Soft-start circuits for LDO linear regulators

By Jeff Falin (Email: j-falin1@ti.com)
Applications, Portable Power

Many low-dropout (LDO) linear regulators do not have an integrated "soft-start" function that limits the in-rush current to the device being powered. In fact, as the simplified block diagram in Figure 1 shows, most linear regulators consist of only a reference, an error amplifier, and a pass element. Thus, at startup, the error amplifier senses that the output voltage is low and drives the pass element as hard as possible. The pass element pulls a large in-rush current to charge the output capacitance and/or load current abruptly, after a short delay. The delay is caused by three factors: the time required for the input voltage to rise above the undervoltage lockout circuitry, if any; the time required for the chip's internal circuitry, particularly the band-gap reference, to power up; and the time required for the regulator to sense its output voltage and turn on the pass element (i.e., the feedback loop bandwidth). The load resistance and the size of the regulator's output capacitance influence the start-up response. If the regulator starts up into a large capacitive or small resistive load, the in-rush current will be large, approaching the regulator's current limit in some cases. This article discusses two methods of slew-rate limiting a linear regulator's output-voltage rise time and, consequently, limiting its in-rush current at startup. The TPS795xx, high-PSRR, low-noise family of regulators, which were designed for approximately 50-µs start-up times and thus large start-up currents, are used as examples.

The simplest method uses a PMOS FET switch following the regulator output, in series with the regulator's load, as shown in Figure 2. Note that the switch must be placed after the regulator's minimum required output capacitance (i.e., C3) to ensure that the regulator remains stable. After the regulator turns on abruptly, FET Q1 operates as a crude supervisor and pulls R_T low. Capacitor C_T, effectively replacing the gate-to-drain capacitance of the FET, then causes the switch to function like an integrator and provides a more linear transition of the drain voltage.

Figure 1. Simplified block diagram of LDO linear regulator

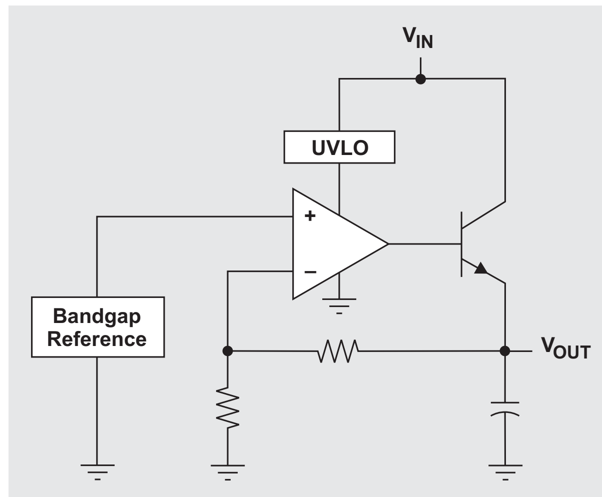
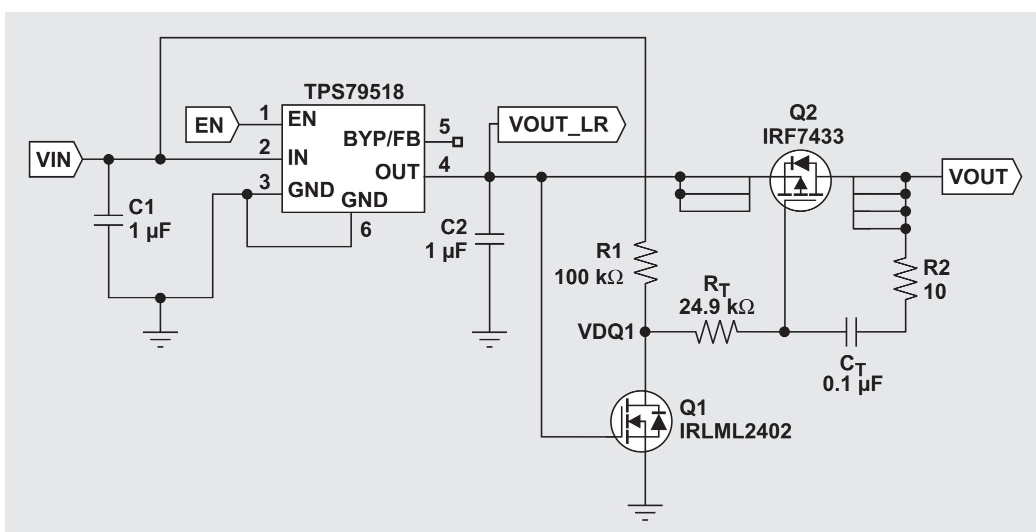


Figure 2. Soft start using a PMOS FET following the output



Careful component selection is critical for proper operation of the circuit. First, Q1 and Q2 must have threshold voltages that are lower than the desired output voltage (i.e., $V_{OUT} > V_{TH1,2}$). Second, Q2's $r_{DS(on)}$ must be small enough so that the drop across it due to the maximum dc load current does not significantly reduce the regulated output voltage. C_T is selected to be much larger than the gate-to-drain capacitance (i.e., $C_T >> C_{GD} = C_{rss}$). R_T is chosen according to the equation

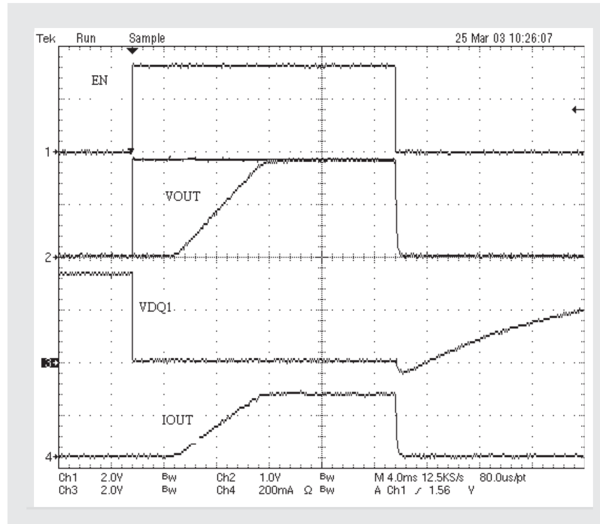
$$R_T = \frac{V_{OUT} - V_{TH}}{C_T \times \frac{V_{OUT}}{t_{Rise}}},$$

where t_{Rise} is the desired rise time (here 5 ms) and V_{TH} is Q2's threshold voltage (here 0.9 V). Resistor R1 is simply a large pull-up resistor. R2 should be selected to be much smaller than R_T.

Figure 3 shows the rise time of the regulator output voltage with and without the additional circuitry for V_{IN} = 3.3 V and I_{OUT} = 300 mA. The measured rise time is 6.5 ms, slightly larger than the designed 5 ms, but within an acceptable margin considering the variation in Q2's threshold voltage, V_{TH}. The 4-ms delay before startup is due to the RC time constant created by the PMOS FET's gate capacitances and R_T. With such a long start-up delay, the variation of threshold voltage of Q1, and thus the exact turn-on time of the switch, can be neglected.

The advantage of this method is its applicability to any regulator or dc/dc converter. The disadvantage is the difficulty in finding FETs either with low enough $r_{DS(on)}$ not to affect regulation under large load currents or with low enough threshold voltages for low output voltages. Another disadvantage is that this circuit does not work properly if V_{IN} is tied to EN. The IRF7433 has a maximum of 46-milliohm $r_{DS(on)}$ at V_{GS} = –1.8 V; so, at 300-mA output current, the output voltage could be 14 mV below the nominal voltage and thus could increase the lower tolerance limit of the regulator solution from –3 to –3.8%. In addition, to prevent large load transients from momentarily turning off the switch and causing the rail voltage to droop, a large output capacitor after the switch is recommended.

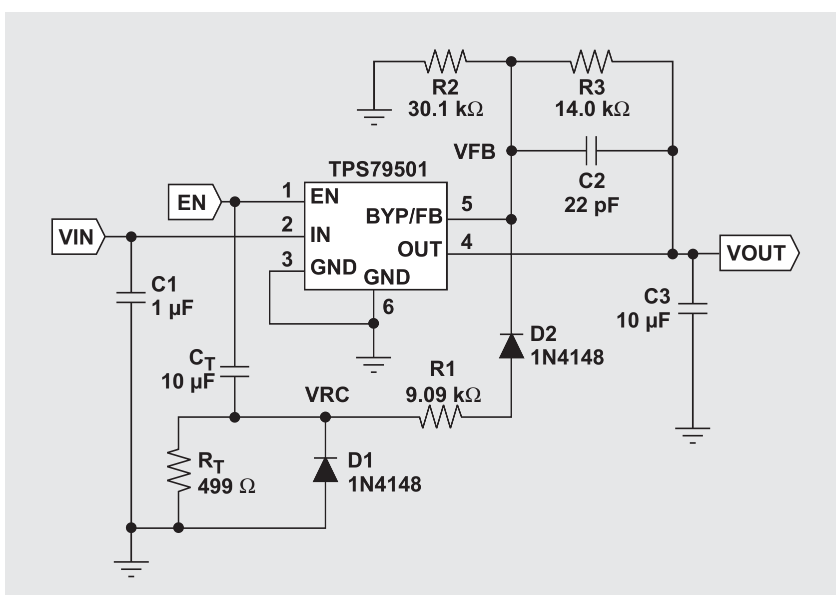
Figure 3. Results from soft-start circuit using a PMOS FET following the output



The second method uses an RC time constant and diode to shape the voltage that is being fed back from the output to the regulator at startup, as seen in Figure 4.

When the enable signal goes high, node V_{RC} charges to V_{EN}. With proper sizing of R1, the feedback node, V_{FB}, artificially rises above the regulated intended feedback voltage of 1.2 V to V_{FB2}. V_{FB2} is chosen to be at least

Figure 4. Soft-start circuit with RC and diode



200 mV above the intended feedback voltage but less than a diode drop below V_{EN}. Capacitor C_T then discharges through R_T and, as the feedback voltage drops, the pass element slowly turns on and the output voltage slowly rises. Diode D2 keeps R1 and R_T out of the feedback-voltage divider and therefore prevents any degradation in output-voltage tolerance during normal operation. Diode D1 clamps node V_{RC} to a diode drop below ground when EN is taken low.

The following equation is used to determine the appropriate size of R1 to raise node V_{FB} to V_{FB2}:

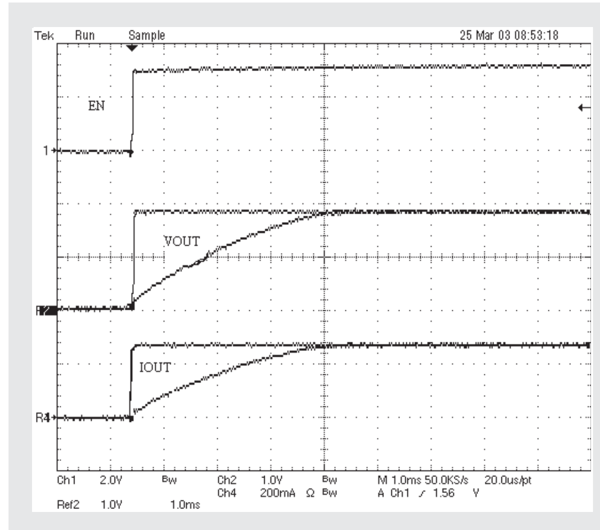
$$R1 = \frac{V_{IN(min)} - 0.6\ V - V_{FB2}}{\dfrac{V_{FB2}}{R2 \| R3}}$$

In this example, V_{FB2} is 1.2 V + 0.2 V = 1.4 V; and $V_{IN(min)}$ is 3.3 V, so the calculated value of R1 is 9 kΩ. Once R1 is determined, R_T is selected to be much smaller than R1 (roughly a factor of 10 or more) so that it will dominate the RC time constant; and then C_T can be sized to provide the appropriate rise time. In this example, the desired t_{Rise} is 5 ms for R_T = 499 Ω; and C_T = 10 µF is required.

Figure 5 shows the rise time of the regulator with and without the additional circuitry for V_{IN} = 3.3 V and I_{OUT} = 300 mA. The measured rise time is slightly below 4 ms.

The advantages of this method are simplicity, low cost, and isolation from the regulator after startup because of diode D2 and also because the control voltage is not a function of the output voltage. The primary disadvantages are that this circuit requires the use of an adjustable regulator and that it does not work with some regulators. Regulators with extra features, like an integrated SVS or a fast transient-assist circuitry, require the output of the regulator to be biased above ground after it is enabled. Using this soft-start method with such regulators could cause the start-up waveform to have an initial voltage spike before the slow rise to the output voltage.

Figure 5. Results from soft-start circuit using RC and diode



Either method limits the in-rush current, slowing the ramp time of the regulator output. The first method is best suited for higher-voltage rails with looser output-voltage tolerances and fewer transients. The second method provides the best performance, since the additional circuitry is effectively removed after startup and thus does not affect regulation; however, it will not work with all regulators.

Related Web sites

analog.ti.com
www.ti.com/sc/device/TPS79501
www.ti.com/sc/device/TPS79518

IMPORTANT NOTICE

Texas Instruments Incorporated and its subsidiaries (TI) reserve the right to make corrections, modifications, enhancements, improvements, and other changes to its products and services at any time and to discontinue any product or service without notice. Customers should obtain the latest relevant information before placing orders and should verify that such information is current and complete. All products are sold subject to TI's terms and conditions of sale supplied at the time of order acknowledgment.

TI warrants performance of its hardware products to the specifications applicable at the time of sale in accordance with TI's standard warranty. Testing and other quality control techniques are used to the extent TI deems necessary to support this warranty. Except where mandated by government requirements, testing of all parameters of each product is not necessarily performed.

TI assumes no liability for applications assistance or customer product design. Customers are responsible for their products and applications using TI components. To minimize the risks associated with customer products and applications, customers should provide adequate design and operating safeguards.

TI does not warrant or represent that any license, either express or implied, is granted under any TI patent right, copyright, mask work right, or other TI intellectual property right relating to any combination, machine, or process in which TI products or services are used. Information published by TI regarding third-party products or services does not constitute a license from TI to use such products or services or a warranty or endorsement thereof. Use of such information may require a license from a third party under the patents or other intellectual property of the third party, or a license from TI under the patents or other intellectual property of TI.

Reproduction of information in TI data books or data sheets is permissible only if reproduction is without alteration and is accompanied by all associated warranties, conditions, limitations, and notices. Reproduction of this information with alteration is an unfair and deceptive business practice. TI is not responsible or liable for such altered documentation.

Resale of TI products or services with statements different from or beyond the parameters stated by TI for that product or service voids all express and any implied warranties for the associated TI product or service and is an unfair and deceptive business practice. TI is not responsible or liable for any such statements.

Following are URLs where you can obtain information on other Texas Instruments products and application solutions:

Products	
Amplifiers	**amplifier.ti.com**
Data Converters	**dataconverter.ti.com**
DSP	**dsp.ti.com**
Interface	**interface.ti.com**
Logic	**logic.ti.com**
Power Mgmt	**power.ti.com**
Microcontrollers	**microcontroller.ti.com**
Applications	
Audio	**www.ti.com/audio**
Automotive	**www.ti.com/automotive**
Broadband	**www.ti.com/broadband**
Digital control	**www.ti.com/digitalcontrol**
Military	**www.ti.com/military**
Optical Networking	**www.ti.com/opticalnetwork**
Security	**www.ti.com/security**
Telephony	**www.ti.com/telephony**
Video & Imaging	**www.ti.com/video**
Wireless	**www.ti.com/wireless**

TI Worldwide Technical Support

Internet

TI Semiconductor Product Information Center Home Page
support.ti.com

TI Semiconductor KnowledgeBase Home Page
support.ti.com/sc/knowledgebase

Product Information Centers

Americas			
Phone	+1(972) 644-5580	Fax	+1(972) 927-6377
Internet/Email	support.ti.com/sc/pic/americas.htm		
Europe, Middle East, and Africa			
Phone			
Belgium (English)	+32 (0) 27 45 54 32	Netherlands (English)	+31 (0) 546 87 95 45
Finland (English)	+358 (0) 9 25173948	Russia	+7 (0) 95 7850415
France	+33 (0) 1 30 70 11 64	Spain	+34 902 35 40 28
Germany	+49 (0) 8161 80 33 11	Sweden (English)	+46 (0) 8587 555 22
Israel (English)	1800 949 0107	United Kingdom	+44 (0) 1604 66 33 99
Italy	800 79 11 37		
Fax	+(49) (0) 8161 80 2045		
Internet	support.ti.com/sc/pic/euro.htm		
Japan			
Fax			
International	+81-3-3344-5317	Domestic	0120-81-0036
Internet/Email			
International	support.ti.com/sc/pic/japan.htm		
Domestic	www.tij.co.jp/pic		
Asia			
Phone			
International	+886-2-23786800		
Domestic	Toll-Free Number		Toll-Free Number
Australia	1-800-999-084	New Zealand	0800-446-934
China	800-820-8682	Philippines	1-800-765-7404
Hong Kong	800-96-5941	Singapore	800-886-1028
Indonesia	001-803-8861-1006	Taiwan	0800-006800
Korea	080-551-2804	Thailand	001-800-886-0010
Malaysia	1-800-80-3973		
Fax	886-2-2378-6808	Email	tiasia@ti.com
Internet	support.ti.com/sc/pic/asia.htm		ti-china@ti.com

C011905

Safe Harbor Statement: This publication may contain forward-looking statements that involve a number of risks and uncertainties. These “forward-looking statements” are intended to qualify for the safe harbor from liability established by the Private Securities Litigation Reform Act of 1995. These forward-looking statements generally can be identified by phrases such as TI or its management “believes,” “expects,” “anticipates,” “foresees,” “forecasts,” “estimates” or other words or phrases of similar import. Similarly, such statements herein that describe the company's products, business strategy, outlook, objectives, plans, intentions or goals also are forward-looking statements. All such forward-looking statements are subject to certain risks and uncertainties that could cause actual results to differ materially from those in forward-looking statements. Please refer to TI's most recent Form 10-K for more information on the risks and uncertainties that could materially affect future results of operations. We disclaim any intention or obligation to update any forward-looking statements as a result of developments occurring after the date of this publication.

Mailing Address: Texas Instruments
Post Office Box 655303
Dallas, Texas 75265