

Input filter design and test strategy for dual unsynchronized Sine Amplitude Converters in space power systems

Including a three-filter comparison for New Space: $100V_{IN}$ $k=3$ BCM[®], $28V_{IN}$ $k=1$ BCM and a $12V_{IN}$ 8-Phase DMP

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The fundamental problem: why a switching converter needs an input filter

Switching converters inject conducted noise back into the input bus

Narrowband ripple at the switching frequency, plus broadband content

The filter also shapes the source impedance seen by the converter

A converter presents negative incremental input resistance — a concern for stability

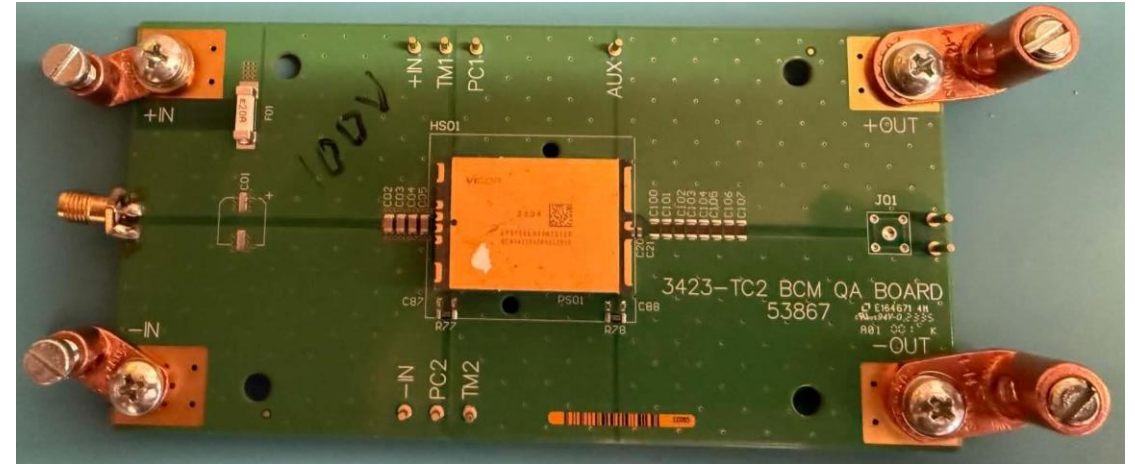
Space platforms impose conducted-emission limits

MIL-STD-461H CE102, DO-160 Section 21, and (Europe) ECSS-E-ST-20-07C set design limits

Goal: meet the emission limit AND preserve performance stability margin

Fundamental test criteria

- We made reasonable efforts to assure that the test conditions were the same for the competing designs
- Both the Vicor and 8-phase DMP evaluation boards are rated for 400W and were tested at 20% capacity
 - To use easy passive cooling, all lab testing was done with 80W loads
 - For the DMP, this meant using >100W capability at 12.5mΩ with bus bar interconnection
 - For the BCM[®], a Kikusui electronic load was used



Fundamental test criteria (continued)

- The Vicor $100V_{IN}$ BCM[®] ($33V_{OUT}$) and the 8-phase DMP ($1V_{OUT}$) were tested with DC loads
 - In application, the Vicor BCM drives downstream PRM[™] and VTM[™] to get to the low output voltage. This means the character of the BCM output load is complex. In actual use, the DMP will also see complex loads.
 - All $28V_{IN}$ testing was done with downstream PRM and VTM providing a low-voltage output (3.3V)
 - Though the BCM is transparent, we noted no significant change to the input filter requirements. Whether this holds for a customer system design remains to be seen
- Low impedance power supplies, short interconnect wiring and the $5\mu H$ LISN provide input impedance stability
 - To remove their effect on the input filter design, input decoupling capacitors were removed from both the Vicor BCM and DMP

The Middlebrook stability criterion

- A regulating converter looks like a negative incremental resistance
- $Z_{IN} = -V_{IN}^2 / P$ at the converter input — a negative incremental input resistance set by the operating point (constant output power)
 - Its magnitude scales as V_{IN}^2 , so the smallest $|Z_{IN}|$ — the worst case for filter interaction — occurs at minimum V_{IN} and maximum power
 - Stability requires the source impedance stay well below $|Z_{IN}|$
- A constant-power load is an “un-resistor”
 - Push more voltage at it and it pulls less current
 - Instead of damping a disturbance on the bus, it amplifies it – which is why an undamped input filter feeding a regulating converter can ring or go unstable
- $|Z_{SRC}| \ll |Z_{IN}|$ across all frequencies of interest
- Design rule used here: a $10 \times$ (20dB) of margin
- Intentionally conservative relative to Middlebrook’s 6 – 10dB guidance

Three filters, three regimes

Parameter	100V k=3 BCM®	28V k=1 BCM	12V DMP
Topology	SAC™, narrowband	SAC™, narrowband	8-phase hard-switched
Z_{IN} / Z_{SRC} Target	$Z_{IN} \approx 25\Omega \rightarrow \leq 2.5\Omega$	$Z_{IN} \approx 2\Omega \rightarrow \leq 0.2\Omega$	broadband DM
Filter / Area	Single 6.8mH CM choke — $\sim 5\text{cm}^2$	CM+DM mixed — $\sim 7.5\text{cm}^2$	$\sim 51\text{cm}^2$

Lower bus voltage $\rightarrow$ higher input current $\rightarrow$ a fundamentally harder, broadband filter problem. The areas mentioned are as-built estimates.

Over-design vs. under-design

- Under-design is the familiar hazard with failed limits due to eroded margin
- Over-design carries penalties too
 - Mass, volume, parts count — and added series Z that can raise $|Z_{OUT}|$
 - Excess stored energy erodes the desired Middlebrook margin
- Margin is legitimate engineering, not gold-plating
 - Anticipate ~20% load growth over the program life
- Reconfigurable loads (FPGA / SoC) draw current as a function of workload
- Resolution: publish the limits to define an operating envelope
 - Converts an unknowable future into a bounded one
 - State power, V_{IN} range and load dynamics → a bounded, right-sized filter, not a worst-case guess

Designing the 100V input filter: process and numbers

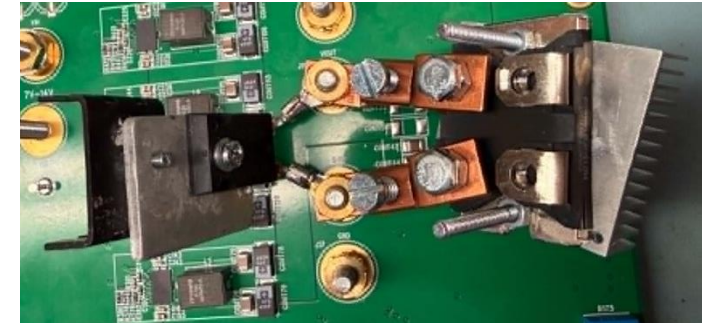
- Regime: narrowband SAC™ emissions near the 1.5MHz switching frequency
- The negative input resistance is benign: $Z_{IN} \approx 25\Omega$
 - Middlebrook target is loose: $|Z_{SRC}| \leq 2.5\Omega$
- **Solution: a single 6.8mH common-mode choke at the converter input**
 - CE102 compliance secured with margin to the limit line
 - Z_{SRC} stays below the 2.5Ω threshold across the beat-frequency band
- **Result: $\sim 2.5\text{cm} \times 2\text{cm} \approx 5\text{cm}^2$ with a single passive component**

Designing the 12V DMP filter: process and numbers

- Regime: 8-phase LTC3888 hard-switched DMP: the comparative foil
 - The low bus voltage forces higher input current for the same power
- The filter must combat massive broadband noise and phase-dithering sidebands
 - Beat frequencies from phase timing errors
- **Solution: a multi-stage broadband network**
 - Wideband attenuation drives a far larger reactive sizing
- **Result: $\sim 17\text{cm} \times 3\text{cm} \approx 51\text{cm}^2$ — an order of magnitude larger than Vicor's $100V_{IN}$ solution**

Measurement setup

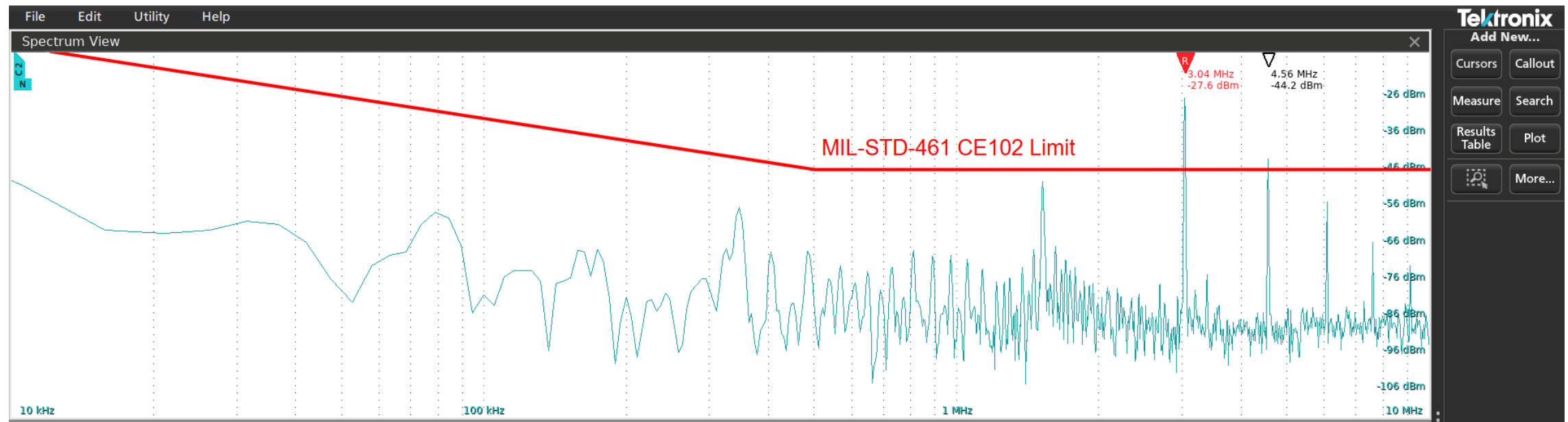
- LISN: 5 μ H TekBox TBL0510-1 with 50 Ω scope termination
 - Per DO-160 5 μ H LISN convention; monitor port read as V_{MON}
- Oscilloscope: Tektronix 6 Series B (MSO66B) with SpectrumView FFT
 - 150kHz - 10MHz capture window, 50 Ω terminated LISN port
- Noise excitation modeled as an AC current source at the load
- Measured LISN-port spectra compared directly against Mil-Std-461H CE102 limits
 - Readily tailorable to ECSS-E-ST-20-07C DM/CM limits — the narrowband SACTM advantage yields similar filter simplifications under the ESA standard



The Kikusui PLZ664WA Electronic Load used for the Vicor BCM[®] would not work at 1V, so a 12.5m Ω resistor array was used for the DMP

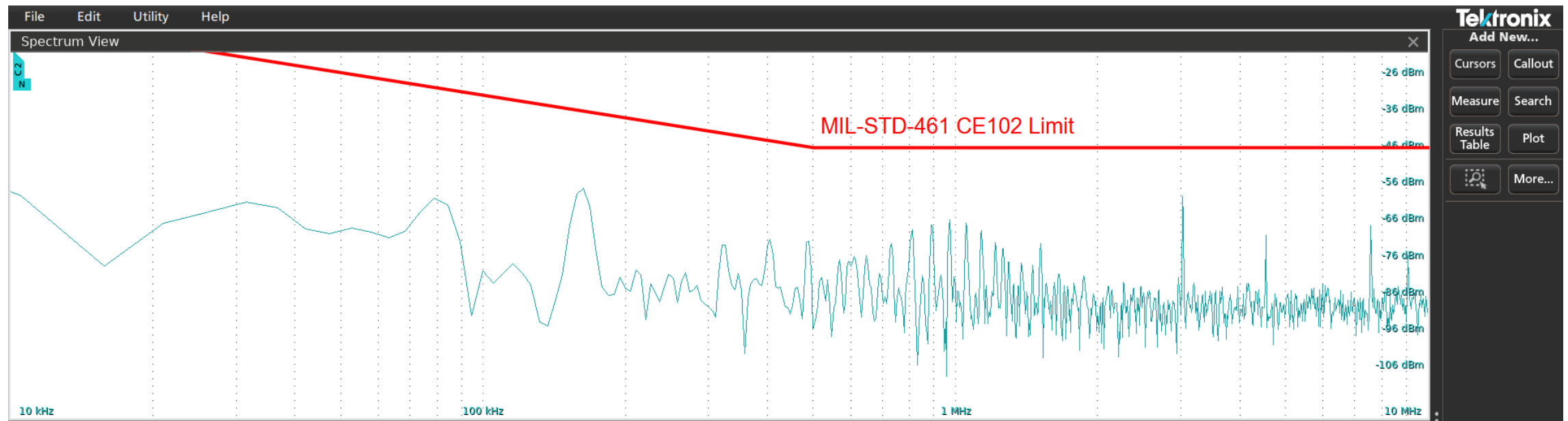
Scope plot 1: 100V_{IN} BCM[®] without filter fails

The measured LISN-port spectrum violates the CE102 limit line at several frequencies



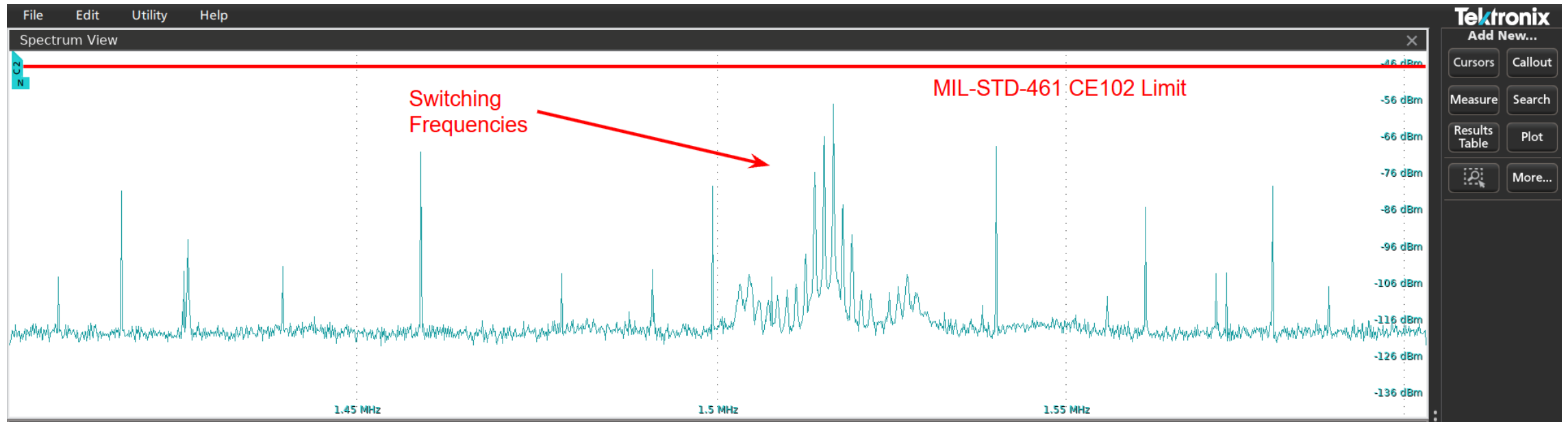
Scope plot 2: $100V_{IN}$ with filter passes with margin

Measured LISN-port spectrum, with the 6.8mH CM choke, against the CE102 limit line at several frequencies



Scope plot 3: $100V_{IN}$ switching frequencies without CM filter

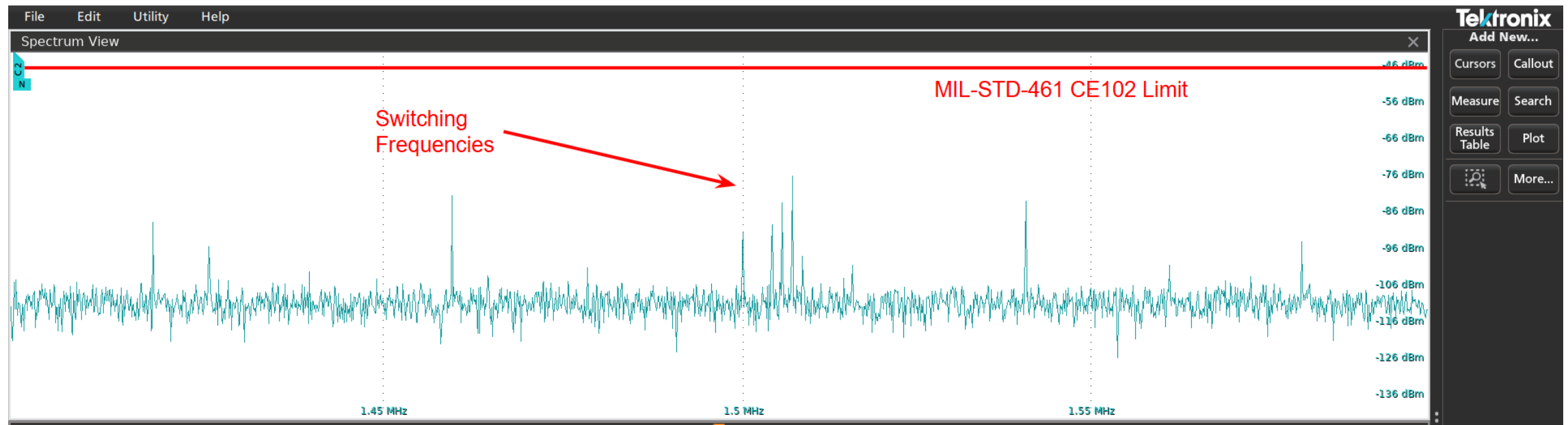
Measured LISN-port spectrum, without the 6.8mH CM choke, against the CE102 limit line at F_{SW} ($\sim 1.5\text{MHz}$)



Two unsynchronized SACsTM drift within 1.4 – 1.6MHz; the “discrete” comb is the time-history of two wandering fundamentals plus their beat products ($f_1 \pm f_2$) — not fixed spectral lines. Allowing a longer period of peak-hold measurements would fill in the valleys.

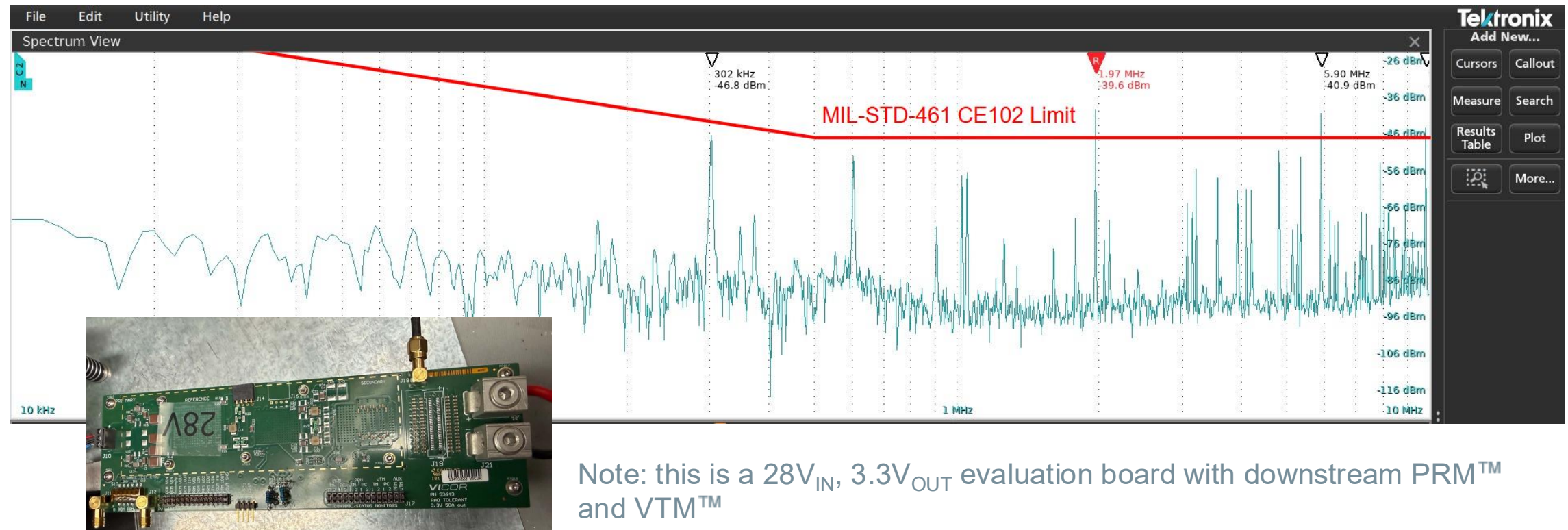
Scope plot 4: $100V_{IN}$ switching frequencies with CM filter

Measured LISN-port spectrum, with the 6.8mH CM choke, against the CE102 limit line at F_{SW} (~1.5MHz).



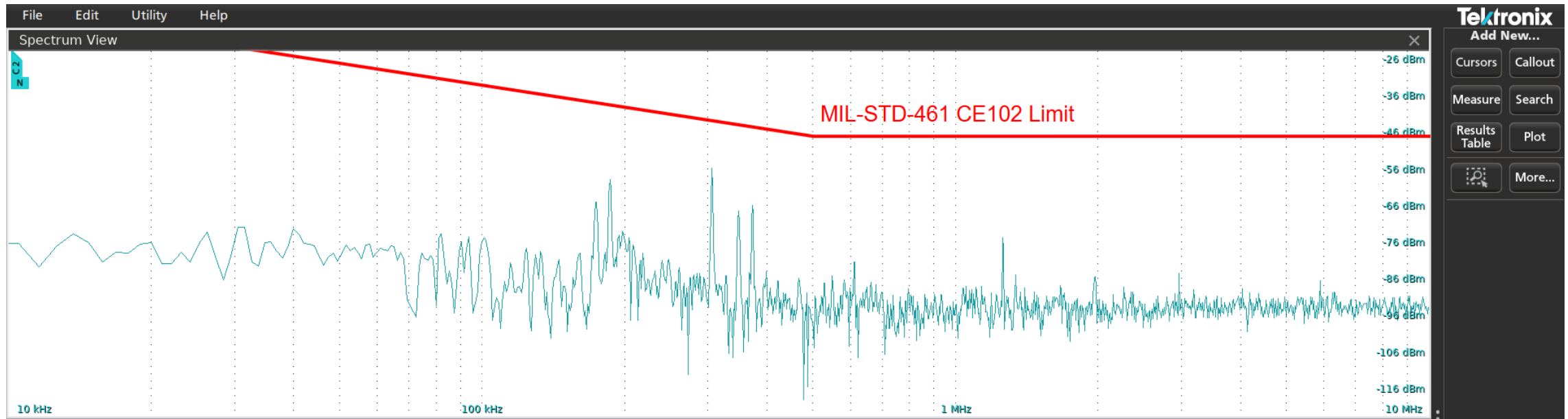
Scope plot 5: 28V evaluation board without filter fails

Measured LISN-port spectrum, without the filter, against the CE102 limit line at several frequencies.



Scope plot 6: $28V_{IN}$ with filter passes with margin

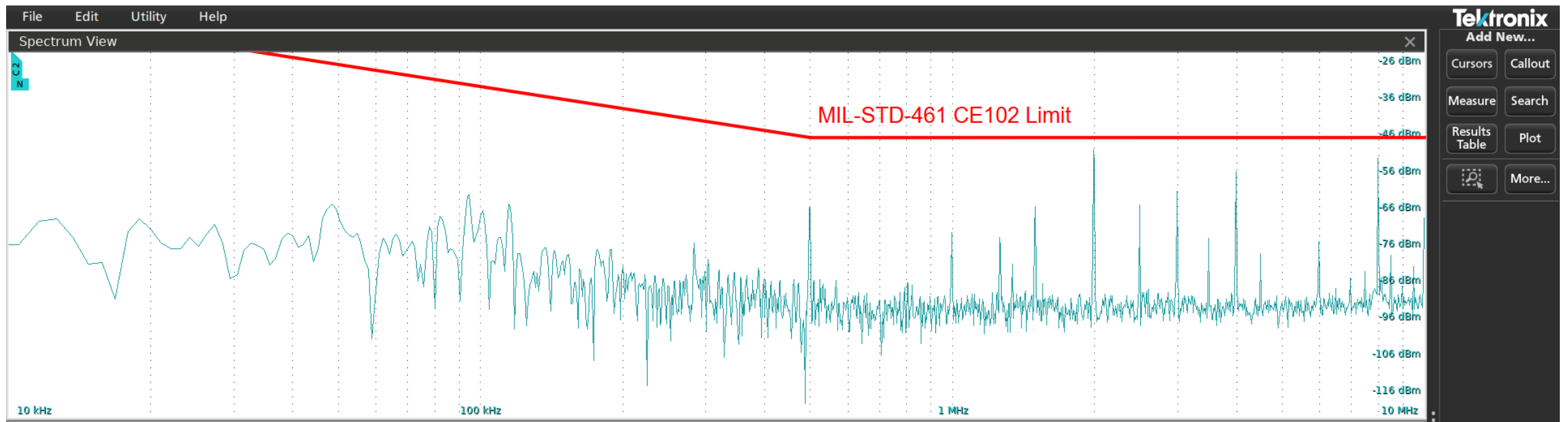
Measured LISN-port spectrum, with the filter, shows approximately 12dB of worst-case CE102 margin



The filter added is a 1mH CM choke, a 4.7 μ F X-cap and two 10nF Y-caps

Scope plot 7: 12V_{IN} DMP with filter passes — barely

Measured LISN-port spectrum, with the filter, against the CE102 limit line at several frequencies



The broadband DMP case is the demanding one: wideband content and beat-frequency sidebands — the much bigger multi-stage filter barely clears the limit.

Filter component comparison

Components	100V	28V	12V
CM Choke	1 x 6.8mH	1 x 1mH	—
X Caps	—	1 x 4.7 μ F	24 x 22 μ F 16 x 47pF
Y Caps	—	2 x 10nF	—
Resistors	—	—	8 x 162k Ω 8 x 300 Ω 8 x 0 Ω
Total Number of Components	1	4	64

Size and weight: 100V filter vs. 12V DMP

100V SAC™ input filter

~5cm²

single 6.8mH CM choke

12V DMP filter

~51cm²

multi-stage broadband network

10:1 footprint reduction at 100V (6.8:1 at 28V)

Mass scales with the magnetics — the DMP carries a substantially higher estimated mass

Why the difference: source impedance sets the burden

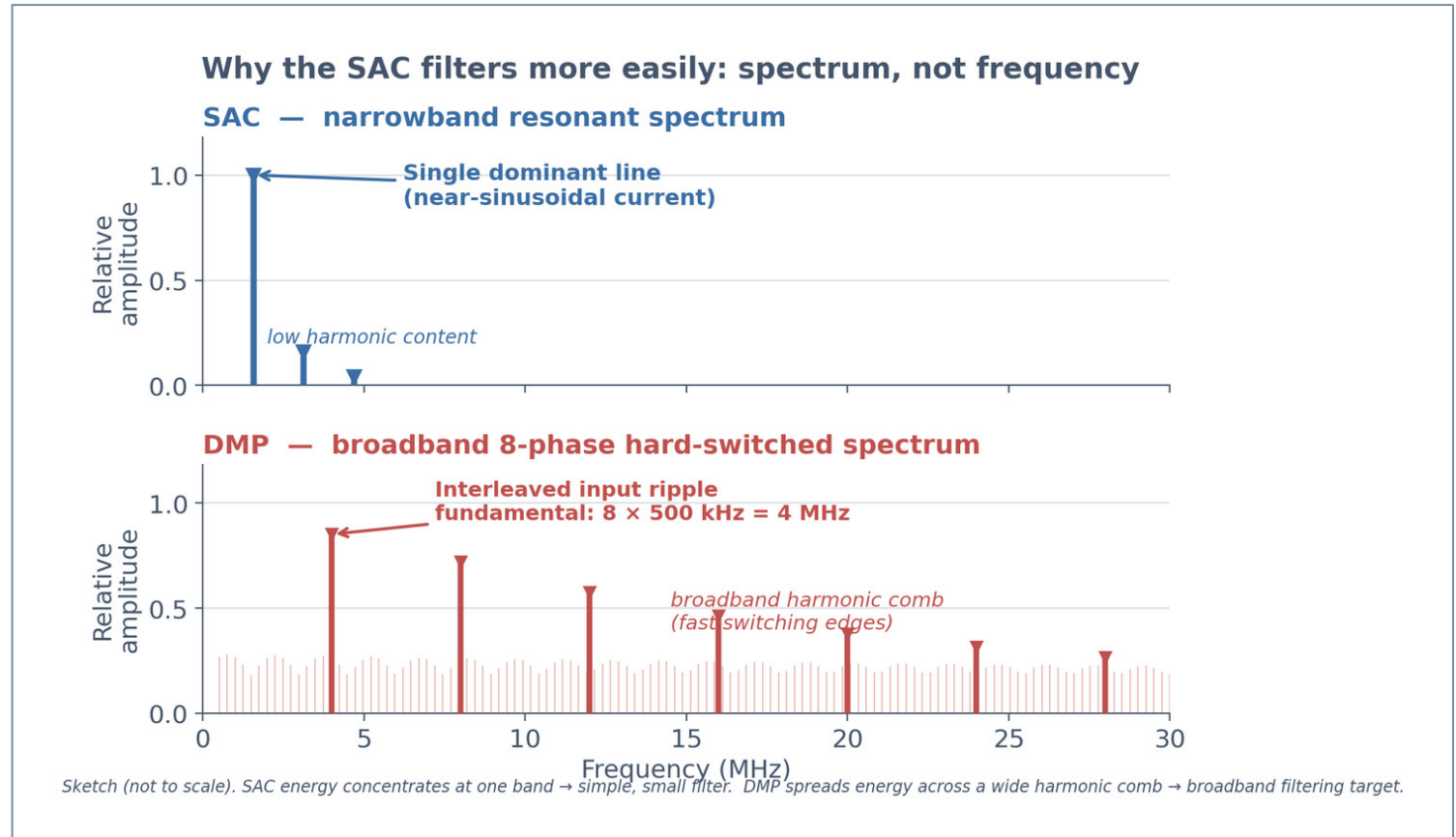
- At constant power, input current scales as $1/V_{IN}$
 - Higher bus voltage → lower current → smaller filter magnetics (e.g. at 400W: ~4A at 100V vs ~33A at 12V)
- The SACTM waveform is narrowband; the DMP waveform is broadband
 - Narrowband emissions need attenuation at one band, not a decade — vs broadband DMP content plus phase-dithering sidebands
 - Dual unsynchronized SACs beat together, but each spectrum stays narrowband — filtering stays simple
- The 10:1 reduction is the product of two independent mechanisms
 - Bus-voltage advantage (current scaling) × SAC waveform advantage

Why the difference: source impedance sets the burden (continued)

- The SAC's advantage is spectral, not just frequency: a fixed resonant tank produces a narrowband, near-sinusoidal current with low harmonic content—energy concentrated around one band. The DMP is hard-switched and broadband (fast edges with rich harmonics), so its filter must attenuate content across a wide span even after 4MHz interleaving
 - Net effect on filter magnetics: the SACTM needs attenuation at essentially one band, so its filter components can be small and simple. The DMP benefits from interleaving (higher effective ripple frequency, partial cancellation) but still faces broadband content — the harder filtering target
 - Dual unsynchronized SACs beat together, but each spectrum stays narrowband — filtering stays simple. (Interleaving is the DMP's analogous spreading mechanism, but it cannot make a hard-switched spectrum narrowband)

Why the difference: source impedance sets the burden (continued)

Right-sizing the filter follows directly from the source-impedance regime



Conclusions

Right-size the filter to the regime

100V_{IN} BCM[®]: a single 6.8mH choke

28V_{IN}: a compact mixed network

12V_{IN} DMP: large

Measured LISN-port spectra confirm the design models

Method is traceable: TBL0510-1 LISN + MSO66B SpectrumView vs CE102

Publish the operating envelope — state the load limits you designed to

Bounds the reconfigurable-load problem and margins

Higher bus voltage with SAC[™] topology yields up to a 10:1 filter footprint reduction for space

Vicor rad-tolerant modules for New Space

- This filter work ties directly to flight-relevant SAC-based hardware
 - Qualified rad-tolerant non-hermetic modules: BCM[®] PRM[™], and two VTMs[™] for LEO/MEO missions
- Radiation ratings
 - TID tested to 50krad; LET ~43MeV·cm²/mg
 - SEE mitigation with autonomous auto-restart hardware and internally redundant powertrains
- Low-noise advantage for system EMI: BCM SAC[™] modules switch above 1 MHz, avoiding the harmful 100 – 500 kHz noise band
 - Example efficiency: 100V_{IN} k=1 / k=3 BCM at up to 97%
- Flight heritage / qualification path strengthens relevance for ESPC and New Space programs

Thank you



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Ken Coffman is a Lead Applications Engineer at Vicor, where he serves as the company's New Space Initiative Subject Matter Expert for radiation effects on electronics. His current work focuses on radiation-tolerant power modules for AI/ML processing loads in LEO and MEO orbits, spanning power-module definition, input-filter design, and EMC pre-compliance testing for space platforms. He has been with Vicor's New Space Initiative since 2019 and previously served as a Senior Principal Field Applications Engineer at Intersil Corporation and Fairchild Semiconductor. He holds a BSEET from Cogswell College North and completed MSEE coursework at the University of Washington. Beyond power electronics, he is an author, publisher and writes the technical newsletter *The Augmented Engineer*.

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