Exclusive Technology Feature

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Three-Switch ZVS Fly-Forward Is Quiet, Efficient, And Scalable

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At Preston Consulting, we have, over the years, modified many existing technologies to make them low loss—typically ZVS, but also combinations of ZVS and ZCS, fixed frequency and variable as best suits the topology. Designing the control for the valley switched (quasi resonant) flyback is a good example here. Not only does the power stage have greatly reduced turn-on losses for the MOSFET, the output diode is soft switched too, which is great for EMC and efficiency.

We have often pondered whether the forward converter and the flyback could be properly combined to give a true "fly-forward" that captured the best bits from both converters, while fully utlizing the transformer core—"storage" for the flyback part and simple transformer action for the forward part—thus fully utilizing the transformer core on both half cycles to push energy to the output.

Some years ago while flying back to Christchurch, NZ, the idea for a three-switch flyback, or resonant reset (of the core) with an auxiliary switch took hold. This is not a new topology per se as it uses a concept from the active clamp forward converter. By the end of the flight, the three-switch ZVS fly-forward was born.

The inventive step was to include a winding for the forward part, another for the flyback part, *and then* to realize that with an output choke for each, ripple cancellation would occur and that the currents would be equal in the two parts. This is very handy for minimal output voltage ripple at full power and lower powers. The output diodes are very nearly soft switched and require only slight snubbing. The MOSFETs are fully ZVS allowing the designer a wide choice of operating frequency. The design is tolerant to leakage inductance in the transformer, lending greatly to high isolation between windings.

In this article, I'll describe the operation of the three-switch ZVS fly-forward circuit and show waveforms from an example design. I'll also note some tips for designing this converter, tradeoffs, and operating conditions for which it is best suited.

An Example Circuit

A basic implementation is depicted in Fig. 1.

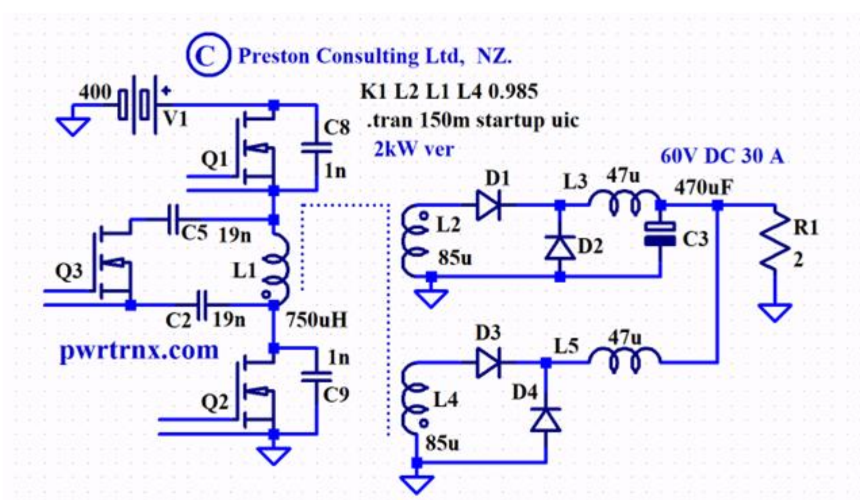

Fig. 1. Basic power schematic for a 2-kW three-switch ZVS fly-forward example. This design has 400-Vdc in and 65-V max out at 30-Adc: Q1 and Q2 are turned on together in a PWM fashion—up to 55% duty cycle typically in an optimized design for full power, Q3 is complimentary, and dead time is typically 100 ns.

For the above implementation, choke currents at full power are shown in Fig. 2.

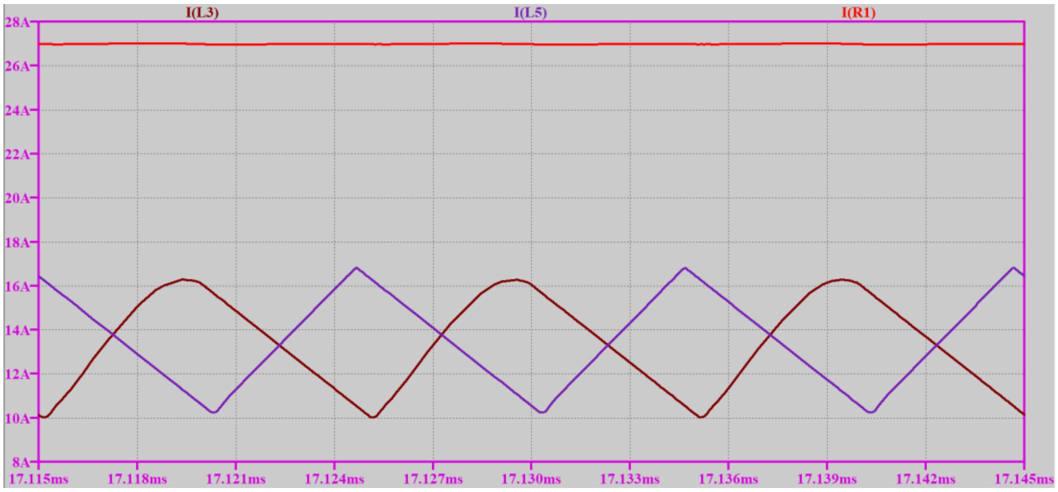

Fig. 2. I(L3) is the flyback current and I(L5) is the forward choke current. Note the average current I(R1) is flat.

One of the key operating principles in this converter is the use of a choke to limit the typically very peaky currents one gets in the output diode of a flyback converter.

For a typical flyback at say 4-A out, operating in DCM at near 50% MOSFET on-time, the peak diode current is 16 A (4 x ave) and the RMS is 6.53 A (63% higher than the ave). Having the choke for the flyback part necessitates a free-wheel diode D2 for the approx 50% of the time the flyback diode is not operating.

The current is spread quite evenly in all four diodes in the output circuit, giving good spreading of heat and therefore more effective heatsinking. Having effectively only a single diode drop in the output circuit benefits efficiency for the converter. Using actual diodes is recommended for the more rugged type PSU, but controlled MOSFETs can be substituted for highest efficiency.

Fig. 3 shows the typical (full power) waveforms for the two main MOSFETs, Q1 and Q2.

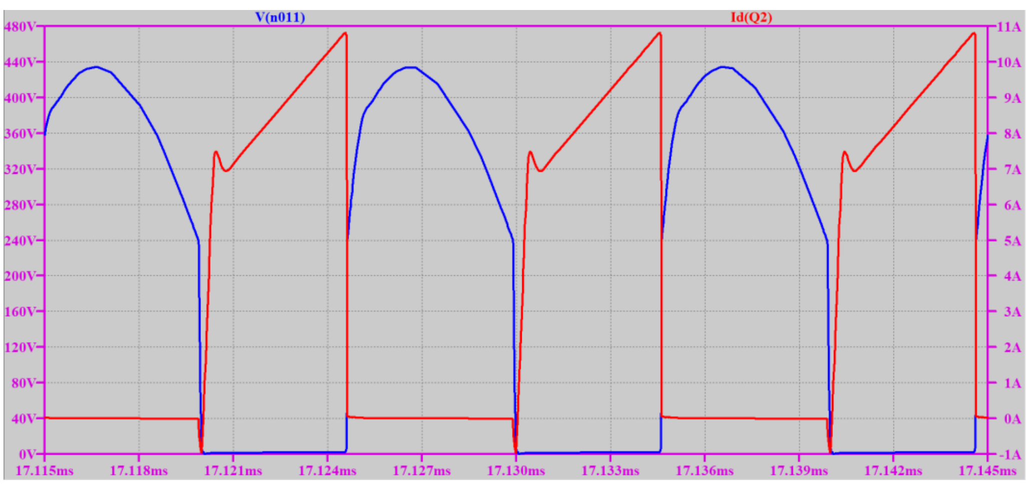

Fig. 3. Q1 and Q2 waveforms at full power.

One can see the pick up of the forward current in a very modest, low RFI way, and then the slope as the transformer core picks up magnetizing current for the flyback section, and more forward converter current.

At turn-off, the resonant clamp MOSFET Q3 picks up the current via the series caps. Fig. 4 shows Vds and Ids for that MOSFET.

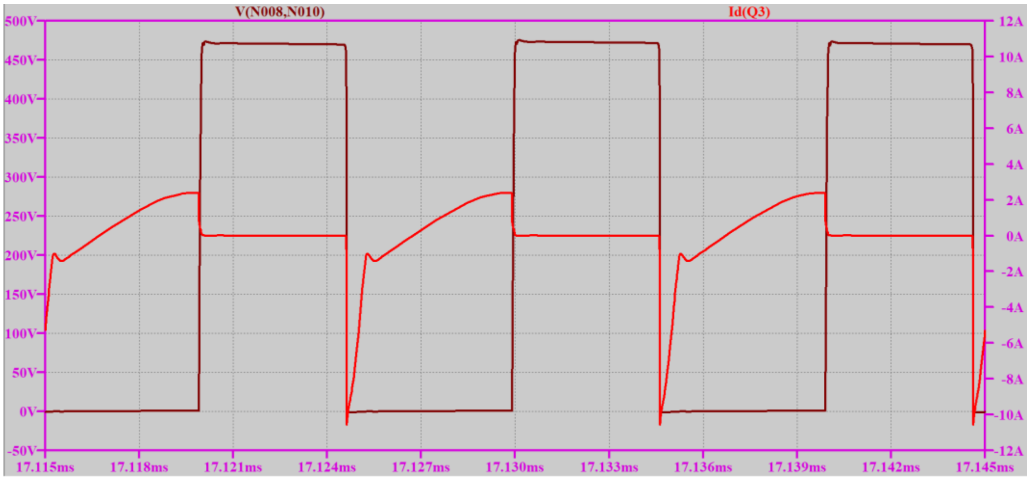

Fig. 4. Q3 voltage and current waveforms.

Notice the peak voltage for all the MOSFETs, 440 to 475 V. This is from a 400-Vdc input. So there is still no such thing as a free lunch in this design. The MOSFETs must be rated higher than Vin.

For the resonant reset MOSFET Q3, the average currents handled are quite low. Here, they are about 2 Arms. So a lower-current MOSFET could be used if this proved to be a cost-effective option.

The transformer voltages and currents appear in Fig. 5.

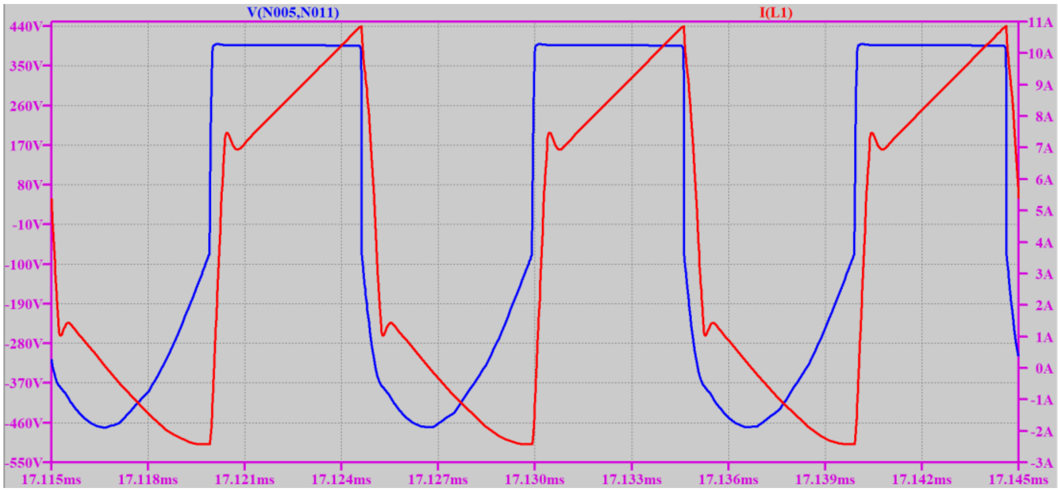

Fig. 5. Transformer voltage and current waveforms.

Here one can see the 400 V applied during forward operation, when Q1 and Q2 are on, and the reset voltage is applied during the flyback part. The same average voltage is seen but with a peak at just over 460 V.

One can see that most of the work is performed in the forward part with 11 A peak in the MOSFETs, and somewhat less through the transformer on the reset stroke, about 2.5 A peak.

The reset caps are split into two (C2 and C5) in series to better center the source pin for ease of (isolated) gate drive and to reduce the voltage stress on these caps. Here, that's 250 V peak each and 2 Arms. The source pin of Q3 jumps from +200 V to -40 V at full power operation with this approach. (Fig. 1 is repeated below for convenience.)

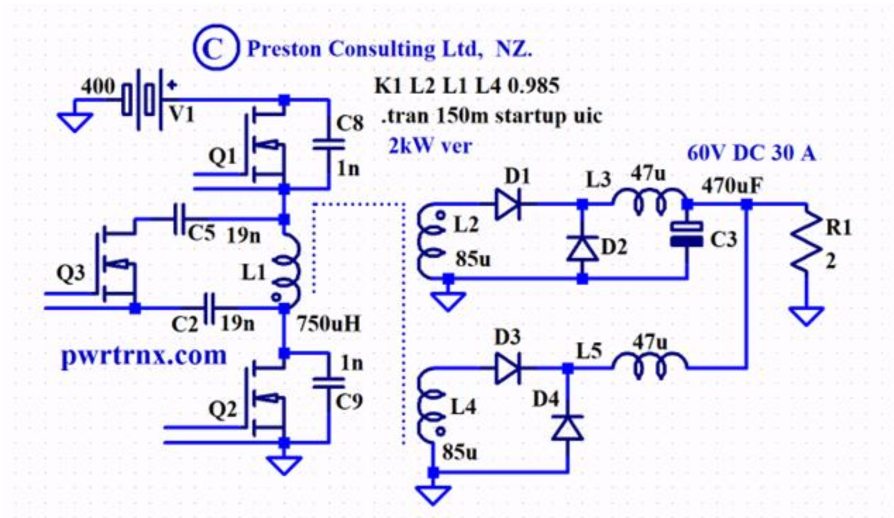

Fig. 1 again. Basic power schematic for a 2-kW three-switch ZVS fly-forward example.

In Fig. 6, I(D1) and V(D1), the flyback diode current (red) and voltage (blue), respectively, are shown.

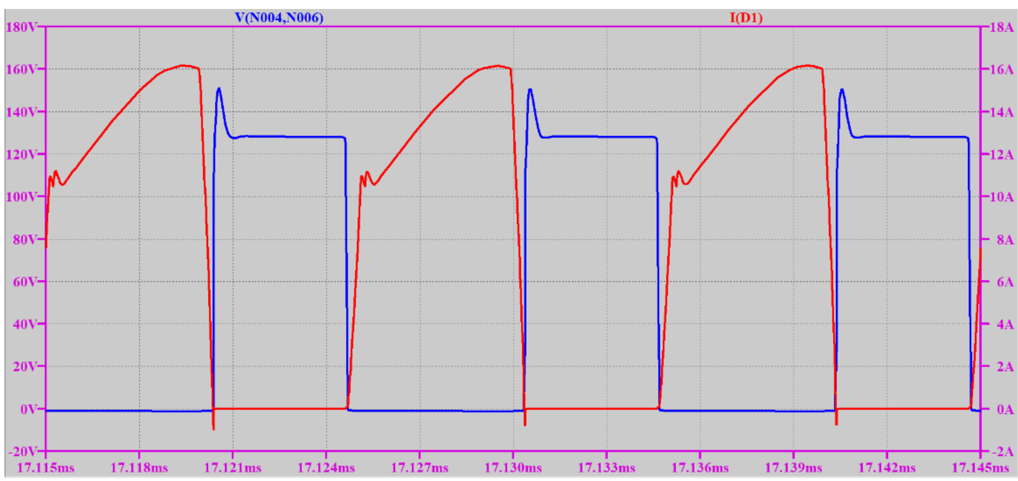

Fig. 6. Flyback diode D1 current and voltage waveforms.

Note the reasonable rate of rise of the current, and the limited overshoot of voltage—here to 150 Vpk. Again, there's no free lunch given all the benefits of low RFI as the diodes must be rated for at least 3 x Vout. In this case, say 65-V out max times 3 = roughly 200 V. That would make the MBR20200CT a very good choice in this application as this diode is notable for it's very fast and soft turn-off and moderately low forward drop.

Now, let us look at the main forward diode D3's waveforms in Fig. 7.

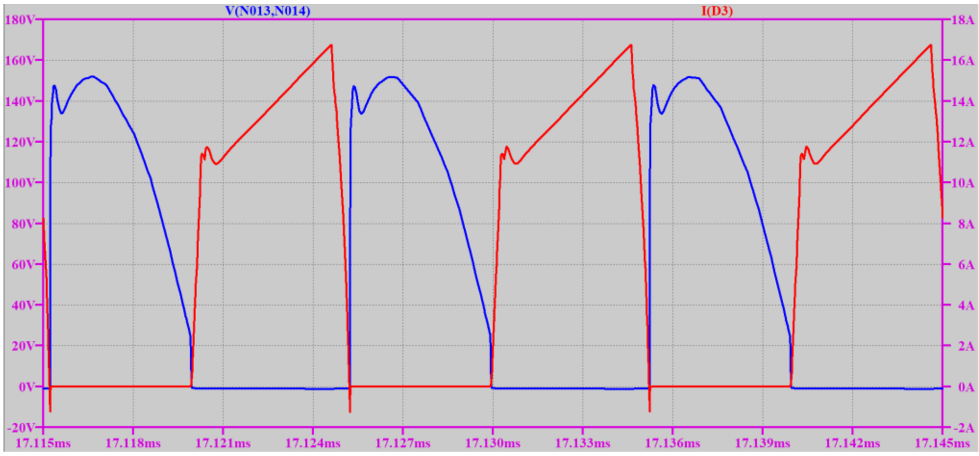

Fig. 7. Forward diode D3 current and voltage waveforms.

Again, the current picks up in a moderate fashion, and turns off moderately too.

Finally, let us see all the diode voltages together in Fig. 8…

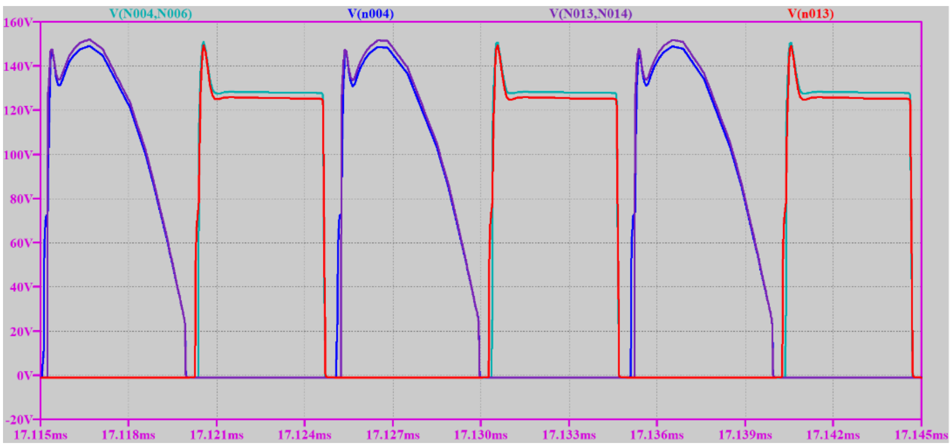

Fig. 8. Diode voltage waveforms.

and all the diode currents (with Iout top) in Fig. 9.

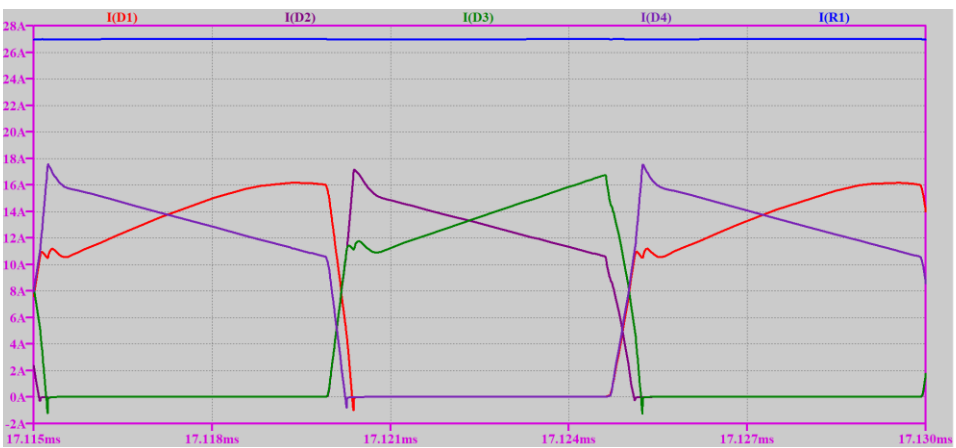

Fig. 9. Diode current waveforms.

Again, note the slopes, where all four diodes are conducting (more easily seen in the Vak diode voltages shot above, Fig. 8), the small reverse-recovery currents, and the generally RF-quiet operation.

Designing the transformer—the exact turns ratio, the gap, the core size and the winding disposition—is an involved topic for another time. One typically strives to reduce the RMS currents in the MOSFETs and the voltage across all devices. This is something of a complex optimization process. Having said that, the schematic above can be scaled for power, Vin and Vout to good effect.

Conclusion

The circuit presented here is a new, low-RFI, versatile, three-switch converter, which is able to run happily in the 100- to 200-kHz sweet spot of modern efficient converters, with simple control and good transient response under peak current mode control. There are extant designs to 4 kW.

About The Author

Colin Tuck, is the founder and CTO of Preston Consulting, which was launched in 1993. Over the course of his career he has worked in various power electronics and consulting companies delivering patentable solutions including control of star-connected switch-modes across a three-phase line, a resonant tap converter topology, and fast 50-kVA modules for harmonic correction on 400-V three-phase line.

Colin has designed high-power, high-frequency resonant solutions for dozens of companies and military customers. He is currently focusing on 1-MW systems for battery-to-battery power flow with 99% efficiency. Colin has degrees in power electronics and engineering management from Auckland University, NZ. Outside of work, he enjoys hiking, traveling, and driving his 928-S4 pretty hard around the track.

For more on designing dc-dc converters, How2Power's Design Guide, locate the "Power Supply Function" category and select "DC-DC Converters". Also see the search links in the "Topology" category.