Design tips for an efficient non-inverting buck-boost converter

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Introduction

Buck-boost (step-down and step-up) converters are widely used in industrial personal computers (IPCs), point-of-sale (POS) systems, and automotive start-stop systems. In these applications, the input voltage could be either higher or lower than the desired output voltage. A basic inverting buck-boost converter has a negative output voltage with respect to ground. The single-end primary inductor converter (SEPIC), Zeta converter, and two-switch buck-boost converters have positive or non-inverting outputs. However, compared with a basic inverting buck-boost converter, all three non-inverting topologies have additional power components and reduced efficiency. This article presents operational principles, current stress and power-loss analysis of these buck-boost converters, and presents design criteria for an efficient non-inverting buck-boost converter.

Inverting buck-boost converter

Figure 1 shows the schematic of a basic inverting buck-boost converter, along with the typical voltage and current waveforms in continuous conduction mode (CCM). In addition to input and output capacitors, the power stage consists of a power metal-oxide semiconductor field-effect transistor (MOSFET), a diode, and an inductor. When the MOSFET (Q1) is ON, the voltage across the inductor (L1) is V_{IN}, and the inductor current ramps up at a rate that is proportional to V_{IN}. This results in accumulating energy in the inductor. While Q1 is ON, the output capacitor supplies the entire load current. When the Q1 is OFF, the diode (D1) is forward-biased and the inductor current ramps down at a rate proportional to V_{OUT}. While Q1 is OFF, energy is transferred from the inductor to the output load and capacitor.

The voltage conversion ratio of an inverting buck-boost in CCM can be expressed as:

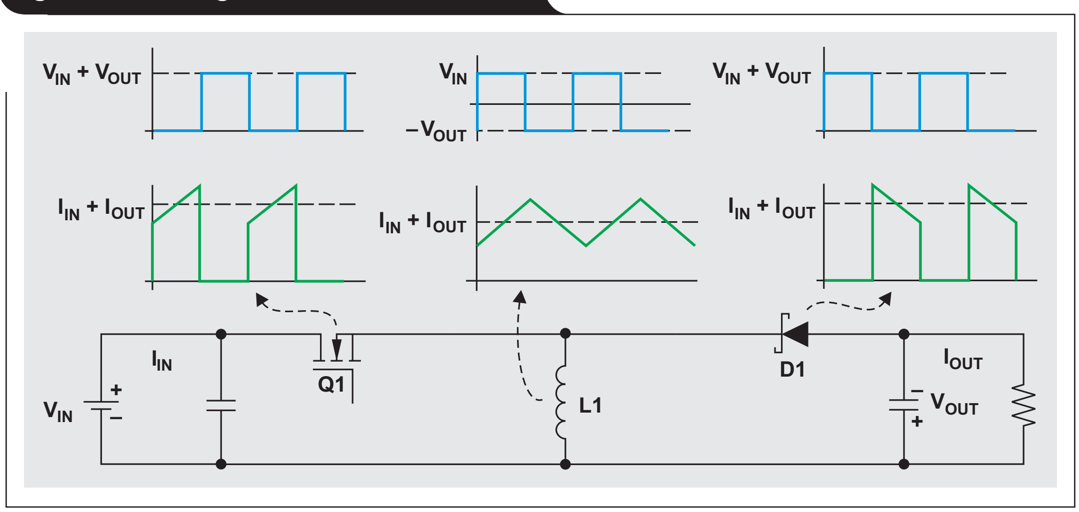
$$M = \frac{V_{OUT}}{V_{IN}} = -\frac{D}{1-D}, \tag{1}$$

where D is the duty cycle of Q1 and is always in a range of 0 to 1. Equation 1 indicates that the magnitude of output voltage could be either higher (when D > 0.5) or lower (when D < 0.5) than the input voltage. However, the output voltage always has an inverse polarity relative to the input.

Conventional non-inverting buck-boost converters

The inverting buck-boost converter does not serve the needs of applications where a positive output voltage is required. The SEPIC, Zeta, and two-switch buck-boost converter are three popular non-inverting buck-boost topologies. The Zeta converter, also called inverse SEPIC, is similar to SEPIC, but less attractive than SEPIC since it requires a high-side driver that increases the circuit complexity.

Figure 1. Inverting buck-boost converter



A SEPIC converter and its ideal waveforms in CCM are shown in Figure 2. The voltage conversion ratio of a SEPIC converter is:

$$M = \frac{V_{OUT}}{V_{IN}} = \frac{D}{1-D}. \quad (2)$$

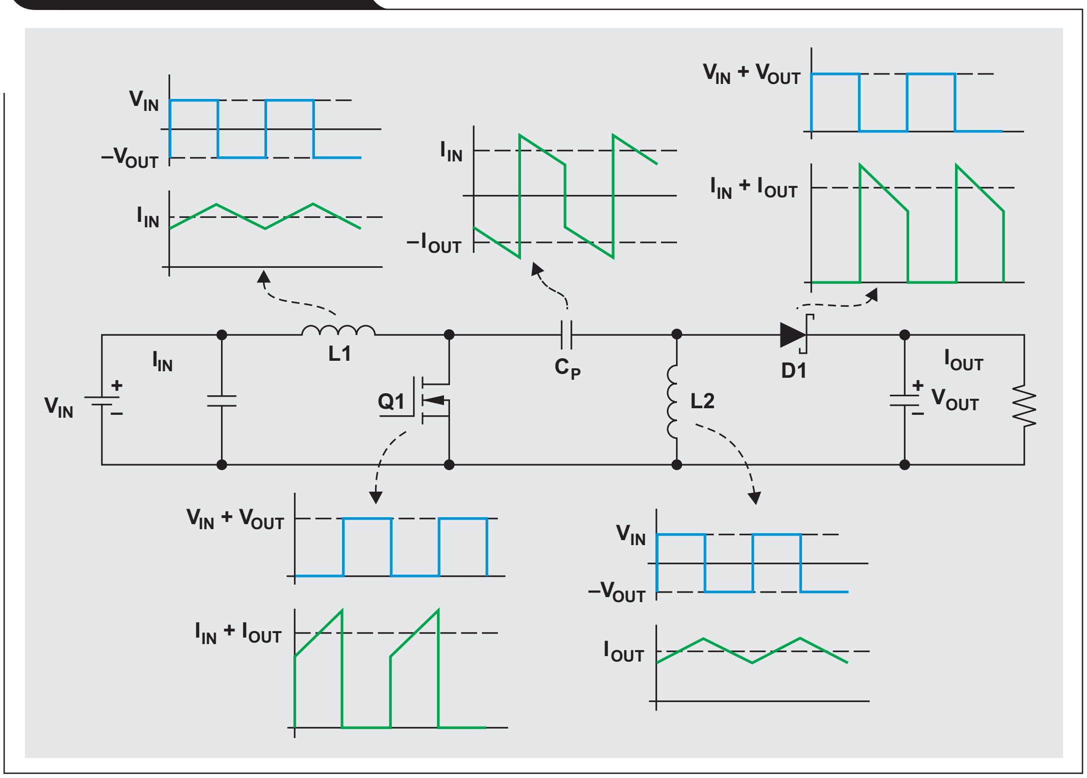
Equation 2 indicates a positive output voltage and the buck-boost capability.

Like an inverting buck-boost converter, a SEPIC converter has a single MOSFET (Q1) and a single diode (D1). The MOSFET and diode in a SEPIC converter have voltage and current requirements similar to their counterparts in an inverting buck-boost converter. As such, the power losses of the MOSFET and diode are similar. On the other hand, a SEPIC converter has an additional inductor (L2) and an additional ac-coupling capacitor (C_P).

In a SEPIC converter, the average inductor current of L1 equals the input current (I_{IN}), whereas the average inductor current of L2 equals the output current (I_{OUT}). In contrast, the single inductor in an inverting buck-boost converter has an average current of $I_{IN} + I_{OUT}$. The coupling capacitor sees significant root-mean-square (RMS) current relative to both input current and output current, which generates extra power loss and reduces the converter's overall efficiency.

To reduce power loss, ceramic capacitors with low equivalent series resistance (ESR) are desired, which usually leads to higher cost. The additional inductor of a SEPIC converter, coupled with the extra coupling capacitor, increases printed circuit board (PCB) size and total solution cost. A coupled inductor can be used to replace two separate inductors to reduce PCB size. However, the selection of off-the-shelf coupled inductors are limited when compared to separate inductors. Sometimes a custom design will be required, which increases cost and lead time.

Figure 2. SEPIC converter

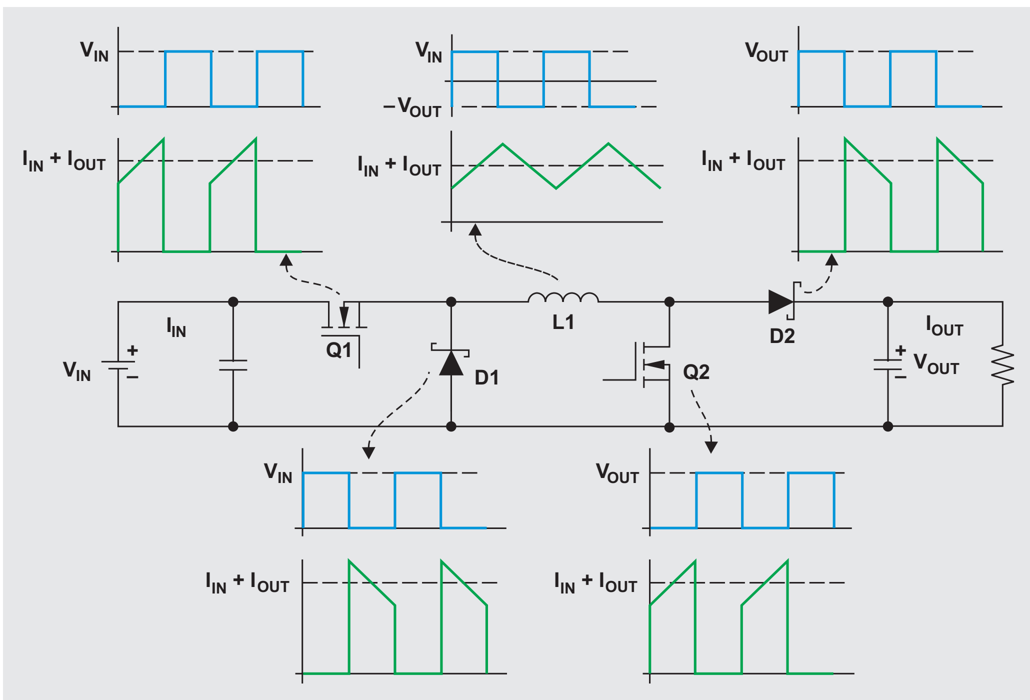


A conventional two-switch buck-boost converter uses a single inductor (Figure 3). However, it has an additional MOSFET (Q2) and an additional diode (D2) compared to an inverting buck-boost converter. By turning Q1 and Q2 ON and OFF simultaneously, the converter operates in buck-boost mode, and the voltage conversion ratio also complies with Equation 2. This confirms that the two-switch buck-boost converter performs a non-inverting conversion. The ideal waveforms of a two-switch buck-boost converter operating in buck-boost mode and CCM are shown in Figure 3. Q1 and D1 both see a voltage stress of V_{IN}, while Q2 and D2 both see a voltage stress of V_{OUT}. Q1, Q2, D1, D2, and L1 all see a current stress of $I_{IN} + I_{OUT}$ with inductor ripple current neglected. The relatively large number of power devices and high-current stress in buck-boost mode prevent the converter from being very efficient.

Operating-mode optimization of a two-switch buck-boost converter

The two-switch buck-boost converter is a cascaded combination of a buck converter followed by a boost converter. Besides the aforementioned buck-boost mode, wherein Q1 and Q2 have identical gate-control signals, the two-switch buck-boost converter also can operate in either buck or boost mode. By operating the converter in buck mode when V_{IN} is higher than V_{OUT}, and in boost mode when V_{IN} is lower than V_{OUT}, the buck-boost function is then realized.

Figure 3. A two-switch buck-boost converter in buck-boost mode of operation



In buck mode, Q2 is controlled to be always OFF, and output voltage is regulated by controlling Q1 as in a typical buck converter. The equivalent circuit in buck mode and corresponding ideal waveforms in CCM are shown in Figure 4. The voltage conversion ratio is the same as that of a typical buck converter:

$$M = \frac{V_{OUT}}{V_{IN}} = D, \tag{3}$$

where D is the duty cycle of Q1. In buck mode, the output voltage is always lower than the input voltage since D is always less than one.

Higher efficiency is possible in buck mode compared to the buck-boost mode for three reasons. First of all, Q2 is always OFF in buck mode, which means there is no power dissipated in it. Second, Q1, D1, and L1 see a lower current stress of only I_{OUT} in buck mode compared to I_{IN} + I_{OUT} in buck-boost mode, which potentially reduces power loss. Third, although conduction loss of D2 stays the same, the reverse recovery loss is eliminated in the buck mode because D2 always conducts.

By keeping Q1 always ON, D1 is reverse biased and stays OFF, and the two-switch buck-boost converter then operates in boost mode. Similar to the typical boost converter, the output voltage is regulated by controlling Q2. The equivalent circuit in boost mode and corresponding ideal waveforms in CCM are shown in Figure 5. The voltage conversion ratio is the same as that of a typical boost converter:

$$M = \frac{V_{OUT}}{V_{IN}} = \frac{1}{1-D}, \tag{4}$$

where D is the duty cycle of Q2. In boost mode, the output voltage is always greater than the input voltage because D is always greater than zero. Similarly, higher efficiency could be achieved in boost mode than in buck-boost mode due to fewer operating power devices and lower current stress.

Figure 4. Buck-mode operation of the two-switch buck-boost converter

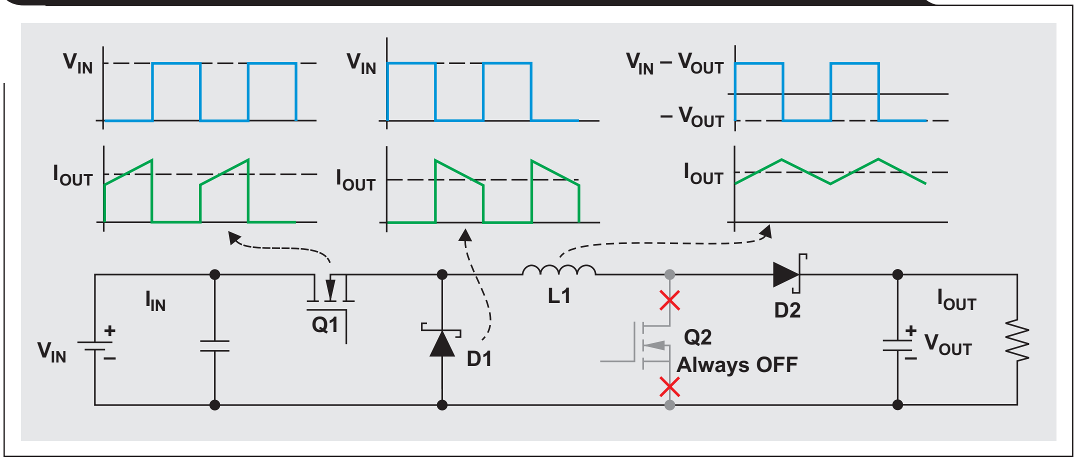
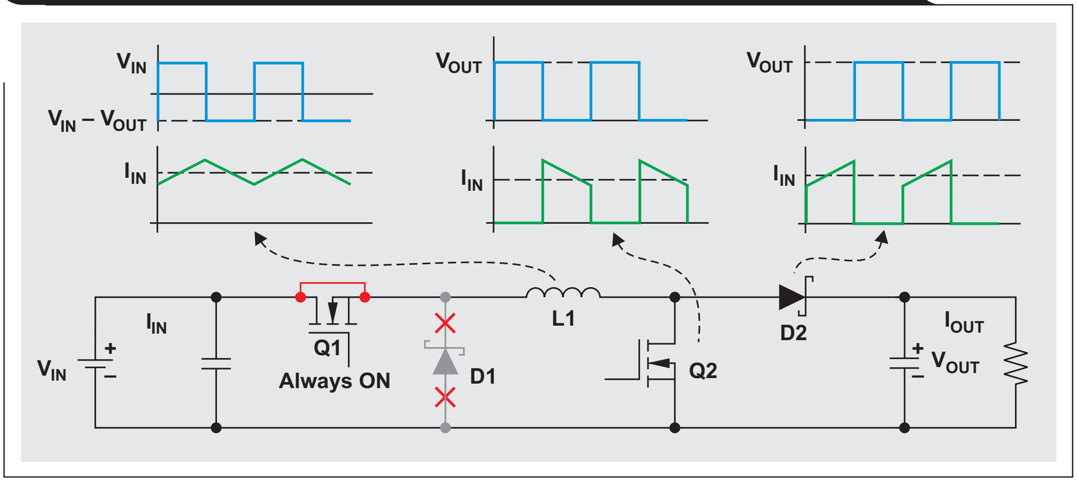


Figure 5. Boost-mode operation of the two-switch buck-boost converter



Implementation of an efficient two-switch buck-boost converter

The two-switch buck-boost converter can function in buck-boost, buck or boost modes of operation. Various combinations of operating modes can be used to accomplish both a step-up and step-down function. Appropriate control circuitry is required to ensure the desired modes of operation. Table 1 summarizes a comparison between four different combinations of operating modes. The buck-boost mode alone features the simplest control, but has low efficiency for both step-up and step-down conversion over the V_{IN} range.

Table 1. Comparison of operating modes

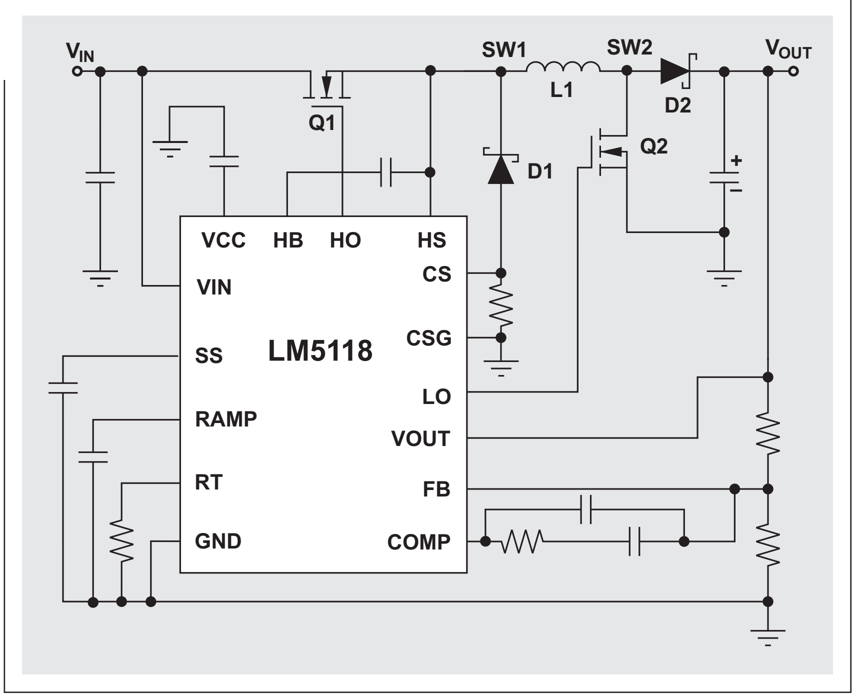
OPERATION MODES	CONTROL COMPLEXITY	EFFICIENCY ($V_{IN} > V_{OUT}$)	EFFICIENCY ($V_{IN} < V_{OUT}$)
Buck-boost	Simple	Low	Low
Buck and buck-boost	Moderate	High	Low
Buck-boost and boost	Moderate	Low	High
Buck, buck-boost, and boost	Complicated	High	High

The combination of buck, buck-boost and boost modes has the potential to achieve high efficiency over the V_{IN} range. However, its control is very complicated due to multiple modes of operation and the resulting transitions between different modes. In many applications, the input voltage usually drops below output for only a short period of time. In such applications, the efficiency of step-up conversion is not as critical as step-down conversion. As such, the combination of buck and buck-boost modes is a good trade-off between control complexity and efficiency.

Figure 6 shows a practical implementation of a two-switch buck-boost converter that uses the LM5118 dual-mode controller from Texas Instruments. This converter acts as a buck converter when the input voltage is above the output voltage. As the input voltage decreases and falls below the output voltage, it transits to buck-boost mode. There is a short gradual transition region between buck mode and buck-boost mode to eliminate disturbances at the output during transitions.

In this example, the nominal output voltage is 12 V. When V_{IN} is above 15.5 V, the converter operates in buck mode. When V_{IN} falls below 13.2 V, the converter operates

Figure 6. Two-switch buck-boost converter features buck and buck-boost operating modes



in buck-boost mode. When V_{IN} is between 15.5 V and 13.2 V, the converter operates in the transition mode. Figure 7 shows voltage waveforms of switch node 1 (SW1) and switch node 2 (SW2). In buck mode (V_{IN} = 24 V), SW2 voltage stays constant which suggests that Q2 is kept OFF. In contrast, Q2 as well as Q1 are switching in buck-boost mode (V_{IN} = 9 V). Figure 8 shows the efficiency with respect to input voltage at 3 A of load current. The improved efficiency for step-down conversion is achieved by operating the converter in buck mode.

Conclusion

SEPIC, Zeta, and two-switch buck-boost converters are three popular non-inverting buck-boost topologies that provide a positive output as well as a step-up/down function. When operating in the buck-boost mode, all three converters can experience high-current stress and high-conduction loss. However, by operating the two-switch buck-boost converter in either buck mode or boost mode, the current stress can be reduced and the efficiency can be improved.

References

1. "AN-1157 Positive to Negative Buck-Boost Converter Using LM267X SIMPLE SWITCHER® Regulators," Application Report, Texas Instruments, April 2013. Available: **www.ti.com/3q14-SNVA022**

Related Web sites

www.ti.com/3q14-LM5118

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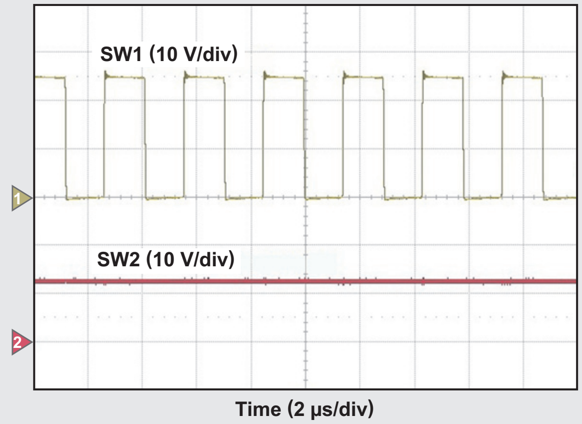
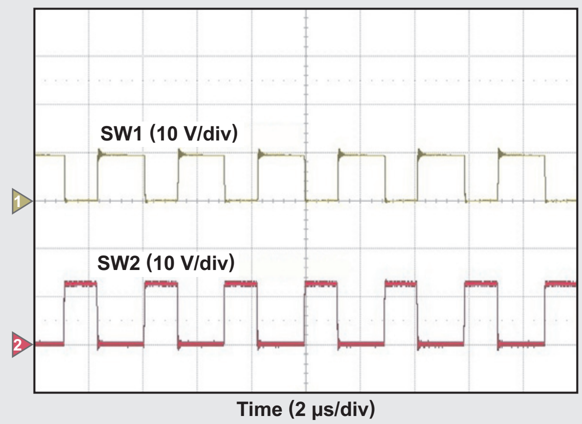
Figure 7. Voltage waveforms at switch nodes

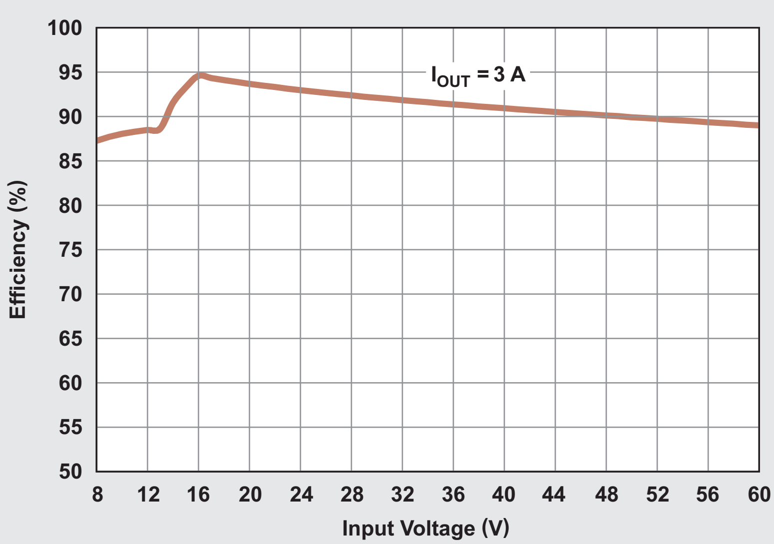


(a.) Buck mode when V_{IN} = 24 V



(b.) Buck-boost mode when V_{IN} = 9 V

Figure 8. Efficiency with respect to the input voltage



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