Leveraging Ultra-High Efficiency in High Power Open Frame Flyback Applications

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Abstract

Efficiency improvements in flyback converters, driven by advancements in wide-bandgap (WBG) switches, synchronous rectification (SR), and adaptive control, are making them suitable for applications that previously relied on resonant topologies. With improved efficiency, the role of flyback converters in mid-power applications – especially open-frame chargers for eBikes and power tools – is expanding. A 300 W implementation using a 750 V GaN primary switch and variable off-time PWM control achieves 93% efficiency without added complexity or significant cost increase. Design considerations for SR, ZVS, and WBG devices are examined. This paper introduces a hybrid switching control approach that maintains high efficiency across a wide load range. Results suggest that, when selectively enhanced, flyback topologies can effectively replace resonant converters in mid-power applications up to 400 W, offering a practical balance between performance and cost.

1. Introduction

1.1. The Convergence of High-Efficiency with High Cost-Effectiveness

Rapid-charge adapters provide the impetus to improve flyback efficiency. Smaller weight and size became market differentiators for vendors, driving innovation that increased flyback efficiency from 89% to 96% in under 5 years. Eliminating more than 50% of wasted energy (heat) allowed the elimination of metal heatsinks for smaller size. Wide-bandgap (WBG) switch technology, synchronous rectification (SR) and advanced switching algorithms all contributed to the efficiency performance leap.

In this paper, we examine how these technology elements can be adopted for open frame power applications – typified by high power eBike and tool chargers, where cost vs. performance expectations impose stringent restrictions on the converter's architecture.

1.2. Moving Highly Efficient to Highly Cost-Effective

Flyback power — long seen as the cost-effectiveness leader in power conversion topologies — has seen efficiency increase to more than 96%. This is a point where the technology can begin to supplant resonant switching half bridge-technologies in higher power applications where efficiency is the overriding requirement.

Many applications in this power range are for less portable equipment - such as eBike and tool battery chargers – which, while enjoying some of the benefits, cannot extract as much value from smallest size and lightest weight as phone and notebook chargers — which drove the charger to higher flyback efficiency. For open frame power, efficiency brings value in terms of smaller size and weight, but the increased circuit cost required for any efficiency gain must also be largely absorbed by tangible savings in physical cost such as parts removed or simplified. Smaller heatsinks, enclosure and PCB area and simplified assembly are the most likely cost savings in this scenario. Intangible value such as increased reliability (and associated brand-value) from lower temperature and (potentially) reduced electrical stress, plus smaller size and weight, are differentiators that add indirect value but cannot be as easily quantified. The choice of which efficiency strategy to adopt must reflect the net cost impact of the benefit gained.

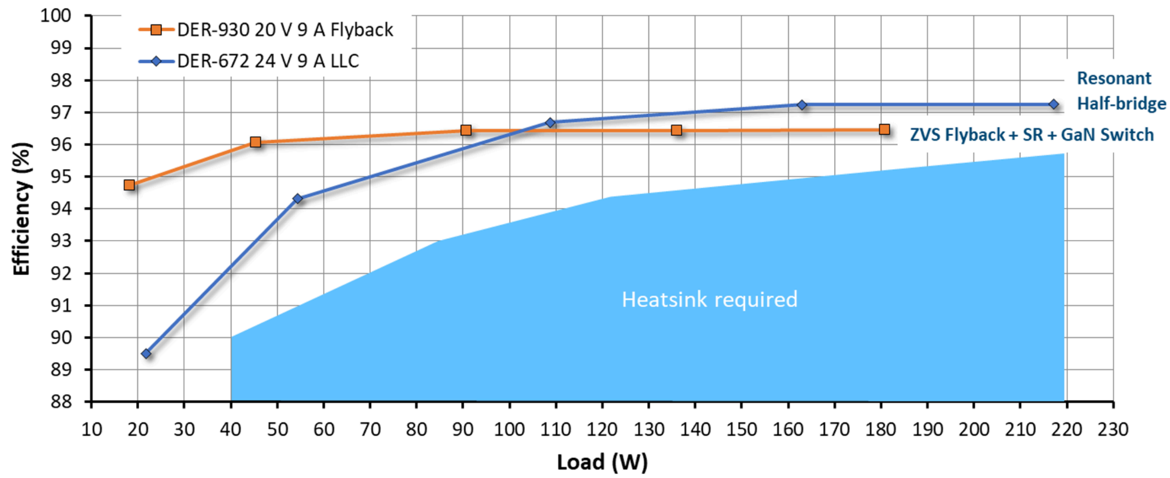

Fig. 1 Multi-output flyback with independent feedbacks

Circuit Element	Efficiency Contribution	Cost Adders	Intangible Benefit	Notes
Switching Algorithm	2%	Zero	Higher light-load efficiency for regulatory compliance	Optimized performance across line and load
Primary Switch Technology (WBG) [2]	1–2%	GaN 1.2 - 1.5 x cost of equivalent silicon MOSFET	Increased protection against surge & line-swell	GaN does not avalanche
Zero Voltage Switching (ZVS)	0.5–1.5%	Active clamp circuit, timing and control functions	Higher switching frequency – smaller magnetics, reduced snubber cost	May restrict operation to narrow I/P & O/P voltage range (DCM)
Synchronous Rectification (SR)	0.2–3%	SR MOSFET replaces diode, timing / control circuits, barrier-crossing	Improved cross regulation in multi-output designs	Best for low O/P volt-age. Negligible contribution >24 V O/P

Table 1 Cost and Benefits Associated with Various High Efficiency Strategies Imposed in Flyback Power Conversion. Cost for GaN Switches will Reduce in Time - Eventually Approaching Silicon [Balakrishnan 2024]

2. Selecting the Efficiency Benefits that Offer Best Return on Investment

The cost burden imposed by maximizing flyback performance can be split into four main areas – switching algorithm, power switch, zero voltage switching (ZVS) and synchronous rectification (SR). The contributions and challenges imposed by each strategy are described in Table 1.

From a cursory examination of Table 1, it is apparent that the switching algorithm is an area that deserves close examination as benefits can be obtained with little direct cost. The conventional pulse width modulation (PWM) technique offers limited performance at low and intermediate loads, - a problem that becomes worse as maximum power increases, pushing up the size of the power switch (and therefore per-cycle switching losses). PWM has a clear benefit in reducing I2R losses in the primary switch – and results in significantly higher efficiency at high load. On-off controllers suffer from noise issues above 20 W due to pulse bunching but provide excellent light-load efficiency from reduced switching loss. The benefits of a hybrid approach to switching will be explored further to show potential improvements in efficiency that it can provide.

Open-frame applications which typically require voltage above logic level, the efficiency benefit of synchronous rectification is low (approach does offer better cross regulation for multi-output designs).

ZVS increases efficiency. It does so by adding considerable cost and complexity to the switching circuit. It requires an energy source – either derived from a primary side active clamp circuit or the secondary-side synchronous rectification stage. In addition, it requires a switching element – a separate high voltage power switch for an active clamp or the SR MOSFET in SR ZVS. While SR ZVS does not add components, it does require accurately synchronized primary and secondary switching stages (typically only achieved through a high level of integration). If SR FETs are not used (replaced by diodes) the efficiency-gain vs. cost benefit of ZVS for open frame PSUs becomes difficult to justify.

The case for WBG gallium nitride (GaN) switches is more nuanced. At lower power the cost vs. efficiency benefit of the GaN device is less apparent as the trade-off between switching and conduction losses for silicon only becomes significant at higher primary current (above perhaps 30 W) where the on-resistance vs. switching loss limitation of silicon becomes pronounced. The performance of GaN switches brings a good efficiency benefit at typical open frame power levels. Integrated GaN devices do not add additional components or complexity to power conversion (not the case when using discrete GaN devices). Noting the anticipated convergence in pricing between GaN and silicon, GaN becomes a good candidate for open frame applications above approximately 50 W and an obvious choice above 150 W.

3. PWM-based Control Using Variable Off-Time (Off-Time Modulation) + Variable Current Limit

To leverage the lower peak current (and corresponding reduced conduction loss) of PWM at high current and the low switching loss of variable frequency operation at light load, a new control approach has been developed. Switching frequency is determined by output load.

Switching requests from the secondary side are transmitted to the primary controller via an optocoupler. The rate at which switching events occur in turn sets the current limit (I_{LIM}) for the primary switch as shown in Figures 2a, 2b, and 2c. Given the fixed ramp-rate of the primary switch current after turn-on (determined by the magnetizing inductance of the power transformer), increasing I_{LIM} effectively increases the conduction angle for each switching cycle. I_{LIM} is further reduced at light loads when switching frequency drops into the audible range – critical to eliminating magneto-inductive audio resonance of the power transformer.

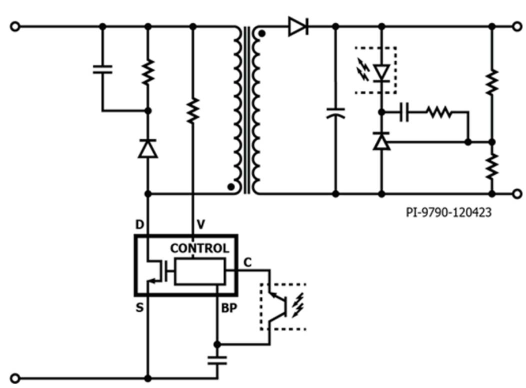

Fig. 2a Simplified Schematic

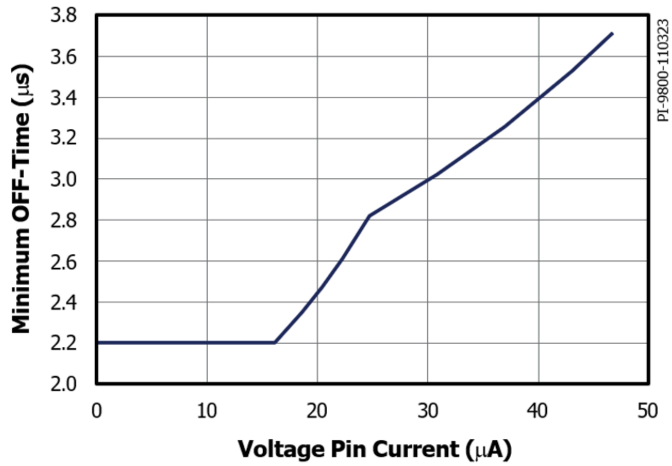

Fig. 2b t_{OFF} C pin current

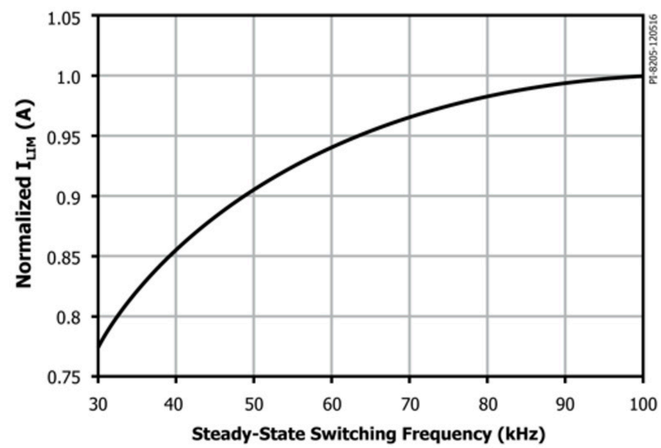

Fig. 2c $f_{SWITHCING}$ to I_{LIM}

Figure 2a, Simplified schematic Showing Feedback Mechanism; Figure 2b, Feedback Off time (and therefore switching frequency) Proportional to Control (C-pin) Currents; Figure 2c, Relationship Between Switching Frequency and the Current Limit (I_{LIM}) for the Primary Switch.

4. High Efficiency Solution for Cost-Optimized Flyback Applications

By harnessing the benefits of a high efficiency GaN switch and coupling it to an improved switching algorithm, high flyback efficiency can be achieved without increasing the cost burden. For lower power applications the same algorithm can be used with a conventional MOSFET switch.

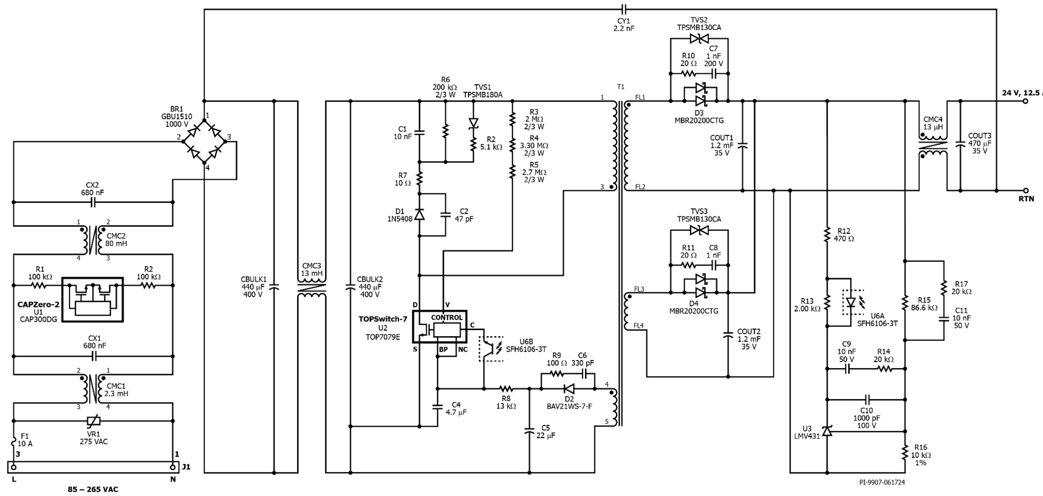

Fig. 3a

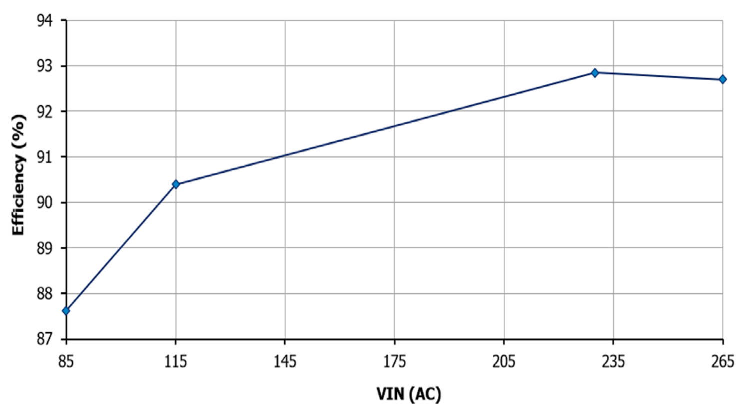

Fig. 3b

Figure 3. 93% Efficiency Achieved Using a Single-ended Flyback Circuit for a Typical 300 W (24 V 2.5 A) Application Using a Combination of 750 V GaN Primary Switch and PWM-Based Variable Off-Time Control.

4.1. Transition Point to LLC

Increasing output power leads to higher primary current, and even though GaN switches with low $R_{DS(ON)}$ help minimize switching losses, there is a practical upper limit to the power that a flyback converter can deliver efficiently. The limited maximum duty-cycle (conduction loss) of a single-ended flyback also constrains transformer utilization (size) and increased conduction loss. As a result, half-bridge converters – offering higher duty cycles and better core utilization – become more suitable above approximately 400 W. A power factor correction (PFC) front end can slightly shift this transition point by increasing the converter's input voltage, but primary switch current remains the dominant limiting factor for single-ended flyback designs.

5. Conclusion

Flyback converters, enhanced with modern WBG switches and improving switching control mechanism, can deliver high efficiency in mid-power open-frame applications while maintaining cost-effectiveness. With proper strategy selection, flyback can displace resonant topologies in the 50–400 W range, offering a simpler alternative with strong performance.

References

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2. Balu Balakrishnan, 2024 APEC Keynote Address: How innovations in efficiency enable us to do good for the environment while doing well as a business, https://ieeetv.ieee.org/live_event/apec-2024-plenary-session

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