Application Report
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Extend the Boost Converter Output Voltage With a Coupled Inductor

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ABSTRACT

Maximum output voltage of a boost converter is normally determined by the voltage rating of the integrated low side MOSFET. This application note introduces a method to extend the maximum output voltage of a boost converter. The application note firstly analyzes the operating principle. Then it provides formulas to calculate the voltage and current rating of the power component. Finally, the application note takes LM27313 as an example to verify the method.

Contents

List of Figures

List of Tables

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1 Introduction

A boost converter IC at least integrates a low-side N-type MOSFET and the control circuit to reduce the cost and total solution size, such as LM27313 in Figure 1. For such a boost converter circuit, the maximum output voltage must be lower than the voltage rating of the N-MOS which is between SW and GND pins. This application note utilizes a coupled inductor to increase the output voltage level while keeping the voltage at SW pin below the absolute maximum ratings.

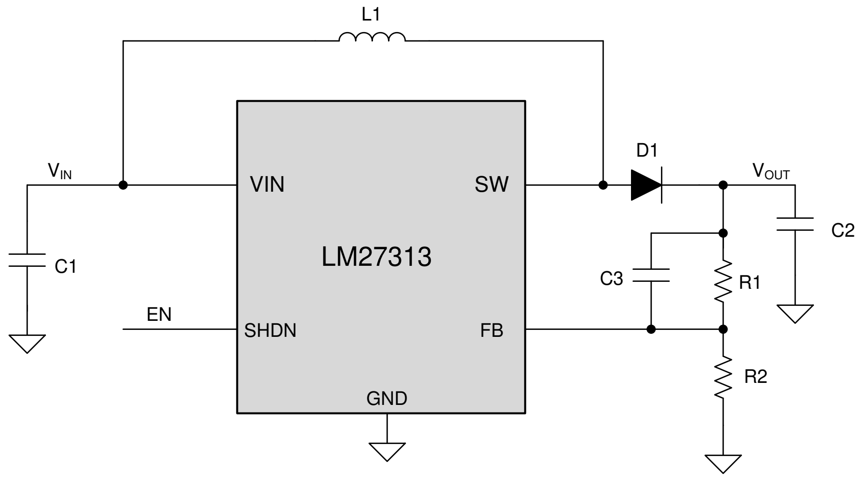

Figure 1. Simplified Schematic of LM27313

2 Operating Principle

The Figure 2 shows the simplified power circuit of a boost converter with coupled inductor. The turns ratio of the two windings is 1:N. The L1 is the inductance of first winding, and L2 is the inductance of the two winding in series. The Q1 is the integrated N-MOS. D1 is the rectifier diode, and the C1 and C2 are the input and output capacitor.

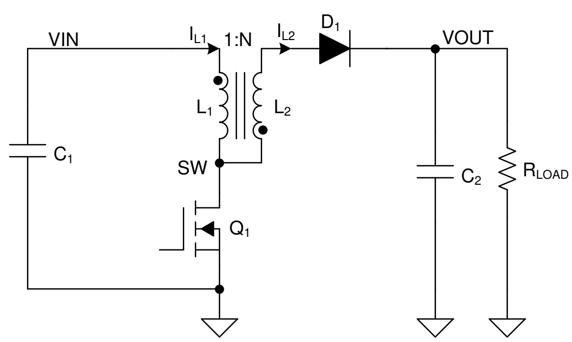

Figure 2. Power Stage of a Boost Converter with Coupled Inductor

Depending on the current of the coupled inductor at this end of each switching cycle, the circuit could operate at CCM, DCM, or BCM:

- Continuous conduction mode (CCM), the inductor current is higher than zero at the end of each switching cycle.
- Discontinuous conduction mode (DCM), the inductor current is zero before the end of each switching cycle.
- Boundary conduction mode (BCM), the inductor current decreases to zero right at the end of each switching cycle.

When the converter operates in CCM, the ideal waveforms of the power components voltage and current are shown in Figure 3, where V_D is the reverse voltage of the D1.

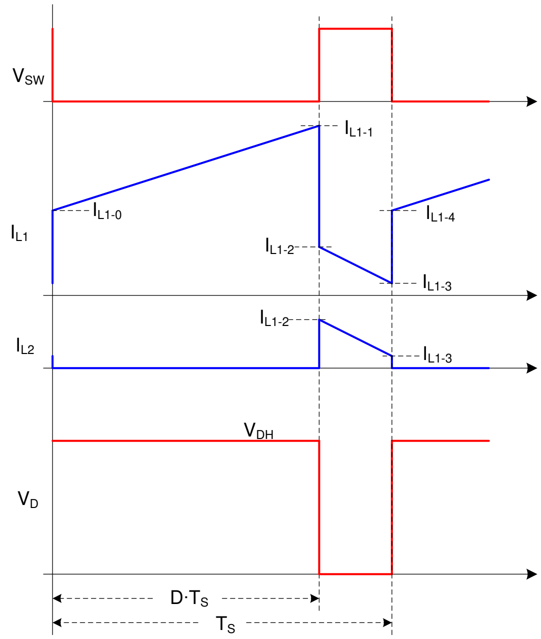

Figure 3. Operating Waveform at CCM

Within one switching period T_S, there are two operating status.

- Between zero to $D{\cdot}T_S$, the low-side MOSFET Q1 is turned on and the D1 is off, so the current through L1 increases linearly from I_{L1_0} to I_{L1_1}, as defined by Equation 1.

$$\Delta I_{L\_1} = I_{L1\_1} - I_{L1\_0} = \frac{V_{IN}}{L_1} \cdot D \cdot T_S \tag{1}$$

  The reverse voltage of the diode D1 is defined by Equation 2, where N is the turns ratio of the coupled inductor.

$$V_{DH} = V_{OUT} + N \cdot V_{IN} \tag{2}$$

- Between $D{\cdot}T_S$ and T_S, the Q1 turns off and the D1 is on. At the moment that the Q1 turns off, the current through L1 decreases suddenly as the inductor energy distributes among all turns. The I_{L1_2} is defined by Equation 3. Then the inductor current linearly decreases as energy transfers to the output. At the end of the switching cycle, the current decrease from I_{L1_2} to I_{L1_3} as in Equation 4.

$$I_{L1\_2} = \frac{I_{L1\_1}}{1 + N} \tag{3}$$

$$\Delta I_{L\_2} = I_{L1\_3} - I_{L1\_2} = \frac{V_{OUT} - V_{IN}}{L_2} \cdot (1 - D) \cdot T_S = \frac{V_{OUT} - V_{IN}}{(1 + N)^2 \cdot L_1} \cdot (1 - D) \cdot T_S \tag{4}$$

  The DC voltage as the SW pin during this period is defined by Equation 5. From the equation, the voltage at the SW pin is reduced because of the turns ratio, comparing to a normal boost converter.

$$V_{SW} = V_{IN} + \frac{V_{OUT} - V_{IN}}{N + 1} \tag{5}$$

- For the next switching cycle, the coupled inductor energy is back to the first winding L1 again. If the input voltage and output current is stable, the I_{L1_4} is equal to I_{L1_0}.

At stable condition, each winding of the coupled inductor has voltage-second balance, so:

$$V_{IN} \cdot T_S = V_{SW} \cdot (1 - D) \cdot T_S = \left(V_{IN} + \frac{V_{OUT} - V_{IN}}{N + 1}\right) \cdot (1 - D) \cdot T_S \tag{6}$$

From Equation 6, the duty cycle D at CCM operation is shown in Equation 7. For a conventional boost converter, the N in the equation is zero.

$$D = \frac{V_{OUT} - V_{IN}}{V_{OUT} + N \cdot V_{IN}} \quad (7)$$

The peak current through the L1 and the internal N-MOS is defined by Equation 8. The saturation current of the coupled inductor must be higher than this peak current.

$$I_{L1\_1} = (1 + N) \cdot \left(\frac{I_{OUT}}{1 - D} - \frac{\Delta I_{L\_2}}{2} \right) + \Delta I_{L\_1} \quad (8)$$

If the device is in BCM, the I_{L1_4} and I_{L1_0} is zero, then the output current is defined by Equation 9.

$$I_{OUT} = \frac{\Delta I_{L\_2}}{2} \cdot (1 - D) = \frac{V_{OUT} - V_{IN}}{2 \cdot (1 + N)^2 \cdot L_1} \cdot (1 - D)^2 \cdot T_S \quad (9)$$

If the output current is small and the device operates at DCM, the operating waveform is as in Figure 4.

- Within $D_1 \cdot T_S$, the N-MOS is on and the inductor current increases linearly from zero.
- Within $D_2 \cdot T_S$, the N-MOS is off and the current decreases to zero.
- In the rest of a switching cycle, both the N-MOS and D1 are off. The V_{SW} are equal to V_{IN} ideally.

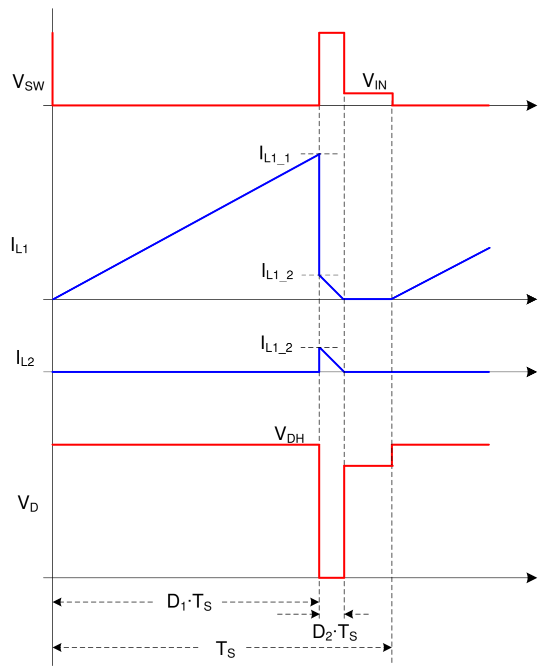

Figure 4. Operating Waveform at DCM

The relation of output current and other parameters in DCM is defined by Equation 10.

$$I_{OUT} = \frac{\Delta I_{L\_2}}{2} \cdot \frac{D_2 \cdot T_S}{T_S} = \frac{V_{OUT} - V_{IN}}{2 \cdot (1 + N)^2 \cdot L_1} \cdot {D_2}^2 \cdot T_S \quad (10)$$

For a specific application condition, the method to determine if the device is in CCM or DCM divides into to three steps.

- Assuming the device is in CCM, the duty cycle can be calculated through Equation 7.
- The output current at the BCM is calculated by Equation 9.
- When the actual output current is lower than the result of the last step, the device is in DCM. Otherwise, the converter is in CCM.

3 Example Using LM27313

The chapter takes LM27313 as an example to design a DC/DC converter with coupled inductor. The design target is 5-V input, 100-V output voltage, and 5-mA output current.

The most critical external component is the coupled inductor in this power topology. The important parameter of the coupled inductor are the turns ratio, saturation and temperature current, and voltage rating. Minimum turns ratio N is limited by voltage rating of the integrated MOSFET and the maximum duty cycle of the IC.

The maximum SW pin voltage of the LM27313 is 30 V. It is suggested to limit the DC voltage below 25 V, considering the voltage spike caused by the leakage inductance of the coupling inductor and parasitic inductor of the PCB. According the Equation 5, the minimum turns ratio can be calculated as Equation 11.

$$N = \frac{V_{OUT} - V_{IN}}{V_{SW} - V_{IN}} - 1 = \frac{100 - 5}{25 - 5} - 1 = 3.75 \tag{11}$$

One off-the-shelf coupled inductor closed to the requirement from Coilcraft is LPR4012-202LMR, which has 10-turns ratio and 2-µH L1 inductance with 1.7-A saturation current. The isolation voltage between the two windings of the coupled inductor is 100 Vac, which is high enough for this application. Using LPR4012-202LMR, the voltage rating of the low-side MOSFET can be calculated by Equation 12.

$$V_{SW} = V_{IN} + \frac{V_{OUT} - V_{IN}}{N + 1} = 5 + \frac{100 - 5}{10 + 1} = 13.6\,V \tag{12}$$

The reverse DC voltage of the diode is defined by Equation 13. From the voltage and current requirement, the BAV3004W-7-F or equivalence can be used as the rectifier diode.

$$V_{DH} = N \cdot V_{IN} + V_{OUT} = 50 + 100 = 150\,V \tag{13}$$

The output current at BCM can be calculated through Equation 14. As the current at BCM is higher than 5 mA, the device operates at DCM.

$$I_{OUT} = \frac{V_{OUT} - V_{IN}}{2 \cdot (1 + N)^2 \cdot L_1} \cdot (1 - D)^2 \cdot T_S = \frac{100 - 5}{2 \times 11^2 \times 2\mu} \times (1 - 0.633)^2 \times \frac{1}{1.6M} = 16.5\,mA \tag{14}$$

In DCM, $D_2 \cdot T_S$ can be calculated by Equation 15 according to the Equation 10.

$$D_2 \cdot T_S = \sqrt{\frac{2 \cdot (1 + N)^2 \cdot L_1 \cdot T_S \cdot I_{OUT}}{V_{OUT} - V_{IN}}} = 0.126\,\mu s \tag{15}$$

Then the inductor peak current is calculated in Equation 16.

$$I_{L1\_1} = \frac{(V_{OUT} - V_{IN}) \cdot D_2 \cdot T_S}{(1 + N) \cdot L_1} = 545\,mA \tag{16}$$

The output capacitor depends on the output ripple requirement as in Equation 17. For example, the effective output capacitor must be higher than 83 nF if it require less than 30-mV ripple. If a much smaller ripple is desired, it is suggested to add RC or LC circuit, instead of pure capacitor, to further filter the switching frequency.

$$C_{OUT} = \frac{I_{OUT}}{\Delta V_{OUT}} \cdot (T_S - D_2 \cdot T_S) \tag{17}$$

Figure 5 shows the schematic of the LM27313 with coupled inductor to support a 5-V input and 100-V, 5-mA output. The output capacitor is two GRM31CR72E224KW43 in parallel, the effective capacitance of which is approximately 0.14 µF with 100-V DC bias voltage. The coupled inductor is LPR4012-202LMR and the D1 is BAV3004W-7-F.

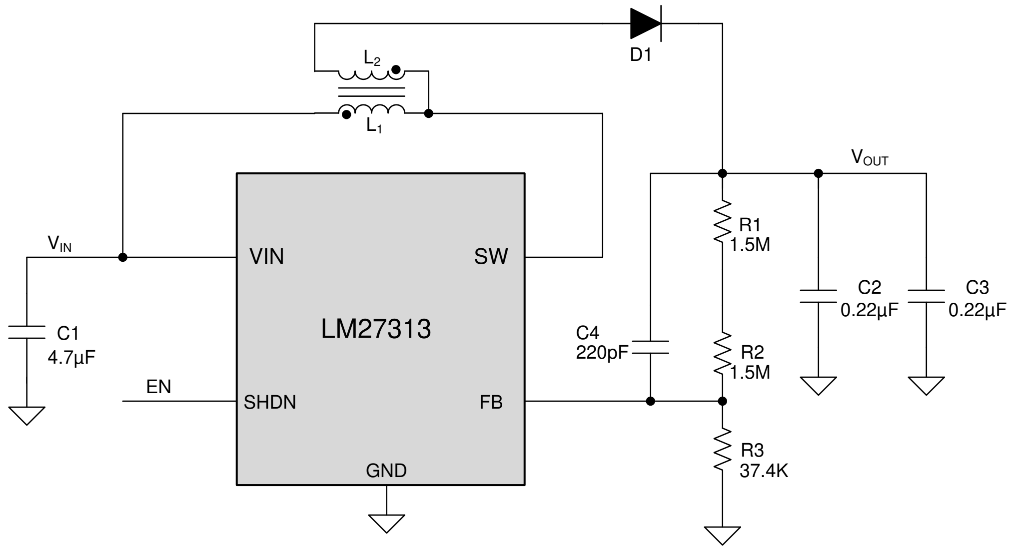

Figure 5. Schematic of LM27313 with Coupled Inductor

Figure 6 shows the start up of the circuit through EN logic. At EN low logic, the output voltage is closed to input voltage, 5 V. At EN high logic, the output voltage smoothly ramps up to 100 V.

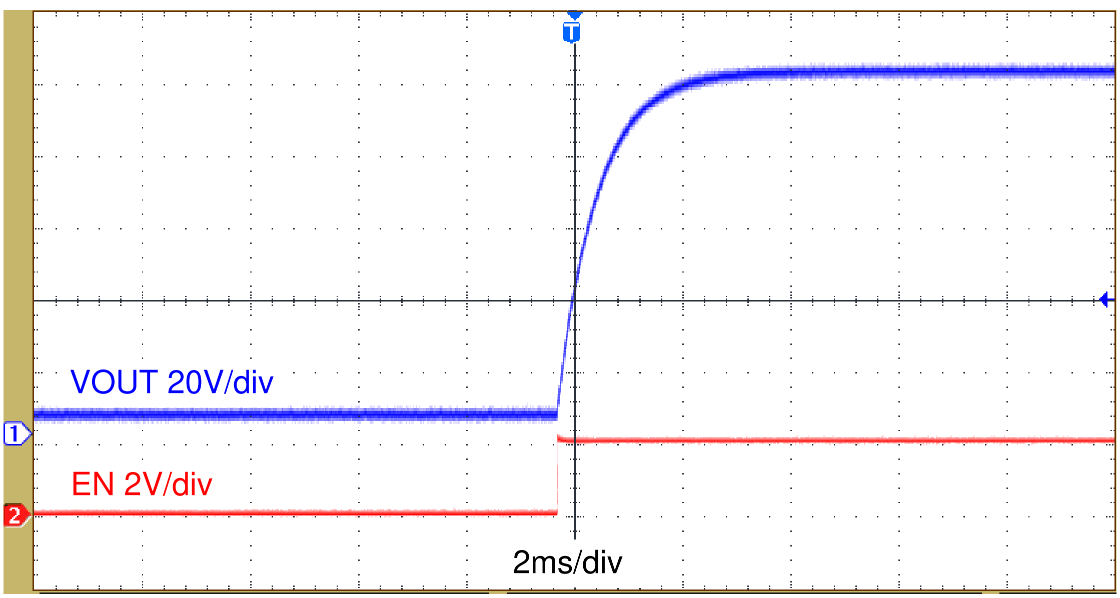

Figure 6. Startup of the LM27313 Circuit

Figure 7 shows the stable operation waveform of the circuit at 5-mA output current. The output voltage ripple is less than 20 mV. The maximum voltage of the SW is approximately 14 V. The circuit operates at DCM:

- Within $D_1 \cdot T_S$, the low-side MOSFET is on, so the SW voltage is closed to zero.
- Within $D_2 \cdot T_S$, the low-side MOSFET is off and the rectifier diode is on, so the SW voltage is approximately 14 V.
- In the rest of one switching cycle, Both MOSFET and diode are off. the SW voltage does not drop to input voltage directly because of the parasitic capacitance of the N-MOS and diode, which causes LC ringing in SW pin until the next switching cycle.

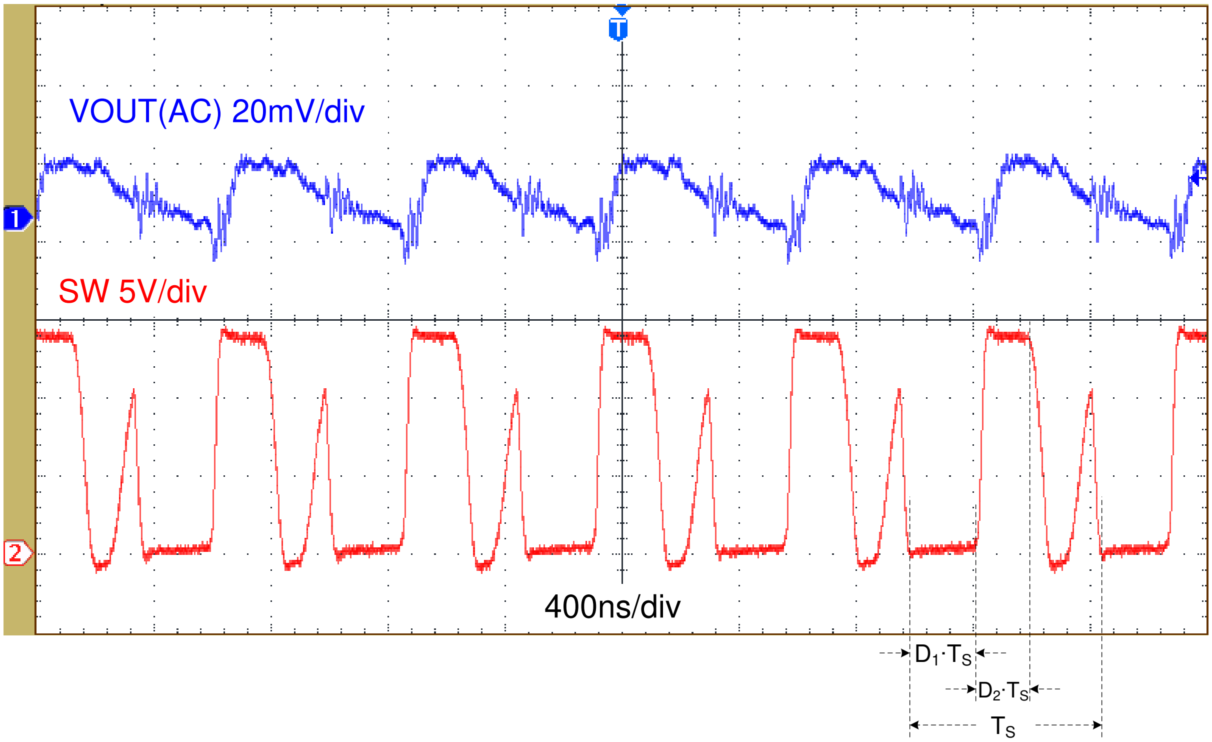

Figure 7. Stable Ripple of the LM27313 Circuit

4 Summary

The application notes introduces the operating principle of the boost converter with coupled inductor at DCM, BCM and CCM. Then, the formulas to calculate the voltage and current of the power components are derived. Finally, the LM27313 is taken as an example to design a 5-V input, 100-V, and 5-mA output converter. The experiments waveforms show the feasibility of the method.

5 References

- Texas Instruments, *Coupled inductors broaden DC/DC converter usage* Technical Brief