Automotive Capacitor Charger for Power Backup Applications Reference Design

TND6362/D

Description

The use case of this application is to have an energy storage unit consisting of capacitor in the power path of an ECU (Electronic Control Unit). Such a storage capacitor is often called a keep–alive capacitor. In the case of a failure of the battery power or during a cold start the charged capacitor provides power to maintain operation for a few milliseconds, to enable bringing the ECU to a defined state to avoid a re–start including booting of the main SoC (System–on–Chip) after recovery of the battery voltage and loss of memory data and settings.
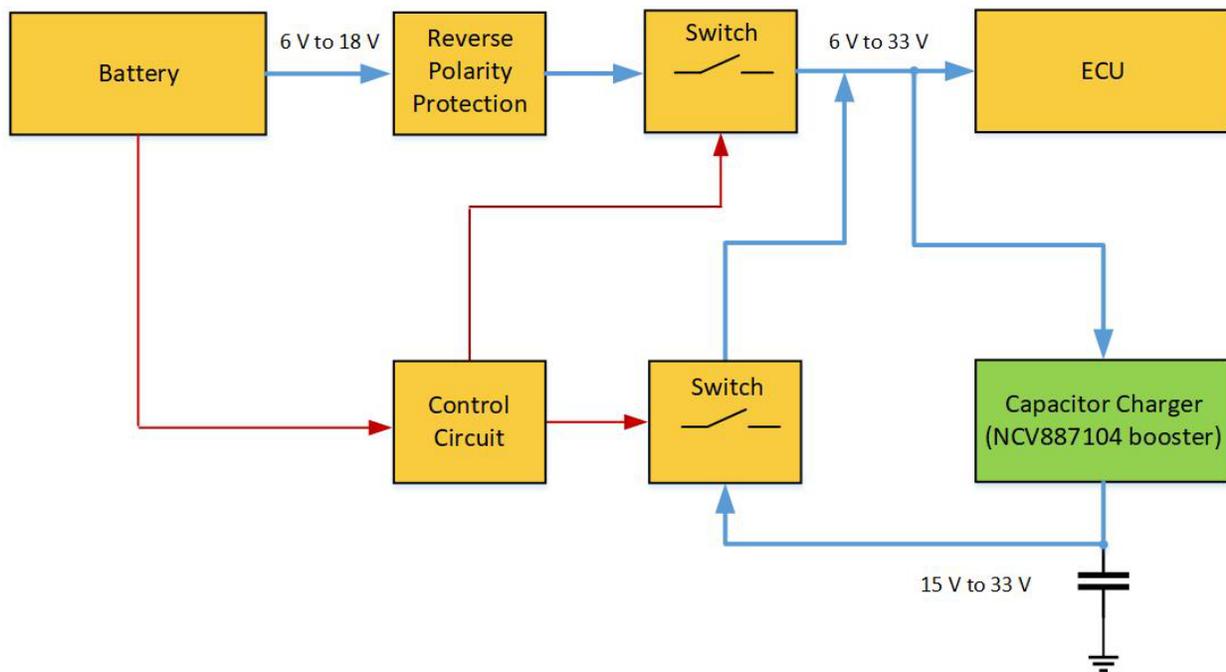

Figure 1. High–Level Power Tree Block Diagram

Figure 1. shows the high–level block diagram with keep–alive capacitor as a backup power source for the ECU. There are two low resistive switches and a reverse polarity protection (RPP) circuit. The control circuit is mainly a voltage monitoring circuit, which enables and disables the two switches dependent on the battery and capacitor voltage. The capacitor charger block is a non–synchronous boost converter based on a NCV887104 boost controller.

In normal operation when the battery voltage is between 6 V – 18 V, battery is used to supply the ECU and also to charge the keep–alive capacitor through the RPP and upper switch which is on the battery line. During this period, the lower switch is switched off to avoid discharging the keep–alive capacitor.

The control circuit is used to monitor the battery voltage all the time. In case of a cold crank or fault of the battery, the battery voltage will be less than 6 V which is not enough to run the ECU. The control circuit switches the load from battery to keep–alive capacitor and flags it to the ECU, so that it will be brought to a defined state. When the battery voltage comes back up to the nominal value the load will again be switched back from keep–alive capacitor to battery.

The capacitor charger is based on a booster which converts 6 V to 18 V input voltage to 33 V output voltage to charge a large electrolytic capacitor (several mF) with a current of around 2 A average. Current limitation is done by the integrated cycle–by–cycle current limit based on the FET (Field Effect Transistor) peak current (ISNS), which is

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set to 5 A maximum. As the peak current depends on the input and output voltage, the output current is not constant but decreases while the capacitor is charged and the voltage increases. Therefore, the charging current is higher than 2 A at the beginning of the charging cycle and decreased toward the end. NCV887104 is a boost controller with a fixed frequency of 340 kHz and uses an external N−FET (N channel Field Effect Transistor) (NVTYS003N04CL) and diode (NRVBS2040LT3G). Generally, a booster is used as a voltage source but for this application it is used as a current

source to charge the capacitor. An important feature is its cycle−by−cycle current limit without any overcurrent shutdown or hiccup mode which enables the booster circuit to be used as a current source, required to charge a capacitance. As soon as the output voltage reaches 33 V, it is regulated by the feedback voltage divider (VFB). To evaluate the charging of a large capacitance, a 50 V low ESR (Equivalent Series Resistance) capacitor bank with 50 mF in total is used.
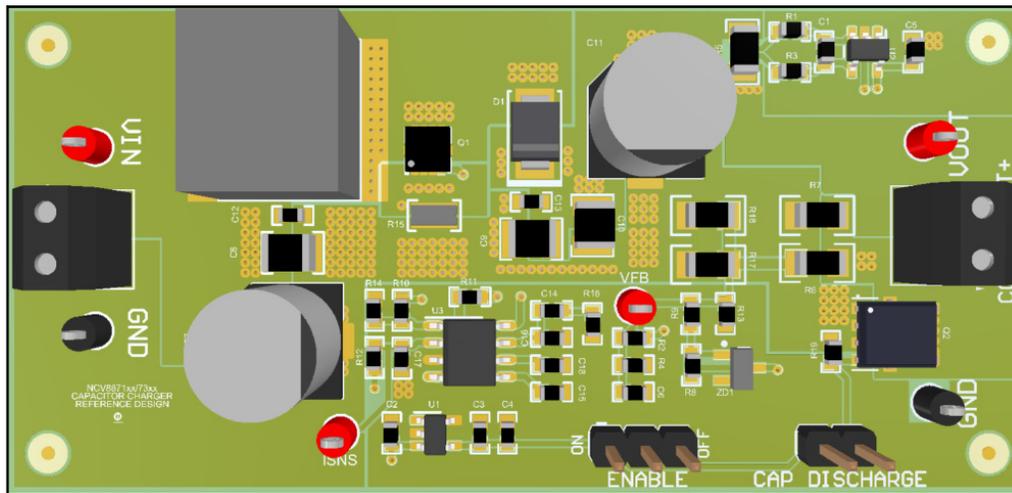

Figure 2. 3D View of the Capacitor Charger Board

Key Features

- Complete automotive reference design
- Non−synchronous boost converter with an input voltage range of 6 V to 18 V and 33 V output voltage
- 340 kHz switching frequency
- 3.3 V auxiliary power supply to enable NCV887104 controller
- **onsemi** NCV887104D1R2G adjustable output non−synchronous boost controller, NVTYS003N04CL 40 V N−FET, NCV4294CSN33T1G 30 mA LDO and NRVBS2040LNT3G Schottky diode
- 76 mm x 37 mm small form factor 4−layer PCB (Printed Circuit Board)

Schematic

Figure 3 shows the schematic with NCV887104 booster circuit and NCV4294C auxiliary power supply. ISNS and VFB test points are used to monitor the current limitation

and voltage regulation during evaluation. The external compensator network contains only a capacitor (C14) connected to the output of the transconductance error amplifier (VC) to stabilize the output voltage. As transient response is not important for this application, a simple type 1 compensation (integrator) is sufficient. The input voltage is connected to J1 to power up the board, electrolytic capacitors with a few mF up to tens of mF will be connected to J2 for charging. J3 is used to enable/disable the booster.

A precise current regulation which provides a constant charging current of 2 A from the beginning until the end of the complete charging cycle would be significantly more complex using an additional current measurement circuit such as an integrated high−side current monitor. As the main purpose of the current limitation is to limit the input current and to avoid too high currents, less precision is acceptable. Relying on the cycle−by−cycle current limitation provides enough accuracy for this use case and keeps the solution cost and space effective.
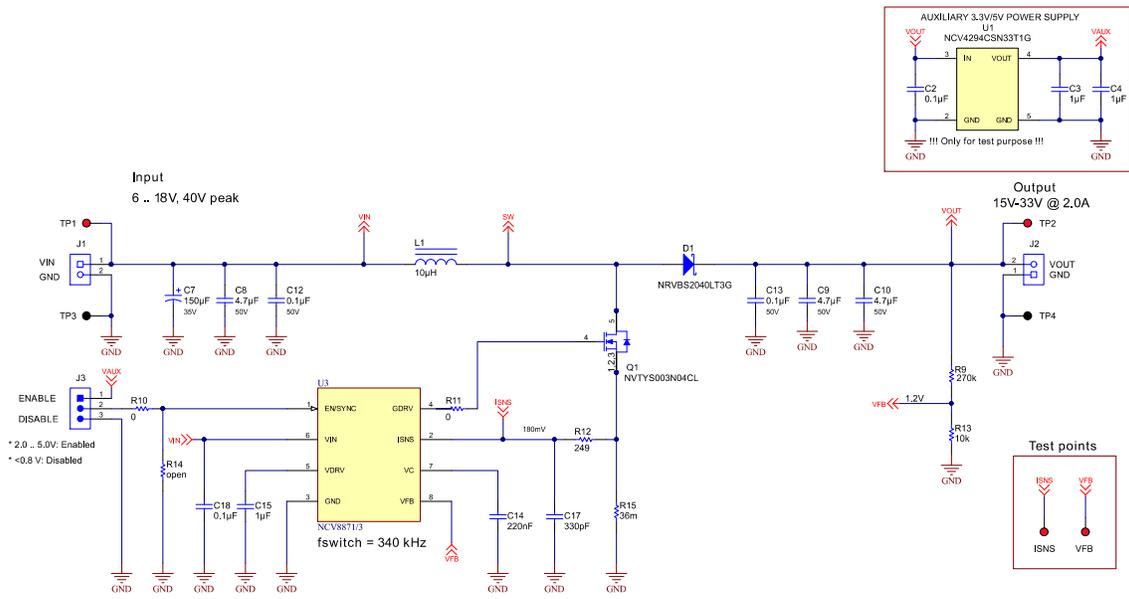
Figure 3. Schematic

Layout

Figures 4 to 7 show the four layers of the layout. The current loops are kept as short as possible to minimize parasitic inductances thereby reducing ringing and EMI (Electromagnetic Interference). An important role is played by the central and compact GND (Ground) plane of the power stage in the middle of the PCB which closes the current loops. The bottom layer is dedicated to the common GND plane and the single point where GND of the power stage and GND of the controller are connected. Power stage and controller GND planes of the upper layers are bifurcated to reduce any interference between high current GND (power stage GND) and signal GND (controller GND). In order to dissipate heat effectively, identical copper pours have been copied to various layers and connected by numerous vias. This helps also to have the current well distributed.

Figure 4. Layout – Top Layer
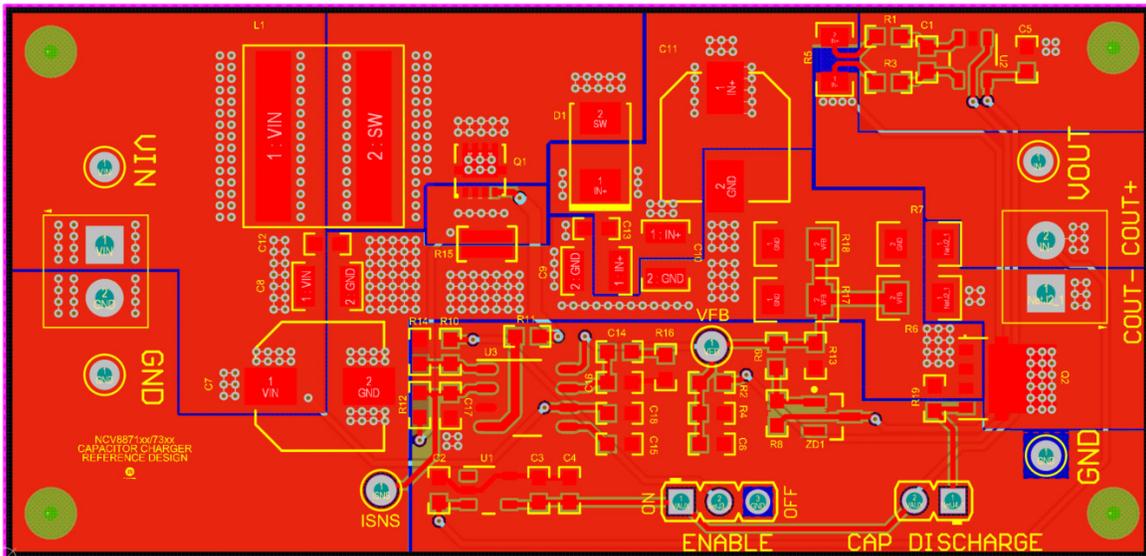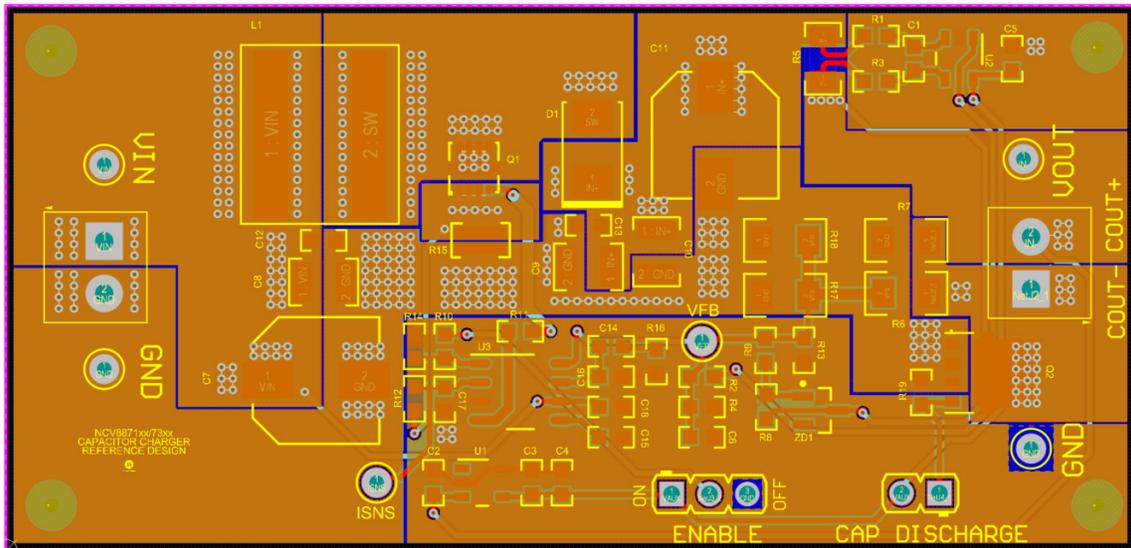
Figure 5. Layout – Inner Layer 1
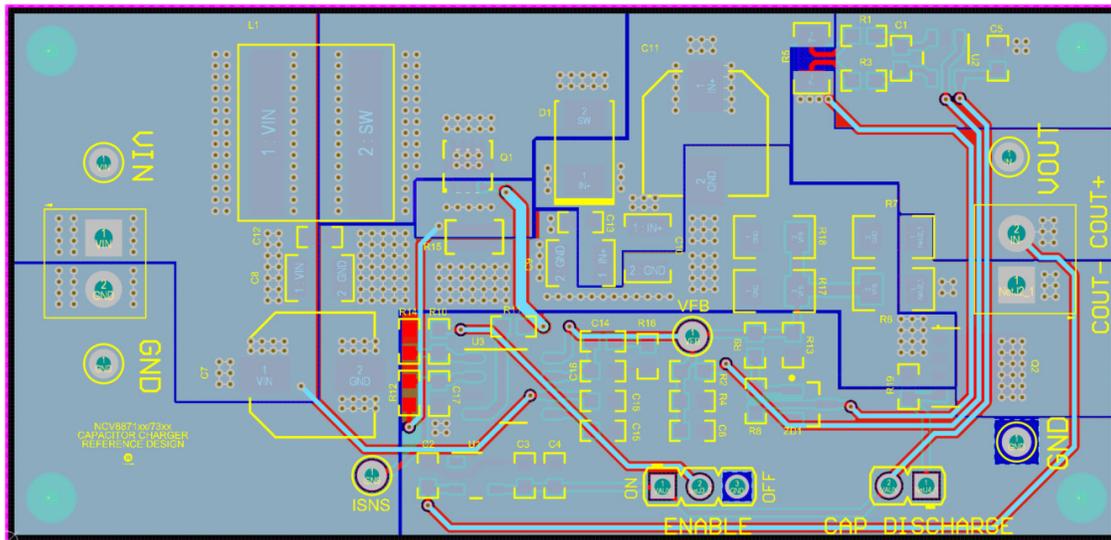
Figure 6. Layout – Inner Layer 2
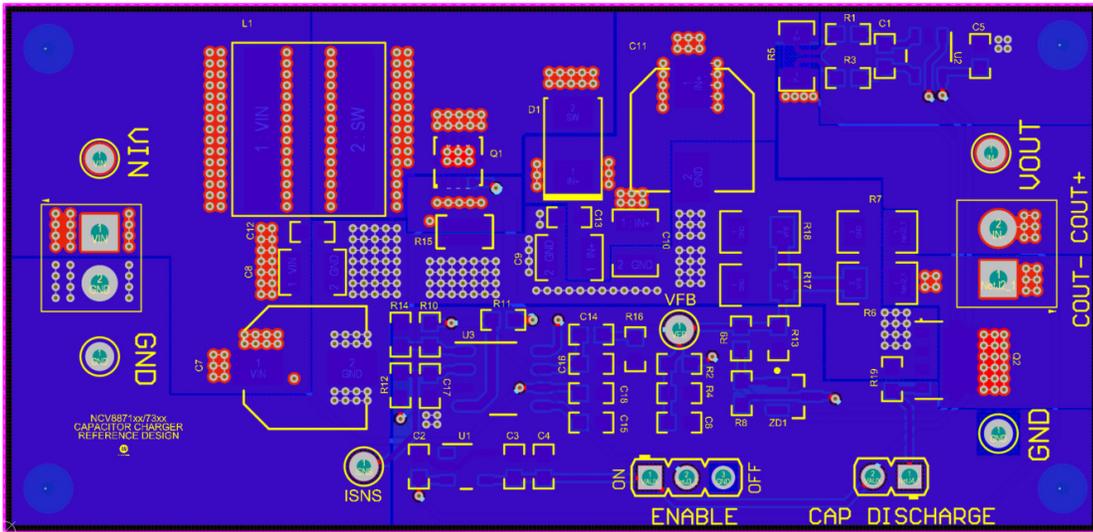
Figure 7. Layout – Bottom Layer

Efficiency Measurement

Efficiency is measured at 12 V and 18 V input voltage. The maximum load was set such that the booster was not in current limitation but could achieve 33 V on the output.

NOTE: For charging cycle measurement (Figure 13) a 50 mF output capacitor was connected as a load. For all other measurements an electronic load, with constant load current, was used.
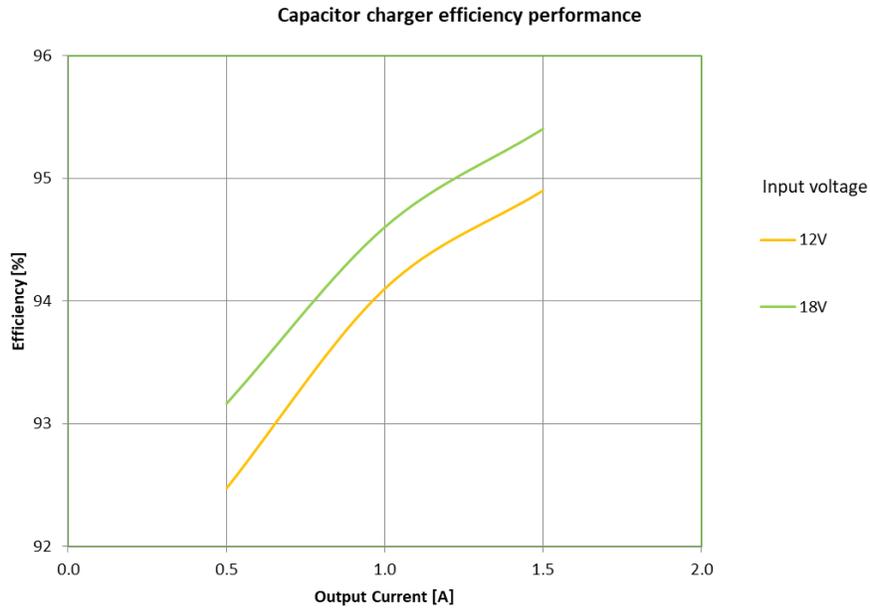

Capacitor charger efficiency performance

Figure 8. Efficiency – 12 V and 18 V Input Voltage

Output Voltage Ripple

- Test Condition: 12 V input voltage, 23 V output voltage, 2 A load
- Channel 4: Output voltage, AC coupled, 200 mV / div, 5 µs / div
- ±600 mV ripple

The board is designed to charge the output capacitor with around 2 A average current. But as the output voltage ramps up, the output current ramps down. In order to measure voltage ripple, the board is forced to supply continuous 2 A at the output by using an external load. At 12 V input voltage and 2 A output current the output voltage settles around 23 V.
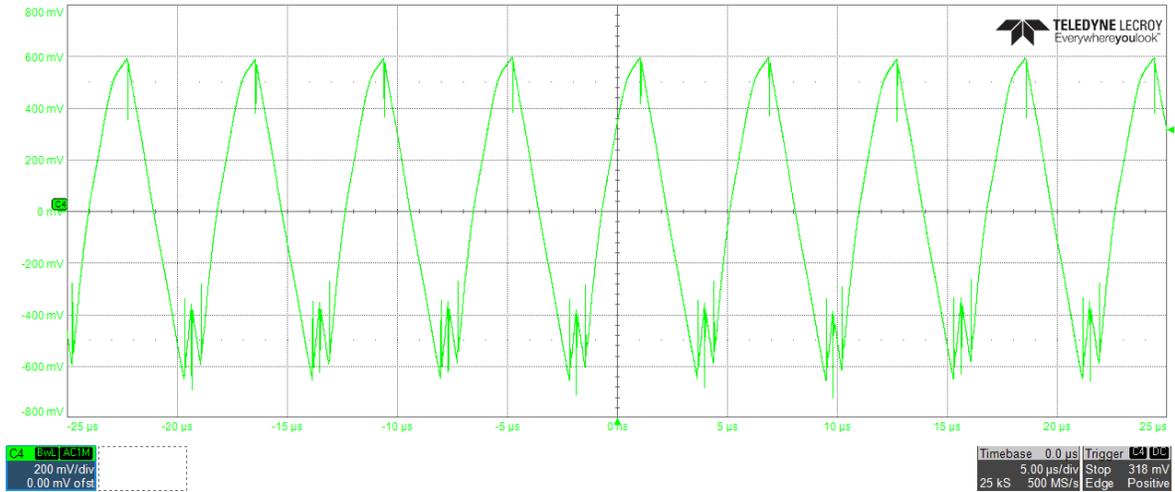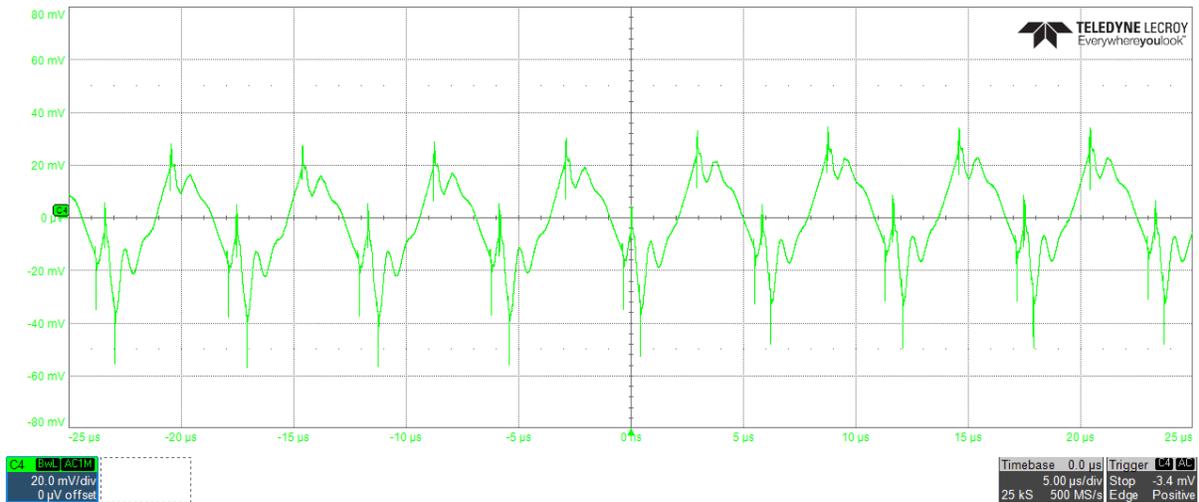
Figure 9. Output Voltage Ripple – 12 V Input Voltage, 23 V Output Voltage, 2 A Load

- Test Condition: 18 V input voltage, 33 V output voltage, 2 A load
- Channel 4: Output voltage, AC coupled, 200 mV / div, 5 µs / div
- ±400 mV ripple

At 18 V input voltage and 2 A load on the output, the booster is not in current limitation anymore and can supply 2 A continuously at 33 V output voltage.
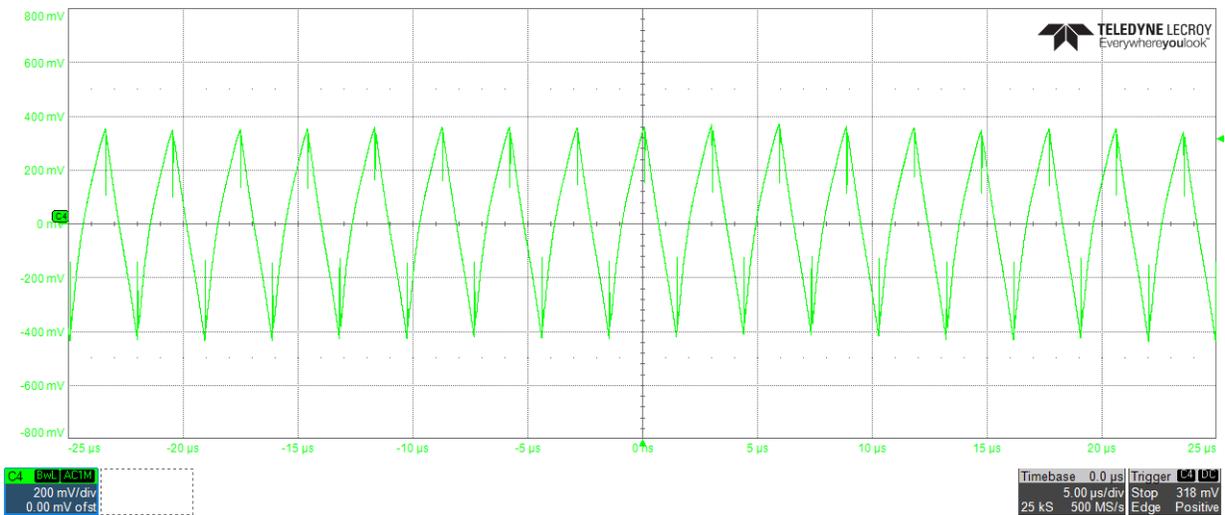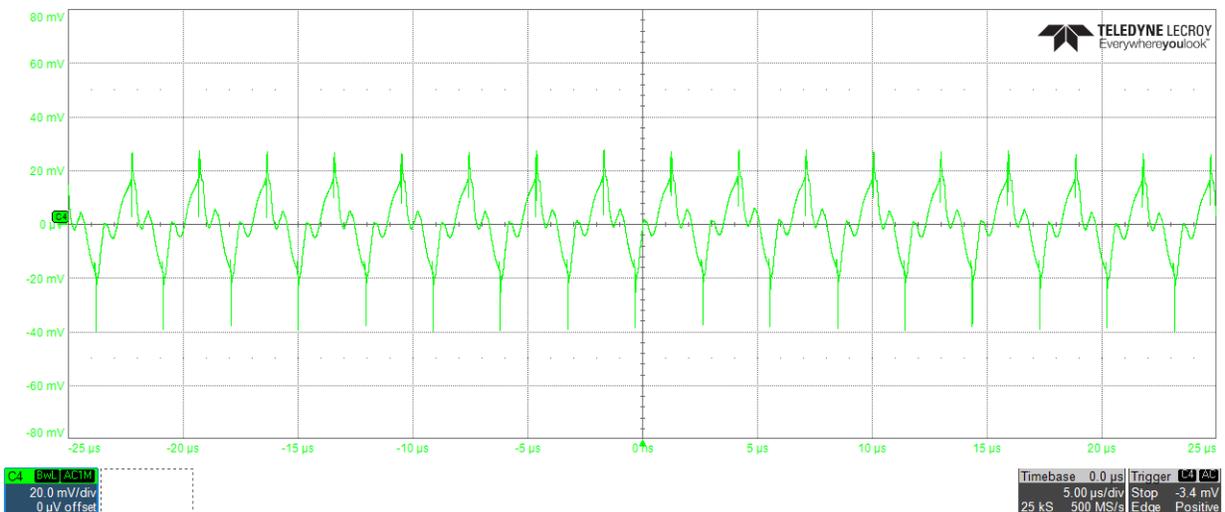
Figure 10. Output Voltage Ripple – 18 V Input Voltage, 33 V Output Voltage, 2 A Load

Input Voltage Ripple

- Test Condition: 12 V input voltage, 23 V output voltage, 2 A load
- Channel 4: Input voltage, AC coupled, 20 mV / div, 5 µs / div
- ±30 mV ripple

The board is designed to charge the output capacitor with around 2 A average current. But as the output voltage ramps up, the output current ramps down. In order to measure voltage ripple, the board is forced to supply continuous 2 A at the output by using an external load. At 12 V input voltage and 2 A output current the output voltage settles around 23 V.

Figure 11. Input Voltage Ripple – 12 V Input Voltage, 23 V Output Voltage, 2 A Load

- Test Condition: 18 V input voltage, 33 V output voltage, 2 A load
- Channel 4: Input voltage, AC coupled, 20 mV / div, 5 µs / div
- ±30 mV ripple

At 18 V input voltage and 2 A load on the output, the booster is not in current limitation anymore and can supply 2 A continuously at 33 V output voltage.

Figure 12. Input Voltage Ripple – 18 V Input Voltage, 33 V Output Voltage, 2 A Load

Capacitor Charging Cycle

- Test Condition: 12 V input voltage
- Channel 1: Input voltage, 2 V / div, 100 ms / div
- Channel 2: Output voltage, 5 V / div, 100 ms / div
- Channel 3: Output current, 1 A / div, 100 ms / div
- Channel 4: Enable signal, 5 V / div, 100 ms / div

During the initial connection of the booster to the supply voltage, the capacitance connected to the output is pre−charged to the input voltage. To avoid an overstress of the booster's diode, the current needs to be limited accordingly. The charging cycle itself starts as soon as the boost converter is enabled (EN goes high).
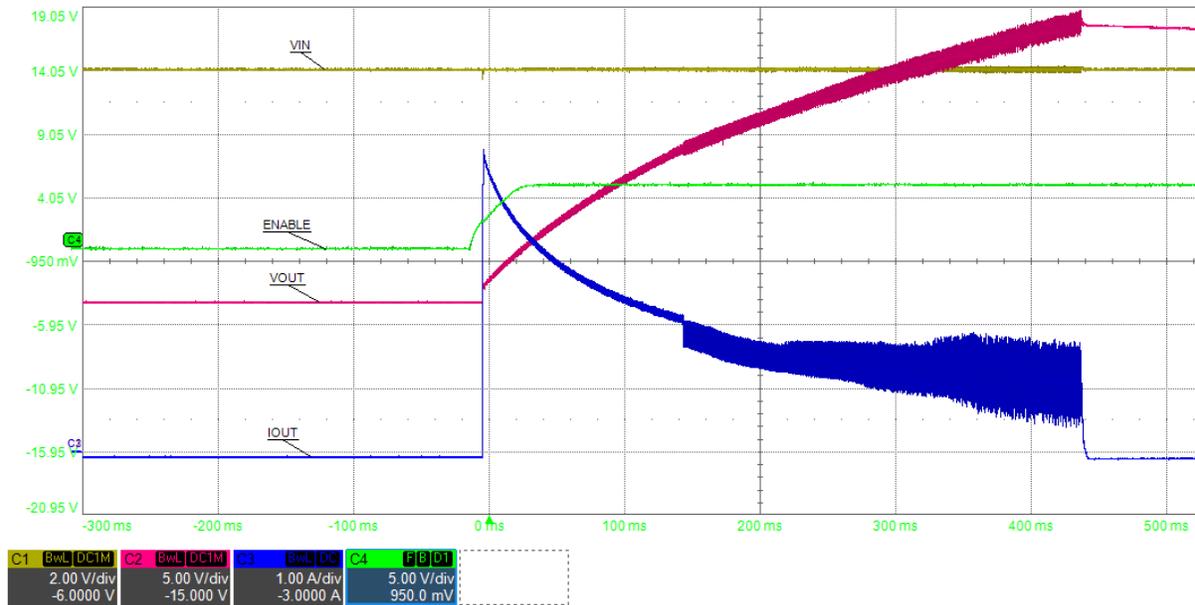
Figure 13. Charging Cycle – 12 V Input Voltage, 50 mF Capacitance

As soon as the booster is enabled (channel 4), the output voltage (channel 2) increases and the capacitance is being charged. At the same time the output current (channel 3) decreases. The reason for that is that the output current is regulated by the cycle−by−cycle current limitation of the controller only, which changes by the ratio of input voltage to output voltage. This is rather inaccurate as described already at the beginning of the application note, but sufficient for this kind of application. It can be seen on channel 3 that the average current over the whole cycle is approximately 2 A. As soon as the output voltage reaches 33 V, the booster stops switching as no load besides the capacitance's leakage current is present.

Bode Measurement

The frequency response at 6 V input voltage and 3 A load is shown in Figure 14.

- Test Condition: 6 V input voltage, 33 V output voltage, 0.5 A load
- 4.4 kHz bandwidth
- 71° phase margin
- −15 dB gain margin
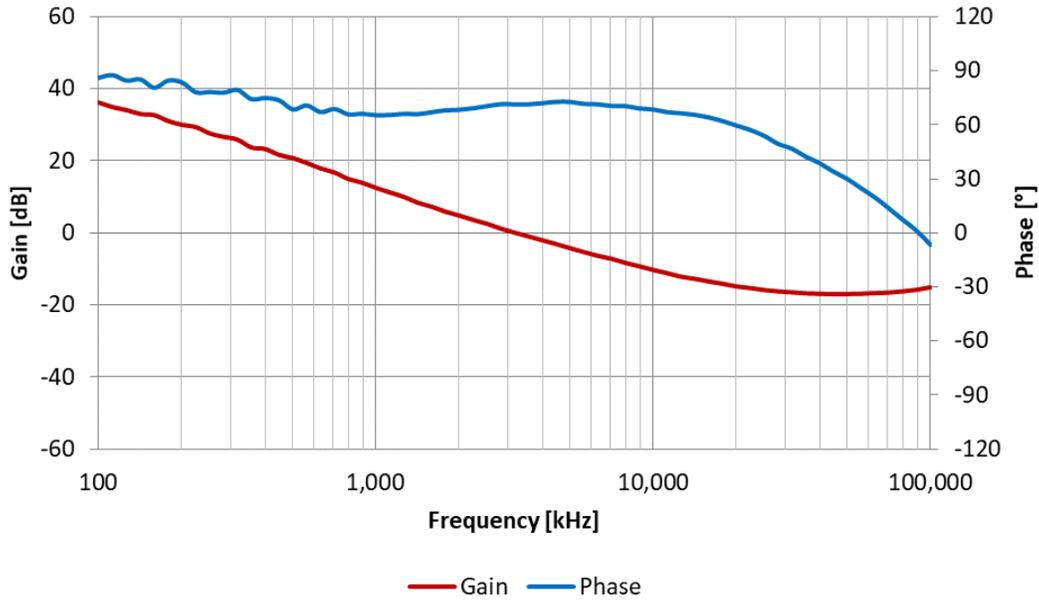
Figure 14. Bode Plot – 6 V Input Voltage, 33 V Output Voltage, 0.5 A Load

Input Voltage	Load	Bandwidth	Phase Margin	Gain Margin
6.0 V	33.0 V @ 0.5 A	4.4 kHz	71.0°	−15.0 dB
9.0 V	33.0 V @ 0.8 A	6.5 kHz	80.0°	−16.0 dB
12.0 V	33.0 V @ 1.0 A	8.5 kHz	84.0°	−16.0 dB
18.0 V	33.0 V @ 2.0 A	12.5 kHz	94.0°	−15.0 dB

Thermal Measurement

Figure 15 and 16 show the circuit at ambient temperature of 24°C.

- Test Condition: 12 V input voltage, 23 V output voltage, 2 A load
- Inductor L1: 65°C
- N−FET Q1: 71°C
- Diode D1: 74°C
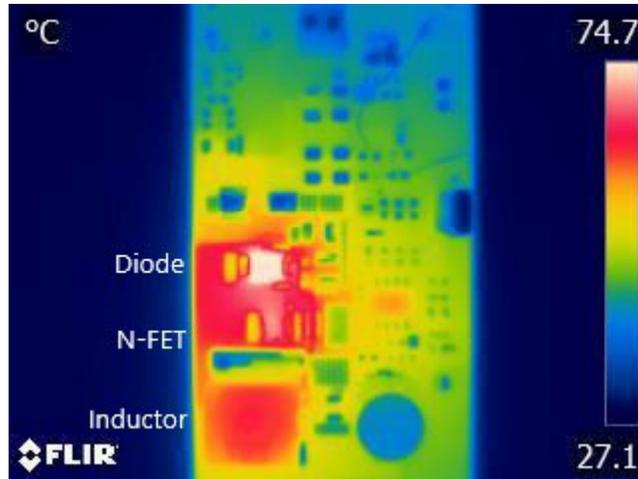
Figure 15. Thermal Image – 12 V Input Voltage, 23 V Output Voltage, 2 A Load

- Test Conditions: 6 V input voltage, 12 V output voltage, 2 A load
- Inductor L1: 50°C
- N−FET Q1: 68°C
- Diode D1: 72°C
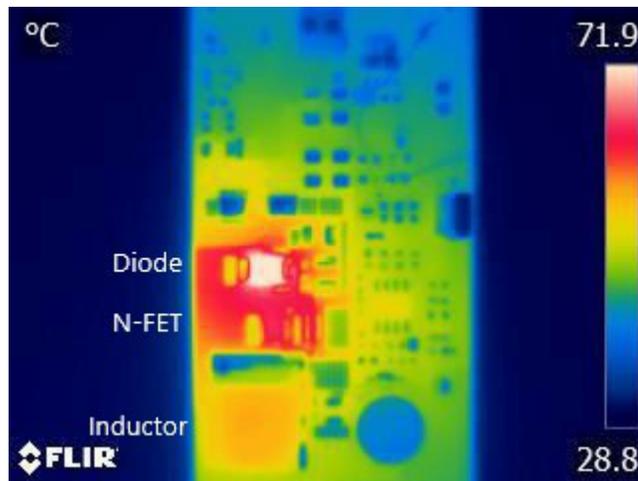
Figure 16. Thermal Image – 6 V Input Voltage, 12 V Output Voltage, 2 A Load

Load Step Response

- Channel 1: Output current, load step 0.5 A to 1.0 A and vice versa
- 250 mA/div, 100 µs/div

- Channel 4: Output voltage, −2.0 V (−6.04 %) undershoot, +1.8 V (+5.45 %) overshoot
- 2 V/div, 100 µs/div, AC coupled
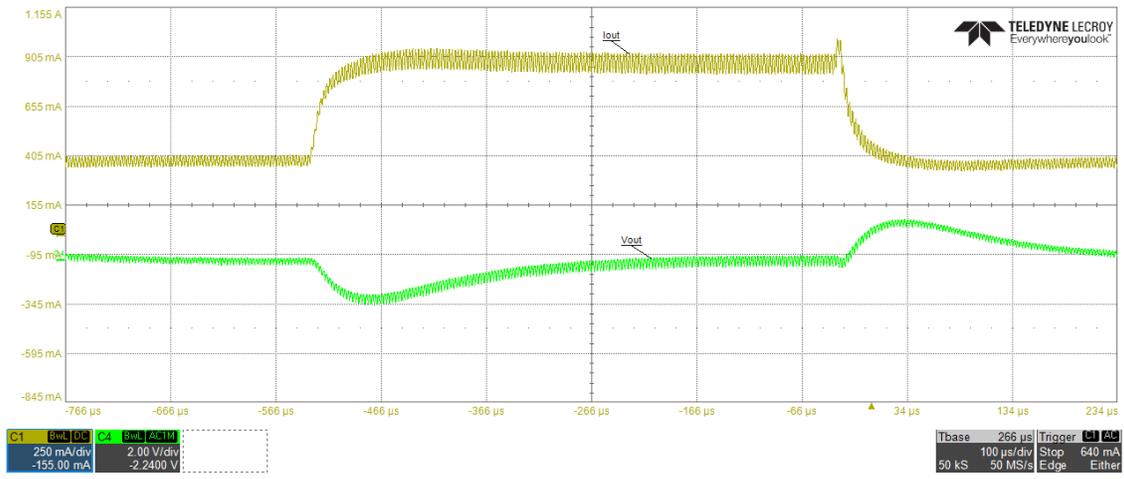
Figure 17. Load Response – 12 V Input Voltage, 33 V Output Voltage, 0.5 A to 1.0 A and vice versa

BOM

QTY	Designator	Manufacturer	Part number	Footprint	Value	Description
4	C2, C12, C13, C18	MuRata	GCM188R71H104KA57D	0603	0.1uF	CAP, CERM, 0.1 μF, 50 V, ±10%, X7R, 0603
3	C3, C4, C15	MuRata	GCM188R71E105KA64D	0603	1uF	CAP, CERM, 1 μF, 25 V, ±10%, X7R, AEC−Q200 Grade 1, 0603
1	C7	Nichicon	UCM1V331MNL1GS	D8xL10mm	150uF	CAP, Hybrid Polymer, 150 μF, 35 V, +/− 20%, 0.027 ohm, SMD
3	C8, C9, C10	MuRata	GRM32ER71H475KA88L	1210	4.7uF	CAP, CERM, 4.7 μF, 50 V, ±10%, X7R, 1210
1	C14	MuRata	GCM188R71H224KA64J	0603	220nF	CAP, CERM, 220 nF, 50 V, ±10%, X7R, 0603
1	C17	MuRata	GRM188R71H331KA01D	0603	330pF	CAP, CERM, 330 pF, 50 V, ±10%, X7R, 0603
1	D1	**onsemi**	NRVBS2040LNT3G	SMB	40V	Diode, Schottky, 40 V, 2 A, SMB
4	ISNS, TP1, TP2, VFB	Keystone	5000	Red Miniature Testpoint		Test Point, Miniature, Red, TH
2	J1, J2	On−Shore Technology	ED555/2DS	7.0x8.2x6.5mm		Terminal Block, 3.5mm Pitch, 2x1, TH
1	J3	Wurth Elektronik	61300311121	Header, 2.54mm, 3x1, TH		Header, 2.54 mm, 3x1, Gold, TH
1	L1	Coilcraft	XAL1010−103MEB	Inductor, 11.3x10x10mm	10uH	Inductor, Shielded, Composite, 10 μH, 15.5 A, 0.01 ohm, SMD
1	Q1	**onsemi**	NVTYS003N04CL	LFPAK8 3x3mm	40V	MOSFET, N−CH, 40 V, 107 A, LFPAK8 3x3
1	R9	Vishay−Dale	CRCW0603270KJNEA	0603	270k	RES, 270k, 5%, 0.1 W, 0603
2	R10, R11	Vishay−Dale	CRCW06030000Z0EA	0603	0	RES, 0, 5%, 0.1 W, 0603
1	R12	Vishay−Dale	CRCW0603249RFKEB	0603	249	RES, 249, 1%, 0.1 W, 0603
1	R13	Vishay−Dale	CRCW060310K0FKEB	0603	10k	RES, 10k, 1%, 0.1 W, 0603
1	R15	Vishay−Dale	WSLP1206R0360FEA	1206	36m	RES, 36m, 5%, 0.25 W, 1206
2	TP1, TP2, TP3, TP4	Keystone	5001	Black Miniature Testpoint		Test Point, Miniature, Black, TH
1	U1	**onsemi**	NCV4294CSN33T1G	TSOP−5		45 V, 30 mA, 3.3V Low−Dropout Linear Regulator, TSOP−5
1	U3	**onsemi**	NCV887104D1R2G	SOIC−8		Automotive grade non−synchronous boost controller

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