

# The PI33xx: Zero-Voltage Switching Applied to Buck Regulation



## Abstract

*The Picor PI33xx Cool-Power® ZVS Switching Regulator series delivers maximum power density and high-efficiency point-of-load DC-DC regulation. This unique, high-density buck regulator integrates a high-performance Zero-Voltage Switching (ZVS) topology along with power and support components all within a surface-mount package. This paper provides a brief description of the performance and value of the ZVS topology within the PI33xx series.*

Buck regulator key requirements are typically based on size and efficiency. Printed circuit board area is a precious commodity and no designer is willing to give up more space than what is needed for their power design or scheme. Also, as existing designs get upgraded with the latest and greatest processors, DSP, etc. the power increases, but the footprint cannot increase in size. Thus, high-density regulators have evolved leveraging the latest in IC integration, MOSFETs and packaging. These high-density regulators still cannot keep pace with the demands put on them by new systems with ever increasing higher density. The primary reason for this is the switching losses hindering performance within the regulator MOSFETs. Without addressing these losses head on, only incremental performance increases can be expected.

Regulator MOSFET switching losses are the losses attributed primarily to: the high-side MOSFET during turn-on, Miller-gate-charge and body-diode conduction losses. High-side MOSFET turn-on is when the regulator MOSFET has the highest voltage and current switching and thus the highest power loss attributed to it. These losses further magnify themselves within a design as higher input voltages are converted or regulated.

The higher the input voltage, the higher the voltage across the primary MOSFET and the higher the losses at turn-on. These switching losses prevent dramatic improvements in overall power-system solutions. For example, within industrial process control systems a desired regulation of 24 – 3.3V typically is achieved by first regulating from 24 to 12V followed by a second regulator converting 12 – 3.3V. In contrast, a single regulation stage, like the PI33xx, can regulate 24 – 3.3V with an efficiency level at or higher than the two stages and dramatically improve cost, board space and reliability.

Switching losses also limit the switching frequency of the regulator. The higher the switching frequency the more time the MOSFET switches and the more losses occur. The inability to switch at a high-frequency limits the use of smaller passive components (R's, C's, and L's), penalizing the density of the regulator.

The PI33xx with its ZVS topology allows for operation at a higher frequency and at higher input voltages without sacrificing efficiency. The ZVS topology is a soft-switching topology in contrast to a hard-switching topology deployed in conventional regulators. The soft-switching technology of the PI33xx provides higher-efficiency and higher-density performance than conventional regulators. ZVS topology is typically associated with high-performance isolated power supplies. Integrating a ZVS topology within the PI33xx is an industry first.

**Figure 1**  
Efficiency performance of  
Picor PI3301 Cool-Power® ZVS  
switching regulator  
vs. competitor

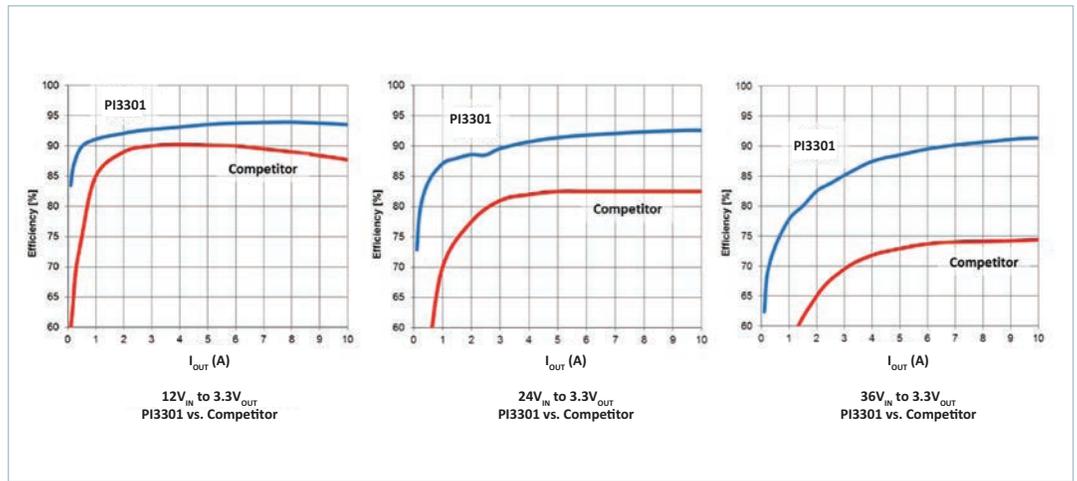


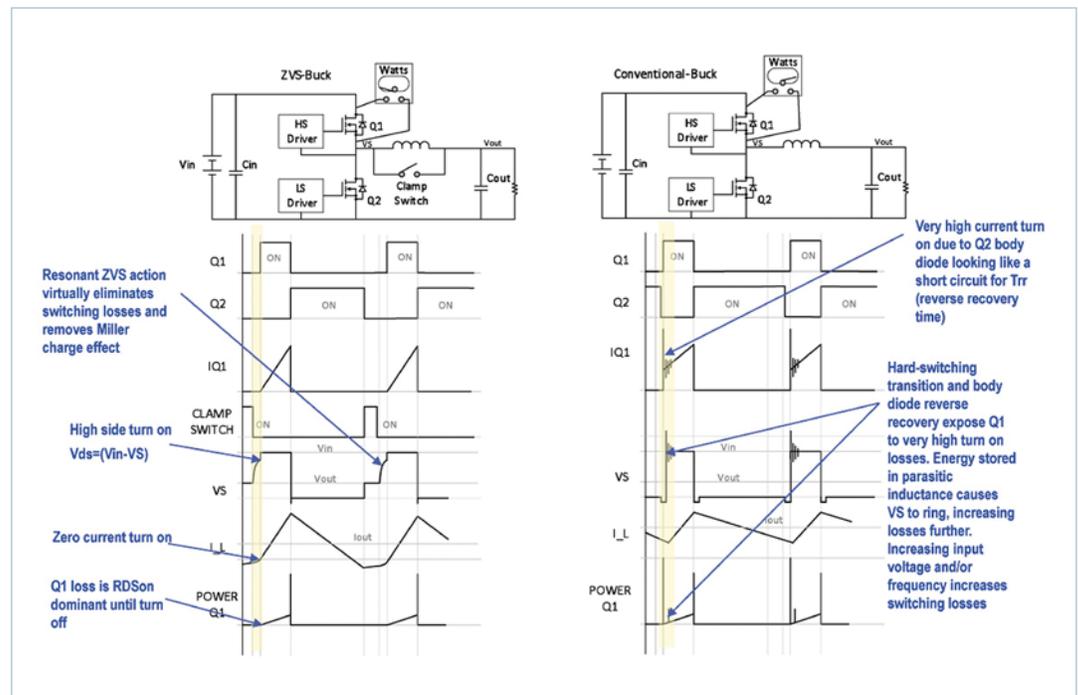
Figure 1 shows efficiency performance for the PI3301 (3.3V version from the PI33xx series) vs. a common industry-used high-density regulator. The PI3301, using a ZVS or soft-switching topology vs. the hard-switching topology competitor, demonstrating high-efficiency performance at 12, 24 and 36V inputs. In contrast, the hard-switching regulator reveals efficiency degradation at higher input voltages. This efficiency degradation is directly attributable to the switching losses within the hard-switching topology.

The PI33xx series operates up to and over 1.5MHz, which is typically 2 – 3X that of conventional high-density regulators. Higher-frequency operation not only reduces the size of passive components but also reduces the burden on external filtering components and allows for fast dynamic response to line and load transients.

### ZVS switching topology within the PI33xx

Referring to Figure 2, a direct comparison can be made between a conventional buck topology and the PI33xx with ZVS buck topology. First, with the typical approach at the start of a complete switching cycle (denoted by the yellow bar), the high-side MOSFET is commanded to turn on. Just prior to turn on, there is inductor current flowing in the output inductor and the synchronous MOSFET. In order to avoid cross conduction of the MOSFETs, there is a delicate balance between turning off the synchronous MOSFET and turning on the high-side MOSFET.

**Figure 2**  
Comparison of conventional  
vs. PI33xx buck topologies



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The result of this design tradeoff is often body diode conduction. Conduction of the body diode requires that the stored charge accumulated while it is conducting at some peak current be swept away before the diode can support any reverse-blocking voltage. As such, the drain-to-source voltage of the MOSFET is practically clamped at the input voltage (strongly dependent on parasitic inductance) while very high current flows through the body diode and through the high-side MOSFET until a depletion region forms and the body diode starts to support reverse voltage.

Until that time, the instantaneous power dissipated in the high-side MOSFET is quite high. Part of the losses is incurred due to the reverse-recovery current and the rest are due to discharging the MOSFET output capacitance. In addition, there are also reverse-recovery losses in the low-side synchronous MOSFET body diode. These losses increase as the switching frequency or input voltage increase. The power curve for Q1 in Figure 2 for the conventional buck regulator shows the effect of turn-on. The peak instantaneous power at turn-on can be a dominant loss contributor for the high-side MOSFET in high switching frequency applications. There have been attempts to remedy the switching loss associated with body diode conduction ranging from switching faster to adaptive gate drivers even to MOSFET improvement through various improved Figure of Merit (FOM) devices.

The PI33xx starts its switching cycle with nearly zero current flowing in the output inductor. The voltage across Q1 is nearly zero as a result of ZVS action. The inductor current ramps up from zero to a peak value followed by Q1 turning off. The inductor current is commutated to the Q2 body diode for under 10ns and Q2 turns on. The stored energy in the inductor is delivered to the load. The turn off of Q2 is delayed until the inductor current is driven negative by current from the output capacitor, thus storing energy in the inductor.

Next, the clamp switch turns on, allowing the stored energy to circulate until Q1 needs to turn on again and clamping  $V_S$  to  $V_{OUT}$ . To facilitate ZVS, the clamp switch opens. The stored energy then resonates with the output capacitance of Q1 and Q2. Resonant current flows into Q1 from source to drain and into Q2 from drain to source. This resonant action discharges Q1 output capacitance and charges Q2 output capacitance. Then Q1 can turn in a lossless manner.

The PI33xx addresses the high turn-on losses of the conventional regulator by eliminating high-current body diode conduction prior to turn on of the high-side MOSFET, bringing the D-S voltage of the high-side MOSFET to zero or nearly zero and produces no high-current spikes or damaging ringing. The ZVS action applied to Q1 removes the Miller effect at turn on of Q1, allowing the use of a smaller driver and lower gate drive at turn on.

Regulation from a higher voltage, at a higher efficiency and in a smaller form factor is realizable with implementation of an improved switching topology. By utilizing the ZVS topology within the PI33xx, Vicor offers engineers a buck regulator that demonstrates high-performance regulation up to  $36V_{IN}$  exceeding the performance found in conventional hard-switching, high-density regulators.

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