Application Report

SLUA905–June 2018

Operating UCC2888x Offline Buck in Saturation for Cost Reduction

Chen, Wei-Hao — Field Applications Engineer

ABSTRACT

The economical UCC28880 and UCC28881 high voltage switchers are designed for AC/DC offline buck converters in low power applications. The device integrates a 700-V power MOSFET and HV Start-up Current Source that allows the design to operate directly from the rectified mains voltage and minimize excessive external components.

Contents

List of Figures

List of Tables

Trademarks

WEBENCH is a registered trademark of Texas Instruments.
All other trademarks are the property of their respective owners.

1 Introduction

See Figure 1 below for the functional schematic of an offline high-side buck converter using UCC2888x. To make the design more economical, this application report reveals an alternative design approach to drive the output inductor into saturation with a much smaller inductor. By doing this, the cost and physical size of the output inductor can be significantly reduced with minor trade-offs in system efficiency, EMI emissions, and output noises. A set of bench tests had been conducted to validate this design approach and the results are included in this application report. This is recommended for low power non-isolated offline power supplies, but which struggle to meet confined space requirements and low budget constraints. The UCC2888x switcher ideally suited for various industrial, appliance and IoT applications such as:

- Smart Meters
- Home Automation Equipment
- LED Lighting
- White Goods
- Bias Power for MCU, RF, and IoT Enabled Devices

2 Functional Schematic

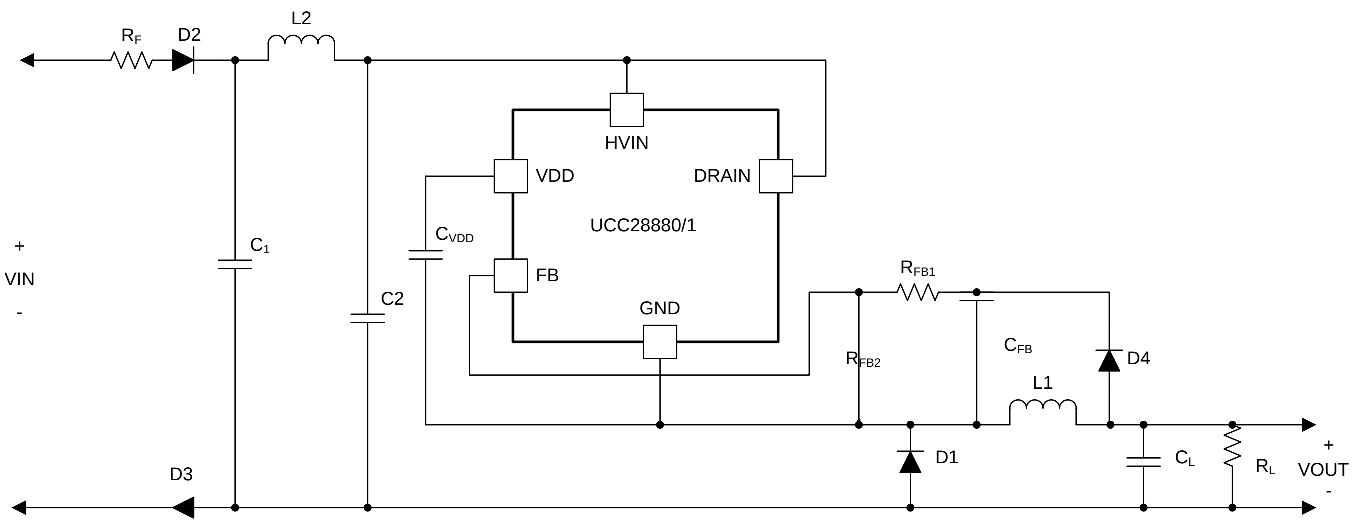

Figure 1. Offline High-Side Buck Converter with On/Off Control

3 Benefits and Trade-offs

The main benefits of driving the output inductor into saturation are cost and board size reductions. The inductor with smaller inductance or lower saturation current rating could be used in this design approach, which may save the cost roughly by 15% - 80%, and PCB size by 20% - 40% for the output inductor, depending on the type of inductor used, manufacturer, distributor and the number of units purchased. Despite all the benefits, there are some minor performance trade-offs such as lower system efficiency and larger EMI emissions for this design approach. The benefits and trade-offs are summarized in Table 1.

Table 1. Benefits and Trade-offs of Driving Output Inductor into Saturation

Benefit	Reason
Overall Board Size Reduction	Inductors with lower inductance or lower Isat rating tend to be smaller in physical size.
Increased Power Density	Reduction in board size increases overall power density.
System BOM Cost Reduction	Smaller or lower Isat rating inductors and smaller size PCBs are less expensive in general.
Smaller Output Ripple	The system switching frequency increases as the effective inductance drops in saturation.
Trade-off	**Reason**
Lower Efficiency	• Larger switching loss: Higher system switching frequency incurs higher switching loss. • Larger conduction loss: Higher RMS current causes more energy to be dissipated through R_{dson} and DCR.
Larger ESL Voltage Spike	A higher leading-edge voltage spike is generated due to larger diL/dt through ESL of the output capacitor when the inductor is saturated.
Thermal Performance	Extra loss in smaller package inductor
EMI	Worse EMI performance due to higher switching frequency and larger ESL spike noise.

4 Output Inductor Selection

In general UCC2888x design guideline, the standard output inductor L1 is selected to meet the following requirements:

1. Inductance large enough to have peak inductor current smaller than ILIMIT for supporting CCM-operation at full load.
2. The inductor saturation current rating higher than the peak inductor current or the maximum current limit $I_{LIMIT(MAX)}$.

In this design approach, the output inductor can be selected to have much lower inductance value and saturation current rating for reducing the cost and size. However, it still has to follow these two rules:

1. An inductor with smaller inductance can be selected, but must keep L1 > L_{MIN} from Equation 1.
2. An inductor with lower saturation current rating can be selected, but must ensure its effective inductance is larger than L_{MIN} when it saturates.

The minimal inductance value can be calculated using Equation 1:

$$L_{MIN} \geq \frac{V_{IN(MAX)} \times \sqrt{2}}{I_{LIMIT(MIN)}} \times T_{ON\_TO} \quad (1)$$

where

- L_{MIN} is the minimal inductance required to avoid current runaway protection
- V_{IN} is the maximum voltage on the DC input.
- $I_{LIMIT(MIN)}$ is the worst case current limit. Use 140 mA for UCC28880; and 315 mA for UCC28881.
- T_{ON_TO} is the Inductor Current Runaway Protection time threshold, which has a typical value of 450 ns.

Otherwise if the selected inductance is too small or the effective inductance drops too much due to saturation, the inductor current could reach the current limit I_{LIMIT} in a very short duration of time (< T_{ON_TO}) due to high di_L/dt in saturation. This will unintentionally trigger the Current Runaway Protection and limit the output power capability of the design.

The Inductor Runaway Protection is originally designed to prevent the loss of control of the inductor current from overload conditions, including a short circuit at the output. Under fault conditions, inductor current I_L would increase from the pre-existing high value because the demagnetization is slow. To prevent I_L rising too high, the current runaway protection will be triggered if the I_L reaches the current-limit I_{LIMIT} before the MOSFET minimum on-time t_{ON_TO}. The UCC2888x device progressively extends MOSFET off-time t_{OFF} cycle-by-cycle to reduce the I_L until $t_{ON} > t_{ON\_TO}$ as Figure 2 illustrated below. Consequently, the output power is reduced and the converter fails to supply the full power to the load.

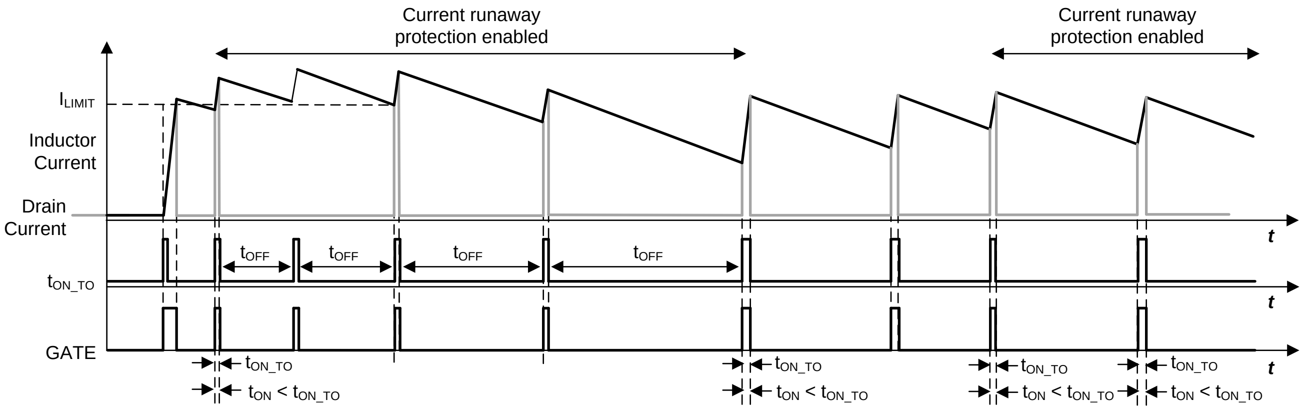

Figure 2. Current Runaway Protection Extends t_{OFF} Cycle-By-Cycle to Reduce Inductor Current

5 System Level and Performance Comparison

To prove the viability of driving the output inductor into saturation for the cost and board size reduction, a 560 µH inductor with 300 mA I_{sat} rating was tested on the UCC28881EVM-680 to compare the cost and size benefits and performance trade-offs against the standard 1 mH inductor on the EVM. The results are summarized below.

Table 2. System and Performance (1)(2)

Inductor	Saturating Inductor	Standard Inductor
Inductance	560 µH	1 mH
I_{sat}	300 mA	600 mA
Inductor Size (mm)	7.30 (W) x 7.30 (L) x 4.5 (H)	Ø 11.0 x 11.5 (H)
	(78% smaller in volume ; 44% smaller in area)	
Relative Cost Scale	**0.216**	1
Peak I_L (3)	804 mA	424 mA
Max. Efficiency (4)	75.91% (230 VAC)	80.66% (230 VAC)
	78.70% (115 VAC)	80.14%(115 VAC)
Output Ripple(3)	**± 8.4 mV (No load)**	± 13.4 mV (No load)
	± 6.1 mV (Full load)	± 7.6 mV (Full load)
ESL Spike on top of V_{out} (3)	34.8 mV	16.6 mV
EMI Performance	CISPR 22 / EN 55022 Class B (5)	CISPR 22 / EN 55022 Class B

(1) All tests were conducted at 25°C room temperature.
(2) The relative cost scale is only for reference purposes and was calculated based on the 1 kU price from online electronics component distributors. The actual price may vary depending on different distributor, manufacturer and the number of units purchased.
(3) The measurements were conducted with 230 VAC input.
(4) The saturating inductor and the UCC28881 IC are slightly hotter than the original EVM design due to the additional losses.
(5) An extra ferrite bead needs to be added before the pi-filter to meet the CISPR 22 and EN 55022 Class B EMI emission requirements, which may raise the cost on EMI filter design by a small portion and reduce the overall cost gain slightly, depending on the EMI requirement.

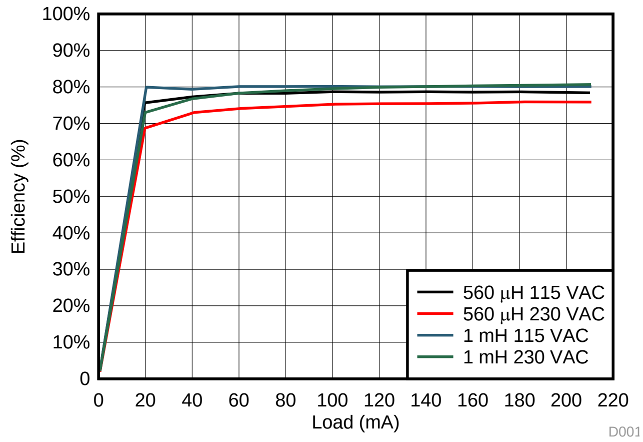

Figure 3. Efficiency Comparison for UCC28881EVM with 560 uH Saturating and 1 mh Standard Inductor

6 Output Ripple and Inductor Current Waveforms

UCC28881EVM Test Waveforms of Output Ripple Voltage, Inductor Current, Load Current.

All measurements were made at 25°C room temperature.

Left column - 560 uH Saturating Inductor

Right column - 1 mH Standard Inductor

Legend

- Dark Blue - Ch2 Inductor Current, I_L
- Purple - Ch3 Output Voltage, V_{OUT}
- Green - Ch4 Output Current, I_{OUT}

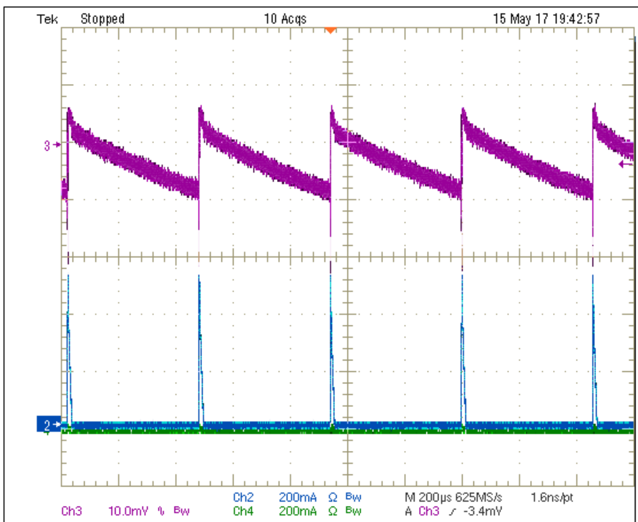

Figure 4. 115 VAC Standby Output Ripple

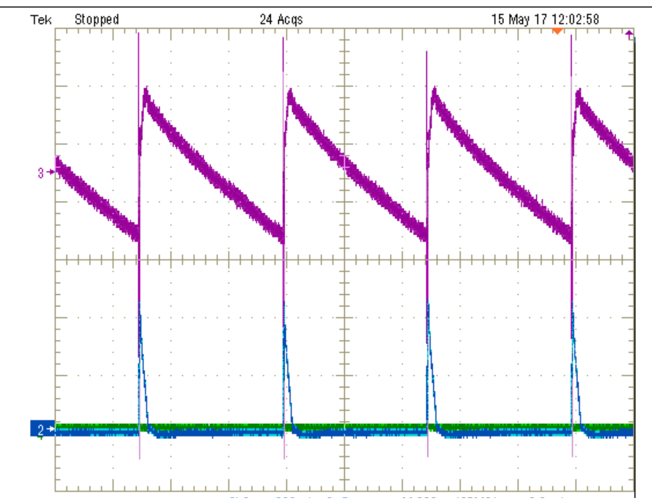

Figure 5. 115 VAC Standby Output Ripple

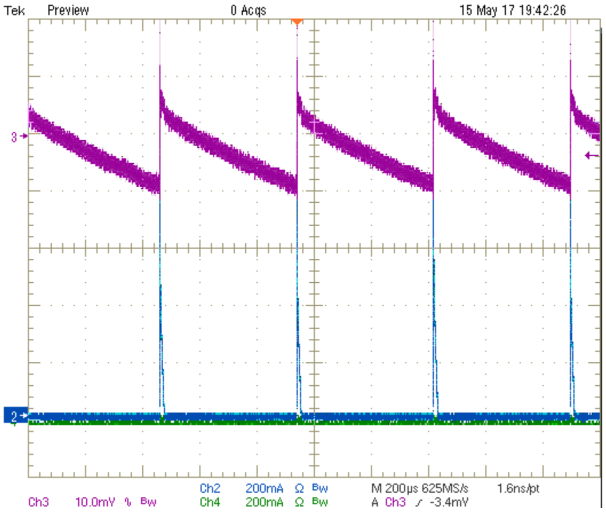

Figure 6. 230 VAC Standby Output Ripple

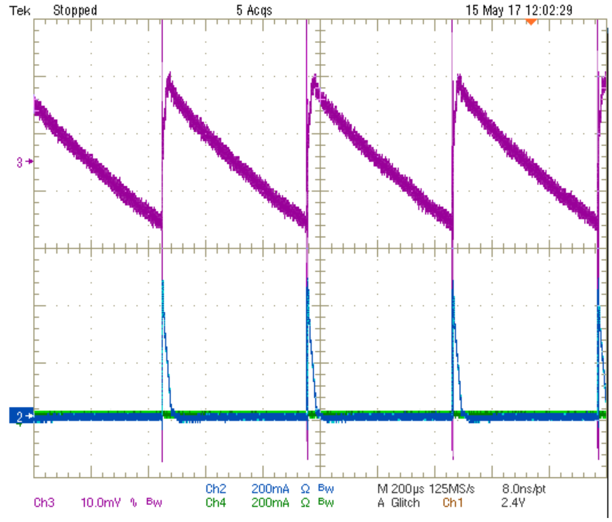

Figure 7. 230 VAC Standby Output Ripple

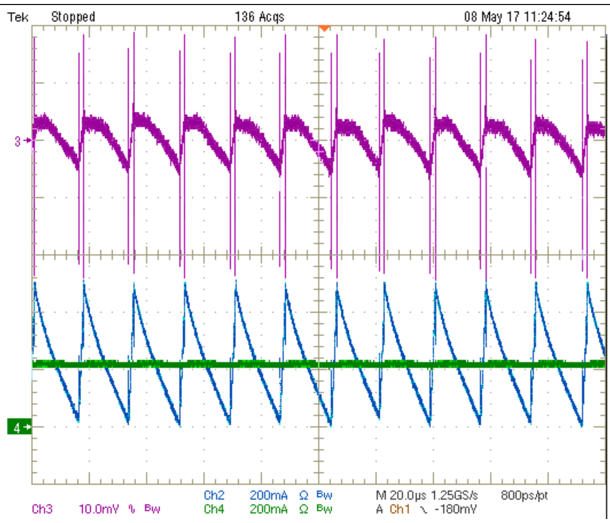

Figure 8. 115 VAC 215 mA Load Output Ripple

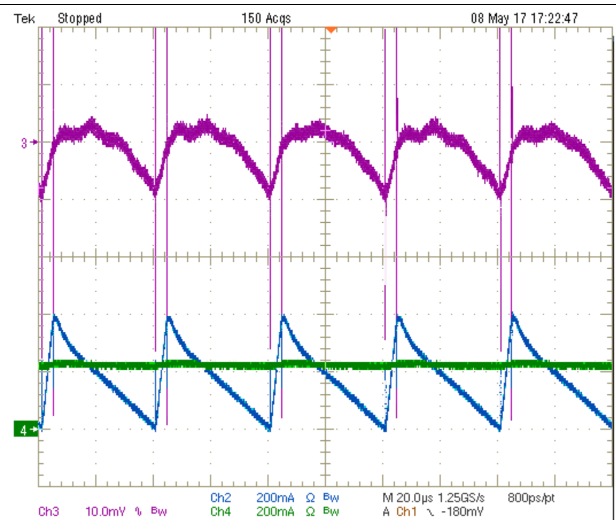

Figure 9. 115 VAC 215 mA Load Output Ripple

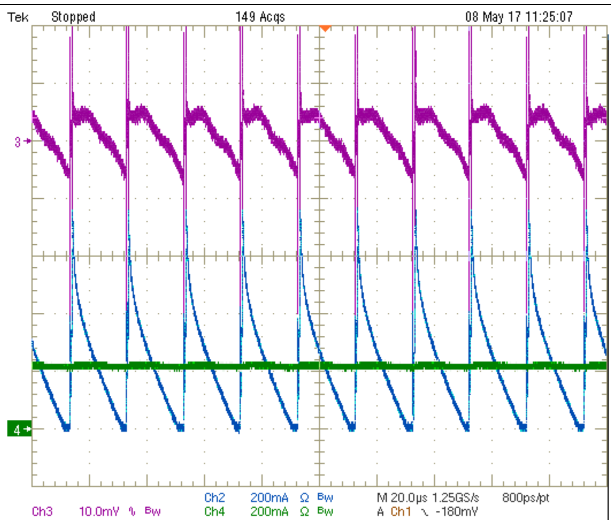

Figure 10. 230 VAC 215 mA Load Output Ripple

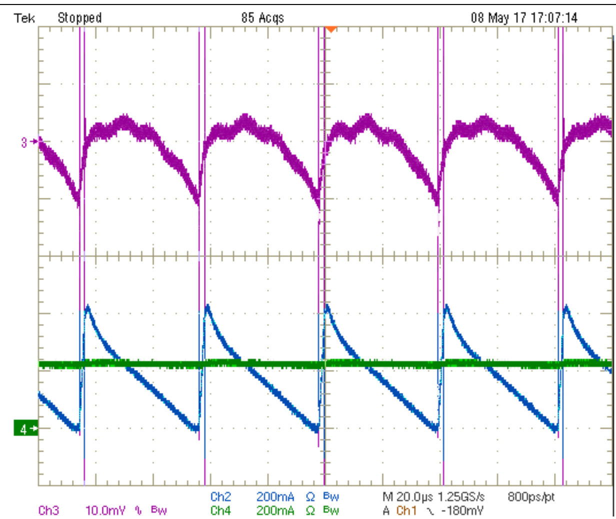

Figure 11. 230 VAC 215 mA Load Output Ripple

7 EMI Performance

Left column - 560 uH Saturating Inductor

Right column - 1 mH Standard Inductor

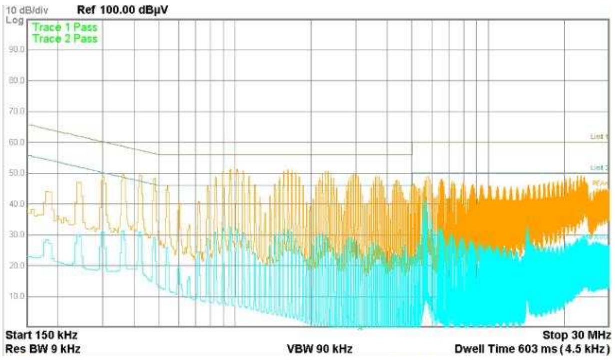

Figure 12. EMI Measurement 115 VAC, 13 V / 215 mA Load, Neutral

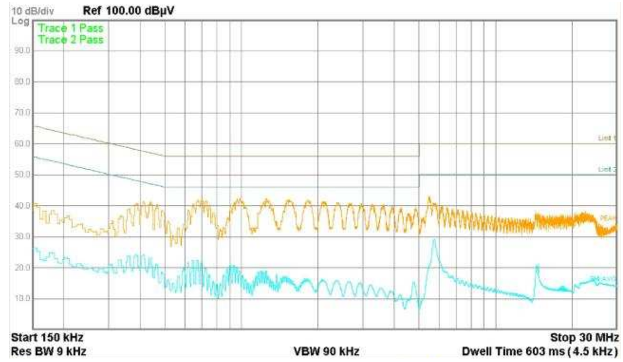

Figure 13. EMI Measurement 115 VAC, 13 V / 215 mA Load, Neutral

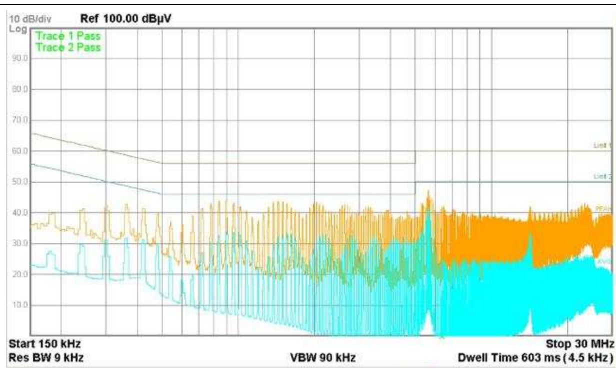

Figure 14. EMI Measurement 115 VAC, 13 V / 215 mA Load, Line

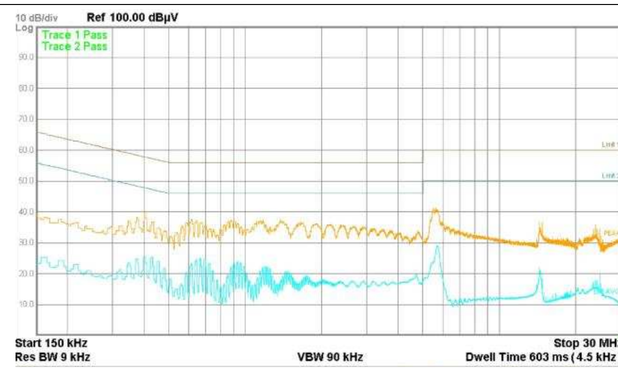

Figure 15. EMI Measurement 115 VAC, 13 V / 215 mA Load, Line

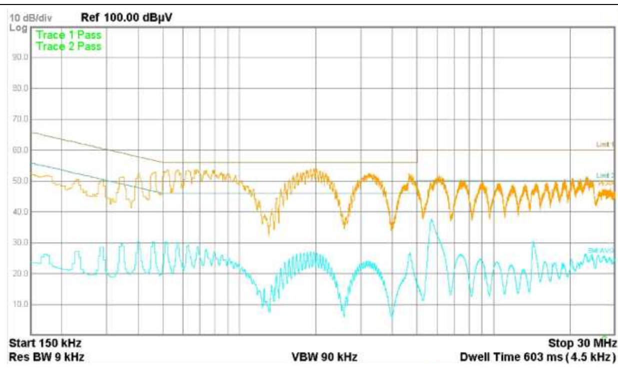

Figure 16. EMI Measurement 230 VAC, 13 V / 215 mA Load, Neutral

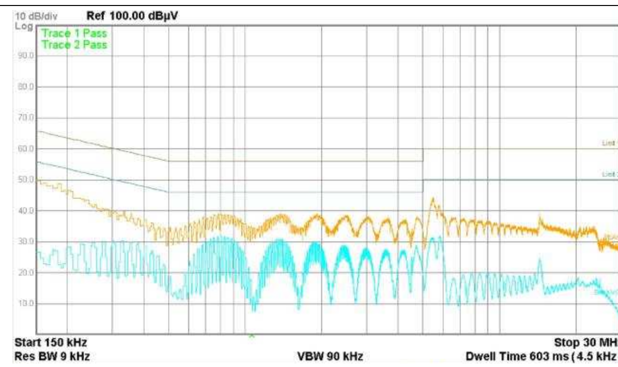

Figure 17. EMI Measurement 230 VAC, 13 V / 215 mA Load, Neutral

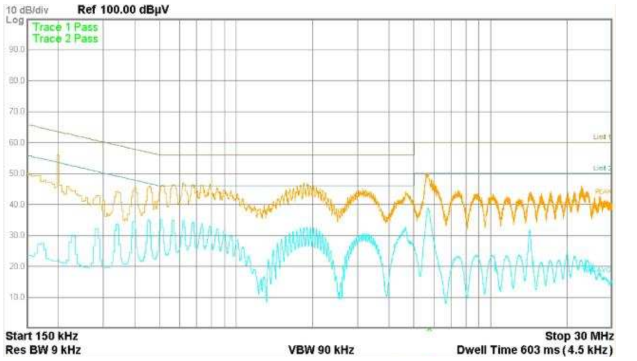

Figure 18. EMI Measurement 230 VAC, 13 V / 215 mA Load, Line

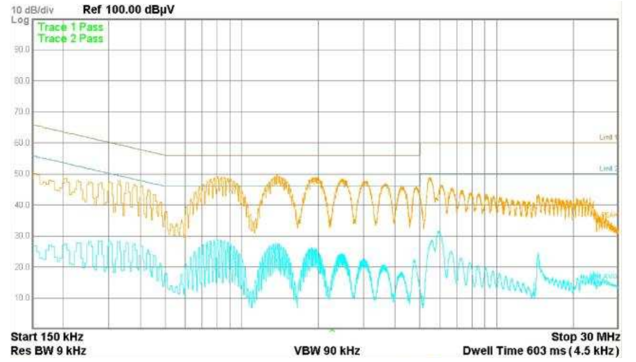

Figure 19. EMI Measurement 230 VAC, 13 V / 215 mA Load, Line

8 Conclusion

Driving the output inductor into saturation for UCC2888x offline buck converter reduces a significant amount of production cost and system board size with minor trade-offs in system efficiency, output noises and EMI emissions. This offers a very cost effective, highly integrated and compact low power AC/DC offline solution ideally suited for many industrial, appliance and IoT applications. Want to achieve high power density at minimal cost while maintaining a good system performance? UCC28880 and UCC28881 Switchers are right in front of your eyes, so why wait?

9 References

- Learn more about UCC2888x Switcher by visiting: http://www.ti.com/product/UCC28880 and http://www.ti.com/product/UCC28881
- Do not miss the training video "How to Modify UCC28880 EVM for Your Custom Design"
- Start the development of your design via WEBENCH® Design Center and get your UCC28881EVM-680 evaluation board today.

IMPORTANT NOTICE AND DISCLAIMER