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John Jovalusky,
QSpeed Semiconductor

Diodes

Have Silicon Carbide Schottky Diodes made Silicon Rectifiers Obsolete?

Power factor is the ratio of the actual power used to the apparent (reactive) power that a piece of equipment draws from the alternating current (AC) line. The reactance of large capacitors or inductors can cause the apparent power drawn from the line to exceed the actual power used, resulting in low power factor (PF). The lower the PF, the more energy is lost along the AC power line. The result is higher electricity bills for the utility customer. That lost energy also lowers the capacity of the utility distribution system.

Most modern equipment uses power semiconductors and reactive components. Their normal operation produces two undesired side effects. First, they cause the equipment to have low power factor. Second, they distort the line current and inject high-frequency electrical noise onto the AC power lines. This is particularly true of switching power supplies.

Regulatory standards, such as IEC 61000-3-2, specify the acceptable levels of line current distortion and PF for a wide variety of electrically powered devices. Power factor correction (PFC) can be achieved different ways. However, the most efficient and cost-effective means of obtaining high PF and minimizing line current distortion uses a boost converter stage.

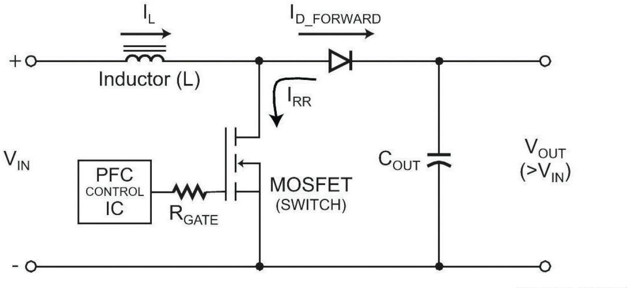

Figure 1. A circuit diagram of the basic boost converter, used for power factor correction. (Note: Some boost converters use up to four switch components — connected and operating in parallel — in order to process the full load power required of the converter.)

Boost converters produce an output voltage that is higher than the input voltage, and typically operate as follows. A PFC control IC turns the boost switch (a MOSFET or an IGBT) on and off, at a fixed switching frequency (typically 60 kHz to 100 kHz). The duration of switch on-time is based on the output voltage, the current through the switch, and the phase angle of the AC input voltage. When the switch turns off, the inductor current (I_L) that was flowing through the switch, flows through the diode ($I_{D\_FORWARD}$), and charges up the output capacitor (C_{OUT}).

Why Boost Diode Performance Matters

Boost converters that deliver more than 250W are usually designed to operate in the continuous conduction mode (CCM). CCM operation enables the use of smaller input filter components by reducing the amplitude of the input ripple current. Although CCM converters require a larger boost inductor than converters designed to operate only in the discontinuous conduction mode (DCM), they are typically smaller, and meet harmonic distortion specifications more easily than DCM designs.

Basic boost converters use two power semiconductors: a switch and a diode (see **Note** in Figure 1 caption). The diode has the more demanding role, since the switch is turned on while the diode is conducting a high forward current. Because P-N junction diodes require a finite amount of time to turn off, large reverse currents can be pulled back through them before they become reverse biased. As the switch is turned on, the diode's reverse recovery current (I_{RR}) flows through it. That extra current increases the operating temperatures and the electrical stress of the switch and the diode, decreases converter efficiency, and generates EMI noise currents and voltages that require dampening, attenuation and/or shielding to prevent them from disturbing other equipment or the AC power line.

Depending on the speed (di/dt) of the switch turn-on rate, the amplitude of the diode's I_{RR} can be fairly large (the red trace in Figure 2). Some Silicon diodes have been designed to have a very short reverse recovery time (t_{RR}), but that does not significantly reduce their I_{RR} (the yellow trace in Figure 2). Additionally, those devices often have abrupt or "snappy" turn-off characteristics, which stimulate high frequency ringing between parasitic circuit inductances and capacitances.

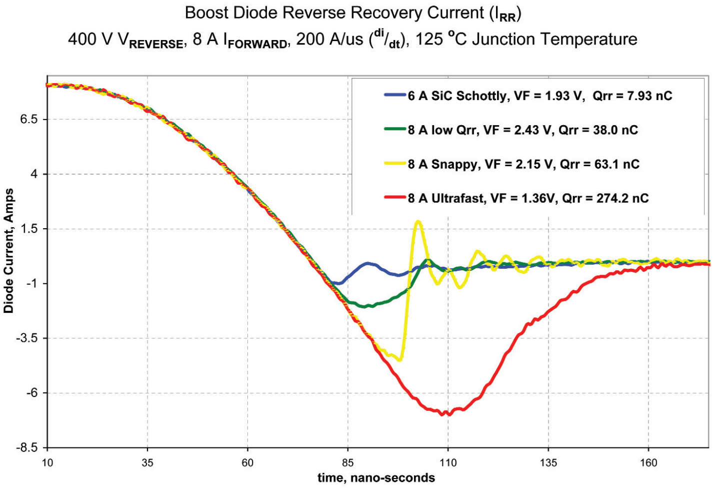

Figure 2. Reverse recovery current (I_{RR}) waveforms of four common, 600V boost diodes.

The Schottky Diode Advantage

Schottky diodes act more like ideal switches than standard P-N junction devices do, particularly with regard to two performance benchmarks: reverse recovery charge (Q_{RR}) and recovery softness. In CCM boost converters, the diode's Q_{RR} is largely responsible for its I_{RR}. High softness reduces the dv/dt and the EMI noise that turn-off commutation generates, and the likelihood that it may interfere with the PFC control IC.

Schottky diodes improve the performance of CCM boost converters, but the reverse voltage limit of Silicon Schottky diodes is around 250V. Because boost diodes must withstand 500V or more, engineers began using Schottky diodes made of Silicon Carbide (SiC), since it can withstand higher voltage ratings. However, due to SiC device costs (three-to-five-times that of equivalent Silicon parts), few applications can afford them. Better Silicon diodes have been developed since SiC Schottky's were introduced (2003), but only the most recent have come close to SiC Schottky performance.

How Silicon Rectifiers Can Compete with SiC Diodes

The amount of I_{RR} that can be pulled back through a P-N junction Silicon diode, before it can block the reverse voltage, is proportional to the Q_{RR} that must be removed from it, the amount of forward current it is conducting when reverse bias is applied, and the di/dt rate at which it is turned off. The only factor the diode designer can control — Q_{RR} — is determined by the duration or the lifetime of minority charge carriers near the P-N junction. Because Schottky diodes consist of a metal contact to N-type material, they have no minority carriers. The small I_{RR} that occurs when a Schottky diode is reverse-biased results from the discharge of the metal contact to diode body capacitance. Silicon diode designers have various techniques to control minority carrier lifetimes in their devices. As can be seen by the green trace in Figure 2, effective minority carrier lifetime control techniques can produce Q_{RR} and I_{RR} performance that is almost as good as that of SiC Schottky devices (the blue trace in Figure 2). Another advantage that SiC Schottky diodes have is that their Q_{RR} does not increase with temperature (the blue trace in Figure 3). A temperature dependent increase in the Q_{RR} of P-N Silicon devices is inevitable. However, a well-designed part, such as the low Q_{RR} LQA08TC600, from Qspeed Semiconductor, will have a minimal increase (the green trace in Figure 3).

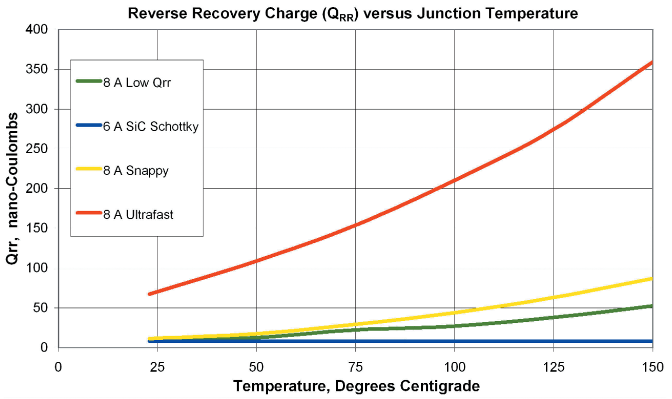

Figure 3. Reverse recovery Charge (Q_{RR}) versus junction temperature plots of four common boost diodes.

Softness specifies how quickly the diode's I_{RR} returns to zero, once its peak negative value has been reached. Silicon diodes that are designed to recover quickly typically use a minority-carrier-lifetime control technique that causes I_{RR} to decrease very abruptly (the yellow waveform in Figure 2). Such snappy turn-off produces high-frequency EMI noise and a large voltage spike on the anode of the diode. Elaborate and costly snubbing circuits are required to counteract the effects of abrupt turn-off recovery. The I_{RR} of diodes with a high softness factor return to zero at a di/dt that is equal to or slower than the rate at which it increased to its peak negative value. Diodes that turn off softly require no snubbers, generate less EMI, and are less likely to interfere with the operation of the PFC control IC.

Conclusion

Because the cost of SiC Schottky diodes is still high, and Silicon rectifiers that rival them are now commercially available, engineers should revisit their PFC boost converter designs to see if they can reduce cost and/or improve performance by taking advantage of the performance of the latest Silicon devices, because SiC Schottky diodes have not made Silicon rectifiers obsolete.

John Jovalusky is the Technical Marketing Engineer for Qspeed Semiconductor. John began his career in electronics at Burr-Brown Research Corp. in 1979. Since 1989, he has designed power supplies for Lambda Electronics and C&D Technologies. He has also worked as an Applications Engineer for Delta Electronics and Astec Power. Most recently, he was the Technical Marketing Engineer for Power Integrations. For more information, contact QSpeed Semiconductor, 3970 Freedom Circle, Santa Clara, CA 95054; (408) 654-1980; www.qspeed.com.