Taming linear-regulator inrush currents

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Many older linear regulators and some regulators specifically designed for fast start-up require significant inrush current at start-up to charge their output capacitors and to provide current to their resistive loads. The relationship $I_{Inrush} = C_{OUT} \times V_{OUT}/t_{Rise}$ predicts the regulator's required input current at start-up for a given rise time, t_{Rise}, where C_{OUT} is the regulator's output capacitance. With no inrush-control (commonly called "soft-start") circuitry, I_{Inrush} is clamped to the regulator's current limit, which is typically significantly higher than the regulator's rated current. If the input power supply is current-limited or connected by long inductive traces, the voltage at the regulator's input will droop, possibly below that of the regulator's undervoltage lockout (UVLO) circuit. Figure 1 illustrates how this causes the regulator to "stair step" or ratchet its way up to regulation, shutting down momentarily while the input capacitor recharges, then starting up again.

In the past, start-up problems were common for linear regulators and can still occur when the output capacitance seen by the regulator is large. End-equipment designers need to take into account how linear regulators handle inrush current, especially if the selected regulator has no inrush-current control other than clamping to its current limit.

Additional circuitry can be configured to manage inrush current for any regulator or converter. Simply by adding a FET and some passive elements following the regulator's or converter's output voltage, the designer can shape the FET's turn-on characteristic and the output-voltage waveform. For example, a designer has minimal control over the inrush current of linear regulators designed for fast start-up, like the Texas Instruments (TI) TPS734xx/5xx, which have a high power-supply ripple rejection (PSRR), low noise, and an ultralow I_q. Figure 2 shows how adding a FET and some passive circuitry to the TPS73525 provides greater control over the inrush current. I_{IN} is measured between the regulator input pin and the input capacitor because both the capacitor and the input power supply will supply the inrush current.

Figure 1. Older regulator with 2.5-V UVLO ratcheting up to regulation with no load

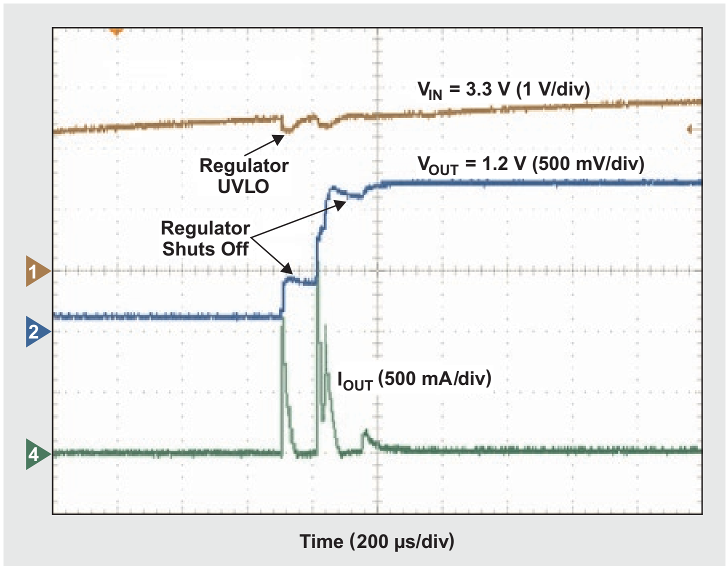
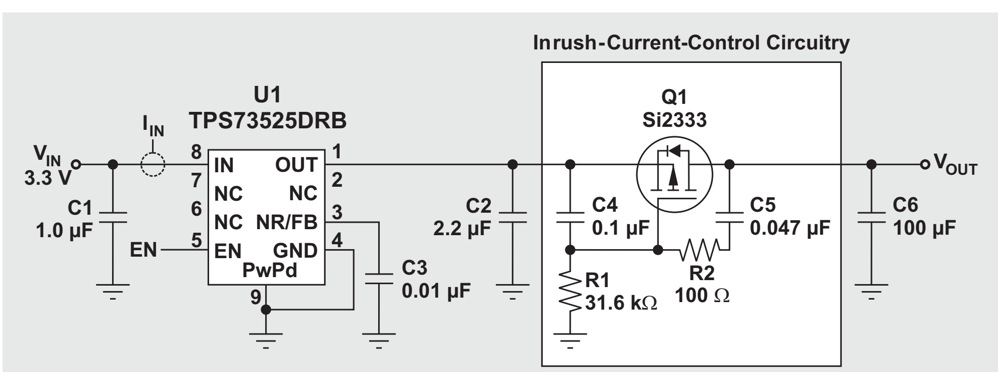


Figure 2. FET following the TPS73525 to provide inrush-current control



Note that in Figure 3 the amplitude and duration of the initial current spike are significantly reduced compared to those in Figure 4 because the output sees only the 2.2-µF capacitor instead of the 100-µF capacitor. Surprisingly, capacitor C5, providing additional FET gate-to-drain capacitance, and resistor R1 set the soft-start time. Reference 1 explains in detail how the additional circuit works, how to choose the FET, and how to size the passive elements.

Some regulators use a topology that has inherent inrush-current control. For example, the TI TPS732xx/4xx/6xx family of linear regulators has an internal charge pump that is needed to drive the gate of the n-channel pass element. At start-up, the charge pump needs a finite amount of time—several hundred microseconds—to charge the internal servo capacitor, which in turn charges the n-FET's gate capacitance. Figure 5 shows the TPS73633 output voltage and inrush current at start-up with C_{OUT} = 1 µF and 10 µF.

Even though these linear regulators have an 800-mA maximum current limit, the inrush current never exceeds 150 mA, after a brief spike to 300 mA, even with a 10-µF output capacitor.

From the relationship $I_{Inrush} = C_{OUT} \times V_{OUT}/t_{Rise}$, and by comparing the output voltage rise times in Figures 4 and 5, one can see that there is an inverse relationship between the output-voltage ramp time and the inrush current. Therefore, in recent years, IC manufacturers have developed linear regulators with user-controllable V_{OUT} ramp time (soft start), not only to manage inrush current but also to meet the power-rail ramp-time requirements of certain DSPs and FPGAs. The simplest integrated soft-start method, used by the TI TPS74x01 family of regulators, is

Figure 3. TPS73525 starting up into 100 µF without FET

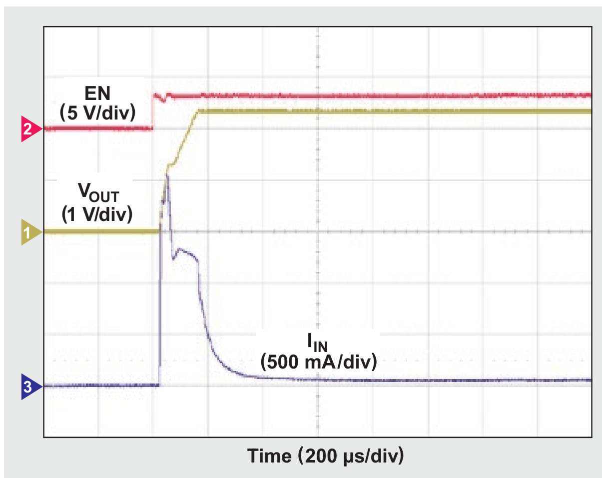


Figure 4. TPS73525 starting up into 100 µF with inrush-current-control FET

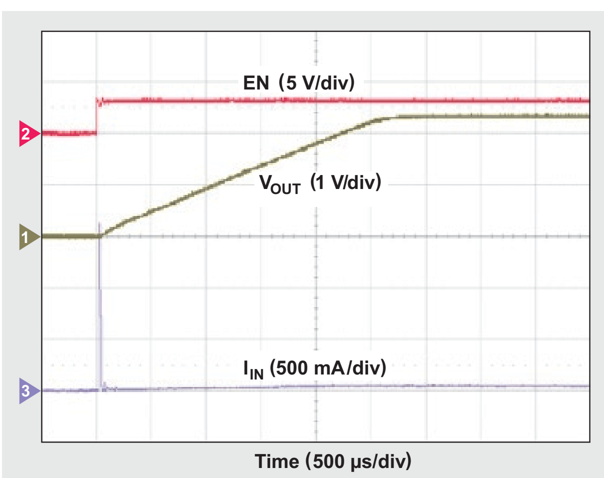


Figure 5. TPS73633 starting up with C_{OUT} = 1 µF and 10 µF

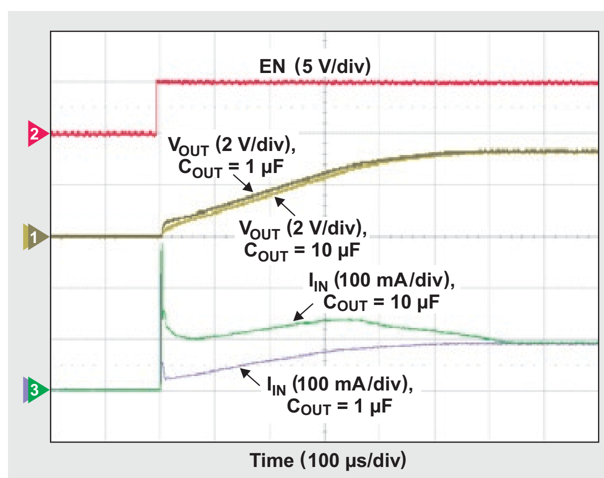


Figure 6. TPS74901 soft starting with C_{SS} = 560 pF and 2200 pF, and C_{OUT} = 10 µF

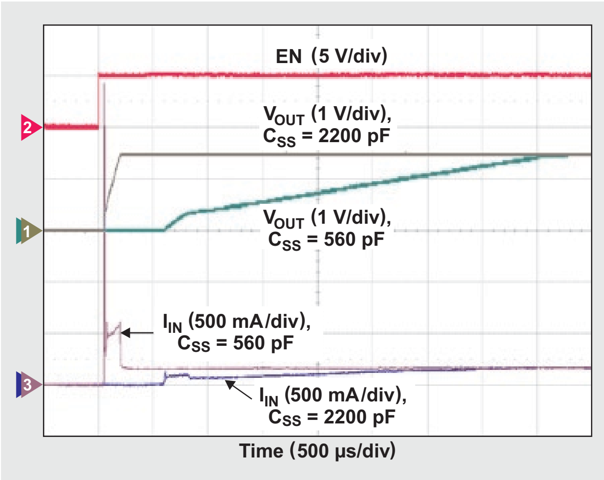
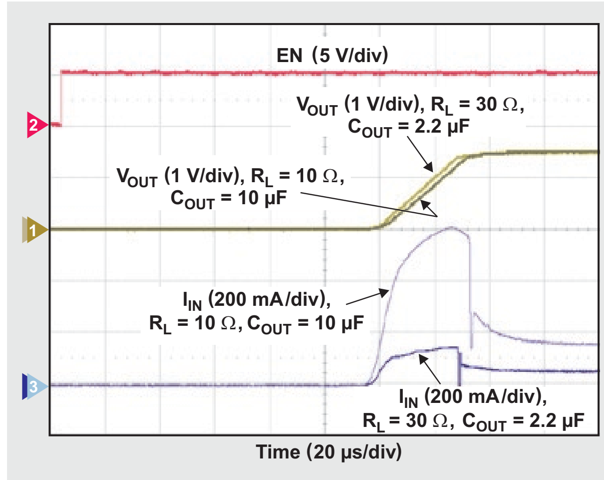


Figure 7. TPS72015 starting up at different loads (R_L)



to slowly ramp the error amplifier's internal reference voltage following an enable signal. The IC uses an external capacitor (C_{SS}) on the soft-start pin and an internal constant-current source (I_{SS}) to linearly charge this capacitor, which is initially tied to the regulator's error amplifier. Once the capacitor is charged to the same value as the internal reference voltage, V_{REF}, the IC switches the error-amplifier connection to the internal reference. Therefore, without affecting regulation, the designer can set the soft-start time as predicted by a simple equation, $t_{SS} = V_{REF} \times C_{SS}/I_{SS}$, by adjusting the capacitor value. Figure 6 shows the TPS74901 output voltage and current at start-up, with two different soft-start capacitors and C_{OUT} = 10 µF.

This soft-start method is very common and works as predicted for start-up loads that are primarily capacitive and not resistive. When the start-up load has resistive loading, the method still works, but the ramp (soft-start) time is a bit longer than predicted by the t_{SS} equation.

TI's low-I_q, dual-rail, 350-mA TPS720xx linear regulator addresses simultaneous capacitive and resistive loads with a novel, internal architecture that limits inrush current. Instead of being clamped to an overcurrent-limit value as with older regulators, the current drawn from the input to the output is limited to a lower value,

$$I_{Inrush\_Limit} = I_{R_L} + C_{OUT}\ (\mu F) \times 0.0455\ (V/\mu s),$$

where I_{R_L} is the start-up resistive loading. Figure 7 shows the TPS72015 starting up at different fixed resistive loads with C_{OUT} = 2.2 µF and 10 µF. The soft-start circuitry scales the soft-start current proportionally with C_{OUT} so that the start-up time is virtually independent of C_{OUT}.

Conclusion

Historically, design engineers chose linear regulators for their low cost, simplicity, low noise, and high PSRR. Rarely did engineers consider a regulator's ability to control inrush current at start-up until after the choice was made. This oversight sometimes rendered the input power supply unable to supply enough start-up current, especially if the regulator had a large output capacitance. To continue going forward, designers had to use external circuitry to provide inrush-current control. Today, however, they can choose from a new generation of linear regulators with integrated soft start/inrush-current control. Taking soft start into consideration early in the design phase provides a problem-free system with controlled, predictable inrush current at start-up.

References

For more information related to this article, you can download an Acrobat® Reader® file at www-s.ti.com/sc/techlit/*litnumber* and replace "*litnumber*" with the **TI Lit. #** for the materials listed below.

Document Title **TI Lit. #**

1. Jeff Falin, "Monotonic, Inrush Current Limited Start-Up for Linear Regulators," Application Report. slva156

Related Web sites

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