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Designing Applications with MCP166X High Output Voltage Boost Converter Family

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INTRODUCTION

This document aims to assist engineers in designing different power applications and to provide an insight on how a simple, Non-Synchronous Boost Converter can be used to develop solutions for non-typical requirements. The following paragraphs will provide examples of converter applications that fulfill a wide variety of the industry requirements.

The solutions provided by Microchip Technology Inc. highlight the use of the MCP1661/3 boost (step-up) regulators, which provide the necessary flexibility required in dealing with the increasing range of the technological field demands.

MCP1661/3 OVERVIEW

The MCP1661/3 devices are compact, highly efficient, fixed-frequency, Non-Synchronous Step-up DC-DC Converters, which integrate a 36V switch. These products provide space efficient, high-voltage step-up, easy-to-use power supply solutions. The MCP1661/3 devices were developed for applications that are powered by two-cell or three-cell alkaline, Ni-Cd, Ni-MH batteries, or Li-Ion or Li-Polymer batteries.

The main characteristics and features include:

- Wide Output Voltage Range: Up to 32V
- Typical Input Peak Current Limit:
  - 1.3A (MCP1661)
  - 1.8A (MCP1663)
- Input Voltage Range: 2.4V-5.5V
- Undervoltage Lockout (UVLO):
  - UVLO @ V_{IN} Rising: 2.3V, typical
  - UVLO @ V_{IN} Falling: 1.85V, typical
- Pulse-Width Modulator (PWM) Operation with Skip Mode: 500 kHz
- Output Overvoltage Protection (OVP) for MCP1661/3 in the event of:
  - Feedback pin shorted to GND
  - Disconnected feedback divider
- Internal Compensation
- Peak Current Mode Control
- Available Packages (pin to pin compatible): 5-Lead SOT-23 and 2x3 mm, 8-Lead TDFN

For further insight and additional information, refer to the MCP1661 Data Sheet – *"High-Voltage Integrated Switch PWM Boost Regulator with UVLO"* (DS20005315), the MCP1663 Data Sheet – *"High-Voltage Integrated Switch PWM Boost Regulator with UVLO"* (DS20005406), the *"MCP1661 High-Voltage Boost and SEPIC Converters Evaluation Board User's Guide"* (DS50002286) and the *"MCP1663 9V/12V/24V Output Boost Regulator Evaluation Board User's Guide"* (DS50002364), available on Microchip's web site.

BATTERY CONSIDERATIONS

The Microchip MCP166X family of Boost Converters enables designers to use a wide variety of batteries as a power source in applications that require higher operating voltages. Batteries are widely available throughout the world, can support a variety of drain rates, and are available in a variety of sizes and chemistries. There are a number of things that designers should keep in mind when choosing a battery solution for their project.

Engineers should avoid deeply discharging primary batteries because it will increase the possibility of leakage. Even though a battery boost circuit might be able to operate down to a very low input voltage, discharging batteries below 0.8V is not advisable. Below 0.8V on the battery, parasitic drains should be kept as low as possible and preferably, removed entirely.

The MCP166X Boost Converters family comes with a UVLO feature which was implemented in order to avoid the above mentioned cases. The device will terminate the operation of the circuit (UVLO Stop) as soon as the V_{IN} will reach the 1.85V value (V_{IN} falling) and it will resume operation (UVLO Start) when at least 2.3V will be detected at the input (V_{IN} rising).

Operating temperature may also impact device performance differently, depending on the battery chemistry. Cold environments, in particular, may reduce run time. Engineers should take into account this aspect and always correlate battery temperature operating ratings and the environment in which their application will be used. For severe ambient temperatures, consider using batteries that have a wider operating temperature range.

APPLICATIONS

Step-up Converter

The most common application for the Microchip MCP166X family is the typical Boost Converter. The step-up topology is commonly used in today's battery-powered devices as it requires the minimum number of components in order to develop a DC-DC Power Converter that provides a stable output voltage from a lower input source ($V_{IN} < V_{OUT}$). Figure 1 shows an idealized version of a Non-Synchronous Boost Converter.

The basic operation of the Boost Converter can be summarized by looking at the two current paths created by the state of the SW switch.

- When the switch is turned on (ON TIME), a DC voltage equal to V_{IN} is applied to the inductor, resulting in a positive linear ramp of the inductor current. The inductor current ramps at a constant rate of V_{IN}, divided by the inductance of L. During this time, the diode D is reverse biased and the energy to the load is provided by the output capacitor.
- When the switch is turned off (OFF TIME), the polarity across the inductor will reverse in order to maintain the current flow towards the load. The voltage across L will be $V_{IN} – V_{OUT}$, resulting in a negative linear ramp of the inductor current. With the switch opened, there is no path from the right side of the inductor to the negative terminal of the power supply. This time, the rectifying diode is forward biased and the energy is delivered to the output capacitor and load.

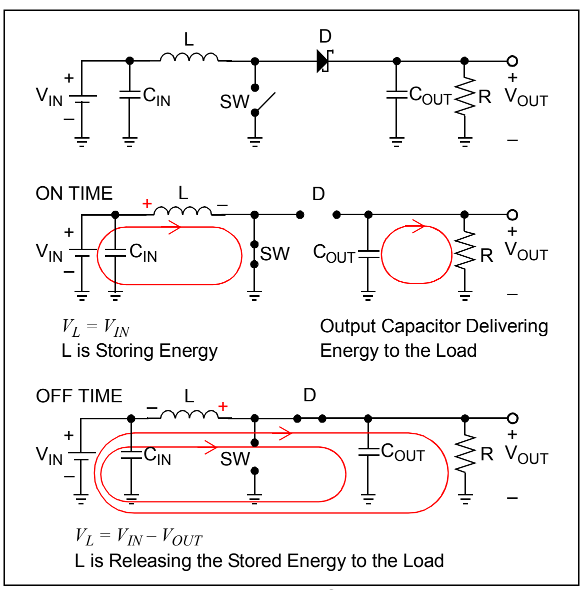


FIGURE 1: *Boost Converter Topology.*

A Boost Converter operates in Continuous Inductor Current mode (Figure 2) if the current through the inductor never falls to zero during the commutation cycle. Provided that the inductor current reaches zero, the Boost Converter operates in Discontinuous Inductor Current mode (Figure 3).

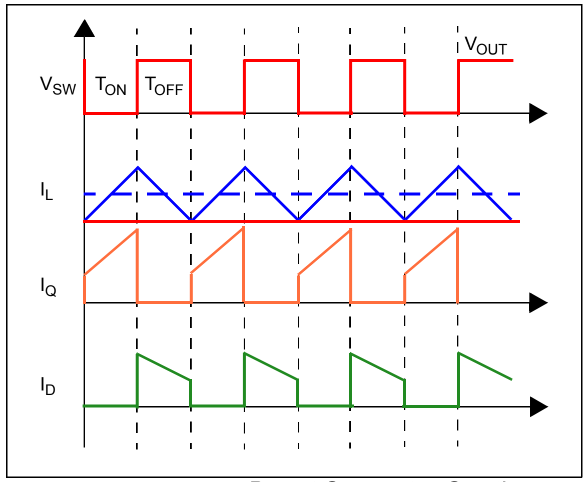


FIGURE 2: *Boost Converter Continuous Conduction Mode Waveforms.*

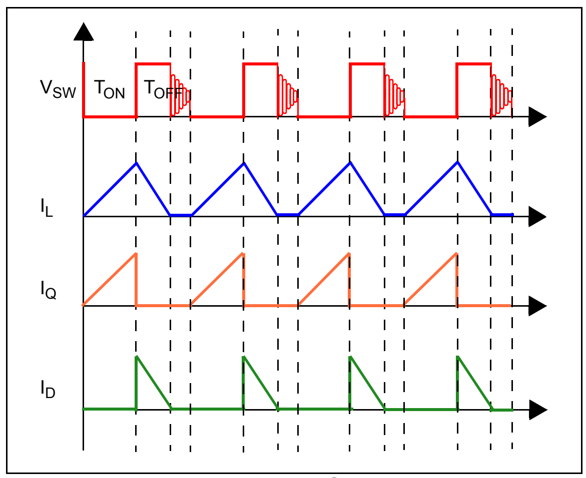


FIGURE 3: *Boost Converter Discontinuous Conduction Mode Waveforms.*

BOOST CONVERTER POWER STAGE DESIGN

In order to build an efficient and competitive power supply that can meet the requirements and industry standards, engineers have to include in the design process the calculation of the external components, based on the input parameters and load requirements of the actual application. In order to do this, there are a few steps that have to be covered.

Tables 1 through 4 provide useful information regarding the notations and their significance used throughout the document.

TABLE 1: SYSTEM PARAMETERS

Parameter	Symbol	Unit
Typical Input Voltage	V_{IN}	V
Minimum Input Voltage	V_{INmin}	V
Maximum Input Voltage	V_{INmax}	V
Output Voltage	V_{OUT}	V
Output Current	I_{OUT}	A

TABLE 2: SYSTEM COMPONENTS

Component	Designator	Unit
Inductor	L	µH
Output Capacitor	C_{OUT}	µF
Output Capacitor ESR	$C_{OUT,ESR}$	Ω
Input Capacitor	C_{IN}	µF
Rectifying Diode	V_D	V

TABLE 3: SYSTEM BEHAVIOR

Parameter	Designator	Unit
Duty Cycle	D	%
Equivalent Output Voltage	V_{OUT}	V
Equivalent Input Current	I_{IN}	A
Maximum Duty Cycle	D_{MAX}	%
Inductor Ripple Current	I_{Lp-p}	A
Inductor Peak Current	I_{PEAK}	A
Output Voltage Ripple	V_{OUTp-p}	mV
Output Current	I_{OUT}	mA
Estimated Efficiency	η_{est}	%

TABLE 4: CONVERTER PARAMETERS

Parameter	Designator	Unit
Switching Frequency	f_{SW}	kHz
NMOS Switch On Resistance	R_{DSON}	Ω
Feedback Voltage	V_{FB}	V

The following equations apply only for Continuous Conduction mode.

EQUATION 1: CALCULATING INPUT CURRENT

$$I_{IN} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times \eta_{est}}$$

EQUATION 2: CALCULATING DUTY CYCLE

$$D = \frac{V_{OUT} - V_{IN} \times n_{est}}{V_{OUT}}$$

Note 1: For minimum duty cycle, replace V_{IN} with V_{INmax} in the formula above.

2: For maximum duty cycle, replace V_{IN} with V_{INmin} in the formula above.

EQUATION 3: INDUCTOR RIPPLE CURRENT

$$I_{Lp-p} = \frac{(V_{IN} - I_{IN} \times R_{DSON}) \times D}{f_{SW} \times L}$$

EQUATION 4: INDUCTOR PEAK CURRENT

$$I_{PEAK} = \frac{I_{Lp-p}}{2} + \frac{I_{OUT}}{(1-D) \times \eta_{est}}$$

EQUATION 5: OUTPUT VOLTAGE RIPPLE

$$V_{OUTp-p} = \frac{V_{OUT} - V_{IN}}{V_{OUT} \times f_{SW}} \times \frac{I_{OUT}}{C_{OUT}}$$

Note: The output voltage ripple caused by the capacitor's ESR is neglected (ceramic capacitors have low-ESR).

Rectifier Diode Selection

To reduce losses, Schottky diodes should be used. The forward current rating needed is equal to the maximum output current, I_{OUT}. The Schottky diode must have a peak current rating higher than the inductor peak current limit. The reverse voltage rating has to be higher than the maximum output voltage of the converter. The rectifying diode should also withstand the power dissipation, as shown in Equation 6.

EQUATION 6: OUTPUT DIODE POWER DISSIPATION

$$P_D = I_F \times V_F$$

Where:

I_F = Average forward current of the rectifier diode (maximum output current)

V_F = Diode forward voltage corresponding to forward current

Feedback Resistors

To calculate the resistor divider values for the MCP1661/3, Equation 7 can be used. Where R_T is connected to V_{OUT}, R_B is connected to GND and both are connected to the V_{FB} input pin.

EQUATION 7: RESISTIVE DIVIDER CALCULATION

$$R_T = R_B \times \left(\frac{V_{OUT}}{V_{FB}} - 1\right)$$

Where:

V_{FB} = 1.227V

Using high-value resistors minimizes the power loss on the divider (which will improve the no load input current and shutdown quiescent current, but increases the noise).

Using low-value feedback resistors provides better accuracy and reduces the noise, but the power losses are higher.

A trade-off between the two cases can be done in order to provide the required V_{OUT} accuracy, and also keep the “no load input current” and “shutdown quiescent current” parameters within acceptable ranges.

EQUATION 8: RESISTIVE DIVIDER CURRENT

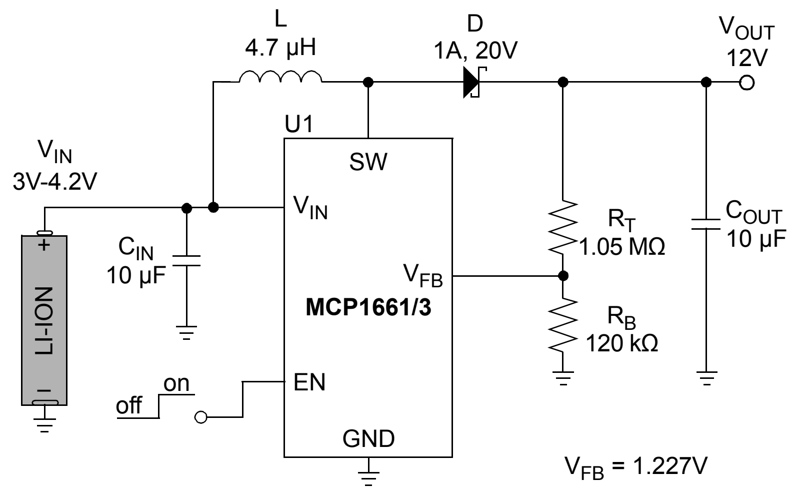
$$I_{Rdiv} = \frac{V_{FB}}{R_B}$$

For applications which require an output voltage higher than 15V, a 10 µH inductor is recommended. For V_{OUT} < 15V, a 4.7 µH inductor can be used. Table 5 provides the values for some commonly encountered cases.

TABLE 5: EXTERNAL COMPONENTS

Output Voltage	Recommended Inductance	R_{TOP}	R_{BOT}
6.0V	4.7 µH	1050 kΩ	270 kΩ
9.0V	4.7 µH	1000 kΩ	160 kΩ
12V	4.7 µH	1050 kΩ	120 kΩ
24V	10 µH	1050 kΩ	56 kΩ
32V	10 µH	1100 kΩ	43 kΩ

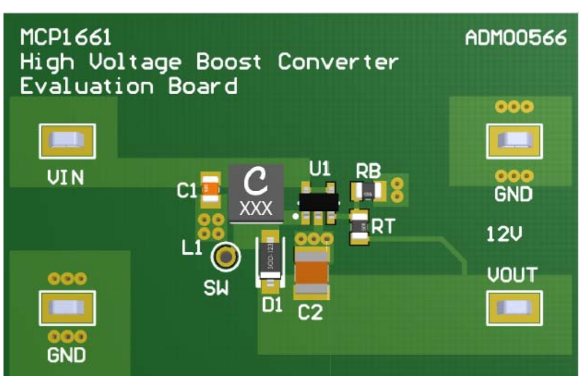
Figures 4 and 5 provide the schematic, Bill of Materials and layout example for developing a Boost Converter using MCP1661/3.

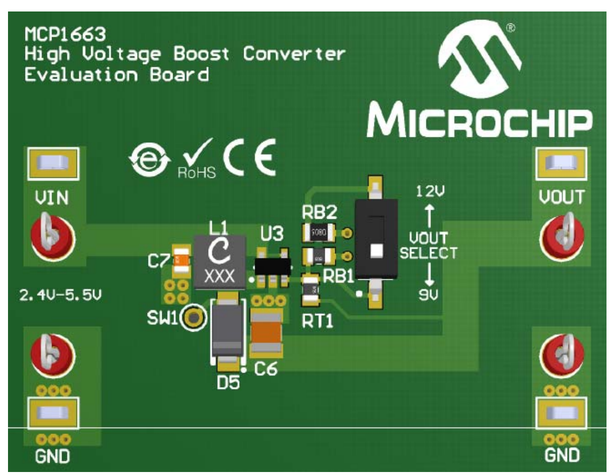


MCP1661/3 BOOST CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{IN}	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
C_{OUT}	10 µF	TDK Corporation	C3225X7R1H106M250AC	Capacitor Ceramic, 10 µF, 50V, X7R, 1210
L	4.7 µH	Wurth Elektronik	744778004	Inductor Power, 4.7 µH, Isat = 4.2A
R_T	1.05 MΩ	Panasonic® – ECG	ERJ-6ENF1054V	Resistor, SMD, 1.05 MΩ, 1%, 1/8W, 0805
R_B	120 kΩ	Panasonic – ECG	ERJ-6ENF1203V	Resistor, SMD, 120 kΩ, 1%, 1/8W, 0805
D	—	ON Semiconductor®	MBRA140T3G	Diode Schottky, 40V, 1A, SMA
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter

FIGURE 4: *MCP1661/3 Typical Boost Application.*





Note: The *"MCP1661 High-Voltage Boost and SEPIC Converters Evaluation Board User's Guide"* and Demo Board (ADM00566) are available on the Microchip Technology Inc. web site for further product evaluation.

FIGURE 5: *MCP1661 and MCP1663 Boost Converter Evaluation Boards.*

APPLICATIONS

- Two and Three-Cell Alkaline, Lithium Ultimate and NiMH/NiCd Portable Products
- LCD Bias Supply for Portable Applications
- Camera Phone Flash
- Portable Medical Equipment
- Handheld Instruments

ADVANTAGES

- Can be used for a large variety of applications
- Easy implementation
- Low component number
- Low price

DRAWBACKS

- This topology does not provide output disconnect or output short-circuit protection

MCP1661/3 NON-SYNCHRONOUS BOOST CONVERTER OUTPUT DISCONNECT

When putting a Non-Synchronous Boost Converter in Shutdown mode (EN = GND), the input voltage is bypassed through the inductor and external rectifying diode to the output. While for some applications this would not represent an issue, others may require a V_{IN} to V_{OUT} disconnected path and output short-circuit protection. By adding a few external components, the typical application can be modified to provide these features. In this configuration (Figure 6), by connecting the EN pin to GND (disabling the device), the direct path from input to output will be interrupted by a PNP transistor.

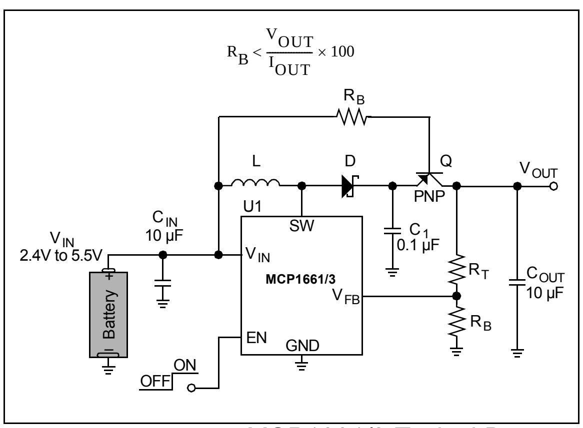


FIGURE 6: MCP1661/3 Typical Boost Application with Output Disconnect.

ADVANTAGES

- Output disconnect
- Output short-circuit protection

DRAWBACKS

- A slight decrease of efficiency is expected because of the additional PNP transistor

MCP1661/3 HIGH INPUT VOLTAGE BOOST CONVERTER

The operating input voltage range for MCP1661/3 is 1.85V (UVLO Stop) to 5.5V (technology specification). However, these devices can still be used for applications where higher input voltages are needed, just by adding some external circuitry.

Two additional configurations can be used to extend and overcome the typical low V_{IN} voltage range, providing significantly more flexibility for applications powered from a higher input, which are presented below:

- The first option used for driving the MCP1661/3 low input (V_{DD}) voltage internal circuitry is to use a Linear Dropout (LDO) regulator to step down the device's supply voltage (V_{IN}) to 5V.
- The second solution to limit the V_{IN} voltage is to use a Zener diode regulator. The MCP1663 low input quiescent current keeps the LDO and the Zener diode circuitry power losses at a low level.

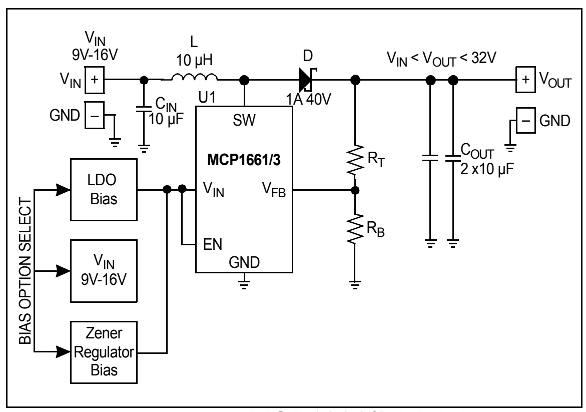


FIGURE 7: MCP1661/3 High Input Voltage Block Diagram.

The advantage of using the LDO is that it can be used for a wide input voltage range without any changes.

The Zener regulator may be cheaper, but it has to be adapted for certain conditions and it is not very suitable for wide input voltage ranges.

The value and power rating of the current set resistor has to be calculated based on the input voltage range. At low-voltage drop, the power loss on this resistor will be reduced, but at high V_{IN}, it will increase, affecting the efficiency. The current drawn by the chip is low, in the µA range, but still, a few mA have to pass through the Zener in order to enable it.

Equations 9 through 12 can be used to calculate the parameters and ratings of the Zener voltage regulator.

EQUATION 9: RESISTOR VOLTAGE DROP

$$V_R = V_{IN} - V_{Dz}$$

Note: V_{Dz} represents the Zener voltage.

EQUATION 10: ZENER POWER RATING

$$P_{Dz} = V_{Dz} \times I$$

Note: Select a Zener diode with a power rating higher than the calculated value.

The power dissipated in the resistor is given by the difference between V_{IN} and the Zener voltage, multiplied by the required current. The higher the voltage drop, the higher the power loss.

EQUATION 11: RESISTOR CALCULATION

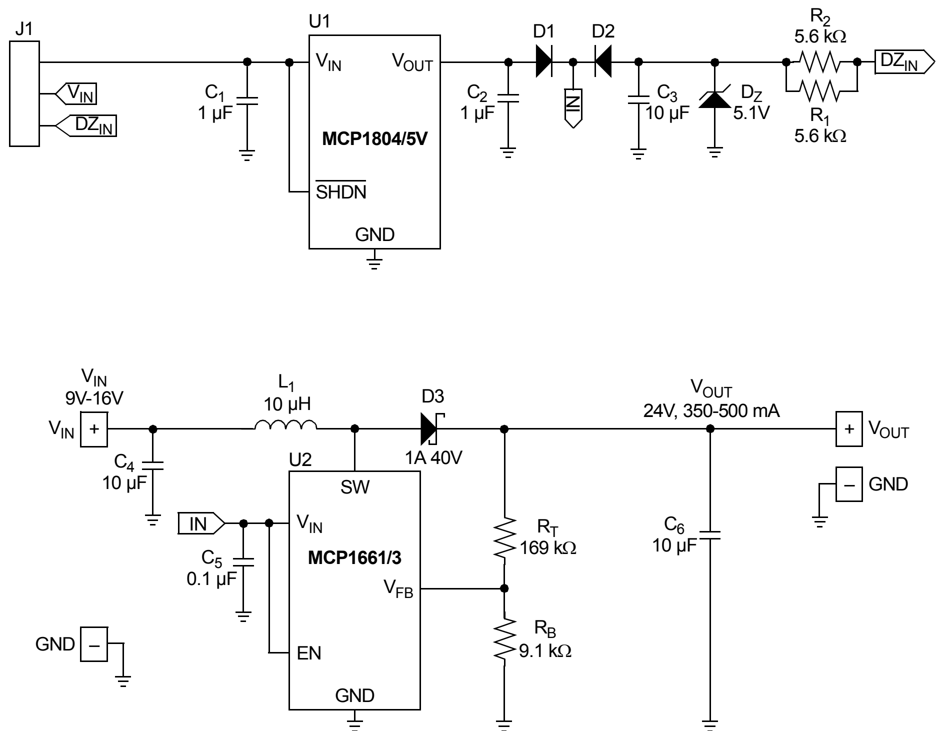
$$R = \frac{V_{IN} - V_{Dz}}{I}$$

EQUATION 12: RESISTOR POWER RATING

$$P_R = (V_{IN} - V_{Dz}) \times I$$

Note: Select a resistor with a power rating higher than the calculated value.

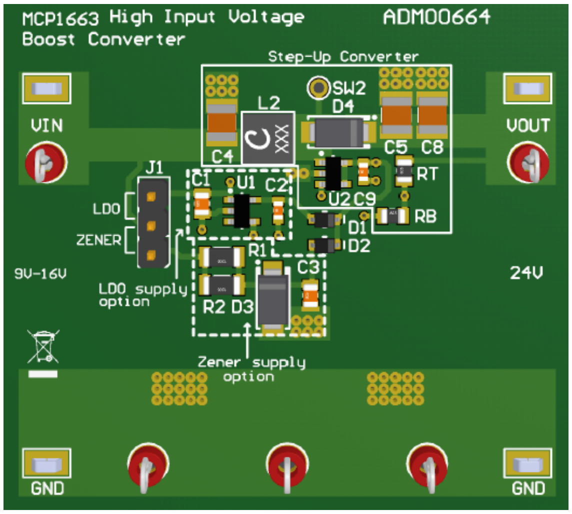
Figures 8 and 9 provide the schematic, Bill of Materials and layout example for developing a high input voltage Boost Converter using the MCP1661/3.



MCP1661/3 HIGH INPUT VOLTAGE BOOST CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C1	1 µF	TDK Corporation	CGA4J3X7R1V105K125AB	Capacitor Ceramic, 1 µF, 35V, X7R, 0805
C2	1 µF	TDK Corporation	C1608X7R1A105M	Capacitor Ceramic, 1 µF, 10V, X7R, 0603
C3	10 µF	TDK Corporation	C2012X5R1C106M/0.85	Capacitor Ceramic, 10 µF, 16V, X5R, 0805
C4	10 µF	TDK Corporation	C3216X7R1V106M160AC	Capacitor Ceramic, 10 µF, 35V, X7R, 1206
C5	0.1 µF	TDK Corporation	C1608X7R1H104M	Capacitor Ceramic, 0.1 µF, 50V, X7R, 0603
C6	10 µF	TDK Corporation	C3225X7R1H106M250AC	Capacitor Ceramic, 10 µF, 50V, X7R, 1210
L1	10 µH	Wurth Elektronik	74477810	Inductor Power, 10 µH, Isat = 2.2A
R_T	169 kΩ	Panasonic® – ECG	ERJ-6ENF1693V	Resistor, SMD, 169 kΩ,1%, 1/8W, 0805
R_B	9.1 kΩ	Panasonic – ECG	ERJ-6ENF9101V	Resistor, SMD, 9.1 kΩ, 1%, 1/8W, 0805
R1, R2	5.6 kΩ	Panasonic – ECG	ERJ-8ENF5601V	Resistor, SMD, 5.6 kΩ, 1%, 1/8W, 0805
D1, D2	—	Diodes® Incorporated	1N4148WS-7	Diode Rectifier, 150 mA, 75V, SOD-323
D3	—	ON Semiconductor®	MBRA140T3G	Diode Schottky, 40V, 1A, SMA
D_Z	—	ON Semiconductor	1SMA5918BT3G	Diode Zener, 5.1V, 1.5W, SMA
U2	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter
U1	5V	Microchip Technology Inc.	MCP1804T-5002I/OT	Microchip Analog, LDO, 5V, SOT-23-5

FIGURE 8: *MCP1661/3 High Input Voltage Boost Converter.*



Note: The *"MCP1663 9V/12V/24V Output Boost Regulator Evaluation Board User's Guide"* and Demo Board (ADM00664) are available on the Microchip Technology Inc. web site for further product evaluation.

FIGURE 9: *MCP1663 High Input Voltage Boost Converter Evaluation Board.*

MCP1661/3 SEPIC Converter

MCP1661/3 devices are easily configurable for SEPIC topology, providing a proper solution for circuits in which the input voltage is either higher or lower than the output voltage. SEPIC Converters are mainly used in photovoltaic applications to obtain the maximum power. As there is no DC path between the input and output, this topology comes with other useful features, such as output disconnect and output short-circuit protection.

The basic operation of the SEPIC Converter can be summarized as follows:

- When the switch is turned on (ON TIME), a DC voltage equal to V_{IN} is applied to L1a and induced to L1b, resulting in a positive linear ramp of the inductor current. During this time, the coupling capacitor C_C is discharging, the diode D is reverse biased and the energy to the load is provided by the output capacitor.
- When the switch is turned off (OFF TIME), the polarity across the inductor will reverse in order to sustain the current flow towards the load. The coupling capacitor C_C is charging from V_{IN}. The voltage across the switch (NMOS transistor in the real application) is V_{IN} + V_{OUT}. The voltage across L1a and L1b is -V_{OUT}, resulting in a negative linear ramp of the inductor current. This time, the rectifying diode is forward biased and the energy is delivered to the output capacitor and load.

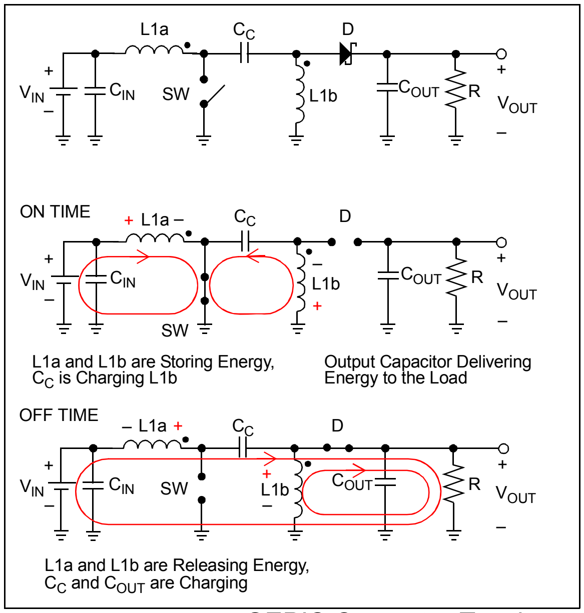


FIGURE 10: *SEPIC Converter Topology.*

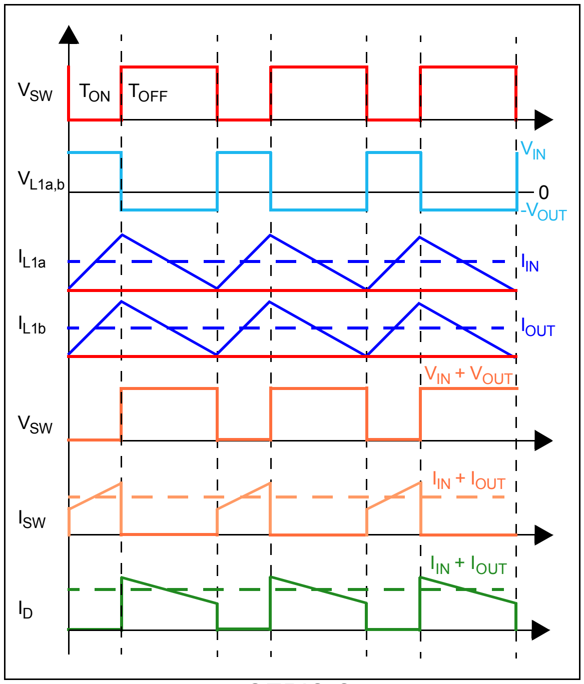


FIGURE 11: *SEPIC Converter Waveforms.*

SEPIC CONVERTER POWER STAGE DESIGN

Equations 13 through 29 can be used to calculate the SEPIC Converter application parameters and external components. Note that the given equations apply for Continuous Conduction mode operation only.

EQUATION 13: DUTY CYCLE

$$D = \frac{V_{OUT} + V_D}{V_{IN} + V_{OUT} + V_D}$$

EQUATION 14:

$$D_{max} = \frac{V_{OUT} + V_D}{V_{INmin} + V_{OUT} + V_D}$$

The duty cycle of the SEPIC Converter can be calculated with the equations above. At Minimum Input voltage (V_{INmin}), the duty cycle has the maximum value. At Maximum Input Voltage (V_{INmax}), the duty cycle has the minimum value.

EQUATION 15: EQUIVALENT INPUT CURRENT

$$I_{IN} = \frac{V_{OUT} \times I_{OUT}}{V_{IN} \times \eta_{est}}$$

EQUATION 16: MAXIMUM INPUT CURRENT

$$I_{INmax} = \frac{V_{OUT} \times I_{OUT}}{V_{INmin} \times \eta_{est}}$$

For the SEPIC Converter, the DC current flowing through L1a is the input current. The maximum input current (keeping the load and output voltage constant) is at the V_{INmin}. The average current flowing through L1b is the output current.

EQUATION 17: L1a MAXIMUM INDUCTOR AVERAGE CURRENT

$$I_{L1amax} = I_{INmax} = \frac{V_{OUT} \times I_{OUT}}{V_{INmin} \times \eta_{est}}$$

EQUATION 18: L1b MAXIMUM INDUCTOR AVERAGE CURRENT

$$I_{L1bmax} = I_{OUTmax}$$

EQUATION 19: INDUCTOR RIPPLE CURRENT

$$I_{Lp-p} = I_{OUT} \times \frac{V_{OUT}}{V_{INmin}} \times k$$

Note 1: k takes values between 0.2 to 0.6.

2: k represents a percentage of the input current.

The inductor ripple current represents a percentage of the DC current. Depending on the application, this percentage usually represents 20% to 60%. The higher the ripple (coefficient k is high), the lower the inductor value. The output current capabilities will be lower as the current ripple will reach the peak current limitation sooner. For lower "k" coefficient values, the inductor will be higher. The output current will increase as the ripple will be lower, requiring more load to hit the current limit. As a result of higher output current, the power dissipation of the device has to be taken into consideration. The converter may enter thermal shutdown before reaching the peak current limit. The requirements of the application will determine the acceptable inductor current ripple range.

- High Ripple Advantages:
  - Lower inductor value required, lowering the necessary board space for the application, decreasing overall costs.
  - Better dynamic response
- High Ripple Drawbacks:
  - Lower output current capabilities due to core losses
  - Increased EMI, requiring additional output capacitance
- Low Ripple Advantages:
  - Higher output current capabilities
  - Decreased Electromagnetic Interference (EMI)
- Low Ripple Drawbacks:
  - Increased inductor value, bigger package/board size, higher costs
  - Higher thermal stress
  - Slower dynamic response (current loop gain is reduced)

EQUATION 20: INDUCTOR VALUE

$$L_{1a} = L_{1b} = \frac{V_{INmin} \times D_{max}}{2 \times I_{Lp-p} \times f_{SW}}$$

Note: L1 and L2 are coupled inductors.

Equation 20 is used for determining the inductor value, assuming that the coupled inductors are used. Coupled inductors are wound on the same core, and due to the mutual inductance, the obtained value is halved.

EQUATION 21: L1a INDUCTOR PEAK CURRENT

$$I_{L1apeak} = I_{IN} + \frac{I_{Lp-p}}{2}$$

EQUATION 22: L1b INDUCTOR PEAK CURRENT

$$I_{L1bpeak} = I_{OUT} + \frac{I_{Lp-p}}{2}$$

An inductor with adequate saturation and RMS current ratings should be used.

EQUATION 23: MAXIMUM OUTPUT CURRENT

$$I_{OUTmax} = \frac{I_{peak} \times \frac{V_{IN} \times \eta_{est}}{V_{OUT}}}{\left(1 + \frac{k}{2}\right)}$$

Note 1: k takes values between 0.2 to 0.6.

2: k represents a percentage of the input current.

The maximum output current of the converter is dependent on the following parameters:

- Peak current limit (the value of this parameter is given in the MCP1661/3 Data Sheet).
- The inductor current ripple, which is designed to meet the application requirements.

During the design phase, the efficiency of the converter is estimated. The real application results may differ to a small extent, influenced by the component/system tolerances and accuracy of the estimated parameters.

EQUATION 24: RECTIFYING DIODE VOLTAGE RATING

$$V_r = V_{INmax} + V_{OUT} + V_D$$

The boost diode has to withstand voltage ratings according to Equation 24. Also, the average forward current is the output current. The power dissipation of the diode is given by the output current of the converter and the forward voltage drop according to:

EQUATION 25: RECTIFYING DIODE POWER DISSIPATION

$$P_D = I_{OUT} \times V_D$$

Schottky diodes are recommended, since they have a low forward voltage drop and fast switching rates.

EQUATION 26: COUPLING CAPACITOR

$$C_C = \frac{I_{OUT} \times D_{MAX}}{r \times V_{INmax} \times f_{SW}}$$

Note: r represents percentage of V_{INmax}.

The maximum voltage across the coupling capacitor C_C is equal to V_{IN}. As a result, the voltage rating has to be chosen accordingly. Low-ESR or ESL ceramic capacitors are recommended.

EQUATION 27: REQUIRED RMS CURRENT RATING

$$I_{CCrms} = I_{OUT} \times \sqrt{\frac{V_{OUT} + V_D}{V_{INmin}}}$$

EQUATION 28: PEAK TO PEAK RIPPLE VOLTAGE ACROSS C_C

$$\Delta V_{C_{Cp-p}} = \frac{I_{OUT} \times D_{MAX}}{C_C \times f_{SW}}$$

EQUATION 29: OUTPUT CAPACITOR

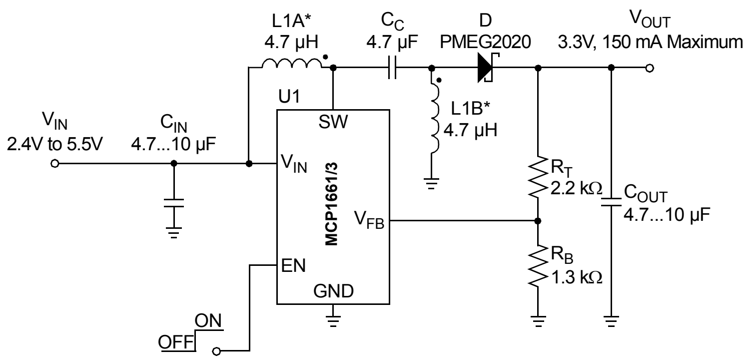
$$C_{OUT} \geq \frac{I_{OUT} \times D}{V_{OUT} \times v \times f_{SW}}$$

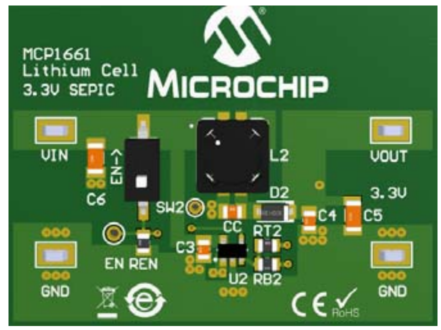
Note: v represents the desired output voltage ripple.

Ceramic capacitors are recommended due to their low-ESR ratings.

The input capacitor C_{IN} should be capable of handling the input RMS current. The input current waveform is continuous and triangular. The inductive input ensures that the input capacitor sees low ripple currents from the power supply. The input capacitor provides a low impedance source for the SEPIC Converter in cases where the power source is not immediately adjacent to the SEPIC power train. Low-ESR ceramic capacitors are recommended.

Figure 12 provides the schematic, Bill of Materials and layout example for developing a SEPIC Converter using MCP1661/3.





Note: *"MCP1661 High-Voltage Boost and SEPIC Converters Evaluation Board User's Guide"* and Demo Board (ADM00566) are available on the Microchip Technology Inc. web site for further product evaluation.

MCP1661/3 SEPIC CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{IN}, C_{OUT}	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
C_C	4.7 µF	TDK Corporation	C2012X7R1A475M125AC	Capacitor Ceramic, 4.7 µF, 10V, X7R, 0805
L1	4.7 µH	Wurth Elektronik	744878004	Inductor Coupled Power, 4.7 µH, Isat = 3A
D	—	NXP Semiconductors	PMEG2020EJ,115	Diode Schottky, 20V, 2A, SOD323F
R_T	2.2 kΩ	Panasonic® – ECG	ERJ-6ENF2201V	Resistor, SMD, 2.2 kΩ, 1%, 1/8W, 0805
R_B	1.3 kΩ	Panasonic – ECG	ERJ-6ENF1301V	Resistor, SMD, 1.3 kΩ, 1%, 1/8W, 0805
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter

FIGURE 12: *MCP1661/3 SEPIC Application.*

APPLICATIONS

- Solar systems
- Battery-powered applications

ADVANTAGES

- Can be used for a large variety of applications in which the input voltage is either higher or lower than the output voltage
- Same polarity with respect to V_{IN}
- Provides output disconnect feature
- Provides output short-circuit protection
- Can be developed using coupled inductors

DRAWBACKS

- The implementation of this topology requires a larger number of external components
- The total application price is higher than the typical boost topology
- The voltage on the SW node is V_{IN} + V_{OUT}, and due to this fact, this configuration cannot be used for high output voltages

Inverting Converter

MCP1661/3 devices can be successfully used to develop inverting topologies (ĆUK Converter). This topology can step up or step down the input voltage. The polarity of the output is reversed compared to the input.

- When the switch is turned on (ON TIME), a DC voltage equal to V_{IN} is applied to L1a; the coupling capacitor is charging L1b, resulting in a positive linear ramp of the inductor current. During this time, the diode D is reverse biased and the energy to the load is provided by L1b.
- When the switch is turned off (OFF TIME), the coupling capacitor C_C is charging from L1a. This time, the rectifying diode is forward biased and the energy is delivered to the output capacitor and load through L1b. During this time, the voltage across L1a is equal to V_{OUT}. The voltage across the coupling capacitor is $V_{IN} - V_{OUT}$; $V_{L2} = V_{OUT}$.

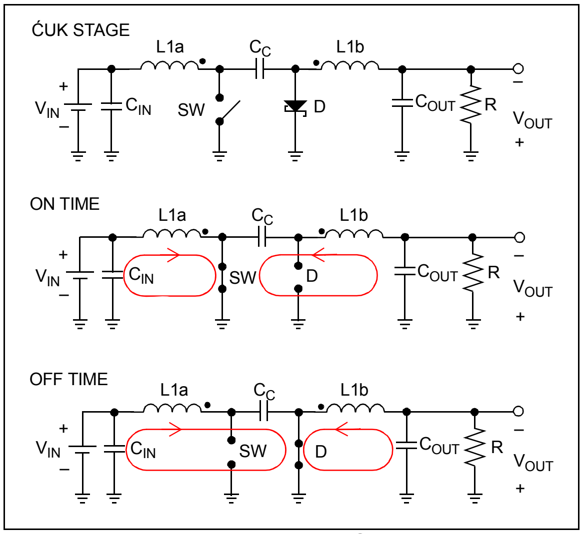


FIGURE 13: *Inverting Converter Topology.*

INVERTING CONVERTER POWER STAGE DESIGN

The formulas for calculating the external components of the inverting topology are similar to the one used for SEPIC. Note that Equation 30 and Equation 31 apply for Continuous Conduction mode operation only.

EQUATION 30: DUTY CYCLE

$$D = \frac{V_{OUT} - V_D}{V_{OUT} - V_D - V_{IN}}$$

EQUATION 31:

$$D_{max} = \frac{V_{OUT} - V_D}{V_{OUT} - V_D - V_{INmin}}$$

The duty cycle of the Inverting Converter can be calculated with Equation 30 and Equation 31 above. At Minimum Input Voltage (V_{INmin}), the duty cycle has the maximum value. At Maximum Input Voltage (V_{INmax}), the duty cycle has the minimum value.

Applications

- Negative rail powered devices
- LCD bias

Advantages

- The output current is continuous (L1b is in series with the output). As a result, the ripple is reduced, requiring a smaller output capacitor.
- Can be used for a large variety of applications in which the input voltage is either higher or lower than the output voltage.
- Can be developed using coupled inductors.

Drawbacks

- The implementation of this topology requires a larger number of external components.

ĆUK-SEPIC Converter

Taking a step forward, the SEPIC and inverting circuits can be combined and controlled by the MCP1661/3, resulting in a dual rail power supply. The SEPIC stage will provide the positive output, whereas the inverting stage will provide the negative output.

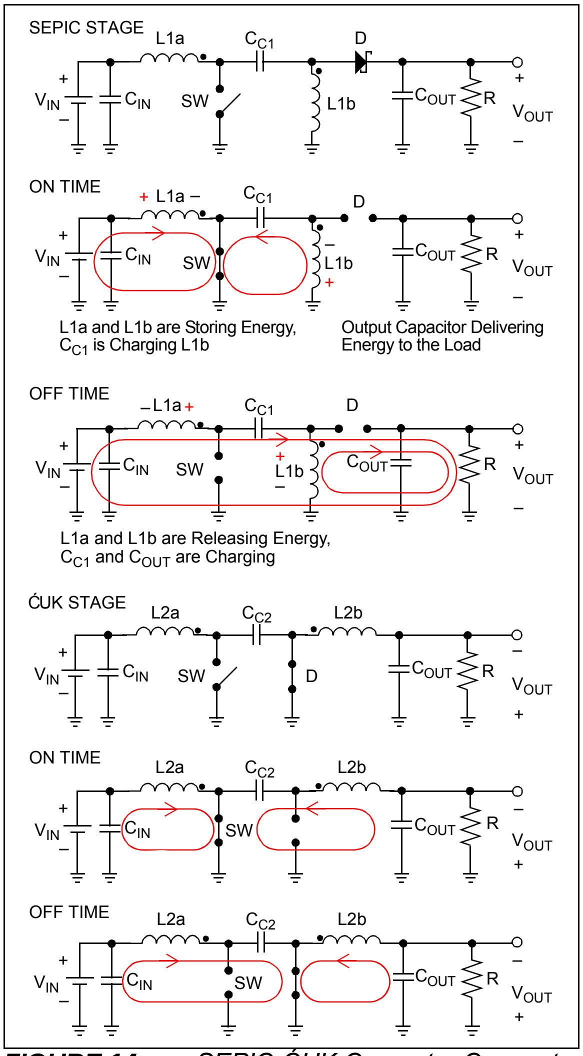
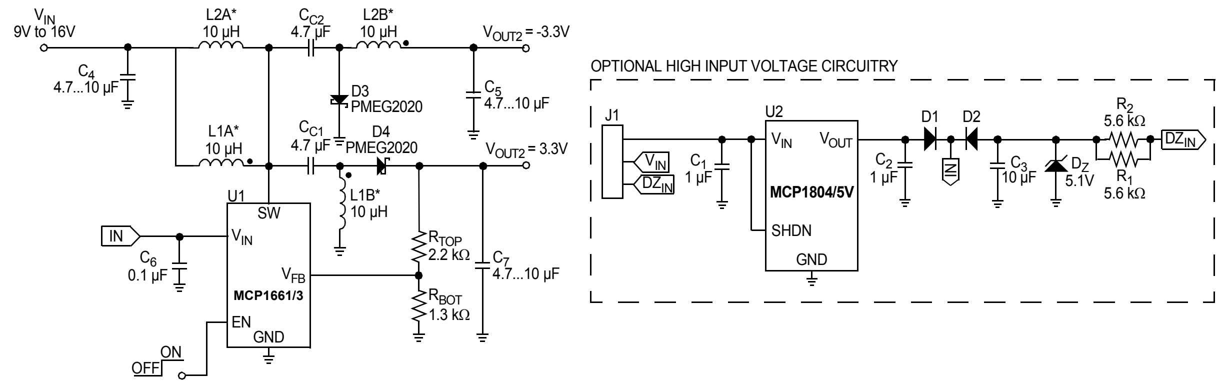


FIGURE 14: *SEPIC-ĆUK Converter Concept.*

Figures 15 and 16 provide the schematic, Bill of Materials and layout example for developing a SEPIC-ĆUK Converter using MCP1661/3.



MCP1661/3 SEPIC-ĆUK CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C1	1 µF	TDK Corporation	CGA4J3X7R1V105K125AB	Capacitor Ceramic, 1 µF, 35V, X7R, 0805
C2	1 µF	TDK Corporation	C1608X7R1A105M	Capacitor Ceramic, 1 µF, 10V, X7R, 0603
C3	10 µF	TDK Corporation	C2012X5R1C106M/0.85	Capacitor Ceramic, 10 µF, 16V, X5R, 0805
C4	10 µF	TDK Corporation	C3216X7R1V106M160AC	Capacitor Ceramic, 10 µF, 35V, X7R, 1206
C5,C7	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
C6	0.1 µF	TDK Corporation	C1608X7R1H104M	Capacitor Ceramic, 0.1 µF, 50V, X7R, 0603
C_{C1}, C_{C2}	4.7 µF	TDK Corporation	C2012X7R1E475K125AB	Capacitor Ceramic, 4.7 µF, 25V, X7R, 0805
L1, L2	10 µH	Wurth Elektronik	744877100	Inductor Power, 10 µH, Isat = 2.8A
R_T	2.2 kΩ	Panasonic® – ECG	ERJ-6ENF2201V	Resistor, SMD, 2.2 kΩ, 1%, 1/8W, 0805
R_B	1.3 kΩ	Panasonic – ECG	ERJ-6ENF1301V	Resistor, SMD, 1.3 kΩ, 1%, 1/8W, 0805
R1,R2	5.6 kΩ	Panasonic – ECG	ERJ-8ENF5601V	Resistor, SMD, 5.6 kΩ, 1%, 1/8W, 0805
D1,D2	—	Diodes® Incorporated	1N4148WS-7	Diode Rectifier, 150 mA, 75V, SOD-323
D3, D4	—	NXP Semiconductors	PMEG2020EJ,115	Diode Schottky, 20V, 2A, SOD-323F
D_Z	—	ON Semiconductor®	1SMA5918BT3G	Diode Zener, 5.1V, 1.5W, SMA
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter
U2	5V	Microchip Technology Inc.	MCP1804T-5002I/OT	Microchip Analog, LDO, 5V, SOT-23-5

FIGURE 15: *MCP1661/3 SEPIC-ĆUK Application.*

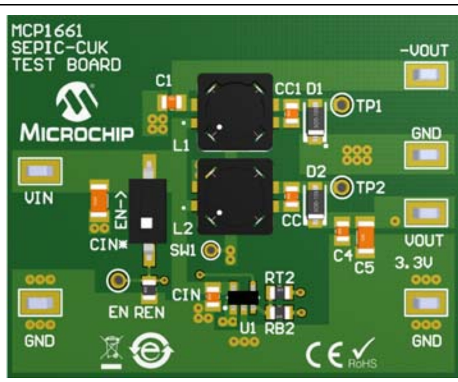


FIGURE 16: *MCP1661/3 SEPIC-ĆUK Design Example.*

MCP1661/3 Flyback Converter

The schematic of a Flyback Converter can be seen in Figure 17. It derives from the buck-boost topology, but uses a transformer instead of the inductor. A very important aspect is that flyback transformers have an air gap, which allows energy storing without the risk of core saturation occurrence. Therefore, the operating principle of both converters is very close:

- During the ON TIME (Figure 17, a), the primary winding of the transformer is connected to the input voltage source. The primary current and magnetic flux in the transformer increases, storing energy in the transformer's core. The voltage induced in the secondary winding is negative, so the diode is reverse biased. In this phase, the output capacitor supplies energy to the output load (LDO's input, in this application).
- During the OFF TIME (Figure 17, b), the primary current and magnetic flux drops. The secondary voltage is positive. The output diode is forward biased, allowing current to flow from the transformer to the capacitor and to the load.

In DCM operation, the entire stored energy is transfered to the output.

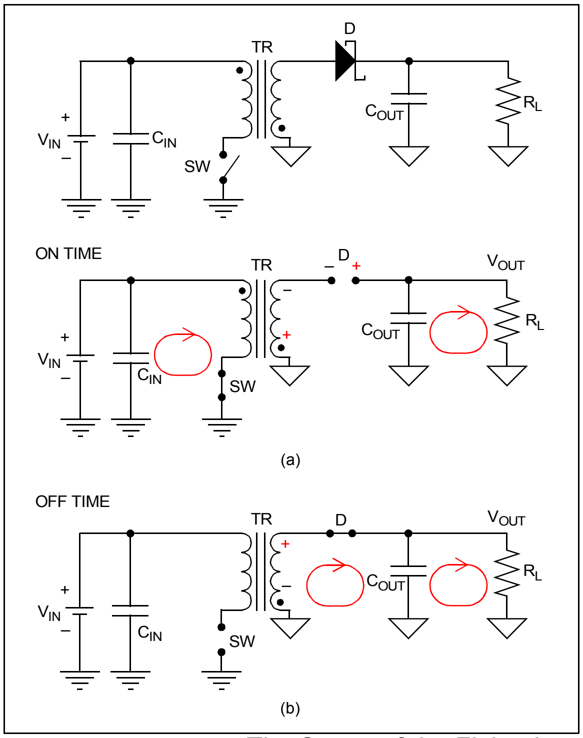


FIGURE 17: The States of the Flyback Converter in Operation.

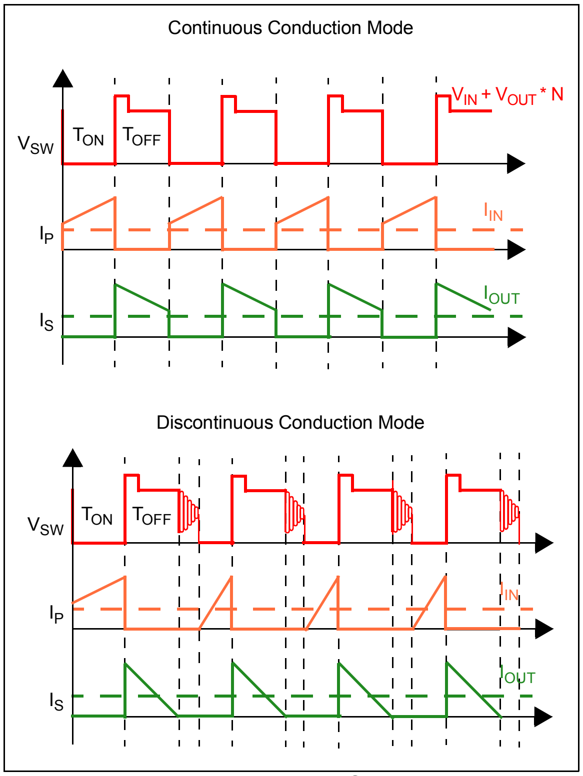
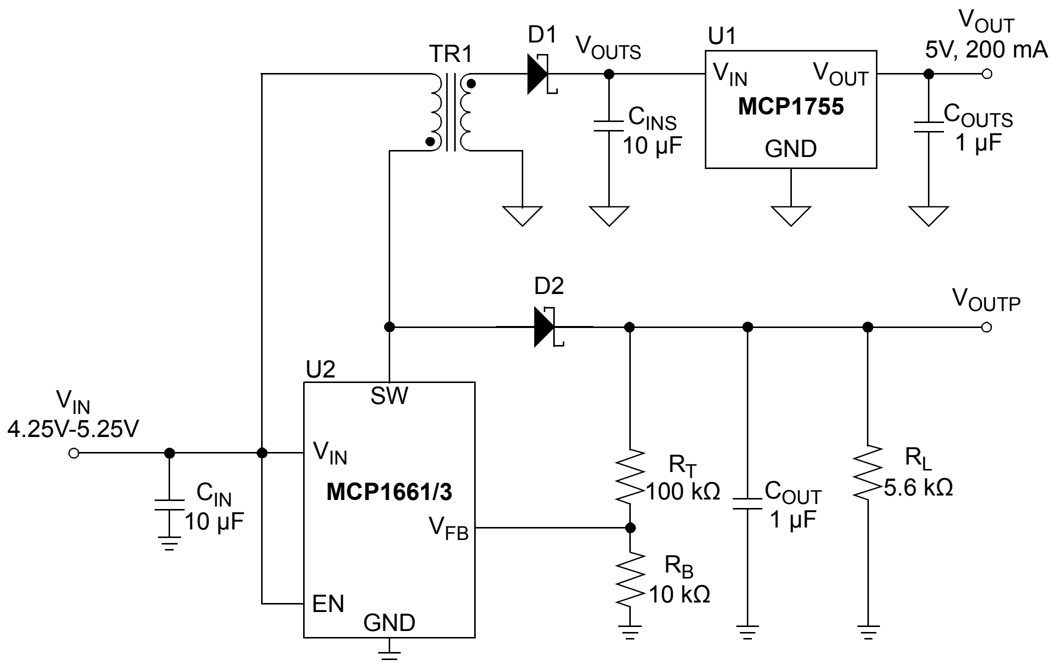


FIGURE 18: Flyback Converter Waveforms.

The transformer has to be designed/chosen to minimize the leakage inductance and core losses. The effects of these undesirable phenomenons include:

- Voltage spike on the switch
- The efficiency of the converter is affected
- The cross-regulation is affected

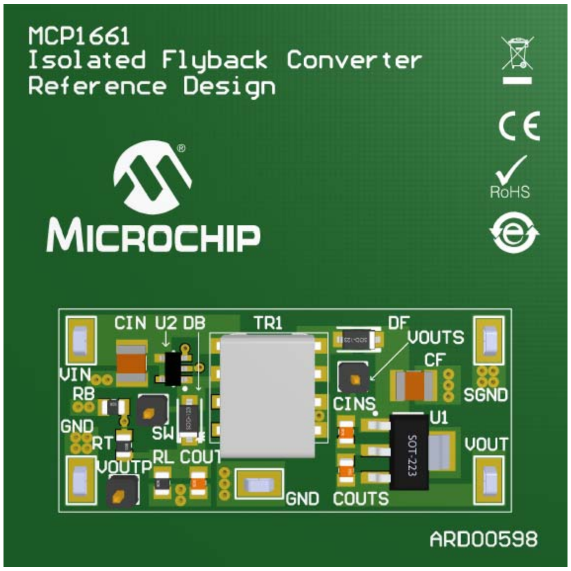
Figures 19 and 20 provide the schematic, Bill of Materials and layout example for developing an Isolated Flyback Converter using MCP1661/3.



MCP1661/3 ISOLATED FLYBACK CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{OUTS}	1 µF	TDK Corporation	C2012X7R1C105K125AA	Capacitor Ceramic, 1 µF, 16V, X7R, 0805
C_{INS}	10 µF	TDK Corporation	C3225X7R1E106K250AC	Capacitor Ceramic, 10 µF, 25V, X7R, 1210
C_{OUT}	1 µF	TDK Corporation	C2012X7R1E105K125AB	Capacitor Ceramic, 1 µF, 25V, X7R, 0805
C_{IN}	10 µF	TDK Corporation	C3225X7R1C106K200AB	Capacitor Ceramic, 10 µF, 16V, X7R, 1210
D1, D2	—	ON Semiconductor®	MBR0540T1G	Schottky Rectifier, 40V, 0.5A, SOD123
R_T	100 kΩ	Vishay Intertechnology, Inc.	CRCW0805100KFKEA	Resistor, 100 kΩ, 1/8W, 1%, 0805, SMD
R_L	5.6 kΩ	Vishay Intertechnology, Inc.	CRCW08055K60FKEA	Resistor, 5.6 kΩ, 1/8W, 1%, 0805, SMD
R_B	0 kΩ	Vishay Intertechnology, Inc.	CRCW080510K0FKEA	Resistor, 10 kΩ, 1/8W, 1%, 0805, SMD
TR1	25 µH	WURTH Elektronik	750310799	Flyback Transformer, 25 µH, 15V, 1:1
U2	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter
U1	5V	Microchip Technology Inc.	MCP1755S-5002E/DB	Microchip Analog, LDO, 5V, SOT-223

FIGURE 19: *MCP1661/3 Isolated Flyback Converter.*



Note: *"MCP1661 High-Voltage Boost and SEPIC Converters Evaluation Board User's Guide"* and Demo Board (ADM00598) are available on the Microchip Technology Inc. web site for further product evaluation.

FIGURE 20: *MCP1661 Isolated Flyback Converter Evaluation Board.*

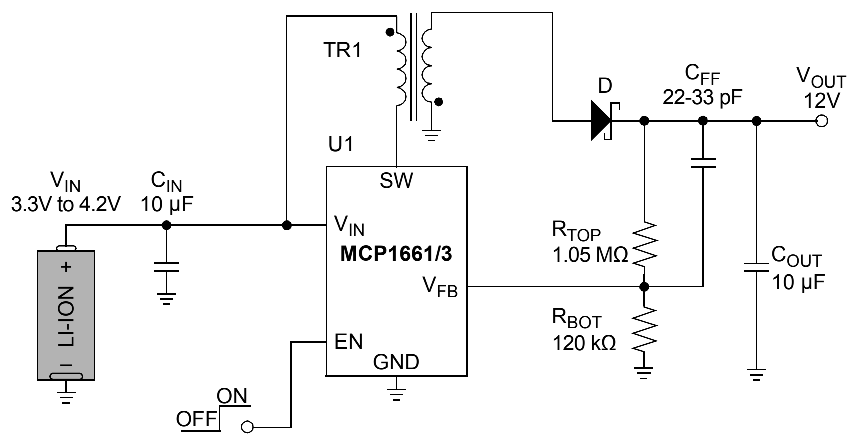
This application uses MCP166X as an open-loop Flyback Converter. The primary winding of the transformer is being used as the inductor for the Boost Converter which clamps the Primary Output Voltage (V_{OUTP}) at around 13.5V. It is very important (for normal operation of the entire circuitry and to avoid damaging some electronic components) not to connect any additional load between V_{OUTP} and GND. The Output Voltage (V_{OUTS}) of the Flyback Converter drops with the increasing of the output current due to the fact that the feedback is taken from the primary side.

In order to achieve a very good Output Voltage (V_{OUT}) regulation in the secondary side, a 5V LDO is placed after the rectifying diode of the Flyback Converter; therefore, the decrease of V_{OUTS} when increasing the load is not critical.

The MCP1661 Isolated Flyback Converter Reference Design can be used for USB-powered applications, where a positive, regulated 5V output voltage is needed from an isolated input voltage that varies from 4.75V to 5.25V.

The converter is configured as non-synchronous; an external diode (D2) is connected between the inductor (primary winding of the transformer) and the High-Voltage Output (V_{OUTP}). The transformation ratio chosen was 1:1, because the difference between the Input Voltage (V_{IN}) range and the Output Voltage (V_{OUT}) is low. The Output Voltage (V_{OUTS}) of the Flyback Converter decreases by increasing the load current, due to the lack of feedback from the secondary side of the transformer. The amount of voltage drop on the entire range of loads can be controlled by changing the Load Resistor, R_L. Charging the primary side of the flyback transformer with a higher current corresponds to a lower voltage drop in the secondary side over the entire load range, but the overall efficiency of the converter will decrease. There is a trade-off between the maximum output current capabilities, input voltage range and efficiency, by varying the values of the Load Resistor (R_L) and Feedback Resistors (R_T and R_B). In this case, those components were chosen in order to achieve good efficiency at 200 mA load current, up to 5.25V input voltage.

Figure 21 provides the schematic and Bill of Materials for developing a Non-Isolated Flyback Converter using MCP1661/3.



MCP1661/3 NON-ISOLATED FLYBACK CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{IN}	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
R_{TOP}	1.05 MΩ	Panasonic® – ECG	ERJ-6ENF1054V	Resistor, SMD, 1.05 MΩ, 1%, 1/8W, 0805
R_{BOT}	120 kΩ	Panasonic – ECG	ERJ-6ENF1203V	Resistor, SMD, 120 kΩ, 1%, 1/8W, 0805
TR1	1 µH	Wurth Elektronik	750311691	Flyback Transformer, 5:1, 1 µH
D	—	ON Semiconductor®	MBRA140T3G	Diode Schottky, 40V, 1A, SMA
C_{OUT}	10 µF	TDK Corporation	C3225X7R1H106M250AC	Capacitor Ceramic, 10 µF, 50V, X7R, 1210
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter

FIGURE 21: *MCP1661/3 Non-Isolated Flyback Converter.*

Advantages

- The Flyback Converter requires a relative small number of components and it can be used to obtain multiple outputs
- Simplicity, low cost
- It can be used to obtain high input-output conversion ratio
- The topology can be used to provide isolation

Drawbacks

- High-value output capacitor is required
- Considerable stress in the switch and output diode
- Cross-regulation may be affected by imperfect coupling
- Regulation may be difficult to obtain in light load condition

MCP1661/3 Coupled Inductor Boost Converter

The MCP1661/3 Coupled Inductor Boost Converter demonstrates the use of a conventional boost topology with a coupled inductor. The center of the coupled inductor tap is connected to the Boost switch. The voltage stress on the MOSFET is reduced because the coupled inductor acts as a step-down auto-transformer that reduces the reflection of output voltage which the MOSFET encounters. The voltage on the switching node is equal to the output voltage divided by the turns ratio. The coupled inductor with a turns 1:1 ratio will reduce the stress on the Boost switch to one-half.

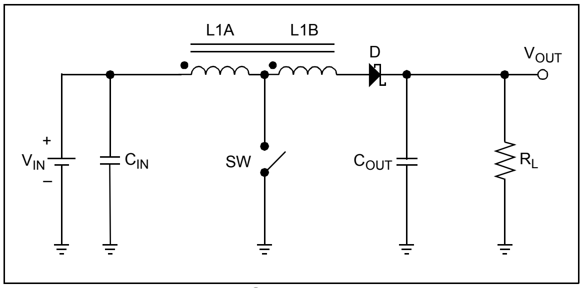


FIGURE 22: *Coupled Inductor Boost Converter.*

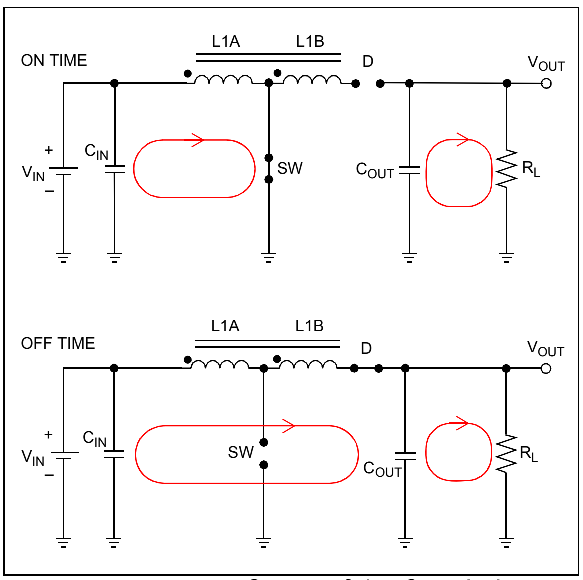


FIGURE 23: *States of the Coupled Inductor Boost Converter.*

Note that Equations 32 to 39 apply for Continuous Conduction mode operation only. They help the engineers to calculate the duty cycle of the Coupled Inductor Boost Converter.

The two inductors are assumed to have the same value.

EQUATION 32:

$$L_{1a} = L_{1b}$$

EQUATION 33:

$$M = n \times k \times L_{1a}$$

Where:

n^* = 1 (turns ratio)

k^* = 1 (magnetic coupling factor)

*Chosen for simplicity reasons.

EQUATION 34:

$$V_L = L \times \left(\frac{di_L}{dT}\right)$$

EQUATION 35:

$$V_L = V_{L1} + V_{L2}$$

EQUATION 36:

$$D = \frac{t_{on}}{T} = \frac{V_{OUT} - V_{IN}}{V_{IN} + V_{OUT}}$$

EQUATION 37:

$$V_{L2(on)} = V_{L1(on)} = V_{IN}$$

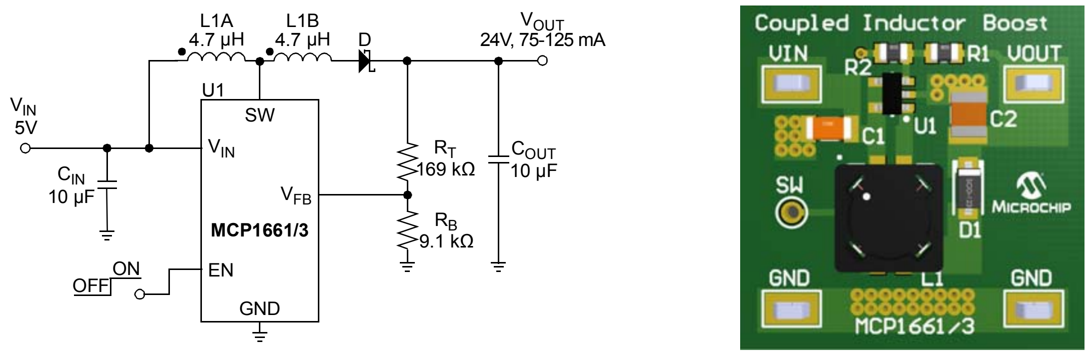
EQUATION 38:

$$I_{L1a(off))} = I_{L1b(off)}$$

EQUATION 39:

$$(V_{IN} - V_{OUT}) = V_{L1a(off)} + V_{L1b(off)}$$

Figure 24 provides the schematic, Bill of Materials and layout example for developing a Coupled Inductor Boost Converter using MCP1661/3.



MCP1661/3 COUPLED INDUCTOR BOOST CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{IN}	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
C_{OUT}	10 µF	TDK Corporation	C3225X7R1H106M250AC	Capacitor Ceramic, 10 µF, 50V, X7R, 1210
L1	4.7 µH	Wurth Elektronik	744878004	Inductor Coupled Power, 4.7 µH, Isat = 3A
D	—	ON Semiconductor®	MBRA140T3G	Diode Schottky, 40V, 1A, SMA
R_T	169 kΩ	Panasonic® – ECG	ERJ-6ENF1693V	Resistor, SMD, 169 kΩ, 1%, 1/8W, 0805
R_B	9.1 kΩ	Panasonic – ECG	ERJ-6ENF9101V	Resistor, SMD, 9.1 kΩ, 1%, 1/8W, 0805
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter

FIGURE 24: *MCP1661/3 Coupled Inductor Boost Converter Application.*

Advantages

- High-voltage conversion ratio
- Reduces the required duty cycle for a certain output voltage
- Reduces the stress across the main switch
- Capable of achieving high efficiency
- Capable of delivering relatively high power using low component count
- Broad range of inductor values
- Smaller size than a Flyback Converter (typically)

MCP1661/3 Voltage Doubler

There are cases in which the voltage requirements for some applications exceed the maximum output voltage of most standard switching regulators. For such cases, the MCP1661/3 Boost Converters can be configured, with minimum additional components, as a voltage doubler. The additional stage (consisting of C1, D1, D2 and C_{OUT2}) delivers twice the peak-to-peak amplitude of the switch voltage. In other words, $V_{OUT2} = 2 * V_{SW}$ (minus the voltage drops of the diodes).

- During the ON TIME of the switch, D2 is forward biased and C1 charges to the Output Voltage (V_{OUT1}). C1 will remain charged as there is no discharging path left (D3 is reverse biased). During this period, D1 is reverse biased and C_{OUT2} supplies the load.
- During the OFF TIME period, D2 is reverse biased. The voltage across C1 adds to the potential of the switch node, forward biasing D1. C_{OUT2} charges with approximately twice the switch voltage, delivering energy to the load.

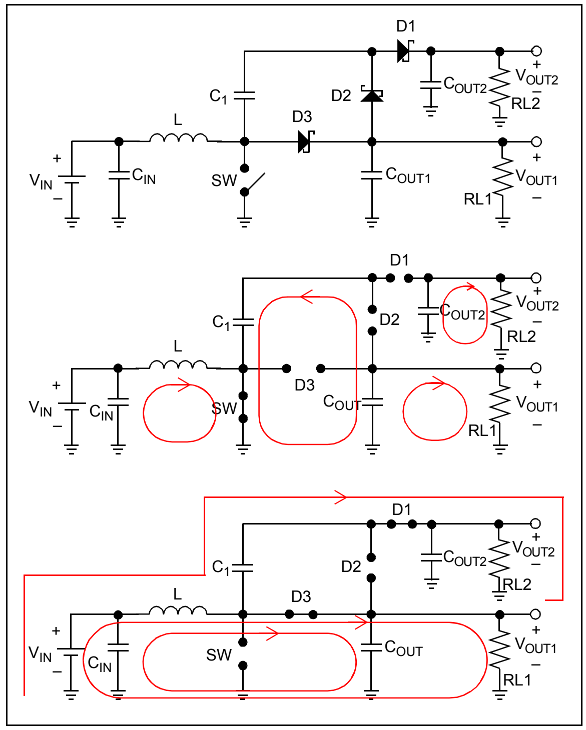
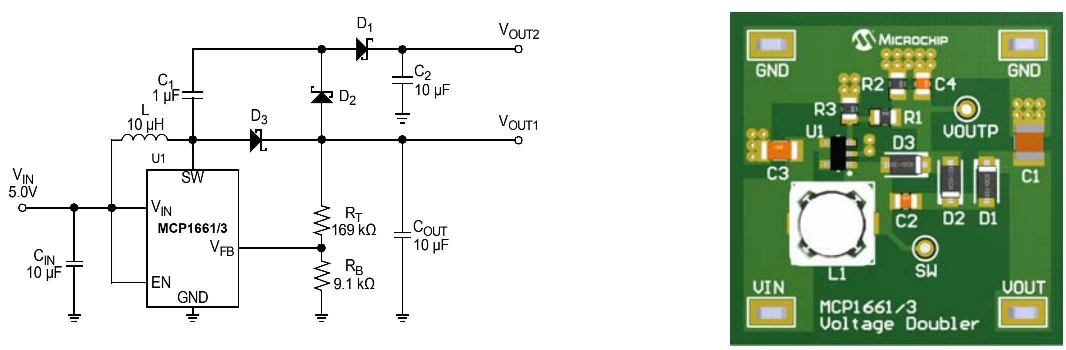


FIGURE 25: The States of the Voltage Doubler in Operation.

Figure 26 provides the schematic, Bill of Materials and layout example for developing a Voltage Doubler Converter using MCP1661/3.



MCP1661/3 VOLTAGE DOUBLER CONVERTER BILL OF MATERIALS

Component	Value	Manufacturer	Part Number	Comment
C_{IN}	10 µF	TDK Corporation	C2012X7R1A106K125AC	Capacitor Ceramic, 10 µF, 10V, X7R, 0805
C_{OUT}, C2	10 µF	TDK Corporation	C3225X7R1H106M250AC	Capacitor Ceramic, 10 µF, 50V, X7R, 1210
C1	1 µF	TDK Corporation	C2012X7R1E105K125AB	Capacitor Ceramic, 1 µF, 25V, X7R, 0805
L	10 µH	Wurth Elektronik	74477810	Inductor Power, 10 µH, Isat = 2.2A
D1, D2, D3	—	Fairchild Semiconductor	MBR0530	Diode Schottky, 30V, 500 mA, SOD123
R_T	169 kΩ	Panasonic® – ECG	ERJ-6ENF1693V	Resistor, SMD, 169 kΩ, 1%, 1/8W, 0805
R_B	9.1 kΩ	Panasonic – ECG	ERJ-6ENF9101V	Resistor, SMD, 9.1 kΩ, 1%, 1/8W, 0805
U1	—	Microchip Technology Inc.	MCP1661T-E/OT or MCP1663T-E/OT	High-Voltage Boost Converter

FIGURE 26: MCP1661/3 Voltage Doubler Application.

CONCLUSION

MCP1661/3 devices are highly integrated DC-DC Converters designed for step-up regulation, but they can be used to develop non-typical applications with minimal changes within the typical schematic. However, for each application, there are some limitations and conditions that must be taken into account for good functionality.

This application note is a brief introduction into a different way of thinking on how to develop a simple and inexpensive solution for various requirements, rather than focusing on obvious approaches.

NOTES:

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as "unbreakable."

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