Application Report
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Power Sharing Between Two Parallel, Four-Switch Buck-Boost Converters

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ABSTRACT

The synchronous 4-switch buck-boost controller LM5176 operates over a wide input voltage range from 4.2 V to 55 V (60 V absolute maximum) to support automotive start-stop system, industrial personal computers (IPCs), and many other applications. It produces a regulated output voltage at, above, or below the input voltage. Paralleling two LM5176 converters is an attractive way to support higher power level.

This application report presents a cost-effective solution to achieve well balanced load sharing between the two paralleled converters within 1% error, without sacrificing the overall performance including the output regulation as well as dynamic response. Design guidelines are given to help readers to design properly for practical applications.

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Trademarks

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1 Introduction

The LM5176 device is a wide input voltage range, four-switch buck-boost controller IC with integrated drivers for N-channel MOSFETs. It operates in the buck mode when V_{IN} is greater than V_{OUT} and in the boost mode when V_{IN} is less than V_{OUT}. When V_{IN} is close to V_{OUT}, the device operates in a proprietary transition buck or boost mode.

One single LM5176 converter can deliver power greater than 200 W with the synchronous MOSFETs. To get higher output power, parallel power stages are needed to solve the excessive board heating problem because of the increased switching and conduction losses. The paralleling method can also provide many other benefits: enhanced modularity, design flexibility, and minimized component ratings. These benefits can be realized only if the two LM5176 converters evenly share the total load power.

This application report presents a power sharing method, which is simple, low cost, and high performance at the same time. With only one OpAmp and few resistors and capacitors, the load sharing can be well balanced. Test results show less than 1% error of sharing without sacrificing the overall performance.

2 Paralleling Method and its Realization

2.1 Why output current difference exists

Figure 1 shows the two parallel LM5176 converters.

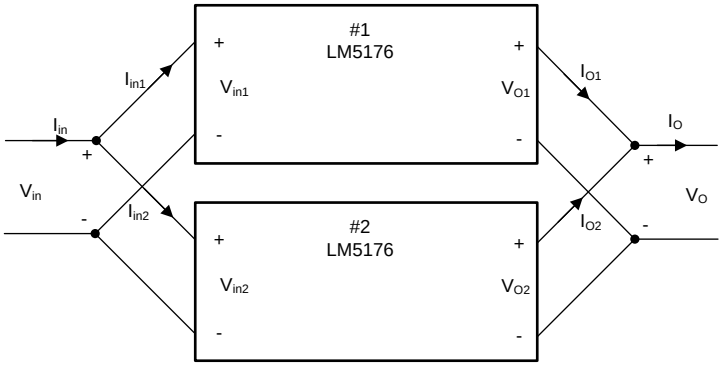

Figure 1. Two Parallel LM5176 Converters as Power Supply

A power supply can be modeled as an ideal voltage source in series with a source resistor shown in Figure 2. Because of regulation tolerance, the two module's output voltages can be slightly different. The output I-V characteristic curves of the two individual converters are shown in Figure 3. $V_{O1}(0)$ and $V_{O2}(0)$ are the two ideal voltage sources at no load and R_{S1}, R_{S2} are the source resistors in series. Figure 3 also explains why there is a big load sharing difference between the two converters if they are simply parallelly connected directly. Normally $V_{O1}(0)$ and $V_{O2}(0)$ are seldom the same. Owing to good regulation performance, the slope of the I-V curve is often very shallow. At the same output voltage V_O, there is a large difference between the two paralleled converters output currents I_{O1} and I_{O2}.

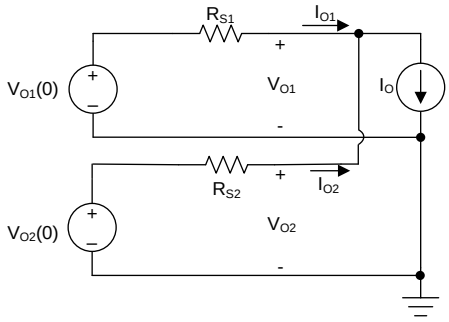

Figure 2. Equivalent Model

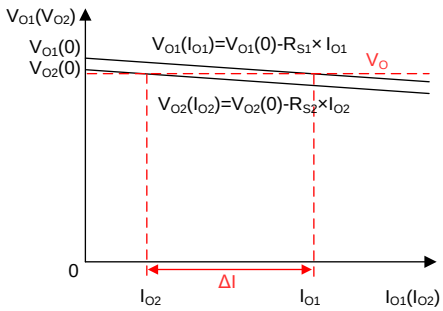

Figure 3. Output I-V Characteristic Curve of Two Parallel LM5176 Converters

2.2 Paralleling method realization

Figure 4 shows the proposed power sharing control circuit. It configures the two parallel converters as master and slave. The sharing control circuit consists of the following: (a) two equal current sense resistors R_{S1} and R_{S2}; (b) two RC networks R_{Fx}, C_{Fx} to filter the corresponding output voltage ripples; (c) a high precision low input offset OpAmp as the error amplifier (using LM8261 in the prototype); (d) an integral capacitor C_P across the inverting input and output of amplifier; (e) a resistor R_c to feed back the current error signal V_{CFB} to the slave control circuit so as to modulate the slave output for balanced power sharing. The whole power sharing control circuit is simple and low cost, but the performance is excellent.

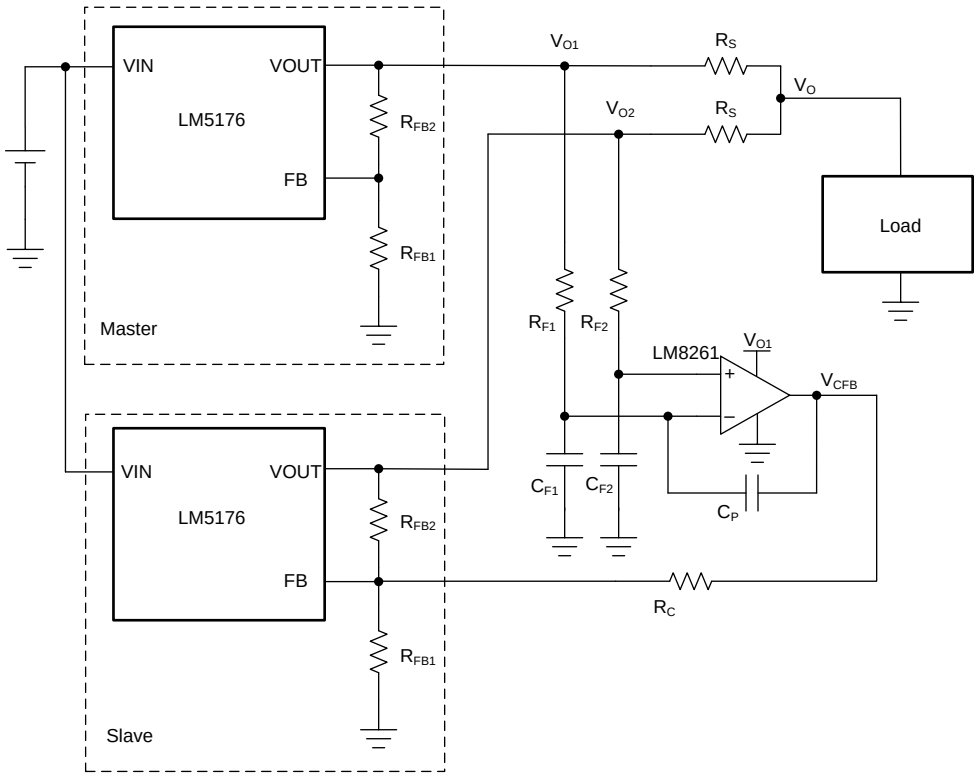

Figure 4. Two Parallel LM5176 Converters with Extra Current Sharing Circuit

The operating principle is as follows. The output currents of two LM5176 converters are monitored by the current sense resistors. The current difference is then amplified by the error amplifier. The amplifier output is sent to the slave converter's feedback circuit through R_c in order to modulate the slave output voltage for a balanced power sharing. To minimize the sharing error, it is important that the sharing control circuit should be laid out and routed symmetrically. As the current sense resistors values are normally very small in milliohms to minimize the incurred power loss and heat, a small resistance difference between R_{S1} and R_{S2} causes a big current sharing difference, which can be shown in the following example. Assuming 4 mΩ current sense resistors are chosen for R_{S1} and R_{S2}, the actual resistance of R_{S2} could be 5 mΩ due to the parasitic resistance of asymmetric layout. Also assuming V_{O1} and V_{O2} values are the same, the output voltage V_O is 12 V and the total load current is 40 A, then it satisfy Equation 1 and Equation 2:

$$\frac{V_{O1} - V_O}{R_{S1}} + \frac{V_{O2} - V_O}{R_{S2}} = I_O \tag{1}$$

$$V_{O1} = V_{O2} = V_O + \frac{R_{S1}R_{S2}}{R_{S1} + R_{S2}} I_o \tag{2}$$

The error of two output currents can be derived by Equation 3:

$$\frac{I_{O1} - I_{O2}}{I_O} = \frac{R_{S2} - R_{S1}}{R_{S1} + R_{S2}} \tag{3}$$

Therefore, the error of load current sharing is 11.1% at 40 A if 1 mΩ difference exists between R_{S1} and R_{S2}. It is highly recommended to minimize the error by placing R_{S1}, R_{S2} and the common node of output as close as possible on the circuit board, and also placing the sensing network near R_{S1} and R_{S2}.

The slave LM5176 converter output voltage can be determined by Equation 4:

$$V_{O2} = \left(1 + \frac{R_{FB2}}{R_{FB1}}\right) V_{REF} + \frac{R_{FB2}}{R_C} (V_{REF} - V_{CFB}) \tag{4}$$

From above equations, it can be seen that by varying V_{CFB} value, the slave output voltage is adjusted up or down to compensate for the output voltage difference from the master output, thus achieving balanced power sharing.

If an extreme condition were to occur, the output of LM8261 has the risk of being railed to the V+ of amplifier or ground. For a 12 V application, with R_1 equals 280 kΩ and R_2 equals 20 kΩ, select R_C as 1 MΩ to establish the boundary of V_{O2} between 8.70 V to 12.23 V.

LM8261 is a rail-to-rail input and output OpAmp which can operate with a wide supply voltage range and has low input offset voltage. Use V_{O1} as the supply voltage. To increase the current sharing accuracy, it's recommended to use resistors to connect to the error amplifier directly instead of resistor divider networks, which avoids the affect of 1% tolerance of the resistor divider network. Table 1 lists all the component parameters for this circuit.

Table 1. Component Parameters for Power Sharing Circuit

R_S(mΩ)	R_{F1}(kΩ)	R_{F2}(kΩ)	C_{F1}(μF)	C_{F2}(μF)	C_P(nF)	R_C(MΩ)	R_{F1}(kΩ)	R_{F2}(kΩ)
4	2	2	1	1	20	1	280	20

3 Test Results

3.1 Load regulation and load distribution

Use the RT/SYNC pin of the LM5176 device to synchronize the pulse-width modulation (PWM) controller to an external clock. The clocks for the two parallel converters can either be 180° out of phase or in-phase.

Figure 5 and Figure 7 show the test results of the error of load currents of 180° interleaved and in-phase separately. The error is less than 2% when the total load current is above 8A and the error is less than 1.1% at full load current under different input voltage conditions. Figure 6 and Figure 8 show the test results of the load distribution of two phases under different input voltage conditions.

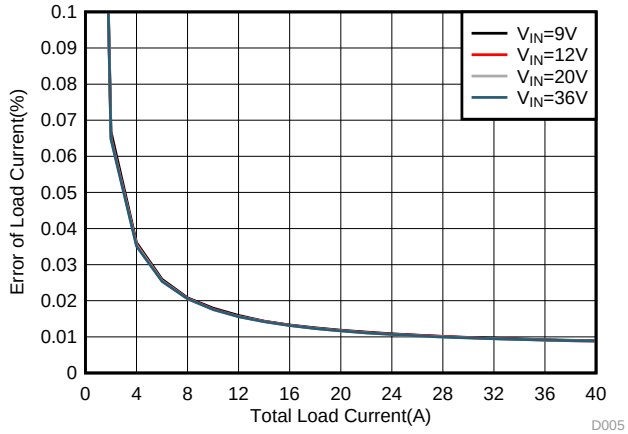

Figure 5. Error of Load Current(Interleaved)

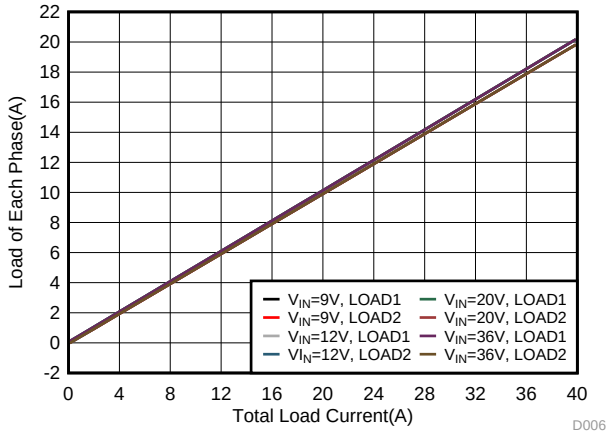

Figure 6. Load Distribution of Two Phases(Interleaved)

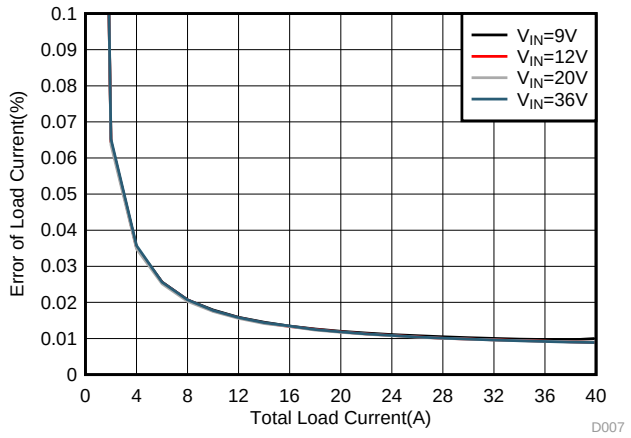

Figure 7. Error of Load Current(In-Phase)

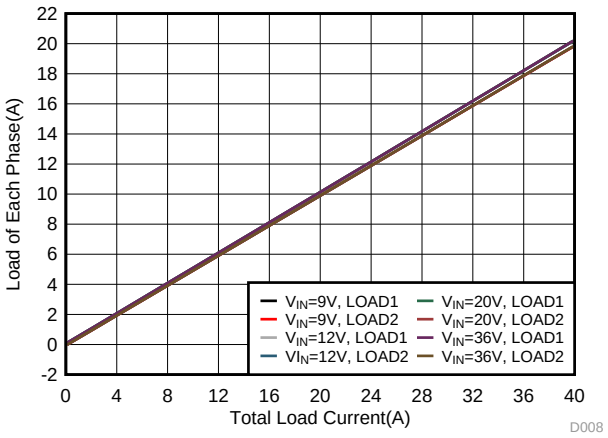

Figure 8. Load Distribution of Two Phases(In-Phase)

Figure 9 shows the load regulation of the whole system under different input voltage conditions. The variation of the output voltage is within ±1%, which indicates an excellent load regulation performance.

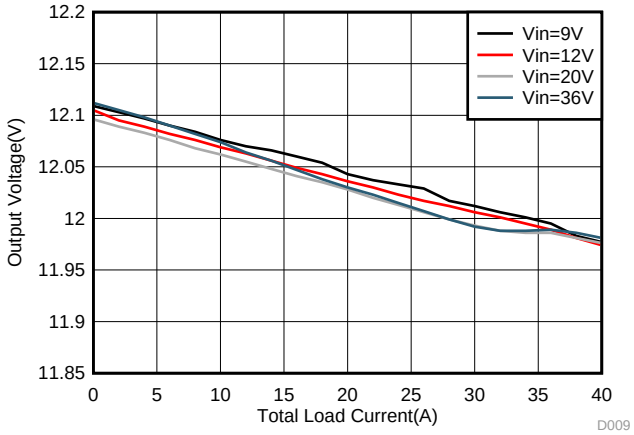

Figure 9. Load Regulation of Parallel Power

3.2 Interleaved SYNC Operation

Figure 10 through Figure 15 show the four switching nodes and inductor current waveforms in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively. The waveforms show that each operation region is stable and the inductor current waveforms of the two phases indicate equally distributed load currents.

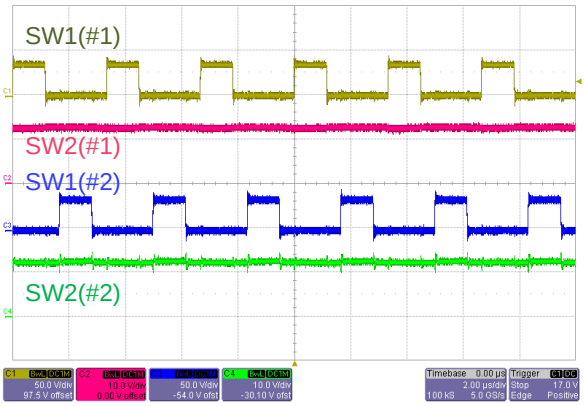

Figure 10. 36-V Buck Region With 40-A Load—Four Switch Nodes

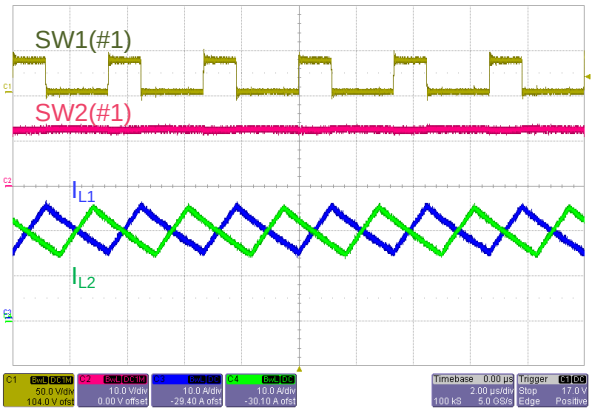

Figure 11. 36-V Buck Region With 40-A Load—Inductor Current Waveforms

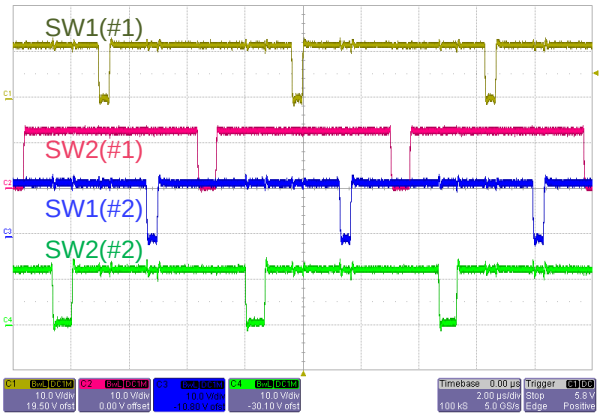

Figure 12. 12-V Buck-Boost Region With 40-A Load—Four Switch Nodes

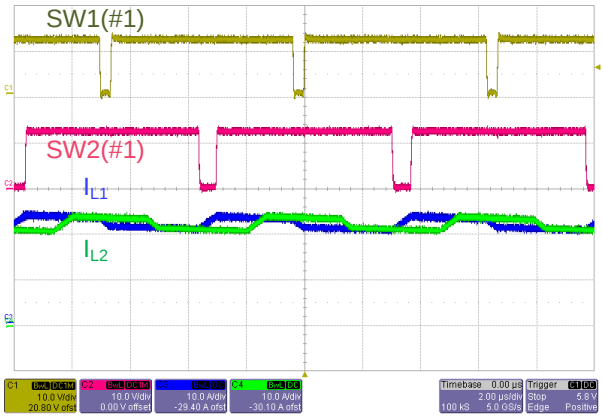

Figure 13. 12-V Buck-Boost Region With 40-A Load—Inductor Current Waveforms

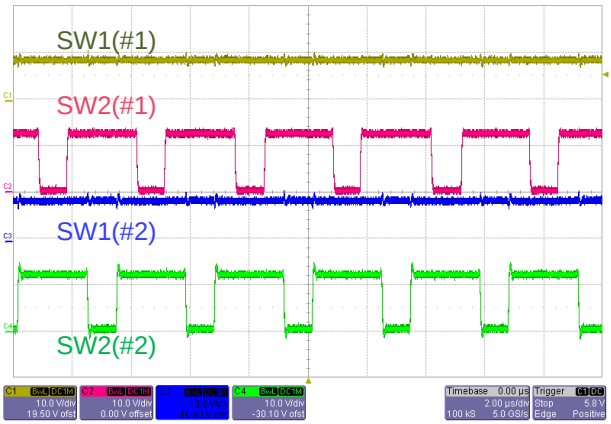

Figure 14. 9-V Boost Region With 40-A Load—Four Switch Nodes

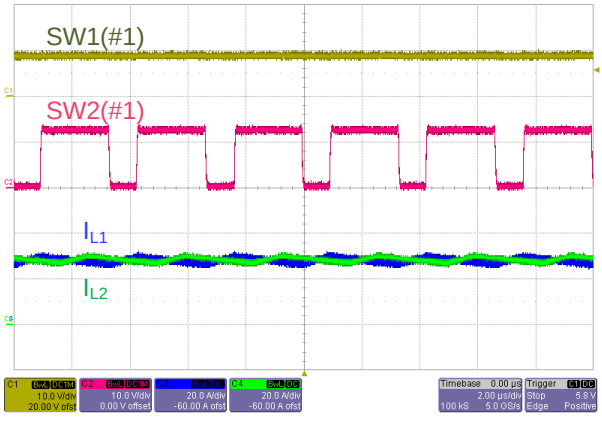

Figure 15. 9-V Boost Region With 40-A Load—Inductor Current Waveforms

Figure 16 through Figure 21 show the load transient of 20 A-40 A and 0 A-40 A waveforms in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively.

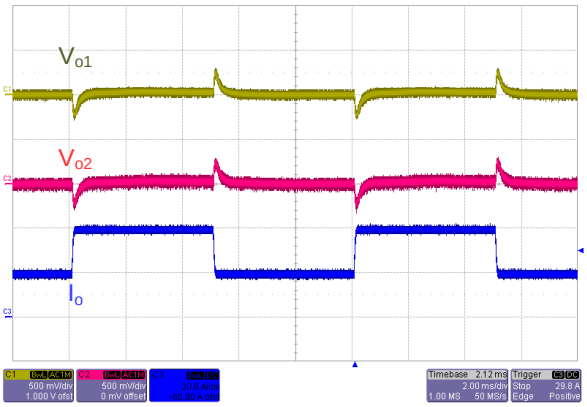

Figure 16. Load Transient in 36-V Buck Region—With 20-A to 40-A Load Step

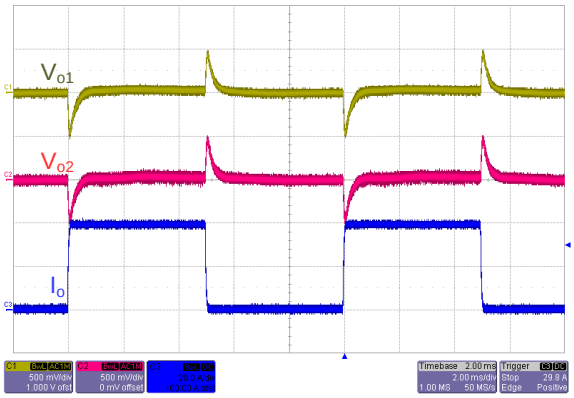

Figure 17. Load Transient in 36-V Buck Region—With 0-A to 40-A Load Step

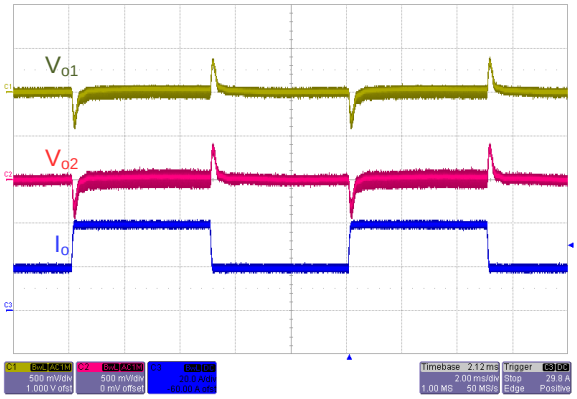

Figure 18. Load Transient in 12-V Buck-Boost Region—With 20-A to 40-A Load Step

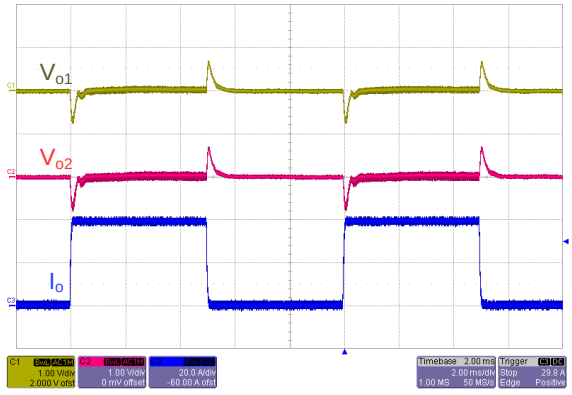

Figure 19. Load Transient in 12-V Buck-Boost Region—With 0-A to 40-A Load Step

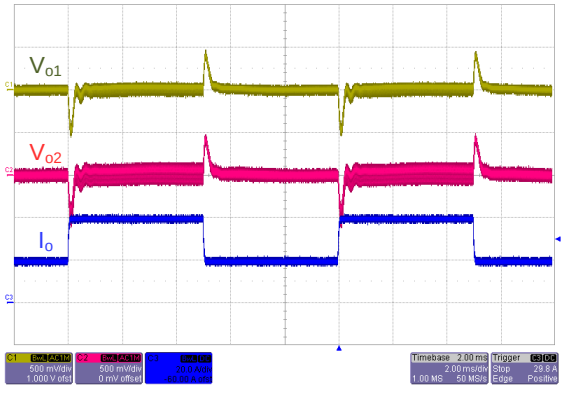

Figure 20. Load Transient in 9-V Boost Region—With 20-A to 40-A Load Step

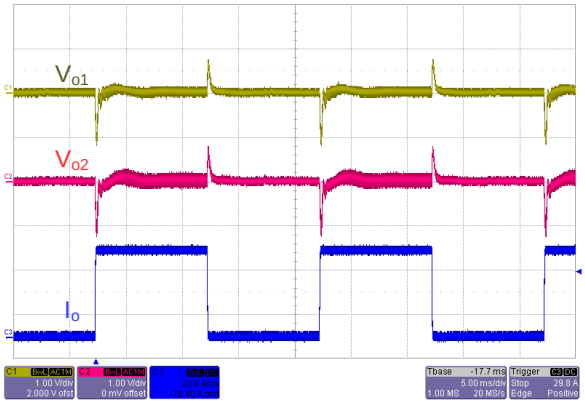

Figure 21. Load Transient in 9-V Boost Region—With 0-A to 40-A Load Step

Figure 22 through Figure 27 show the output ripple waveforms in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively.

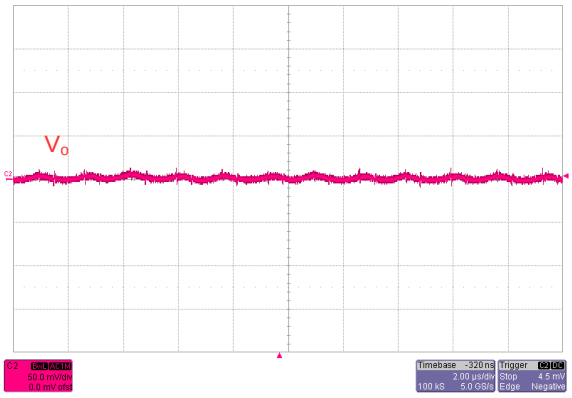

Figure 22. Output Voltage Ripple in 36-V Buck Region—No Load

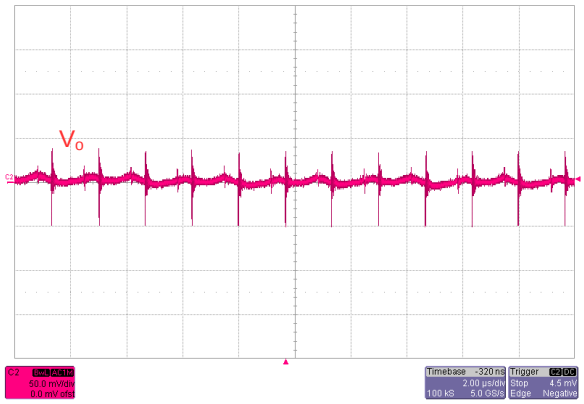

Figure 23. Output Voltage Ripple in 36-V Buck Region—40-A Load

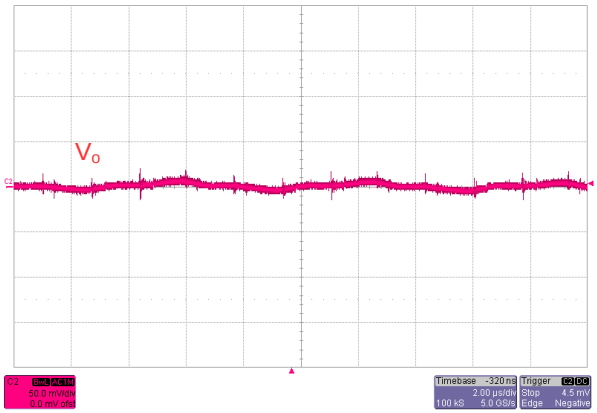

Figure 24. Output Voltage Ripple in 12-V Buck-Boost Region—No Load

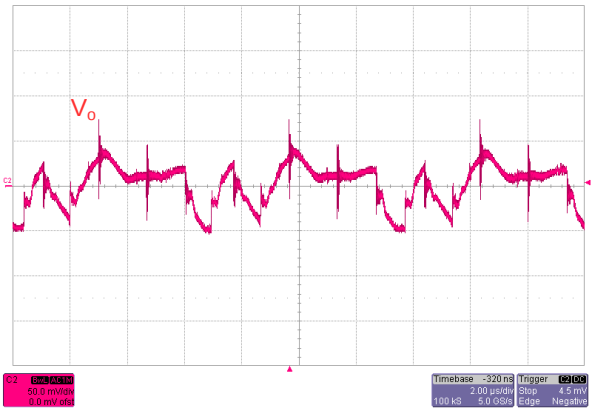

Figure 25. Output Voltage Ripple in 12-V Buck-Boost Region—40-A Load

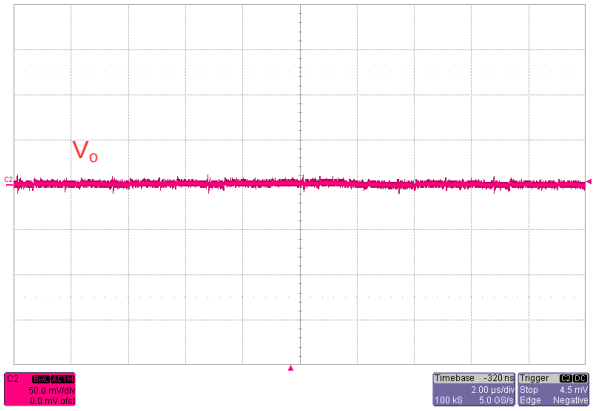

Figure 26. Output Voltage Ripple in 9-V Boost Region—No Load

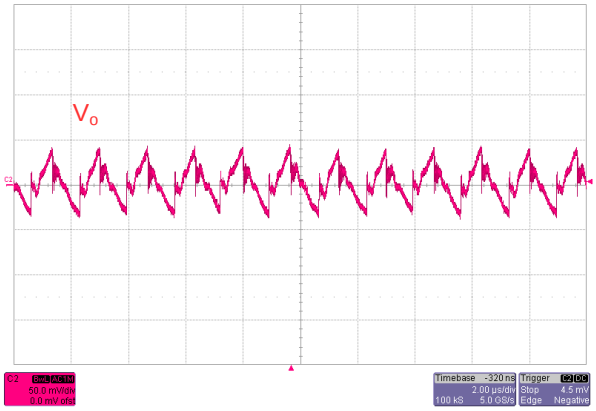

Figure 27. Output Voltage Ripple in 9-V Boost Region—40-A Load

Figure 28 through Figure 33 show the start-up waveforms in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively. The loads are not equally distributed during a certain period of the start-process due to a sequential order during start-up and the necessary time for a current sharing-circuit to build up and get ready.

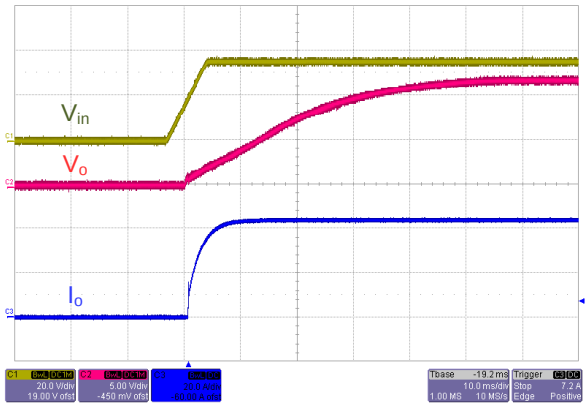

Figure 28. 40-A Start-Up in 36-V Buck Region—Total Output Current Waveform

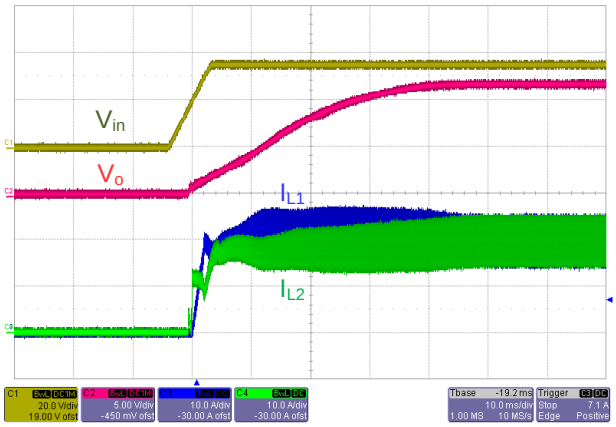

Figure 29. 40-A Start-Up in 36-V Buck Region—Two Phase Inductor Currents

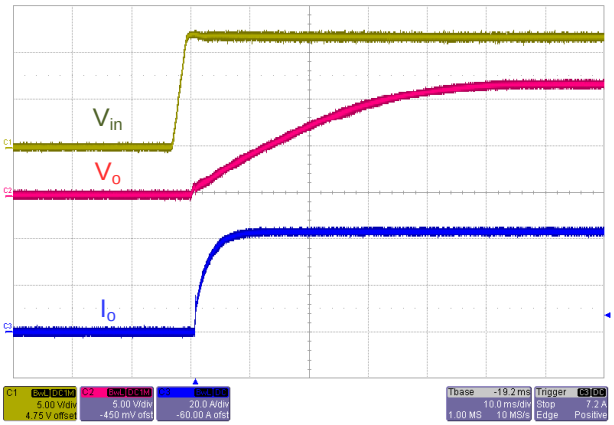

Figure 30. 40-A Start-Up in 12-V Buck-Boost Region—Total Output Current Waveform

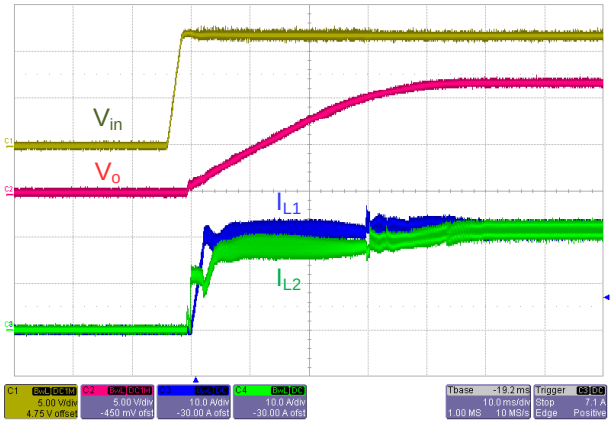

Figure 31. 40-A Start-Up in 12-V Buck-Boost Region—Two Phase Inductor Currents

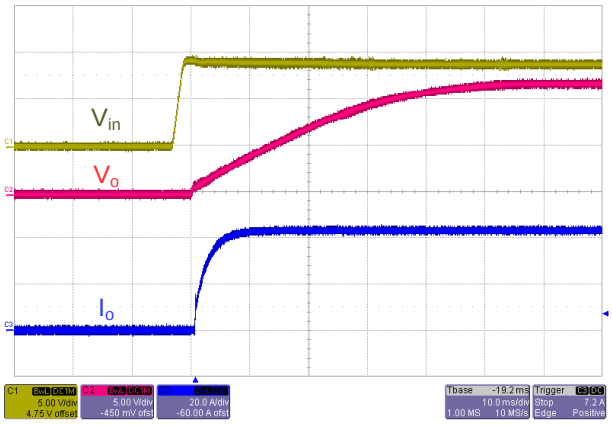

Figure 32. 40-A Start-Up in 9-V Boost Region—Total Output Current Waveform

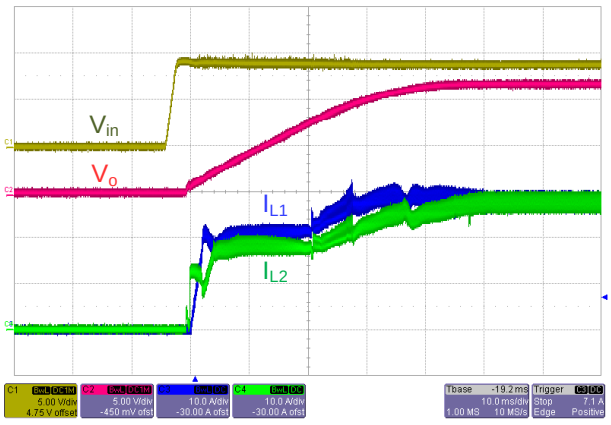

Figure 33. 40-A Start-Up in 9-V Boost Region—Two Phase Inductor Currents

Figure 34 through Figure 39 show the 40 A load two boards thermal condition in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively. The heat is distributed on two boards equally. The test results are captured with a 600-CFM airflow.

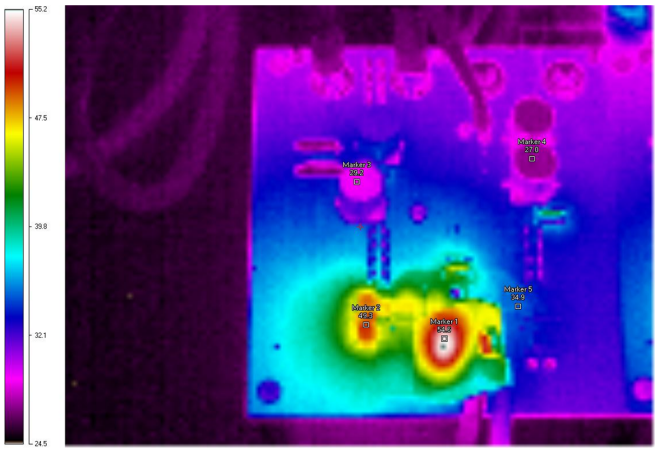

Figure 34. 40-A Load Thermal Condition in 36-V Buck Region—First Board

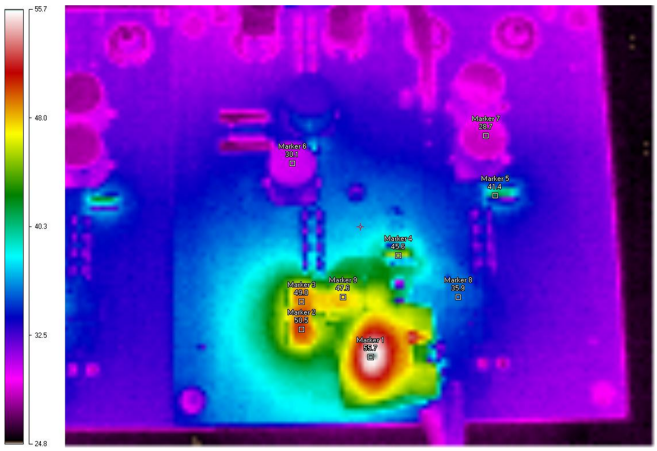

Figure 35. 40-A Load Thermal Condition in 36-V Buck Region—Second Board

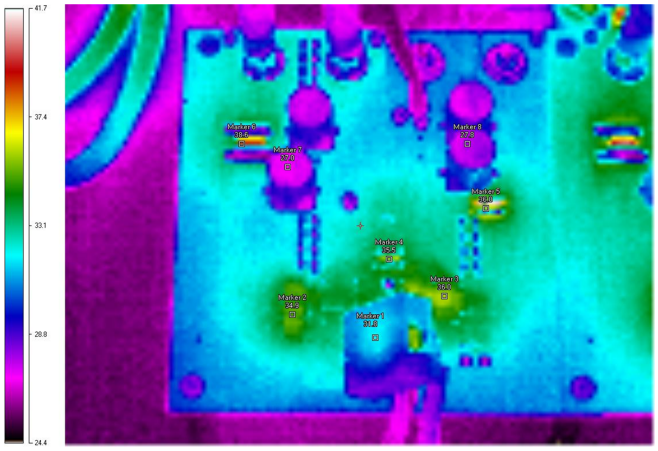

Figure 36. 40-A Load Thermal Condition in 12-V Buck-Boost Region—First Board

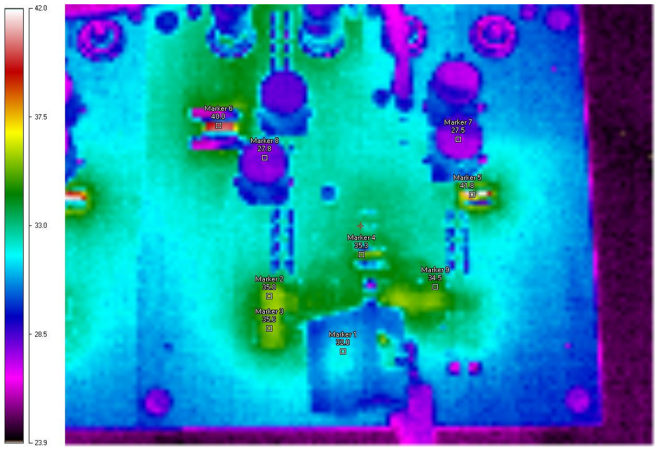

Figure 37. 40-A Load Thermal Condition in 12-V Buck-Boost Region—Second Board

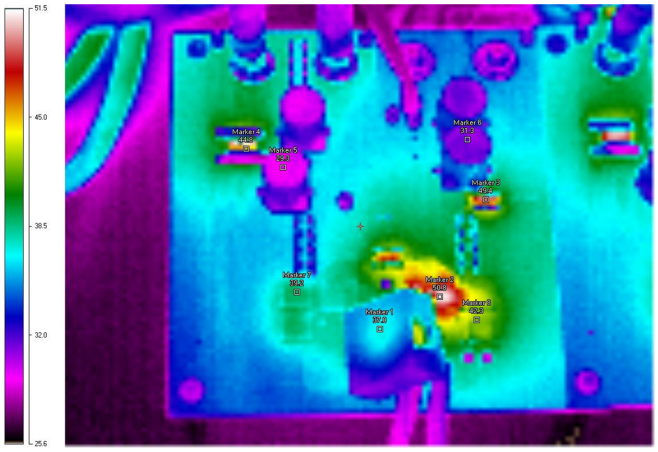

Figure 38. 40-A Load Thermal Condition in 9-V Boost Region—First Board

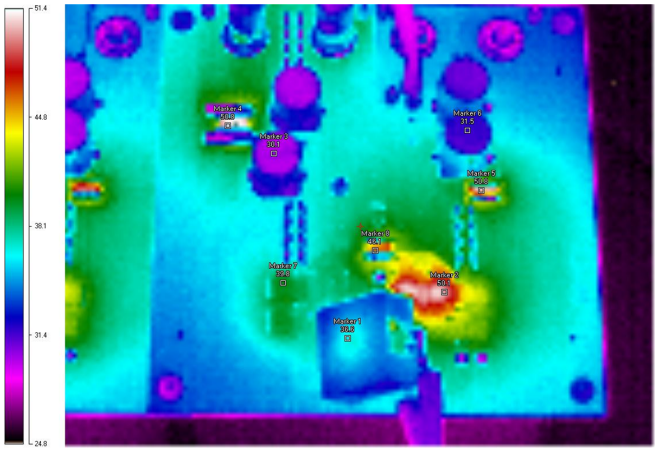

Figure 39. 40-A Load Thermal Condition in 9-V Boost Region—Second Board

3.3 In-phase SYNC Operation

Synchronizing the two parallel LM5176 converters with the same clock.

Figure 40 through Figure 45 show the four switching nodes and inductor current waveforms in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively.

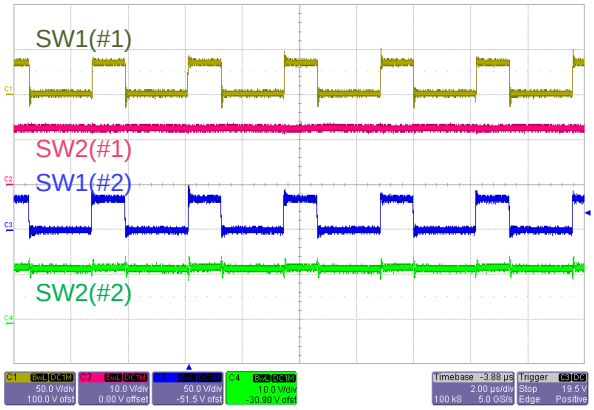

Figure 40. 36-V Buck Region With 40-A Load—Four Switch Nodes

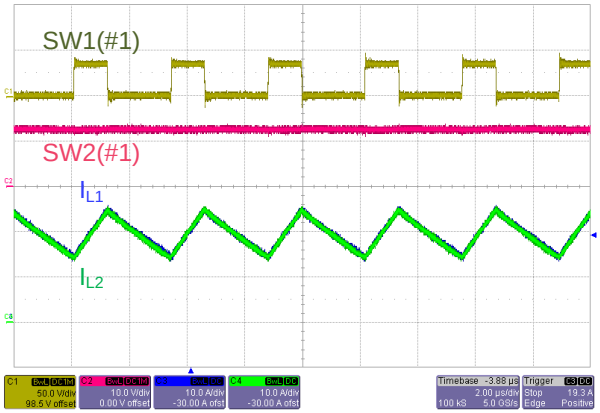

Figure 41. 36-V Buck Region With 40-A Load—Inductor Current Waveforms

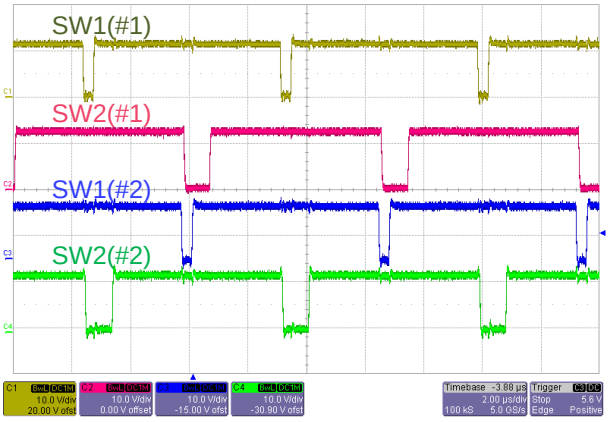

Figure 42. 12-V Buck-Boost Region With 40-A Load—Four Switch Nodes

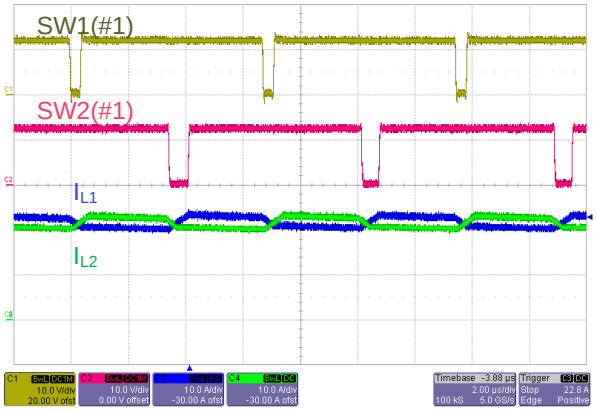

Figure 43. 12-V Buck-Boost Region With 40-A Load—Inductor Current Waveforms

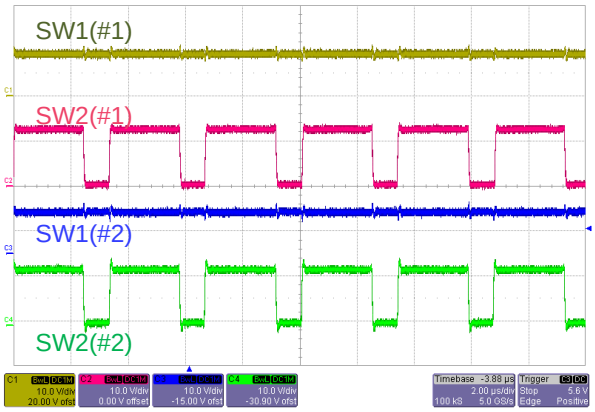

Figure 44. 9-V Boost Region With 40-A Load—Four Switch Nodes

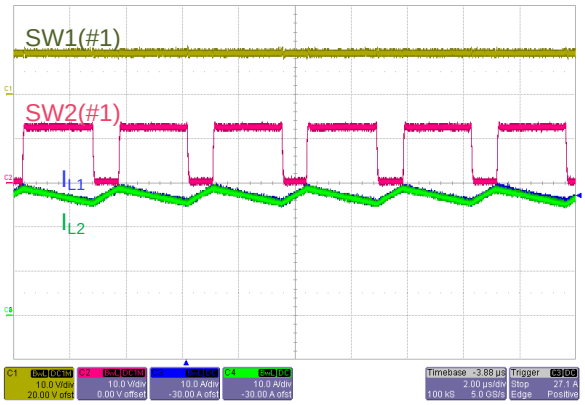

Figure 45. 9-V Boost Region With 40-A Load—Inductor Current Waveforms

Figure 46 through Figure 51 show the output ripple in the 36-V buck, 12-V buck-boost, and the 9-V boost regions, respectively. In comparison with Figure 22 through Figure 27 when two converters are interleaved paralleled, the ripples are higher. Interleaved architecture provides a better solution for smaller output voltage ripple.

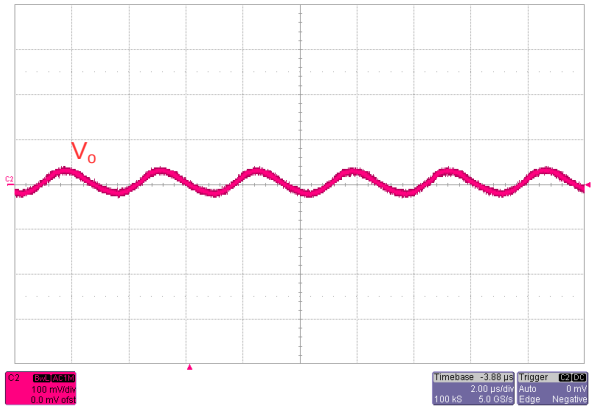

Figure 46. Output Voltage Ripple in 36-V Buck Region—No Load

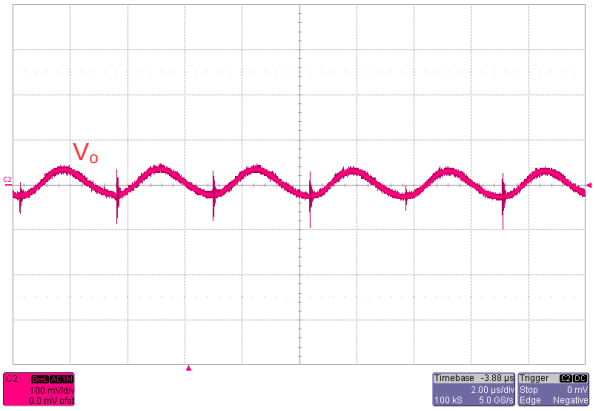

Figure 47. Output Voltage Ripple in 36-V Buck Region—40-A Load

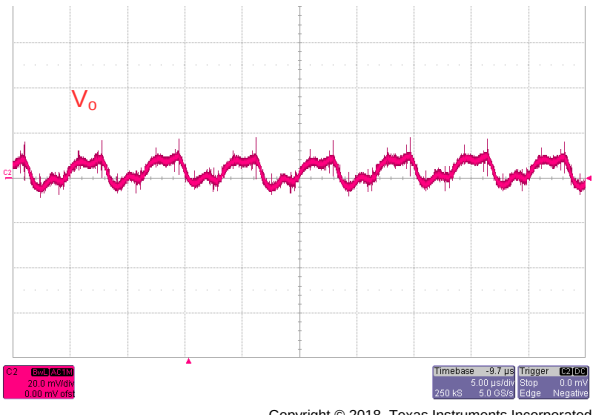

Figure 48. Output Voltage Ripple in 12-V Buck-Boost Region—No Load

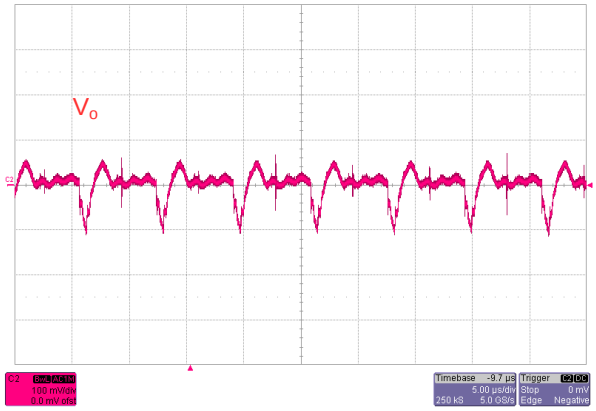

Figure 49. Output Voltage Ripple in 12-V Buck-Boost Region—40-A Load

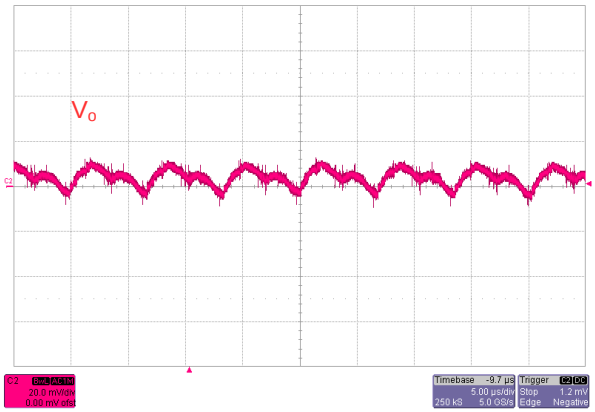

Figure 50. Output Voltage Ripple in 9-V Boost Region—No Load

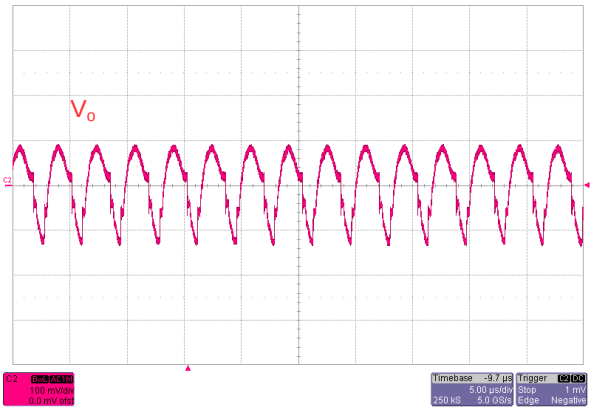

Figure 51. Output Voltage Ripple in 9-V Boost Region—40-A Load

4 Conclusion

The proposed current sharing method provides a high performance, cost effective solution to achieve well balanced power sharing between two LM5176 converters. With a simple external circuit of only one amplifier and few resistors, capacitors, the slave can accurately follow the master to deliver the same amount of load current and with an error that is within 1% at full load. The experiment results of the parallel LM5176 converters with a 480 W capability were presented as proof of concept. The proposed method can be readily applied to support high power level.

5 References

1. Texas Instruments, LM5176 55-V Wide VIN Synchronous 4-Switch Buck-Boost Controllers Datasheet
2. Texas Instruments, LM5176 Wide-VIN Buck-Boost Controller EVM

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