Low-noise electrification using 48-V automotive systems

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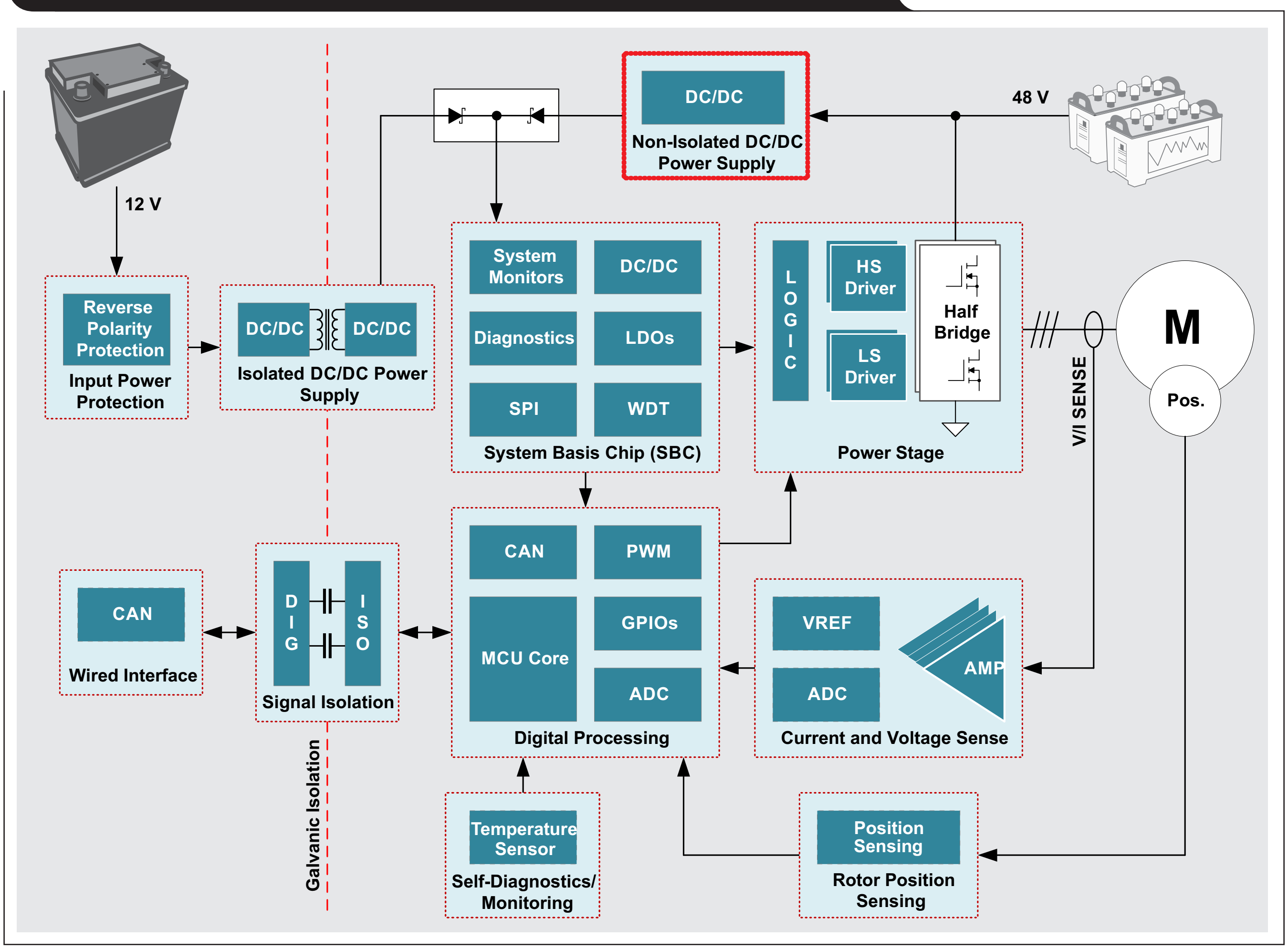
Introduction

Modern emission standards are driving the need for more efficient automobiles. Although car manufacturers can achieve a greener vehicle by electrifying more car functions, such an approach requires a revision of 12-V car systems to handle larger power demands without affecting system efficiency or cost.

Auto manufacturers are creating greener cars through a dual-source electrical platform, as in mild-hybrid-electric vehicles (mHEVs). The mHEV combines a 12-V battery (for compatibility with current systems) with a 48-V Lithium-ion battery pack to run high-power loads such as the starter generator (see Figure 1). A conventional, integrated starter generator (ISG) is capable of delivering less than 15 kW of power given the inefficient power transfer between its belt and the car's drivetrain. Newer variations of ISGs enable higher efficiency, with parallel (P2/P3/P4) architectures able to deliver up to 20 kW, reducing carbon-dioxide production by about 15%.[1]

The increasing power demands of starter generators in mHEVs have designers turning toward 48-V batteries. P2/P3/P4 starter generators can deliver more power to drive auxiliary components. A 48-V powered starter generator will allow for a higher output power, with reduced current delivery. A lower current demand enables the use of smaller wire thickness for the 4-km wiring harness,[2] which leads to significant weight reduction, furthering car efficiency and reducing system costs.

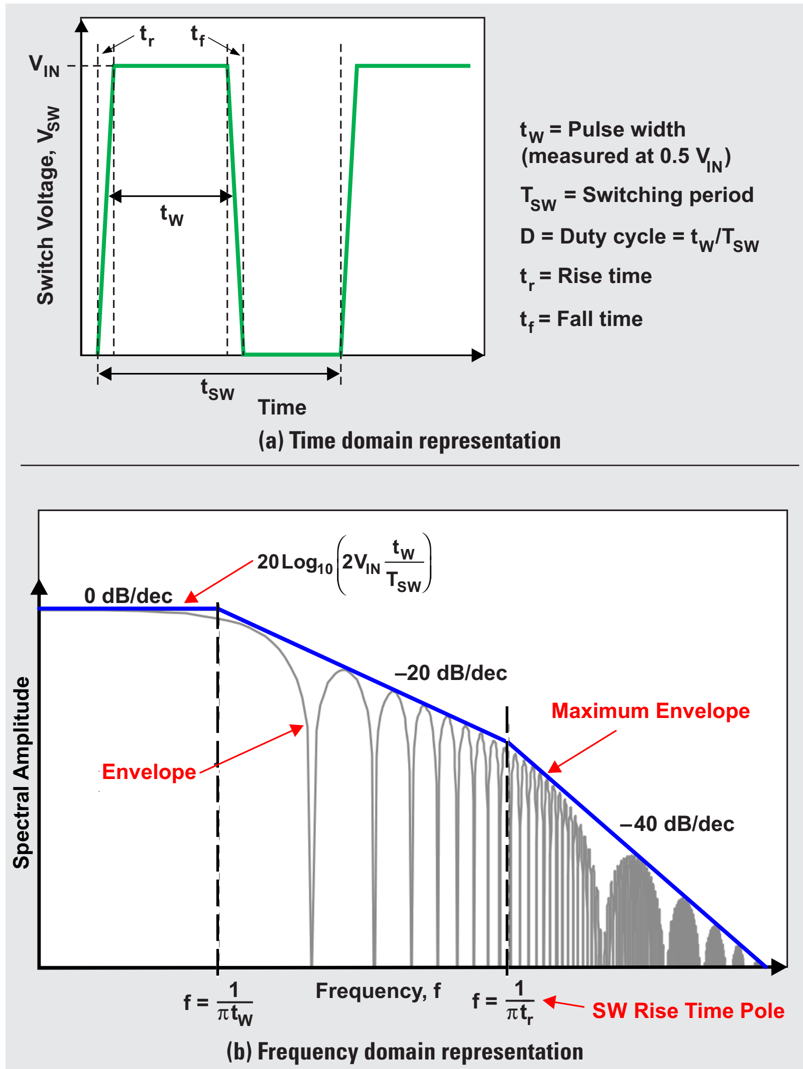
Figure 1. Example block diagram of an mHEV starter generator system[3]



In addition to driving the power train, the 48-V battery acts as a backup power source to 12-V powered components, with a DC/DC regulator generating the redundant 12-V supply from the 48-V battery. Given the simplicity of step-down regulators, they can create a simple bias supply for the MOSFET gate drivers. A 1-A step-down converter provides the bias supply's 500-mA load requirement. The LM5164-Q1 can satisfy this power demand in addition to the typical 70-V transient requirement specified in International Organization for Standardization (ISO) 21780.

It is also important to consider the step-down regulator's electromagnetic interference (EMI) performance, as 48-V subsystems are subject to Comité International Spécial des Perturbations Radioélectriques (CISPR) 25 Class 5 compliance testing.

Figure 2. Time- and frequency-domain representation of the switched voltage waveform



EMI issues with dual-battery 12-V and 48-V systems

The general principles of mitigating EMI do not change between 12-V and 48-V step-down regulators. The regulator's discontinuous input current and switch-node voltage waveform will generate EMI, while a step-down converter can cause electromagnetic-compatibility (EMC) compliance failures with an improper input filter or layout design. Fortunately, because the same output power capability at 48 V with a reduced load current lessens conducted (differential) emissions, the switched waveform, the second predominate source of EMI, requires the most attention. The switched waveforms' increased amplitude leads to more EMI.

As shown in Figure 2a, the regulator's switched waveform is a trapezoidal waveform with a magnitude equal to that of the input voltage. For simplification purposes, assuming equal edge rates, the amplitude of the Fourier coefficients of this waveform directly relates to its magnitude. The spectral envelope's upper limit (at DC) going from V_{IN} = 12 V to V_{IN} = 48 V would correspond to a 12-dB increase, as shown in Figure 2b.

The increase in the amplitude of the switch-node voltage waveform leads to the presence of more energy at higher frequencies, where CISPR 25 Class 5 limits also become more stringent. This high-frequency energy becomes more of a problem with faster edge rates on the switched waveform. Faster edge rates facilitates lower switching losses within a regulator design, but at the cost of increased noise, an idea explained by the location of the "SW rise-time pole" in Figure 2b. The trapezoidal waveform's spectral envelope rolls off by –40 dB/dec at this pole location. A higher SW rise-time pole or a faster rise time leads to more high-frequency energy content on the switched waveform.

Remember that the switch node can radiate noise. A large copper area (including the inductor) increases the noise generation, especially for the 48-V input case. This increase is evident in the regulator's 30-MHz to 108-MHz conducted emissions EMI sweep. Figure 3 compares the EMI performance with 24-V and 48-V inputs.

The inductor ripple current should ideally be 30% to 40% of the load current to ensure low core loss and output ripple. Equation 1 calculates the inductor ripple:

$$\Delta I_L = \frac{(V_{IN} - V_{OUT}) \times D}{f_S \times L} \qquad (1)$$

A higher input-to-output voltage differential requires a higher inductance, which means that an inductor with a larger package is required. For example, the inductor ripple should be limited to 150-mA for a 500-mA bias supply. As such, a 12-V to 5-V, 400-kHz converter would require a 47-µH inductor. In contrast, a 48-V to 12-V conversion would require a 150-µH inductor. Ensuring a similar power rating would require a much larger inductor, which will generate substantially more noise.

The conversion from 48-V to 12-V needs a lower switching frequency (sub-AM band, such as 400-kHz) in order to remain above the minimum on-time requirement. The regulator's minimum on-time requirement is an integrated circuit (IC) specification, which typically describes the time it takes for the regulator to properly sense the inductor current. A lower switching frequency will also require a larger output filter. The relative inductance and capacitances will increase to ensure both stability and sufficient performance. The larger inductance value leads to a larger physical size of the output filter, causing more noise generation.

Switch-node noise capacitively couples back onto the input lines of a 12-V car battery system. The dual-battery mHEV system calls for the grounds of the 48-V (KL41) and the 12-V source (KL31) to remain separate[4]—the chassis will be connected to KL31 and will capture this switch-node noise, possibly leading to additional radiated emissions known as common-mode noise. The generation of this noise must be suppressed; otherwise the 48-V powered subsystem will not be CISPR 25 Class 5 compliant.

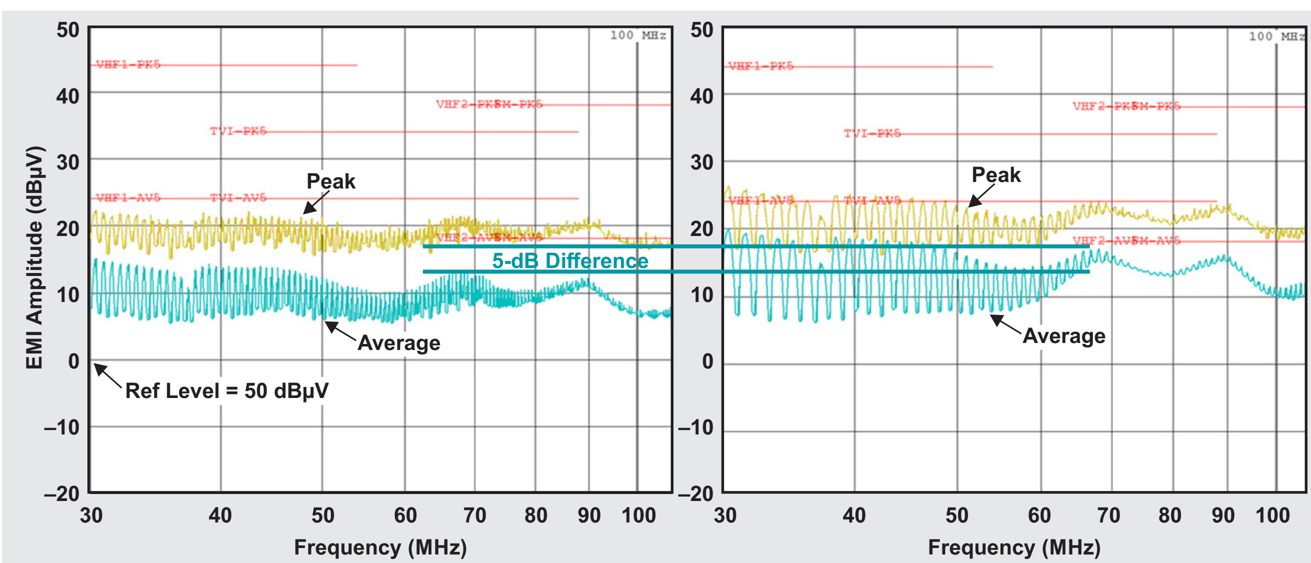
Suppressing 48-V step-down regulator common-mode noise

The high edge rate on the switch node creates noise above the 30-MHz range, extending into the FM band and creating a challenge for compliance testing. Noise mitigation techniques can reduce this noise and result in a CISPR 25 Class 5-compliant design.

Low-noise automotive power regulators contain spread spectrum for reduced noise. Modulating the switching frequency reduces peak energy in the emissions spectrum. Triangular spread-spectrum (TRSS) modulation is one way to reduce the peak energy.

TRSS is optimized for spreading energy at lower frequencies. The TRSS frequency of modulation is close to the 9-kHz resolution-bandwidth (RBW) filter used for CISPR-25 Class 5 150-kHz to 30-MHz conducted testing, enabling a peak reduction in this CISPR 25 Class 5 frequency band. At higher frequency bands, unfortunately, TRSS it is not as effective, but in such cases, pseudo-random spread-spectrum (PRSS) techniques will make up for the TRSS shortfall. Because most EMI challenges originate at a higher frequency (the FM band), PRSS is able to

Figure 3. LM5164-Q1 EMI performance with 24-V and 48-V inputs with the same load conditions



(a) EMI with 24-V input

(a) EMI with 48-V input

modulate at a more appropriate frequency for CISPR 25 Class 5, 30-MHz to 108-MHz testing. An effective modulation frequency can be achieved that's more broadband and better suited to a higher-frequency RBW filter (120 kHz) with PRSS.

Dual-random spread-spectrum (DRSS) is the latest iteration of spread spectrum modulation offered by Texas Instruments. Because DRSS implements cycle-by-cyle pseudo-random dithering on top of its low-frequency, triangular-modulated waveform, it implements the best features of both TRSS and PRSS. This modulation technique appeases the RBW filter bandwith used in low- and high-frequency CISPR 25 Class 5 measurements.

Low-noise power regulators implement many of these spread-spectrum techniques; in fact, many 100-V controllers (Figure 4) often contain a SYNCIN pin for applying an external clock source that can be modulated with one of the spread-spectrum techniques described, as well as an additional SYNCOUT pin to buffer out the external clock source. Ultimately, synchronizing multi-regulator designs allows beat-frequency generation caused by small differences in the switching frequencies to be avoided.

Furthermore, as advanced driver assistance system (ADAS) applications evolve and require more processing power or sensors (or both), system designs may require even more output power from the 48-V to 12-V regulator. Paralleling regulators with SYNCIN and SYNCOUT facilitates higher output-power capability in addition to ripple cancellation. The 180-degrees out-of-phase SYNCOUT pin in the LM5146-Q1 enables low-noise through input ripple cancelation. This allows for a compliant, high-current, multiouput capable power design for the 48-V battery. The versatile LM5146-Q1 provides a modular power supply for design reuse across evolving ADAS platforms.

The high edge rates of the switch voltage extend the power spectral-density plot up into the FM band. The conversion from 48-V to 12-V requires a converter operating at below the AM band frequency (400 kHz). The "low" switch frequency, in tandem with the subampere load requirement on the starter generator's bias supply, results in a low-loss converter. The improved efficiency allows for slower rise times to reduce noise, which a compliant design may in fact require.

Figure 4. Low-EMI, high-current LM5146-Q1 controller with 48-V battery input

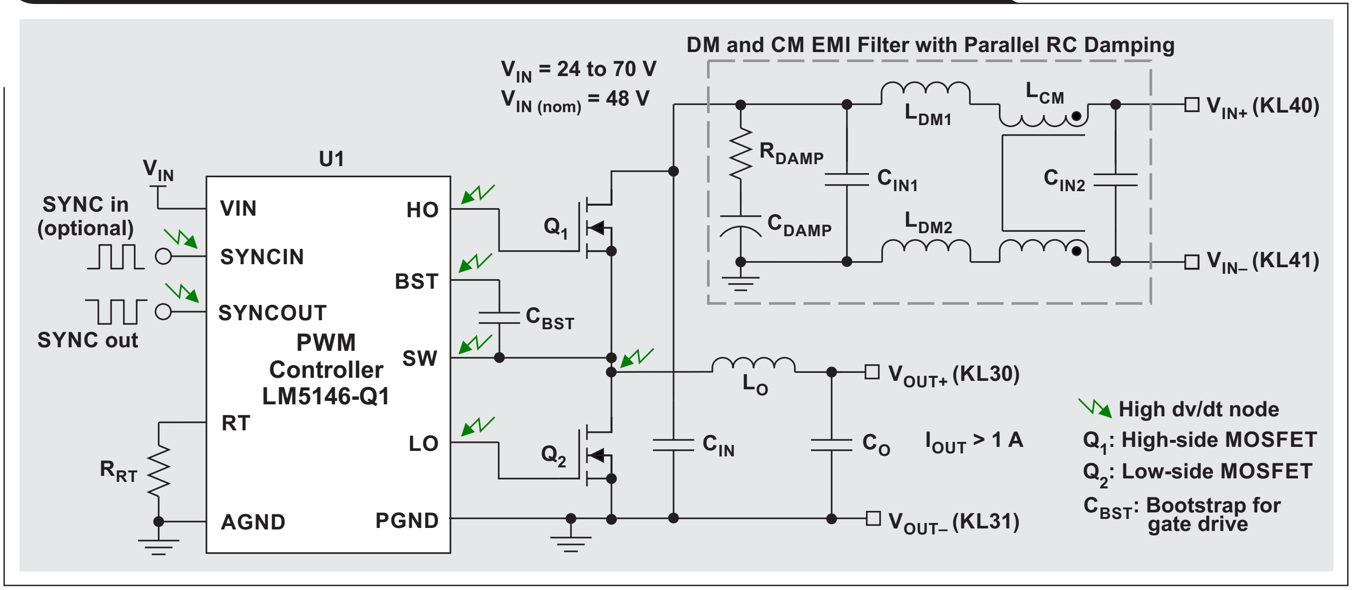
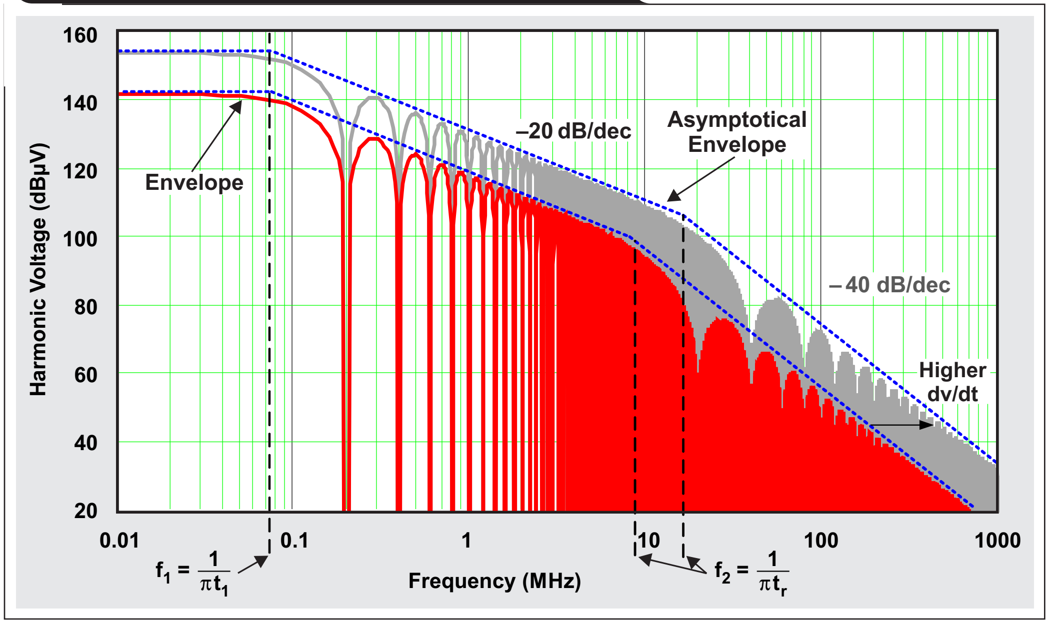


Figure 5. Comparison of switch-node power spectral-density plots with varying rise times



One method to reduce rise times involves creating a slower rise time of the MOSFET gate voltage by adding a series resistance with the boot capacitor (C_{BST} in Figure 4). The slower MOSFET turn-on will lead to a lower-frequency SW rise-time pole. Figure 5 demonstrates a 20-dB reduction using this method, with a switch-node voltage waveform having a rise time 100% larger than the default.

The number of EMI tools implemented into power regulators continues to increase to accommodate increasing demands to operate at higher frequencies, achieve higher power densities and comply with more stringent EMI standards. Unfortunately, such requirements often require further EMC filtering beyond IC EMI mitigation techniques.

Conclusion

Before selecting a power regulator for a 48-V application, it is important to evaluate the impact of a higher input voltage on EMI. It's also important to select a power regulator with multiple EMI mitigation features to reduce additional noise from the higher input voltage. Even with low-noise regulators, it's a good idea to follow low-noise PCB layout practices and take a methodical approach when selecting EMC components. Emulating data-sheet and evaluation board examples are good first steps when designing a low-noise power converter.

References

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4. Timothy Hegarty, "Why use PSR-flyback isolated converters in dual-battery mHEV systems," Texas Instruments Analog Design Journal (SLYT791), 2Q 2020.

Related Web sites

Product information:
LM5146-Q1
LM5164-Q1

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• Timothy Hegarty, "The Engineer's Guide To EMI In DC-DC Converters (Part 8): Common-Mode Noise Mitigation In Isolated Designs," How2Power Today, February 2019.
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• Timothy Hegarty, "The Engineer's Guide To EMI In DC-DC Converters (Part 13): Predicting The Common-Mode Conducted Noise Spectrum," How2Power Today, June 2020.

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