Deflux Windings Benefit Forward Converters But Not Flybacks

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A circuit technique that increases the efficiency of low- to medium-power (<1 kW) converters with transductors (multiple-winding magnetic components) is to add a winding that conducts current during the on-time to off-time transition, returning the leakage-inductance energy to either the input or output port. This article demonstrates how this technique for *defluxing* the primary winding works in the forward converter and also, why it is not feasible for flyback converters. This discussion thereby demonstrates the more detailed magnetics behavior of deflux circuits.

For those familiar with active-clamp "reset" techniques, the method described here for recovering the transformer's leakage energy is similar in function. Using either this technique or active-clamp reset, the added circuitry defluxes the primary winding when it is shut off. However, the deflux method described here is much simpler and more likely to be applied as it only requires the addition of a small winding and a diode.

Forward Converter With Deflux Winding

The efficiency of forward and boost push-pull converters can be increased by recovering magnetic energy that otherwise would have been dissipated by adding a deflux winding to the transformer. The case of the forward converter is shown in Fig. 1. The primary and deflux windings have n turns relative to the secondary winding turns (normalized to one). During the on-time, $t_{on} = D \cdot T_s$, where D is the duty ratio and T_s is the period of the switching cycle, both primary and secondary windings conduct. The dotted terminals of the windings are positive, and the deflux winding voltage applied to its series diode keeps it off.

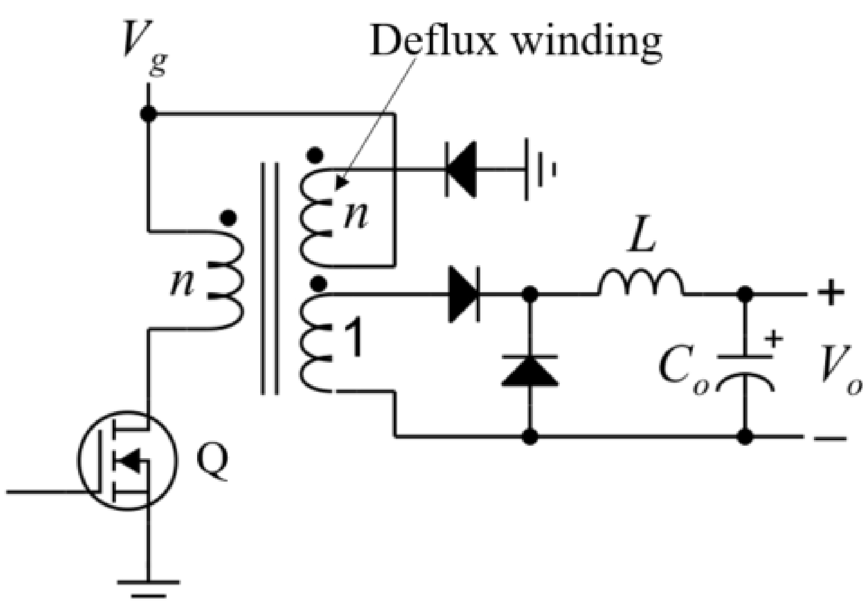

Fig. 1. Basic forward converter with deflux winding, closely coupled to the primary winding (usually bifilar-wound) to return leakage-inductance energy to the input at the commencement of off-time, $t_{off} = D' \cdot T_s$.

When the active switch Q (the MOSFET) in the primary circuit shuts off, there is a short but finite amount of time during which the primary winding current, i_p, decreases quickly and the current in the deflux winding increases quickly, returning current during this short interval to the input supply V_g, thereby increasing converter efficiency.

Fig. 2 shows the equivalent circuit at the beginning of off-time, during transition time, t_d—a time during which complete transfer of the primary current to the deflux winding is delayed by the time it takes to *deflux* (not "discharge"—this is not a capacitor, nor "reset"—this is not a flip-flop) the primary-side leakage inductance, L_{lp}.

Because the coupling, k between primary and deflux windings is not perfect ($k < 1$), a low-power clamp consisting of a series diode and avalanche diode shunt the primary winding to provide a path for i_p while ramping down to zero current. This constant-voltage clamp of V_{CL} dissipates $V_{CL} \cdot i_p(t)$. Meanwhile, the secondary winding quits conducting when the switch shuts off and the polarity across the windings reverses. The secondary winding also has leakage inductance, L_{ls} and will also continue to conduct briefly until L_{ls} is defluxed. Then the series rectifier diode switches off and the circuit shown in Fig. 2 is all that is left for circuit behavior.

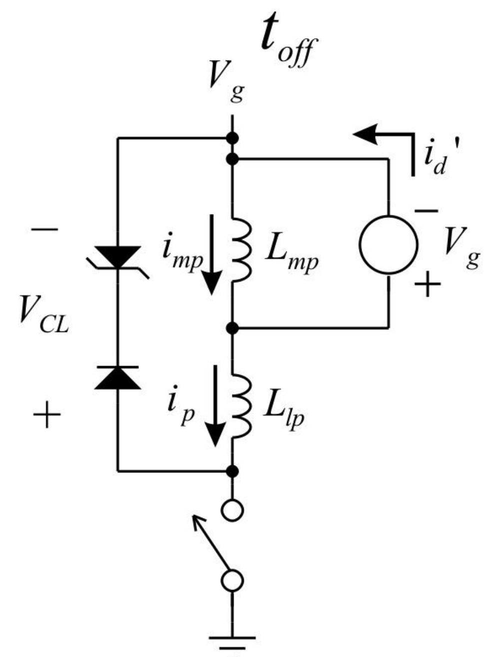

Fig. 2. Equivalent primary-winding circuit of the forward converter during the transition of current between primary and deflux windings. The transition time, t_d, persists until L_{lp} is defluxed and i_p = 0 A. Then all current, i_{mp} of the magnetizing inductance, L_{mp} transfers to the deflux winding, loaded by the primary-referred deflux-winding voltage, $V_s' = n \cdot V_s = n \cdot (V_o + V_D) = V_g$.

Fig. 3 shows the waveforms of the circuit at the beginning of off-time. While i_p is transferring to the deflux winding as $i_d' = i_d$ (primary-to-deflux winding turns ratio = 1) where i_d is the deflux winding current and i_d' is the primary-referred deflux winding current, the magnetizing current i_m is also decreasing slowly, at the rate of

$$\frac{di_{mp}}{dt} = -\frac{V_g}{L_{mp}}$$

At the end of the transfer at t_d, the magnetizing current will no longer be the peak primary current, $\hat{i}_p$ at switch-off but will have ramped down to what in Fig. 3 is I_{CL}, the magnetizing current value at t_d. This is the peak deflux current. The difference in current, $\hat{i}_p - I_{CL}$ corresponds to a loss of some magnetizing energy, and this loss is in the constant-voltage clamp.

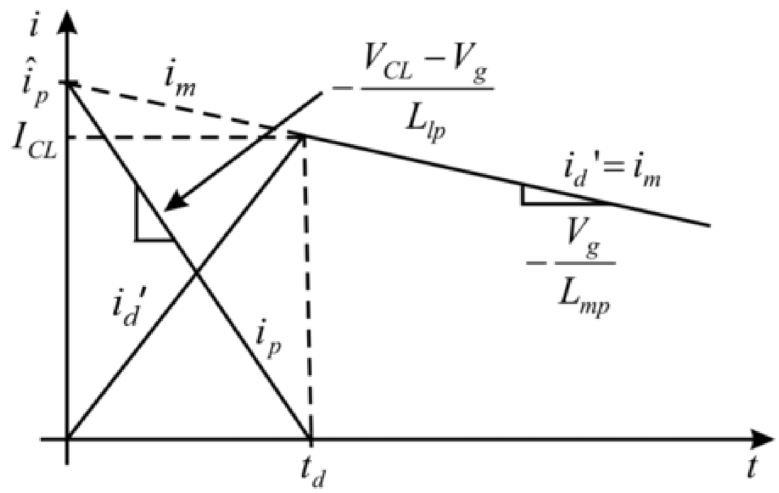

Fig. 3. Primary (i_p) and deflux winding (i_d') currents at the beginning of off-time, when primary current is transitioning to the deflux winding.

Two different losses occur in the clamp, the leakage-inductance energy, W_l of L_{lp} and some of the magnetizing-inductance energy, W_{CLm}. Total clamp energy loss is

$$W_{CL} = W_{CLm} + W_l = \tfrac{1}{2} \cdot k \cdot L_p \cdot \alpha^2 \cdot \hat{i}_p^2 + \tfrac{1}{2} \cdot (1-k) \cdot L_p \cdot \hat{i}_p^2$$

where α is a loss factor,

$$\alpha = \left(\frac{1-k^2}{k} \right) \cdot \left(\frac{k \cdot V_g}{V_{CL} - k \cdot V_g} \right)$$

The α term is derived from circuit analysis of the flyback converter and applies here because the winding polarities of the forward primary and deflux (not secondary) winding are that of a flyback converter. (This derivation is found in a previous related article (see the reference).

To determine the required power rating of the clamp components, the average power loss is simply the energy rate, $\overline{P}_{CL} = W_{CL} / T_s$. In switching converters with switching frequency, $f_s = 1/T_s$, power is per-cycle energy and it is sometimes more insightful to express circuit behavior in power flow or per-cycle power than energy.

Flyback Converters With Deflux Windings?

The same basic deflux-winding scheme can be attempted in the flyback converter by adding an additional, tightly-coupled winding to the primary, as shown in Fig. 4, as a bifilar winding for which $k > 0.995$, and can be higher for lower-power transductors. The coupling, however, is never perfect and might require a low-power voltage clamp, V_{CL}, as it also might in the forward converter.

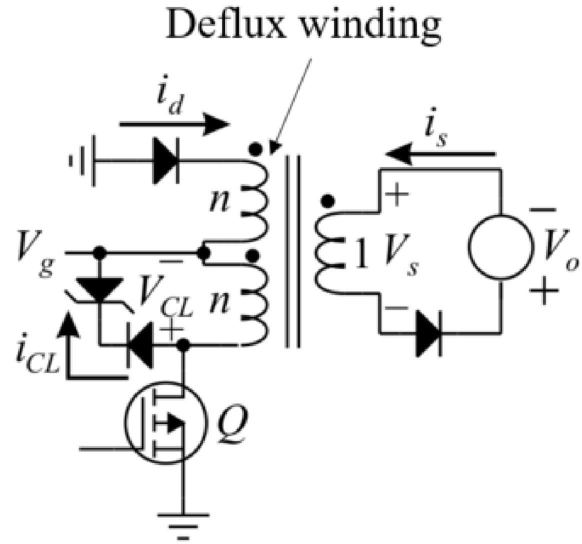

Fig. 4. A proposed deflux-winding scheme for the flyback converter. Is it feasible?

When *Q* switches off, off-time begins, and $i_p = \hat{i}_p$. At this time, i_p diverts to the voltage clamp where it is opposed by the voltage, $V_{CL} - V_s'$ across L_l, with polarity shown on the above circuit diagram. As i_{CL} ramps down, i_{mp} transfers to the other windings, ramping up as i_d the deflux current and i_s the secondary current. This is the same thus far as the forward converter except that now, two off-time windings are conducting, and i_d reaches a maximum of $\hat{i}_d < \hat{i}_p$ because i_s' and i_{CL} are being diverted from it. i_p ramps down at the rate of

$$-\frac{di_p}{dt} = \frac{di_d}{dt} + \frac{di_s'}{dt} \approx \frac{V_{CL} - k \cdot n \cdot V_s}{(1-k^2) \cdot L_p}$$

where *k* is the primary coupling to both deflux and secondary windings. The deflux winding voltage is the same as that of the primary-referred secondary winding: $V_s' = V_d' = V_g - V_D$, where V_D is the series diode voltage. If coupling were ideal ($k = 1$), i_p would instantly be zero, the i_{CL} down-ramp on the graph would be vertical, and t_d would be 0 s. Instead, i_d of the deflux winding, with its closely-coupled, 1/1 turns ratio with the primary, ramps up more quickly than i_s' as i_{CL} decreases.

The equivalent circuit during t_d is shown in Fig. 5. i_{mp} is divided between deflux and secondary windings and is opposed by the same voltage, $V_s' = V_g - V_D$. Thus, the voltage across both leakage inductances is the same. If the i_d rate of rise is $di_d/dt > di_s/dt$, and most of i_p is diverted to i_d, then it must be that $L_{ld}' = L_{ld} << L_{ls}'$. This is achieved by tighter coupling so that $k_d > k_s$.

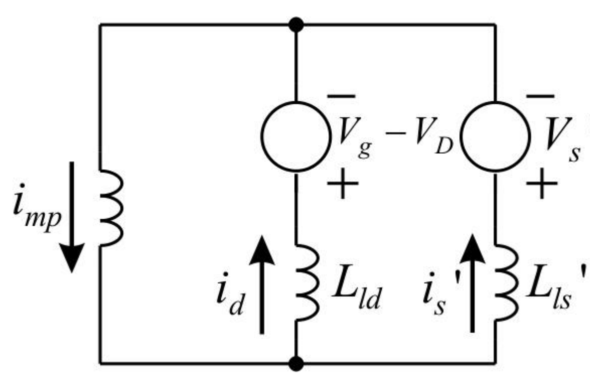

Fig. 5. Equivalent circuit for the transductor during flyback converter current transition.

When the clamp shuts off, *at* t_d, all primary current is transferred to deflux and secondary windings. $i_d' = i_d$ and i_s' are both opposed by the same voltage, $V_s' = V_g - V_D$. Decreasing i_d and i_s' split the decreasing i_{mp} by an inductive current-divider fraction. With L_{ld} much smaller than L_{ls}', the rate of decrease of i_d in L_{ld} is much faster than of i_s', as shown in the Fig. 6 waveforms graph.

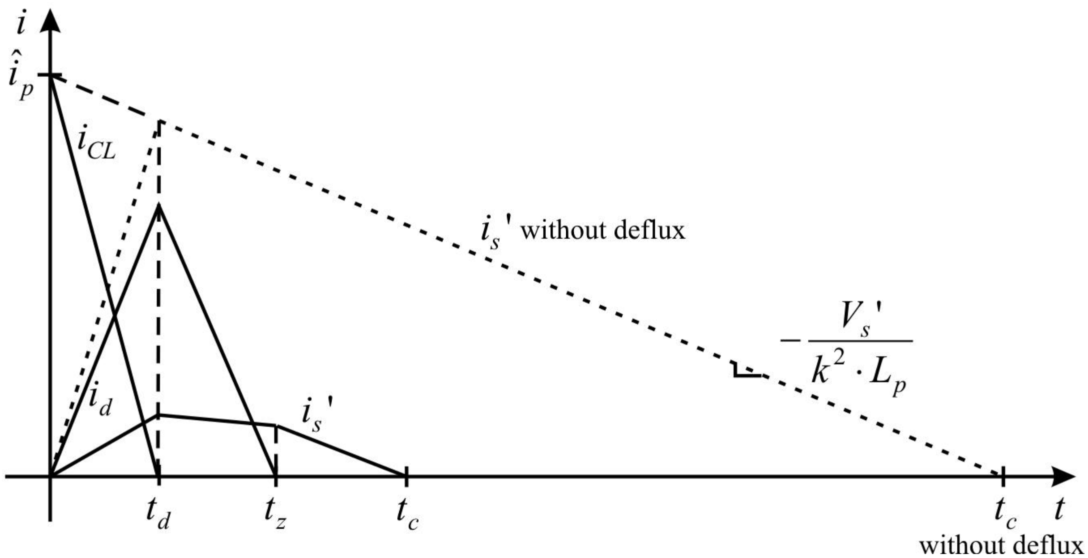

Fig. 6. Current waveforms for the flyback converter with deflux winding. The secondary current is deprived of most of the transfer current from the primary by the deflux winding, which recirculates it to the input. The result is far less output current and much lower converter transfer efficiency.

Between t_d and t_z, i_d ramps down at a faster rate than i_s' until i_d = 0 A at t_z. At t_d , the clamp quits conducting and becomes an open-circuit, leaving the Fig. 5 equivalent circuit. The voltage across L_{mp} has the polarity as shown, and i_{mp} , i_d , and i_s' are opposed by V_s'. These currents continue to flow in the same direction (and the deflux diode remains on) but they now decrease instead of increase.

When the current slopes change polarity, the leakage-inductance voltage polarities also change, but the magnetizing current continues to decrease and its dominating voltage, in series with the leakage-inductance voltages, does not change in polarity, keeping the secondary winding diodes on.

Most of i_{mp} is returned to V_g as i_d so that at t_z , i_s' is much reduced from what it would have been without the shunting effect of the deflux winding. After t_z, all current is in the secondary winding and peak i_s occurs at t_d. Referred to either primary or deflux winding, i_s' then continues to ramp down at the rate of $- V_s'/k^2 \cdot L_p$.

Conclusion

The flyback deflux-winding scheme is not feasible because it returns most of the inductor energy to the input instead of transferring it to the output, leaving little for the output and defeating converter function through low transfer efficiency. The overall converter efficiency seems higher than without it because less energy is lost in the clamp, but it is also superfluous because the secondary winding can perform the same function if it is more tightly coupled to the primary winding.

On the other hand, forward converters operate typically at higher power and the clamp loss is more significant, often meriting the addition of the deflux scheme. It functions advantageously for the forward converter because the secondary winding is not competing with the deflux winding for transfer current.

Consequently, it is only in those design plans where the secondary is constrained to a much looser coupling that the addition of a bifilar deflux winding to the primary can reduce clamp power loss. And this is uncommon because flyback converters are optimal (especially if operated in DCM) only at low power (<100 W). Thus, the clamp power loss is that much lower and not worth the addition of an extra winding and diode.

Overall, the conclusion is that flyback deflux winding recovery of power is not feasible. On the other hand, forward converters operate typically at higher power and the clamp loss is more significant, often meriting the addition of the deflux winding.

Reference

"Flyback Magnetics: Winding-Current Transition Is Key To Efficiency" by Dennis Feucht, How2Power Today, November 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.

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