Application Report

Improving Efficiency at Higher Loads with High Switching Frequencies

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ABSTRACT

Operating at higher switching frequencies increases the switching losses of buck converters, but it can also decrease the conduction losses at higher load currents. The lower the inductance required, generally, the lower the DCR of the inductor will be. Or, if solution size is more important, the higher switching frequency allows for a physically smaller inductor with a similar DCR. This application note reviews the primary contributors of buck converter power losses, and then compares the efficiency of two different switching frequency synchronous buck converter designs to show the benefits of high switching frequencies.

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1 Introduction

With the never-ending trend of faster data rates, smaller form factors, and increased power density, board space is becoming gradually scarcer. This makes the job of the power-supply designer increasingly difficult as trying to fulfill all the design requirements, while keeping solution size to a minimum, is no small feat.

One way to go about minimizing the footprint that the power supply leaves on the total design is to choose a converter with a high switching frequency. With higher switching frequencies, design requirements such as output current ripple, output voltage ripple, and load transient can be achieved by using less inductance and output capacitance. This reduces solution size and decreases the total BOM cost of the power supply.

One of the disadvantages of going for higher switching frequencies is increased switching losses. The increased switching losses do not always correlate to decreased efficiency throughout the output current range. It should not be overlooked that switching losses are only one part of the total losses that occur during the operation of a buck converter. As a matter of fact, at higher currents, the conduction losses become the dominant contributor of power loss.

TI's TPS628512 is a high frequency synchronous buck converter with a small 1.6-mm x 2.1-mm package which provides a small solution size optimized for space constrained applications. Later on in this application note, the TPS628512 will be compared with the TPS54218 to show the impact of conduction losses, in particular, conduction losses in the inductor, on the final efficiency.

2 Main Sources of Power Losses in Synchronous Buck Converters

There are three main sources of power loss in synchronous buck converters: quiescent losses (static losses), switching losses and conduction losses. In today's buck converters the quiescent losses generally represent only a small percentage of the total losses when the load at the output of the converter is above a few tens of milliamps. This application note looks at relatively higher currents, in which case, the switching and conduction losses play a much bigger factor than the quiescent losses – which can be neglected.

The following two sections will briefly go through the causes of switching losses and conduction losses in synchronous buck converters.

Switching Losses

Switching losses in synchronous buck converters are the result of charging and discharging the gate to drain and gate to source capacitances of the power MOSFETs when they are turned on and off. These losses can be calculated with the following equations:

$$P_{SW\text{-}TURN\ ON} = \frac{1}{2} \times V_{IN} \times I_{OUT} \times \Delta T_{ON} \times f_{SW} \quad (1)$$

$$P_{SW\text{-}TURN\ OFF} = \frac{1}{2} \times V_{IN} \times I_{OUT} \times \Delta T_{OFF} \times f_{SW} \quad (2)$$

Where:

- $P_{SW\text{-}TURN\ ON}$ and $P_{SW\text{-}TURN\ OFF}$ are the switching losses caused by turning-on and turning-off the MOSFET respectively
- V_{IN} is the input voltage
- I_{OUT} is the output current
- f_{SW} is the switching frequency
- ΔT_{ON} is the turn-on time of the MOSFET
- ΔT_{OFF} is the turn-off time of the MOSFET

Important to note is that the switching losses are linearly proportional with the switching frequency and with the output current.

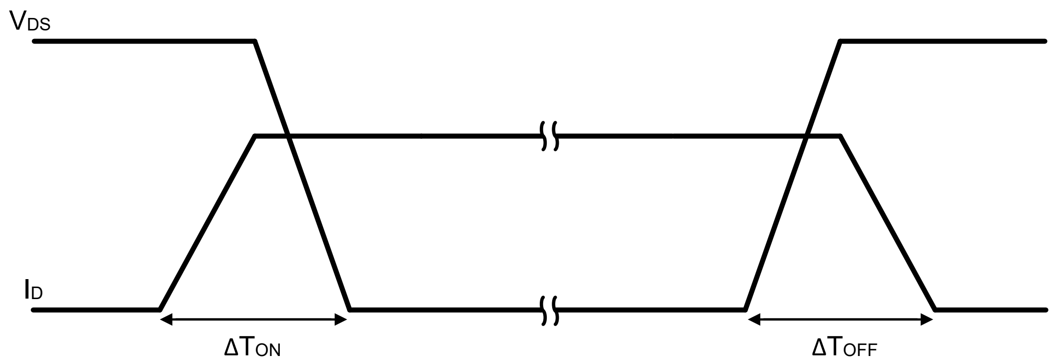

Figure 2-1. MOSFET Turn-on and Turn-off

Conduction Losses

One part of the conduction losses (Joule losses) in a buck converter are due to the drain-source on-state resistance of the power MOSFETs:

$$P_{ON\text{-}HIGH} = R_{DS(ON)\text{-}HIGH} \times I_{HIGH(RMS)}{}^2 = R_{DS(ON)\text{-}HIGH} \times \frac{V_{OUT}}{V_{IN}} \times \left(I_{OUT}{}^2 + \frac{(I_P - I_V)^2}{12}\right) \tag{3}$$

$$P_{ON\text{-}LOW} = R_{DS(ON)\text{-}LOW} \times I_{LOW(RMS)}{}^2 = R_{DS(ON)\text{-}LOW} \times \left(1 - \frac{V_{OUT}}{V_{IN}}\right) \times \left(I_{OUT}{}^2 + \frac{(I_P - I_V)^2}{12}\right) \tag{4}$$

and the other part is due to the DCR of the inductor:

$$P_{DCR} = DCR \times I_{L(RMS)}{}^2 = DCR \times \left(I_{OUT}{}^2 + \frac{(I_P - I_V)^2}{12}\right) \tag{5}$$

Where:

- $P_{ON\text{-}HIGH}$ and $P_{ON\text{-}LOW}$ are the conduction losses in the high-side and low-side MOSFETs respectively
- P_{DCR} are the conduction losses due to the resistance of the inductor
- $R_{DS(ON)\text{-}HIGH}$ and $R_{DS(ON)\text{-}LOW}$ are the drain-source on-state resistances of the high-side and low-side MOSFETs respectively
- $I_{HIGH\text{-}RMS}$ and $I_{LOW\text{-}RMS}$ are the RMS values of the current flowing through the high-side and low-side MOSFETs respectively
- V_{OUT} is the ouptut voltage
- I_P is the peak of the inductor current
- I_V is the valley of the inductor current

What is important to notice from these equations is that the conduction losses are dependent on the square of the RMS value of the current flowing through the particular MOSFET and through the inductor. And unlike the switching losses they are independent of switching frequency, as long as the inductor current ripple is held constant.

Figure 2-2 shows a calculated example efficiency curve of a synchronous buck converter plotted on the left y-axis along with the corresponding switching and conduction losses plotted on the right y-axis with respect to output current. This figure clearly displays how, due to the dependency on the square of the output current, at a certain point the conduction losses become the dominating factor and at higher currents their effect on efficiency is much more significant than that of the switching losses. In general, the switching losses and conduction losses are equal near the peak of the efficiency curve.

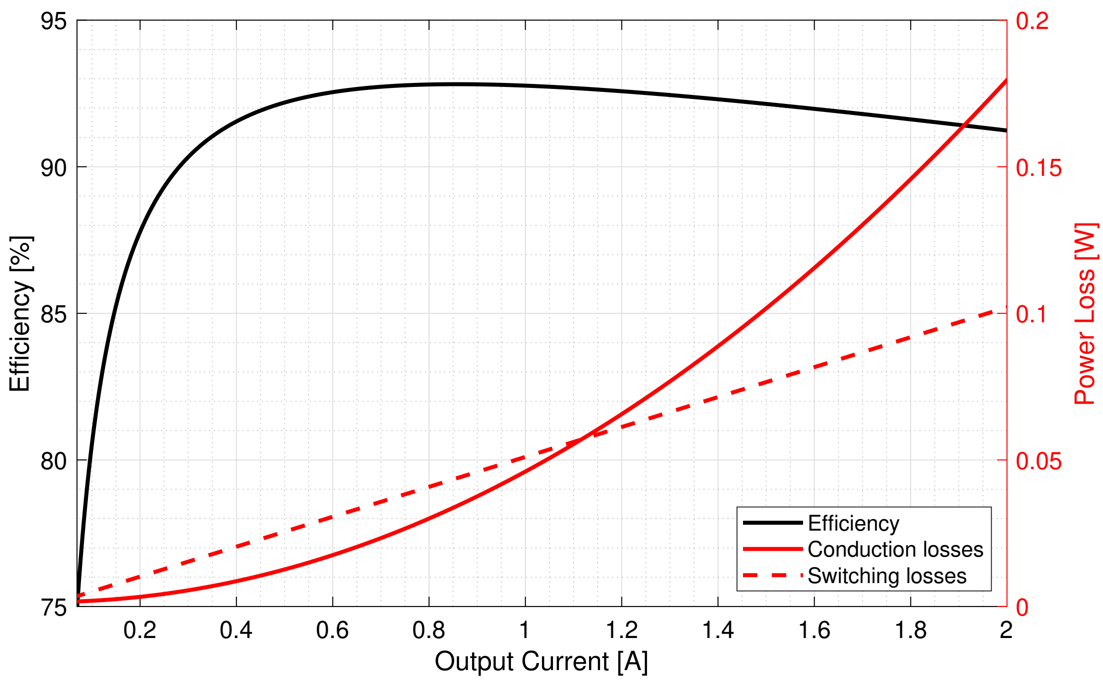

Figure 2-2. How Conduction and Switching Losses Vary with Output Current

3 Design Example

This section will compare the design and performance of two 2-A buck converters; the TPS54218 and the TPS628512 which have been set to operate with a switching frequency of 200-kHz and 1.8-MHz respectively.

The inductors used for this example come from the same series of inductors from Coilcraft (the XGL4030) with a size of 4-mm x 4-mm x 3-mm and their inductances were selected so that the inductor current ripple is similar for both designs – this is important for a fair efficiency comparison since the RMS value of the inductor current affects the conduction losses. The inductor current ripple and the ripple ratio in a buck converter can be calculated with the following equations respectively:

$$\Delta I_L = \frac{V_{OUT} \times (V_{IN} - V_{OUT})}{L \times f_{SW} \times V_{IN}} \tag{6}$$

$$K = \frac{\Delta I_L}{I_{OUT(MAX)}} \tag{7}$$

A 1-uH inductor was chosen for the TPS628512 which is operating with a switching frequency of 1.8-MHz and an 8.2-uH inductor was selected for the TPS54218 operating at 200-kHz. The resulting inductor current ripple ratio at 2-A is 0.32 for the TPS628512 and 0.35 for the TPS54218, the current ripple ratios are sufficiently close for this test.

The fact that both the 1uH and the 8.2-uH inductors are the same size, means that the 8.2-uH inductor will naturally have a greater DCR. The reason for that is, in order to achieve a higher inductance, the winding of the inductor has to contain a higher number of turns – thereby increasing the length of the copper wire which increases its resistance.

For this particular design the 1 uH inductor has a typical DCR of 6.5-mOhms and the 8.2-uH inductor has a typical DCR of 55-mOhms. It can be concluded that the DCR of the inductor has increased by the same factor as the inductance, almost 8-fold.

Figure 3-1 compares the measured efficiencies of both designs at V_{IN} = 5-V and V_{OUT} = 1.8-V, showing that the TPS628512 has less losses when the output current exceeds 1-A. The TPS628512 also has a Power Save Mode, allowing the converter to operate with pulse-frequency modulation at lower currents which decreases the switching losses and increases efficiency.

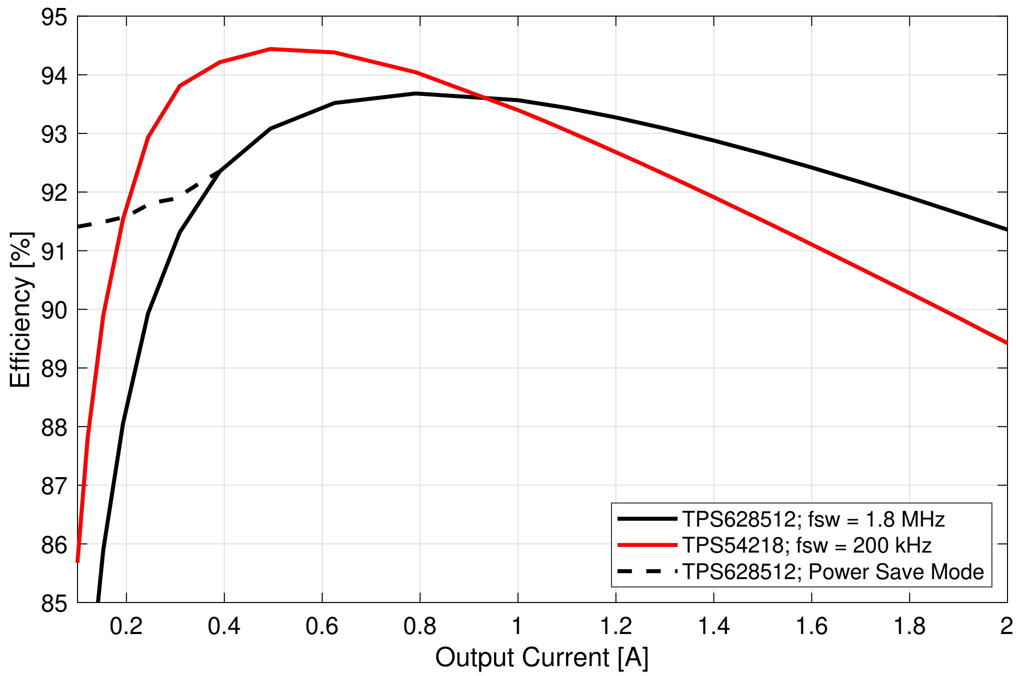

Figure 3-1. Efficiency Comparison

This efficiency improvement goes on top of the other benefits of high switching frequency converters such as having a smaller solutions size because of requiring less output capacitance to meet the same output ripple and transient performance as the low switching frequency converters. In this case, due to the lower BOM count and the lower output capacitance, the total solution size of the TPS628512 comes in at 48mm^2, whereas the TPS54218 running at a lower switching frequency takes up 92 mm^2 of board space – almost twice as much.

4 Summary

As with every power supply design, there are trade-offs to be made, but losing efficiency when using high-switching frequency converters doesn't necessarily have to be one of them. This application note shows that at higher loads operating at high-switching frequencies can have an efficiency benefit at higher currents, due to the fact that they allow for the use of inductors with a lower inductance and as a result lower DCR.

5 References

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