Current Doubler Rectifier Offers Ripple Current Cancellation

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ABSTRACT

The current doubler rectifier is a popular alternate choice for the output stage of a buck derived power converter, which would otherwise use a conventional center-tapped transformer with secondary-side, full-wave rectification. Power topologies within this class would include the push pull, half bridge and full bridge. There are many advantages that can be gained by using a current doubler rectifier but by far the least mentioned is the ability to cancel ripple current seen at the output capacitor. Output ripple current cancellation reduces the required output capacitance producing less noise at the power supply output. The degree of ripple current cancellation is duty cycle dependent, so design specifications such as input voltage and transformer turns ratio need careful attention.

1   Introduction

As illustrated in Figure 1, the current doubler uses two output inductors, each carrying half the total load current and operating at half the switching frequency. Initially, this may not seem like an advantage, especially considering that the full-wave approach uses only one output inductor. However, from an energy storage point of view, the total area product required for each case is the same, so the total magnetic core volume is the same. Using two inductors in the output stage additionally provides the ability to better distribute heat dissipation, which is especially a problem with high current output designs. It is also critical that the currents in each output inductor remain equal under all operating conditions. For this reason, current mode control is a requirement with the current doubler rectifier. To the designer, this should not be a problem, especially with the availability of advanced current mode PWM controllers such as the UCC3895 Phase Shift PWM Controller or the UCC3808 Push Pull PWM Controller shown in Figure 1.

Another benefit of the current doubler is the simplification of the transformer design. Without the center-tapped secondary, characteristic of all full-wave rectifiers, the transformer output is more easily terminated to the rest of the power stage. Also, a finer resolution in the transformer turns ratio is possible since the two secondaries of the full-wave rectifier are now replaced with a single secondary winding in a current doubler application.

For higher current, low voltage applications, the current doubler also makes control driven synchronous rectification much simpler because each output rectifier is referenced directly to secondary ground. Having the output rectifiers both referenced to ground eliminates the need to develop a high-side gate drive, allowing the use of a low-side MOSFET gate driver such as the UCC37324 shown in Figure 1. This results in less circuitry, saving precious board space, and a greater selection of low-side gate driver devices to choose from.

TEXAS
INSTRUMENTS
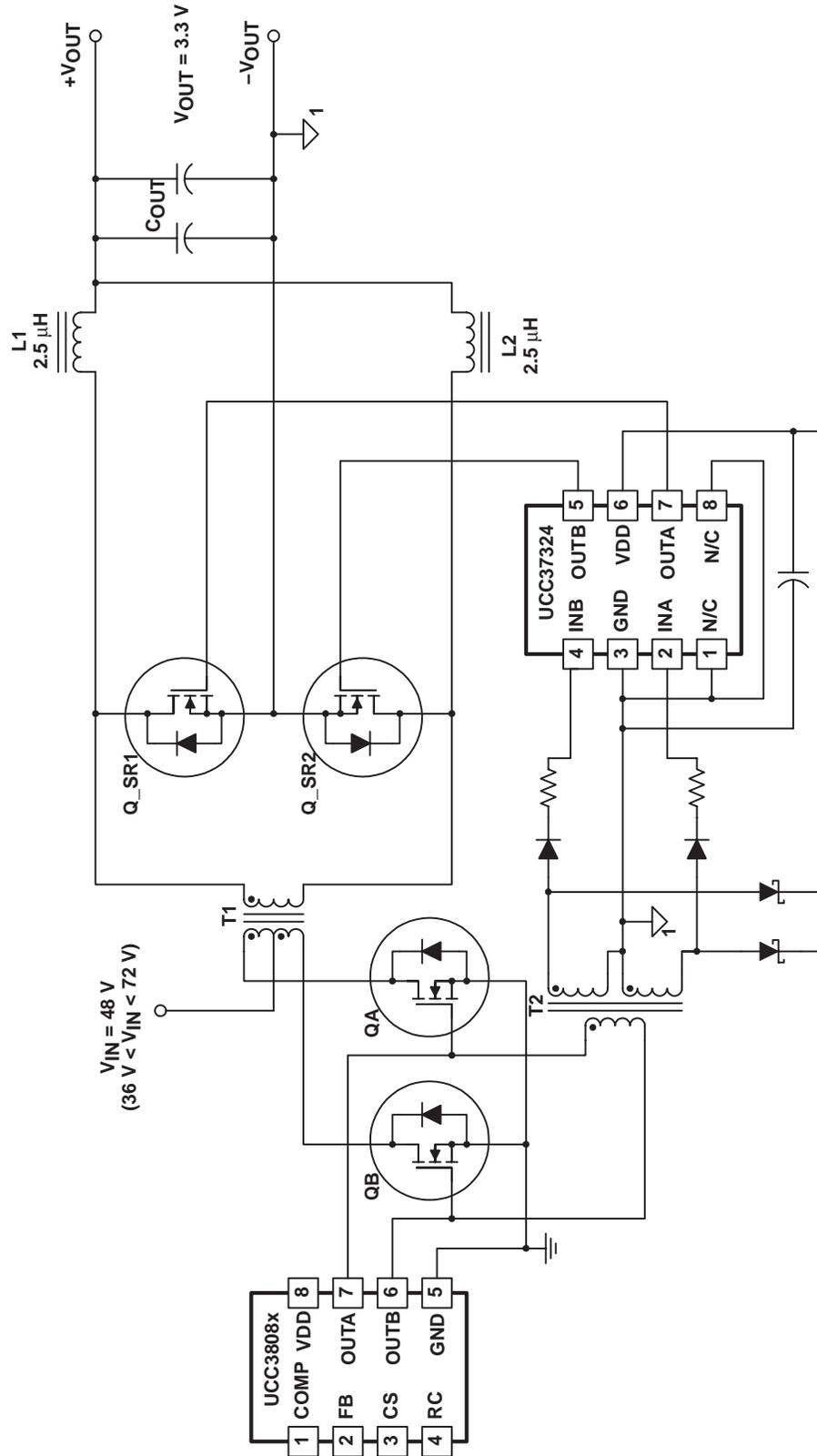
Figure 1. Push-Pull Converter With Synchronous Current Doubler Rectifier

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2   Ripple Current Cancellation

While all of these benefits are noteworthy, perhaps the greatest motivation for using the current doubler rectifier is the reduced ripple current seen by the output capacitors. In some sense, the current doubler rectifier can be thought of as a two-phase, interleaved synchronous buck. As shown in Figure 2, maximum ripple current cancellation for a two-phase synchronous buck occurs when each phase is operating at 50 percent duty cycle. However, because the volt-seconds applied to the transformer primary must be equal for each half of the power transfer cycle, the current doubler is limited to a maximum duty cycle of 50 percent per phase, whereas the two-phase synchronous buck can operate at greater than 50 percent duty cycle per phase.

**RIPPLE CURRENT
vs
DUTY CYCLE**
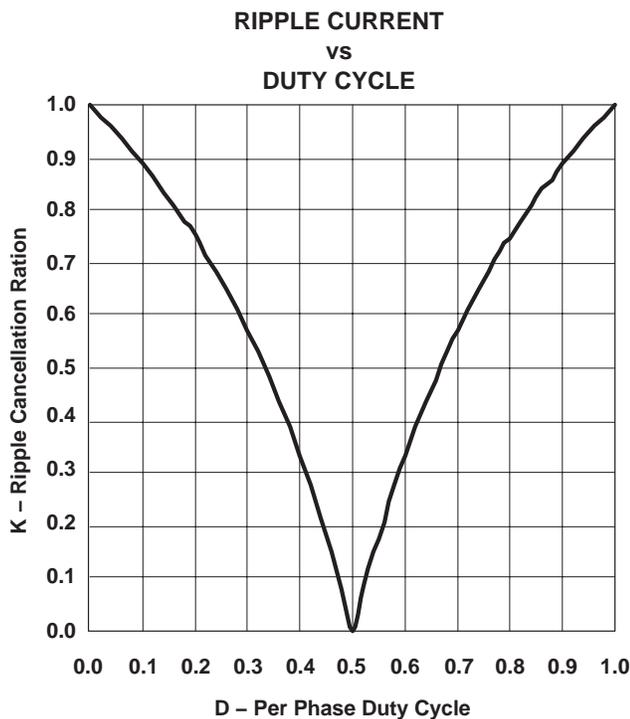
Figure 2.

In terms of ripple current cancellation, one of the biggest differences between the two-phase buck and the current doubler is the way that the duty cycle is defined by the power transfer function. For the buck regulator, the transfer function is simply the ratio of V_{OUT} to V_{IN}. The current doubler rectifier transfer function is given in equation (1).

$$\frac{V_{OUT}}{V_{IN}} = \frac{D}{2 \times N}$$

(1)

Here, D is the duty cycle defined as the total positive and negative power transfer duty cycle, and N is the primary to secondary transformer turns ratio. From Figure 1, QA and QB are each limited to 50 percent duty cycle each, however the total power transfer duty cycle seen at the current doubler can approach 100 percent.

Using the waveforms of Figures 3 and 4, taken from the current doubler rectifier of Figure 1, an expression for ripple current cancellation can be derived for the current doubler rectifier.

L1 AND L2 RIPPLE CURRENT
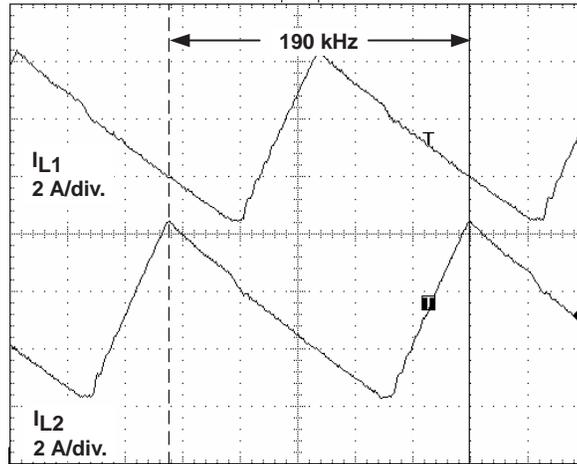
Figure 3.

L1 AND L2 OUTPUT RIPPLE CURRENT
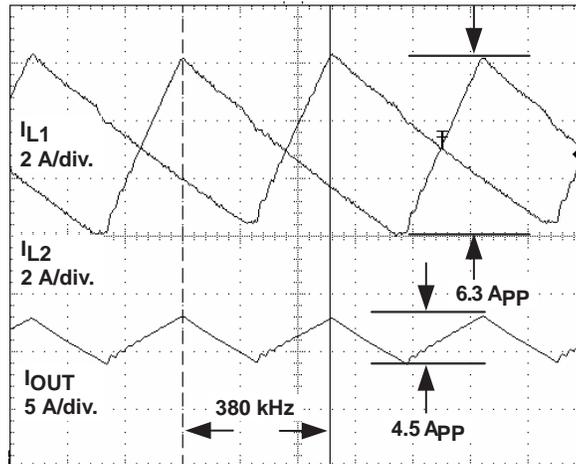
Figure 4.

The peak current for each individual inductor can be defined as:

$$\Delta I_L = \left[\frac{\frac{V_{IN}}{N} - V_{OUT}}{L}\right] \times \frac{D}{F} \tag{2}$$

Which simplifies to:

$$\Delta I_L = \frac{V_{IN} \times D - \left(D \times N \times V_{OUT}\right)}{F \times N \times L} \tag{3}$$

The output peak ripple current, which is really the sum of the two inductor currents, I_{L1} and I_{L2} can be defined as:

$$\Delta I_{OUT} = \left[\frac{\frac{V_{IN}}{N} - V_{OUT}}{L}\right] \times \frac{D}{F} - \frac{V_{OUT}}{L} \times \frac{D}{F} \tag{4}$$

Which simplifies to:

$$\Delta I_{OUT} = \frac{V_{IN} \times D - \left(2 \times D \times N \times V_{OUT}\right)}{F \times N \times L} \tag{5}$$

Knowing the peak values for the individual inductor current and the out ripple current, the ripple cancellation factor, K, is now defined and simplified to give:

$$K = \frac{\Delta I_{OUT}}{\Delta I_L} = \frac{V_{IN} \times D - \left(2 \times D \times N \times V_{OUT}\right)}{V_{IN} \times D - \left(D \times N \times V_{OUT}\right)} \tag{6}$$

And from the current doubler power transfer function defined by Equation (1), the duty cycle is given as:

$$D = \frac{V_{OUT}}{V_{IN}} \times 2 \times N \tag{7}$$

Substituting the value of D from (7) into the expression for K from (6) and simplifying gives:

$$K = \frac{1 - D}{1 - \frac{D}{2}}$$

(8)

Equation (8) can now be plotted against D for $0 \leq D \leq 1$ to graphically show the ripple current cancellation effect for the current doubler rectifier.

RIPPLE CURRENT CANCELLATION
vs
DUTY CYCLE (V_{OUT} = 3.3 V, 36 V < V_{IN} < 72 V)
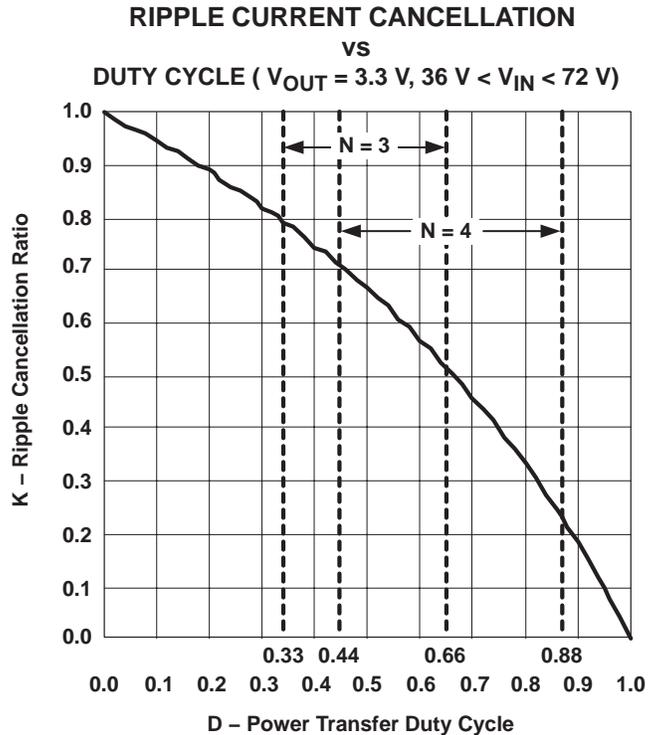
Figure 5.

Figure 5 shows a graphical representation of the ripple current cancellation effect that would be expected for a current doubler rectifier. The defined areas for N = 4 and N = 5 show the effect that transformer turns ratio has on ripple cancellation for a 3.3-V (plus 0.7-V drop) typical telecom converter operating from an input voltage range of 36 V = V_{IN} = 72 V. Notice that for larger values of N, the ripple cancellation ratio moves closer to zero. For example, when N is equal to four, the duty cycle varies between 0.44 for VIN = 72 V and 0.88 for VIN = 36 V, corresponding to a minimum cancellation ration of 0.7 where the ripple current is reduced by 30 percent, to a maximum cancellation ratio of 0.25 equaling a reduction of 75 percent. Clearly the transformer turns ratio deserves careful consideration as it has a direct effect upon the amount of output ripple current cancellation that can be achieved.

3   Benefits of Reducing Output Ripple Current

As can be seen by comparing the waveforms of Figure 4 to Figure 3, the frequency of the output ripple current is twice the frequency of each individual inductor ripple current. This higher frequency ac ripple current results in lower output capacitance, or lower inductor value for the same output ripple current obtained using a full-wave rectifier. Having already calculated the output ripple current in (5), we can derive an expression for the required output capacitance.

$$\Delta I_{OUT} = C\frac{dv}{dt} = C \times dv \times \frac{F}{D}$$

(9)

Equating (9) to (5) gives:

$$C \times dv \times \frac{F}{D} = \frac{V_{IN} \times D - \left(2 \times D \times N \times V_{OUT}\right)}{F \times N \times L}$$

(10)

And solving for C gives:

$$C = \frac{D \times \left[V_{IN} - \left(2 \times D \times N \times V_{OUT}\right)\right]}{F^2 \times N \times L \times dv}$$

(11)

Many factors, such as transient response and ESR, come into play when determining the minimum required output capacitance. However, from (11) it should be noted that when the frequency is doubled the required capacitance is reduced by a factor of four. Also from (9) it can be shown that capacitance is directly proportional to ripple current.

Using a current doubler rectifier helps minimize the required output capacitance by reducing the amount of output ripple current seen by the output capacitor. The degree to which this is achievable increases with duty cycle. While there are many factors to consider when designing the power transformer, a higher turns ratio will produce a greater degree of ripple cancellation. Reduced ripple current also results in lower noise levels at the power supply output, translating to lower radiated emissions. When considering a push pull or bridge topology for mid to high-power, high-current power supply applications, the current doubler rectifier offers many benefits worthy of careful consideration.

4   References

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3. *Configuring the UCC3895 for Direct Control Driven Synchronous Rectifier Applications*, by Steve Mappus, Texas Instruments User's Guide, Literature No. SLUU109A

4. UCCx8083/4/5/6, *8-Pin Current Mode Push-Pull Controllers With Programmable Slope Compensation*, Texas Instruments Datasheet, Literature No. SLUS488B

5. UCCx7323/4/5, *Dual 4-A Peak High Speed Low-Side Power MOSFET Drivers*, Texas Instruments Datasheet, Literature No. SLUS492B

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