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How to Automatically Optimize Your LDO Regulator's Efficiency Using Voltage Input-to-Output Control

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Abstract

A low dropout (LDO) regulator is a dependable tool to power noise-sensitive equipment. Aside from providing direct power rails, LDO regulators also post-regulate other power sources. Noise from switching converters permeates many designs and often requires an LDO regulator downstream to eliminate it. While effective, an LDO regulator's power dissipation can negatively impact a system's efficiency. The unique voltage input-to-output control (VIOC) pin reduces power dissipation and increases efficiency through a single connection. VIOC introduces automated control of a switching converter to provide the best possible efficiency of the system. This article highlights an ultralow noise LDO regulator that outperforms LDO regulators without VIOC.

Introduction

People rely on precision electronic equipment in many areas of daily life. These devices provide precise medical diagnoses, quality control of end products, accurate measurements of chemical concentration in water and air, and many more. The precise hardware built into the test equipment and instrumentation consists of noise-sensitive devices and requires complex planning in design and testing to reduce noise. A key area to reduce system noise is in the power supply rails. Supply rails must have the capability to deliver a voltage with minimal noise and ripple to provide the best performance in noise-sensitive applications. In contrast, supplying a noisy power rail to a signal chain results in poor system performance. One type of device that offers low noise power is the LDO regulator.

The LDO regulator reliably steps down and regulates DC voltages through a simple resistive divider setting or a single resistor setting. LDO regulators feature clean, low noise outputs, but have the drawback of lower efficiency compared to another voltage regulation device, the switch-mode power supply (SMPS). Modern SMPS devices have efficiencies that exceed 90%. However, switching converters deliver noisy outputs due to the rapid switching of current across their inductor, producing a current that resembles a triangular waveform. The voltage of an inductor is proportional to the differential current of the current running through it. An example of the current waveform is shown in Figure 1.

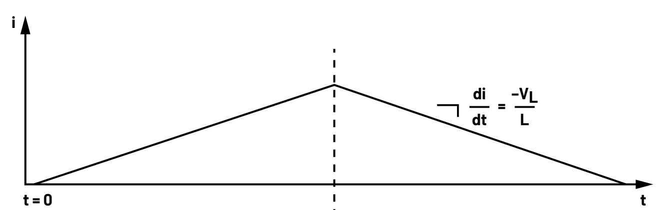

Figure 1. The output current of a buck converter.

A switching converter also produces voltage spurs at its switching frequency and higher harmonics. This can be shown in the spectral noise content of any switching converter. An image of the voltage noise can be seen in Figure 2.

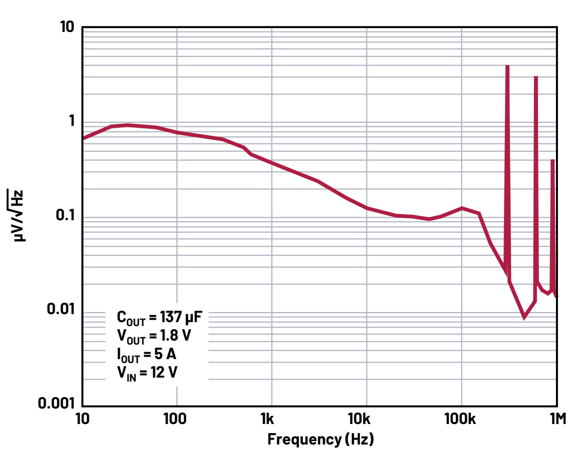

Figure 2. The voltage noise of a switching converter.

Filtering the output of the switching converters reduces noise. However, it requires bulk capacitors that introduce parasitic effects like equivalent series resistance (ESR). ESR increases the power dissipation of the power supply and can result in decreased efficiency. In addition to switching noise ripple, switching converters are also susceptible to wideband noise, high frequency spikes, and ringing.

Combining a switching converter with a postregulating LDO regulator mitigates noise. An LDO regulator downstream from the switching converter combines the efficiency of a switching converter with the inherent power supply rejection ratio (PSRR) of the LDO regulator to clean the noisy output. However, this implementation still suffers from inefficiency depending on the voltage drop across the LDO regulator.

Analog Devices' unique VIOC technology addresses the competing requirements of low noise and efficiency, by reducing the voltage drop of a downstream LDO regulator. VIOC is an active control system that provides feedback from the LDO regulator to regulate the output voltage of a switching converter. An LDO regulator with VIOC automatically optimizes a switching converter's output voltage. This article will discuss the technical detail of the VIOC function, provide experimental evidence of the efficiency improvement, and consider additional ways in which VIOC may be used for variable downstream power rails.

LDO Regulators Used for Postregulation

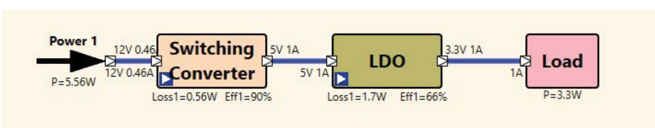

Figure 3. A block diagram of an LDO regulator in postregulation.

In Figure 3, the switching converter steps down the input voltage to provide power to the LDO regulator. This output will typically contain a ripple, as shown in Figure 4.

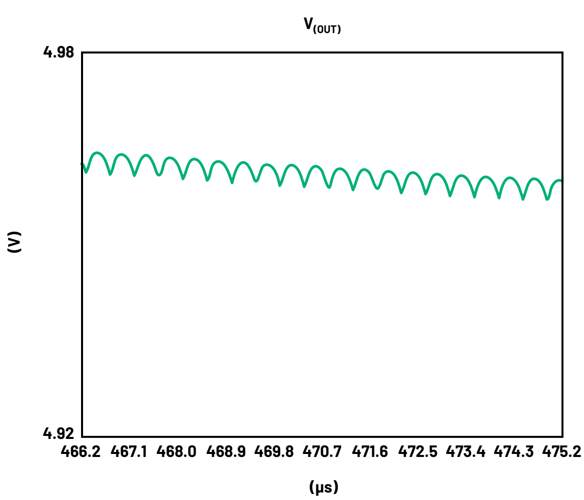

Figure 4. A switching converter output voltage.

The LDO regulator steps down and regulates the switching converter's output voltage to its programmed output voltage, producing a clean voltage signal that is ideal for precise signal chains. The measurement that determines how well an LDO regulator can reduce noise is PSRR. PSRR can be calculated using PSRR = $|20 \log(\Delta V_{INPUT})/(\Delta V_{OUTPUT})|$, this measurement is taken across a wide frequency spectrum usually in the 10 Hz to 1 MHz range. An LDO regulator with a high PSRR, such as 80 dB at 1 MHz, provides the best attenuation for switching noise making it the perfect device to clean a distorted output voltage. An example of the LDO regulator's output rail is shown in Figure 5.

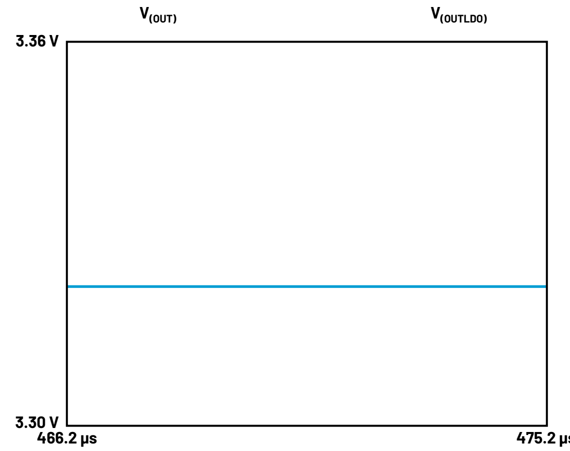

Figure 5. An LDO regulator output voltage.

While a postregulating LDO regulator effectively cleans noisy power rails, the solution is inefficient. In the system in Figure 3, the switching converter is 90% efficient, while the LDO regulator is 66% efficient, resulting in an overall efficiency of ~59%.

Design Challenges for a Postregulating LDO Regulator Without VIOC

The challenge with postregulating LDO regulators is designing a system with maximum efficiency. The low efficiency in Figure 3 suggests a significant power dissipation across the LDO regulator, a result of the large input-to-output differential voltage and load current. Equation 1 shows how to calculate power dissipation across an LDO regulator.

$$P_{DISS} = (V_{IN(LDO)} - V_{OUT(LDO)}) \times I_{LOAD} \quad (1)$$

Using ADI's ultralow noise LDO regulators with VIOC and pairing it with a switching converter increases system efficiency. The VIOC pin influences the switching converter to regulate its output voltage to an optimum level that enhances an LDO regulator's efficiency by decreasing the voltage drop across it.

VIOC Operation

Figure 6 demonstrates the connection of an LDO regulator with VIOC, the LT3041, to an upstream switching converter. The connection between VIOC and the switching converter's feedback (FB) pin ensures the voltage differential across the LDO regulator will be set to the regulated FB pin voltage of the switching converter. By selecting a switching converter with a low FB voltage, typically less than 1 V, the voltage differential across the LDO regulator can be minimized to improve the overall efficiency. In an example using an LT8648S as the upstream converter with a 600 mV FB pin, the LDO regulator will maintain a constant 600 mV drop across itself. Through this connection, the VIOC pin will then influence the output of the switching converter to produce an input voltage signal that satisfies Equation 2.

$$V_{OUT(SWITCHER)} = V_{IN(LDO)} = V_{OUT(LDO)} + V_{VIOC} \quad (2)$$

By setting the voltage differential across the LDO regulator, the VIOC reduces the output voltage of the switching converter and makes the LT3041 a reliable power savings tool.

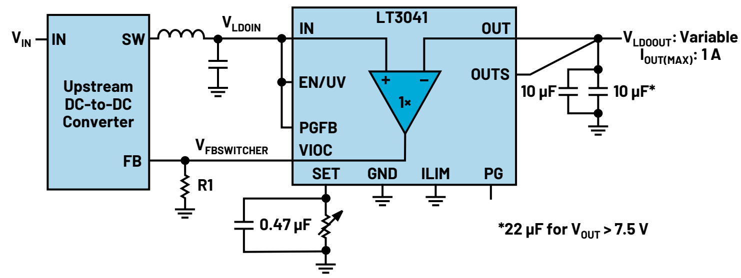

Figure 6. A typical application circuit.

The Benefits of VIOC

Figure 7 shows the postregulating LDO regulator solution used to experimentally demonstrate the impact of VIOC. The evaluation kit of the LT3041 resides downstream of the evaluation kit of ADI's Silent Switcher® 2 technology, the LT8648S. The switching converter features a regulated FB pin value of ~600 mV, thus ensuring a ~600 mV differential across the LDO regulator when the FB pin and VIOC pin are connected. The LT8648S evaluation kit produces a 5 V output voltage and the LT3041 evaluation kit outputs 3.3 V. The following section compares the performance of this system without VIOC and with VIOC. For each experiment, 12 V DC from a power supply, powers the LT8648S. The results of the experiments are shown in Table 1 and Table 2.

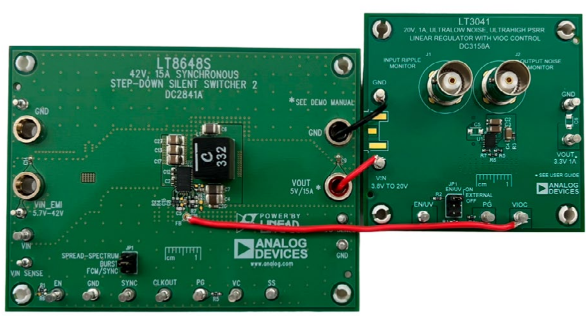

Figure 7. An evaluation board connection.

In the first experiment, with the VIOC pin not connected, the switching converter regulates close to 5 V to power the LDO regulator. The LDO regulator's efficiency shown in Table 1 is ~67%, as expected in Figure 3 since the LDO regulator's main function is postregulating the switching converter's output. While this solution produces clean power rails, it does so inefficiently. As mentioned previously, the inefficiency is caused by the LDO regulator dissipating a significant amount of power due to the voltage differential.

Table 1. LT3041 Postregulating LT8648S Without VIOC

I_{OUT} (A)	V_{IN} LDO (V)	V_{OUT} LDO (V)	VIOC (V)	P_D LDO (mW)	LDO Efficiency
0.1	4.981	3.310	1.667	167	66.4
0.5	4.948	3.308	1.629	815	66.8
1	4.904	3.306	1.577	1577	67.4

In the second experiment, the VIOC connection between the LT8648S and the LT3041 causes the switching supply to regulate its output voltage to $V_{OUT(LDO)} + V_{VIOC}$. When the VIOC pin is connected to the feedback pin, $V_{VIOC} = V_{FB}$ = 600 mV. Since the LT3041 has a V_{OUT} of 3.3 V, the result of the input voltage of the LDO regulator is ~3.9 V. Table 2 shows the produced input voltage of the LDO regulator.

Table 2. The LT3041 Postregulating the LT8648S with VIOC

I_{OUT} (A)	V_{IN} LDO (V)	V_{OUT} LDO (V)	VIOC (V)	P_D LDO (mW)	LDO Efficiency
0.1	3.926	3.309	0.610	61.02	84.3
0.5	3.904	3.308	0.584	291.89	84.7
1	3.901	3.306	0.575	574.70	84.7

The LT3041 with VIOC successfully decreases the voltage differential across the LDO regulator to increase efficiency. Rather than passing a 5 V signal from the switcher, the VIOC pin forces the switching converter to produce ~3.9 V. With the VIOC connection, the LDO regulator drops ~600 mV while the other experiment had a 1.7 V voltage differential. The decreased input voltage of the LDO regulator results in efficiencies of ~84% as shown in Table 2, a 17% efficiency increase, and a 2.7× lower power dissipation, compared to the previous experiment. The two systems have a drastic difference in power dissipation even though they both output the same amount of power. For any given load, an LDO regulator with VIOC will outperform an LDO regulator without VIOC. With VIOC, the system is capable of providing the most ideal voltage for the LDO regulator.

The connection between VIOC and a switching converter's feedback pin does not guarantee the power-saving benefits of VIOC. VIOC can reduce a switching converter's output voltage, but it is not able to increase it. Following the inequality, $V_{OUT(SWITCHER)} > V_{OUT(LDO)} + V_{VIOC}$ ensures that VIOC is saving power. If the inequality mentioned previously is violated, then the LT3041 still regulates its output voltage but it does not optimize the switcher's output voltage.

The following experiment is an example of the system pushing its boundaries to ensure power savings. In this test, the LDO regulator's output voltage is altered to produce a nominal 4.32 V output. From Table 3, $V_{OUT(LDO)} + V_{VIOC}$ does not yet exceed the switching converter's regulated output voltage of 5 V, which allows VIOC to optimize for power savings. Notice the switching regulator is supplying input voltages that satisfy $V_{IN(LDO)} = V_{OUT(LDO)} + V_{VIOC}$. Also, the LDO regulator maintains a ~600 mV drop with VIOC. Without VIOC, the LDO regulator would pass an input voltage of ~5 V. Conversely, Table 4 shows the system without VIOC and a 5 V switching converter output. Notice the input voltage of the LDO regulator is much closer to 5 V than in Table 3. While the efficiency of the LDO regulator with VIOC is better by a small amount, the data in tables 3 and 4 demonstrates that VIOC will reduce power dissipation, even by small amounts.

Table 3. LT3041 Postregulating LT8648S with VIOC

I_{OUT} (A)	V_{IN} LDO (V)	V_{OUT} LDO (V)	VIOC (V)	P_D LDO (mW)	LDO Efficiency
0.1	4.96	4.33	.607	62.2	87.4%
0.5	4.94	4.33	.581	305.2	87.6%
1	4.90	4.33	.561	559.8	88.5%

Table 4. Input Voltages Without VIOC

I_{OUT} (A)	V_{IN} LDO (V)	V_{OUT} LDO (V)	LDO Efficiency
0.1	4.989	4.34	86.9%
0.5	4.987	4.34	87.0%
1	4.982	4.34	87.1%

Some applications with variable load voltages cause $V_{OUT\_LDO} + V_{VIOC}$ to increase past the regulated output voltage of the switching regulator. Consider the LT8648S regulator with a 5 V regulated output and an FB voltage of 600 mV but paired with the LT3041 that now outputs 5 V. When used with VIOC, the combination of parts results in an LDO regulator input voltage of 5.6 V based on the equation $V_{IN(LDO)} = V_{OUT(LDO)} + V_{VIOC}$. This value is much larger than the 5 V output of the switching regulator. This scenario disables the power savings from the LDO regulator.

Power Savings for Variable Loads

In situations with variable loads, VIOC may be programmed with three resistors, as shown in Figure 8. This setup can program the input-to-output differential by setting the resistors R1, R2, and R3. To properly size the three resistors, refer to the LT3041 data sheet. Although this method is not as effective in saving power as connecting VIOC straight to the feedback pin of the switching converter, it is still dependable for applications that have variable loads. By programming the voltage differential to a set voltage, users will be able to take advantage of a constant voltage drop across the LDO regulator despite a variable output voltage. Figure 8 is an example of a scenario of a variable load with and without the resistors.

Consider the block diagram in Figure 9, an LDO regulator that postregulates a switching converter without VIOC. The switching converter produces a 6.5 V output and the LDO regulator produces a 5 V output.

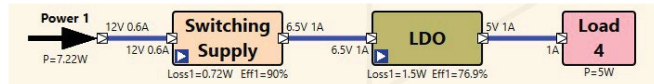

Figure 9. A 5 V LDO regulator output without VIOC.

This system results in a voltage drop of 1.5 V across the LDO regulator and a 1.5 W power loss. Since the load is variable, the output voltage of the LDO regulator changes. In this example, the output voltage of the LDO regulator decreases to 3.3 V, as shown in Figure 10.

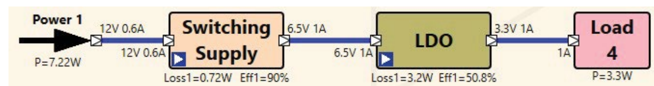

Figure 10. A 3.3 V output without VIOC.

The new 3.3 V load results in a 3.2 V drop across the LDO regulator, a 3.2 W loss in power, and a reduction in LDO regulator efficiency from 79.9% to 50.8%.

In contrast, setting the resistors shown in Figure 8 eliminates the fluctuations in power dissipation and efficiency when under a variable load. Consider the previous scenario in Figure 10 but instead with the LDO regulator utilizing VIOC and the three resistors setting the voltage differential set to 1.5 V. The switching converter will output $V_{OUT(SWITCHER)} = V_{DIFFERNTIAL(LDO)} + V_{OUT(LDO)}$. When a variable load causes the output voltage to drop from 5 V to 3.3 V, the switching converter output voltage decreases to 4.8 V, instead of its programmed 6.5 V output, as shown in Figure 11.

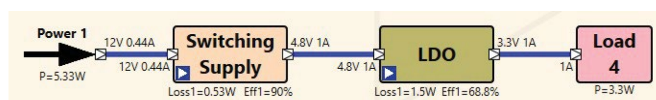

Figure 11. A 3.3 V output with VIOC.

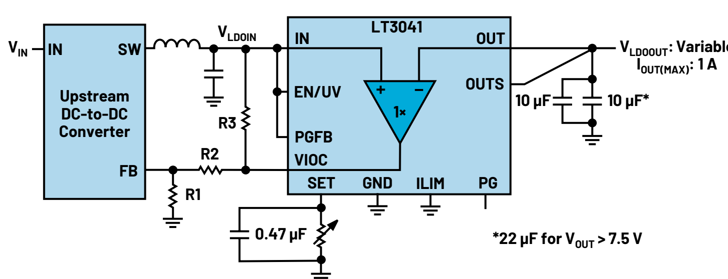

Figure 8. A variable load circuit configuration.

The three resistors program the voltage differential and set a constant 1.5 V drop across the LDO regulator. Instead of a 3.2 W loss in power, the LDO regulator loses 1.5 W of power for a 1 A load. With VIOC and the three resistors, the LDO regulator saves more than double the power when the load voltage drops to 3.3 V. The connection resulted in an efficiency of 68.8% for a 3.3 V load, while the previous scenario resulted in 50.8% efficiency for the same load. While these two systems deliver the same amount of power, the LDO regulator with VIOC supplies power much more efficiently.

Conclusion

Overall, an LDO regulator with VIOC outperforms an LDO regulator without VIOC. ADI's ultralow noise LDO regulators with VIOC provide an elegant balance of efficiency and quality output signals. The combination of VIOC and an LDO regulator's PSRR makes the LT3041 a dual-purpose tool that handles noisy inputs and optimizes a system's efficiency. The VIOC pin adjusts automatically to optimize a system when the load is variable. In all conditions, the LDO regulator with VIOC proves to be superior. It also increased efficiency and decreased power dissipation. The major difference between an LDO regulator with VIOC and an LDO regulator without VIOC is the control VIOC introduces. The automated control allows for an LDO regulator to make on-the-fly adjustments to an upstream DC-to-DC converter that result in the best possible efficiency. The automated control pushes ADI's technology toward the trend of telemetry in power circuits. With the growing use of PMBus® and other methods of gathering data to improve power systems, VIOC provides another layer of automated power control.

About the Author

Kristian Cruz was part of ADI's New College Graduate Rotation Program. Kristian has spent time in Central Applications supporting customers' technical inquiries and has also spent time working in the Power Business Unit. He is now an applications engineer for the Bay Area Sales Organization. Kristian holds a Bachelor of Science degree in electrical engineering from California Polytechnic State University, San Luis Obispo.