Overcoming the Duty Cycle Limits of the Two-Switch Forward

By John Bottrill, Texas Instruments 03.14.2005 0

The two-switch forward has some obvious advantages. These include the transformer magnetization energy being recovered while the EMI is reduced. This improves the efficiency and reduces the filtering requirements caused by high voltage spikes when the magnetizing energy is not recovered. In addition, the MOSFET switches only need to be able to withstand the maximum line voltage when the magnetizing energy is being recovered. This usually results in lower voltage MOSFET switches that have considerably lower Rdson and lower drive requirements.

The power converter has one obvious disadvantage, however. The maximum duty cycle that this topology can support is 50 percent. Beyond this limitation, the transformer will saturate and either the unit will shut-down or the transformer's current will increase to the point that the switches are destroyed. This limitation forces the use of a larger capacitor to hold-up the voltage to overcome short duration outages.

If the duty cycle needs to be extended beyond the 50 percent limit, a normal single switch forward can be used. But, that requires that you increase the switch's voltage rating to significantly more than twice the input voltage to cover the transformer's reverse-recovery voltage and the leakage inductance. In addition, additional circuitry is required to handle the leakage energy and the high frequency spikes during the switching transients. This is particularly true when the forward converter follows a Power Factor Correction (PFC) circuit. As a result, the FET conduction losses will go up and the magnetizing energy will no longer be recovered. Because the magnetizing energy is now being lost, additional circuitry is required to absorb this energy. Furthermore because the energy is no longer being recovered in a lossless manner, the converter's EMI levels will increase substantially and additional filtering will be needed to meet the requirements. All of these differences result in additional cost and lower efficiency.

There is a circuit that allows the duty cycle to be extended and the converter to be made from the lower voltage components with very little in the way of modifications.

First consider the transformer in a standard two-switch forward topology. The secondary windings are usually interleaved between two halves of the primary. The standard two-switch forward converter can be modified to a three-switch forward by splitting the primary winding in half and add a third switch at the junction of the primary's two halves. Two additional diodes will be needed from this new switch to-and-from Vcc and ground (See Figure 1). The necessary drive circuitry for the third switch requires an additional winding off the transformer that is already being used for the high-side switch of the two-switch forward and similar circuitry around this switch and transformer output.

In the case of the two-switch forward, the minimum input voltage has to be high enough so that the voltage appearing at the input to the inductor is twice the output voltage because of the 50 percent duty ratio limit. With the three-switch forward that duty ratio is now 67 percent and the input voltage can be reduced to the point where the voltage presented to the inductor is now 1.5 times the output voltage. This allows the input voltage range lower limit to be 75 percent of what the allowable minimum input voltage was for the two-switch forward. This in turn allows for a reduction in the input capacitor's size to achieve the same hold-up time. This one modification alone results in significant savings in both board real estate and in component cost particularly in the case of a PFC.

Figure 1 shows a schematic of the basic three-switch forward. The switches Q1 and Q2 along with diodes D1 and D2 are the same as the standard two-switch forward. Q3, D3 and D4 are the added components for the three-switch forward. Transformer windings 1-2 and 3-4 are the windings that interleave the secondary. They are the same as on the two-switch forward and would be shorted together in the two-switch forward topology. Since the windings are interleaved, the only cost in making this change is having the ends brought out to separate pins on the transformer.

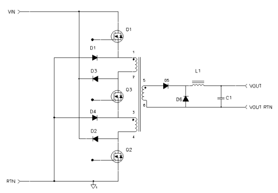

Figure 1 – The Three-Switch Forward Topology

Figure 2 show the voltages and currents paths associated with the switching cycle's power portion for this circuit. When the switches are "ON" the input voltage is applied across the primary from transformer pin 1 to pin 4 and the transformer output voltage at pins 5 and 6 is a reflection of the input voltage times the turns ratio. The current's flow (darkened lines) is from VIN, through Q1, through winding 1-2, through Q3, through winding 3-4, and finally through Q2 to the return/ground. This current is made of two components the magnetizing current and the reflected secondary current. The input voltage is split evenly across winding 1-2 and winding 3-4. This would be identical to a two-switch forward if Q3 were replaced by a short.

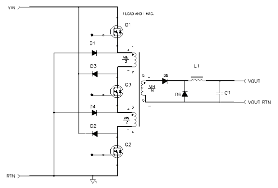

Figure 2 – Voltages and Currents During the Power Portion of a Three-Switch Forward Converter

The difference in the three-switch forward occurs when the switches are turned "OFF.". This is shown in Figure 3. The primary magnetizing current that was stored during the "ON" time in the windings 1-2 and 3-4 now has to be recovered. When the switches "open", the magnetizing current continues to flow and causes the voltage across the winding to switch polarity resulting in the voltage on transformer pins 1 and 3 to drop and the voltage on pins 2 and 4 to rise until the magnetizing currents can flow from ground to VIN through the diodes. The magnetizing current in winding 1-2 flows from ground through diode D1 into winding 1-2 at terminal 1 and out at terminal 2 then through diode D3 into VIN. The same thing occurs for winding 3-4 with the current flowing from ground through D4, winding 3-4, and diode D2. The result is that the voltage across each winding is equal to the input voltage but in the opposite polarity to what it was during the "ON" time and each winding has an initial current equal to the magnetizing current portion of the "ON" current that was in that winding when the switches were turned "OFF".

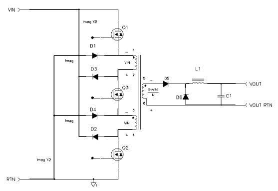

Figure 3 – Magnetic Flux Re-set Portion of the Switching Cycle for a Three-Switch Forward Converter

With this configuration instead of having the input voltage across the total primary as in a two- switch forward, the input voltage is across each half of the primary. This results in twice the volts per turn that would be present in the two-switch forward. Because magnetizing energy is a product of voltage and time, this higher "volts-per-turn" allows the magnetizing energy to be recovered in half the time. Because the transformer can be re-set in half the time, the duty cycle increases to 2/3 of the total time, leaving 1/3 of the time for re-setting the transformer as shown in the equation below.

$$\frac{VIN}{N} \cdot \frac{2}{3} T := \frac{VIN}{\frac{N}{2}} \cdot \frac{1}{3} \cdot T$$

Figure 4 shows the waveforms developed during maximum duty cycle and a 1:1primary-to- secondary turns ratio. The figure shows the waveforms for a two-switch forward on the left and the three- switch forward on the right. These waveforms show that the voltage stress on the FETs are the same, however it also shows that the reverse voltage stress on the diodes will be twice as high for the three- switch forward. It also shows that the response to a load transient for a sudden increase in load current will be higher for the three-switch forward because the circuit can, on each cycle, apply the voltage to the input of the inductor for 2/3 of a cycle instead of 1/2 of a cycle.

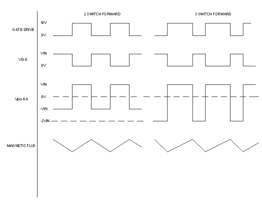

Figure 4 – Typical Waveforms Showing the Difference between a Two-Switch Forward and a Three- Switch Forward

Looking at the secondary output voltage waveform, the voltage developed on the output is equal to the total primary voltage because the turns ratio of the total primary winding to secondary winding turns ratio is 1 when the switches are "ON.". This is true for both the two-switch forward and for the three-switch forward.

For the two-switch forward the primary-to-secondary turns ratio remains the same and the reverse recovery voltage remains the same.

However, in the case of the three-switch forward at maximum duty cycle, because each half of the primary is connected across the input voltage during the time the FETs are "OFF", the turns ratio has changed and the primary winding appears as though the two halves are in parallel and the turns ratio primary to secondary is now 1:2. This causes the voltage on the secondary during this portion of the cycle to be twice the input voltage.

Because the duty cycle for the steady state case is inversely proportional to the input voltage the magnetic flux which is a product of the "ON" time and the input voltage will be the same for a two-switch forward as a three-switch forward. The duty cycle increases linearly as the input voltage decreases resulting in a constant volt seconds across the primary each cycle.

Figure 5 shows a typical drive configuration for the drive circuit. Note the device chosen as a PWM controller has a maximum duty cycle clamp that can be set to just under 67 percent. The transformer that is used to drive the Q1 and is needed for the two-switch forward has an additional winding added to it to drive Q3.

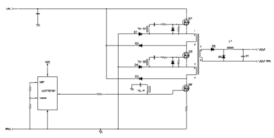

Fig 5 Typical drive configuration for drive circuit

The topology for the three-switch forward is covered by US patent #6,707,690 which is assigned to Texas Instruments. However, if the controller used for the control of a converter with this topology is a Texas Instruments product a license is granted to the user for that unit.

About the author

John Bottrill is a Senior Applications Engineer for Texas Instruments in the Power Converter Products group. He earned his BSEE at Queen's University, Kingston, in Ontario, Canada.

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