# THE ART OF ELECTRONICS

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THIRD EDITION

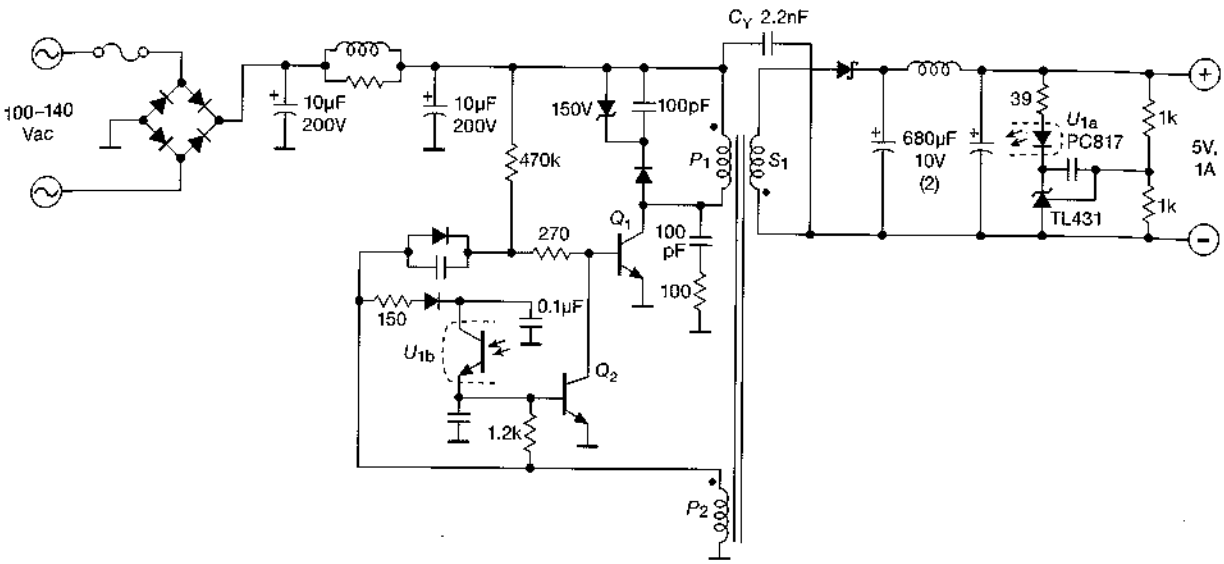


**Figure 9.74.** An inexpensive 5 W flyback converter, powered from 115 Vac line voltage, that uses a self-excited "blocking oscillator." Winding P2 provides positive feedback to sustain oscillation. The output voltage is sensed and compared with the TL431 shunt regulator, fed back via the optocoupler $U_1$ to adjust the conduction cycle.

input voltage $V_{in}$, during primary switch conduction, to a secondary voltage $(N_{sec}/N_{pri})V_{in}$. That transformed voltage pulse drives a buck converter circuit, consisting of catch diode $D_2$, inductor $L$, and output storage capacitor. The extra diode $D_1$ is needed to prevent reverse current into the secondary when the switch is OFF. Note that here, in contrast to the flyback converter, the transformer is "just a transformer": inductor $L$ provides the energy storage, as with the basic buck circuit. The transformer does not need to store energy, because the secondary circuit conducts at the same time as the primary (energy goes "forward"), as you can see from the polarity marking.

Analogous to the buck converter, (eq'ns 9.3a–9.3h), the output voltage is simply

$$V_{out} = V_{in}\frac{N_{sec}}{N_{pri}}\frac{t_{on}}{T} = D\frac{N_{sec}}{N_{pri}}V_{in} \quad \text{(in CCM)}. \qquad (9.8)$$

**Resetting the core** In contrast to the flyback circuit, there's an additional winding in Figure 9.73B, which is needed to *reset* the transformer's core.[92] That is because the volt-second product[93] applied to the transformer must average zero (i.e., no average dc input) in order to prevent a continual buildup of magnetic field; but the input switch alone always applies voltage in one direction only. The tertiary winding fixes this by applying voltage in the opposite direction during the switch-OFF portion of the cycle (when diode $D_R$ conducts, from continuity of current in the winding as the magnetic field collapses).[94]

**Additional comments** (a) As with the flyback, and indeed with any transformer-coupled converter, the forward converter allows multiple independent secondaries, each with its inductor, storage capacitor, and pair of diodes. Regulating feedback then holds one output particularly stable. (b) The transformer isolates the output in a forward converter, if you happen to need isolation (as in a powerline-input converter); in that case you must galvanically isolate the feedback signal as well, typically with an optocoupler (as in the block diagram of Figure 9.48, or the detailed diagrams of Figures 9.74 and 9.83). On the other hand, if you do not need isolation you can have a common ground reference, and bring the error signal back to the PWM control circuit directly.

92 Reset is inherent in the flyback, but not in the single-ended forward converter, as will become evident.

93 Sometimes call "volt-time integral."

94 There are clever circuits that reset the core without requiring a tertiary winding: one method uses a pair of primary switches, one at each end of the winding, in collaboration with a pair of diodes, to reverse the voltage across the single primary (see if you can invent the circuit!). Another method uses instead a second switch to connect a small capacitor across the primary during main switch-OFF; this clever method is known as "active clamp reset," and was devised independently by Carsten, Polykarpov, and Vinciarelli. It has the virtue of *reversing* the magnetic field in the transformer core, providing better performance by allowing double the normal flux excursion.

the switching circuitry. This serves three important purposes: (a) it provides galvanic isolation, which is essential for converters that are powered from the ac line; (b) even if isolation is not needed, the transformer's turns ratio gives you an intrinsic voltage conversion, so that you can produce large step-up or step-down ratios while staying in a favorable range of switching duty cycle; and (c) you can wind multiple secondaries, to produce multiple output voltages; that's how those ubiquitous power supplies in computers generate outputs of +3.3 V, +5 V, +12 V, and −12 V, all at the same time.

Note that these are not the heavy and ugly laminated-core transformers that you use for the 60 Hz ac powerline: because they run at switching frequencies of hundreds to thousands of kilohertz, they do not require a large magnetizing inductance (the inductance of a winding, with all other windings open-circuited), and so they can be wound on small ferrite (or iron powder) cores. Another way to understand the small physical size of the energy-storage devices in switchmode converters – that is, the inductors, transformers, and capacitors – is this: for a given power output, the amount of energy passing through these devices in each transfer can be much less if those transfers are taking place at a much higher rate. And less stored energy ($\frac{1}{2}LI^2$, $\frac{1}{2}CV^2$) means a smaller physical package.[90]

### 9.6.11 The flyback converter

The *flyback* converter (Figure 9.73A) is the analog of the inverting non-isolated converter. As with the previous non-isolated converters, the switch is cycled at some switching frequency $f$ (period $T = 1/f$), with feedback (not shown) controlling the duty cycle $D = t_{\rm on}/T$ to maintain regulated output voltage. As with the previous converters, the pulse-width modulation can be arranged as voltage mode or current mode; and the secondary current can be either discontinuous (DCM) or continuous (CCM) from each cycle to the next, depending on load current.

What is new is the transformer, which in the flyback converter topology acts simply as an inductor with a tightly coupled secondary winding. During the switch-ON portion of the cycle, the current in the primary winding ramps up according to $V_{\rm in} = L_{\rm pri}\, dI_{\rm pri}/dt$, flowing into the "dotted" terminal; during that time the output diode is reverse biased because of the positive voltage on the dotted terminals of both windings.

[90] For the particular case of the flyback converter, discussed next, you can think of the transformer as formed by a second winding on the already-small inductor used for energy storage in the non-isolated inverting (buck–boost) converter.

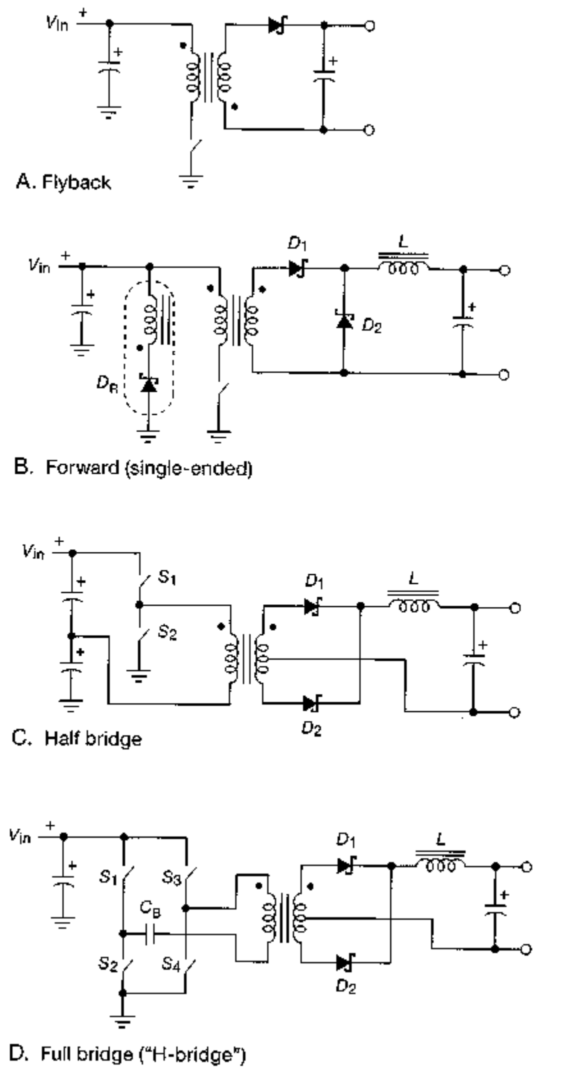


**Figure 9.73.** Isolated switching converters. The flyback converter (A) uses an energy-storage inductor with a secondary winding, whereas the forward and bridge converters (B–D) each use a true transformer with no energy storage (and thus require an output energy-storage inductor). The diode $D_R$ and tertiary winding in the forward converter is one of several ways to reset the core in this single-ended design. The dc blocking capacitor $C_B$ in the H-bridge prevents flux imbalance and consequent core saturation; for the half-bridge the series pair of capacitors serves the same function, while acting also as the input storage capacitor.

During this phase the input energy is going entirely into the magnetic field of the transformer's core. It gets its chance to go somewhere else when the switch turns OFF: unlike the situation with a single inductor, with *coupled* inductors the requirement of continuity of inductor current is satisfied if the current continues to flow in *any* of the windings. In this case the switch-ON current, flowing into the dotted terminal, transfers itself to a similarly directed current in the secondary, but multiplied by the turns ratio $N \equiv N_{\text{pri}}/N_{\text{sec}}$. That current flows to the output (and storage capacitor), ramping down according to $V_{\text{out}} = L_{\text{sec}}\, dI_{\text{sec}}/dt$. From equality of inductor volt-seconds, the output voltage is simply

$$V_{\text{out}} = V_{\text{in}} \frac{N_{\text{sec}}}{N_{\text{pri}}} \frac{t_{\text{on}}}{t_{\text{off}}} = V_{\text{in}} \frac{N_{\text{sec}}}{N_{\text{pri}}} \frac{D}{1-D} \quad \text{(in CCM).} \qquad (9.6)$$

And, as usual, efficiency is high, so power is (approximately) conserved:

$$I_{\text{in}} = I_{\text{out}} \frac{V_{\text{out}}}{V_{\text{in}}}. \qquad (9.7)$$

You can wind additional secondaries, each with its diode and storage capacitor, to create multiple output voltages (as set by the turns ratios). And, because the output windings are isolated, you can as easily generate negative outputs. Having chosen one of the outputs for regulating feedback, however, the others will not be as tightly regulated. The term "cross regulation" is used to specify the output-voltage dependencies.

### A. Comments on flyback converters

**Power level** Flyback converters have full pulsations of input and output current. For this reason they are generally used for low- to medium-power applications (up to ~200 W). For higher power you usually see designs using the *forward* converter, or, for really high power, *bridge* converters.

**The transformer is an inductor** The input energy each cycle is first stored in the transformer core (during switch-ON), then transferred to the output (during the switch-OFF). So the transformer design must provide the correct "magnetizing inductance" (acting as an inductor), as well as the correct turns ratio (acting as a transformer). This is quite different from the situation with the forward converter and the bridge converters, below, where the transformer is "just a transformer." We won't go into further detail about transformer design here, simply noting that the design of the "magnetics" is an important part of switching converter designs in general, and flybacks in particular. You have to worry about issues such as core cross-section, permeability, saturation, and deliberate "gapping" (in general, energy-storage inductors are gapped, whereas pure transformers are not). Extremely helpful resources for design are found in IC datasheets and design software (usually available at no charge from the manufacturer) that provide specifics about the choice of magnetics. We explore this important topic further in §*9x.4*.

**Snubbers** With ideal components, the primary current would transfer completely to the secondary when the switch turns OFF, and you wouldn't have to worry about bad things happening on the dangling drain terminal of the switch. In reality the incomplete coupling between primary and secondary creates a series "leakage inductance," whose craving for current continuity generates a positive voltage spike at the switch, even though the secondary is clamped by the load. This is not good. The usual cure is to include a *snubber network*, consisting of an *RC* across the winding, or, better, a "*DRC*" network of a diode in series with a parallel *RC*.[91]

**Regulation** Flyback converters can be regulated with conventional PWM, either voltage mode or current mode, with a free-running oscillator calling the shots. Alternatively, you will see inexpensive designs in which the transformer itself becomes part of a *blocking oscillator*, thereby saving a few components. We cracked open some samples of low-power (5–15 W) "wall warts" and found, well, just about *nothing* inside! We reverse engineered them to look at the circuit tricks (Figure 9.74). They seem to work just fine.

**Off-line converters** This final circuit (Figure 9.74) is an example of a power converter that *requires* galvanic isolation. The transformer provides isolation for the power flow; in addition, the feedback signal from the dc output must be isolated as well on its way back to the primary side. This can be done with an optocoupler, as here, or with an additional small pulse transformer. We discuss these offline converters briefly in §9.7, and in Chapter *9x* we discuss high-efficiency ("green") power supplies, including a graph comparing the performance of this 5 W supply (whose standby power is 200 mW) with others.

### 9.6.12 Forward converters

The *single-ended forward converter* (Figure 9.73B) is the transformer-isolated version of the buck converter. It is helpful to refer back to the basic buck circuit (Figure 9.61A), to see how it goes. The transformer converts

91 Leakage inductance values are typically ~1% of the magnetizing inductance. You can reduce leakage inductance greatly by splitting one of the windings (say primary) into two, with the other (secondary) sandwiched in between. And *bifilar* windings (wind primary and secondary as a pair of wires together) can reduce the leakage inductance to a low value. However these techniques increase inter-winding capacitance, and bifilar windings suffer from poor voltage insulation ratings.