

# ***Output Noise Filtering for DC/DC Power Modules***

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## **ABSTRACT**

A key concern in power management design is implementing the right techniques to filter electromagnetic interference (EMI) and reduce output noise. A switching buck regulator inherently passes noise through to the output. This noise can be seen as the low frequency output ripple (LF ripple) and high frequency output noise (HF noise). A small and effective solution for filtering ripple and noise can be achieved by using a power module with a post-filter. This application report provides a comparative analysis between an LDO and a second stage LC filter to minimize the output of the LMZM33606 power module.

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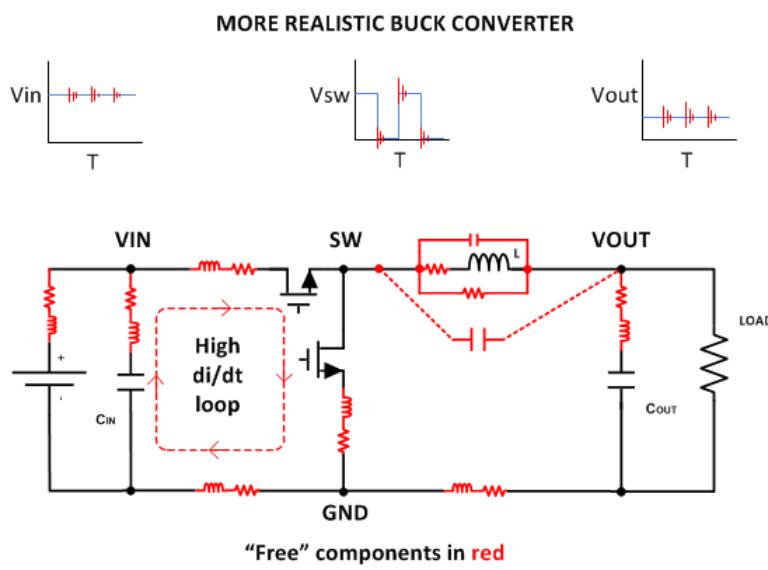
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## 1 Introduction

### 1.1 Parasitic Elements in a Common Buck Switching Regulator

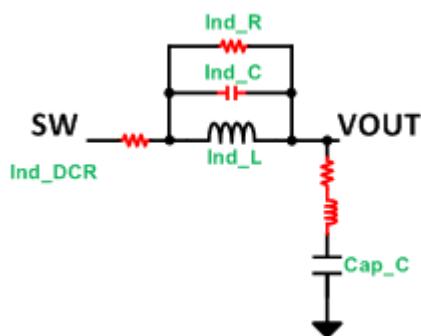
A switching buck regulator is a step-down power converter that takes a higher input voltage and drops it down to a lower regulated output voltage. Many input sources inherently have some amount of noise that pollutes the power path of the power module. As the HIGH-side MOSFET and LOW-side MOSFET alternate in switching, noise from the input source and the parasitic inductance in the high di/dt loop appears on the switch node. The noise can be coupled and propagated onto the output voltage through the parasitic capacitance associated with the package, inductor, and PCB layout as shown in [Figure 1](#). This noise appears as high frequency noise in the megahertz (MHz) range.



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**Figure 1. Realistic Buck Converter With Parasitic Elements**

A parasitic element can come in the form of resistance, inductance, or capacitance. For example, a capacitor has a nominal capacitance but also comes with unwanted electrical elements of equivalent series resistance (ESR) and equivalent series inductance (ESL). Wire-wound inductors have some DCR and parasitic capacitance that is formed from the individual turns of the winding. This is further illustrated in [Figure 2](#).



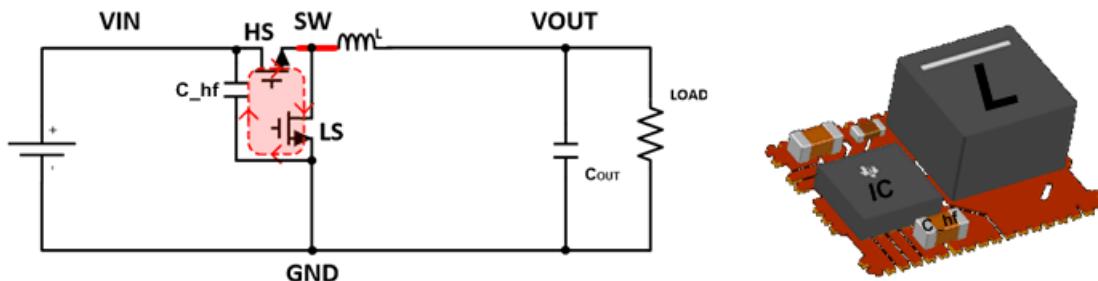
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**Figure 2. Free Parasitic Elements In Common Components**

Normally with a 20 MHz bandwidth limited oscilloscope, only the output voltage ripple is measured. However applications that are more sensitive to high frequency noise require tests and measurements done with a wider ranged oscilloscope bandwidth and must be re-evaluated with this new understanding of unwanted free parasitic elements.

## 1.2 Power Module Advantage

Most power modules integrate the high frequency input capacitor and shielded inductor. This reduces the high  $di/dt$  loop area and provides a compact solution size. As a result, there is less ringing and lower noise coupling to the output by simply using a power module in a design. Although reduced, there is still some parasitic elements present in the power module.

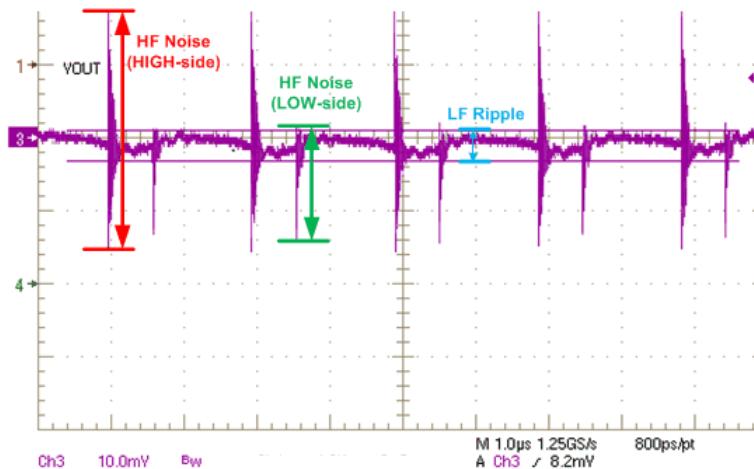


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**Figure 3. Power Module with Improved High  $di/dt$  Loop Area**

## 2 Noise Contributions

**Figure 4** shows an AC coupled output voltage measurement. In this image, the three noise elements that couple onto the output voltage are the HIGH-side HF noise, LOW-side HF noise, and LF ripple.



**Figure 4. HF Noise and LF Ripple on the Output of a Buck**

### 2.1 Low Frequency Ripple

The LF ripple is a byproduct of the inductor ripple current and output capacitor(s) impedance. Inductor ripple current can be lowered by either increasing the switching frequency or increasing the inductance. Capacitor impedance can be lowered by choosing lower ESR/ESL capacitors or by cascading multiple capacitors in parallel. Alternatively, a second stage filter or low dropout regulator (LDO) can be used to attenuate the LF ripple. Note that by attenuating the low frequency ripple, the high frequency noise can also be reduced.

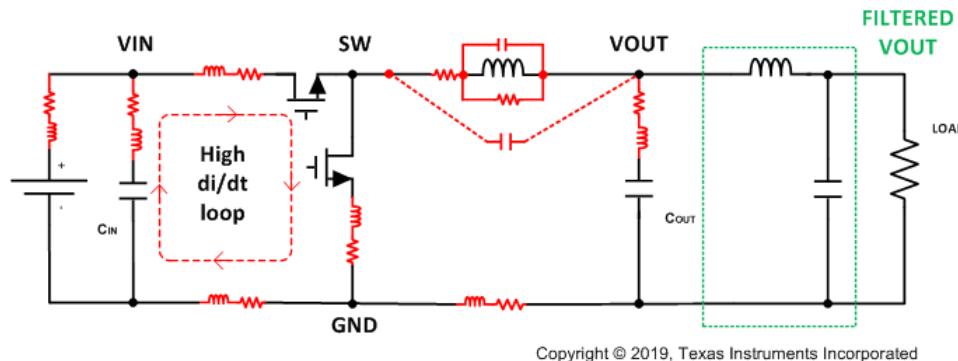
### 2.2 High Frequency Noise

Most problems that designers experience when designing with power supplies are related to noise coupling from the parasitic components in the design. The first thing to look at when optimizing for a low noise design is the reduction of the high di/dt loop formed by the input capacitor and the power MOSFETs. The input capacitor placement affects the output noise. Placing the input capacitors close to the input and GND pin of the DC/DC converter reduces the inductance of the loop which lowers the ringing on the switch node and results in an overall reduction in output noise. Unfortunately, there is still some "stray" noise from the input that couples onto the output. Additionally, as the part is switching the HIGH-side and LOW-side MOSFETs, high frequency noise can pollute the output voltage. Using an external post-filter (eg. LDO, LC filter) helps attenuate the output voltage noise for any low noise application.

### 3 Filtering Design and Implementation

#### 3.1 LC Filter

Certain applications, such as test and measurement, are sensitive to output voltage ripple and routinely require low output voltage ripple. Designing a second stage filter starts with first understanding what noise needs to be attenuated. The [Design a Second-stage Filter for Sensitive Applications page](#) on the TI E2E Community forum provides guidance for the LC filter design. Figure 5 shows a typical schematic of a second stage LC filter used to attenuate the output voltage noise of a buck regulator.



**Figure 5. Second Stage LC Filtering Connection**

Placing an output filter in the output path result in a voltage drop across the inductor due to the parasitic DCR and load current. With high load currents, the output voltage begins to droop below the expected regulated output voltage. For applications with strict load regulation requirements, placing the LC filter inside the feedback loop helps mitigate these losses since it allows the sense loop to compensate for the resistive drop.

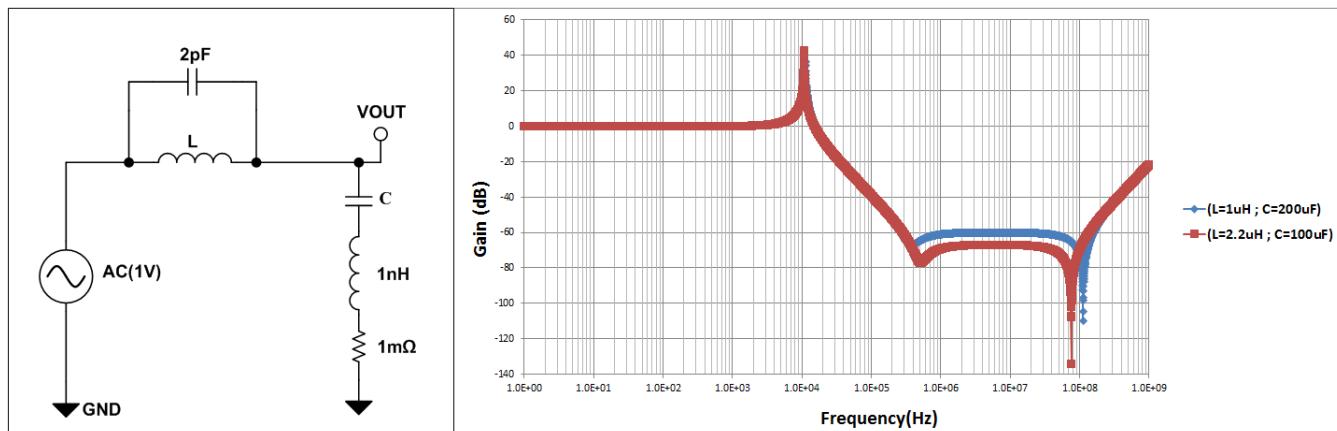
However, this impacts the control-to-output transfer function and may cause instability in the form of oscillations coming from the resonant frequency of the LC filter. To compensate for stability issues, the addition of a damping resistor in parallel to the LC inductor helps provide dampening of these resonant oscillations. A typical value for the damping resistor is somewhere within the range of 100 mΩ – 500 mΩ. It is critical that engineers take extra precaution when modifying the feedback loop as this can result in unstable design.

When talking about LC filters, it is also important to understand the self resonant frequency (SRF) spec. This is the point when an inductor stops behaving like an inductor and instead behaves like a capacitor. For frequencies after this point, the inductor slowly has less AC blocking capabilities and noise may be able to pass through to the downstream circuit. The higher the SRF rating of the inductor, the better the inductor is at filtering high frequency noise.

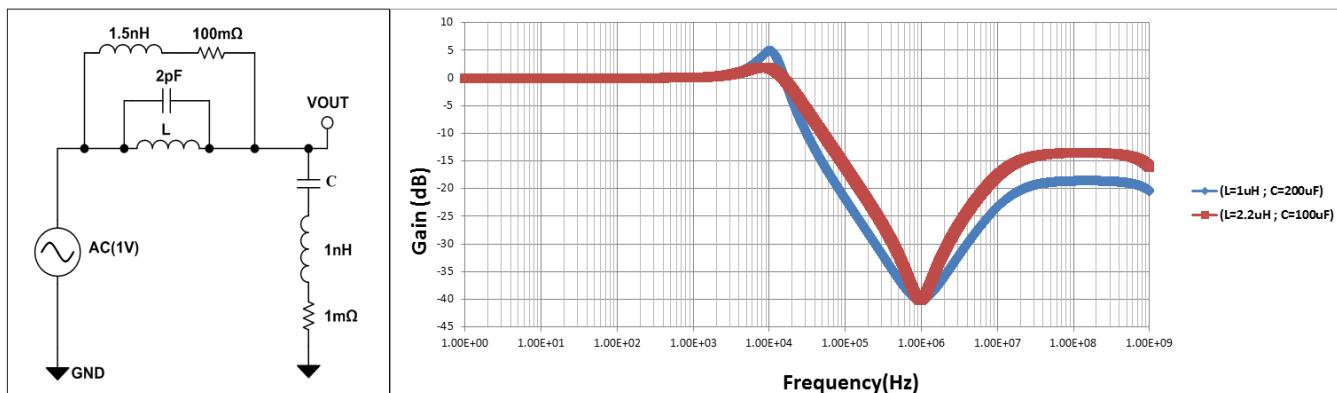
Using a SPICE simulation, 1 μH/200 μF LC filter is compared to a 2.2 μH/100 μF LC filter. The inductor case size is kept fixed to demonstrate the effects of the SRF of the inductor on the overall noise attenuation. Parasitic elements are taken into consideration and kept constant for both variations of the LC filters (eg. LC filter with and without damping resistor).

Part Number	Inductance (uH)	DCR (mOhms)	SRF (MHz)
XAL5030-102ME	1	8.5	68
XAL5030-222ME	2.2	13.2	38

**Figure 6. Inductor Typical Value Specs**



**Figure 7. SPICE LC Filter Frequency Response Comparison**



**Figure 8. SPICE LC Filter With Rdamp Frequency Response Comparison**

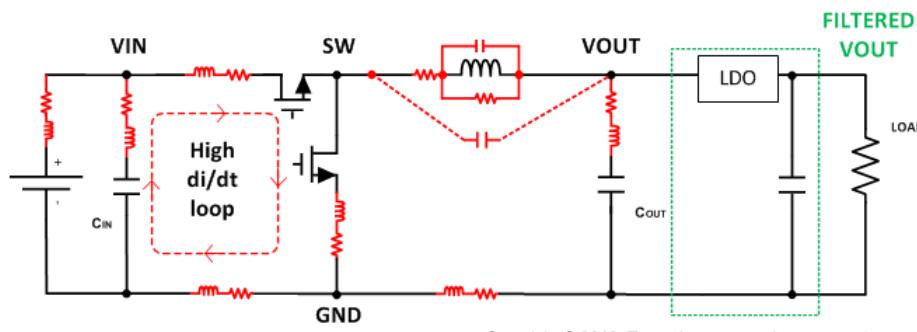
Above is the frequency response of the 1  $\mu$ H/200  $\mu$ F and the 2.2  $\mu$ H/100  $\mu$ F LC filters. The simulation data illustrates the idea that higher SRF rated inductors is better at mitigating noise at high frequencies.

Between the two LC filters, for designers that care about noise attenuation, the 1  $\mu$ H/200  $\mu$ F LC filter may be the obvious choice. Note that in this case, picking the better SRF value of the two inductors requires a larger amount of output capacitance. Engineers with PCB design space constraints must take this into consideration when designing a second stage LC filter.

Both LC filters create a frequency cutoff around 10 kHz. Low frequency noise in the frequency range below this cutoff frequency can be amplified and pass through the LC filter. This issue is present for applications that implement power savings mode (PSM) such as battery powered applications. In power savings mode, the frequency of the switching regulator folds back as load current decreases. As a result, the LDO used as a post filter may be the better alternative for applications that desire PSM operation.

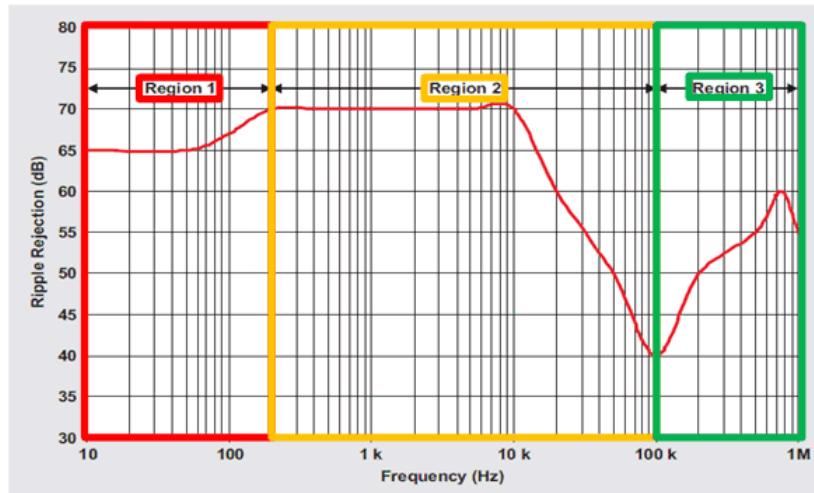
### 3.2 LDO Filtering

LDOs can be used to filter out ripple from a switching regulator. When looking for an LDO to filter noise, the key specification to look for is the power supply ripple rejection ratio (PSRR). PSRR is the measurement of the output ripple compared to the input ripple. The higher the PSRR, the better the LDO is for rejecting input ripple. Figure 9 is an illustration of the buck converter and LDO connection. Note that the LDO needs some input bypass capacitor and output capacitor to properly function.



**Figure 9. LDO Filtering**

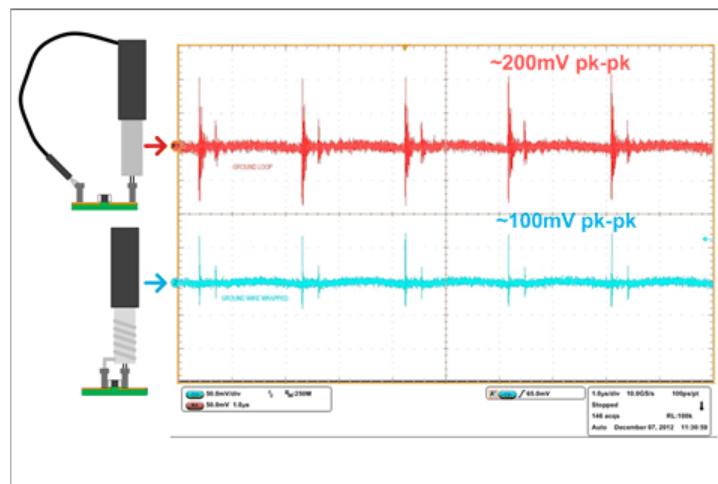
The PSRR characteristics of the LDO can be divided into different regions. The first region depends on the internal reference and internal filtering of the LDO. The second region depends on the open loop gain of the LDO error amplifier. Lastly, the third region depends on the total parasitic elements and output capacitance of the LDO. Larger amounts of output capacitors allow more noise to be shunted to the system return path and result in an overall lowering of the output noise.



**Figure 10. Different Regions of a LDO PSRR Plot**

### 3.3 Proper Measurement Technique

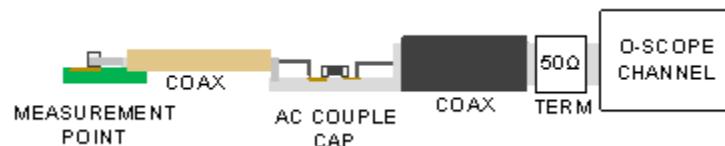
It is important to understand the real output noise of the system before considering the use of post filtering. The placement of the probes and ground connection is critical for a proper output noise measurement. [Figure 11](#) shows the difference between an improper and proper measurement technique.



**Figure 11. Improper vs Proper Measurement Technique Comparison**

Improper measurement techniques can exaggerate the output noise and result in an overly conservative filter design which may not necessarily be required. The extra long ground loop formed from the alligator clip in the improper measurement can act like an antenna and pollute the actual output ripple measurements with externally coupled noise. Reducing the ground lead by implementing the pigtail ground connection results in a proper and more accurate output noise measurement.

For best results it is recommended to use a 1X scope probe to properly measure the output voltage ripple in the milli-volts range. The 1X scope probe can be created with an AC coupling capacitor and an external  $50\Omega$  termination resistor. [Figure 12](#) shows a typical 1X scope probe setup for measuring output voltage ripple.

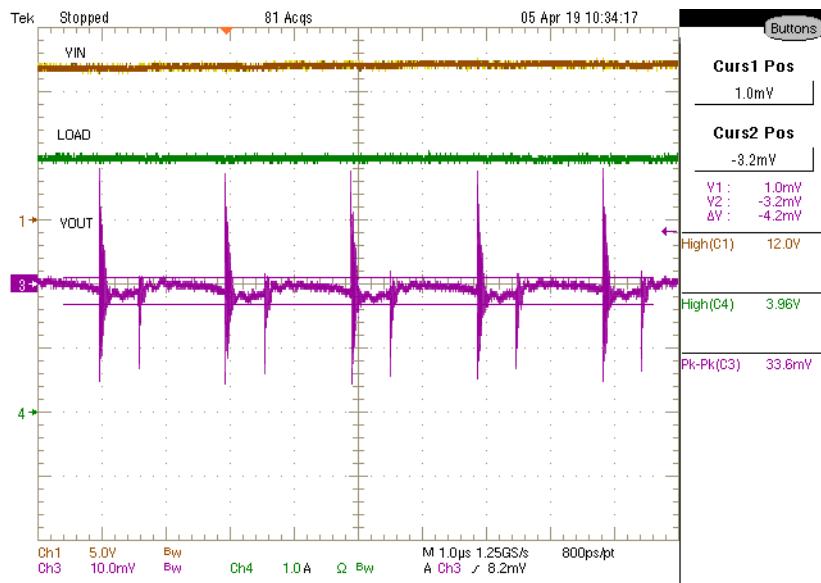


**Figure 12. 1X Scope Probe Connection**

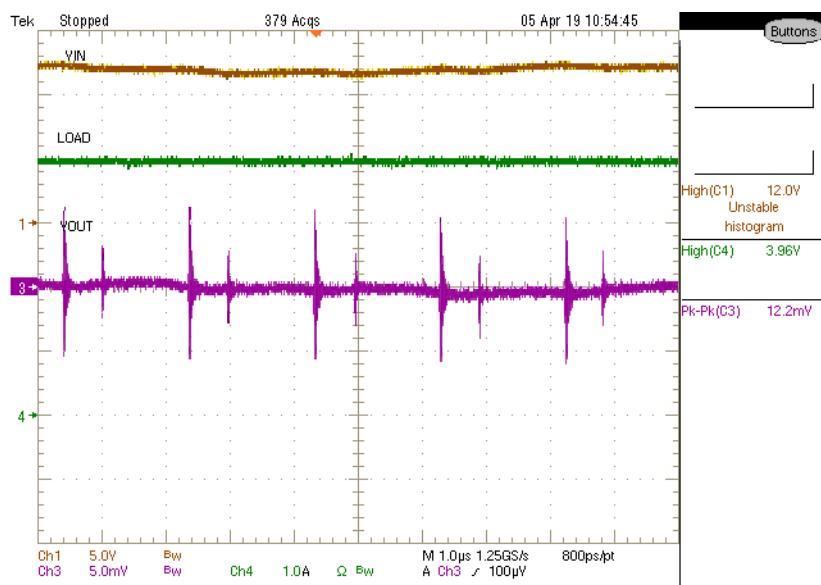
## 4 LC Filter and LDO Data Results

### 4.1 Time Domain

In this experiment, the LDO (TPS7A85) was compared to the "LC Filter 1" ( $1\text{ }\mu\text{H}/300\text{ }\mu\text{F}$ ) and "LC Filter 2" ( $2.2\text{ }\mu\text{H}/150\text{ }\mu\text{F}$ ). All time domain LC filter measurements were taken using the better LC filter ( $1\text{ }\mu\text{H}/300\text{ }\mu\text{F}$ ) of the two. The initial conditions were fixed to the following values:  $\text{VIN}=12\text{ V}$ ,  $\text{VOUT}=3.3\text{ V}$ ,  $\text{IOUT}=4\text{ A}$ . The capacitance of the bench-tested LC filters was slightly increased from the simulation capacitor values in consideration for the derating at  $3.3\text{ V}$  output. Figure 13 shows the bench and EMI measurements of the LDO and LC filters.



**Figure 13. LMZM33606EVM Output Voltage**



**Figure 14. LMZM33606EVM with LC Filter 1 (Output Voltage)**

Compared to the  $33.6\text{ mV}$  of HF noise from the default LMZM33606EVM, the LC Filter 1 was able to attenuate the noise down to  $12.2\text{ mV}$ . This effectively results in an attenuation of roughly  $9\text{ dB}$ . The LF ripple has been significantly reduced from the base default EVM measurements.

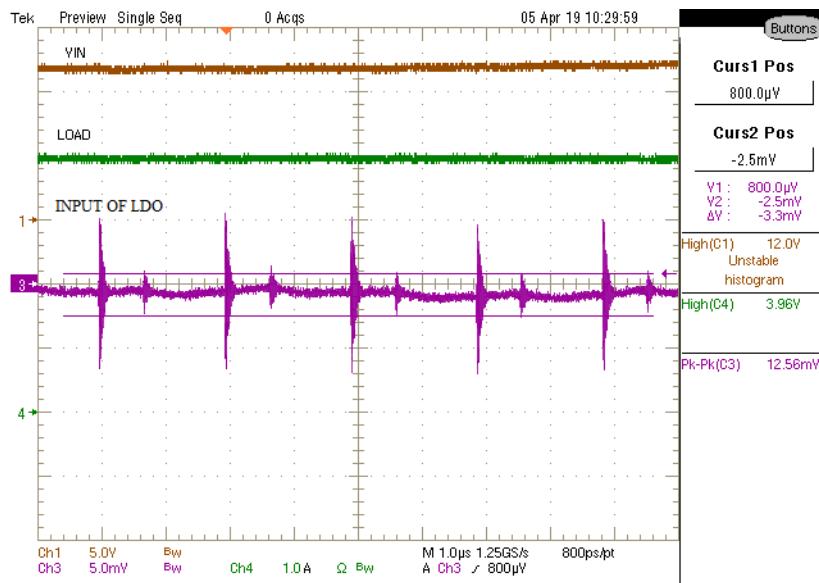


Figure 15. LMZM33606EVM with LDO (Input Voltage)

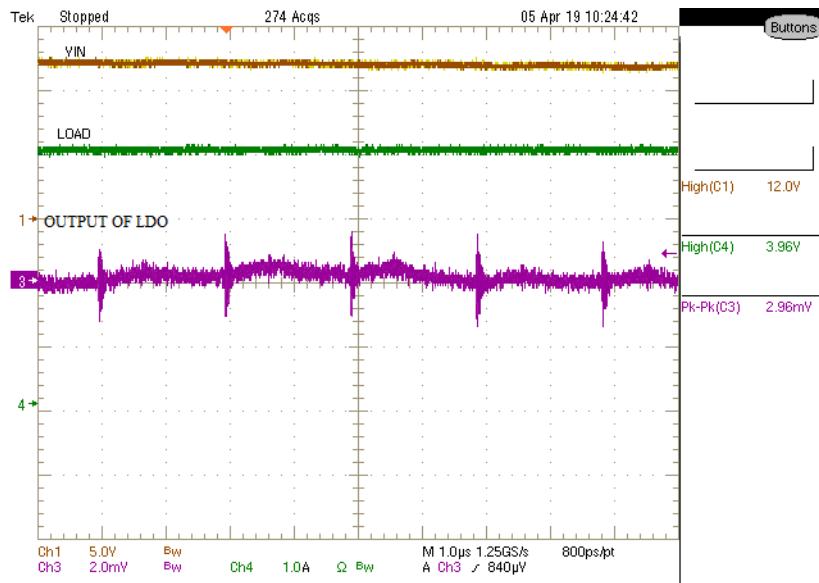
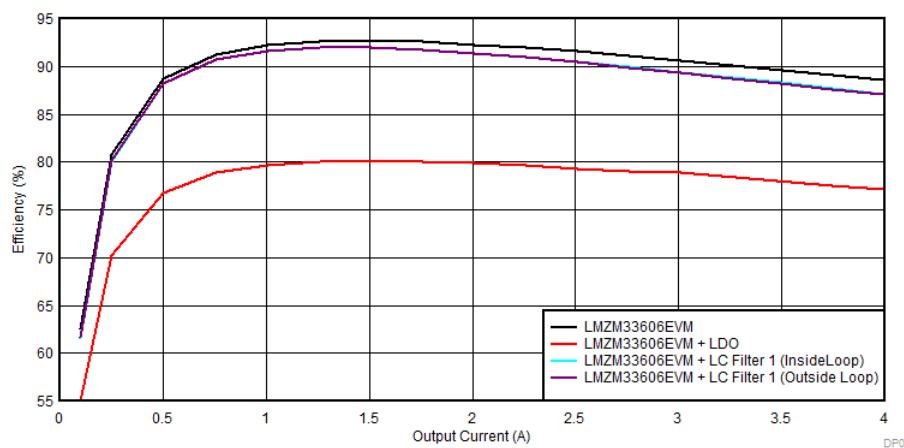


Figure 16. LMZM33606EVM With LDO (Output Voltage)

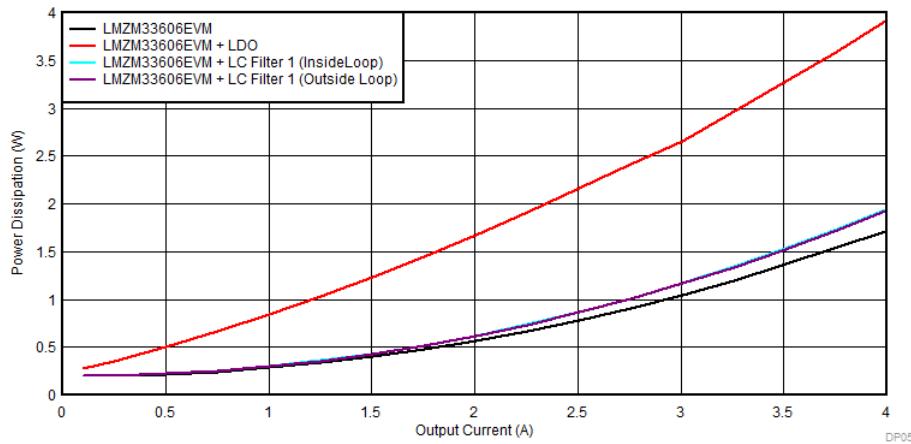
Note that the LDO and LMZM33606EVM are not on the same board. The output of the LMZM33606EVM was connected to the input of the LDO through twisted pair wires that were approximately three inches in length. This small inductance creates another small LC filter together with the input capacitance (39  $\mu$ F//4.7  $\mu$ F//4.7  $\mu$ F) of the LDO circuit. This provides initial filtering of the switcher output noise. See [Figure 13](#) versus [Figure 15](#).

It is good practice to place the LDO closer to the load in an actual application. Placing the LDO closer to the load allows a better regulated output and better noise mitigation.

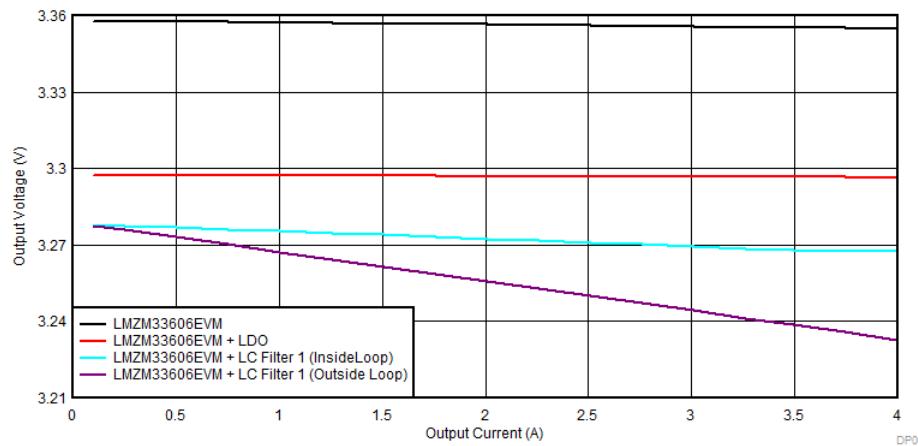
To understand the noise attenuation performance of the LDO, the input ripple to the LDO is compared to the output ripple. In this case, the LDO circuit (LMZM33606EVM with LDO) provides HF noise attenuation of roughly 12 dB (measured between input voltage of LDO to output voltage of LDO). The total HF noise attenuation measured between output of LMZM33606EVM and output of the LDO is roughly 21 dB.



**Figure 17. Efficiency Comparison Between Different Output Filter Techniques**

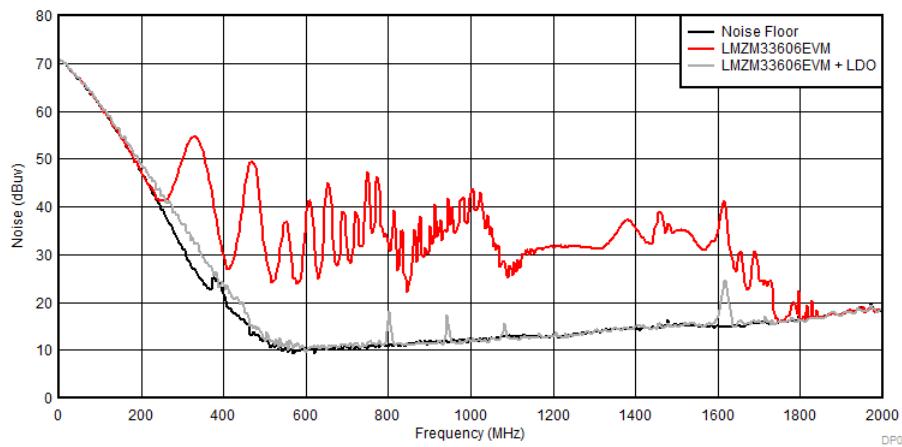


**Figure 18. Power Dissipation Comparison Between Different Output Filter Techniques**

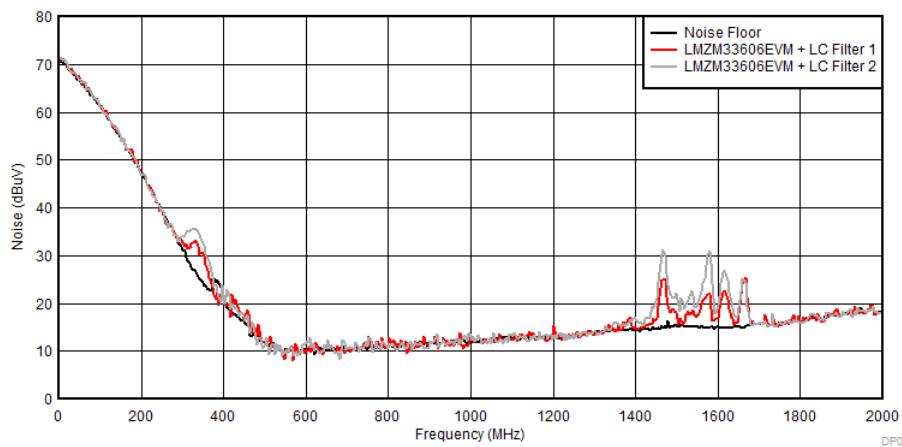


**Figure 19. Output Voltage Regulation Comparison Between Different Filter Techniques**

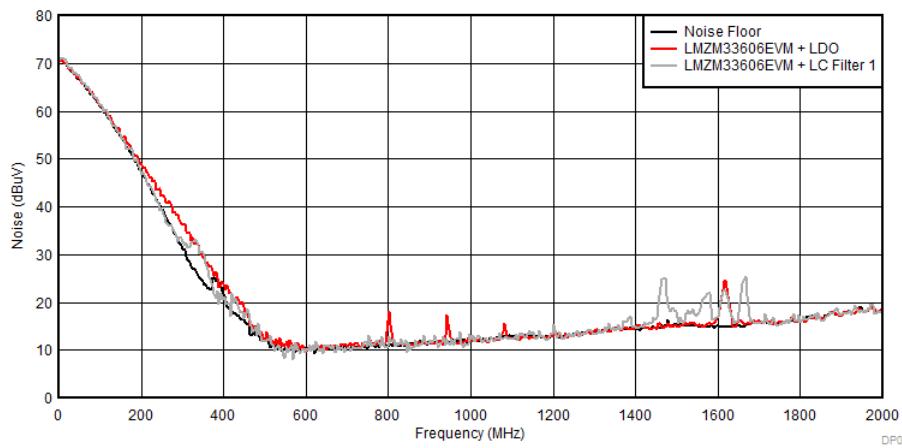
## 4.2 Frequency Domain



**Figure 20. LMZM33606EVM vs LDO Conducted Noise Measurements**



**Figure 21. LC Filters Conducted Noise Measurements**



**Figure 22. LDO vs LC Filter Conducted Noise Measurements**

## 5 Key Takeaways and Considerations

### 5.1 Second Stage LC Filter

A second stage LC filter can help reduce both LF ripple and HF switching noise. If the LC filter is inside the feedback loop, regulation penalties are completely avoided. It is important to restate that care must be taken when modifying the feedback loop of the switching regulator to ensure stability. For applications that require light-load power savings mode, the LC filter needs to be adjusted for the appropriate frequency fold-back. This filtering option requires more design validation and engineering involvement to account for parasitic elements and stability but can offer a lower BOM count with almost no additional power loss compared to the LDO.

### 5.2 LDO

LDO can be a straight-forward solution for filtering both LF ripple and HF switching noise. The LDO inherently performs better at filtering low frequency ripple. This filtering option requires little design validation but has many trade-offs. One clear trade-off is power dissipation or overall efficiency. Since the LDO requires some headroom to regulate the output voltage, the expected additional power dissipation compared to a default DC/DC switcher is the headroom voltage multiplied by the load current. Another trade-off is the solution size since the LDO could require additional components such as feedback resistors and reference filter capacitors.

## 6 Conclusion

Every switching converter output inherently has high frequency noise and low frequency ripple. The use of a low noise output filter can be required for noise sensitive applications and systems. In terms of design the LDO is relatively straight-forward and can be used in applications that require power savings mode. The LC-filter provides an adequate enough noise attenuation within a compact solution size. Additionally the [EMI Mitigation Techniques Using the LMZM23601 Application Report](#) details different PCB layout design techniques to help further reduce output noise.

## 7 References

1. Texas Instruments, [\*Using a High-frequency Switching Regulator Without a Linear Regulator to Power a Data-converter System Technical Brief\*](#)
2. TI Training, [\*You Think LDOs are Simple?\*](#)
3. [\*When Inductors Self Resonate\*](#)
4. T. John, "[\*Understanding Power Supply Ripple Rejection in Linear Regulators Technical Brief\*](#)"
5. [\*Design a Second-stage Filter for Sensitive Applications\*](#)

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