ANALOG DEVICES
AHEAD OF WHAT'S POSSIBLE™

How to Select a Transformer When Designing an Isolated Buck Converter

Yaxian Li, Applications Engineer

Abstract

This article explains how an isolated buck converter works and how to select a transformer, a pivotal step in designing an isolated buck converter. It discusses which parameters to consider, the mathematics that should be followed when choosing a transformer, and how these parameters influence the overall circuit.

How Does an Isolated Buck Converter Work?

An isolated buck topology, as shown in Figure 1, is similar to a generic buck converter. By replacing the inductor in a buck circuit using a transformer, we can get an isolated buck converter. The transformer's secondary side has an independent ground.

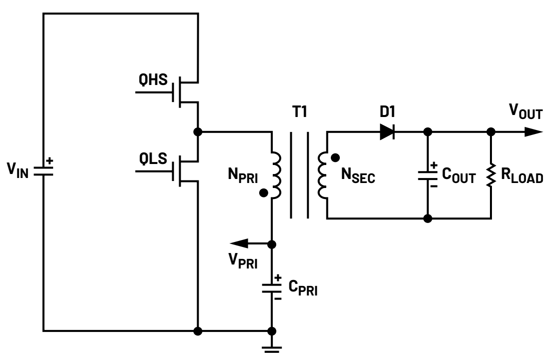


Figure 1. An isolated buck topology.

During on-time, the high-side switch (QHS) is on and the low-side switch (QLS) is off. The transformer's magnetizing inductance (L_{PRI}) is charged up. The arrows in Figure 2 show the current flow direction. The primary current increases linearly. The current ramping slope depends on (V_{IN} – V_{PRI}) and L_{PRI}. The secondary side diode, D1, is reverse biased during this time interval and loads current flow from C_{OUT} to load.

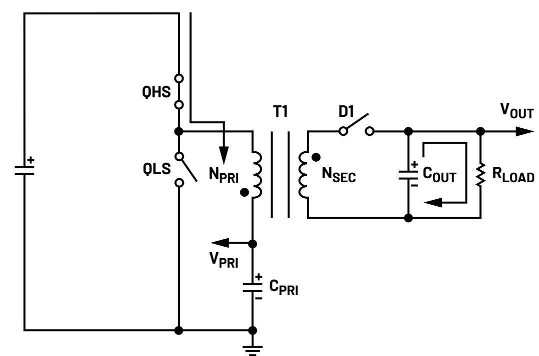


Figure 2. On period equivalent circuit.

During off-time, QHS is off and QLS is on. The primary inductor is discharged. The primary current flows from QLS to ground, D1 is forward biased, and the secondary current flows from the second side coil to C_{OUT} and to load. C_{OUT} is charged up in this time period. (Turning off QHS and turning on QLS cannot change current direction; it can only change the current slope. The positive current decreases until 0 A, then the negative current increases.)

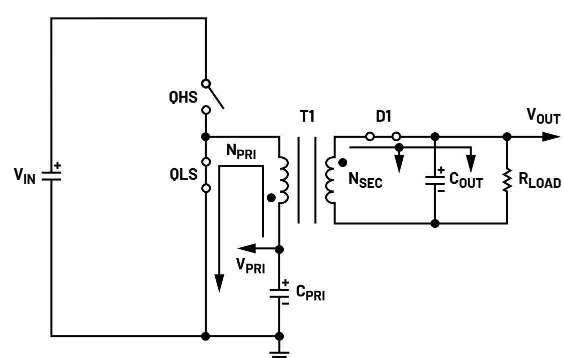


Figure 3. Off period equivalent circuit.

Which Specifications Will Influence the Transformer?

When designing a converter, some specifications should be declared and cleared. It will determine which component will be used especially when choosing a transformer.

- Input voltage range
- Output voltage
- Maximum duty cycle
- Switch frequency
- Output voltage ripple
- Output current
- Output power

Maximum duty cycle (D) is usually assigned in the range of 0.4 to 0.6. The minimum input voltage (V_{IN_MIN}) and maximum duty cycle will determine the primary output voltage (V_{PRI}). Then, the primary output voltage (V_{PRI}) and secondary output voltage (V_{OUT}) will determine the transformer turns ratio.

Output current (I_{OUT}) and output power (P_{OUT}) are key parameters that influence transformer selection. Output current determines the thickness of the copper wire, while output power determines which transformer bobbin should be used. The permeability of the bobbin shows how much energy it can store and how much power it can put out. Generally, the DC output current multiplied by a coefficient is assigned to the inductor's (transformer's) ripple current. Duty cycle and switch frequency are used to calculate T_{ON} time, while V_{IN}, V_{PRI}, and ripple current determine the primary inductance. The assigned coefficient must not be too large or too small since a large coefficient can lead to a large ripple current. A large ripple current may reach half of the H-bridge current limit and damage the MOSFET. This will lead to a large ripple voltage on the output capacitor due to its ESR and ESL. On the contrary, when an extremely small ripple current is needed, we need to use a high inductance value inductor (transformer). If the coil has many turns, this will require a bulky bobbin. The large inductance will limit loop bandwidth and reduce the dynamic response index.

Choosing a Transformer

Energy is transmitted to secondary coil only in T_{OFF} time. The turns ratio can be determined by Equation 1:

$$\frac{V_{OUT} + V_D}{V_{PRI}} = \frac{N_{SEC}}{N_{PRI}} \quad (1)$$

Where V_D is the secondary diode forward bias voltage. For V_{PRI}, we usually assign a maximum duty cycle in the range of 0.4 to 0.6. The V_{PRI} can be calculated using Equation 2:

$$V_{PRI} = D \times V_{IN\_MIN} \quad (2)$$

Where D is the maximum duty cycle and V_{IN_MIN} is the minimum input voltage. From Equation 2, we can calculate the turns ratio. In a non-isolated buck converter, the ripple current is the same on both sides of the inductor. Easily, we can calculate the inductance required using Equation 3.

$$L = \frac{(V_{IN\_MIN} - V_{OUT}) \times D}{f \times \Delta I} \quad (3)$$

Where f is the switching frequency and ΔI is the ripple current. As discussed previously, ripple current equals the DC output current multiplied by a coefficient:

$$\Delta I = I_{OUT} \times K \quad (4)$$

Where K is the coefficient. But in an isolated buck converter topology, there is a transformer and not an inductor. How do we deal with it when the component is a transformer rather than a inductor? As we know, the current ratio equals the inverse of the turns ratio:

$$IPRI_{TOFF} = I_{SEC} \times \frac{N_{SEC}}{N_{PRI}} \quad (5)$$

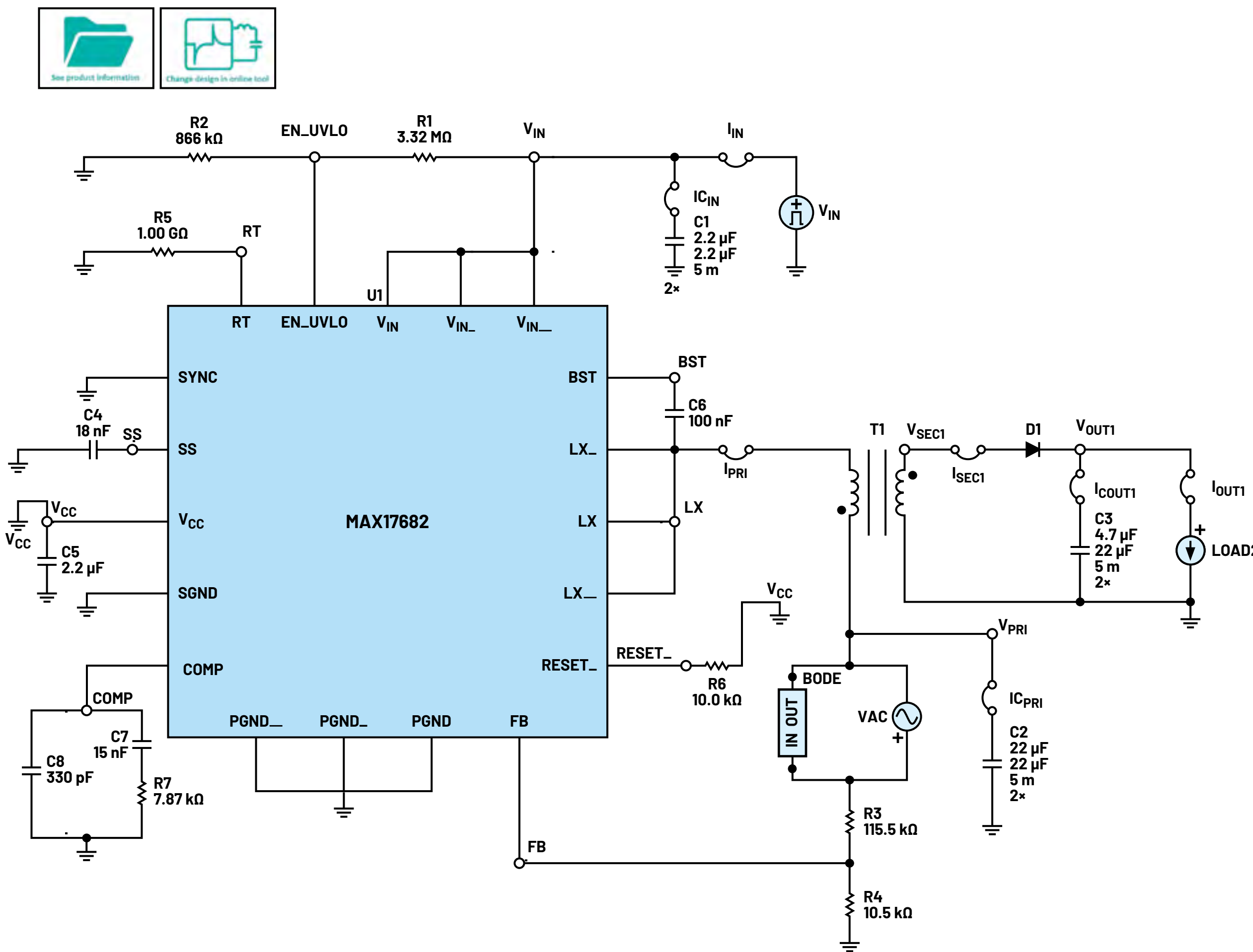
Where $IPRI_{TOFF}$ is the secondary current that is converted to a primary current in T_{OFF} time. We should add a transformer's two-coil current as an equivalent inductor current.

$$ILeq = I_{PRI} + I_{SEC} \times \frac{N_{SEC}}{N_{PRI}} \quad (6)$$

Where ILeq is the equivalent inductor current. If the transformer has three more windings, then

$$ILeq = I_{PRI} + I_{SEC} \times \frac{N_{SEC}}{N_{PRI}} + I_{THI} \times \frac{N_{THI}}{N_{PRI}} + \cdots \quad (7)$$

Is this correct? Let's see a simulation result based on the MAX17682. Figure 4 shows a MAX17682 circuit, which was drawn in EE-Sim® OASIS, powered by SIMetrix/SIMPLIS. Current probes, labeled I_{PRI} and $_{ISEC1}$, have been placed at both sides of the transformer.



MAX17682 Initial Conditions

Initial Conditions can speed up simulations, but are not always necessary for running most simulations.

Seven adjustable parameters, IC_RESET, IC_SSDONE, IC_EN, IC_COMP, IC_FB, IC_V_{REF}, and IC_CLK are built into the MAX17682 model for setting internal initial conditions. These parameters can be edited by double clicking the MAX17682, then entering the desired values in the GUI box that pops up. Click OK when done making edits.

For AC, POP (Steady State), Load Step and Line Transient Analyses, Initial conditions are as follows:
I_{OUT} is the load current
1. Initial condition of C2 is V_{PRI}.
2. Initial condition of C3 is V_{SEC}.
3. Initial condition of C4 is 5.
4. Initial condition of C5 is 5.
5. Initial condition of C6 is -5.
6. Initial condition of C7 is V_{COMP}.
7. Initial condition of C8 is V_{COMP}.
8. IC_RESET = IC_SSDONE = IC_EN = 5
9. IC_COMP = V_{COMP}
10. IC_FB = IC_V_{REF} = 0.9
11. IC_CLK = 1.78

For Start-up Analysis
1. Initial condition of C2, C3, C4, C5, C6, C7 and C8 is 0.
2. IC_RESET = IC_V_{REF} = IC_SSDONE = IC_EN = 0
3. IC_COMP = IC_FB = 0
4. IC_CLK = 0

$dI = V_{PRI} \times (1 - (V_{PRI}/V_{IN}))/(Lm \times Fsw \times 1000)$
$IL = I_{PRI} + (I_{SEC} \times K)$
$V_{COMP} = 0.875 + (0.25 \times IL) + (0.125 \times dI)$

Figure 4. A MAX17682 typical circuit in EE-Sim OASIS, powered by SIMetrix/SIMPLIS.

MAX17682 Notes
Circuit parameters for various simulation types

When downloaded from the on-line EE-Sim design tool, this file is configured for the simulation type selected in the downloading processes. It can easily be modified for other simulation types.

If you are new to SIMPLIS or simulation in general and you want to run a different kind of simulation (Load step, Line Transient, AC, Steady State, Start Up) following how it was done on-line, you can always download a separate schematic for each available simulation type as separate files. Doing so has the advantage that all simulation options and parameters, source and load parameters as well as initial conditions are set up for that type of simulation.

You can also to go to the menu item Simulator > Choose Analysis and set up the simulation parameters appropriately for the desired simulation. The load and source parameters and initial conditions are set by editing the parts on the schematic. The following are instructions and details you will need for modifying the schematic & simulator settings to run different simulations yourself.

The BODE and VAC devices are in place to allow measuring the control loop with AC simulations. Their presence does not adversely affect the other simulations. In a real circuit they would be replaced with a short.

LOAD1 and LOAD2 have several parameters to modify for different simulations. The load acts as a resistor in parallel with a pulsed current for transient Load Step simulations. When a Load Step/Pulse is not used the load acts as a resistor.

Double-click the load for a pop-up window with editable parameters for timing and amplitude of the pulse.
1. - 4.) Delay Time, Rise Time, Pulsewidth and Fall Time are used to set the timing of the pulsed load
5. Source Resistance sets the lower current of the pulse waveform; Current = V_{OUT}/Source Resistance
6. Start Current: This parameter informs the simulator what the lower current is per the prior step
7. Pulsed Current determines the higher peak current of the pulsed waveform.

The current set by the Source Resistance is present throughout the simulation. The Load device calculates the magnitude of the added pulse as (Pulsed Current - Start Current). In order to ensure the maximum current is the same as the value entered for Pulsed Current make sure the value entered for Start Current matches the current created by the Source Resistance; = V_{OUT}/Rsource.

There are two more Load parameters that are used but which are not included in the load pop-up GUI. These parameters can be edited by selecting the load, then right clicking on it and choosing "Edit/Add Propertiesâ€¦" from the pop-up list. When the Edit Properties windows opens, double click on the property you want to change. Change the value in the Edit Property window and click on OK. Then click on OK in the Edit Properties window.
1. ANALYSIS is a parameter that determines if the load pulse is used or if the load is a resistance
1.1. For Load Step (Pulse) simulations set ANALYSIS to TRAN and the pulsed current will be used
1.2. For all AC simulations and any transient simulations other than Load Step, set ANALYSIS to AC
2. AC_RSRC sets the load resistance value used when ANALYSIS = AC (TR_RSRC does so for TRAN)

The voltage source, V_{IN}, device is set to a DC voltage for all simulations other than Line Transient. When double clicked a GUI pops up with parameters that you can change. To make this into a DC source, set the Start Voltage and the Pulse Voltage to the same value

POP Simulation Settings. Accessible from the Simulator menu, Choose Analysis.

Needed for AC and Steady-state simulations as run online. Usually also used for Load Step and Line Transient Simulations. POP can be problematic at light load. If this is a problem for Load Step simulations you can set the starting current to be the higher level and the Step/pulse current to be the lower level.

Trigger Gate: X$U1.X$DRIVER.X$UPOP.!DCOMP
Max. Period: 10 μ
Cycles before launching POP: 100
Click the Advanced button for the next three parameters:
Convergence: 10 n
POP iteration limit: 20
Enable automatic transient analysis after a failed POP: Box is checked

V_{IN}, LOAD1, LOAD2, BODE & VAC are "test equipment" and not part of the circuit. BODE is replaced with a short in the real circuit.
Components representing open circuits: 1 GΩ Resistors, 1 fF Capacitors
Components representing short circuits: 1 mΩ Resistors

Figure 4 (continued). A MAX17682 typical circuit in EE-Sim OASIS, powered by SIMetrix/SIMPLIS.

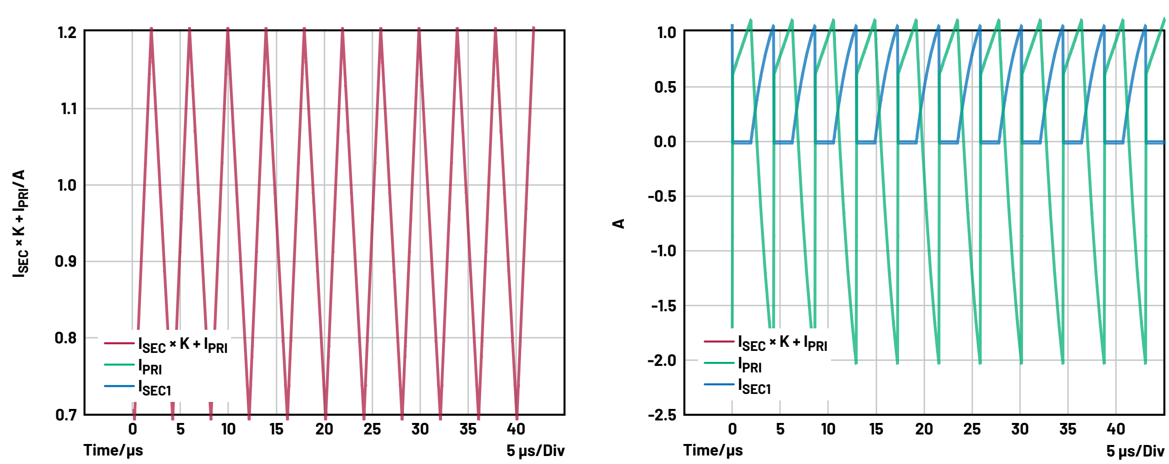


Figure 5. A MAX17682 typical circuit simulated current waveform.

Figure 5 shows a transient simulation result from the two probes. The two current waveforms were added utilizing Equation 6.

The added current results (red) in a triangle wave and behaves just like the inductor in a non-isolated buck converter. So the transformer's primary ΔI can be easily calculated:

$$\Delta I = \left(I_{PRI} + I_{SEC} \times \frac{N_{SEC}}{N_{PRI}}\right) \times K \tag{8}$$

Usually, we assign a load ripple current that is 0.2 times the DC output current. So K can be assigned to 0.2 times N_{SEC}/N_{PRI}. At the same time, the primary peak current should be designed less than the switch current limitation, where I_{PK} is:

$$I_{PK} = ILeq_{DC} + \frac{\Delta I}{2} \tag{9}$$

Then the transformer's primary inductance can be easily calculated:

$$L_{PRI} = \frac{(V_{IN\_MIN} - V_{PRI}) \times D}{f \times \Delta I} \tag{10}$$

By using the turns ratio, primary inductance, output power, output current, and isolation voltage, we can decide which inductor will be used or designed.

Why a Simplified Equation Can Work

Let's see how we can better understand and apply the equation shown in the MAX17682 data sheet (see Figure 6).

Primary Inductance Selection

Primary inductance value determines ripple current in the transformer. Calculate required primary inductance using the equation:

$$L_{PRI} = \frac{V_{PRI}}{f_{SW}}$$

where V_{PRI} and f_{SW} are nominal values.

Figure 6. A screenshot of the MAX17682 data sheet.

According to the previous discussion, Equation 10 can be rewritten to follow Equation 11 for T_{OFF} time.

$$L_{PRI} = \frac{V_{PRI} \times (1 - D)}{f \times \Delta I} \tag{11}$$

Assuming D is 0.6, if and only if ΔI were 0.4 A, the polynomial (1 – D) and ΔI can be reduced. Then Equation 11 and the equation from Figure 6 are the same. The equation in the data sheet already selects the primary ripple current. If we assign D as 0.6, the primary ripple current is 0.4 A. In quantity, T_{OFF} duty cycle equals the primary ripple current.

$$\Delta I = 1 - D \tag{12}$$

Conclusion

By using the simplified equation shown in Figure 6, the user ensures a faster design with a primary ripple current that equals the T_{OFF} duty cycle. If you want to modify primary ripple current or use another parameter, you can follow this tutorial.

About the Author

Yaxian Li is an applications engineer in the Training and Technical Services Group at Analog Devices. He focuses on GMSL and RF techniques. Yaxian joined Maxim Integrated (now part of Analog Devices) in 2020 after graduating from Hangzhou Dianzi University with a bachelor's degree in electrical engineering and automation in 2018. He is good at badminton and swimming.

TA24087-2/23(A)