Applications of E-CAPs Part 1:

Bypass capacitors for high frequency switching regulators: breaking the 5MHz barrier

AN-ECxx-1

Empower Semiconductor, Inc.
August 2022

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Applications of E-CAPs

2 Introduction

The E-CAP family of silicon capacitors is a new technology developed and marketed by Empower Semiconductor that offer breakthroughs in density and performance. This technology offers both discrete and integration capabilities for broad market and custom, monolithic solid-state device in the world's thinnest, most compact, and most flexible capacitor solution. Designed using the advanced deep trench capacitor technology, the latest E-CAP solutions offer densities of 1.1 µF/mm^2(with a path to 1.5 µF/mm^2) which is over twice the density of alternative silicon capacitor technologies. Figure 1 shows an illustration of the space saving that can be achieved with E-CAP solutions. By integrating an array of capacitors into a single die, this technology allows for better component placement, flexible pin-out and the use of different value capacitors to save a significant amount of area and reduce the number of discrete components. In addition to the density, thinness levels can be achieved below 50 µm in overall height. E-CAP density is over five times that of leading multilayer ceramic capacitors (MLCCs) with improved equivalent series inductance (ESL in the pH range) and equivalent series resistance (ESR in the 10 of mΩ range) characteristics that improves power supply bypassing and PDN optimization over a broad frequency range.

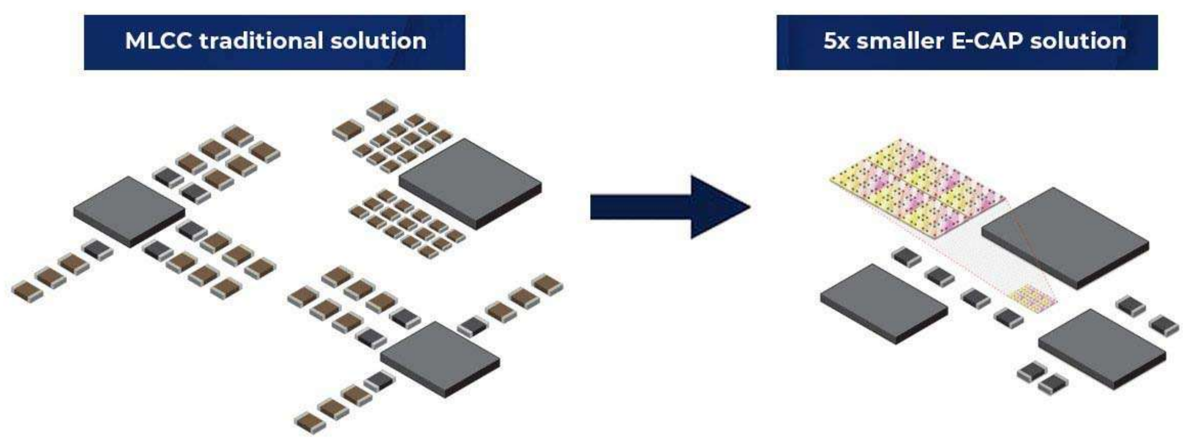

Figure 1. Discrete MLCC capacitors vs E-CAP solutions.

The primary benefit of E-CAP in a system is to provide a superior high-frequency de-coupling solution with a much smaller footprint and component count than traditional MLCC-based solutions. E-CAP also provides the added benefit of simplified design thanks to customizable form factors, flexible packaging options and negligible de-rating requirements. This collection of app-notes explores a few applications of this technology, Part 1 focuses on enabling high frequency DC/DC converters. To know more about additional benefits and performance parameters of the technology, including lack of aging effects and DC bias derating more information can be found at https://www.empowersemi.com/ECAPs or https://www.empowersemi.com/ecap-new-capacitor-silicon-revolution/.

3 Bypass capacitors for high frequency switching regulators

The original application for E-CAP was born out of necessity when Empower Semiconductor identified the limitations of MLCCs while developing its family of high frequency integrated voltage regulators (IVRs). Determining that 'off-the-shelf' devices were not good enough for high frequency IVRs, the company developed its own capacitor technology: E-CAP™. The performance benefits of E-CAP have allowed the company to capitalize on the improvements that IVRs deliver over conventional power management solutions. The general trend of increased switching frequency to reduce the solution size of DC/DC converters has been leveraged for years by multiple IC vendors. Higher frequency and smaller passive component size (inductor and capacitors) enables greater than 0.3 A/mm^2 solution density as achieved by Empower's IVR products. Like any engineering decision, this does not come without tradeoffs or limitations, from voltage conversion ratio to efficiency to cost. At times technological advances are necessary, e.g., advancement in magnetic materials for inductors, semiconductor device technology. Similarly, the capacitor technology advancement from electrolytic to tantalum to ceramic has enabled and supported higher frequency of operations.

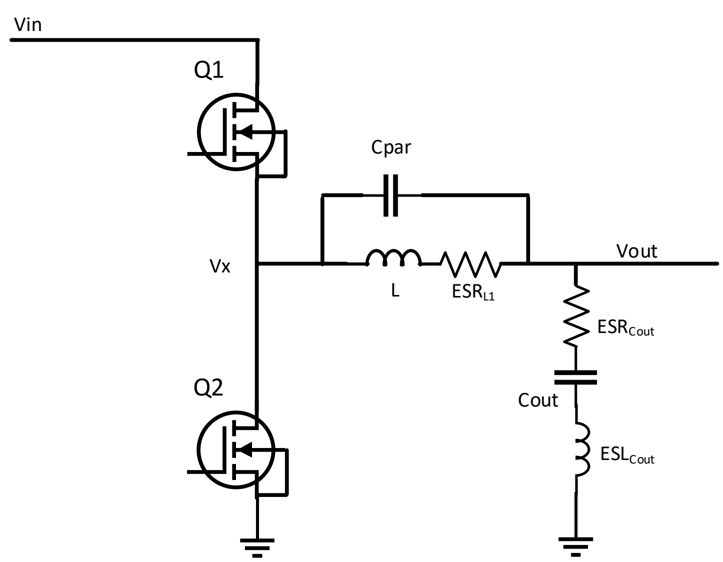

Figure 2. Buck regulator topology with parasitic components of capacitors and inductor.

Figure 2 shows a buck regulator topology highlighting the parasitic components associated with the main inductor (L) and capacitors (Cout) in the circuit such as the equivalent series inductance (ESL) and an equivalent series resistance (ESR) of the output capacitor. With higher operating frequencies these components – often-neglected at low switching frequencies – become critical design elements and need to be optimized as they affect the noise (not just ripple) and transient response of the circuit beyond the ability of the control loop to influence the system behavior.

Inductor (L1): Inductor values are typically based on a target ripple current (ΔI_L) at a specific switching frequency (f_{sw}). Figure 3 highlights this direct correlation between inductor value and switching frequency as described by equation 1.

$$\Delta I_L = \frac{V_{out}}{f_{sw} \times L}\left(1 - \frac{V_{out}}{V_{in}}\right) \qquad (1)$$

Output Capacitor (C_{out}): The capacitor is used to both absorb the current ripple as well as limit the voltage fluctuations during a load transient (along with the regulator control loop) to acceptable levels. Like the inductor, the C_{out} capacitance is inversely proportional to the switching frequency and that ratio between L and $C_{out}$is typically constant. The first step in sizing the output capacitor is to determine its value based on the output voltage ripple target (ΔV_{out}) requirement with the following equation.

$$C_{out} = \Delta I_L \frac{1}{8 \times f_{sw} \times \Delta V_{out}} \quad (2)$$

Let use the example of a buck converter with 5V input to 1V output conversion ratio, a 500mA current ripple and an output voltage ripple target of 10 mV to explore some of the parameters that affect the converter noise performance and understand when they need to be taken into consideration. A switching regulator operating at 100 kHz requires a 10µH inductor and over 100 µF of output capacitance; at 2 MHz the passive components could be reduced below 1 µH and 10 µF; and at frequencies above 10 MHz an inductance less than 100 nH and a small 1 µF capacitor are sufficient to address the design targets, as shown in Figure 3.

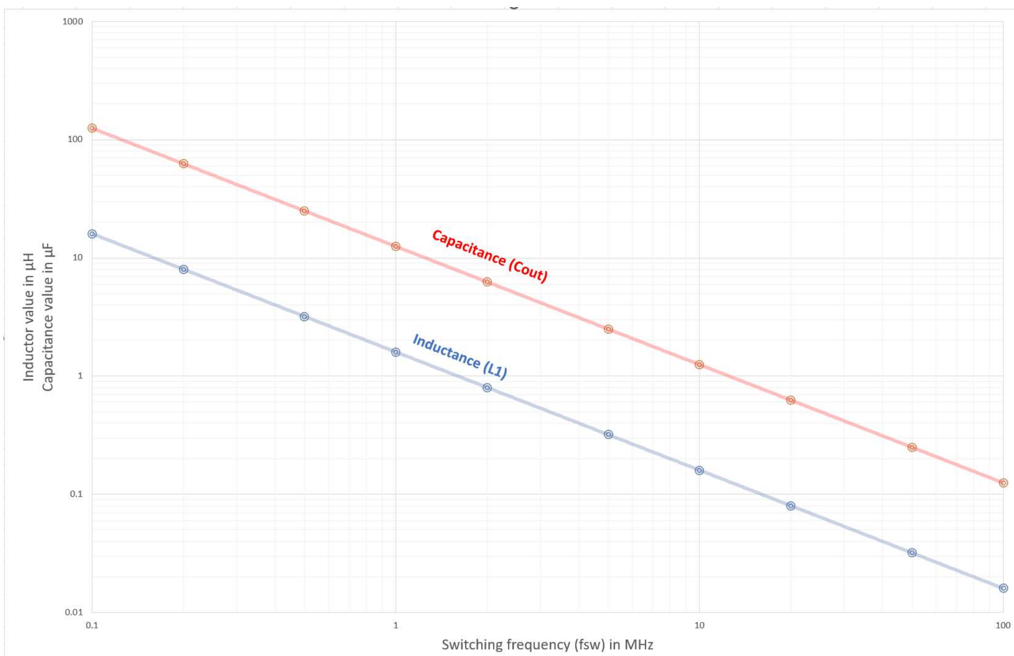

Figure 3. Inductance and output capacitance requirements vs DC/DC switching frequency.

With increased switching frequency and the ongoing trend for lower output voltages, this first approximation approach has limitations, as even the smallest 10uF MLCC capacitor (0402 package) still presents about 200 pH of ESL (equivalent series inductance) [1].

Figure 4 shows the typical frequency response of different ceramic capacitors with minimum equivalent series resistance (ESR zero) or self-resonance anywhere between 200 kHz and 20MHz. MLCC manufacturers offer capacitors in the reverse geometry configuration to reduce inductance but even those capacitors struggle to provide less than 100 pH of inductance for a 2.2uF capacitor in a 0306 case size [2].

Conventional DC/DC converters assume that they always operate at frequencies below the resonant frequency of the output capacitor and the control loop usually assumes a minimal ESL contribution to the loop. Operating above the resonant frequency is possible but the control loop needs to be designed to compensate for the characteristics of these capacitors.

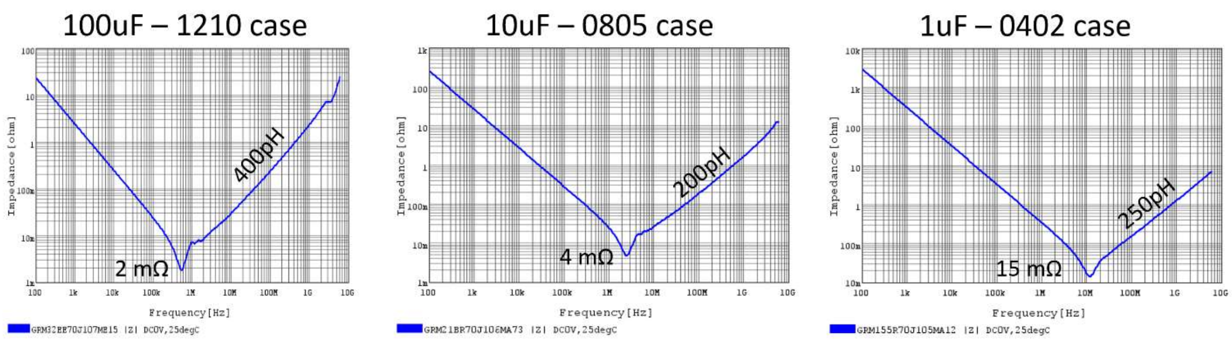

Figure 4. Examples of MLCC impedance characteristics with small ESR.

To consider the effects of the parasitic properties to the output ripple (noise in general), let us consider the following 5 terms:

$$\text{Term 1: } \Delta V_{out}{}^{1} = \Delta I_L \times \frac{1}{8 \times f_{sw} \times C_{out}}$$

Term 1 is the starting design target. Its contribution to the output ripple is flat over the fundamental switching frequency (f_{sw}) of the DC/DC converter. For a 10mV ripple target it is wise to add some margin due to the typical derating (DC bias, AC bias, temperature, and aging). A good starting point for the example used in this design is 5 mV. This first term is the dominant contributor for any frequency below 1 MHz, as illustrated in Figure 5.

Term 2 is associated with the ESR of the capacitor:

$$\text{Term 2: } \Delta V_{out}{}^{2} = \Delta I_L \times ESR_{C_{out}}$$

With a constant ripple current and an increased ESR due to the smaller capacitor the contribution to ripple tends to increase with frequency. Starting at 1 MHz, this ripple component becomes material with an additional 2 mV of ripple, and it becomes the dominant component at 5 MHz.

Term 3 and Term 4 are associated with the ESL of the capacitor:

$$\text{Term 3: } \Delta V_{out}{}^{3} = ESL \times \frac{di}{dt}$$

$$\text{Term 4: } \Delta V_{out}{}^{4} = V_{in} \times \frac{ESL_{C_{out}}}{(ESL_{C_{out}} + L1)}$$

The ESL of capacitors is dependent on the case size and the ratio of capacitance to size is somewhat limited by the insulation material and voltage rating. Effectively the ESL of a capacitor for our design is somewhat fixed to the minimum possible as we mentioned previously (about 250 pH). With decrease in L and, hence, increase in di/dt with higher switching frequencies, the region above 2 MHz is also where Terms 3 and 4 become significant. Any design operating in this region will require the right choice of capacitor or requires a network of multiple capacitors to reduce the effective ESL. At 10MHz operation the ESL of the output capacitor is no longer negligible, and the associated ripple terms are of concern.

Term 4 relates to the extremely high slew rate of the switching node voltage (V_X), that is, high dv/dt step stimulus at the input of the output LC filter. This can also be referred as a feedthrough noise component and the higher the input voltage the more influence it will have on the output voltage.

In Figure 5, Terms 1 through 4 are plotted to shows the relative amplitude of each term separately, considering the typical values from commercially available components. The horizontal axis represents the fundamental switching frequency of the DC/DC converter.

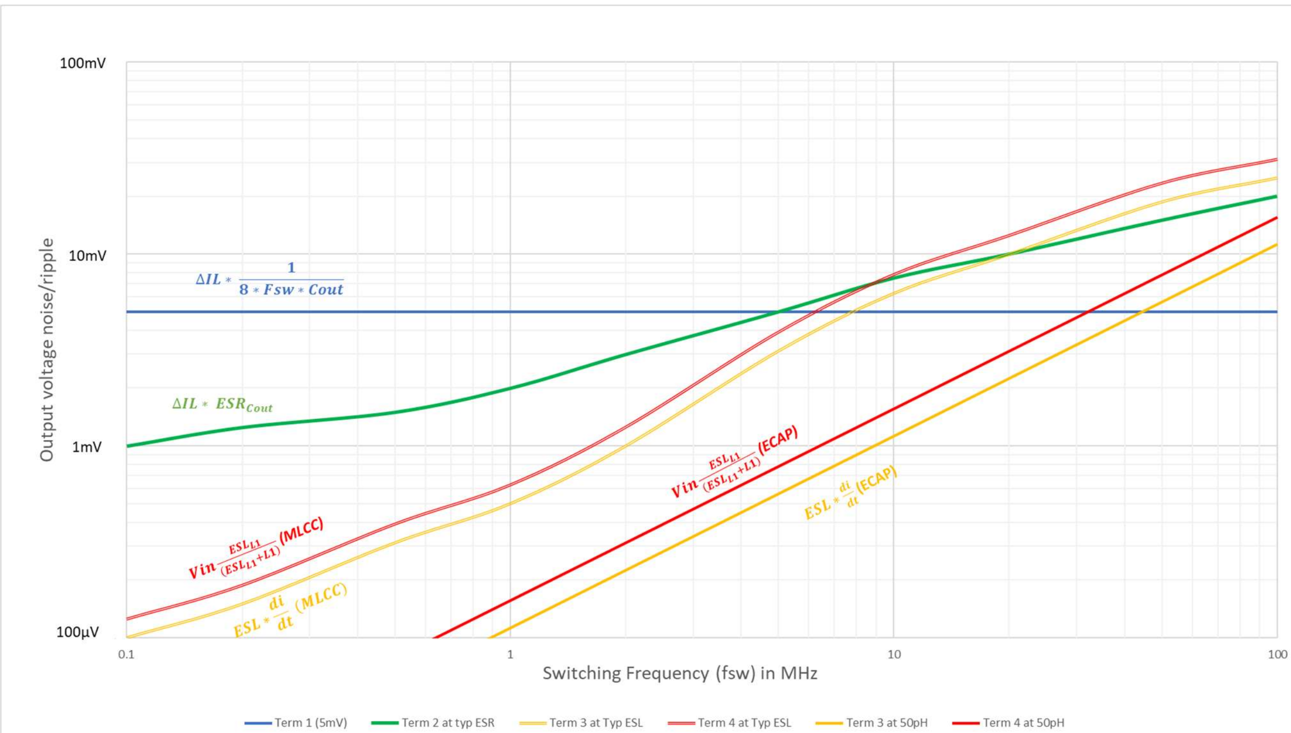

Figure 5. Ripple and noise contributors over switching frequency.

As the analysis highlights, commercially available MLCC capacitors are suitable at switching frequencies up to a few MHz. The E-CAP technology, however, provides a breakthrough for the 5MHz barrier with respect to MLCCs. With E-CAPs, the ESL is reduced by a factor of 10 and enables the operating range of switching regulators to frequencies well above 20 MHz.

Figure 6 shows the impedance curve for a standard 220nF E-CAP from Empower Semiconductor (EP1001), with less than 20 pH of effective ESL and 40 mOhm of ESR. The E-CAPs have a resonance frequency at a much higher frequency, well above 100 MHz, enabling a new paradigm for switching regulators operating frequencies and its associated benefits such as solution size and control loop bandwidth, that is the speed of its response to transients.

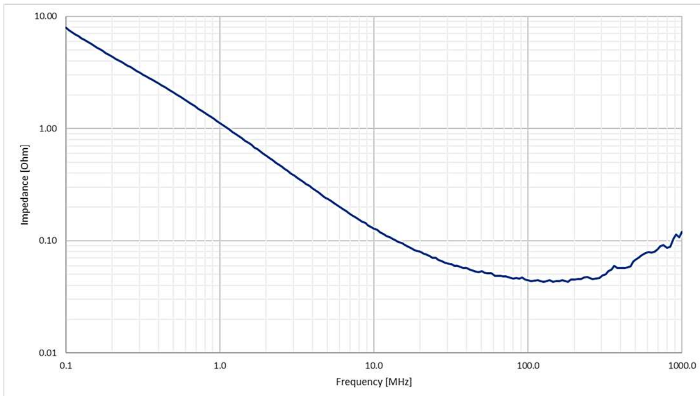

Figure 6. EC1001 E-CAP impedance characteristics.

The use of E-CAPs alone or the combination of E-CAP with ceramic caps will extend the operating frequency of the bypass network reducing the contributions to output noise from Terms 3 and 4. As an example, one or two E-CAPs in parallel with a 10uF MLCC capacitor would achieve an impedance profile (Figure 7) that extends the useable frequency of operation of the bypass network and enables higher switching frequency DC/DC converters (beyond 10 MHz).

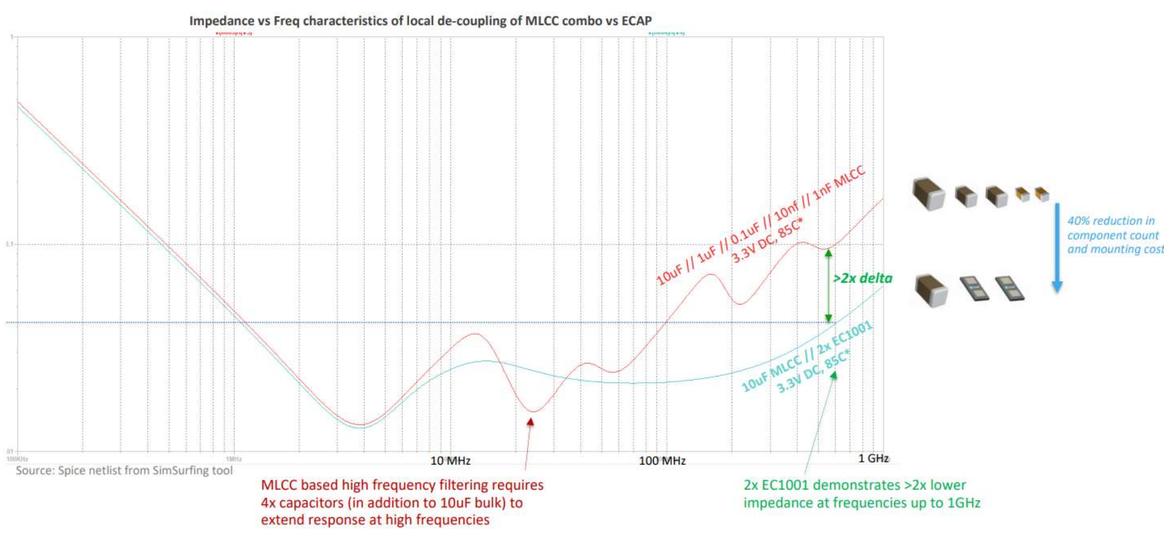

Figure 7. MLCC only network in comparison to MLCC + E-CAP.

An even more useful approach is what Empower has done with increasing the switching frequency of the IVR to 10s of MHz and only requiring a few micro-Farads of output capacitance and no MLCCs at all.

Finally let us analyze term 5. This term also is related to the high dv/dt of the switching node (V_X):

$$\text{Term 5: } \Delta V_{out}{}^{5} = V_{in} \frac{C_{par}}{(C_{out}+C_{par})}$$

The value of the parallel interwinding capacitance (C_{par}) decreases over frequency due to the smaller geometries and fewer number of turns used for lower inductances, its effect on noise contribution to the output is going to start having an impact at frequencies well above the 10MHz mark. Most applications are not affected by this winding capacitance unless the noise target falls below the 10µV level. As a sanity check, we can look at the series resonant frequency (SRF) specification of some common inductors and determines the value of C_{par} based on equation 5. Looking at most modern inductors [4], a 10µH/2A inductor will have an SRF around 10 MHz, making Term 5 close to 100 nV. At higher frequencies, the geometry, material, shielding as well as the winding construction plays a more significant role. For example, a 100nH inductor suitable for 10 MHz operation will have a range of SRF between 100 MHz for a “bulky” inductor to well above 1 GHz for smaller, more lossy inductors. This will contribute 2 - 100 uV in additional noise at the output of the switching converter. In this case only the most noise sensitive designs would have to consider this term and likely other effects like layout and magnetic coupling will be more noticeable.

$$SRF = \frac{1}{2\pi\sqrt{(L1 \times C_{par})}} \quad (5)$$

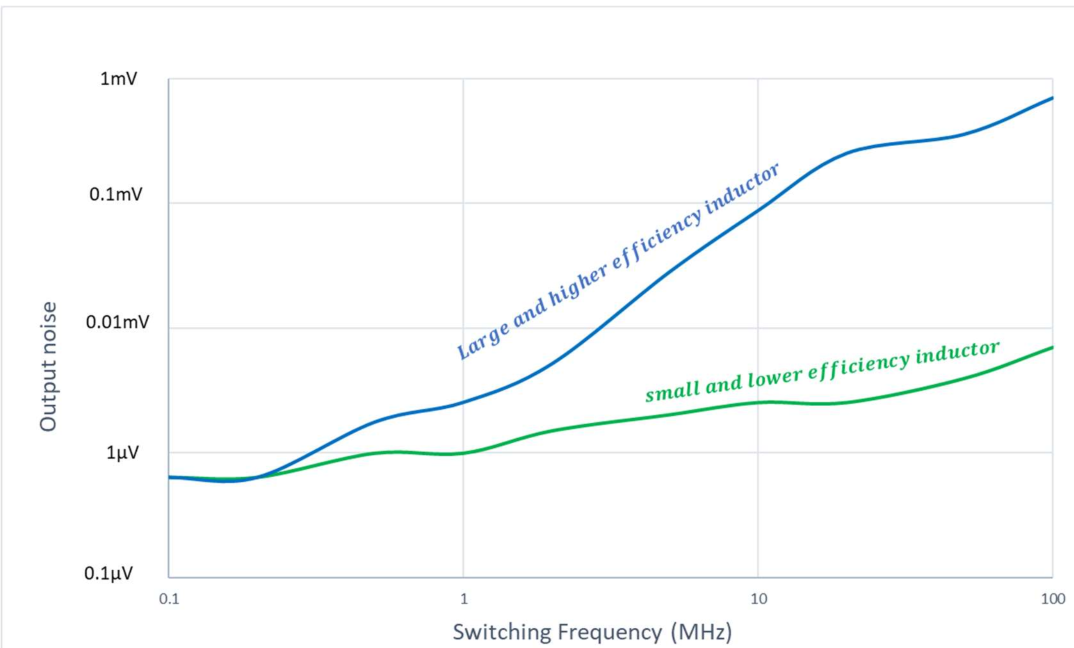

Figure 8. Term 5 component (Cpar influence) to output noise.

Figure 9 and Figure 10 compare the simulated output voltage ripple of the converter that is discussed in this document for the three following cases taking into consideration ESR and ESL of the respective capacitors.

- MLCC only
- MLCC combined with E-CAP
- E-CAP only

A switching regulator operating at 5 MHz switching frequency, can achieve a 10mV ripple using a 4.7µF MLCC, while the same ripple can be achieved by using only 2.2 µF E-CAPs. At 10 MHz the benefits are even more noticeable: 13 mV ripple with a 2.2µF MLCC and 7 mV ripple with a 1.1 µF E-CAP. An alternative is the combination of E-CAP and MLCCs, as show in Figure 10, by reducing the MLCC to 1 µF and adding a 220nF ECAP (EC1001) the ripple is reduced below 10 mV.

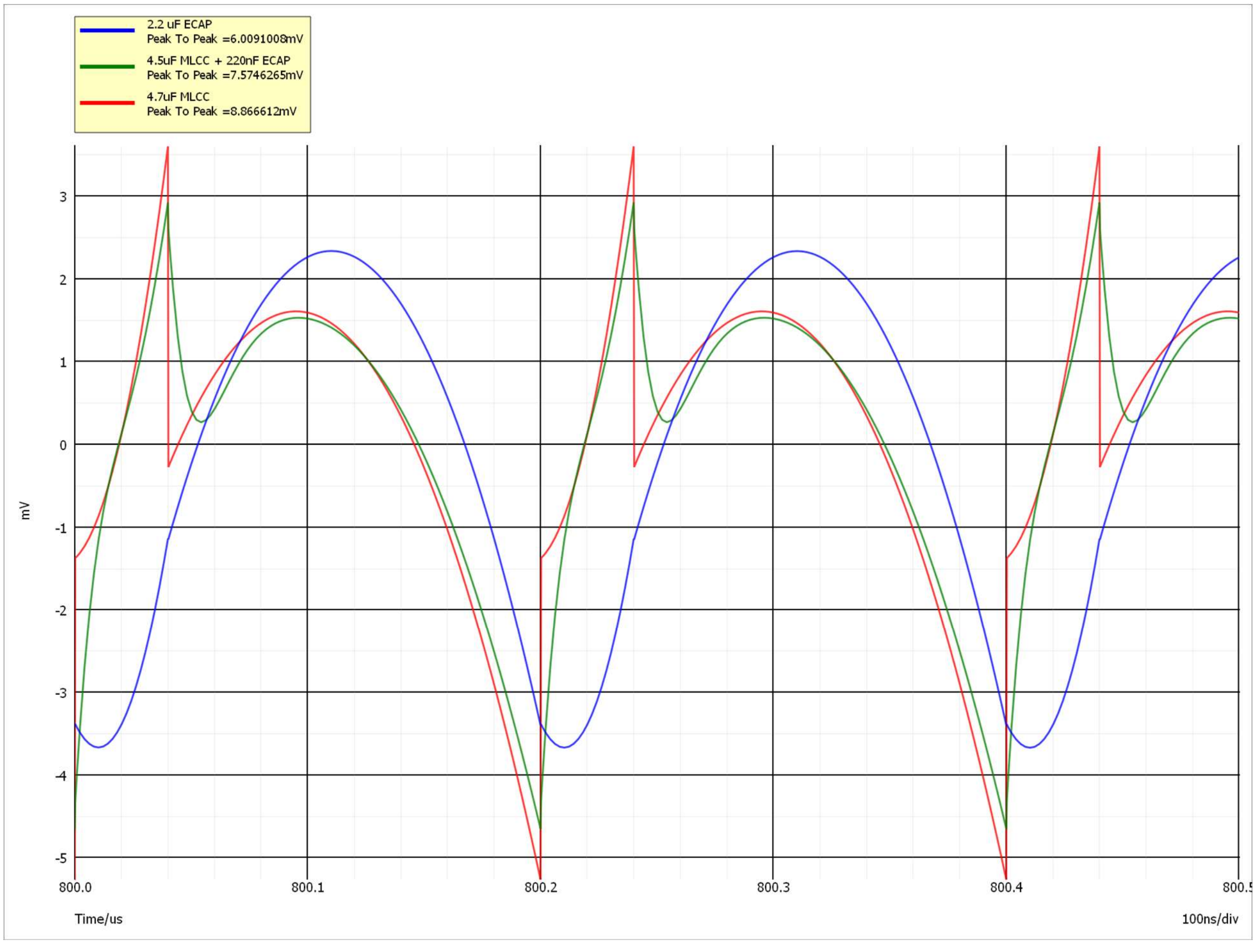

Figure 9. Output voltage ripple comparison at 5 MHz switching frequency.

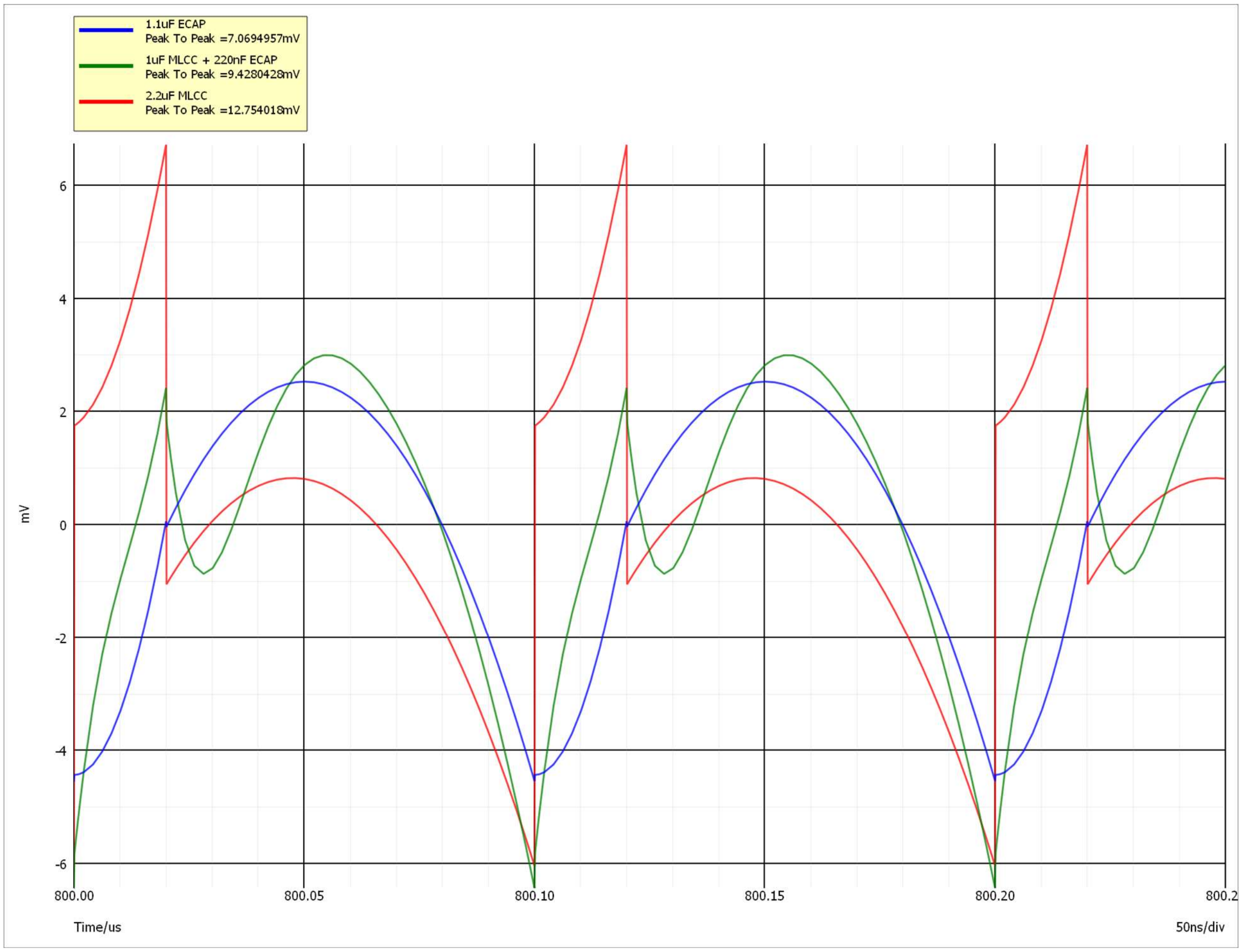

Figure 10. Output voltage ripple comparison at 10 MHz switching frequency.

Also noticeable is the shape of the waveforms, the ripple waveform is smoother with E-CAP resulting in fewer harmonics and lower frequency noise reducing EMI radiation of the design (Figure 11).

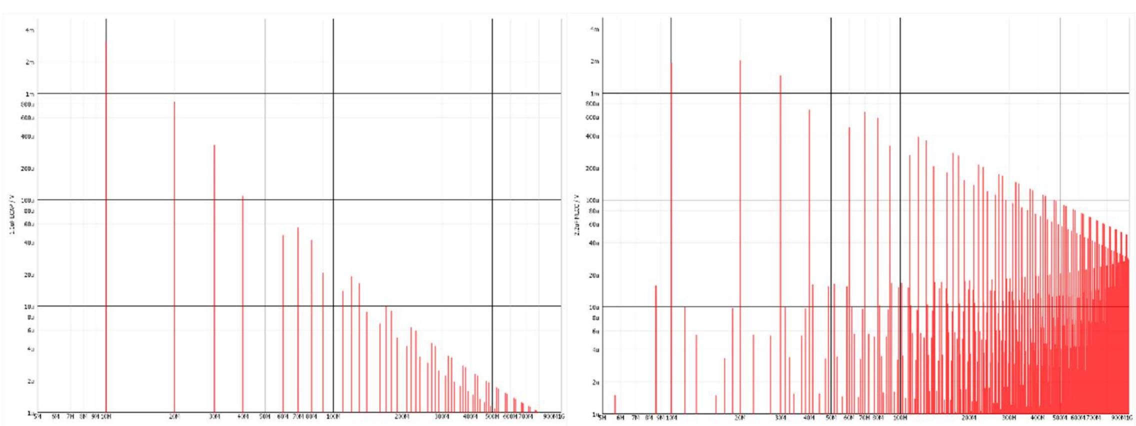

Figure 11. Frequency spectrum of the output voltage ripple with ECAP (left) and MLCC (right).

4 Conclusions

Switching regulators striving for operating frequencies above 5 MHz will have performance limitations due to parasitics found in traditional capacitors that are often used for the output filter. The development of E-CAP has achieved a breakthrough in performance, especially in the achievable low ESL. The E-CAP technology is very suitable for and enables operation in the 10s of MHz for switching regulators. In turn, this enables low-ripple and low-noise solutions without the need to use several capacitors in parallel to reduce these parasitics. E-CAP products are the perfect solution for high-frequency switching regulators. They are now available as standard or custom products in either standalone or an array of capacitors in a single package, these capacitors are also used in the IVR™ family of devices from Empower Semiconductor.

5 References

[1] Murata, Simsurfing tool MLCC specifications: https://www.murata.com/en-us/tool/simsurfing

[2] Taiyo Yuden, reverse geometry capacitor: AWK107C7225MV-T specification

[3] Empower, EC1001 datasheet: https://www.empowersemi.com/wp-content/uploads/2022/02/EC1001-Product-Brief-Rev1p1-10_20_2021.pdf

[4] Coilcraft, Power Inductor Finder and Analyzer: https://www.coilcraft.com/en-us/tools/power-inductor-finder/#/search