Magnetics Utilization Vs. Converter Topology: A Little Extra Silicon Goes A Long Way

by Dennis Feucht, Innovatia Laboratories, Cayo, Belize

The last edition of this column offered an introduction to the topic of waveform-based design and explained the parameters of interest when using this approach (see the reference). In this column, we'll discuss one way in which waveform-based design can be applied to optimization of power magnetics, highlighting the influence of topology selection on transformer and inductor performance.

One of the goals of magnetics design is to achieve the greatest *utilization* possible from a magnetic component, to get the most use out of it as possible. Utilization is defined quantitatively based on waveforms, usually current waveforms, and is

$$U = \frac{\overline{x}}{\hat{x}}$$

where x is voltage or current, $\overline{x}$ is the average x, and $\hat{x}$ is the peak or maximum x.

U expresses the extent to which a component is able to deliver the desired quantity, the average, relative to the maximum of that quantity that it must handle, or the peak rating. The ideal value is $U = 1$; the component need not be rated at any greater amount than what is used. Although the ideal of one is desired, the extent that it can be achieved varies based on the circuit of the magnetic component.

In this article, we'll examine four popular isolated power supply topologies—the flyback, forward, full bridge and half bridge converters—to see the impact that each has on utilization of the transformer. By looking at the current flows and duty ratios of these current flows, we can understand why transformer utilization is higher or lower in these topologies. At the same time, we can uncover the costs in terms of power switches and capacitors required to achieve the higher utilization as well as other design tradeoffs.

Low-Utilization Converters

A circuit *topology* is the circuit without regard to scaling—in other words, without component values. The "simpler" converter topologies have the lowest U. As shown in Fig. 1, they include the flyback (common-active, CA) and forward buck (common-passive, CP) converters, as prime examples.

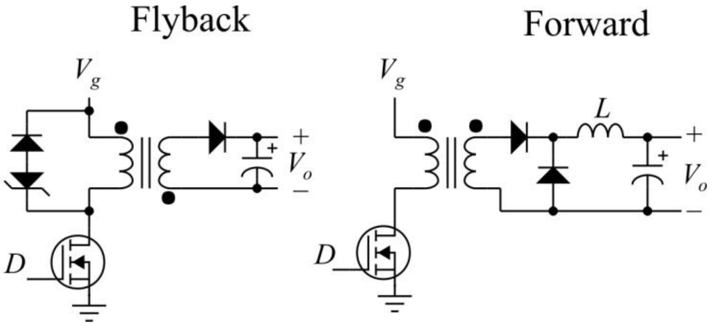

Fig. 1. The flyback and forward converters have utilization of primary and secondary windings of ½. The core flux in each is unipolar and extends over only half of the full magnetic flux range.

In both of these converters, primary and secondary currents are unidirectional (unipolar), resulting in unipolar magnetic flux in the core. Only half of the full bipolar range of the core is utilized. Voltage utilization of the flyback switch is also low because its voltage rating must be at least twice that of the supply voltage, V_g, because of off-time output voltage referred to the primary winding as $n \cdot V_o$, where n is the turns ratio, N_p / N_s.

In the forward converter, current in both windings is not only unipolar but it is non-zero (except for magnetizing current) only during the on-time of the switching cycle. During the off-time, the transformer is doing nothing—it is not being used to transfer power.

The flyback converter has no primary current (except for clamp current) during off-time and the secondary has none during on-time—a utilization at D = 0.5 of half for each winding. D = 0.5 is the optimal duty-ratio in that it gives equal time to primary and secondary currents, thus resulting in equal form factors, κ = rms current/average current. (Form factor is another optimization parameter along with U.) Form factor κ is a measure of the value of current that causes power loss (rms) to that of interest (average) in delivering power. Hence the ideal is to minimize κ to one in designs.

The time during which power is being transferred through a magnetic component is the time it is being used according to its purpose. In discontinuous-current mode, DCM, the *deadtime*, during which no primary or secondary current flows, reduces U accordingly and is found only in low-power converters not requiring high power density or efficiency. The deadtime not only is wasted time for power transfer, but it also increases κ because the on-time average currents must be higher to deliver more power to make up for that not delivered during deadtime.

With higher κ values for the power components, power loss is also higher. This applies as much to magnetic components as to switches and capacitors, and is the circuit-related aspect of magnetics design. Optimized magnetics begin with the optimal converter topology.

Converters With Improved Utilization

The full-bridge converter is the prime example, shown in Fig. 2, of a topology that drives the transformer primary winding current in both directions to cover the full core flux range.

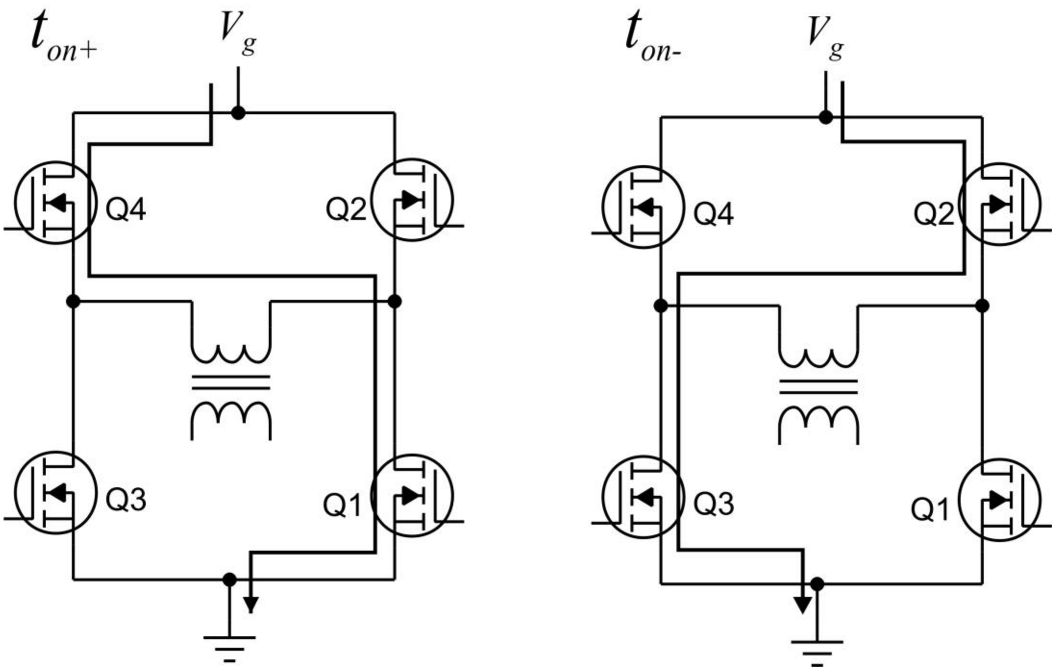

Fig. 2. Full-bridge circuit during on-time for both half-cycles. Current in the transformer primary winding is bipolar and flux is driven over the full allowable range.

On-time current flows for the full-wave bridge are shown in Fig. 2 for each half-cycle. Four power switches are needed in this scheme to switch the current in both directions through the primary winding. During off-times the MOSFET body-drain diodes become the reverse-conducting switches that deliver current back to the V_g supply and sustain magnetizing current in the transformer. (Some of it transfers to the secondary winding—a topic for a converter article.)

The full input voltage is applied by the switches across the primary winding in each half-cycle as a bipolar voltage of $\pm V_g$, allowing maximum power delivery to the winding. Primary winding voltage U = 1 and current U = 1 because both voltage and current applied to the winding cover their full rated range for the winding.

The tradeoff for maximum utilization is the cost of four power switches and their drive circuitry. However, the transformer size is also reduced, and silicon (or SiC or GaN) is lower in cost than copper and ferrite cores. If primary and secondary windings equally split the transformer winding window, and primary winding U increases from half to one, that increases the total transformer U by 25% and its size is reduced by about the same fraction.

A variation on the full-bridge converter with half the power switches but twice the input capacitors is the half-bridge converter. It is shown in Fig. 3 with current flows during the on-times of each half-cycle. The half-bridge circuit replaces one of the full-bridge branches with two series capacitors of value C. The center-node of the capacitor branch can be thevenized as a voltage source of $V_g/2$ in series with a capacitance of $2\cdot C$.

The half-bridge differs from the full-bridge circuit mainly in two ways. First, the primary winding now has a capacitance in series with it, which gives rise to possible resonance; and second, to achieve bipolar voltages, V_g has been halved so that $\pm V_g/2$ is applied to the primary winding. To deliver the same power as the full-bridge circuit, the switch and capacitor current must double. Of course, this affects the primary winding design and requires larger wire but fewer turns of it because the applied circuit flux is halved by halving the voltage (with the same switching on-time). In effect, the half-bridge has one fourth the impedance of the full-bridge relative to the primary winding.

Unlike the forward and flyback converter secondary circuits which have unipolar currents, the secondary circuit in Fig. 3 is shown to have a full-wave rectifier bridge of four diodes, allowing bipolar currents to the output from the secondary winding. This results in full utilization of the secondary winding and transformer utilization overall is $U = 1$.

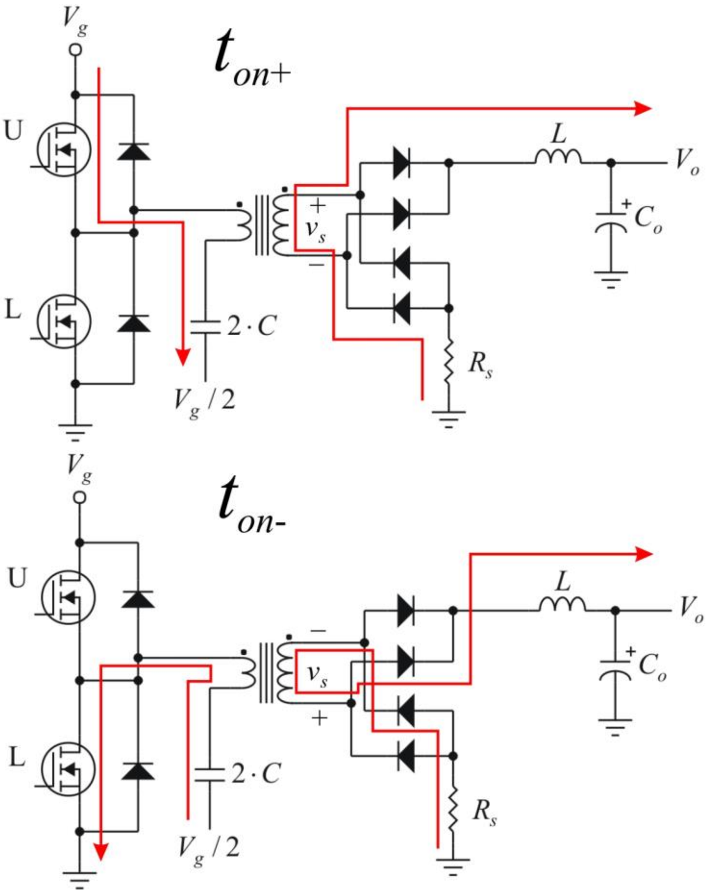

Fig. 3. On-time half-cycles for the half-bridge circuit. Primary winding current is bipolar as is transformer flux. Secondary current is also bipolar with a full-wave rectifier bridge. Both windings are fully utilized.

The bipolar secondary current decreases κ_s and also affects winding design in that the winding operates cooler with bipolar current. In the forward converter, the half-wave rectifier allows secondary current only during on-time (and only in one direction) so that for the same output power, the current must be that much greater when it *is* delivering power. Ideally, output current should be flowing all the time, in which case its value can be lowest and $\kappa = 1$. The ideal converter waveforms are constant voltages and currents, but reactive power transfer requires changes in them—a fundamental conflict in converter design!

This conflict creates a design tradeoff between low ripple (Δi) versus how large of an inductance can be tolerated (in size and cost) to achieve lower ripple, either in L for converter current ripple or in primary inductance, L_p for reducing magnetizing current ripple. Ideally, core winding windows (and copper budgets) allow high L_p to minimize primary-referred magnetizing current, i_{mp}—another magnetics design consideration affecting the overall converter circuit design.

Closure

Magnetics design begins with circuit design. The choice of converter topology interacts with magnetics tradeoffs, and the magnetics designer cannot merely receive transformer (or inductor) specifications from the converter engineer if an overall optimization is to be achieved. The magnetics designer must be good at everything—a power-electronics polymath—to achieve an optimal converter, one that can compete in an increasingly globally-competitive marketplace.

Reference

"Waveform-Based Design: Key Parameters And Figures Of Merit For Power Circuit And Magnetics Optimization" by Dennis Feucht, How2Power Today, September 2019 issue.

About The Author

Dennis Feucht has been involved in power electronics for 30 years, designing motor-drives and power converters. He has an instrument background from Tektronix, where he designed test and measurement equipment and did research in Tek Labs. He has lately been working on projects in theoretical magnetics and power converter research.

For more on magnetics design, see these How2Power Design Guide search results.