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Delivering higher power density and low noise for New Space applications

VICOR

To reduce expensive communication traffic between satellites and the Earth, increased processing power is being hosted on satellite platforms. To meet the demands of additional onboard computation, signal- and data-processing hardware, system power and point-of-load (PoL) requirements must increase. Because hard-switched converters have drawbacks in size, efficiency and electromagnetic interference, system engineers and power supply designers are driven to consider more advanced power supply topologies.

Due to the physical size of modern ASICs, FPGAs, CPUs and GPUs—and their necessary cooling solutions—circuit board real estate around these big chips is precious. These chips require progressively lower voltages with increasing currents—hence the need for an optimized power delivery network (PDN).

Therefore, it is helpful to divide the PDN task into two sections: a regulation section that can be placed in a convenient location, and a power delivery section that benefits from being placed as close to the load as possible. This is a fundamental principle of the Vicor Factorized Power Architecture (FPA™).

Soft-switching topologies have distinct advantages over hard-switched converters by enabling high fundamental conversion frequencies with low harmonic noise.

Compared to a hard-switched, multi-phase topology…

1. A zero-voltage switching (ZVS) and zero-current switching (ZCS) topology, running at the highest practical frequency, is more space-efficient and dissipates less wasted power.
2. A zero-voltage switching (ZVS) and zero-current switching (ZCS) topology does not have the high-frequency, harmonic-series noise profile character.
3. With a >1MHz operating frequency, Vicor converters do not have troublesome 100-500kHz frequency content.
4. With low harmonic content and high fundamental conversion frequency, the noise-filter implementation is compact.

Vicor power modules operating at >1MHz help engineers create low common- and differential-mode (CM and DM) noise designs, particularly when component arrangements and device interconnects are properly considered.

As always, input and output filters are required and must be designed and placed properly, but the inherent nature of Vicor converters make this task easier.

Factorized Power: Delivering high current and low voltage efficiently

Top challenges for satellite power system designers:

1. Higher and higher load current requirements, from 10s of amps to 100s of amps.
2. Loads requiring faster transient response with tighter tolerance windows.
3. Requirements for lower PDN losses and impedances.
4. Expanding use of higher-voltage busses to reduce conductor sizes.

In addition to the advancing electrical requirements in space, radiation TID (total ionizing dose) and SEE (single-event effects) requirements are added. In some cases, the New Space philosophy of smaller, faster and cheaper space platforms and launches led to the adoption of rad-tolerant design methods as a cost-reduced substitute for radiation-hardening. This new approach is based on determining an acceptable level of performance and reliability based upon the specific mission, then developing boards and electronics based on size, weight and power consumption (SWaP) tradeoffs, as well as cost-effectiveness. This design strategy suits LEO and MEO satellite orbits inside the Van Allen radiation belt.

Optimizing for a high-current, high-density PDN calls for a new approach and a Factorized Power Architecture should be considered. The Vicor New Space FPA divides the PDN into three stages. Fixed ratio, non-regulated isolated DC-DC bus converters (BCM®), isolation and voltage transformation module (VTM™) convert voltages from one level to another. Pre regulation module (PRM™) regulators provide voltage regulation and control the converter output voltage to a target value when the input voltage and output load varies.

In the current generation of Vicor New Space converters, an unregulated first-stage BCM provides isolation from the spacecraft bus, a supply voltage for the downstream converters and voltage transformation to create an intermediate bus voltage compatible with the downstream converters. The current BCM design offers a 3:1 transformation ratio to convert $100V_{DC}$ to $33V_{DC}$, but other transform ratios are being studied and considered to support other bus voltages.

The second-stage PRM performs accurate output voltage regulation with a trimmable output voltage range of 13.4V – 35V.

The third stage VTM is the power delivery stage. It transforms the higher voltage from the PRM to the voltage required by the load. Currently, there are two transformation ratios: 8:1 and 32:1. VTMs are called current multipliers because the input to output current transformation is the inverse of the voltage transformation ratio. As an example, 6A injected into the 8:1 VTM results in a 48A output current.

Designing a low-noise Factorized Power Architecture for New Space

BCMs, PRMs and VTMs are the components that make FPA possible. The current generation of radiation-tolerant New Space BCMs, using patented Vicor Sine Amplitude Conversion (SAC™) topology, has an impressive peak efficiency of 96.9%.

Vicor PRMs use a patented ZVS buck-boost regulator control architecture to give high-efficiency step-up and step-down voltage regulation and soft start. Maximum efficiency is achieved when $V_{IN} \approx V_{OUT}$, with 97% peak being achieved with the latest PRMs.

VTM current multipliers are high-efficiency voltage transformation modules using a proprietary ZCS/ZVS Sine Amplitude Converters which transforms a nearly pure sinusoidal waveform with high spectral purity and common-mode symmetry. These characteristics mean it does not generate the harmonic content of a typical hard-switched PWM type converter and generates minimal noise. The control architecture locks the operating frequency to the powertrain resonant frequency, enabling up to 97% efficiency and minimizing output impedance by effectively canceling reactive components. This very low, non-inductive output impedance allows it to respond almost instantaneously to step changes in the load current.

The VTM responds to load changes regardless of magnitude in less than a microsecond. The VTM's high bandwidth obsoletes the need for large point-of-load capacitance. Even without external output capacitors, the output of a VTM exhibits a limited voltage perturbation in response to a sudden power surge. A minimal amount of external bypass capacitance (in the form of low equivalent series resistance/equivalent series inductance (ESR/ESL) ceramic capacitors) minimizes the output transient voltage overshoot.

Because the VTMs are nearly transparent without capacitive or inductive storage, bulk capacitance can be placed on the input voltage side—taking advantage of the squared voltage term along with the linear voltage transform ratio.

$$Ej = 1/2\ CV^2$$

Ej = Stored Energy in joules

C = Capacitance in farads

V = Voltage in volts

As an example, for equivalent energy storage with the Vicor VTM with an 8:1 transform ratio, 25µF of input capacitance at 28V acts very much like 1600µF of output capacitance at 3.3V (see Figure 1).

Because the VTMs are nearly transparent, the capacitance transfer ratio between input and output can help with pulsed loads. This transform means smaller values of capacitance (at the higher voltage) can be used to serve pulse-load requirements.

Vicor radiation-tolerant New Space VTMs have peak efficiencies of 94.7% for 8:1 transformation (3.3V at 50A) and 92.9% for higher-current 32:1 transformation with 0.8V at 150A capability.

Energy storage and dynamic response the FPA way

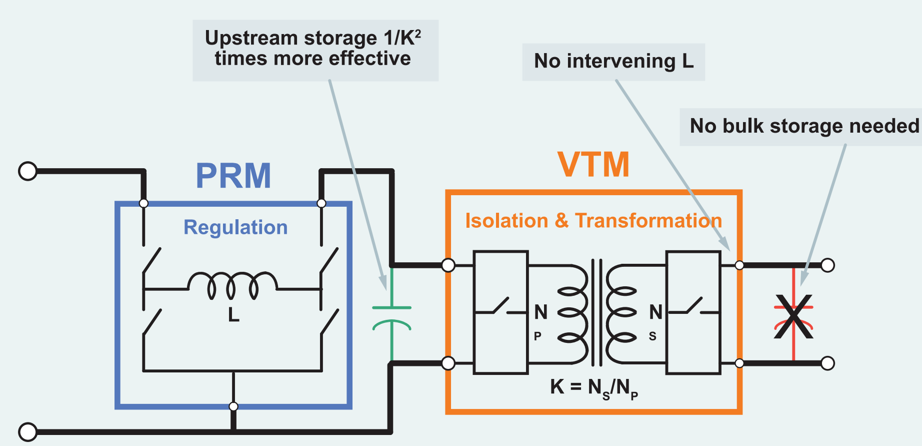

Figure 1: Diagram showing the more efficient and flexible Factorized Power Architecture (FPA) using Vicor PRM and VTM module products.

Benefits of FPA

The Factorized Power Architecture (FPA™) enables power system density and high-current demands to keep pace with rapidly advancing CPU, GPU and ASIC technologies. Some key system design advantages include:

- Reduced PDN real estate consumption near the CPU/GPU by 50% or more
- Reduction by an order of magnitude in PDN and associated board losses
- Unfettered performance by placing the PRM in non-critical board edge areas
- Simplified CPU I/O routing
- Mitigated risk of placement near the processor's SerDes because of lower noise performance of the VTM

Overall peak efficiency for a power system—including the combination of a BCM, PRM and VTM — operating from an unregulated DC source and supplying a regulated, low-voltage DC output is 89% (for 100V:3.4V at 50A transformation) and 87.3% (for 100V:0.8V at 150A transformation). With higher efficiency comes lower total heat dissipation, an important consideration in a power system design for spacecraft where cooling mechanisms require additional mass and structure.

A summary of radiation tolerance parameters for the Vicor New Space power solution

A lot of work is required to create power modules that will survive useful periods in Low Earth orbits (LEO) and Medium Earth orbits (MEO).

In order to meet TID requirements, components must be carefully selected, screened for radiation performance and parameter variations are included in worst case analysis to assure performance.

In order to meet enhanced low dose rate sensitivity (ELDRS) requirements, only known-ELDRS-performance-rated components are used or the parts are tested at low-dose rates.

In order to meet single-event performance requirements extensive testing with accelerated charged particles has been performed. All parts that are used are tested and analyzed to survive up to a linear energy transfer of 35MeV-cm^2/mg. To mitigate for single event functional interrupts (SEFIs), dual-redundant internal powertrains with monitoring and power-cycling capability are implemented.

Vicor New Space radiation-tolerant power modules are survival-rated at 35MeV-cm^2/mg and TID rated at 50krad.

Worst case circuit analysis (WCCA) was performed on all circuits including statistical confidence limits (90% confidence with 99% probability) based on sample testing of the parts. Extreme value analysis (EVA), root-sums-squared (RSS) and Monte Carlo analysis methods were used where appropriate to evaluate the power module designs to ensure all parts will perform as expected.

Conclusion

In summary, Vicor technology has key advantages for New Space missions. To explore Vicor solutions in more detail, Vicor shares more information and radiation test data under NDA with select customers.

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