AN1348: Si34071 Active Clamp Forward Transformer Design Principles

Skyworks' Si34071 Power over Ethernet (PoE) powered device integrates an IEEE 802.3bt compliant interface with a high-efficiency dc-dc controller optimized for flyback or forward converters. In order to achieve maximum efficiency, the Si34071 utilizes a hybrid forward converter, which operates using both a reset winding and an active clamp.

One of the most challenging aspects of developing an Si34071-based forward converter is transformer design. This application note describes the necessary design criteria and provides detailed examples to help designers understand the correct transformer specifications for their system.

KEY FEATURES

- The Si34071 forward converter features both reset-winding and active-clamp operation.
- The forward-converter transformer is fundamentally different from a flyback transformer and has unique design specifications.
- Detailed equations and examples provide a starting point for forward-converter transformer design.

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1. Introduction

In order to provide optimal efficiency and power, the Si34071 is optimized for a hybrid forward converter topology that can operate either in reset-winding mode or active-clamp mode, depending on the input current. As shown in the figure below, this topology requires a transformer that has at least three windings on the bobbin: a reset winding and a primary winding on the primary side and at least one secondary winding. The turns ratio between the primary and secondary windings has two key design criteria: reset-winding operation and active-clamp operation.

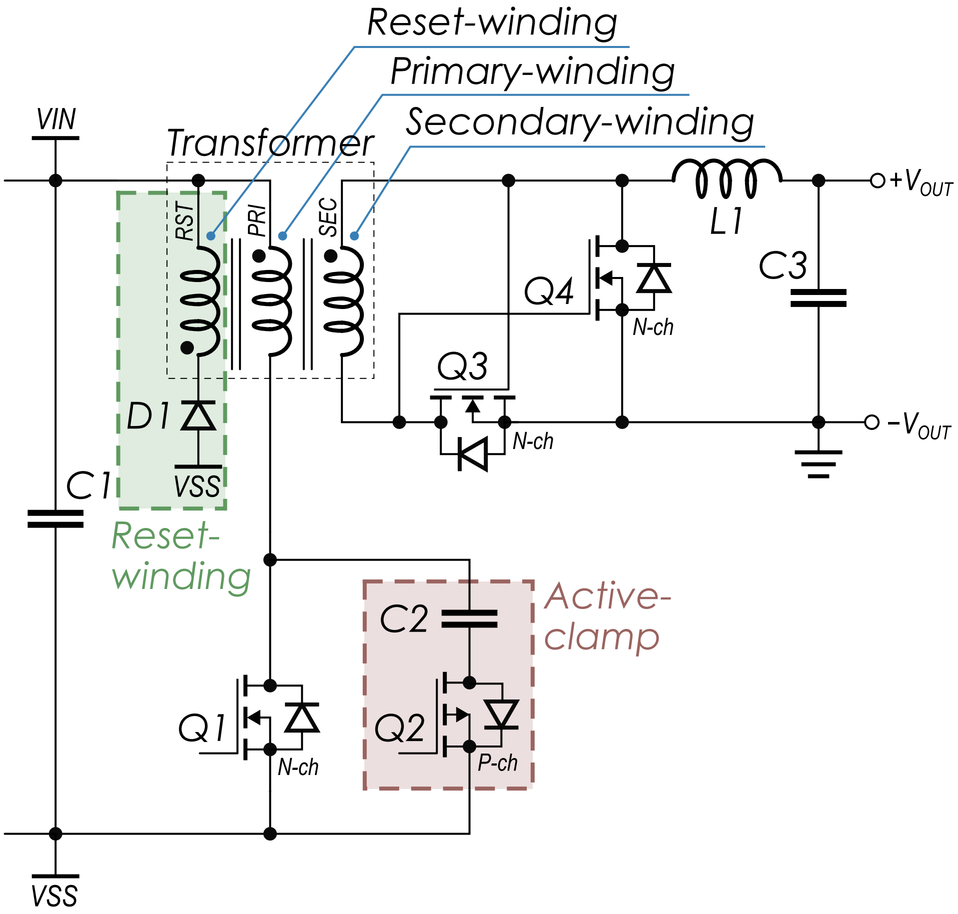

Figure 1.1. Transformer Design for Si34071 Hybrid Forward Converter Topology

1.1 Steady-State Operation

At steady state, while Q1 is turned on, the primary winding current is composed of three components:

- Transformer magnetizing current (I_{MAG}).
- The reflected output current.
- The reflected ripple current of the (L1) output filter inductor.

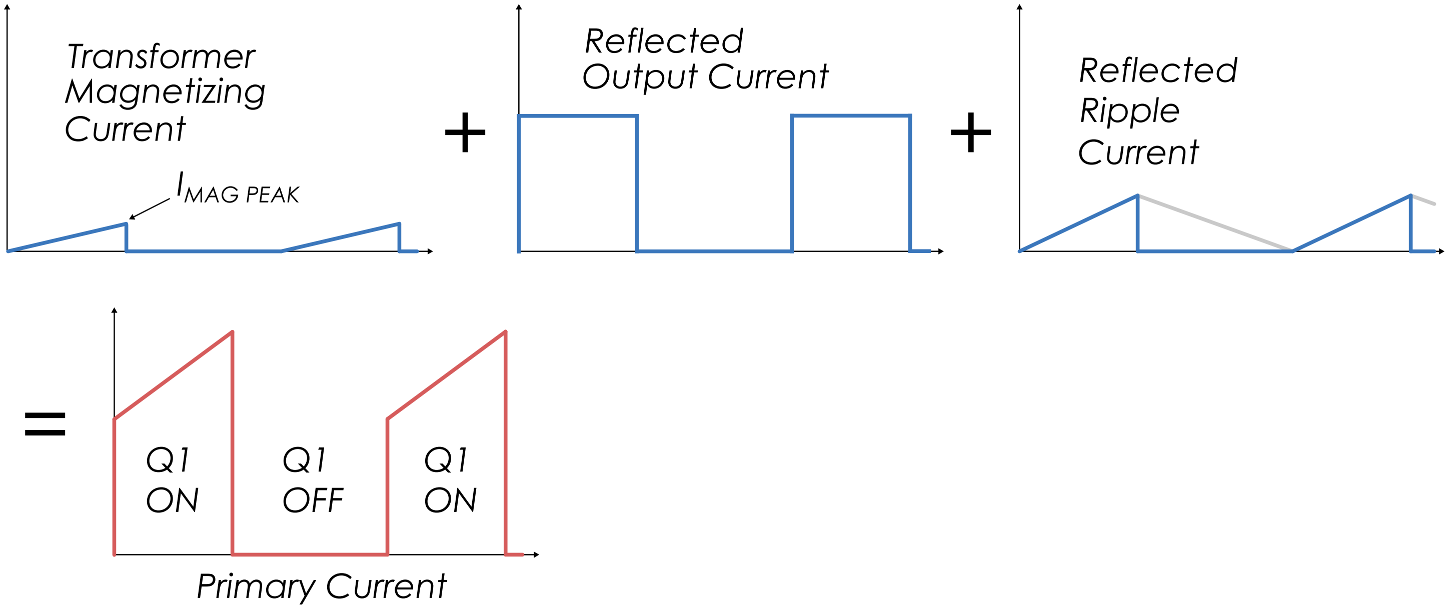

Figure 1.2. Primary Winding Current Components

Only the magnetizing current component is related to the transformer magnetization and is the focus of the following sections. The forward transformer stores energy during Q1's on time and releases it during Q1's off time, as determined by the transformer's magnetizing current (I_{MAG}) in each cycle. In a flyback converter, this energy is transferred to the secondary side. However, in a forward converter, the transformer construction prevents this energy transfer, which necessitates an extra circuit to deliver the energy back to the C1 input capacitor. This extra circuit can be either a reset winding or an active clamp circuit. Depending on the input current of the dc-dc converter, the Si34071 switches automatically between the two modes.

2. Reset Winding Operation

In reset-winding mode, the maximum allowed duty cycle is limited to 50% in order to ensure proper reset of the transformer's magnetizing inductance. The magnetization of the core is performed by the primary winding during Q1's on-time, but the demagnetization is realized by the reset winding during the off-time. The primary current is composed of three components, but, for simplicity, the following figure shows only the magnetization portion of the primary winding and the demagnetization current of the reset winding.

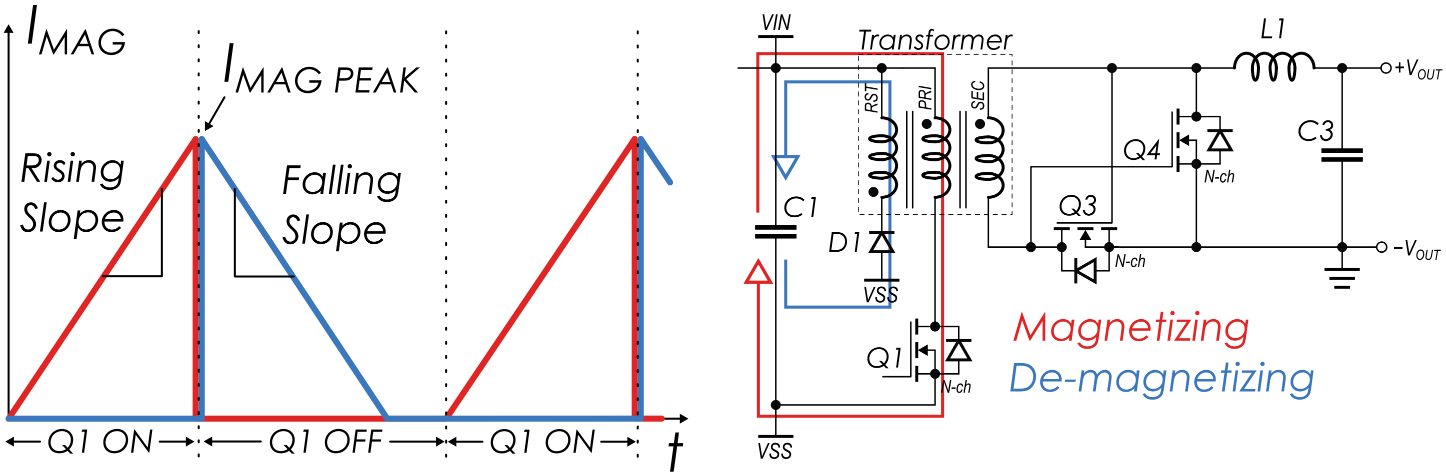

Figure 2.1. Primary Winding Magnetization Current and Reset Winding Demagnetization Current

The I_{MAG} magnetizing current in the primary winding starts to build up from zero at the beginning of each cycle and reaches $I_{MAG\ PEAK}$ just before Q1's turn-off. The rising slope of the magnetizing current (di_{MAG}/dt) during T_{ON} is determined by two factors, the voltage on the primary winding (equal to the input voltage) and the inductance of the primary winding: $di_{MAG}/dt=V_{IN}/L_{MAG}$. During Q1's on period, the D1 reset diode is reverse-biased, and current cannot flow through the reset winding. After Q1's turn off, the transformer starts to release its previously accumulated energy back to the input capacitor. The only way to do this is through the reset winding and the D1 reset diode. Voltage reverses on all windings; D1 opens, and the magnetizing current commutates into this diode and the stored energy from the core recovers back to the input capacitor. The falling magnetizing current slope during Q1's off-time is exactly the same as during the rising phase because the voltage of the reset winding is clamped to the input voltage: $-di_{MAG}/dt=V_{IN}/L_{MAG}$. The symmetry of the rising and falling slopes requires the duty cycle of the converter to be below 50% in order to ensure proper reset of the core. Above 50% duty cycle, the magnetizing current cannot fall back to zero and instead increases with every cycle until the core saturates. In a practical design, some margin is needed to ensure safe operation even at low input voltages. The output voltage of the converter can be calculated as follows:

$$V_{OUT} = V_{IN} \times D \times \frac{N_S}{N_P}$$

Where V_{IN} and V_{OUT} are the respective input and output voltages; D is the duty cycle, and N_S/N_P is the reciprocal of the transformer turns ratio.

As the input voltage decreases, the dc-dc controller increases the duty cycle to produce constant output voltage. Selecting a proper turns ratio prevents the duty cycle from reaching 50%, even under worst-case conditions when the input voltage is the lowest.

Design Example

An IEEE802.3bt compliant Class 8 PoE Powered Device accepts a dc input voltage in the range of 41.1 to 57 V. A 5 V output voltage and 220 kHz switching frequency gives a maximum output current of 14 A. A 45% maximum duty cycle gives a 5% margin for safety.

$$\frac{N_P}{N_S} = \frac{V_{IN\ MIN} \times D}{V_{OUT}} = \frac{41.1V \times 0.45}{5V} = 3.7$$

With this configuration, the turns ratio (defined as N_P/N_S) cannot be greater than 3.7; otherwise, the core will go into saturation at low input voltages. If a diode rectifier is used on the secondary side instead of a MOSFET rectifier, the diode drop at full load should be added to the value of V_{OUT} in the above equation.

3. Active Clamp Operation

When the converter switches to active-clamp mode, the reset-winding is no longer responsible for the demagnetization of the core. It is done solely by the active-clamp circuit; therefore, the reset-winding is not shown on the schematic below. In steady-state, the sum of the applied volt-second during on-time and off-time must be equal to zero.

$$V_{IN} \times T_{ON} + V_{RST} \times T_{OFF} = 0 \quad or$$

$$V_{IN} \times D + V_{RST} \times (1 - D) = 0$$

Since the reset lasts the whole off-time in the active-clamp mode, its value can be lower than the voltage in reset-winding mode. Choosing a proper turns ratio for the transformer ensures the peak reset-voltage in active-clamp mode is always below the voltage in reset-winding mode. This is needed for the distinct operation of the two different modes of the converter.

The brief operation of the core reset is shown in the following figure.

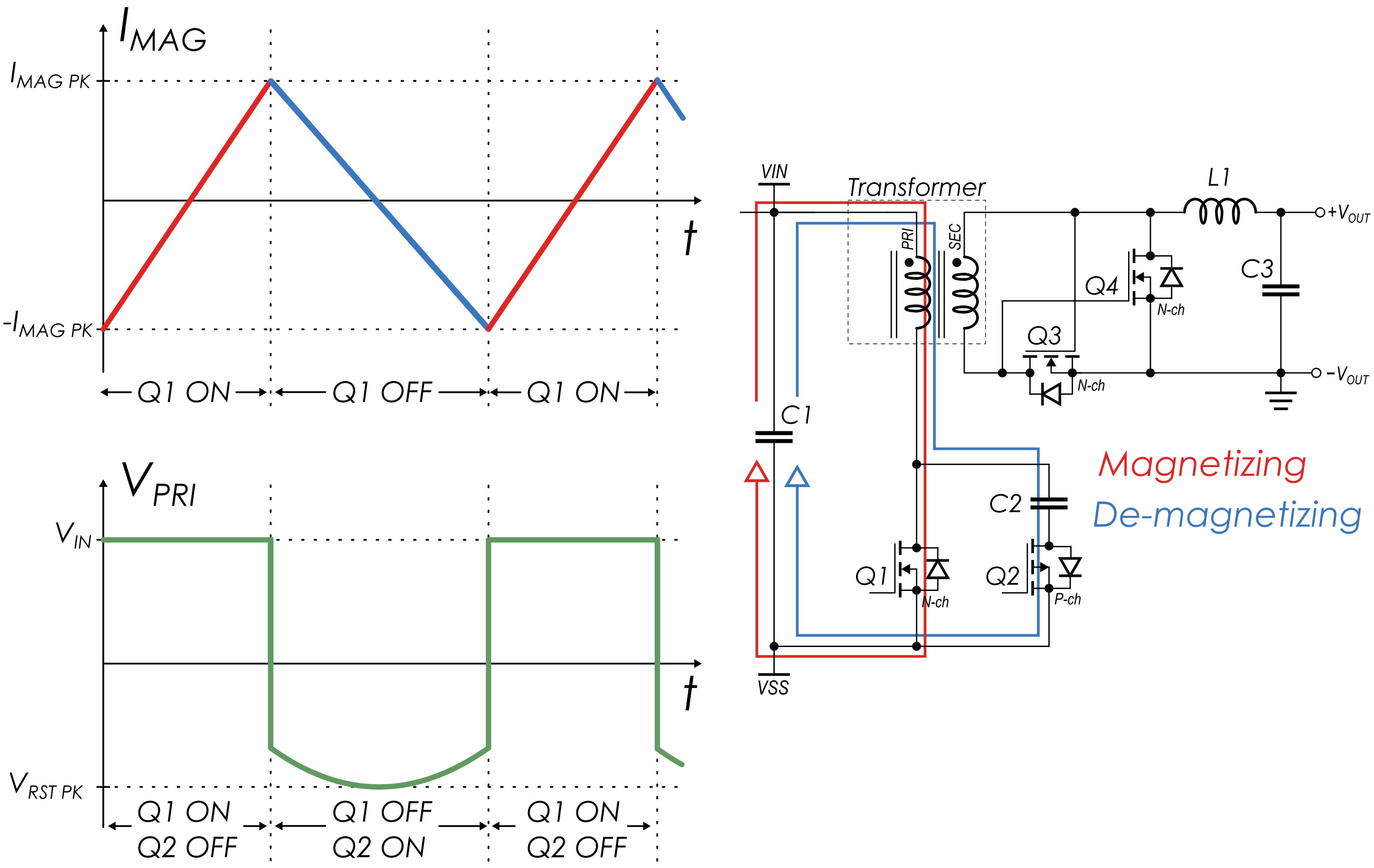

Figure 3.1. Forward Converter Operation in Active-Clamp Mode

At the beginning of the on-time, the forward switch, Q1, is on; the reset switch, Q2, is off, and the clamp capacitor, C2, is charged to a voltage of $V_{IN}/(1\text{-}D)$. The magnetizing current is now symmetrical around zero and starts to build up from its negative peak ($-I_{MAG\ PK}$) value and reaches positive peak ($I_{MAG\ PK}$) just before Q1's turn-off. At the end of the on-time, Q1 turns off and Q2 turns on. The magnetizing current now diverts from Q1 to the path of C2/Q2. The primary winding sees reversed voltage because the C2 clamp capacitor voltage is higher than the input voltage (the voltage of C1). Therefore, the magnetizing current starts to decrease, and the stored energy of the core starts to transfer into the clamp capacitor. The magnetizing current reaches its zero value when the magnetizing energy is depleted from the core. This happens exactly in the middle of the off time at the exact same moment that the voltage of the transformer reaches its peak at $V_{RST\ PK}$. In a simple summarized form: the previously accumulated magnetizing energy of the transformer is now transferred to the clamp capacitor.

After proper core reset, the primary winding still sees $V_{RST\ PK}$ because Q2 is still open, and, therefore, magnetizing current starts to build up in the opposite direction sourced by the C2 clamp capacitor. The current rises in this reversed direction, and C2 clamp capacitor starts to remagnetize the core of the transformer in the opposite direction (in the third quadrant of the B-H curve). At the moment the C2 clamp capacitor returns all of its previously captured energy back to the core of the transformer, the off-time ends and Q2 switches off.

This stored energy in the magnetizing inductance will be used to facilitate zero voltage switching for Q1 at its next turn-on. An automatic self-correction occurs in each cycle so the clamp capacitor voltage returns to its starting point at the beginning of the off-time.

As stated earlier, for steady-state operation, the sum of the applied volt-second during on-time ($D{*}T_{SW}$) and off-time ($(1-D){*}T_{SW}$) must be zero:

$$[V_{IN} \times D \times T_{SW}] + [V_{RST} \times (1 - D) \times T_{SW}] = 0$$

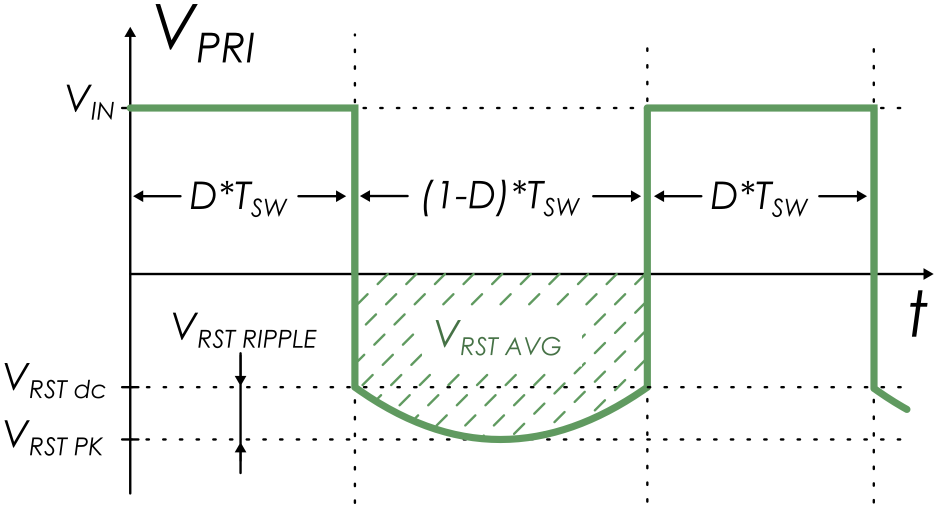

Figure 3.2. Steady-State Operation

From the above equation, the average reset voltage at off time can be calculated as:

$$V_{RST\ AVG} = -\frac{V_{IN} \times D}{1 - D}$$

This average voltage is composed of two components:

- a dc part ($V_{RST\ dc}$)
- and a ripple part ($V_{RST\ RIPPLE}$)

The ripple part is due to resonant operation between the clamp capacitor and the magnetizing inductance. This ripple component can be calculated as:

$$V_{RST\ RIPPLE} = -\frac{V_{IN} \times D \times (1 - D)}{4 \times f^2_{SW} \times L_{PRI} \times C_{CLAMP}}$$

And the peak of the reset voltage is defined by the following equation:

$$V_{RST\ PK} = V_{RST\ AVG} + \left(1 - \frac{2}{\pi}\right) \times V_{RST\ RIPPLE}$$

The absolute value of the peak reset voltage should be lower than the converter input voltage to have properly separated operation between the active-clamp and the reset-winding modes.

$$|V_{RST\ PK}| < V_{IN}$$

Design Example:

The values of the previous example can be used to check whether $V_{RST\ PK}$ satisfies the above requirement, namely that its absolute value should not be higher than the input voltage. Worst-case occurs when the input voltage is the applicable minimum.

$$V_{RST\ AVG} = -\frac{V_{IN} \times D}{1 - D} = -\frac{41.1V \times 0.45}{1 - 0.45} = -33.6V$$

$$V_{RST\ RIPPLE} = -\frac{V_{IN} \times D \times (1 - D)}{4 \times f^2_{SW} \times L_{PRI} \times C_{CLAMP}} = -\frac{41.1V \times 0.45 \times (1 - 0.45)}{4 \times 220kHz^2 \times 100\ \mu\ H \times 47nF} = -11.2V$$

$$|V_{RST\ PK}| = \left|V_{RST\ AVG} + \left(1 - \frac{2}{\pi}\right) \times V_{RST\ RIPPLE}\right| = \left|-33.6V + \left(1 - \frac{2}{\pi}\right) \times (-11.2V)\right| = 37.7V$$

Although the result satisfies the $|V_{RST\ PK}| < V_{IN}$ criteria (37.7 < 41.1V), the margin is only 3.4 V. The turns ratio of the transformer needs to be decreased to have at least 10 V margin. Lowering the maximum duty cycle from 45% to 40% allows a lower turns ratio between the primary and the secondary winding.

$$\frac{N_P}{N_S} = \frac{V_{IN\ MIN} \times D}{V_{OUT}} = \frac{41.1V \times 0.40}{5V} = 3.3$$

Calculate the new value of $V_{RST\ PK}$:

$$V_{RST\ AVG} = -\frac{V_{IN} \times D}{1 - D} = -\frac{41.1V \times 0.4}{1 - 0.40} = -27.4V$$

$$V_{RST\ RIPPLE} = -\frac{V_{IN} \times D \times (1 - D)}{4 \times f^2_{SW} \times L_{PRI} \times C_{CLAMP}} = -\frac{41.1V \times 0.40 \times (1 - 0.40)}{4 \times 220kHz^2 \times 100\ \mu H \times 47nF} = -10.8V$$

$$|V_{RST\ PK}| = \left|V_{RST\ AVG} + \left(1 - \frac{2}{\pi}\right) \times V_{RST\ RIPPLE}\right| = \left|-27.4V + \left(1 - \frac{2}{\pi}\right) \times (-10.8V)\right| = 31.3V$$

Now the design has adequate margin. When V_{IN} = 41.1 V, the margin between $|V_{RST\ PK}|$ and V_{IN} is 9.8 V. With a turns ratio of N_P/N_S = 3.3, reliable operation of the converter is ensured in both reset-winding and active-clamp modes.

4. Conclusion

Designing a PoE Powered Device with the Si34071 has several design criteria that must be considered when selecting the forward transformer. Both operation modes, reset-winding and active-clamp mode, have their own design criteria that must be observed. In reset-winding mode, the designer must carefully choose the duty cycle selection, while in active-clamp mode the maximum absolute value of the peak reset voltage plays a key role in the proper operation of the converter. With both of these requirements in mind, an efficient Si34071-based forward converter can be developed to power the next generation of PoE devices.

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