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Rad Hard MOSFETs Enable Easy Upgrade Of Flight-Proven DC-DC Converter

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Designing power electronics for space applications is often a balance between high reliability and risk. Design engineers look to develop architectures that meet mission requirements for cost and performance, balanced against acceptable risk levels to the mission.

In this article, we will look at how a new generation of rad hard silicon MOSFETs enables efficiency and power density improvements in a heritage space-grade dc-dc converter. Specifically, we will examine how the use of IR HiRel's R9 rad hard MOSFETs enable an increase in efficiency and power output capability in a flight proven dc-dc converter simply by replacing the previously used R5 rad hard MOSFETs with minimal changes to the rest of the circuitry.

The converter built with the previous gen R5 MOSFETs delivered 190 W of output. With their lower on-resistance and faster switch transitions, the R9 MOSFETs applied in the same converter design can produce this same power output with better than 1% improvement in efficiency, which equates to a 20% reduction in losses. But more importantly, the R9 MOSFETs can be used to increase output power to 260 W. In this article, a 260-W rad hard dc-dc converter is built to demonstrate this capability and the design reusability that can be achieved with the new silicon MOSFETs.

The dc-dc converter featured here uses a full-bridge with Hy-bridge (current doubler) synchronous rectifier. It has a single 24-V output voltage and uses peak-current-mode control for closed-loop control. The power stage uses the R9 MOSFETs in an SMD-0.5e package. A best-in-class efficiency of 95% is achieved, which includes losses in both power stage and small-signal housekeeping. A direct performance comparison is made by replacing IR HiRel's R5 MOSFETs with the R9 devices.

In this discussion, we'll explain the reasoning behind key device specifications, as well as component, topology and control scheme choices. This design sticks with silicon (Si) MOSFETs rather than the newer gallium nitride (GaN) power switches. For stressful SOA requirements, Si is competitive with GaN, offering high efficiency and higher reliability in space applications.

Project Motivation: A Simple Upgrade For Flight-Proven Designs

Space presents unique operating challenges for electronics, because they need to function in a radiation environment: radiation coming from the sun, from galactic cosmic radiation, or due to the particles that are ever present in the Van Allen radiation belt.

When designing electronics for high-reliability applications in space, engineers need to balance resources in their circuit designs. Consider a dc-dc converter: the designer needs to weigh the time and money spent on converter topology, gate-driver circuits and board-layout optimization. Working under budget and deadline constraints, it can be difficult to deliver a higher performing product or a higher performing electrical power system that also provides the same level of reliability.

In this example, we started from an existing isolated dc-dc converter and PWB layout. Created by IR HiRel's design center specialized in power supplies, this is a proven topology currently flying on multiple satellites. The original dc-dc converter delivered a maximum output power of 190 W and used R5 rad hard silicon MOSFETs from IR HiRel as previously noted.

Our main inquiry focused on whether we could maximize design reuse by replacing the older generation silicon MOSFET with the newer generation, R9, rad hard silicon MOSFET for efficiency or performance improvements. The goal was to keep the same power stage and control strategy, which would require neither board layout optimization nor other major circuit component changes. We just replaced R5 with R9, and altered only a few resistor values in the gate-drive circuitry.

R5 and R9 are different device types, with R5 being a planar and R9 being a superjunction device. IR HiRel's newer devices are optimized to have higher gain (i.e. low $R_{DS(ON)}$ and improved figure of merit). However, with each new generation, SEE ruggedness is also improved. So for the targeted dc-dc converter design, R9 offered the advantages of higher power efficiency with improved SEE immunity.

Based on this design, we demonstrated a competitive peak performance and easy design reusability of the dc-dc converter. Table 1 outlines the converter specifications. As shown, the output voltage is 24 V in its steady state, and it can deliver an output current up to 11 A. The peak efficiency is 95.5%, which is observed at cold temperature.

Table 1. Key dc-dc converter specifications.

Parameter	Conditions	Min	Max	Unit
Input voltage	Steady-state	48	52	V
Output voltage	Steady-state	24 ±0.01		V
Output current	Steady-state	0	11	A
Switching frequency	Steady-state	120		kHz
Power efficiency	Load: 37% to 100% Temperature: -45°C to +85°C	93	95.5	%

Converter Design: Maximize Design Reuse And Improve Performance

Fig. 1 shows the block diagram of the isolated dc-dc converter that we built. The driving factors for topology selection included galvanic isolation (achieved by the transformer), higher power conversion efficiency and improved thermal performance. To demonstrate efficiency, for the input stage we have chosen a full bridge and on the secondary side we have used a Hy-bridge (current doubler) topology using a synchronous rectifier on the output. All circuits employ R9 MOSFET switches.

There is also a small auxiliary power supply that provides internal housekeeping and allows for the PWM controller for the main converter to be placed on the secondary side to ease direct sense and regulation of the output. However, we'll be ignoring its relatively small contribution to losses when taking our efficiency measurements.

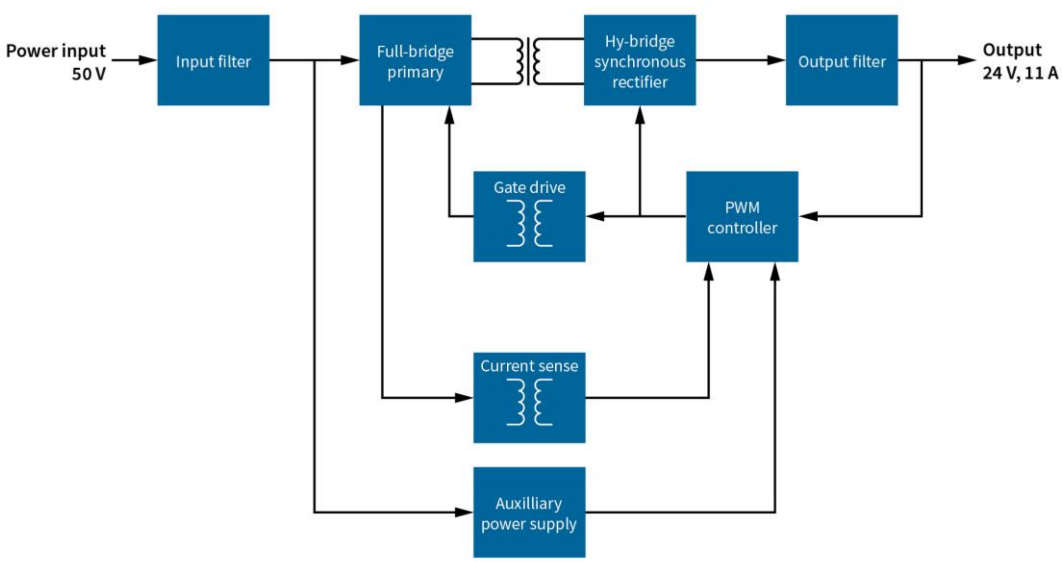

Fig 1. Block diagram of IR HiRel's rad hard 260-W isolated dc-dc converter.

Delving into more detail on the power stage, since it operates on a 50-V bus, we use a full-bridge topology where the voltage stress is equal to the input voltage. In order to achieve a good derating, the MOSFET selected is a 100-V, 35-A rad hard R9 MOSFET (IRHNKC9A7130), which has a low $R_{DS(ON)}$ of 34 mΩ and a gate charge of 48 nC at room temperature. The radiation specification for this device is 100 krads for TID and for SEE, it has a minimum LET of 90 MeV/mg/cm^2. This MOSFET is also offered with a TID rating of 300 krads.

When we look at the output side of the current doubler topology in Fig. 2, we can say that it is almost like a classical full-bridge rectifier. If you consider that Q5 and Q6 are two of the rectifiers and the two chokes (L1 and L2) are the other ones, using chokes instead of semiconductors here means there is only one voltage drop compared to the full bridge rectifier. We get the same good performance in terms of doubling the ripple frequency, making it is a very efficient topology.

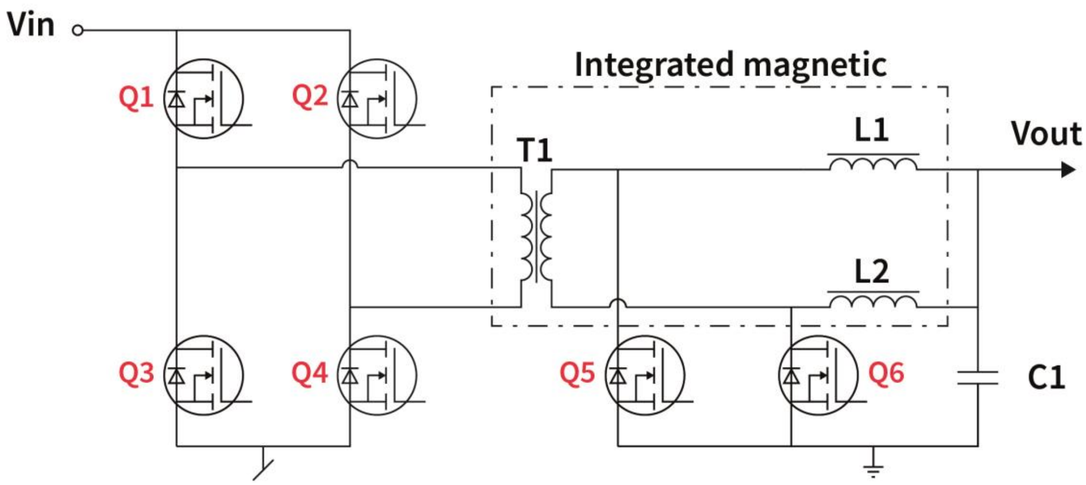

Fig. 2. Simplified power stage schematic.

The converter combines the main transformer and the output chokes on one core, or so-called integrated magnetic, for optimizing overall size. The general concept has been used on numerous space programs and there are thousands of units in orbit that are based on this topology. In terms of regulation, the control scheme uses a cycle-by-cycle current-mode control. This has advantages in controlling the currents in the inductors, which ensures that there will never be any problems with saturation in the transformer during start-up or other, abnormal conditions.

Moving on to the control strategy and the EMI filter, the design uses peak-current control to minimize the transients. This stabilizes the output voltage and equalizes the current through both inductors, which is important for the current-doubler topology. For closed-loop control, we use a rad hard UC1825 PWM controller IC. This provides peak-current-mode control with slope compensation and also limits the duty cycle with each PWM output.

We use current transformers to measure the current in the switch transistors, and drive different transistors through a gate-drive transformer.

This is a complete converter with input and output filtering. We use a standard second-order LC filter with LR dampening and the attenuation is such that it meets typical conducted emission requirements for satellite platforms (see Fig. 3). The first harmonic can be identified at about 240 kHz corresponding to a doubling of the switching frequency for each of the legs in the full bridge, which is 120 kHz.

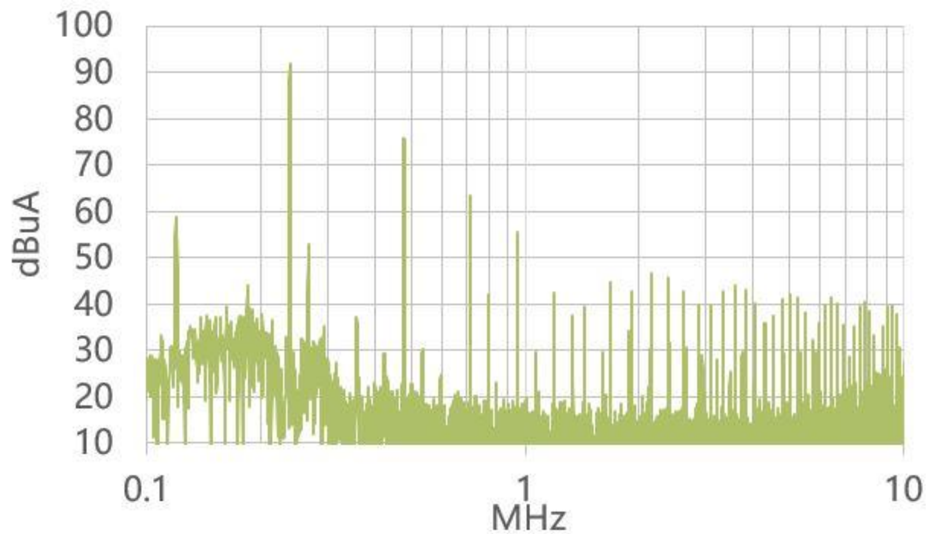

Fig. 3. Conducted EMI at the input of dc-dc converter.

Measuring Performance Of The Upgraded DC-DC Converter

Looking at the actual measurements obtained when running the converter with the R9 devices, we can identify the gate voltages and the drain voltages of the MOSFETs in the full bridge and in the synchronous rectifiers on the oscillograph. As seen in Fig. 4, the waveforms are stable and as expected—with low and well-controlled source-voltage overshoot.

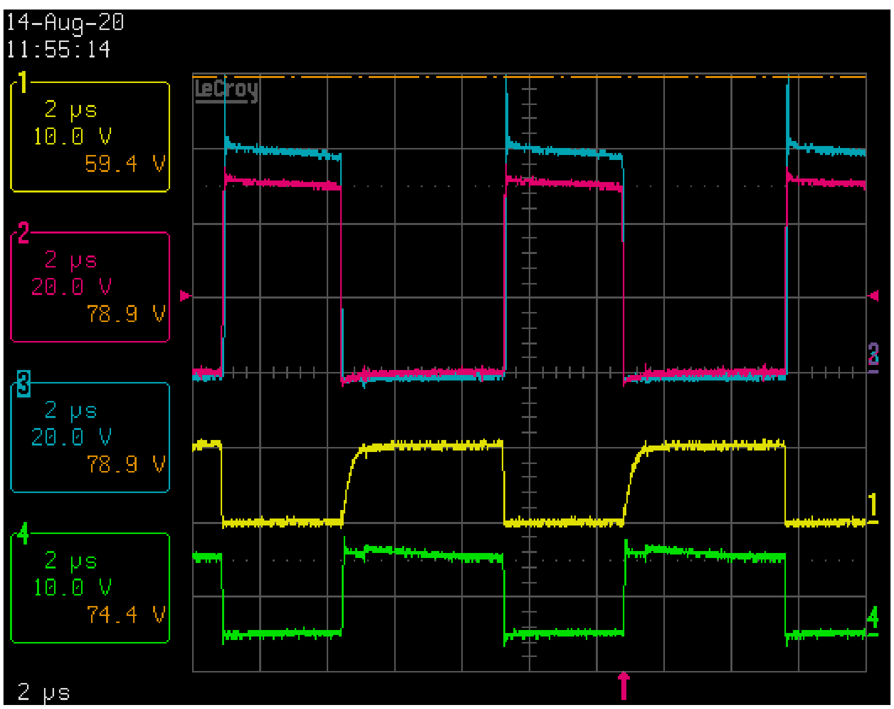

Fig. 4. Gate and drain voltage waveforms across MOSFETs Q4 and Q6, the low-side switches in the full bridge and synchronous rectifier, respectively. Ch 1 = Q4 gate voltage, Ch 2 = Q4 drain voltage, Ch 3 = Q6 drain voltage and Ch 4 = Q6 gate voltage.

Fig. 5 shows the output voltage ripple. From this measurement, we can determine that the output ripple is twice the switching frequency and see that it is controlled switching. The time domain peak-to-peak voltage ripple is about 26 mV for a 24-V output corresponding to approximately 0.1% of the output voltage. And when we look at it in the frequency domain, we have a ripple of around 1.5 mVrms, which makes the output well suited for many applications of a sensitive nature, like the drain supply for a high-power, microwave amplifier.

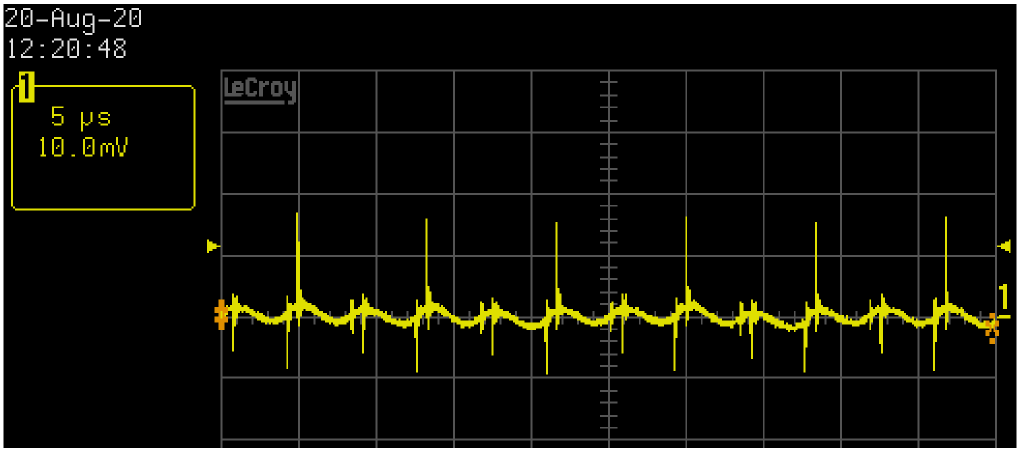

Fig. 5. Output voltage ripple. The asymmetry observed in the waveform of the output voltage ripple is due to the noise from the main transformer being picked up by the measuring probe at the output.

Improved Efficiency, Higher Output Power

To assess efficiency, we first compare the output and relative power losses of R5 and R9 MOSFETs in the dc-dc converter. We see that switching to R9 presents an improvement in the efficiency of about 1%. When considering efficiencies in the 94% to 95% range, this essentially is a 20% reduction of the power losses.

That is how it allows us to increase the load from 195 W (with R5) up to 260 W (with R9), a 33% gain in the peak power capability. When looking at the power losses in the circuit, we see lower losses with R9, which is a clear improvement that allows higher maximum output power. Calculations of converter efficiency and max load obtained with the two generations of power MOSFETs are given in Table 2.

Table 2. Modeled calculations of power conversion efficiency.

Rad hard MOSFET generation	Max load	Efficiency
R9	260 W	95.49%
R5	195 W	94.89%
R9	195 W	95.89%

Fig. 6 shows efficiency comparisons versus load across different generations of IR HiRel's MOSFETs, R5 to R6 to R9. With each new MOSFET generation, we see improvement in efficiency as well as load power capability. With R5, we start at 195 W going up to 8 A at 24 V. With R6, the maximum power increases to 9.5 A with output power around 230 W. With R9, the maximum power increases further to 11 A with output power at about 260 W.

In changing the switches, only the die were replaced, as the packages were kept the same. The newer generation devices enable design reuse, which means that designers can upgrade existing flight-proven designs and gain higher performance while maintaining high reliability.

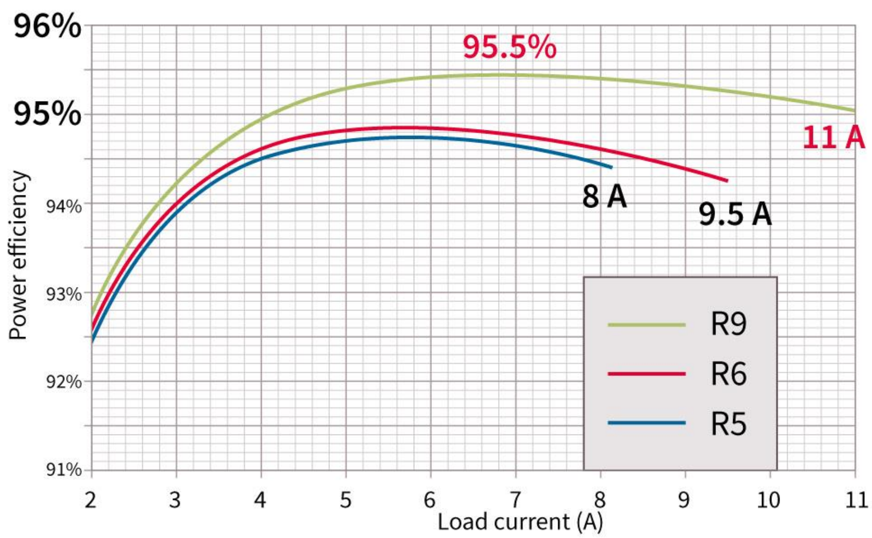

Fig. 6. Modeled efficiency vs. load curve of rad hard dc-dc converter obtained at a 25°C baseplate temperature (V_{out} = 24 V).

Fig. 7 shows the measured efficiency with load variation at different temperatures. As we know, space electronics are always required to work over a quite extensive temperature range and still have full performance and meet derating, both temperature and power, voltage, stress and more. Shown here are measurements taken at room temperature as well as at cold and hot temperatures. The total temperature span is 120°C; from -45°C to +75°C. Peak performance is obtained at the lowest temperature.

As previously described, the converter topology uses a MOSFET for the full bridge and a MOSFET in the synchronous rectification. With the MOSFET's $R_{DS(ON)}$ being temperature dependent, there is a slight decrease in efficiency at higher temperature, but it is less than a one percentage point difference between the curves. This points to the MOSFET's stable and controlled operation.

Note that there is no required derating of the output power over the full temperature range. The converter is fully analyzed and justified by a part stress analysis over the full specified operating range.

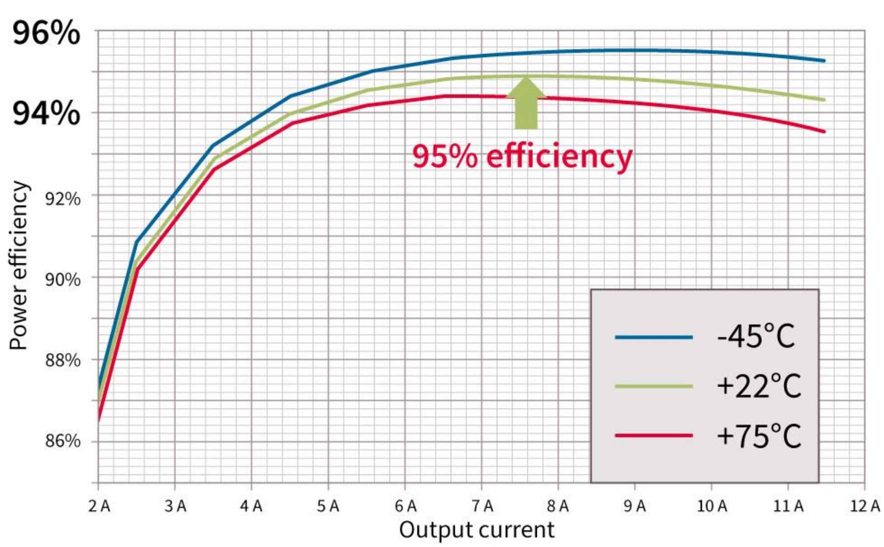

Fig. 7. Measured efficiency vs. load curve (without auxiliary power supply consumption).

It's interesting that it doesn't take retooling or changes in circuit design to increase output power and increase efficiency to a best-in-class level of 95%; it only requires replacing the switches from the previous generation with the new R9 MOSFETs. A few resistors could be optimized, which is a typical task when changing MOSFETs. But when we experimented with optimization of gate resistors, it only yielded 0.1% improvement in efficiency.

Effectively, you can make a drop-in replacement of R5 with R9 without changing any component values or anything other than the switches, and still achieve the one percentage point improvement. Doing so would require very minimal work on the design justification documentation to certify the design.

Higher Performance With Shorter Design And Approval Time

As we have seen, it is possible to take a newer generation R9 rad hard silicon MOSFET, drop it into a qualified converter design and see a significant improvement in power density and efficiency with very minor design changes. This is easily explainable to your stakeholders.

With R9's faster switching behavior, higher switching frequency, optimized (new or redesigned) dc-dc converters could also benefit. Lower losses reduce heatsinking requirements. This increases power density and improves transient response and efficiency. In the output stage, the designer would have the choice of using a full bridge rectifier, if balancing budget constraints, or maximizing efficiencies by using R9 MOSFETs for synchronous rectification. Overall, the design would also benefit from the higher SEE immunity with R9 than that of prior generations.

IR HiRel's R9 rad hard MOSFETs follow the same rigorous testing, verification and qualification as previous MOSFET generations—all with the DLA QPL certifications. With a well-known gate-driver setup, R9 is a low risk upgrade path to higher-performing space-grade power systems, with assured confidence in overall system reliability.

Reference

For more information, see the R9 rad hard MOSFET technology page.

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For further reading on power semiconductors and power converters for space applications, see How2Power's Space Power section.