Test Report: PMP23061

Pre-Regulated Isolated Driver Bias Supply Reference Design for Traction-Inverter Applications

1 Description

This pre-regulated isolated open-loop LLC transformer driver converter provides four 18-V outputs up to a total of 6 W for traction-inverter applications. The LLC topology allows the transformer to have significant leakage inductance, but a much smaller primary-secondary capacitance, which significantly reduces common-mode current injection through the bias transformer. The boost pre-regulator is designed to provide 7.5 W to the LLC converter, which can support a maximum of 6-W output.

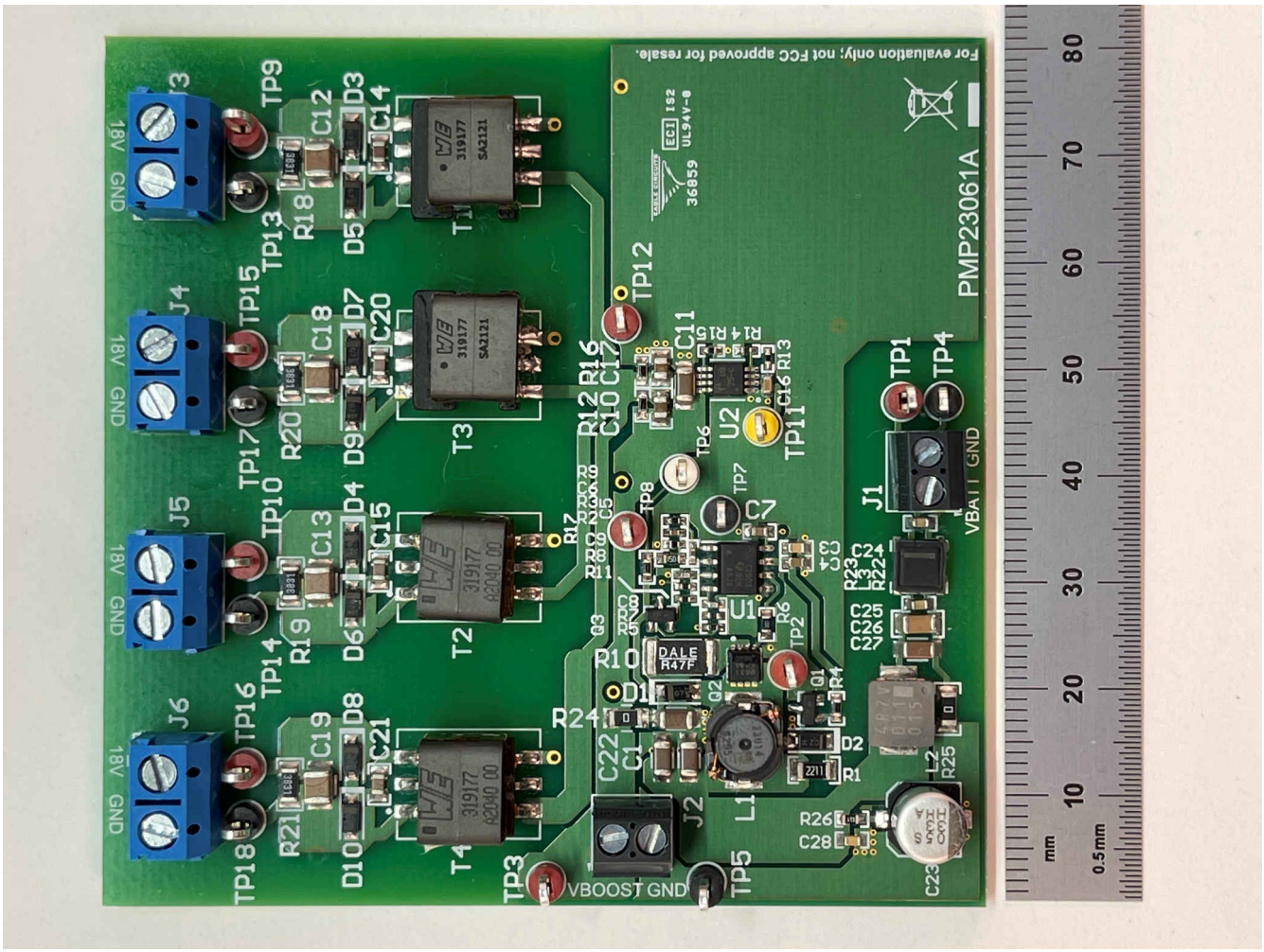

Figure 1-1. Top Photo

2 Test Prerequisites

2.1 Voltage and Current Requirements

Table 2-1. Voltage and Current Requirements

Parameter	Specifications
Input voltage range	6 V–28 V
Output voltage and current	4 × 18-V rails, 1 × 167 mA, 3 × 56 mA, 6 W maximum
Switching frequency	Boost: 300 kHz, LLC: 1 MHz
Isolation	Yes
Topology	Open-loop LLC transformer driver with boost pre-regulator

2.2 Required Equipment

- Resistive loads
- Power supply capable of 30 V, 10 W minimum
- Oscilloscope and probes
- Digital multimeters

3 Testing and Results

3.1 Efficiency and Power Dissipation Graphs

The efficiency of the boost converter and the open-loop LLC were measured separately. For the boost measurements the LLC was disabled by shorting the DIS/FLT pin of the UCC25800-Q1 (TP11) to GND and a resistive load was applied across the connector labeled VBOOST (J2). Efficiency curves were measured for inputs of 6 V, 12 V, 24 V, and 28 V.

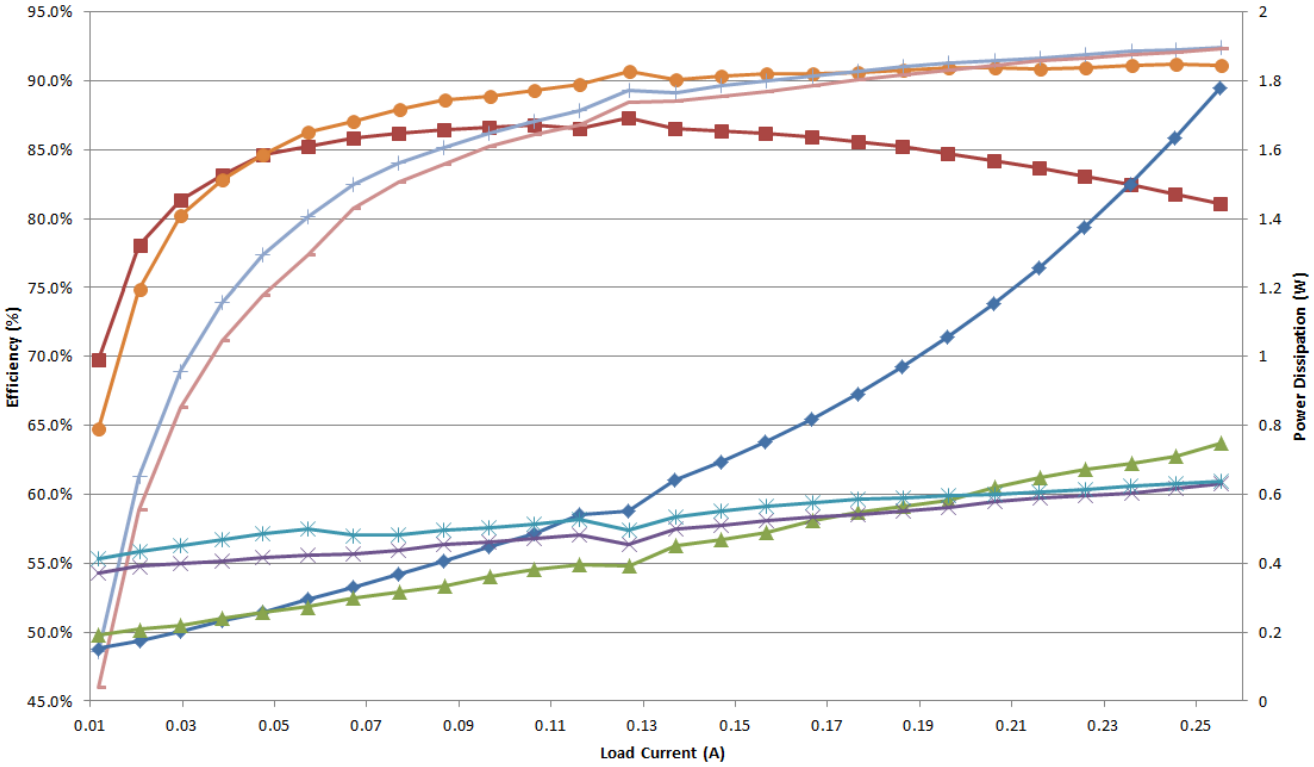

Figure 3-1. Boost Efficiency and Power Dissipation

The LLC measurements were taken with a regulated 30 V applied at the connector labeled VBOOST (J2) and with the boost input (J1) disconnected.

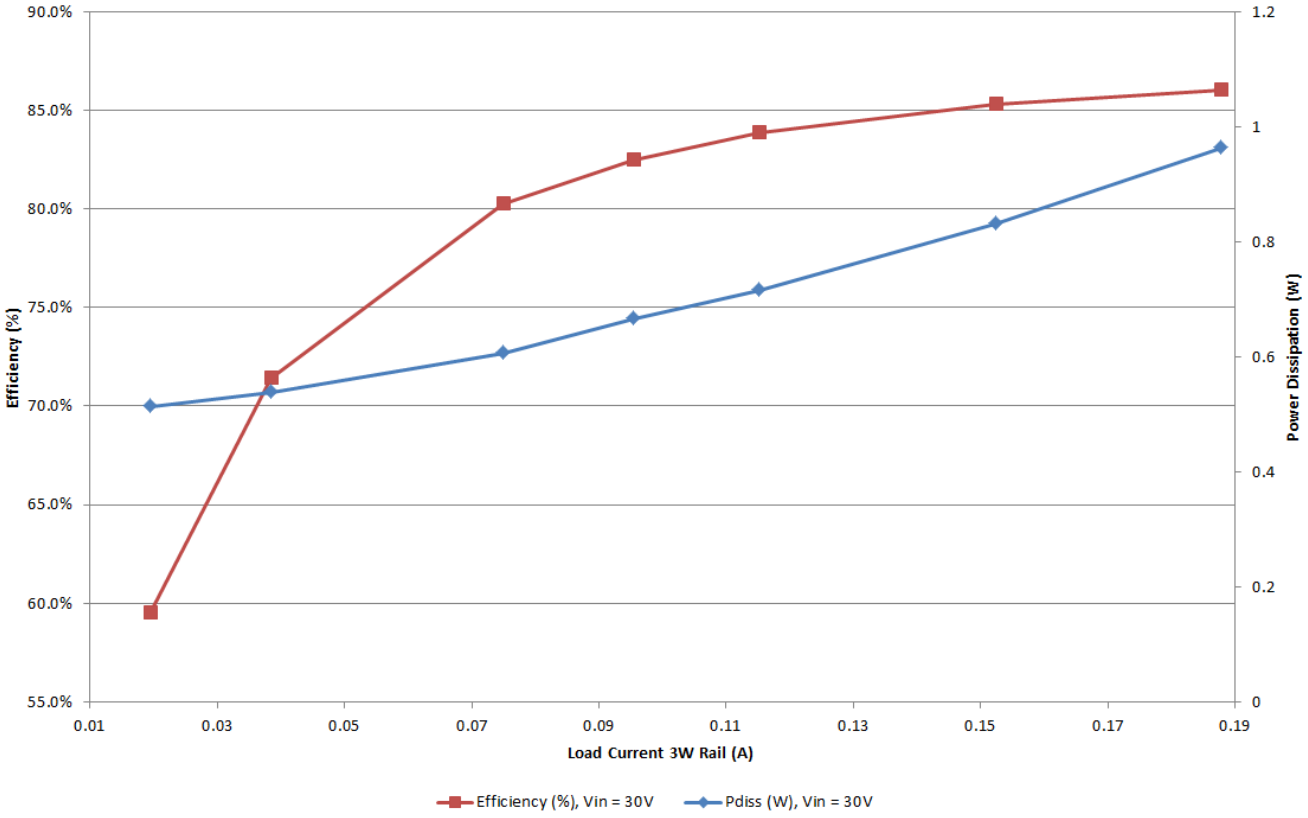

Figure 3-2. LLC Efficiency and Power Dissipation

3.2 Efficiency and Power Dissipation Data

The efficiency and power dissipation data for the boost and LLC stages is shown in the following tables.

Vin	Iin	Vout	Iout	Po	Pin	Efficiency	Pdiss (W)
6.658	0.0755	29.949	0.01170	0.350	0.503	69.7%	0.152
6.795	0.1168	29.950	0.02068	0.619	0.794	78.0%	0.174
6.774	0.1610	29.952	0.02963	0.887	1.091	81.4%	0.203
6.752	0.2056	29.951	0.03856	1.155	1.389	83.2%	0.234
6.730	0.2496	29.949	0.04747	1.422	1.680	84.6%	0.258
6.706	0.2998	29.947	0.05724	1.714	2.011	85.2%	0.297
6.680	0.3504	29.943	0.06709	2.009	2.340	85.8%	0.331
6.655	0.4015	29.942	0.07694	2.304	2.672	86.2%	0.368
6.628	0.4532	29.937	0.08675	2.597	3.004	86.5%	0.407
6.602	0.5055	29.936	0.09655	2.890	3.337	86.6%	0.447
6.576	0.5577	29.929	0.10631	3.182	3.668	86.8%	0.486
6.547	0.6130	29.927	0.11606	3.473	4.013	86.5%	0.540
6.520	0.6664	29.928	0.12679	3.795	4.345	87.3%	0.551
6.487	0.7300	29.927	0.13687	4.096	4.736	86.5%	0.640
6.457	0.7876	29.927	0.14678	4.393	5.086	86.4%	0.693
6.427	0.8457	29.927	0.15651	4.684	5.435	86.2%	0.751
6.396	0.9074	29.927	0.16658	4.985	5.803	85.9%	0.818
6.363	0.9699	29.927	0.17647	5.281	6.171	85.6%	0.890
6.329	1.0334	29.926	0.18618	5.572	6.540	85.2%	0.968
6.294	1.1001	29.926	0.19606	5.867	6.924	84.7%	1.057
6.256	1.1704	29.925	0.20611	6.168	7.323	84.2%	1.155
6.219	1.2406	29.925	0.21579	6.457	7.716	83.7%	1.258
6.180	1.3149	29.924	0.22565	6.752	8.126	83.1%	1.374
6.138	1.3935	29.923	0.23569	7.053	8.553	82.5%	1.500
6.096	1.4724	29.922	0.24537	7.342	8.975	81.8%	1.633
6.051	1.5559	29.921	0.25521	7.636	9.415	81.1%	1.778

Figure 3-3. Boost Converter Efficiency, 6 V_{IN}

Vin	Iin	Vout	Iout	Po	Pin	Efficiency	Pdiss (W)
12.325	0.0439	29.932	0.01170	0.350	0.541	64.8%	0.191
12.262	0.0674	29.938	0.02066	0.619	0.826	74.9%	0.207
12.202	0.0906	29.942	0.02961	0.887	1.106	80.2%	0.219
12.138	0.1148	29.946	0.03855	1.155	1.394	82.8%	0.239
12.367	0.1358	29.949	0.04747	1.422	1.680	84.6%	0.258
12.353	0.1609	29.951	0.05724	1.714	1.987	86.3%	0.273
12.340	0.1871	29.953	0.06710	2.010	2.309	87.1%	0.299
12.326	0.2127	29.955	0.07698	2.306	2.622	88.0%	0.316
12.313	0.2384	29.956	0.08679	2.600	2.935	88.6%	0.335
12.298	0.2648	29.957	0.09661	2.894	3.256	88.9%	0.362
12.285	0.2905	29.958	0.10642	3.188	3.569	89.3%	0.381
12.271	0.3160	29.958	0.11618	3.481	3.877	89.8%	0.397
12.257	0.3421	29.959	0.12692	3.802	4.193	90.7%	0.391
12.241	0.3723	29.959	0.13701	4.105	4.557	90.1%	0.453
12.227	0.3984	29.959	0.14694	4.402	4.872	90.4%	0.470
12.214	0.4245	29.959	0.15668	4.694	5.184	90.5%	0.490
12.199	0.4524	29.958	0.16674	4.995	5.518	90.5%	0.523
12.184	0.4794	29.958	0.17664	5.292	5.841	90.6%	0.549
12.171	0.5054	29.959	0.18639	5.584	6.151	90.8%	0.567
12.156	0.5317	29.959	0.19627	5.880	6.464	91.0%	0.584
12.141	0.5601	29.957	0.20633	6.181	6.800	90.9%	0.619
12.127	0.5871	29.957	0.21604	6.472	7.120	90.9%	0.648
12.113	0.6143	29.957	0.22592	6.768	7.440	91.0%	0.672
12.098	0.6414	29.957	0.23595	7.068	7.759	91.1%	0.691
12.084	0.6677	29.956	0.24565	7.359	8.069	91.2%	0.710
12.069	0.6960	29.954	0.25549	7.653	8.401	91.1%	0.748

Figure 3-4. Boost Converter Efficiency, 12 V_{IN}

Vin	Iin	Vout	Iout	Po	Pin	Efficiency	Pdiss (W)
24.136	0.0299	29.939	0.01170	0.350	0.722	48.5%	0.371
24.105	0.0419	29.939	0.02067	0.619	1.010	61.3%	0.391
24.074	0.0534	29.939	0.02961	0.887	1.286	68.9%	0.399
24.044	0.0649	29.940	0.03854	1.154	1.562	73.9%	0.408
24.014	0.0765	29.940	0.04746	1.421	1.837	77.4%	0.416
23.981	0.0891	29.941	0.05722	1.713	2.137	80.2%	0.424
23.947	0.1018	29.942	0.06709	2.009	2.437	82.4%	0.428
23.913	0.1147	29.942	0.07694	2.304	2.742	84.0%	0.439
24.147	0.1264	29.943	0.08675	2.598	3.052	85.1%	0.455
24.140	0.1389	29.944	0.09656	2.891	3.354	86.2%	0.463
24.133	0.1515	29.944	0.10636	3.185	3.657	87.1%	0.472
24.127	0.1641	29.945	0.11615	3.478	3.959	87.8%	0.481
24.120	0.1764	29.946	0.12687	3.799	4.255	89.3%	0.456
24.112	0.1908	29.946	0.13697	4.102	4.601	89.1%	0.499
24.106	0.2036	29.948	0.14689	4.399	4.909	89.6%	0.510
24.099	0.2164	29.948	0.15662	4.691	5.214	90.0%	0.523
24.092	0.2294	29.948	0.16668	4.992	5.527	90.3%	0.535
24.085	0.2421	29.949	0.17660	5.289	5.831	90.7%	0.542
24.079	0.2546	29.950	0.18633	5.581	6.131	91.0%	0.550
24.072	0.2675	29.950	0.19623	5.877	6.440	91.3%	0.563
24.065	0.2808	29.951	0.20629	6.179	6.756	91.4%	0.578
24.058	0.2934	29.951	0.21600	6.469	7.059	91.7%	0.589
24.051	0.3061	29.951	0.22587	6.765	7.363	91.9%	0.598
24.044	0.3190	29.952	0.23594	7.067	7.671	92.1%	0.604
24.038	0.3317	29.953	0.24563	7.357	7.973	92.3%	0.616
24.031	0.3447	29.953	0.25549	7.653	8.284	92.4%	0.632

Figure 3-5. Boost Converter Efficiency, 24V_{IN}

Vin	Iin	Vout	Iout	Po	Pin	Efficiency	Pdiss (W)
28.094	0.0272	29.946	0.01171	0.351	0.763	46.0%	0.412
28.067	0.0375	29.946	0.02067	0.619	1.051	58.9%	0.432
28.040	0.0477	29.946	0.02961	0.887	1.338	66.3%	0.451
28.013	0.0579	29.946	0.03855	1.154	1.622	71.2%	0.468
27.986	0.0682	29.945	0.04747	1.421	1.909	74.5%	0.487
27.957	0.0792	29.945	0.05723	1.714	2.215	77.4%	0.501
27.931	0.0891	29.946	0.06710	2.009	2.490	80.7%	0.480
27.903	0.0999	29.947	0.07696	2.305	2.788	82.7%	0.483
27.874	0.1110	29.946	0.08677	2.598	3.094	84.0%	0.496
28.101	0.1208	29.946	0.09658	2.892	3.394	85.2%	0.502
28.095	0.1317	29.946	0.10636	3.185	3.700	86.1%	0.515
28.089	0.1426	29.946	0.11614	3.478	4.006	86.8%	0.528
28.084	0.1529	29.947	0.12687	3.799	4.295	88.5%	0.495
28.077	0.1651	29.947	0.13696	4.102	4.635	88.5%	0.533
28.071	0.1763	29.947	0.14688	4.398	4.949	88.9%	0.551
28.065	0.1873	29.946	0.15661	4.690	5.257	89.2%	0.567
28.059	0.1984	29.946	0.16669	4.992	5.568	89.6%	0.577
28.054	0.2093	29.946	0.17658	5.288	5.872	90.0%	0.585
28.048	0.2200	29.946	0.18631	5.579	6.170	90.4%	0.590
28.042	0.2308	29.946	0.19619	5.875	6.471	90.8%	0.596
28.036	0.2417	29.946	0.20625	6.176	6.778	91.1%	0.601
28.031	0.2523	29.946	0.21595	6.467	7.073	91.4%	0.606
28.025	0.2633	29.946	0.22583	6.763	7.378	91.7%	0.615
28.019	0.2744	29.946	0.23587	7.063	7.688	91.9%	0.625
28.013	0.2850	29.946	0.24556	7.353	7.985	92.1%	0.632
28.008	0.2959	29.946	0.25542	7.649	8.287	92.3%	0.638

Figure 3-6. Boost Converter Efficiency, 28 V_{IN}

% Load	Vin	Iin	Vo1	Io1	Vo2	Io2	Vo3	Io3	Vo4	Io4	Pin	Ptot_out	Efficiency	Pdiss (W)
100%	30.0294	0.2289	16.251	0.18775	16.731	5.7%	16.740	0.057	16.716	0.057	6.874	5.912	86.0%	0.962
80%	30.0518	0.1879	16.447	0.15226	16.852	4.6%	16.861	0.046	16.828	0.045	5.646	4.816	85.3%	0.831
60%	30.0600	0.1473	16.652	0.11516	16.972	3.6%	16.981	0.036	16.963	0.035	4.428	3.713	83.9%	0.715
50%	30.0822	0.1261	16.761	0.09545	17.045	3.0%	17.045	0.030	17.027	0.029	3.794	3.129	82.5%	0.665
40%	29.5748	0.1036	16.567	0.07489	16.794	2.4%	16.806	0.025	16.790	0.024	3.064	2.458	80.2%	0.606
20%	29.7996	0.0633	16.904	0.03846	17.070	1.4%	17.079	0.014	17.069	0.013	1.885	1.346	71.4%	0.539
10%	29.9165	0.0423	17.114	0.01947	17.252	0.8%	17.262	0.009	17.265	0.007	1.266	0.753	59.5%	0.513

Figure 3-7. LLC Converter Efficiency, 30 V_{IN}

3.3 Thermal Performance

The following thermal image shows the board running with 6 V_{IN} and 6 W being drawn from the 18-V LLC outputs (3 × 1 W and 1 × 3 W).

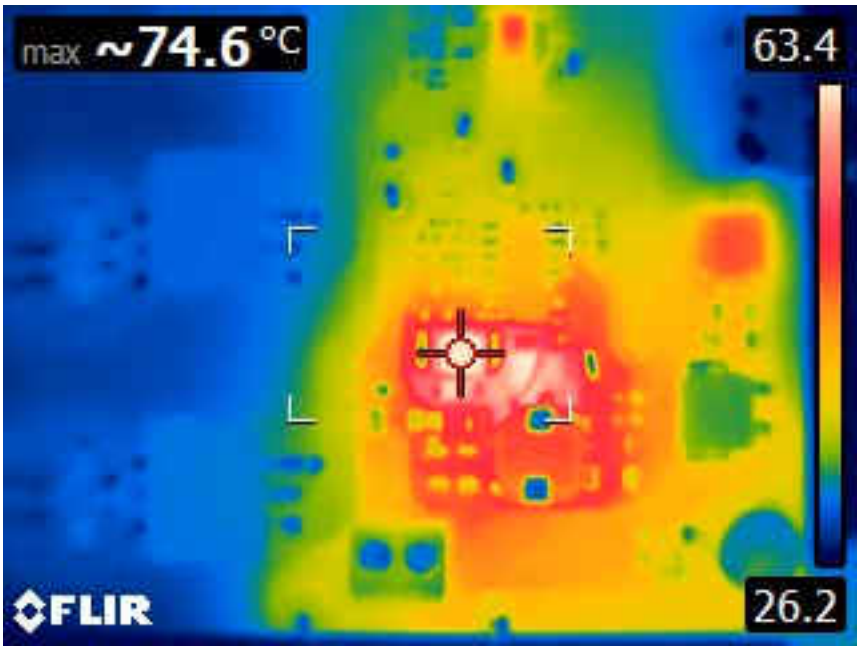

Figure 3-8. Top Thermal Image

3.4 Bode Plot

The loop stability of the boost converter is shown in the following plot. The plot was obtained with the LLC converter disabled and a resistive load applied across J2.

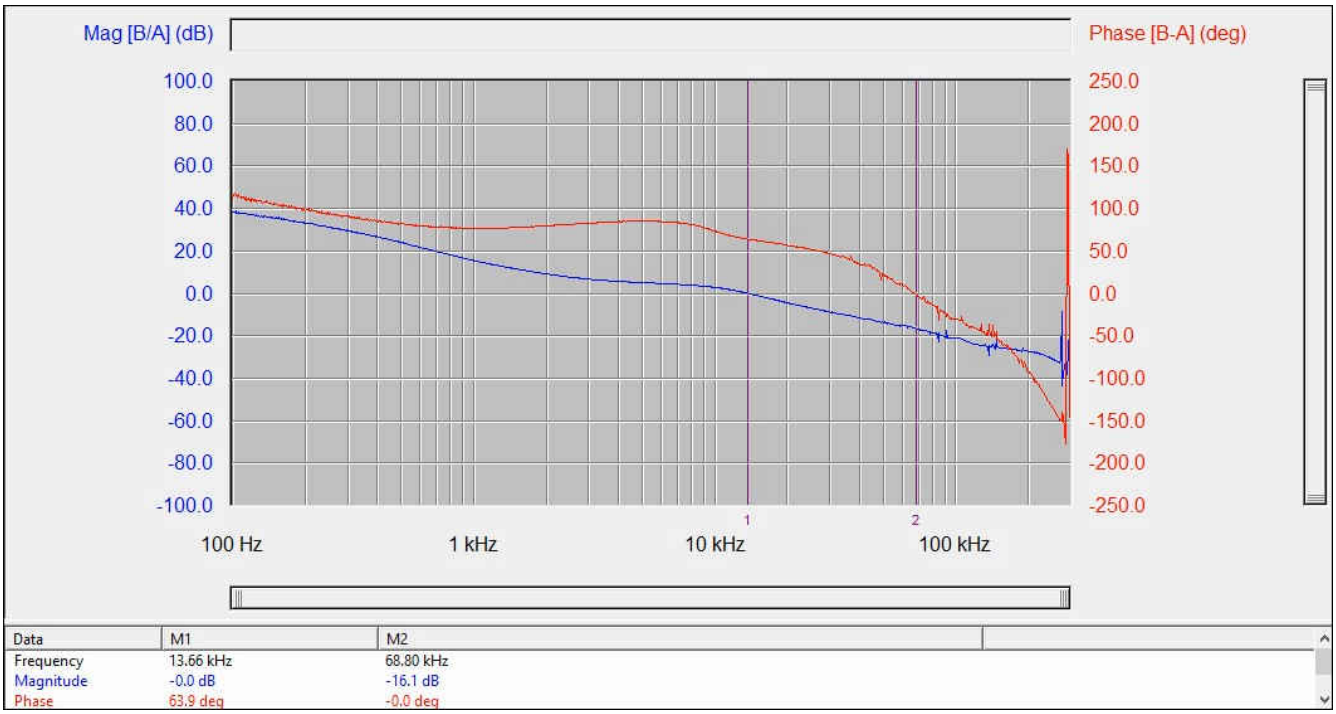

Figure 3-9. Loop Stability, 12 V_{IN}, 250-mA Load

3.5 Voltage Regulation

The voltage regulation of the LLC converter outputs is shown in the following figures.

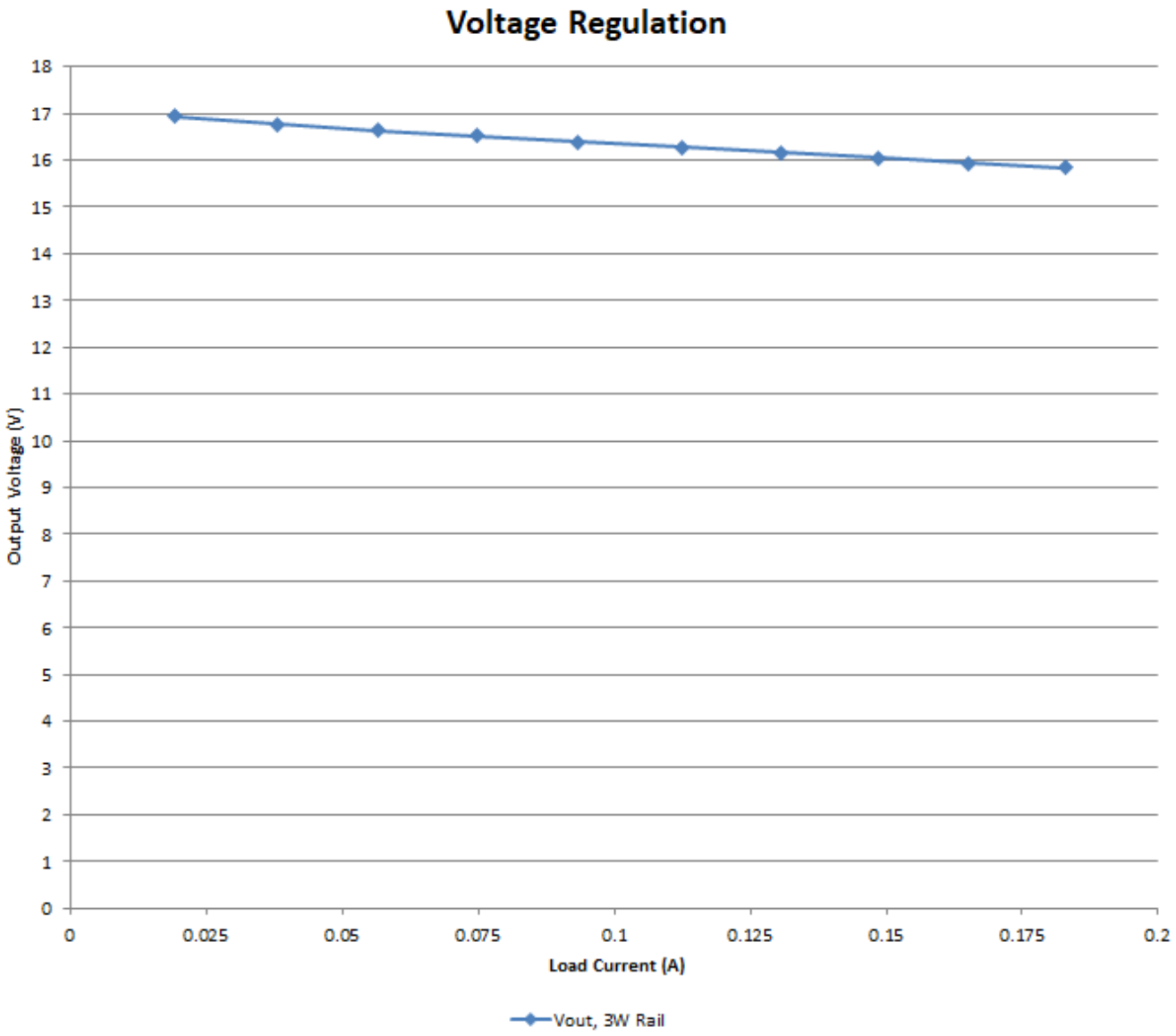

Figure 3-10. 3-W Rail Regulation Graph

Iout	Vout
0.02	16.9358
0.04	16.7660
0.06	16.6367
0.07	16.5165
0.09	16.3948
0.11	16.2709
0.13	16.1579
0.15	16.0451
0.17	15.9450
0.18	15.8361

Figure 3-11. 3-W Rail Regulation Table

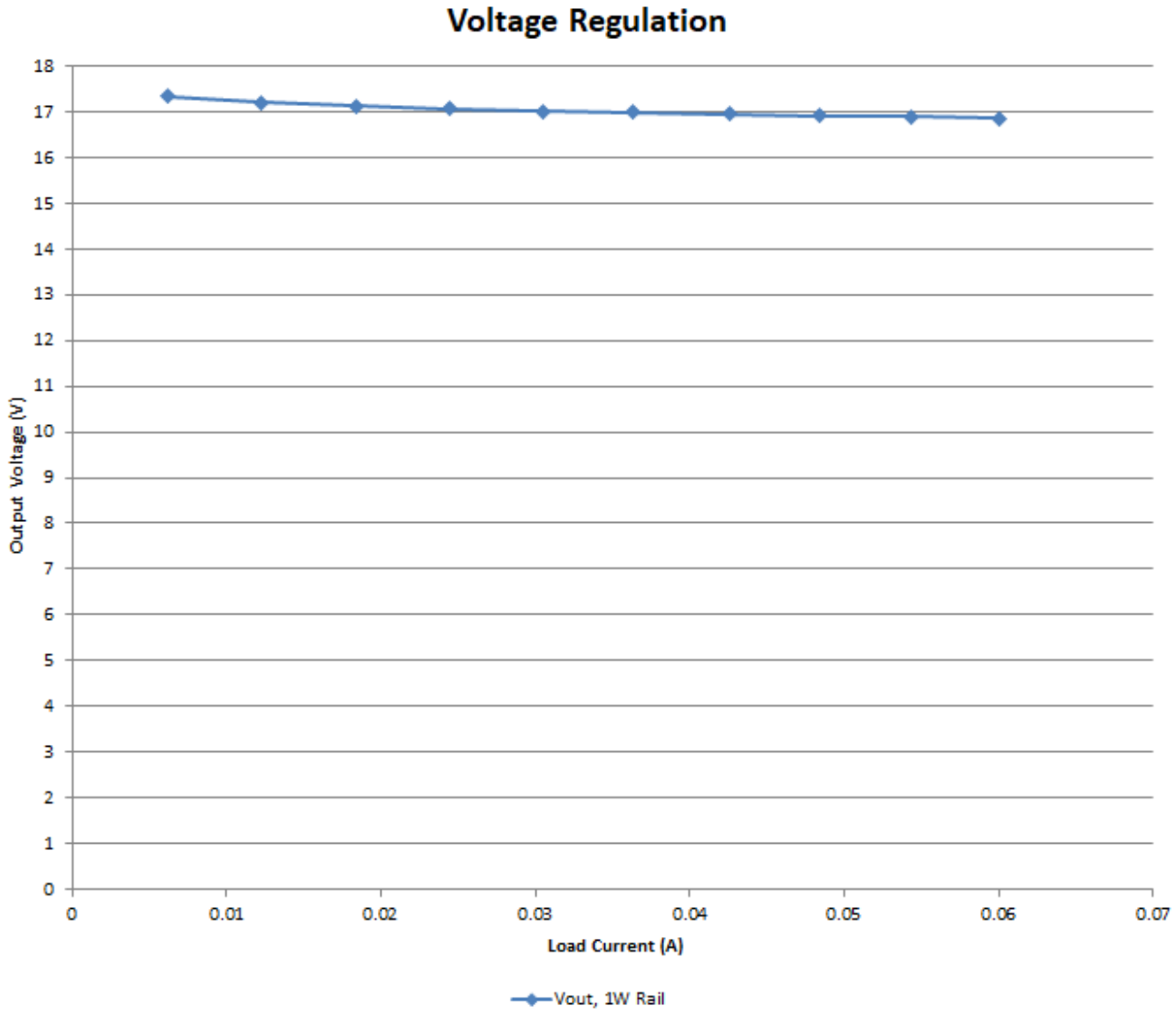

Figure 3-12. 1-W Rail Regulation

Iout	Vout
0.01	17.3481
0.01	17.2040
0.02	17.1340
0.02	17.0698
0.03	17.0223
0.04	16.9860
0.04	16.9510
0.05	16.9195
0.05	16.8890
0.06	16.8588

Figure 3-13. 1-W Rail Regulation Table

The cross regulation was measured to showcase the effects of varying load on the other outputs of the LLC converter. The 3-W rail (Vo3W) and one of the 1-W rails (Vo1W3) were varied while the other 2 rails (Vo1W1 and Vo1W2) were held constant.

Vo3W	Load %	Vo1W1	Load %	Vo1W2	Load %	Vo1W3	Load %
15.62	100%	16.08	100%	16.09	100%	16.07	100%
15.68	100%	16.14	100%	16.16	100%	16.28	50%
16.15	50%	16.29	100%	16.30	100%	16.28	100%
16.37	50%	16.64	50%	16.66	50%	16.64	50%
15.81	100%	16.42	50%	16.44	50%	16.42	50%
16.30	50%	16.57	50%	16.59	50%	16.43	100%

Figure 3-14. Cross Regulation Table

4 Waveforms

4.1 Switching

The switching behavior of both converters is shown in the following figures. As in previous sections, the two converters were evaluated separately.

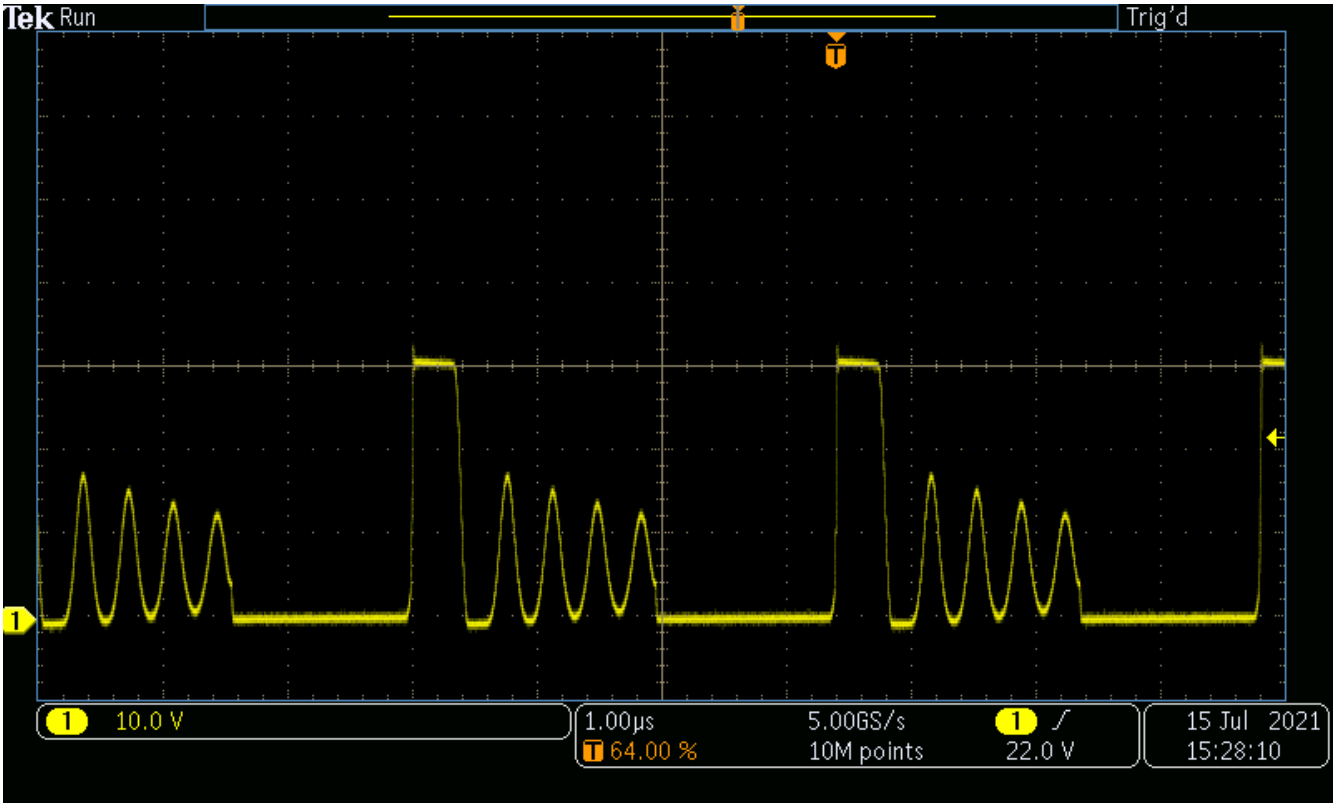

Figure 4-1. Boost Converter Switch Node, 6 V_{IN}, Light Load

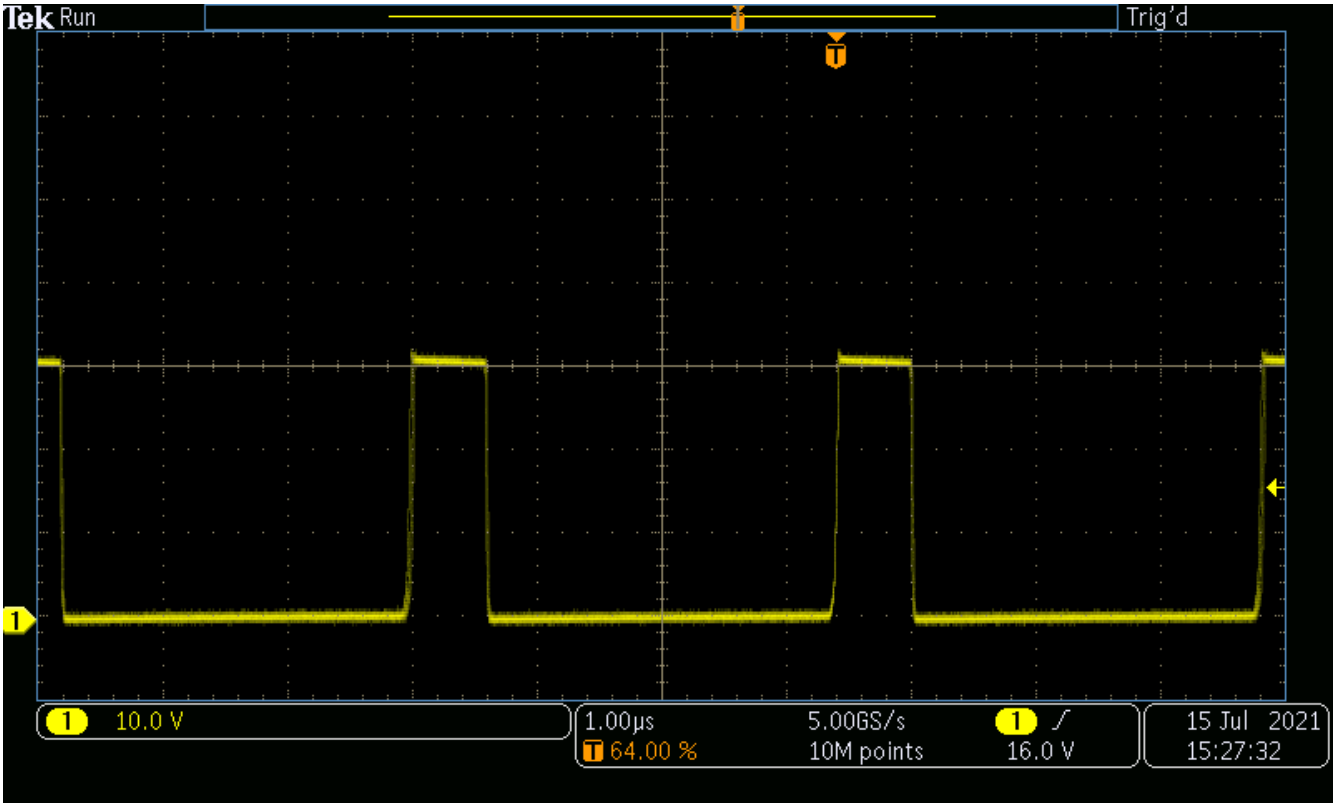

Figure 4-2. Boost Converter Switch Node, 6 V_{IN}, Maximum Load

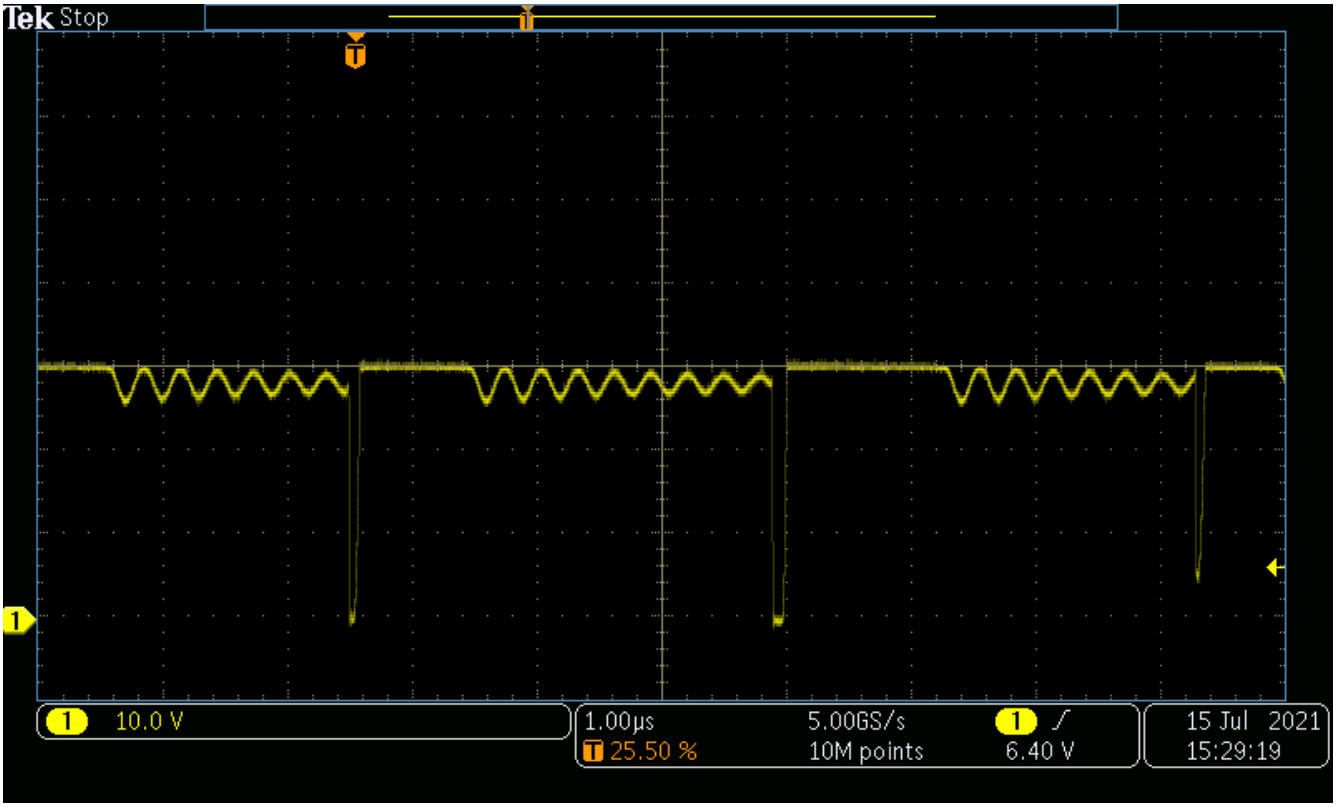

Figure 4-3. Boost Converter Switch Node, 28 V_{IN}, Light Load

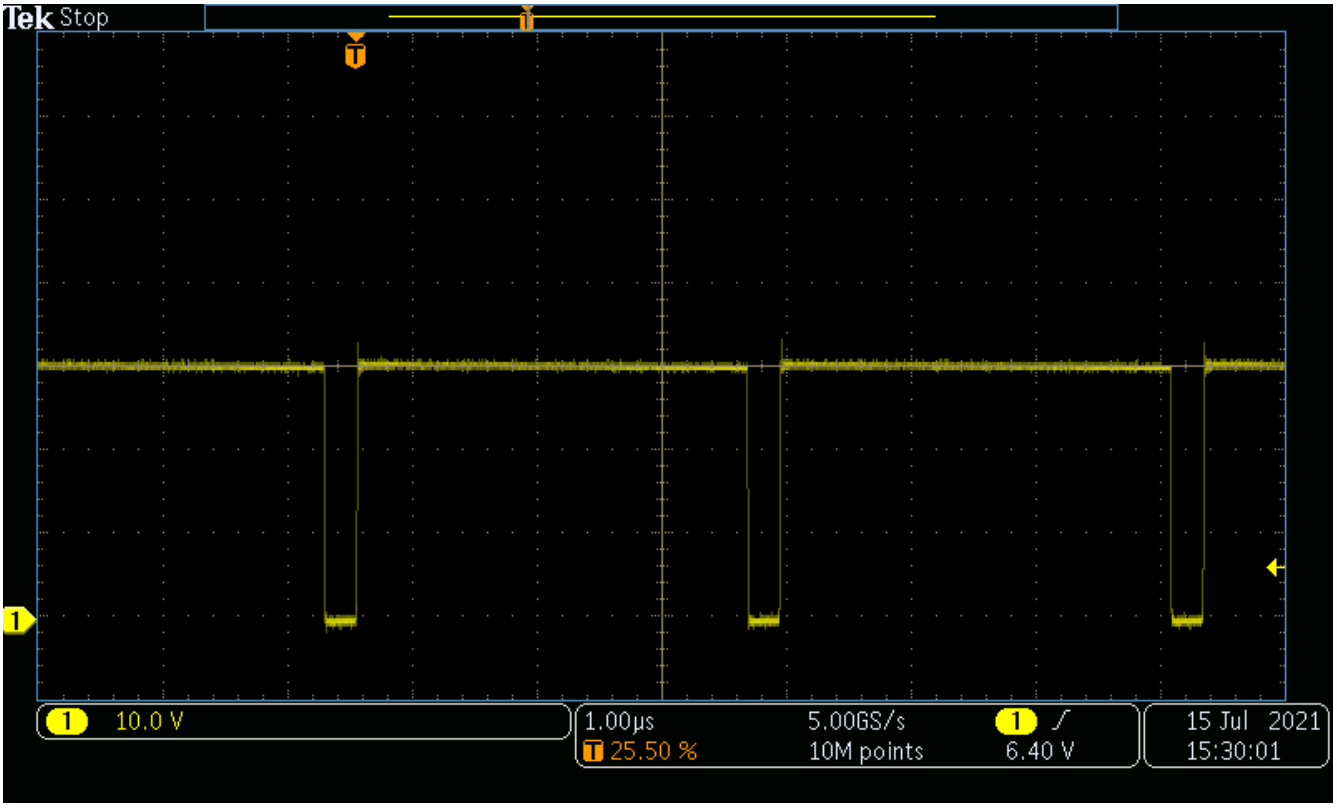

Figure 4-4. Boost Converter Switch Node, 28 V_{IN}, Maximum Load

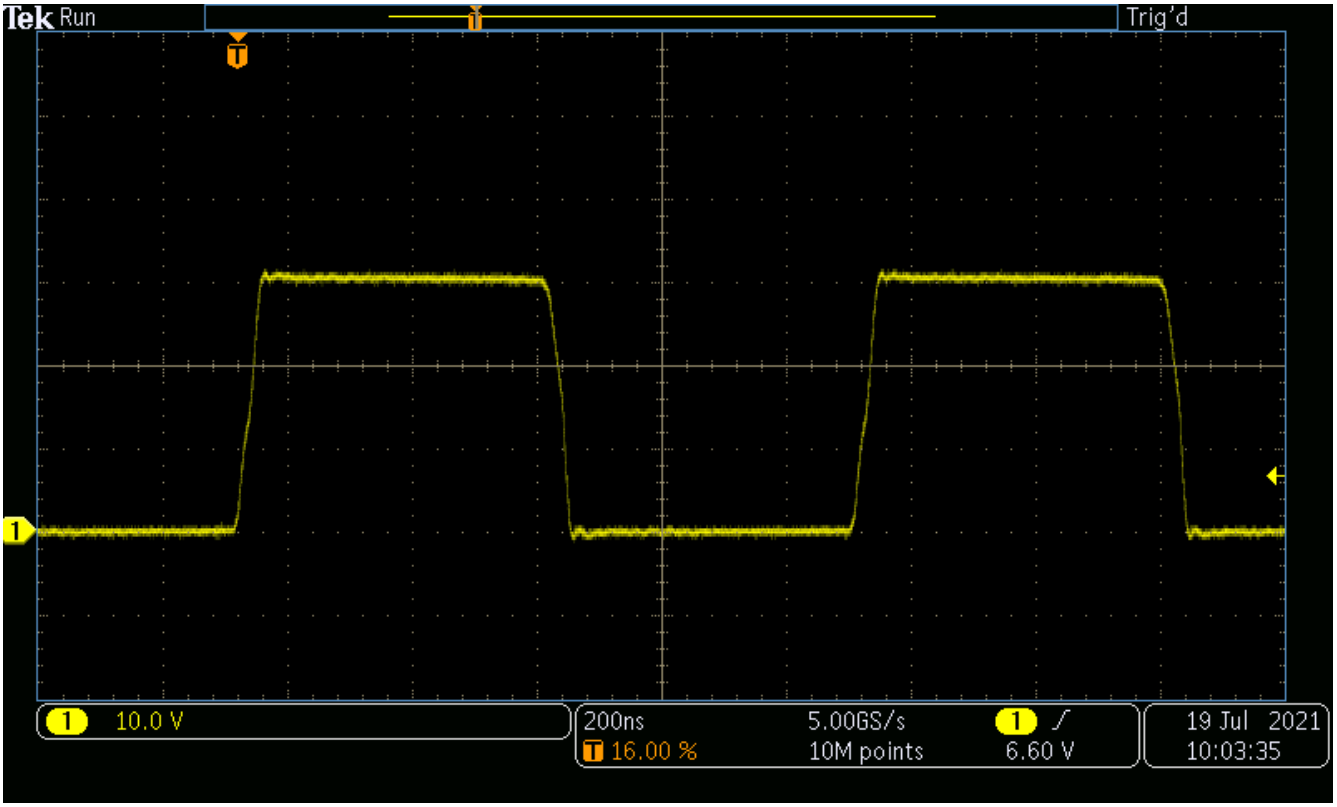

Figure 4-5. LLC Converter Primary Side Switch Node, 30 V_{IN}, No Load

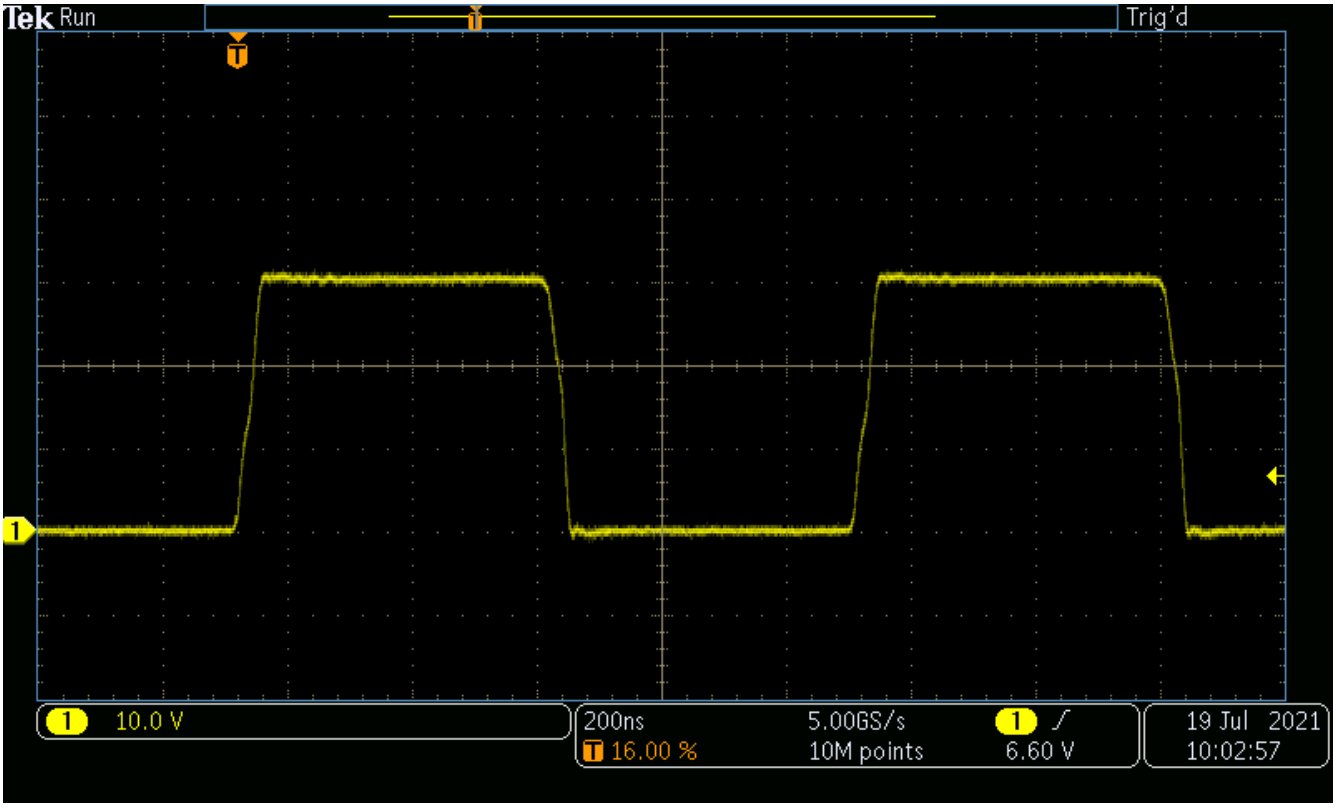

Figure 4-6. LLC Converter Primary Side Switch Node, 30 V_{IN}, 50% Load

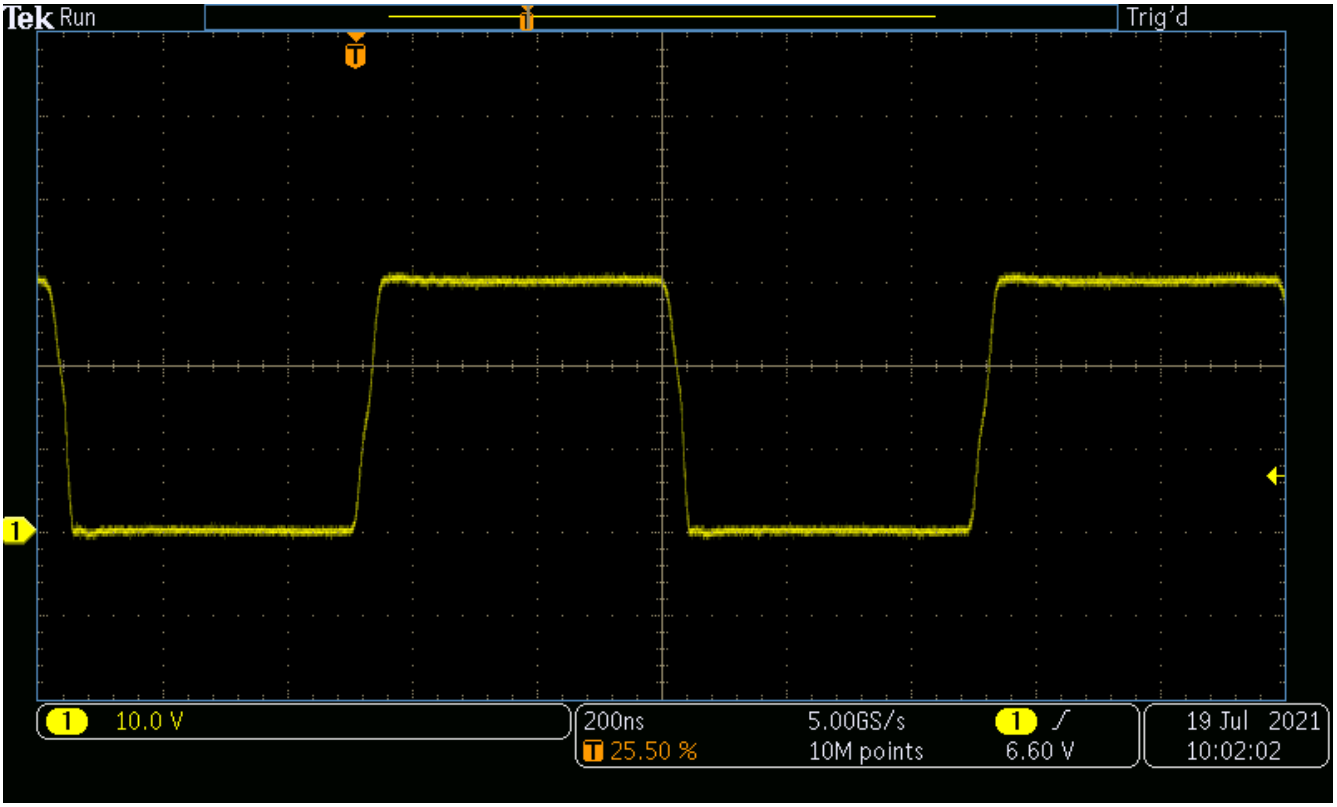

Figure 4-7. LLC Converter Primary Side Switch Node, 30 V_{IN}, Max Load

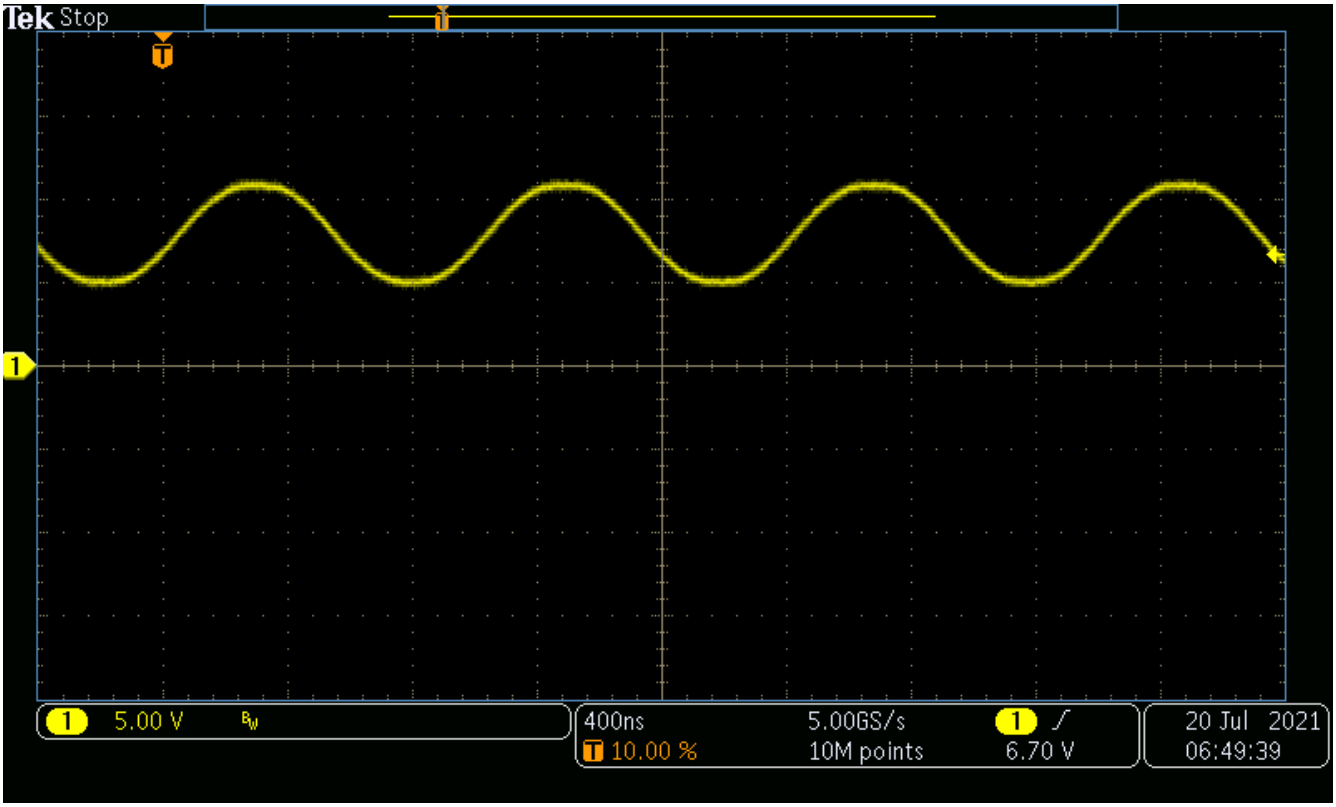

Figure 4-8. LLC Converter Secondary Side Resonant Capacitor, 30 V_{IN}, Max Load

4.2 Output Voltage Ripple

The output voltage ripple of each converter is shown in the following figures.

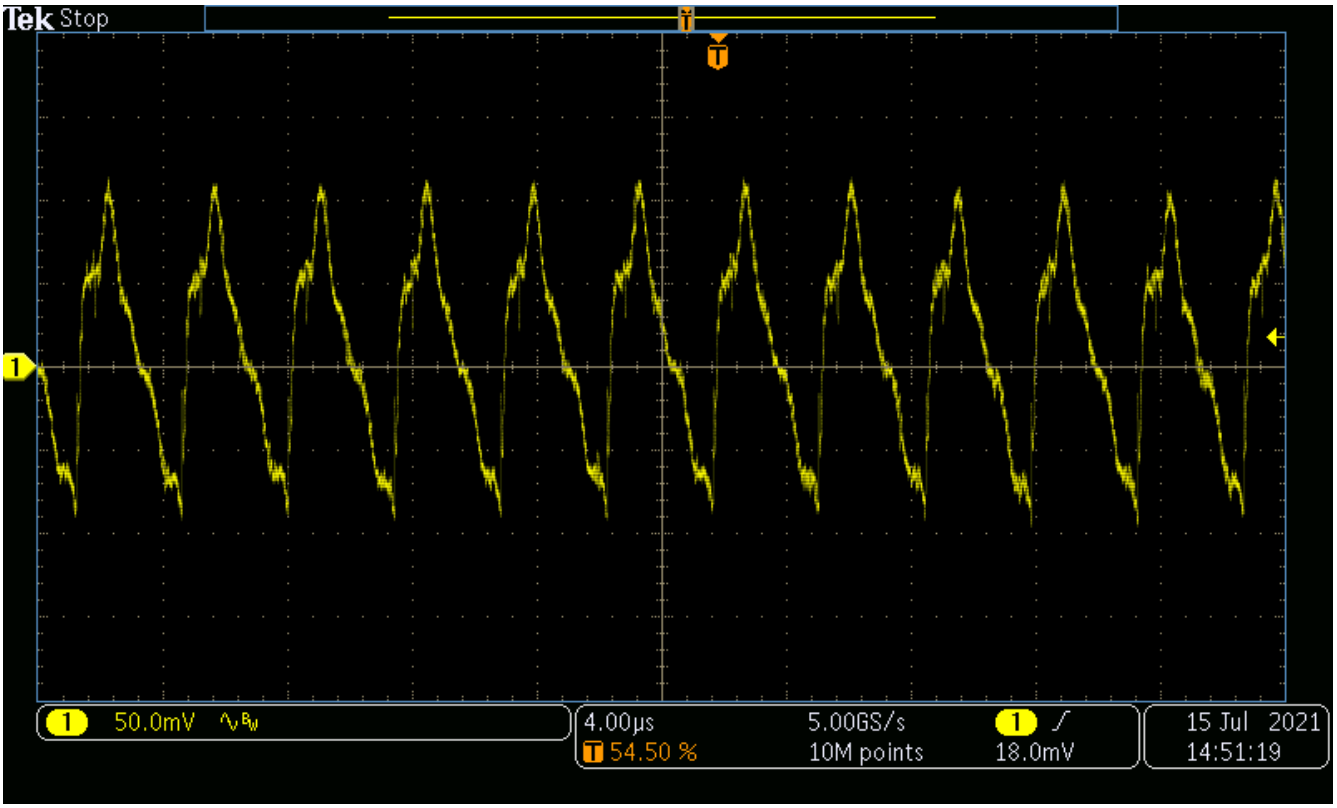

Figure 4-9. Boost Converter Output Ripple, 6 V_{IN}, Maximum Load

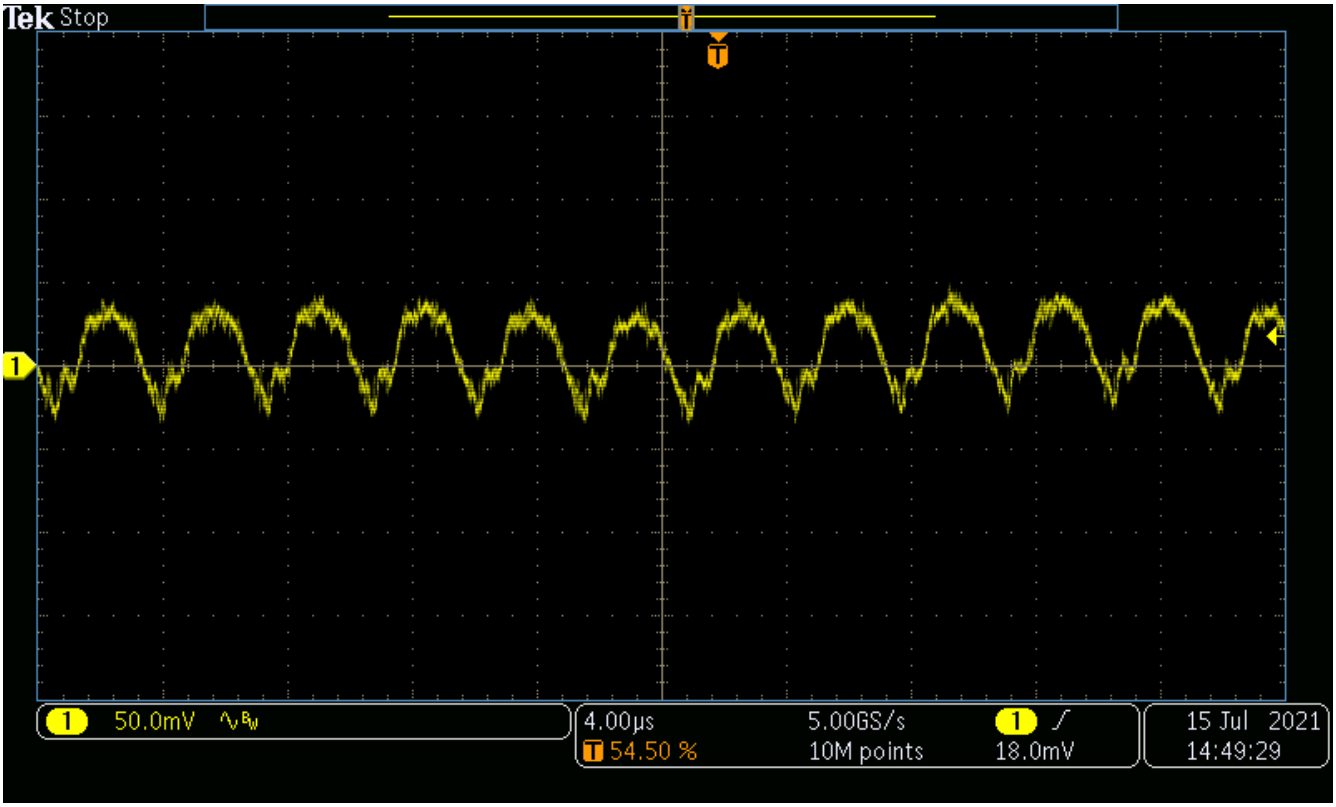

Figure 4-10. Boost Converter Output Ripple, 28 V_{IN}, Maximum Load

The LLC output ripple was measured on the 3-W rail to show the worst-case ripple.

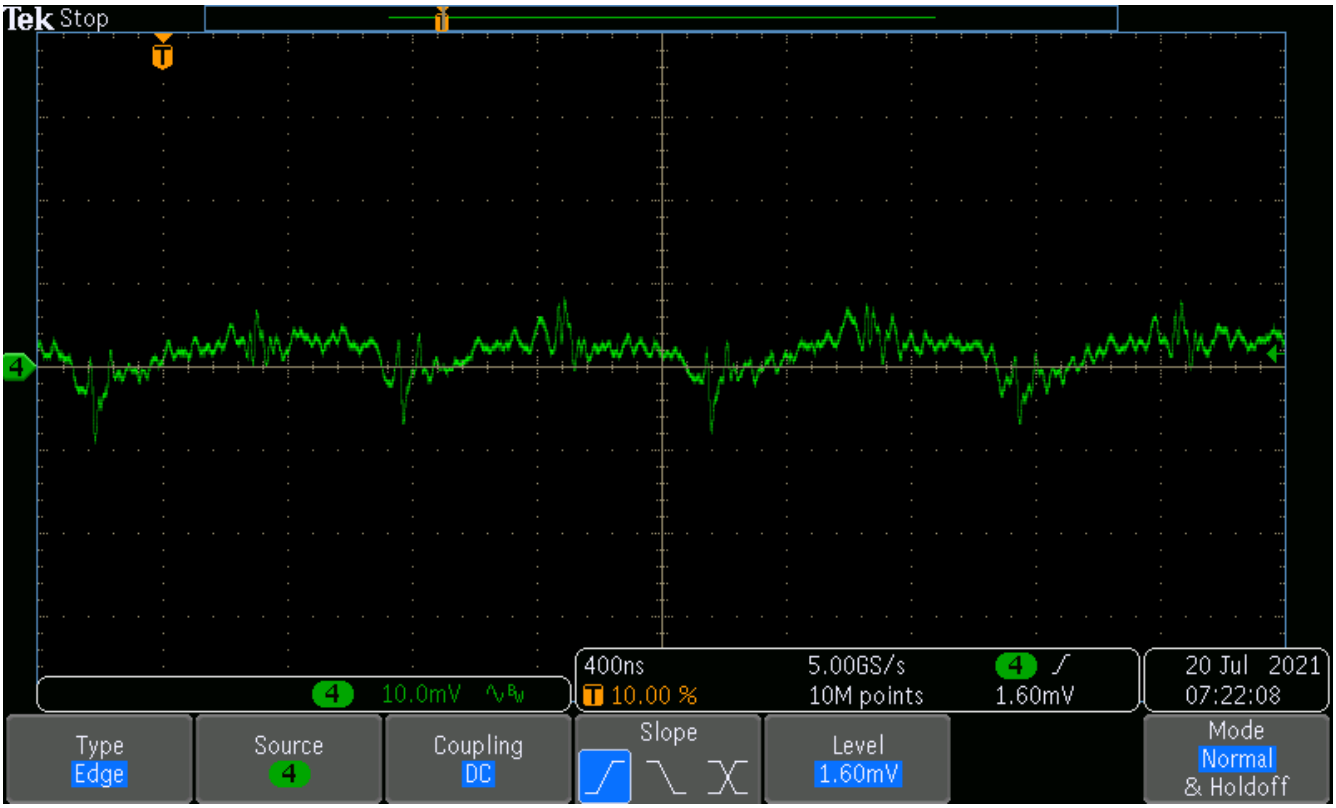

Figure 4-11. LLC Converter Output Ripple, 30 V_{IN}, Maximum Load

4.3 Start-up

The start-up behavior of each converter is shown in the following figures. The boost converter start-up was measured on controller enable, the controller was disabled by shorting the COMP pin to GND. V_{OUT} is shown in yellow.

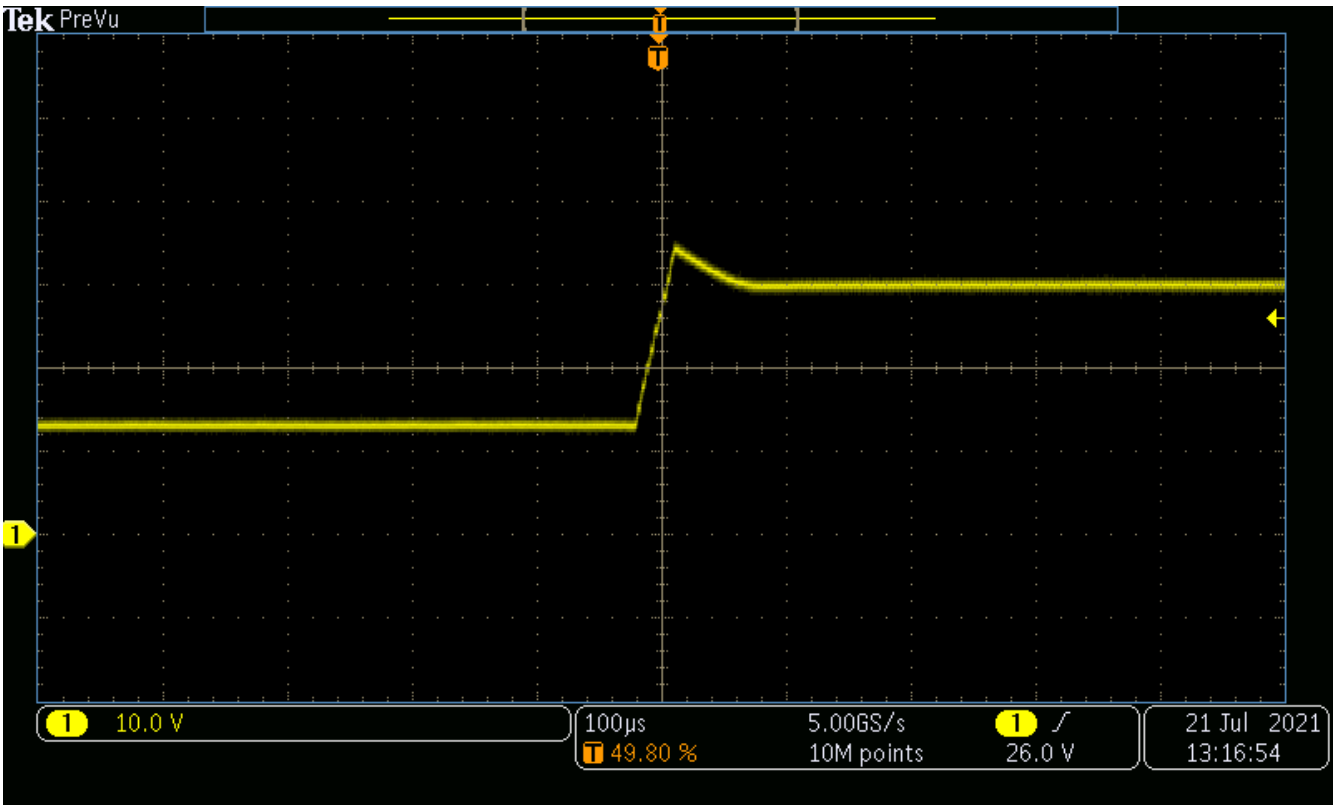

Figure 4-12. Boost Converter Start-up, 13.5 V_{IN}, Maximum Load

For the LLC converter, a 3-W output (yellow) and a 1-W output (blue) are shown.

Figure 4-13. LLC Converter Start-up, 30 V_{IN}, No Load

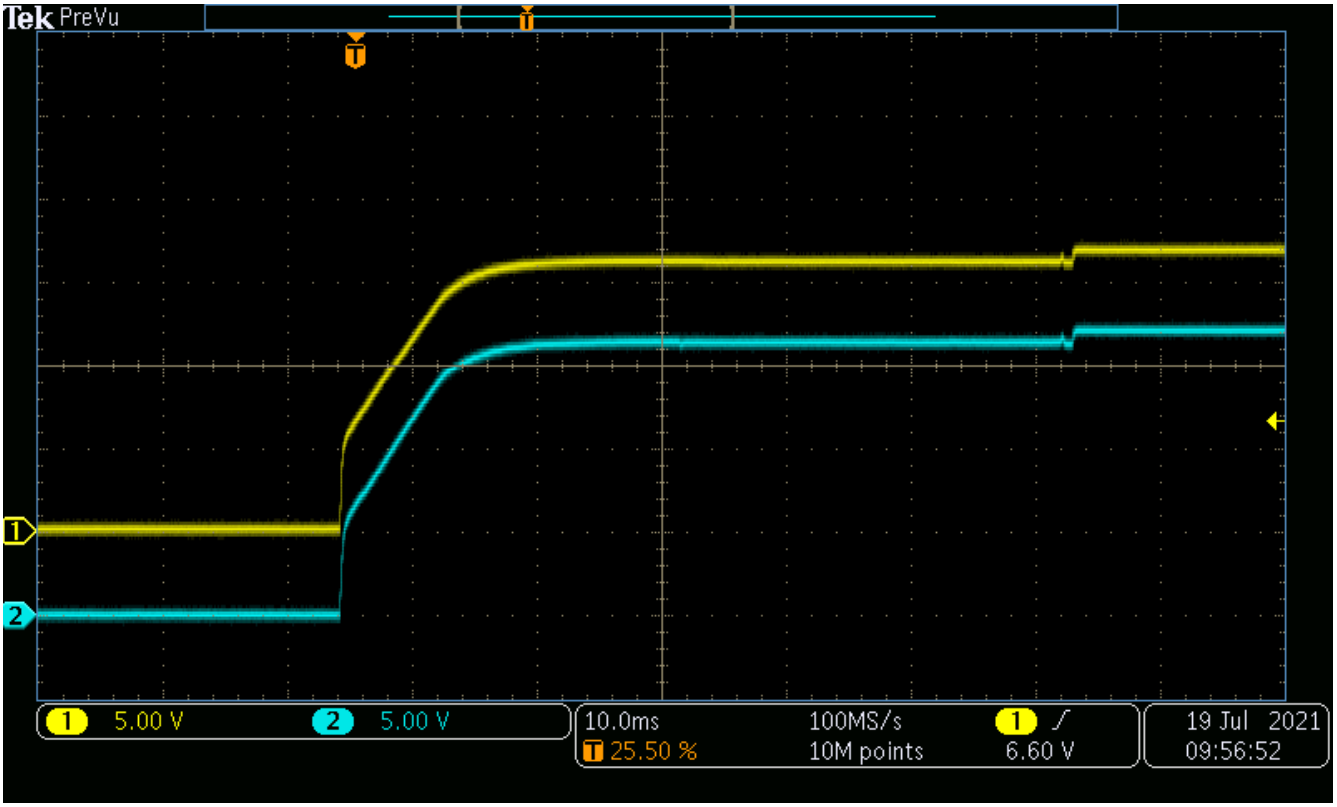

Figure 4-14. LLC Converter Start-up, 30 V_{IN}, 50% Load

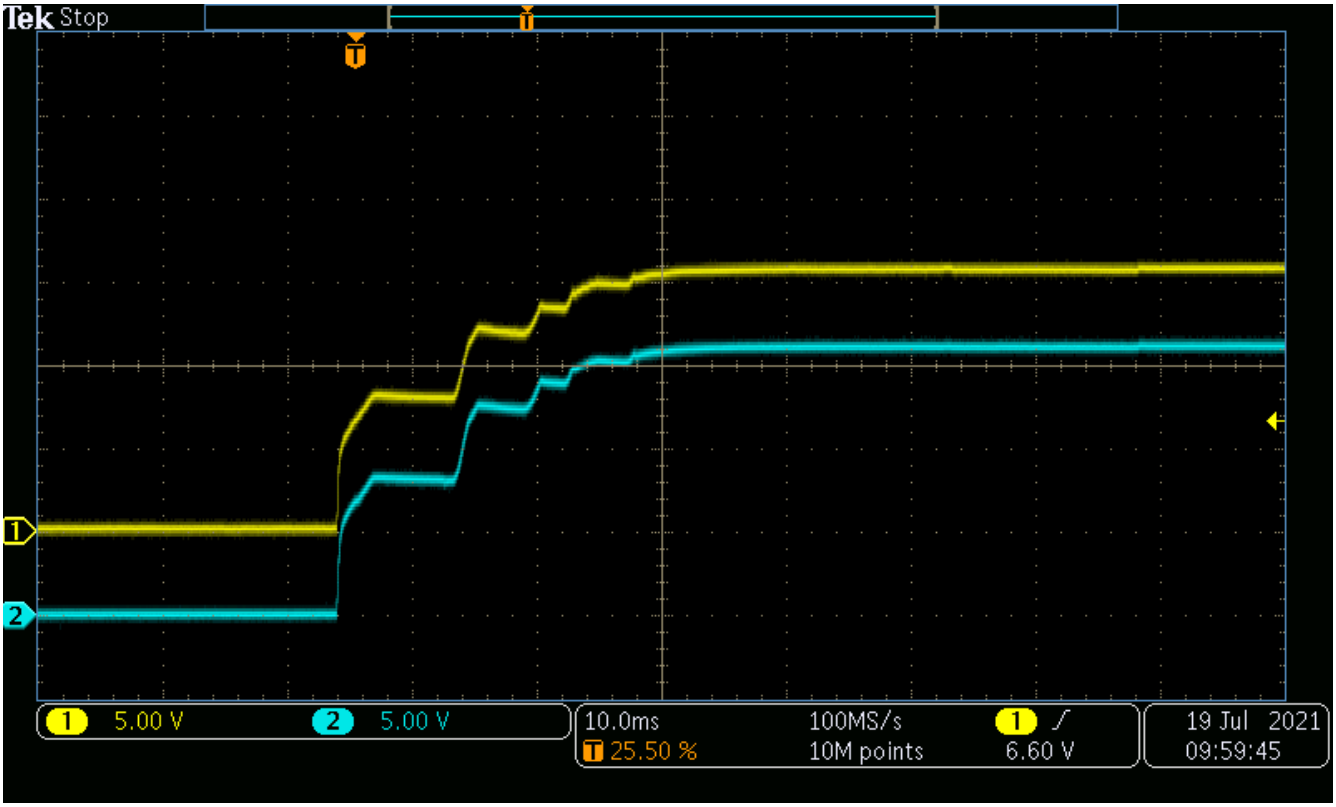

Figure 4-15. LLC Converter Start-up, 30 V_{IN}, Maximum Load

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