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Off-Time Control Raises Flyback Power Rating While Maintaining High Efficiency

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Power Integrations' TinySwitch product families incorporated the on-off-based approach to switching control, which enabled high efficiency at low, no, and light load and also in standby in flyback converters. This was accomplished more than a decade before efficiency at different load points became a critical circuit parameter. The TinySwitch architecture dramatically simplified power supply design, removing the challenges associated with loop stability analysis realized through the investigation of Bode plots.

The latest addition to this series, TinySwitch-5 extends this legacy by preserving the core benefits of on-off control at light load and in standby, while also maximizing efficiency across the entire load range. In this article, we will review how the classic TinySwitch control engine operates and then explain how the advanced control techniques used in TinySwitch 5 build upon the original architecture to deliver improved performance and overcome well-known limitations of the classic on-off control engine.

The article begins by explaining the principles of operation for on-off control as implemented by existing TinySwitch controllers. This includes a discussion of how current limits are adjusted to prevent switching in the audible frequency range, how elimination of the error amplifier (required in PWM control) avoids the need for phase compensation and how scaling of switching frequency leads to flat efficiency over the load range.

Limitations of on-off control, which limit maximum power output with TinySwitch's on-off control, are also discusssed. These include lower efficiency at full load versus PWM control, and other factors such as output ripple and noise.

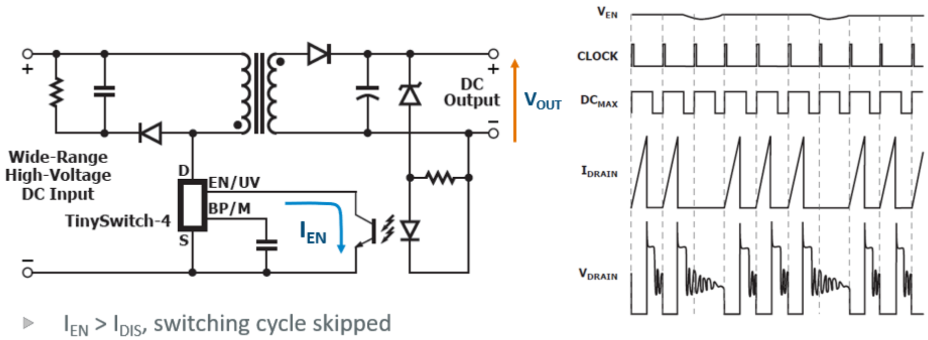
With that as background, the off-time modulation control scheme used in TinySwitch 5 is introduced. This section of the article describes how it works conceptually, and its benefits with respect to higher power output and flat efficiency over load. The subsequent section provides further details on how this new control method is implemented including use of on-time extension to prevent transformer saturation in low-line conditions. Performance results are given for example designs.

The discussion then turns to how to optimize converter designs using TinySwitch 5. This is mainly an explanation of where to place the crossover point for CCM to DCM operation.

The Original On-Off Control Scheme

At the start of each potential switching cycle, a TinySwitch controller evaluates whether the output requires additional energy. If so, it initiates a switching pulse. This has the advantage of only switching (and therefore dissipating energy in turning on and turning off the primary switch) when energy is required by the output—most beneficial at light load.

The switch is held on while the primary switch current (I_D) ramps. The switching pulse is terminated when the primary current exceeds an I_{LIM} value. The maximum value of I_{LIM} is reached at full load and is limited by the switch in the TinySwitch device, which is described by the part number. This operating mechanism is shown in Fig. 1.



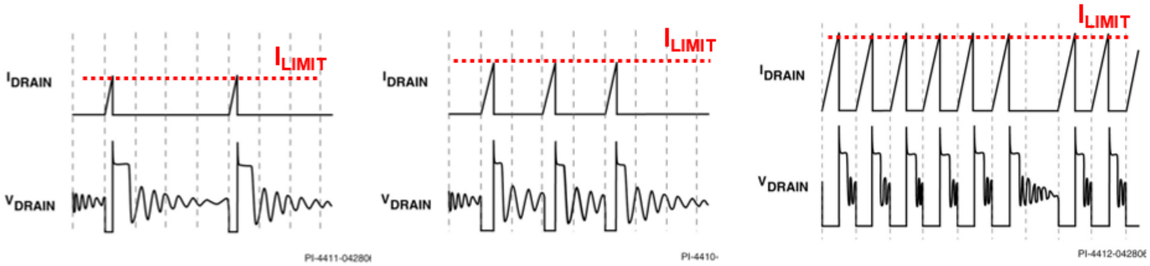
- $I_{EN} > I_{DIS}$, switching cycle skipped
- $I_{EN} < I_{DIS}$, switching cycle enabled

Fig. 1. On-off control as implemented by TinySwitch controllers.

A simple optocoupler feedback mechanism allows current to be drawn from the EN/UV pin, triggering a switching cycle when the current drawn drops below a threshold. Maximum duty cycle (DC_{MAX}) is limited by primary switch current limit (I_{LIM}). Depending on the TinySwitch part number and device setting, I_{LIM} can range from 210 mA to 850 mA. The maximum switching frequency is fixed and limited by the controller clock frequency (132 kHz). An end-stop duty cycle of 67% is included to terminate switching if I_D does not reach I_{LIM} within a cycle limit.

This approach works effectively, but the variable switching frequency inherent to the on-off mechanism can sometimes move the switching frequency down into the audible-resonant range (ARR). The ARR spans approximately 10 kHz to 30 kHz, exciting mechanical resonance in the transformer. This is recognized by the designer as an audible buzz.

To prevent operation in this undesirable frequency range, TinySwitch devices use a gearing mechanism to dynamically increase the I_{LIM} as the rate of switching requests rises. This approach is illustrated in Fig. 2.



Light Load I_{LIMIT} = 40% **Mid Load I_{LIMIT} = 70%** **Full Load I_{LIMIT} = 100%**

Fig. 2. I_{LIM} gearing adjusts I_{LIM} as load changes to prevent operation in the ARR.

The gain of the internal current comparator—which determines whether a new switching pulse is required—is sufficient to make the on-off control decision without an error amplifier or ramp generator, both of which are required in conventional pulse width modulation (PWM) control. By eliminating the error amplifier, the architecture removes the phase lag responsible for loop instability, and it also eliminates the need for loop compensation (no pole-zero).

As a result, designers avoid the phase-compensation process entirely, significantly simplifying the overall design effort. Additional benefits of this architecture include low variation in Zener voltage (and hence constant Zener feedback current) inherent in on-off control and the resulting excellent regulation accuracy, lumped parameters (I^2f) and on-time extension.

Because the switching frequency (i.e., the number of switching cycles) scales with load, efficiency remains flat across the entire operating range. A representative efficiency curve for a 20-W design is shown in Fig. 3. This load-dependent frequency characteristic makes the TinySwitch approach ideal for applications that demand high performance at light load.

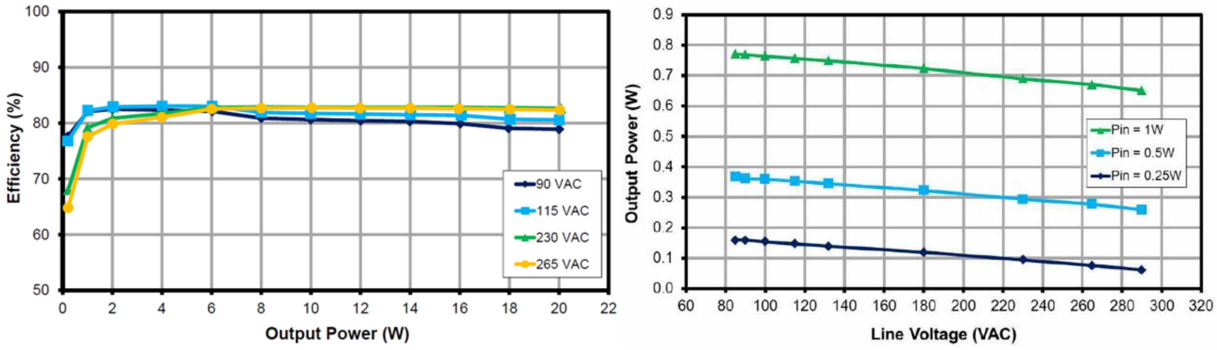
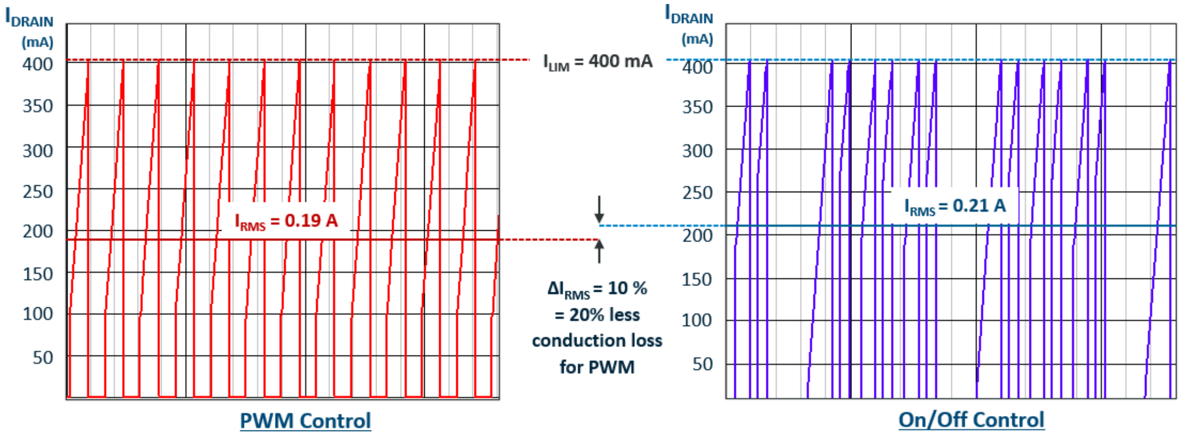


Fig. 3. Efficiency of a 20-W TinySwitch-4 design is flat across the load range. The on-off engine also ensures good power delivery during standby.

On-off control has demonstrated clear benefits throughout the TinySwitch product lineage, but the approach does have inherent limitations. The on-off control engine interprets repeated switching request rates beyond a certain threshold as an output short circuit. This limits the available switching cycles at full load to below the maximum possible switching frequency of the device. This together with fixed I_{LIM} result in higher RMS current per switching cycle compared to a PWM architecture.

Fig. 4 shows a comparison of the primary-current waveforms for the two approaches. This higher per-cycle primary current in on-off control increases conduction loss in the primary switch. While some of this loss can be mitigated by using a larger primary switch to lower $R_{DS(ON)}$, doing so only partially addresses the issue. Consequently, full-load efficiency for PWM-based converters is higher than with on-off control.



Vin = 100 VDC, O/P = 5 V 2.5A, L_p = 1.5 mH, n (turns ratio) = 0.0458, I_p = 0.4 A

Fig. 4. Comparison of primary switch current at full load for an on-off control approach vs. PWM in a flyback converter. For a 12.5-W load, PWM has ~10% lower RMS current and ~20% lower I^2R *loss than on-off control with the same* I_{LIM}.

In addition, challenges with output noise and hysteresis can lead to pulse-bunching in on-off control circuits, where sub-harmonics of the average switching frequency create audible noise and increase output ripple. Together, these factors limit the practical output power of on-off-controlled power supplies to approximately 25 W. Although this power range is generally adequate for auxiliary and bias supplies in appliance and industrial applications, scaling beyond this point requires a different approach.

A New Approach For SSR Flyback With High Efficiency At All Load Points

Off-Time Modulation Replaces On-Off Control

The TinySwitch-5 product family introduces a new control engine that maintains the hallmark advantages of the TinySwitch architecture—flat efficiency across the load range, simple design, and accurate regulation using a standard optocoupler and basic diode rectification—while significantly improving full-load performance. The new devices achieve up to 92% efficiency at high line and greater than 85% efficiency down to 1% load. Meanwhile, maximum output power has been extended to over 170 W for high-line designs, and output ripple is reduced.

Fig. 5 illustrates the new control approach. Importantly, the basic flyback topology remains very similar to that of earlier TinySwitch families which has proven so attractive due to its simplicity and reliability.

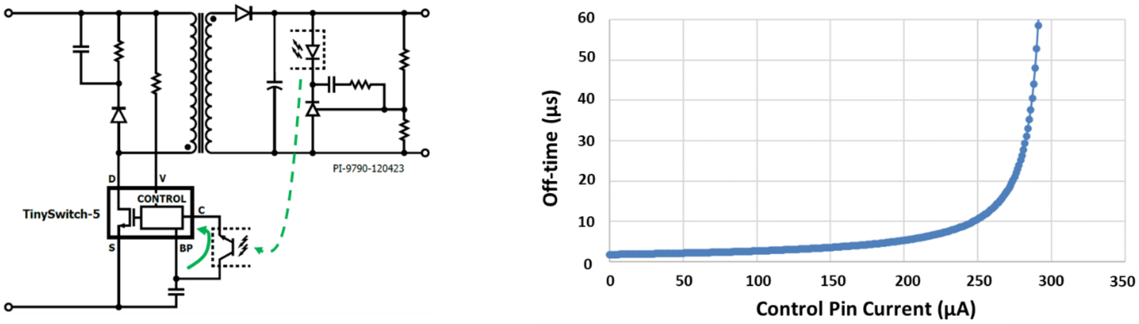


Fig. 5. TinySwitch-5 offline flyback converter basic schematic and waveform show relationship between off-time and control pin current.

In the off-time modulation scheme, the controller uses the analog feedback current to determine the off-time duration (T_{OFF}). T_{OFF} is proportional to the feedback current: higher feedback current (corresponding to higher output voltage) produces longer off-times and therefore lower switching frequency. As load decreases, the control-pin current increases, extending the off-time and reducing switching frequency. At the end of each off cycle, the off-time modulator generates a request for a new switching cycle and turns on the integrated power switch.

On-time is made proportional to switching cycle request rate, as shown in Fig. 6. Primary current limit, I_{LIM}, is proportional to the time between turn-off of the previous cycle and turn-on of the next cycle. As a result, I_{LIM} increases as switching frequency rises (with increasing load), allowing the converter to deliver more energy per cycle and maintain flat efficiency across the entire load range.

The maximum switching frequency is now 150 kHz, with a 66% maximum duty cycle. When the load-induced switching frequency exceeds 100 kHz, I_{LIM} remains at its maximum value. At the opposite end of the operating curve, I_{LIM} is reduced to ~30% of its maximum when the frequency falls below 25 kHz. This prevents audible noise.

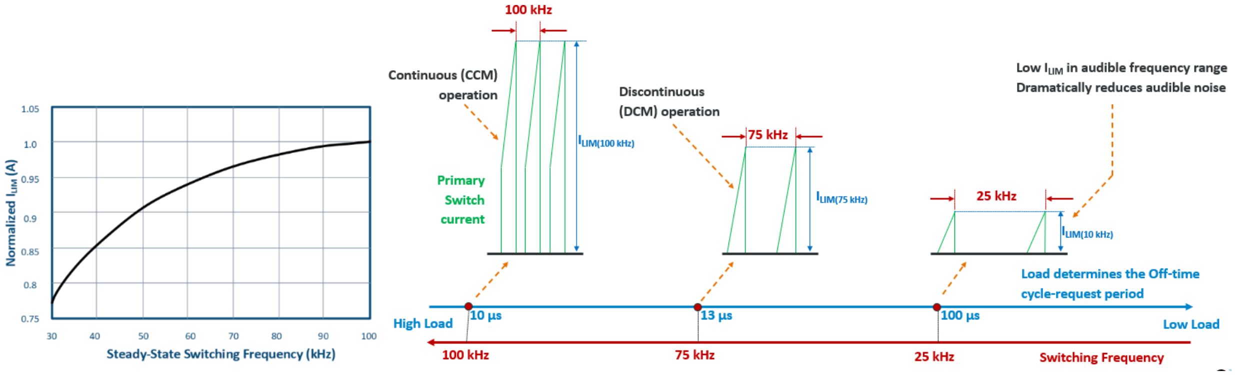
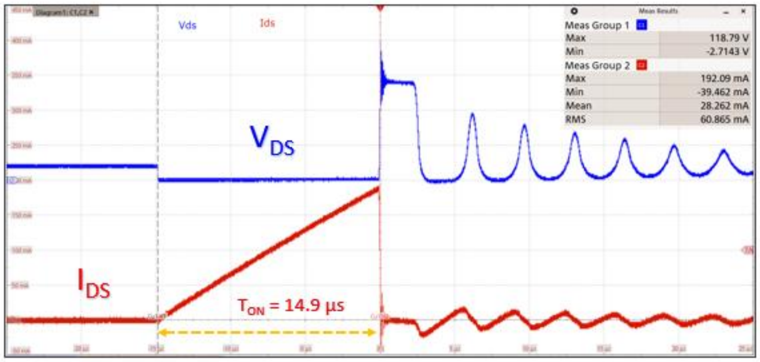


Fig. 6. Steady-state switching frequency (controlled by switch off-time) adjusts I_{LIM} across the load range. I_{LIM} is suppressed at low frequency to prevent audible noise.

Controller Operation

Somewhat counter-intuitively, it is helpful to begin the analysis at the end of the on-time interval of the power switch. On-time is terminated by the primary current reaching the I_{LIM} point. However, if the current ramp is too slow to reach I_{LIM}, the on-time is ended at 66% duty cycle to prevent core saturation. Under low line conditions, the reduced voltage applied to the fixed magnetizing inductance may cause the primary current to ramp too slowly and limit power delivery.

In order to deliver sufficient energy to the output, the controller will detect the slow ramp associated with low-line operating condition and extend the on-time up to a maximum of 15 µs, as shown in Fig. 7. This allows the design to deliver more power during the voltage trough at low ac input for a given input bulk capacitance. Fig. 8 shows the internal timing circuit that determines when to terminate the off-time interval, thereby controlling voltage regulation in the TinySwitch-5 IC.



Meas Group 1 🟦	
Max	118.79 V
Min	-2.7143 V
Meas Group 2 🟥	
Max	192.09 mA
Min	-39.462 mA
Mean	28.262 mA
RMS	60.865 mA

Fig. 7. On-time extension gives the primary current additional time to ramp, transferring more energy to the magnetizing inductance and allowing higher power delivery at low line without saturating the transformer.

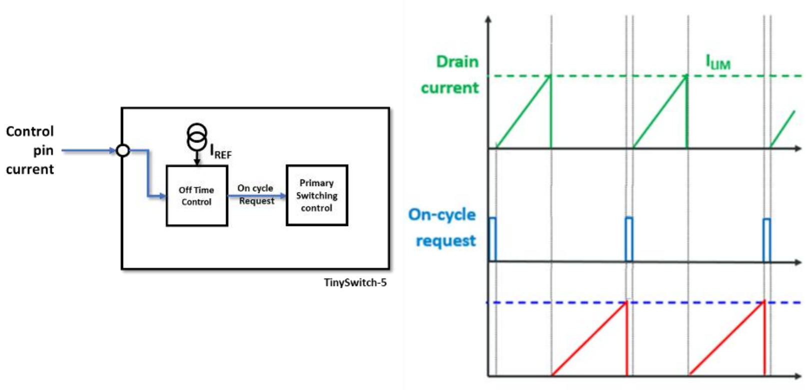


Fig. 8. The primary-side controller in the TinySwitch-5 IC regulates the output by delaying the on-cycle request according to the current flowing into the C-pin.

The control pin current is inversely proportional to output load. This is applied to an off-time modulator circuit to create an off-time that increases with control pin current. The on-cycle request is then used to initiate the switching cycle at the end of the off-time, as shown in Fig. 9.

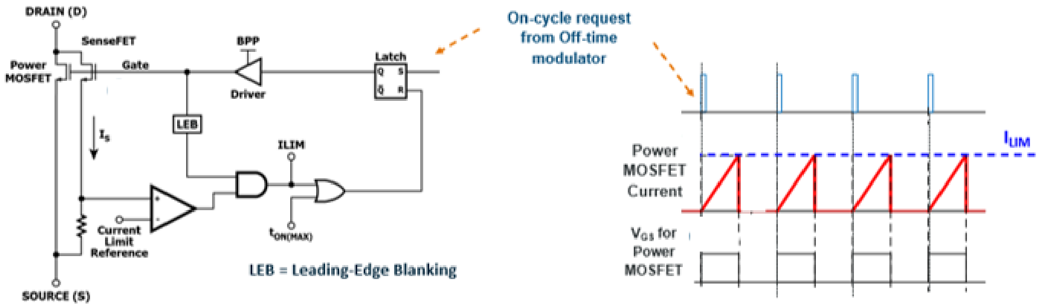
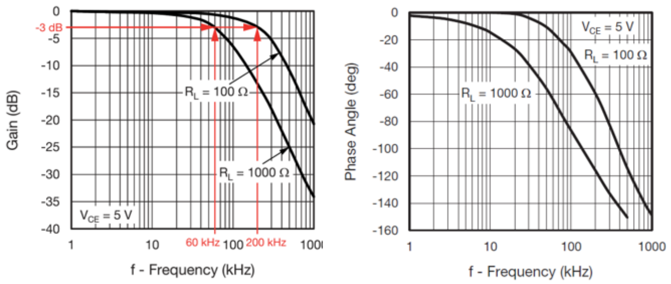
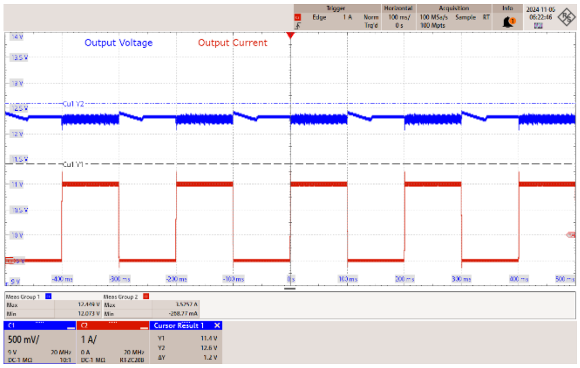


Fig. 9. An on-cycle request sets a latch driving the primary switch on. Primary switch current ramps and is measured against a reference. Current limit reference scales with switching cycle request rate.

Excellent regulation and consistent loop response are achieved via optocoupler feedback by maintaining a constant C-pin impedance (R_L = 200 Ω) and voltage (2 V) across a wide range of feedback currents. This is accomplished using a regulation FET on the C pin, which stabilizes impedance and ensures minimal gain and phase variation across frequency, as shown in Figs. 10a and 10b.



(a) Loop response.



Meas Group 1
Max 12.449 V
Min 12.073 V

Meas Group 2
Max 3.5257 A
Min -288.77 mA

C1
500 mV/
9 V 20 MHz
DC-1 MΩ 10:1

C2
1 A/
0 A 20 MHz
DC-1 MΩ RT-ZC20B

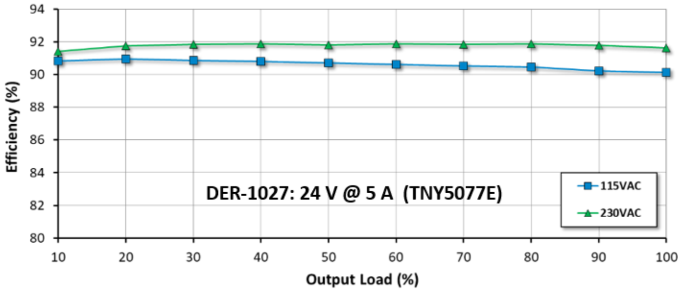
Cursor Result 1
Y1 11.4 V
Y2 12.6 V
ΔY 1.2 V

(b) Transient response.

Fig. 10. System bandwidth is limited by phototransistor capacitance and control pin impedance. By controlling C-pin impedance dynamically, constant loop gain and phase is maintained (a), resulting in excellent transient response. Transient response for 0 to 100% loop step-response (85 Vac) shows less than 1% change in output voltage (12-V/3-A design) (b).

Overall performance is excellent: efficiency remains flat across load and line (Fig. 11), and the low switching frequency under light load minimizes switching losses, enabling high light-load and no-load efficiency. A 190-W design with low audible noise is feasible for 400-Vdc input. This is made possible because I_{LIM} is reduced to 30% of its maximum value below 25 kHz, allowing the TinySwitch-5 control engine to deliver significantly more power.

Transient response is also very good. The control pin impedance remains low (~200 Ω) across the feedback current, ensuring a consistent and fast loop response for wide range of optocoupler CTRs. The current limit engine takes three pulses to reach 100% I_{LIM} (compared to ~12 pulses for TinySwitch-4). This faster I_{LIM} ramp-up results in excellent transient response.



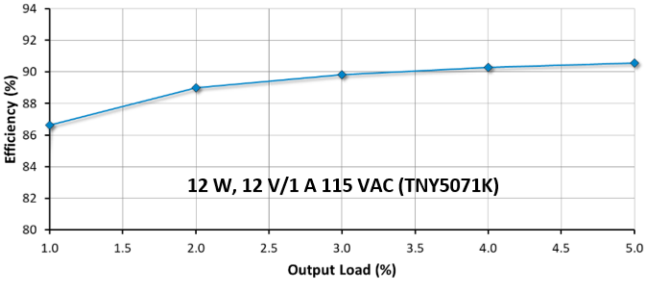


Fig. 11. Very high efficiency across the load range has been demonstrated by practical TinySwitch-5 designs employing conventional diode rectification on the output. Results are shown here for a 100-W (top) and 12-W (bottom) design.

The complete 12-W design is shown in Fig. 12.

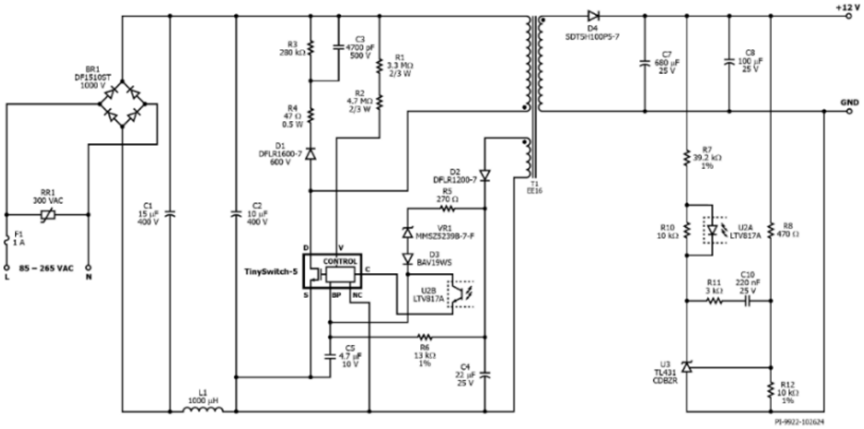


Fig. 12. Complete schematic for a high-efficiency 12-W PSU design, which is more than 86% efficient at 1% load and can deliver more than 200-mW output at 300-mW output (ErP 2025 appliance limit).

Optimizing IC Performance In A Practical Offline Flyback Converter

A comprehensive guide to design optimization would typically require its own dedicated review, so for this section we will focus on determining the best mode of circuit operation. That is, detailing how continuous to make the design for best efficiency, and the implications of that decision on other circuit elements.

This analysis leans heavily on the PI Expert software suite (see the reference) which is a free-to-use online tool for power design from Power Integrations. PI Expert operates as a "circuit chooser" rather than a full system-modeling environment. Instead of running brute-force simulations to derive a functional design, it uses embedded design rules to identify optimal circuit configurations. The result is a fast and accurate process that produces practical, ready-to-build solutions that work the first time.

A key parameter in flyback design is the reflected output voltage, VOR, which is the output voltage reflected to the primary side according to the turns ratio of the transformer. Selecting the correct VOR determines the transformer turns ratio, influences whether the converter operates in discontinuous-conduction mode (DCM) or continuous-conduction mode (CCM), and sets the transition point between these modes.

The optimal value of VOR depends on the output voltage of the power supply. VOR can be thought of as the mechanism for distributing voltage stress between the primary power switch (flyback spike when the device turns off) and the reverse voltage on the output rectifier diode.The table (developed from literally thousands of power supply designs) provides recommended starting values of VOR for practical designs.

Table. Recommended VOR for different output voltages.

Output voltage (V)	Suggested VOR value (V)	Suggested range (V)
5	55	45 to 60
9	85	80 to 90
>12	110	90 to 130

The value of VOR can be adjusted to meet different output-voltage requirements, and this choice directly determines the peak inverse voltage (PIV) stress on the output rectifier diode. The following formula can be used to estimate this effect:

$$\mathrm{PIV} = \left(\frac{\mathrm{V_O} + \mathrm{V_D}}{VOR}\right) \times \mathrm{V_{MAX}} + \mathrm{V_O}$$

where V_O is the output voltage, VOR is the output voltage reflected to the primary (dependent on transformer turns ratio), V_D is the forward drop of the output diode, V_{MAX} is the maximum primary switch voltage and PIV is the peak inverse voltage on the output rectifier diode.

Higher VOR reduces the voltage stress on the output diode, potentially allowing the use of lower-voltage-rated diodes for improved efficiency in that section of the circuit. However, higher VOR increases peak and RMS current on the secondary side. This can increase copper losses in the transformer's secondary winding and elevate diode conduction losses, which in turn reduces overall efficiency.

Because there is no universally optimal VOR value—each choice involves tradeoffs—guidance drawn from large volumes of real-world designs (such as the recommendations in the table, and the more advanced version embedded in PI Expert) is extremely valuable. If PIV becomes excessive, the selection of suitable rectifier diodes narrows, and their efficiency and performance may suffer.

VOR also contributes to the continuous-discontinuous crossover point for the design. This effect is illustrated in Fig. 13, which highlights the change in the crossover point (in this case RMS input voltage) from continuous to discontinuous mode of operation as VOR is reduced from 140 V to 80 V.

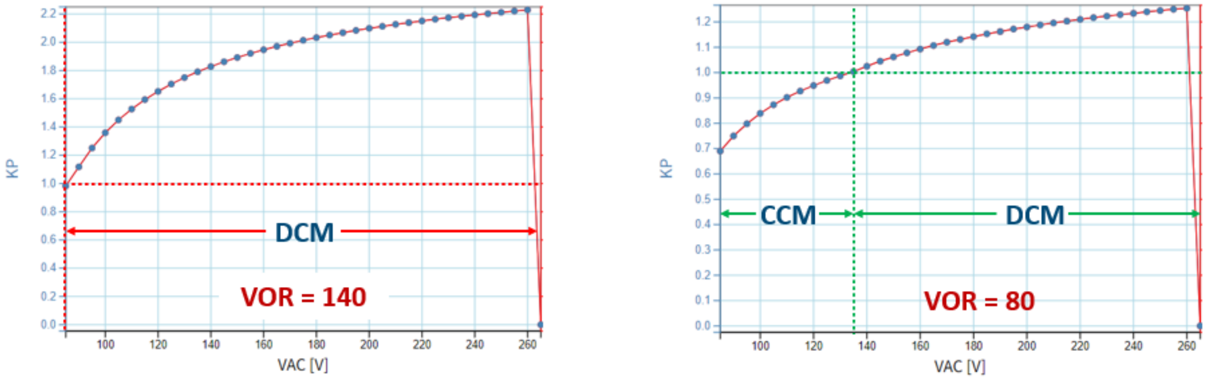


Fig. 13. The role of VOR in changing the power supply's operation between continuous mode to discontinuous mode is clearly seen in the two figures. K_P is determined at full load. The graphics were extracted from the PI Expert design tool.

The K_P is a ratio used to quantify how continuous or discontinuous a design is. A K_P of 1 represents the boundary between CCM and DCM, and the higher the number, the more discontinuous the design is. The method for calculating K_P varies slightly depending on whether the converter is operating in DCM or CCM, as shown in Fig. 14. One key advantage of the TinySwitch-5 family is its ability to seamlessly transition between CCM and DCM.

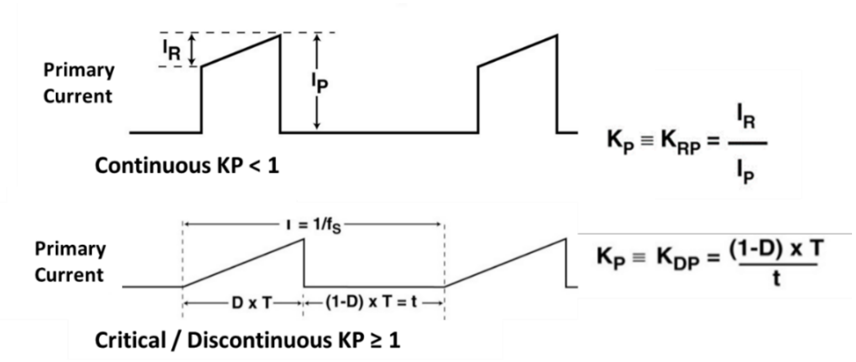


Fig. 14. K_P describes how continuous or discontinuous a design is.

In DCM, all the energy stored in the transformer's magnetizing inductance is fully transferred to the output circuitry—specifically into the output bulk capacitors (C7 and C8 in Fig. 12)—before the next switching cycle begins. During each cycle, the secondary-winding current falls completely to zero.

In CCM, the primary-switch off-time is not long enough for the secondary current to decay to zero. Instead, current is interrupted when the next switching cycle begins, and the residual energy stored in the core continues to discharge into the output filter in the following cycle. This energy is then supplemented by the additional energy stored during the primary side on-time of the next cycle.

The placement of the DCM/CCM crossover point is critically important:

- At low line, CCM operation reduces RMS primary and secondary currents, lowering conduction losses. Therefore, it is advantageous to design for a K_P slightly below 1.
- At high line, DCM operation reduces switching losses and reverse-recovery losses, improving overall efficiency.

In the example shown in Fig. 12, selecting a VOR of 80 V produces this K_P characteristic, and results in a power supply efficiency profile that is flat across input line. Experience indicates that designs with K_P lower than 0.4 (very continuous) should be avoided due to excessive current-induced losses in windings and diode circuits. Conversely, a very discontinuous design might struggle to deliver sufficient energy to the output.

Additional VOR-related considerations:

- Low VOR is usually better suited for multiple-output flyback designs or circuits delivering high output current. Low VOR inherently produces higher secondary peak current. While high secondary current does not necessarily degrade multi-output performance, it increases leakage energy, which can exacerbate cross-regulation effects between outputs.
- Low VOR provides additional margin for primary switch breakdown and improves efficiency.
- Low VOR increases reverse voltage across the secondary diode, which limits diode choice.

The PI Expert tool is extremely helpful in optimizing circuit design and determining the optimal VOR value for a given application. Engineers can adjust their target values while the software automatically recalculates and updates other circuit parameters to keep the power supply operating within recommended limits.

PI Expert also issues warnings when a design exceeds acceptable operating margins or overstresses components. For new engineers, it is an invaluable learning resource that highlights how different circuit elements interact.

Summary And Future Work

By re-imagining the control algorithm, it has been possible to dramatically increase the capabilities of the TinySwitch product family, making it ideal for applications that require excellent performance across the load range (including standby) and allowing the same simple circuit to address ten times more power than previous TinySwitch circuits. The move from on-off to off-time modulation plus load-dependent on-time (I_{LIM}) provides a control approach that reduces output ripple, provides higher efficiency, allows constant steady-state operating frequency for lower output ripple, and dramatically improves transient response.

With TinySwitch-5, the primary limitation on output power is now due to conduction losses in the primary switch, rather than the audible-noise constraints that limited previous on-off controlled families. Looking ahead, the extremely low on-resistance achievable with gallium-nitride (GaN) power switches presents a promising path to push flyback power delivery even higher—potentially beyond 500 W.

Reference

PI Expert software suite

For more on power supply control methods, see How2Power's Design Guide, locate the "Design area" category and select "Control Methods". For more on designing flyback-based power converters, see the "Topology" category and select "Flyback".