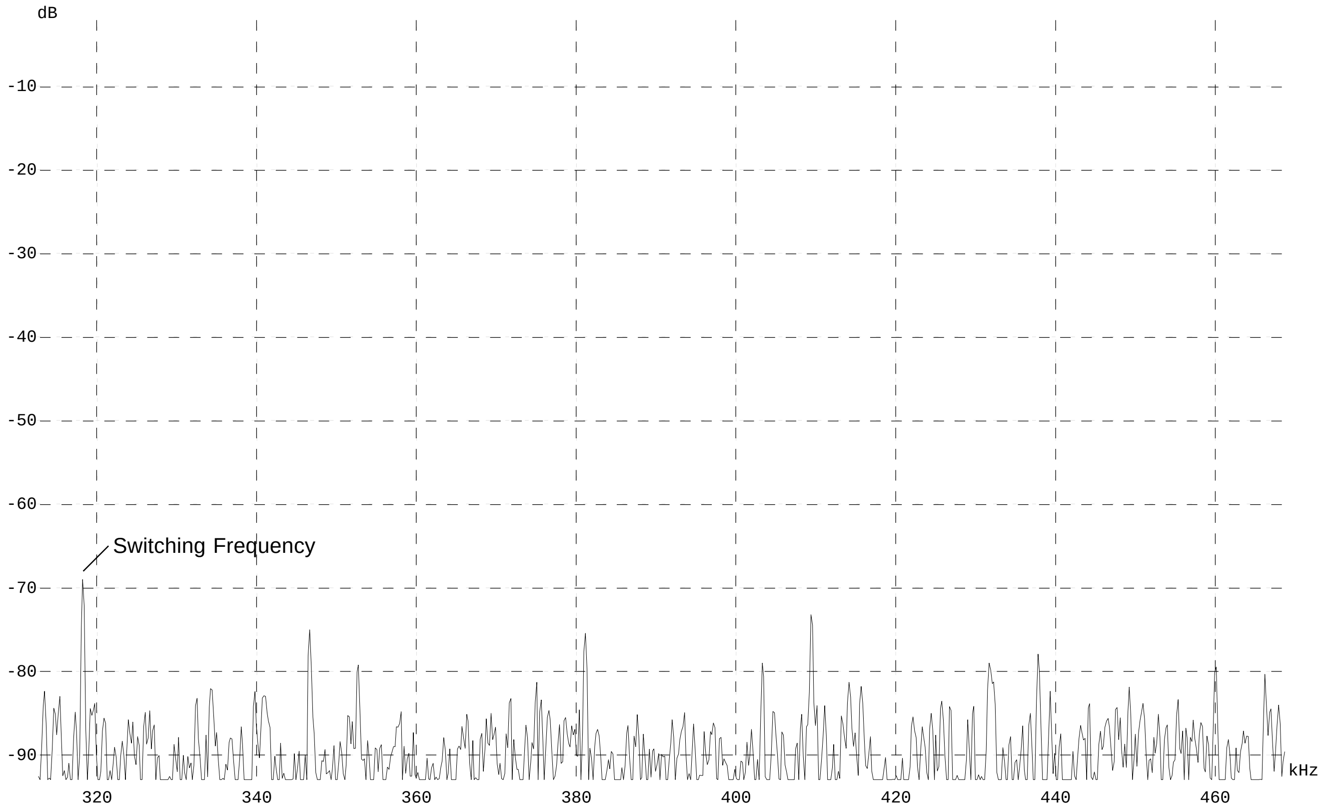

FIGURE 3C. Spectrum of V_{OUT} at Point C in Figure 2
(Linear regulator output *without* 6.8µF capacitor at the output)

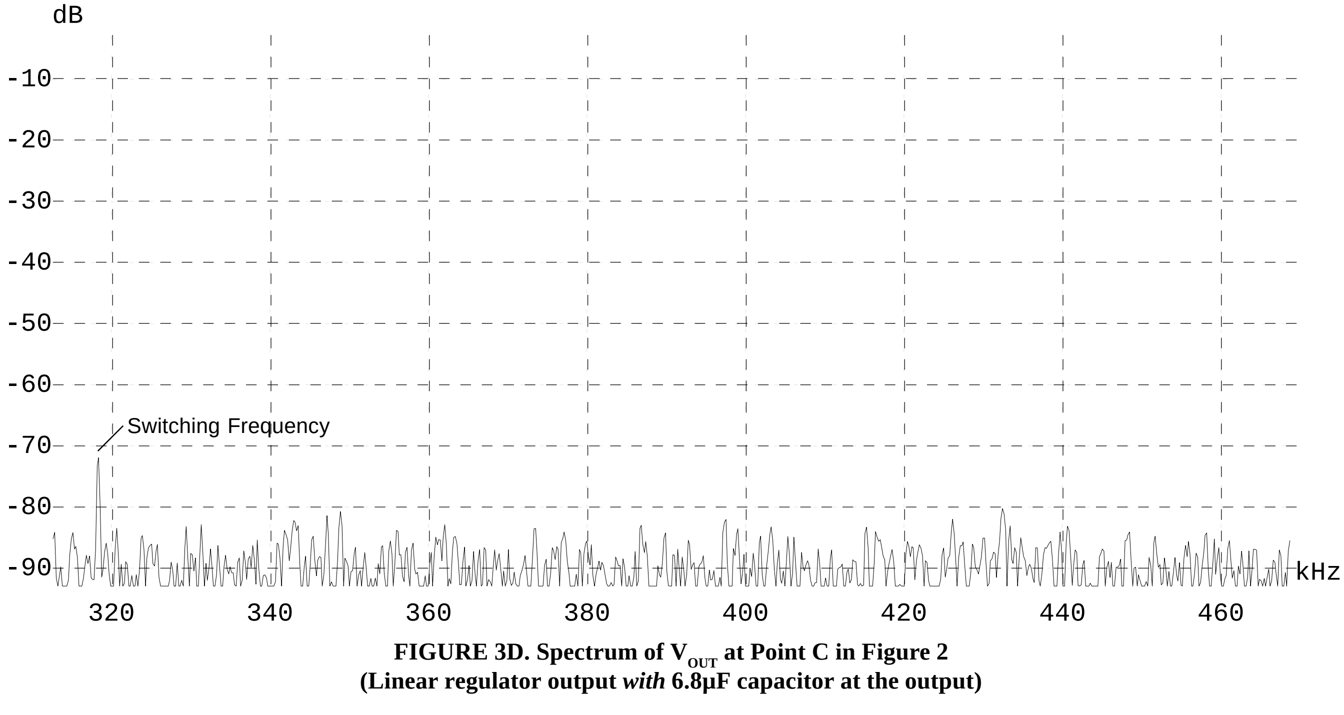

FIGURE 3D. Spectrum of V_{OUT} at Point C in Figure 2
(Linear regulator output *with* 6.8µF capacitor at the output)

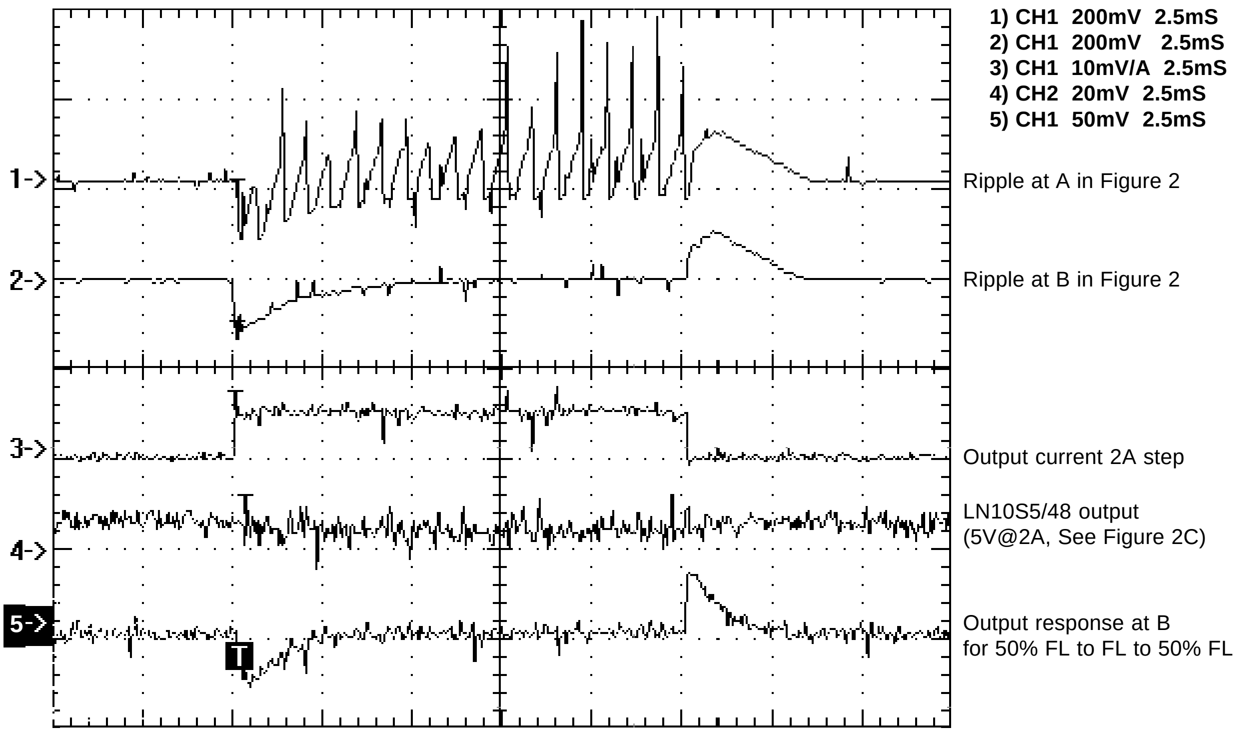

FIGURE 4. Transient reponse of LN10S5/48

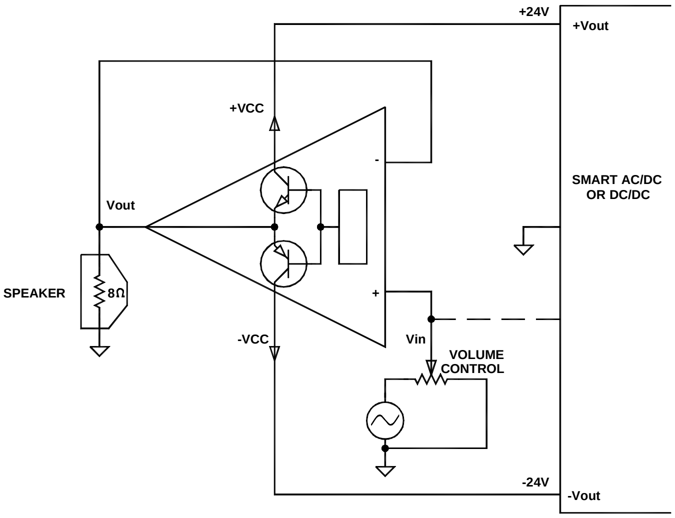

FIGURE 5. 60W power amplifier with dual power supply

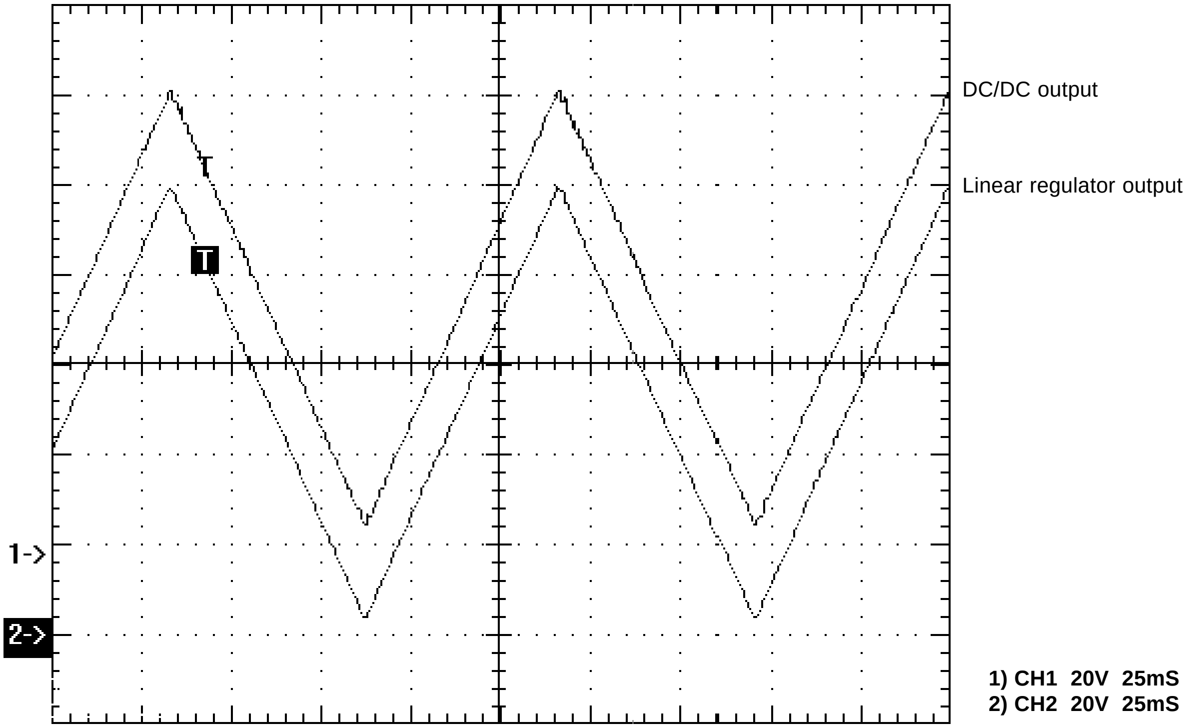

FIGURE 6. 10Vdc to 100Vdc adjustable output, isolated DC/DC converter with linear regulator (35S100/24AD)

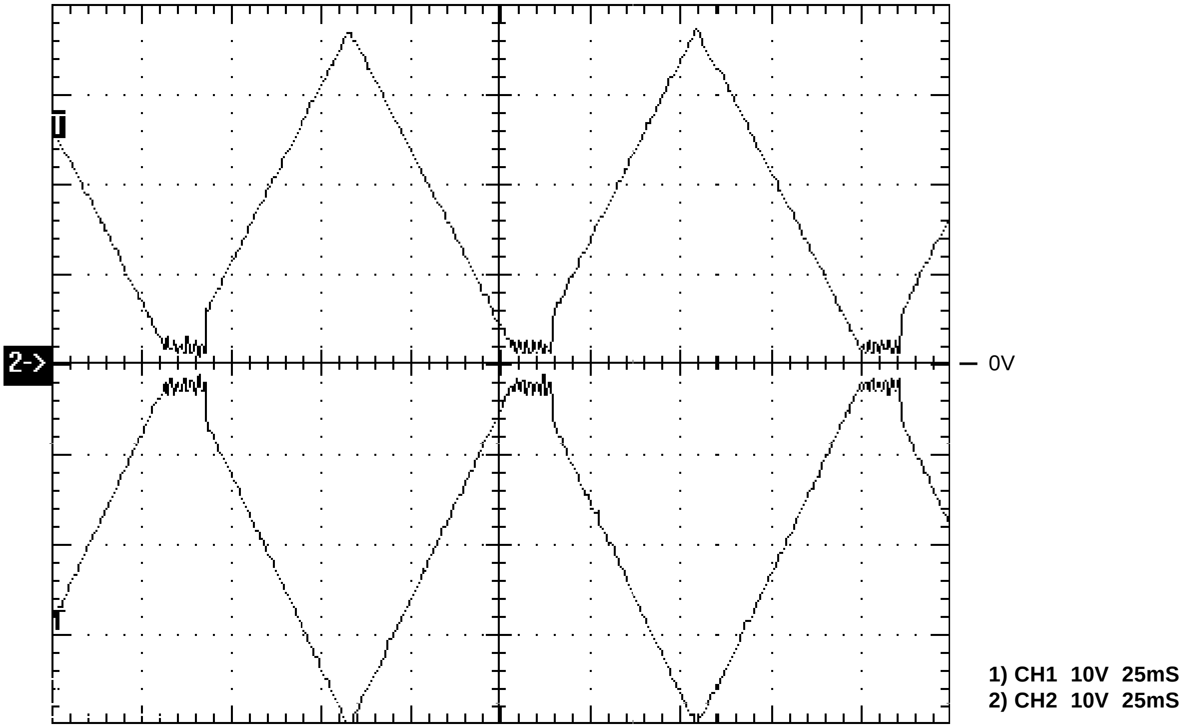

FIGURE 7. Dual ±5V to ±50V adjustable DC/DC converter (35D50/24AD)

Linear Regulators Review

Before the age of switching power supplies, the 120VAC or 220VAC through a step-down transformer was rectified and filtered to provide a raw DC voltage source. The rectified 50Hz or 60Hz sinewave voltage not only requires big output capacitors as filters, but due to different loading and impedance of the utility lines the fluctuation of the raw DC can be as much as 10% to 30% more.

To stabilize (regulate) this raw voltage, linear regulators are inserted between the raw DC source and the load. Most popular bipolar linear regulators were 78xx series for positive output voltage and 79xx series for negative output. For this article, we are using only positive voltage regulators.

Due to the low current gain of the series pass transistors, two or more were connected in parallel or in series as a Darlington pair. In Figure A, a Darlington pair with a current sense resistor of the 7805 linear regulator is presented.

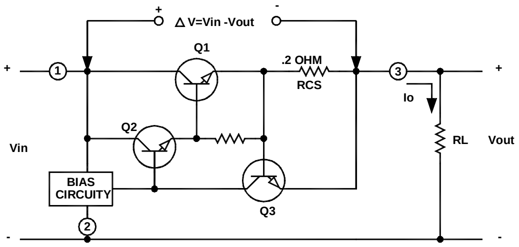

FIGURE A. 7805 voltage regulator with Darlington pair (Q1, Q2) and output current limiting transistor Q3

The minimum $\Delta V = V_{IN} - V_O$ required by the 7805 regulator to maintain regulation is defined as a "dropout" voltage. The dropout voltage of the 7805 is given as 2V and its output current is 1A. Therefore, at full load the regulator dissipates 2 watts and delivers 5 watts to the load. Its efficiency is: $P_{OUT} / P_{IN} * 100 = (5 / 7) * 100 = 71.4\%$, under the best operating condition, which is at minimum dropout and minimum V_{IN}.

In Figure B, the series pass Darlington of Q1, Q2 in Figure A is replaced with a PNP transistor that has a gain (B) of 30 and saturation voltage of 0.5V. For the same output power as in Figure A, the input power is $P_{IN} = V_{IN} * I = V_{IN} (I_O + I_{Q2}) = V_{IN} (I_O + I_O/b) = V_{IN} (1 + 1/30) = V_{IN} (1.033)$ and the minimum dropout voltage is the Q1 saturation voltage plus the RCS * I_{IN} = 0.2 * 1.033 = 0.2066 and $\Delta V = 0.7066V$.

For $5V_{OUT}$, V_{IN} Min is 5.7066. P_{IN} = 5.7066 * 1.033 = 5.89. The efficiency is 85%, a 13.5% increase.

In Figure B, Q2 is used to increase the driving capability of A1 and R_{CL} is used as a current limiting resistor for Q2. Also the current limiting transistor Q3 is moved to the input side of the regulator.

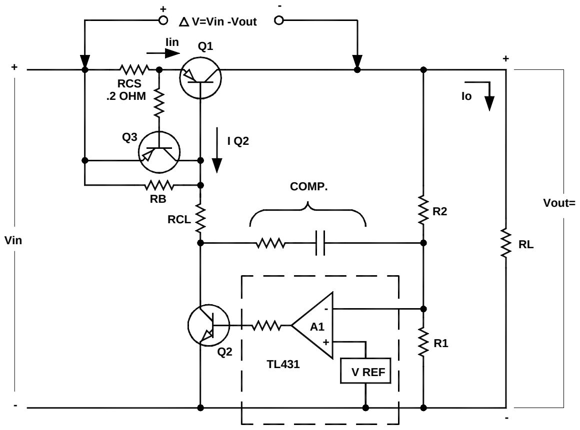

FIGURE B. Linear regulator with a PNP transistor (Q1)

For applications that require up to 3 amps of output current and the input source is current limited, one can design a low dropout linear regulator with only three active devices: Q1, Q2 and TL431, as shown in Figure C.

The only limiting factor on the output current in Figure C is the maximum current through the adjustable zener TL431, which is 100mA. By selecting a better gain transistor for Q1, the output current can be increased.

Note: A P channel MOSFET is not recommended for Q1 in Figure C unless it has $1V_{GS}$ to $2V_{GS}$. For output voltages lower than 5V, use the $1.2V_{OUT}$ version of the TL431.

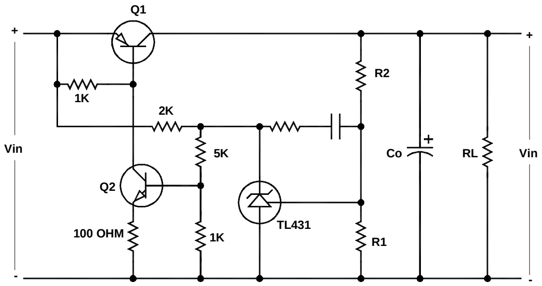

FIGURE C. Low-cost linear regulator for $V_{OUT} \geq 3.3V$

Replacing Q1 in Figure B with a P channel MOSFET, the highest efficiency linear regulator can be designed as shown in Figure D. As a voltage device, MOSFETs require much less power to drive and offer much less dropout voltage than the equivalent bipolar transistors. The dropout voltage is the product of the output current and the ON resistance of the MOSFET.

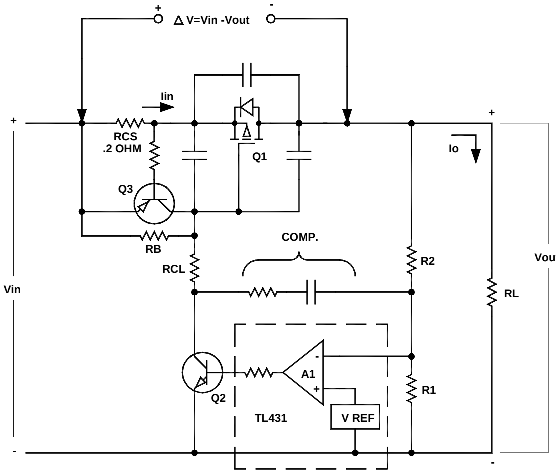

FIGURE D. Linear regulator with P channel MOSFET Q1 for $V_{OUT} \geq 5V$

Even though linear regulators, such as the one shown in Figure D, offer the best efficiency, they cannot be used for high power or low output voltages. MOSFETs with low R_{DS} ON resistance have high parasitic capacitance such as C_{GS}, C_{DG}, and C_{DS}. High capacitance increases the transient response time of the regulator and requires a low impedance source for gate drive. The gate threshold voltage of the MOSFET sets the minimum output voltage of the regulator. Low threshold MOSFETs together with rail-to-rail OPAMs will make it possible to have a $3.3V_{OUT}$ regulator with 5A to 10A of I_O. The C_{DS} (drain to source) capacitance will couple high frequency noise from input to output, but most linear regulators require large output capacitance for stability and improvement of transient response. The high capacitance output will eliminate any noise coupling to the output capacitor. The parasitic drain to source diode will pass any load dump charges from the output of the regulator to the output of the DC/DC converter, which may destroy both the output capacitors of the converter and the regulator. In this case, a high-power zener for overvoltage protection at the output is highly recommended.

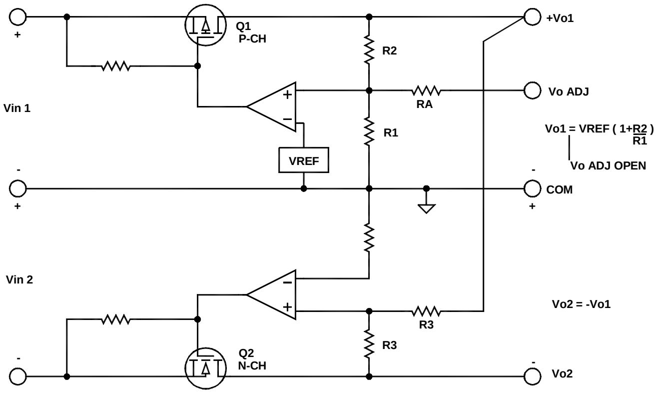

FIGURE E. Dual tracking regulator

BICMOS technology offers the advantages of both bipolar and CMOS technologies and can be applied to develop linear regulators to operate below 1V at high output currents.

One can use the same techniques to design efficient negative linear regulators. A combination of a positive and negative regulator is the dual tracking regulator shown in Figure E. It is called so because the negative output of the regulator tracks the positive output. These regulators are used with dual (or bipolar) AC/DC or DC/DC power supplies.

As the low-output voltage regulators have their own unique design problems, high-voltage linear regulators up to 1KV present unique design challenges as well.

High-voltage linear regulators not only require high-voltage transistors, but also any OPAM or reference voltage must operate in the micro power region. Also, different design techniques for short circuit protection must be used together with thermal protection, overvoltage protection, etc. Even though designing high-voltage DC/DC and linear regulators is challenging, it can be done.