4-Switch Buck-Boost Converter

MAXREFDES1255

Introduction

MAXREFDES1255 is a 4-switch buck-boost converter that gives a positive step-up/stepdown output voltage. It uses MAX20048 IC, a current-mode buck-boost controller, which drives four MOSFETs to generate positive buck-boost output. This reference design can operate from 5V to 36V input and deliver up to 5A of load current at 12V output. This design targets automotive applications.

The main features of this reference design are:

- High efficiency of 90%
- Very low line and load regulation < 0.5%
- Output voltage ripple 1% at nominal V_{IN}
- Internal soft-start

Hardware Specification

Table 1 is an overview of the design specification.

Table 1. Design Specification

PARAMETER	SYMBOL	MIN	TYP	MAX
Input Voltage	V_{IN}	5V	14V	36V
Load Current	I_L		5A	
Output Voltage	V_{OUT}	—	12V	—
Frequency	f_{SW}	—	400kHz	—
Maximum Efficiency	η	—	90%	—
Output Power	P		60W	

Designed-Built-Tested

This document describes the hardware in Figure 1. It provides a detailed, systematic technical guide to design a 4-switch buck-boost converter using Maxim's MAX20048 current-mode controller.

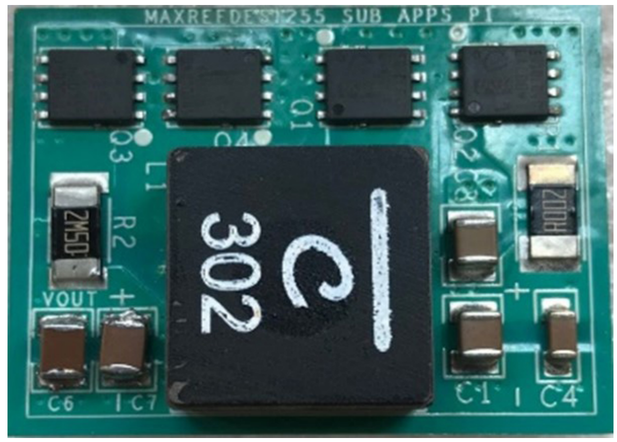

Figure 1. MAXREFDES1255 hardware.

Quick Start

Required Equipment

1) DC power supply
2) DC electronic load
3) Multimeter
4) Oscilloscope

Procedure

The reference design is fully assembled and tested. Follow these steps to verify the board operation:

1) Connect a 60V supply to the input.
2) Configure the 60V supply to 24V and turn on.
3) Observe the output voltage using a multimeter. It must show 12V.
4) Connect a DC electronic load at the output and load up to 10A. Observe the output voltage regulation and output ripple.

4-Switch Buck-Boost Principle

A 4-switch buck-boost converter, unlike a traditional buck-boost, operates in three different modes: buck, boost, and buck-boost. The converter transitions from one mode to the other based on the input-output voltage relation. It operates in the buck mode when the input is greater than output. It operates in the boost mode when the input is less than the output. It operates in the buck-boost mode when the input is equal to the output.

Buck Mode

The MAX20048 operates in the buck mode when the input voltage is much higher than the output voltage. Switch Q3 is always on and switch Q4 is always off in this configuration. Switch Q2 is turned on at the beginning of the clock cycle (CLK1), and the inductor current ramps down. The MAX20048 uses an average-current-mode control scheme to determine the ON pulse width for switch N2. Q1 is turned on once Q2 is turned off. Switches Q1 and Q2 alternate, behaving like a synchronous buck regulator.

Boost Mode

The MAX20048 operates in the boost mode when the input voltage is much lower than the output voltage. Switch Q1 is always on and switch Q2 is always off in this configuration. Switch Q4 is turned on at the beginning of the clock cycle (CLK2), and the inductor current ramps up. The MAX20048 uses an average-current-mode control scheme to determine the ON pulse width for switch Q4. Q3 is turned on once Q4 is turned off. Switches Q3 and Q4 alternate, behaving like a synchronous boost regulator.

Buck-Boost Mode

The MAX20048 operates in the buck-boost configuration when the V_{IN} is close to V_{OUT}. All four switches have PWM voltages on the gates in this configuration. All four switches are switching at the switching frequency. There are two different configurations in the buck-boost mode.

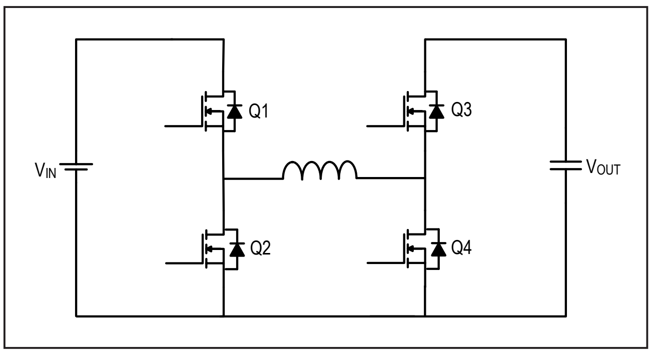

Figure 2. 4-switch buck-boost principle.

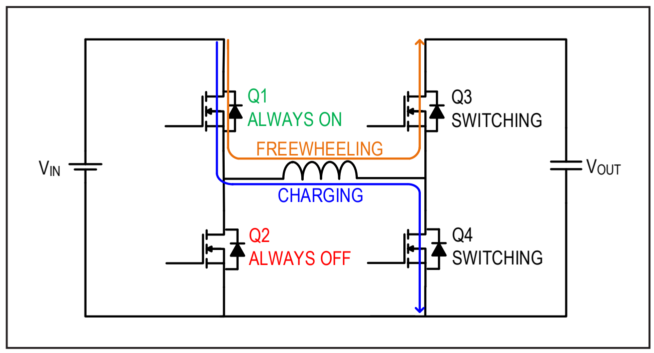

Figure 4. Boost mode.

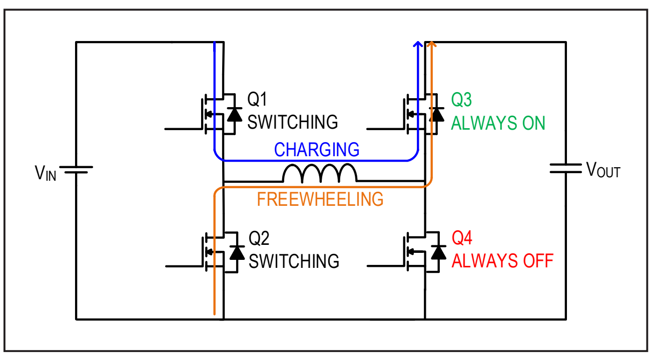

Figure 3. Buck mode.

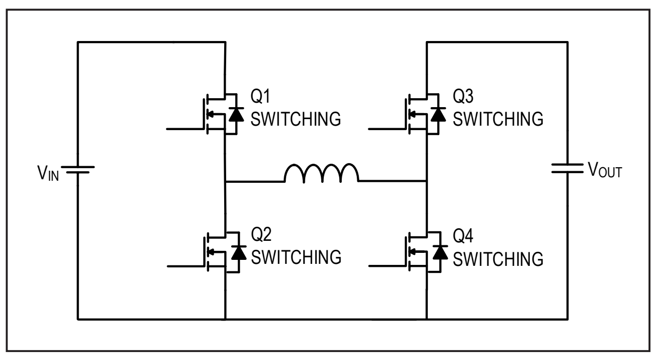

Figure 5. Buck-boost mode.

Design Procedure for the 4-Switch Buck-Boost Converter Using the MAX20048

This document is primarily concerned with the design of the power stage and feedback loop. It complements the information in the MAX20048 data sheet.

The switching frequency is determined by the operating range of the controller used in the Maxim design. The MAX20048 has a 220kHz to 2.2MHz frequency range. A switching frequency of 400kHz is selected for this design.

$$f_{SW} = 400kHz$$

This design is optimized for a 12V output.

Step 1. Calculating the Inductance

The inductance is calculated as:

$$L_{BUCK} = \frac{[(V_{INMAX\_BUCK} - V_{OUTNOM}) \times V_{OUTNOM}]}{f_{SW} \times I_{OUTNOM} \times \Delta I_L \times V_{INMAX\_BUCK}}$$

$$L_{BUCK} = \frac{[(14V - 12V) \times 12V]}{400kHz \times 5A \times 0.3 \times 14V} = 2.8\mu H$$

Select a commercial value always higher than the critical inductance. This guarantees continuous-conduction mode (CCM) operation throughout the application range. Select the following value for the inductor to ensure a 12V output operation:

$$L_{BUCK} = 3\mu H.$$

Step 2. Selecting the Input Capacitor

The RMS value for the input current is given in the following equation. The maximum value of the input RMS current occurs when the output voltage is equal to twice the input voltage.

$$I_{RMS} = \frac{I_{LOAD} \times \sqrt{V_{OUTNOM} \times (V_{IN} - V_{OUTNOM})}}{V_{IN}}$$

$$I_{RMSMAX} = \frac{I_{LOAD}}{2} \text{ at } V_{OUTNOM} = 2 \times V_{IN}$$

$$I_{RMSMAX} = \frac{5A}{2} = 2.5A$$

Step 3. Selecting the Output Capacitor

The output capacitance is selected to satisfy the output load-transient requirements. Select a capacitor based on the maximum allowable overshoot/undershoot on the output voltage. Typically, the worst-case response from a load transient is in the boost mode. Use the following equations to contain the undershoot within the given specifications in the boost mode:

$$C_{OUT} >= \frac{L \times \Delta I_{LSTEP}^2}{2 \times V_{INMIN} \times D_{MAX} \times V_{UNDER}} + \frac{(\Delta I_{LSTEP} \times \Delta t_{DELAY})}{V_{UNDER}}$$

$$C_{OUT} >= \frac{3\mu H \times 2.5A^2}{2 \times 13V \times 0.8 \times 1.2V} + \frac{2.5A \times 25\mu s}{1.2V} = 54.9\mu F$$

The selected value of C_{OUT} is 4 × 47μF and 1 × 2.2μF = 192.2μF.

Step 4. Selecting the Feedback Resistor

Here, R_{FB2} = 10kΩ. Using this value, for V_{OUTNOM} = 12V and V_{FB} = 1.25V, R_{FB1} is:

$$R_{FB1} = R_{FB2}\left[\left(\frac{V_{OUTNOM}}{V_{FB}}\right) - 1\right]$$

$$R_{FB1} = 10k\Omega \times \left(\frac{12V}{1.25V} - 1\right) = 86k\Omega$$

Step 5. Selecting the Current-Sense Resistor

The MAX20048 uses two external current-sense resistors to control the inductor current and implement the current limit. The input current-sense resistor feedback is used for the current loop, setting the peak and PFM current limits. The output current-sense information is used for the runaway current limit, zero-crossing threshold, and negative-current threshold in the skip-mode operation.

$$I_{INPEAK} = \frac{V_{OUTNOM} \times I_{OUTNOM}}{V_{INMIN}} + \frac{V_{INMIN} \times \left(1 - \frac{V_{INMIN}}{V_{OUTNOM}}\right)}{L \times f_{SW} \times 2}$$

$$I_{INPEAK} = \left(\frac{12V \times 5A}{3V}\right) + \left[\frac{3V \times \left(1 - \frac{3V}{12V}\right)}{3\mu H \times 400kHz \times 2}\right] = 20.93A$$

$$R_{CS1} = \frac{50mV}{I_{LIM}}$$

$$R_{CS1} = \frac{50mV}{20.93A} = 2.38m\Omega$$

$$R_{CS2} = \frac{75mV}{I_{LIM\_RUNAWAY}}$$

$$R_{CS2} = \frac{75mV}{1.2 \times 20.93A} = 2.9m\Omega$$

R_{CS1} is selected as 2mΩ and R_{CS2} as 2.5mΩ based on these calculations.

Step 6. Selecting the Slope Compensation Resistor

The MAX20048 offers a simple way to set the slope compensation by connecting a resistor between the SLP pin and AGND.

$$M_C = \frac{\left(\frac{0.3185}{Q_P} + 0.5\right)}{1 - \frac{V_{OUTNOM}}{V_{INMAX}}}$$

$$S_N = (V_{INMAX} - V_{OUNOM}) \times \frac{G_{CS}}{L_{SEL}}$$

where, $G_{CS} = R_{CS1} \times 24$

$$S_E = (M_C - 1) \times S_N$$

$$R_{SLOPE} = \frac{1.25V \times 0.09}{S_E \times 8pF}$$

$$M_C = \frac{\left(\frac{0.3185}{0.6} + 0.5\right)}{1 - \frac{12V}{36V}} = 1.5462$$

$$S_N = (36V - 12V) \times \frac{0.002 \times 24}{3\mu H} = 384000$$

$$S_E = (1.5462 - 1) \times 384000 = 209740$$

$$R_{SLOPE} = \frac{(1.25 \times 0.09)}{(209740 \times 8pF)} = 67k\Omega$$

Step 7. Selecting the Compensation Component

The controller uses a peak current-mode-controlled architecture to regulate the output voltage by forcing the required current through the external inductor.

A convenient way to design the compensation for both the buck and boost modes is at the minimum input voltage and heavy load (deep-boost mode). RHP zero is at its lowest frequency at this operating point. Design the compensation to achieve a bandwidth close to 1/4 of the RHP zero frequency in the deep-boost mode.

$$R_L = \frac{V_{OUTNOM}}{I_{OUTNOM}}$$

$$R_L = \frac{12V}{5A} = 2.4\Omega$$

$$f_{PHOOST} = \frac{2}{2 \times \pi \times R_L \times C_{OUT}}$$

$$f_{PHOOST} = \frac{2}{2 \times \pi \times 2.4\Omega \times 192\mu F} = 442Hz$$

$$f_{ESR} = \frac{1}{2 \times \pi \times R_C \times C_{OUT}}$$

$$f_{ESR} = \frac{1}{2 \times \pi \times 1m \times 300\mu} = 530kHz$$

$$f_{RHP} = \frac{R_L \times (1 - D)^2}{2 \times \pi \times L}$$

$$f_{RHP} = \frac{2.4\Omega \times (1 - 0.75)^2}{2 \times \pi \times 3\mu} = 7952Hz$$

A target bandwidth close to 100Hz is selected for the closed-loop converter with RHP zero at 848Hz. The zero of the error amplifier must be placed well below the bandwidth for enough phase boost at the crossover frequency. Typically, the zero is placed close to the low-frequency pole.

$$R_{ZERO} = 2 \times \pi \times f_{BW} \times \frac{G_{CS} \times C_{OUT}}{G_M \times (1 - D_{BOOST})} \times \frac{R_{BOT} + R_{TOP}}{R_{BOT}}$$

$$R_{ZERO} = 2 \times \pi \times 100Hz \times \frac{0.002 \times 24 \times 192.2\mu F}{750\mu \times (1 - 0.75)} \times \frac{10k\Omega + 86k\Omega}{10k\Omega}$$

$$R_{ZERO} = 9.21k\Omega$$

$$f_{ZCOMP} = 1kHz$$

$$C_{ZERO} = \frac{1}{2 \times \pi \times R_{ZERO} \times f_{ZCOMP}}$$

$$C_{ZERO} = \frac{1}{2 \times \pi \times 10k\Omega \times 1k\Omega} = 15nF$$

$$C_{POLE} = \frac{1}{2 \times \pi \times R_{ZERO} \times f_{P2COMP}}$$

$$C_{POLE} = \frac{1}{2 \times \pi \times 10k\Omega \times 200k\Omega} = 79.8pF$$

Design Resources

Download the complete set of **Design Resources** including schematics, bill of materials, PCB layout, and test files.

Revision History

REVISION NUMBER	REVISION DATE	DESCRIPTION	PAGES CHANGED
0	10/20	Initial release	—