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Beware Of Zero-Voltage Switching

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"High frequency? No problem! We do resonant switching" is an often heard mantra in the design of power converters today. Zero-voltage switching (ZVS) is considered the panacea for all the challenges posed by high frequency and higher efficiency requirements. While ZVS is indeed a blessing, designers need to be aware of its limitations and also watch out for a whole range of traps in the implementation.

The basic idea of zero-voltage switching is simple. Prior to turn-on, the MOSFET V_{DS} is at a high voltage, which is also the voltage to which C_{OSS} is charged. To achieve ZVS, the C_{OSS} is tricked into discharging its energy before the gate signal is applied. Even a partial discharge is beneficial though ideally, all of the energy stored in C_{OSS} must be discharged into the load, bringing V_{DS} to zero.

Fig. 1a shows inductive current and voltage crossover losses at turn-on under hard-switched conditions. Fig. 1b shows the same waveforms with ZVS. Switching losses are eliminated as there is no crossover between V_{DS} and I_{DS}. In addition to switching loss, ZVS also minimizes the switching noise during turn-on and associated EMI.

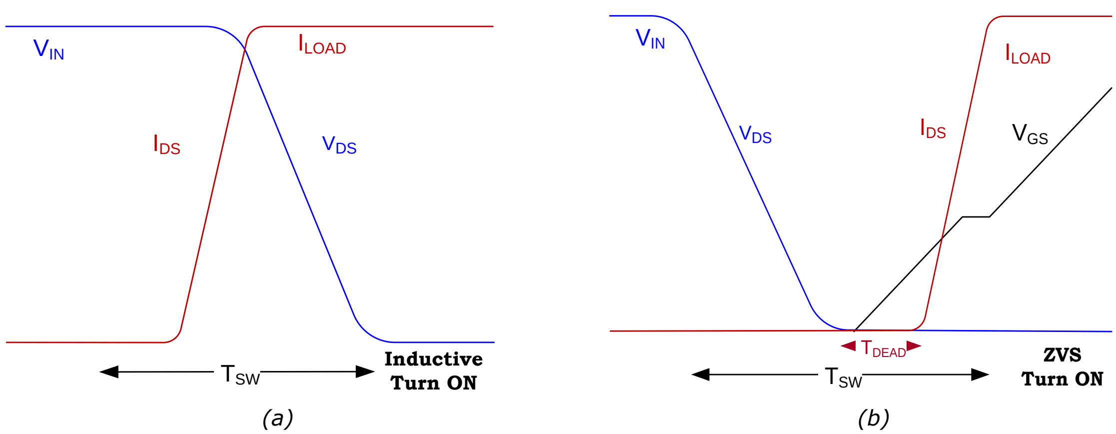

Fig. 1. Comparing inductive, hard-switched turn-on of a power MOSFET (a) with inductive, ZVS turn-on (b).

While there is an enormous amount of literature on how to implement ZVS, very little has been written from the perspective of the device that is actually doing the switching. In this article we will look at zero voltage switching from the MOSFET's point of view. But before we can delve into the subject, we'll need to discuss a bit of semantics. Though the terms ZVS, resonant, and soft switching are used interchangeably, there are certain differences among them.

Understanding The Terminology

Soft Switching

This is the most general term and includes both zero-voltage and zero-current switching, the latter done typically at turn-off. Soft switching can also indicate switching the MOSFET on with low voltage across drain and source, not necessarily zero. This is sometimes referred to as quasi-resonant switching. Two examples are quasi-resonant flyback and PFC, where the MOSFET is turned on during the parasitic resonance that follows the inductor current hitting zero. Quasi resonance typically involves critical-conduction-mode and variable-frequency operation.

Resonant Switching

Resonance can happen between the parasitic elements in the circuit, such as leakage inductances and C_{OSS} of the MOSFET being turned on, or among the main components of the power train itself, as in LLC converters. In the former case, the operating frequency is constant. The power train may be the same as in a hard-switched operation or have additional low-power elements to facilitate ZVS. The switching sequence is manipulated by the control circuit to achieve zero-voltage turn-on.

The latter case, where resonance is achieved among the non-parasitic elements of the circuit, requires variable-frequency operation. The switching frequency must be set above the natural resonance of the circuit to present an inductive load. This ensures that the current is negative at the zero crossover of the fundamental component of the applied voltage. Resonance is a common technique for achieving ZVS, but not the only one.

Synchronous Switching

The term "synchronous" refers to a class of converters where a MOSFET replaces a rectifier. The circuits were originally conceived and work normally with rectifiers, which have been replaced by MOSFETs to reduce the forward drop. Examples are synchronous buck, synchronous boost, and secondary synchronous rectifiers. Though not usually perceived as examples of zero-voltage switching, ZVS of the synchronous switch is an inherent feature of these topologies. They operate at fixed frequency, do not need any resonance, and the MOSFETs conduct entirely in the third quadrant.

ZVS Doesn't Eliminate All Switching Losses

There are different ways of achieving the ZVS goal, each with its own features. No matter which approach is used, designers need to remember a fundamental limitation of zero-voltage switching—it reduces switching losses only at turn-on. The crossover losses at turn-off continue to be incurred. It may sound obvious when stated plainly, but there is no such thing as a zero-voltage turn-off. Ideally, turn-on should be at zero voltage and turn-off at zero current to eliminate all switching losses. But achieving zero current in the circuit at turn-off requires a level of complexity that generally outweighs its benefits.

Another switching loss at turn-on comes from the energy stored in C_{OSS}. Modern MOSFET structures have become rather complex, leading to extremely non-linear capacitance curves. It no longer makes sense to refer to C_{RSS} or C_{OSS} as individual capacitance values. What is relevant are their effective charges and stored energies, represented as Q_{GD}, Q_{OSS}, and E_{OSS}.

If a MOSFET is hard switched at a frequency F_{SW}, the stored energy E_{OSS} in the output capacitor is discharged into the channel, causing a power loss of E_{OSS} x F_{SW}. With zero-voltage switching, this energy is delivered either to the load or the input and not lost. However, ZVS does not eliminate all the losses associated with E_{OSS}. What is not often realized is that there is a loss in the circuit associated with charging of the C_{OSS} capacitor as well.

By simple circuit theory, if a constant capacitor is charged and discharged to a certain voltage V, the total energy loss is ½CV^2 (during charging) + ½CV^2 (during discharging). This loss is entirely a function of the stored energy and independent of the method used for charging or discharging the capacitor. The charging loss is commonly overlooked since it is incurred by the system as a whole, not the parent MOSFET. With ZVS, only the discharging half of the energy is delivered to the load and reclaimed. But the charging half of the loss, when the MOSFET is turned off, is still incurred by the circuit.

Fig. 2 illustrates voltage waveforms for a quasi-resonant flyback. C_{OSS} losses are reduced at turn-on but a much larger E_{OSS} loss in the circuit is inevitable at turn-off when the C_{OSS} charges up to V_{DSOFF}. Obviously the loss component is much more significant at higher voltages due to the V^2 term. A constant capacitor has 2000 times more E_{OSS} at the 540-V peak of a flyback circuit compared to the 12 V of a synchronous buck. This is one of the reasons why it gets progressively more difficult to operate ac-dc converters at higher frequencies, even with zero-voltage turn-on.

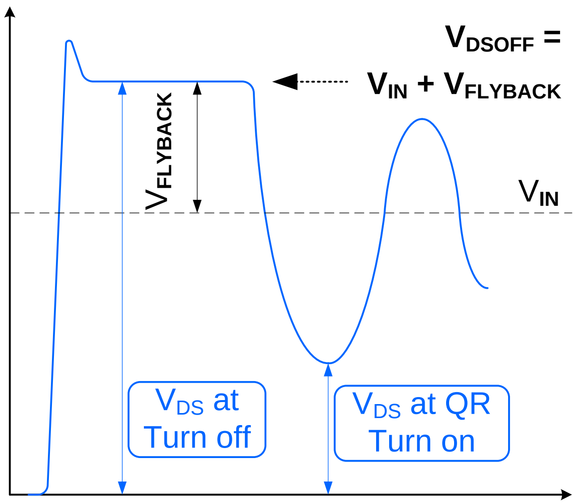

Fig. 2. Turn-off voltage in a quasi-resonant flyback converter.

Fig. 3a shows the MOSFET equivalent circuit comprised of all the capacitors and the body diode. The output capacitance C_{OSS}, by definition, is the sum of C_{DG} and C_{DS}. The output capacitance and its charge Q_{OSS} are inseparable from the body diode and its Q_{RR}. Any circuit set up to measure reverse recovery will actually measure the combined charges of Q_{RR} + Q_{OSS} as shown in Fig. 3b. When analyzing the behavior of MOSFET body diode, it is important to take into account not only its own Q_{RR}, but also the inseparable Q_{OSS}.

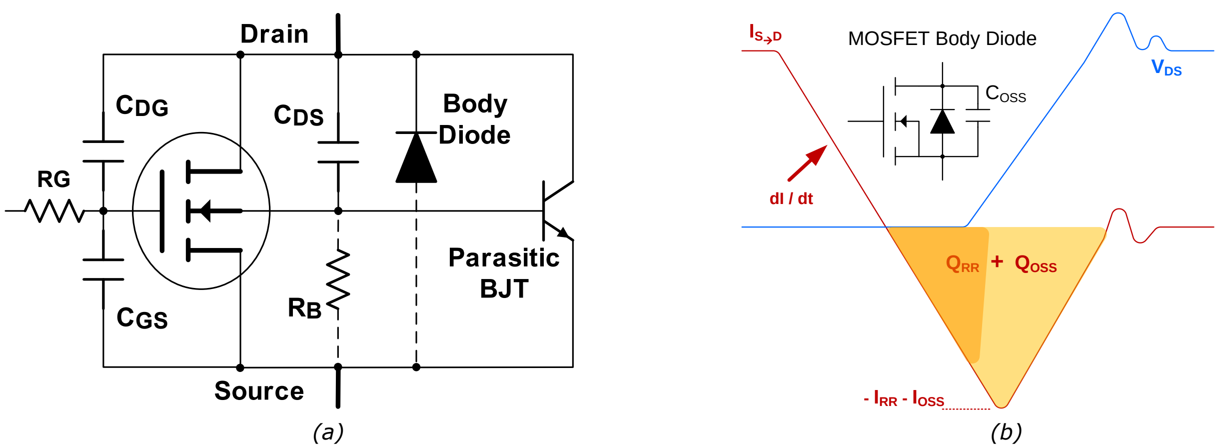

Fig. 3. Because the MOSFET output capacitance and body diode (a) are inseparable, any measurement of the body diode's Q_{RR} must measure the combined reverse charge Q_{RR} + Q_{OSS} (b).

The table below lists the characteristics for different types of MOSFETs and discrete diodes of comparable ratings. Generally, compared to discrete diodes, the MOSFET body diodes have much higher Q_{RR} and larger capacitances in parallel. The presence of a large Q_{OSS} in parallel makes the body diode look like a "soft recovery" rectifier, especially for low-voltage MOSFETs.

Note that with different voltage ratings, the underlying semiconductor structure also changes dramatically.[1] As a result, the relative magnitudes of the two charges vary widely with the voltage ratings of the device. The properties of a 600-V MOSFET cannot just be extrapolated from those of a 30-V device.

Table. Switching characteristics of MOSFETs (shown in red) and diodes (shown in blue).

Voltage rating	Device	Technology	V_{FWD} (diode) or R_{DS} (typ.) (MOSFET)	$Q_{JUNCTION}$ (diode) or Q_{OSS} (MOSFET)	Q_{RR} (diode or MOSFET)
30 V	SS15P3S	Schottky	0.42 V at 15 A	15 nC	—
	SiRA04DP	trench	2.5 mΩ at 4.5 V	33 nC	24 nC
100 V	UB8xT	ultrafast	1 V at 10 A	2.5 nC	7 nC
	SiR882ADP	trench	7.2 mΩ at 10 V	95 nC	54 nC
600 V	VS-15EWH06FN-M3	ultrafast	1.2 V at 15 A	7.5 nC	90 nC
	SiHP33N60E	superjunction	83 mΩ at 10 V	220 nC	8500 nC
	SiHP33N60EF	superjunction with fast recovery diode	85 mΩ at 10 V	210 nC	1000 nC

MOSFET Body Diode And Its Impact On ZVS Reliability

There are more serious considerations for MOSFETs operating in ZVS circuits, arising from their body diode recovery. It is a given that in any circuit that achieves full ZVS, the body diode must necessarily get into conduction. Any current that discharges the output capacitor will invariably forward bias the body diode and continue to flow through it. There is an efficiency penalty due to increased forward drop, but it can be minimized by optimizing the system dead time. The real issue is that the body diode also needs to recover when the MOSFET turns off.

Depending on the "flavor" of ZVS implemented, body diodes can commutate differently. In synchronous circuits the MOSFET current is always in the third quadrant, from source to drain. Any current from drain to source either discharges the output, or is a sign of shoot through. The sequence of current transfer is:

1. Output capacitor is discharged.
2. Body diode turns on.
3. Dead time.
4. MOSFET is turned on and carries current.
5. MOSFET is turned off.
6. Body diode takes over the current.
7. Dead time.
8. Complementary MOSFET is turned on.
9. Body diode undergoes hard commutation.

The resulting currents are illustrated in Fig. 4 for the classical synchronous buck. The incoming high-side device switches on with three currents, one each for the load, Q_{OSS}, and Q_{RR}. The charging and recovery currents must eventually die down, but can cause severe ringing and voltage spikes in the process. The ringing can be traded for switching speed by slowing down the incoming MOSFET.

While this is manageable for 30-V MOSFETs where the Q_{RR} is a few tens of nanocoulombs, things can get very difficult with 600-V rated devices where the Q_{RR} is measured in microcoulombs. The reverse-recovery current component I_{RR} is quite large, and in some cases can trigger bipolar latch-up leading to the destruction of the MOSFET. This is why there are not many high-voltage “synchronous” circuits.

The classic boost converter for PFC works in the asynchronous mode with a SiC boost diode because a high-voltage silicon MOSFET is unthinkable in that function. The totem-pole PFC is an attractive rectifierless topology. But it is basically a double-ended synchronous boost structure and cannot be implemented without switching devices having extremely low Q_{RR} and Q_{OSS}.

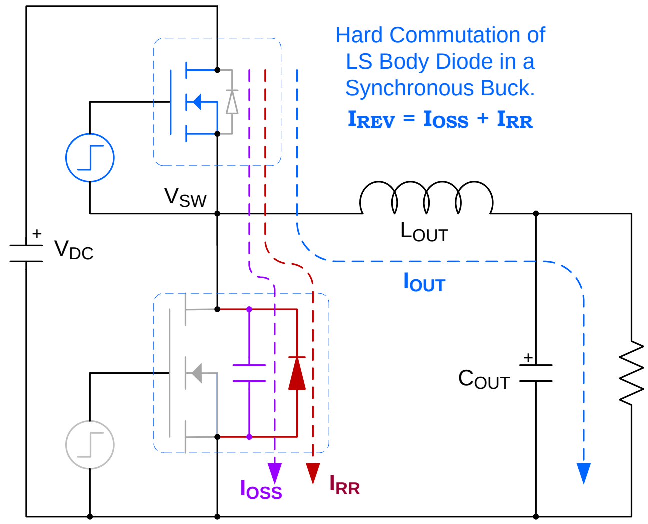

Fig. 4. Body diode hard commutation in a synchronous buck.

It is possible for the body diode to be soft commutated. Typically this happens in resonant converters where the MOSFET current starts in the third quadrant, from source to drain, but reverses direction and goes into the first quadrant by the end of the cycle. The phase-modulated ZVS bridge is a good example. The sequence of current transfer now is:

1. Output capacitor is discharged.
2. Body diode turns on.
3. Dead time.
4. MOSFET is turned on and carries current from source to drain.
5. Body diode commutates under zero current and voltage.
6. MOSFET current reverses and moves into first quadrant.
7. MOSFET is turned off.
8. Body diode blocks the off state voltage.

Fig. 5 illustrates the difference between hard and soft commutation sequences detailed above. The turn-on sequence is common but the diode behavior at turn-off varies drastically with the topology.

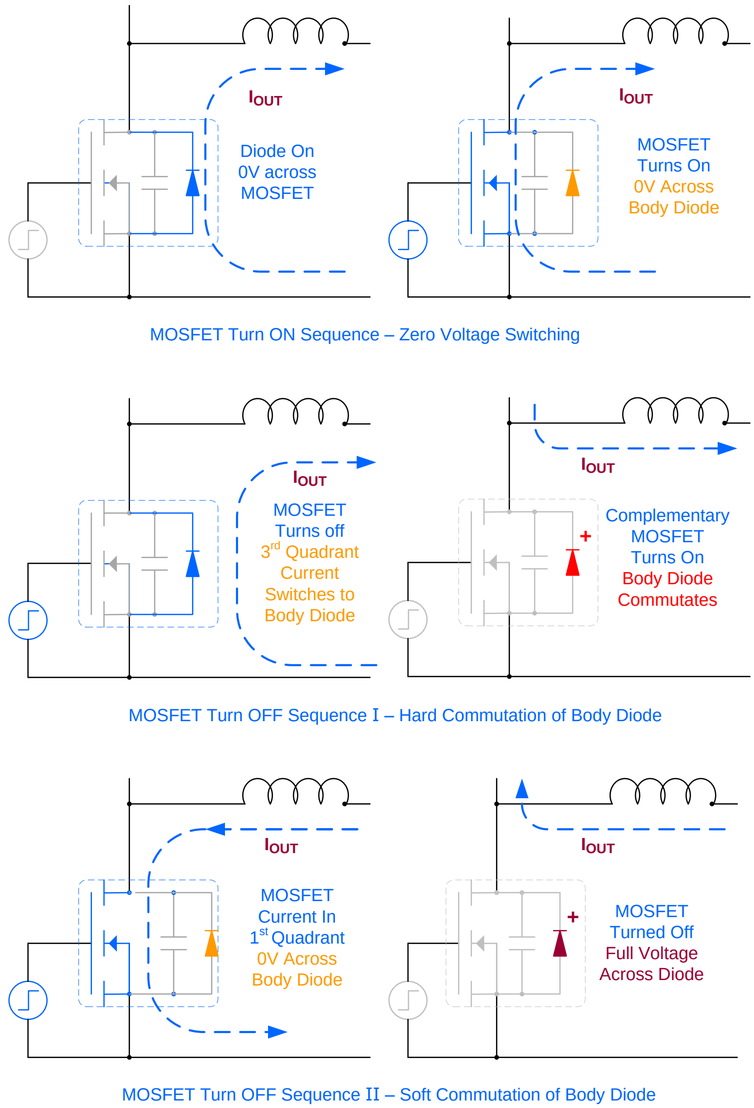

Fig. 5. Zero-voltage turn-on and diode commutation sequences.

While soft commutation is a more benign environment for the circuit, it comes with a hidden failure mechanism. In hard commutation, the applied reverse voltage creates an electric field that rapidly sweeps away electrons and holes from the drift region. However, there is no such mechanism in the near-zero forward voltage of the channel during soft commutation. The electrons and holes that make up the plasma have to recombine on their own, at a rate dictated by the carrier lifetime.

If the recombination process is not complete and the diode has not recovered its reverse blocking ability at the end of the conduction period, results can be unpredictable, including failure. Again, the risk of failure increases dramatically with the voltage rating of the MOSFET. Several studies have demonstrated the link between inexplicable failures in ZVS bridges and recombination phenomena.[2]

Almost all soft-switching topologies have potential operating regimes where ZVS is lost. This typically happens under light load conditions where the parasitic elements, or even the load, do not provide sufficient energy to discharge the output capacitance. In addition to the turn-on losses, the body diodes also change the mode from soft to hard commutation. Designers should be aware of these operating modes and make sure that the system will withstand the stress of sudden hard commutation, continue to meet all of its environmental specifications and operate reliably.

Factors Favoring ZVS

While all this may create the impression that the problems associated with hard turn-off and/or risk of failures override the benefits of ZVS, there are some factors that do work in favor of the user. It has been pointed out that the actual charge to be recovered or recombined in switching circuits is much lower than what is specified in the datasheet for the body diode.[3]

The reverse-recovery parameters of the MOSFET body diode are measured using the same procedures defined for discrete rectifiers. Prior to being turned off, the diode is allowed to carry the test current long enough to accumulate the full charge in the drift region. The entire charge is recovered during commutation and measured. However, with high-frequency zero-voltage switching, the body diode has to conduct only during a short dead time and system designers go out of their way to minimize it.

The conduction time of the body diode is limited, from a few nanoseconds for low-voltage MOSFETs to a few hundred nanoseconds for high-voltage superjunction devices. As a result, the effective reverse-recovery charge is only a fraction of the datasheet value. While it is difficult to quantify the Q_{RR} as a function of the forward conduction period, any effort to reduce the dead time does shorten the recombination time necessary before the diode regains its full blocking capability. That, combined with smaller carrier lifetimes due to high doping concentrations, makes low-voltage MOSFETs quite immune to soft commutation failures.

For higher-voltage devices, manufacturers continue to improve body diode characteristics and reduce the recovery times. Carrier recombination characteristics, though not the same, are closely related to reverse recovery. In other words, Q_{RR} is also an indirect measure of how reliably the body diode can regain voltage blocking ability under soft commutation.

For 500 V and higher, MOSFETs with fast-recovery body diodes are now available. Note that these soft-recovery diodes are not external to the MOSFET or co-packaged with it. These devices have been processed to reduce carrier lifetimes of the integral body diode by factors of 5x to 10x compared to standard-recovery MOSFETs. The EF device shown at the end of the table illustrates the Q_{RR} improvements achieved from lifetime control.

While MOSFETs with standard-recovery diodes may work reliably in many applications, especially with lower frequencies and minimal dead times, users may want to opt for fast-recovery versions for some specific designs. There are certain tradeoffs required by way of higher R_{DS} and cost, but the improvement in reverse recovery makes them suitable for higher frequencies of operation. Every operating environment is different and the designers have to exercise their own judgement whether to use a fast-recovery MOSFET in their application.

Conclusion

Zero-voltage switching is essential to achieving higher frequencies of operation, but it is not an unmixed blessing or the end of all switching losses. Designers should be aware of its limitations, potential impact on circuit operation, and reliability if it enters a hard-switching mode, and use that knowledge to select the right MOSFETs for their application.

References

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About The Author

Sanjay Havanur currently serves as the senior manager of System Applications for Vishay Intertechnology. He is a member of IEEE, holds seven patents in the field of power conversion, and has authored several papers. Havanur holds a bachelor's degree in electrical engineering and a master's degree in power electronics from the Indian Institute of Technology.

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