DC/DC Converter Output Capacitor Benchmark

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Abstract

Switching power supplies (SMPS) are commonly found in many electronic systems. Important SMPS requirements are a stable output voltage with load current, good temperature stability, low ripple voltage and high overall efficiency. If the electronic system in question is to be portable, small size and light weight are also important considerations. One key component in switching power systems is the output capacitor – used to store the charge and for smoothing and therefore their careful selection plays a vital role in determining the overall parameters of the power supply. Different capacitor technologies – tantalum, ceramic MLCC, NbO niobium oxide and aluminium - are suitable to meet different electrical requirements.

This paper presents the results of an output capacitor benchmark study used in a step-down DC/DC converter design, based on a well-used control circuit (MAX 1537) with a 6-24V input voltage range and two separate voltage outputs of 3.3 and 5V. The behaviour of different output capacitor technologies was evaluated by measuring the output ripple voltage. Defined fixed load and fixed switching frequency settings were used for all measurements.

Introduction

The selection of suitable output capacitor plays an important part in the design of switching voltage converters. "Some 99 percent of the ,'design' problems associated with linear and switching regulators can be traced directly to the improper use of capacitors", claims the National Semiconductor IC Power Handbook – Ref. 1. The importance of output capacitor in switching DC/DC converters is related to the fact that it is (together with the main inductor) the reservoir of electric energy flowing to the output and it smoothes the output voltage.

Today, one can hardly find a consumer, industrial or high reliability electronic device that does not make use of a voltage regulator. Designers basically use two types of regulators, linear LDO (low dropout) and step-down switch-mode DC/DC regulators to convert voltage to lower level. Switching DC/DC regulators are preferred for applications that require a greater difference between input and output voltages because they are more efficient. This type of circuit has been selected for our experimental measurements as they are most often used in today's power supply circuits.

Frequency Dependence of Capacitance, ESR (effective serial resistance) and stability with operational temperature and DC bias voltage are the important parameters of output capacitors that define performance and functionality of the complete power system. Therefore, it is these key parameters that have been measured on different capacitor technologies for the purpose of benchmarking.

Notebooks are one of the most demanding electronics applications where DC/DC converters are typically used with high output current requirements. Notebook supply voltages usually fall into a range of between 15V and 22V with 3.3V and 5V internal power buses commonly seen. To satisfy market demand, semiconductor manufacturers offer integrated DC/DC controllers optimized for these voltage ranges. Such controllers, soldered on a PCB together with all necessary passive and discrete components function as DC/DC converters with maximal output currents of up to several amperes. One notebook power supply converter evaluation kit, based around Maxim's MAX1537 has been chosen as the real application example for the evaluation of different capacitor technologies.

Measuring appliance

Initially, the frequency characteristics of capacitance and ESR of two capacitor groups was measured. The first group included different capacitors specified for the 3.3V output with capacitance C = 220µF; the second group contained capacitors for the 5V output where C = 150µF. Electrical parameters were measured by an HP 4194A impedance/gain-phase analyser (Ref. 4) in a frequency range of 120Hz to 1MHz (capacitance) and 120Hz to 10MHz (ESR).

The temperature stability of the converter is one of industry's most common requirements. Thus the second measurement concentrated on capacitance and ESR stability with temperature and DC voltage bias. The 3.3V output capacitor group was measured using an HP 4192A impedance analyser and a Keithley 7002 switch system across the DC bias voltage range 0 – 4V conditioned in a Votsch VC 7018 laboratory oven over the temperature range of -55 to +125 °C.

Maxim Integrated Products' MAX1537EV KIT (Ref. 3) converter was used for the benchmarking tests. The evaluation kit provides two power outputs, 3.3V and 5V, both with a maximum current I_{out} of 5A. A photograph of the kit is shown in Figure 1. The recommended output capacitance, C, for the 3.3V output is 220µF (see position C6 in Figure 2); for 5V output the value of C is 150µF. AC ripple voltage values and wave forms have been used as the main indicator of filtering quality. A Goldstar GP-505 stabilized power supply was used to supply the kit with a fixed input voltage V_{in} of 20V.

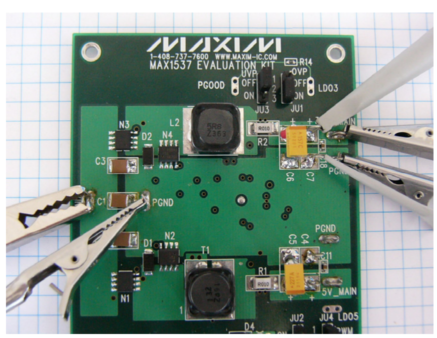


Figure 1: MAX1537EV evaluation kit

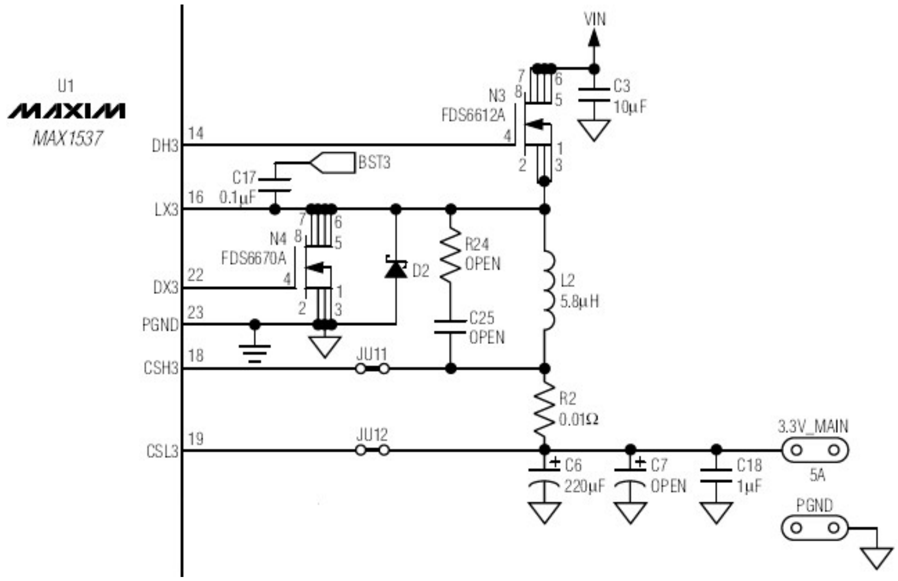


Figure 2: Part of the MAX1537EV evaluation kit schematic diagram with 3.3V output

An output load was set up using resistors and capacitor to draw two thirds of the maximum current. (For 3.3V output this was a parallel combination of 2.2Ω resistor (R) and 4.7µF tantalum capacitor (C); for the 5V output the value of R=3.2Ω (see Figure 3). Voltage waveforms and relevant AC Vrms (effective value) were displayed using an Agilent Infiniium 54830B digital oscilloscope (Ref. 5).

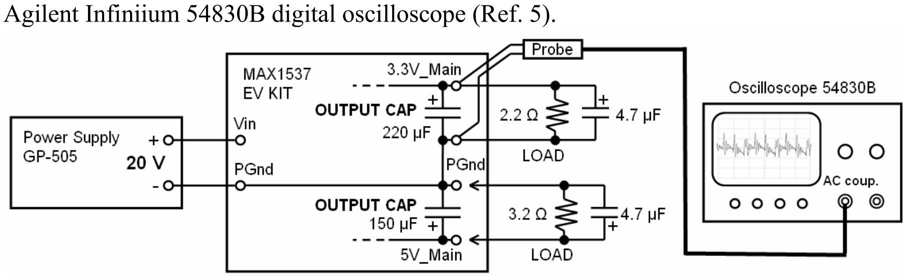


Figure 3: MAX1537EV evaluation kit measurement connection diagram

Frequency characteristics of various capacitors used for 3.3V output

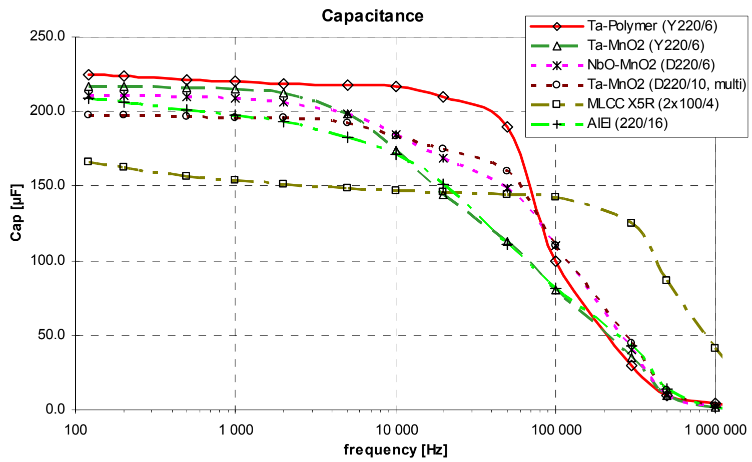


Figure 4: Capacitance vs. frequency of various capacitors for 3.3V output

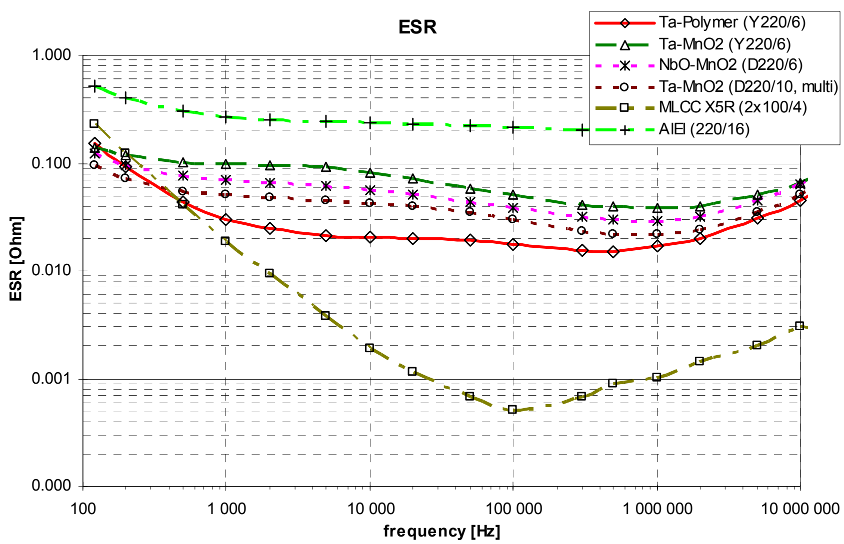


Figure 5: ESR vs. frequency of various capacitors for 3.3V output

The graphs above show the frequency characteristics of several different technology capacitors used for the 3.3V evaluation kit output with nominal capacitance C = 220µF (except MLCC where two parallel 100µF were used). The capacitor technologies chosen were Tantalum-Polymer, Tantalum-MnO_2 (single and multi-anode construction), Niobium Oxide-MnO_2, Multilayer Ceramic, and Aluminium-Electrolytic.

We can observe a relatively small drop in capacitance in the frequency range 10 – 100kHz in the case of Tantalum-Polymer and Tantalum-MnO_2 multianode construction capacitors (see Figure 4), whereas Tantalum-MnO_2 and Aluminium-electrolytic capacitors exhibit a larger drop across the same range. The actual capacitance of the MLCC capacitor suffers due to its dependence on the DC bias voltage, which was applied during measurement. The very low ESR performance of the MLCC parts, and still relatively low ESR of the Tantalum-Polymer capacitors is shown in Figure 5. The ESR of Aluminium-electrolytic capacitors is relatively high over the complete measured frequency range.

Frequency characteristics of various capacitors chosen for 5V output

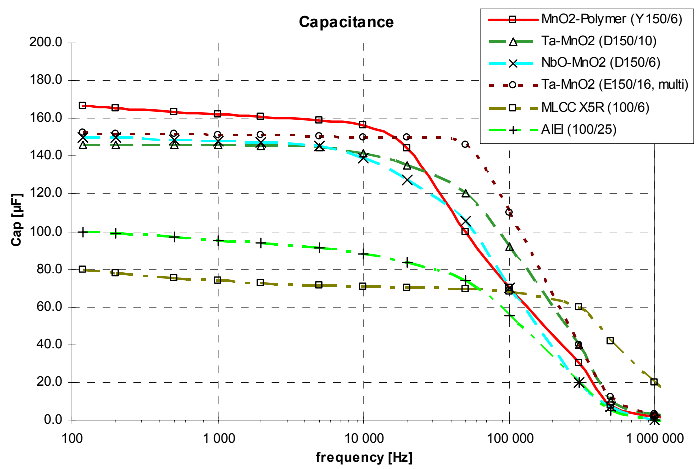


Figure 6: Capacitance vs. frequency of various capacitors for 5V output

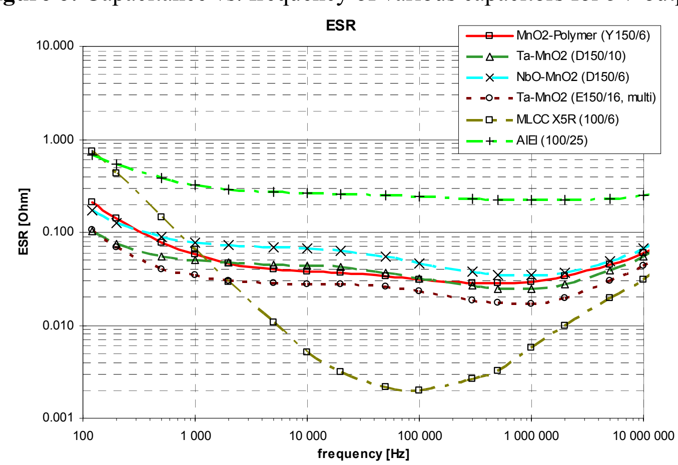


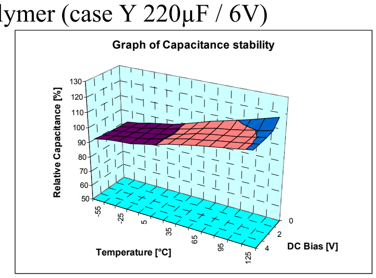
Figure 7: ESR vs. frequency of various capacitors for 5V output

The graphs above show the frequency characteristics of different technology capacitors used with the 5V evaluation kit output with nominal capacitance (C) of 150µF (except MLCC (100µF) and AlEl (100µF)). (Technologies as for the 3.3V output tests, detailed in the paragraph above.)

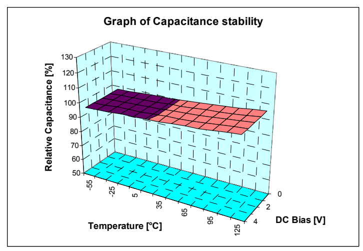
Both Tantalum-MnO_2 single and multi-anode capacitors retain a higher capacitance at higher frequencies (above 100kHz), whereas Niobium Oxide-MnO_2 and Aluminium-electrolytic capacitors lose their capacitance faster at lower frequencies (see Figure 6). MLCC exhibits very low ESR around the 100kHz frequency range; Tantalum-MnO_2 multianode and Tantalum-Polymer capacitors show low ESR in the same frequency range, whereas Aluminium-electrolytic capacitor has a high ESR over all frequency ranges.

Capacitance stability vs. DC bias voltage and temperature

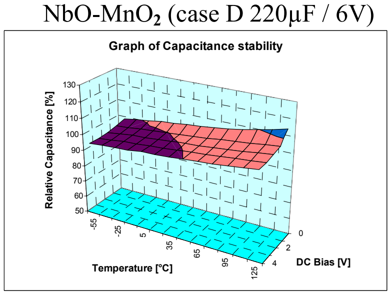
Ta-Polymer (case Y 220µF / 6V)



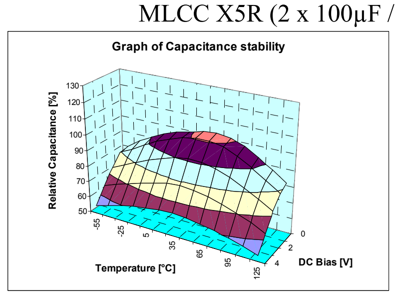
Ta-MnO_2 (case Y 220µF / 6V)



NbO-MnO_2 (case D 220µF / 6V)



MLCC X5R (2 x 100µF / 4V)



AlEl (220µF / 16V)

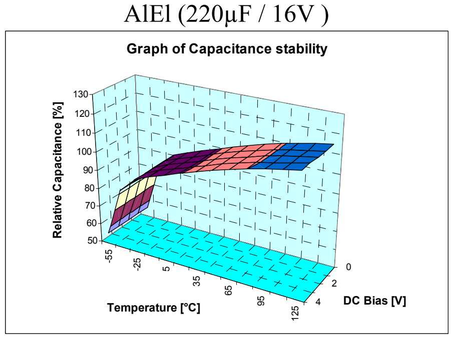
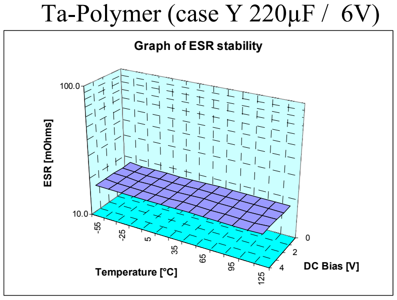


Figure 8: Capacitance stability of various capacitors for the 3.3V evaluation kit output

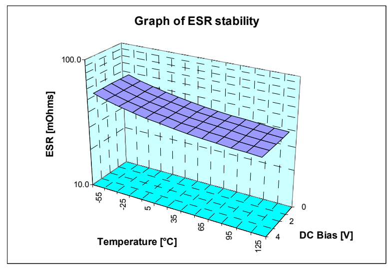
The experiments showed that the best overall capacitance stability is exhibited by theTantalum-MnO_2 technology capacitor (see Figure 8). The capacitance of Niobium Oxide-MnO_2 devices is more sensitive to DC bias voltage and Tantalum-Polymer is more sensitive to temperature changes. The capacitance of MLCC is very dependent on both actual temperature and DC bias. The capacitance of Aluminium-electrolytic capacitors is stable with DC bias but very dependent on temperature.

ESR stability vs. DC bias voltage and temperature

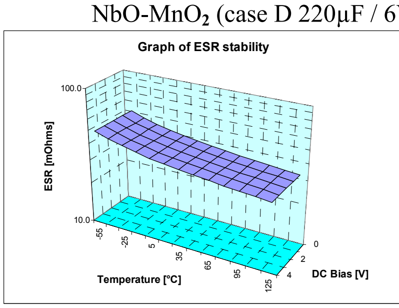
Ta-Polymer (case Y 220µF / 6V)



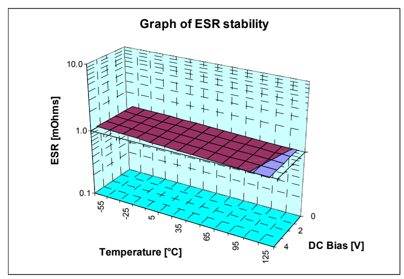
Ta-MnO**2** (case Y 220µF / 6V)



NbO-MnO**2** (case D 220µF / 6V)



MLCC X5R (2 x 100µF / 4V)



AlEl (220µF / 16V)

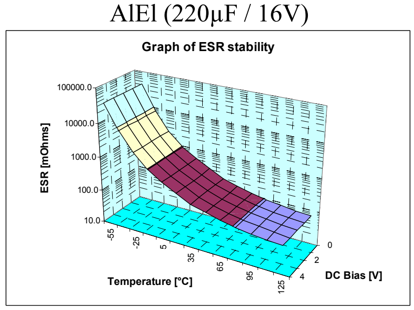
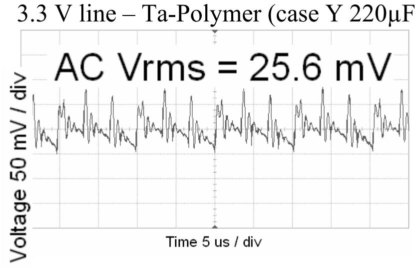


Figure 9: ESR stability of various capacitors dedicated for 3.3 V evaluation kit output

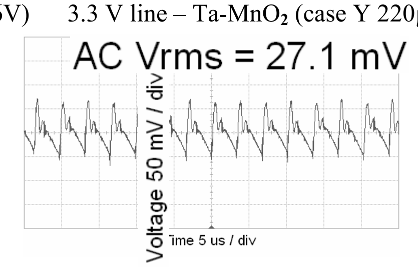
We can see that ESR is relatively stable vs. DC bias voltage for all capacitors. Differences can be seen when we compare ESR stability versus temperature (see Figure 9). Tantalum-Polymer and MLCC capacitors exhibit the most stable ESR, where the ESR of MLCC device is very low over the whole temperature range. With Tantalum-MnO_2 and Niobium Oxide-MnO_2 devices, ESR decreases as temperature increases. Aluminium-electrolytic capacitors behave differently – ESR grows to very high values at low temperature (below 0 °C), due to the limitation of wet electrolyte conductivity at low temperatures.

DC/DC converter output ripple voltage waveform

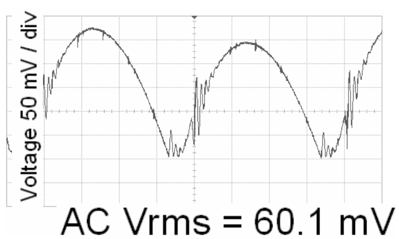
3.3 V line – Ta-Polymer (case Y 220µF / 6V)



3.3 V line – Ta-MnO_2 (case Y 220µF / 6V)



3.3 V line – MLCC X5R (2 x 100µF / 4V)



3.3 V line – AlEl (220µF / 16V)

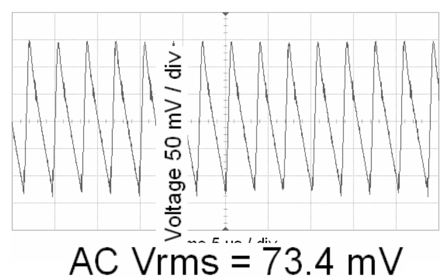
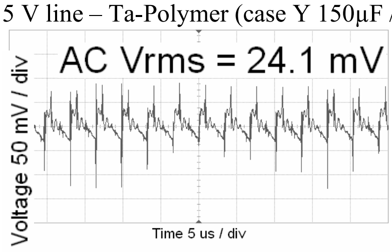
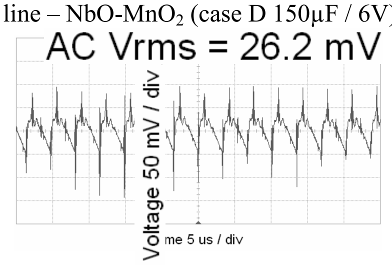


Figure 10: Output ripple voltage waveforms on the 3.3V rail with selected capacitors

5 V line – Ta-Polymer (case Y 150µF / 6V)



5V line – NbO-MnO_2 (case D 150µF / 6V)



5 V line – MLCC X5R (100µF / 6V)

5 V line – AlEl (100µF / 25V)

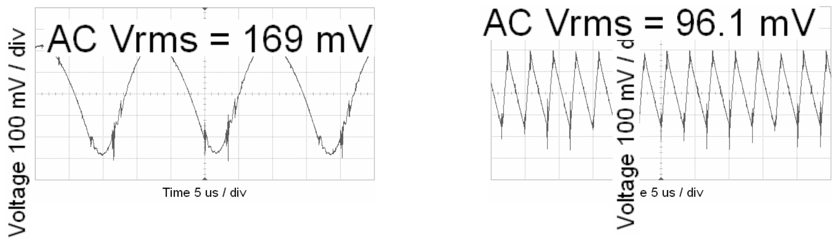
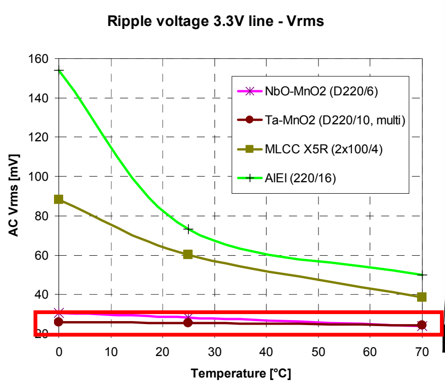


Figure 11: Output ripple voltage waveforms on the 5V rail with selected capacitors

Figures 10 and 11 show the different waveform shapes that occur when different capacitors types are used. Comparing Tantalum-Polymer and Tantalum-MnO_2 capacitors shows that the ripple voltage using Tantalum-MnO_2 device has a lower level of higher harmonic components for both 3.3V and 5V outputs. The basic frequency of the ripple voltage is naturally equal to the switching frequency of the converter f_{sw} = 300kHz. When using MLCC capacitors, both 3.3V and 5V circuits exhibited undesirable oscillations with frequency approximately f_{osc} = 50kHz and high AC Vrms due to the regulator instability. Aluminium-electrolytic types did not perform well, as can be seen on the waveforms of both outputs measured by a relatively high AC Vrms.

Temperature effect on output ripple voltage



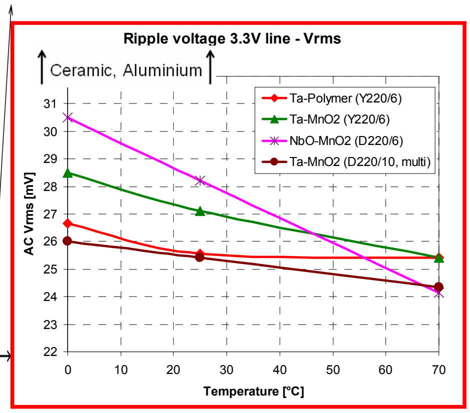
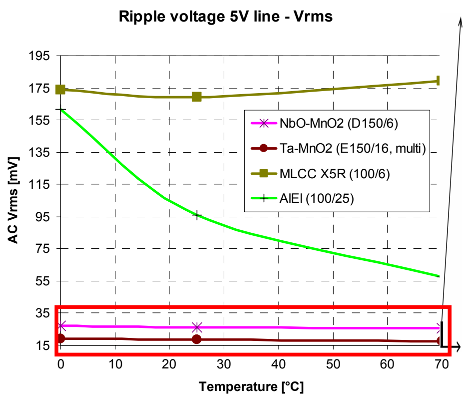


Figure 12a: **Figure 12b:**

3.3V output Vrms of ripple voltage benchmark, magnified scale on right side



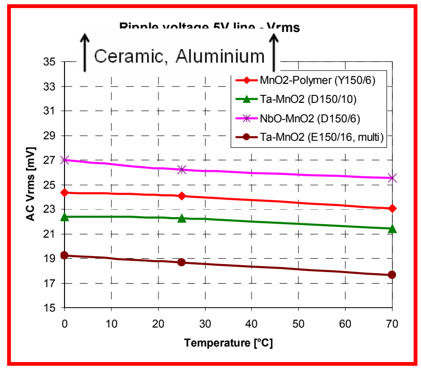


Figure 13a: **Figure 13b:**

5V output Vrms of ripple voltage benchmark, magnified scale on right side

Aluminium-electrolytic and MLCC capacitor Vrms behaviour across a wide Vrms range is displayed in Figures 12a and 13a . Figures 12b and 13b show a much smaller range in magnified scale. For both outputs and most of the capacitor technologies the output ripple Vrms decreases with increasing temperature nearly linearly. Aluminium-electrolytic and MLCC capacitors are exceptions due to their exponential change in capacitance and ESR with temperature (from Figure 8 and Figure 9). Aluminium-electrolytic capacitors exhibit a too high level of ESR across the temperature range, so their smoothing ability is limited, as the output ripple voltage is much higher than with other technologies. When MLCC is used the very low ESR levels cause circuit instabilities so output ripple voltage is also high. Among the other technologies we can observe that ripple voltage at the output will be lower when ESR is low and capacitance at switching frequency is high.

Summary

Table of output capacitor preliminary static measurements

Capacitor technology	Level of the ESR at f_{sw} = 300kHz	Capacitance stability vs. temperature	Capacitance stability vs. DC voltage bias	ESR stability vs. temperature
Ta-Polymer	++	+	+	++
Ta-MnO_2 (single)	+	++	++	+
NbO-MnO_2	+	+	+	+
Ta-MnO_2 (multi)	++	++	++	+
MLCC	- (too low)	0	-	++
Aluminium-el.	- (too high)	-	++	-

Explanation: ++ very good, + good, 0 neutral, - not good

Table showing output capacitor application measurements

Capacitor technology	AC Vrms at 25 °C	Vrms stability vs. temperature	Case size
Ta-Polymer	+	++	++
Ta-MnO_2 (single)	+	+	+
NbO-MnO_2	0	0	+
Ta-MnO_2 (multi)	++	++	0
MLCC	-	-	+
Aluminium-el.	-	-	-

Explanation: ++ very good, + good, 0 neutral, - not good

Low output ripple voltage for the DC/DC converter can be achieved using output capacitors with low ESR at the switching frequency - in our case Tantalum-polymer and Tantalum-MnO_2 multi-anode capacitors. How fast the actual capacitance is decreasing with frequency in relation to the resonance frequency is also important.

Tantalum-MnO_2 capacitors are recommended in applications with variable output voltages because they offer the best capacitance stability versus DC bias voltage.

It is strongly recommended that designers consider the capacitance and ESR temperature stability of output capacitors when deciding on the system's operating temperature. From this point of view, Tantalum-Polymer and Tantalum-MnO_2 capacitors were found to be the most stable, whereas MLCC and Aluminium-electrolytic capacitor are the least.

Comparing capacitor size: in our benchmark, Tantalum-Polymer and Tantalum-MnO_2 low profile capacitors were the smallest suitable capacitors followed by Niobium Oxide-MnO_2 with the same footprint but a little taller. Aluminium-electrolytic radial leaded capacitors require a bigger footprint and are much bigger in volume.

Conclusions and Recommendations

As the main energy carrier, the output capacitor plays an important role in DC/DC switching converter functionality. The capacitance and ESR of the output capacitor can significantly influence the DC/DC converter regulator feedback loop, which defines the stability of the converter operation. These parameters have to be in a certain range to assure stability of the system. In our experiments, MLCC output capacitors had too low an ESR (in range of 1 – 2mΩ), which resulted in oscillations of the circuit and a relatively high ripple voltage. Therefore, MLCC devices cannot be recommended in our experimental study. The use of MLCC capacitors can be recommended only under careful evaluation of their low ESR versus stability of the loop.

Using of generic Aluminium-electrolytic capacitors resulted in high output ripple voltage and poor filtering due to their higher ESR characteristics. This also significantly deteriorates at lower temperatures.

Based on our measurements using the Maxim MAX1537EVKIT evaluation kit we can conclude that using low ESR output capacitors such as Tantalum-Polymer and Tantalum-MnO_2, especially with multi-anode construction, leads to the best results measured by AC Vrms of output ripple voltage and Vrms temperature stability. MLCC and Aluminium Electrolytic technologies can be used as long as attention is paid to the instability (MLCC) and output ripple (Aluminium). Good cost versus performance value can be also achieved using NbO capacitors.

References

1] Chester Simpson, Member of Technical Staff, Power Supply Design Group, National Semiconductor

2] Datasheet and product flyer of Maxim MAX1537 main power supply controller, http://www.maxim-ic.com/quick_view2.cfm/qv_pk/4521

3] Datasheet of product flyer of Maxim MAX1537EVKIT evaluation kit, http://www.maxim-ic.com/quick_view2.cfm/qv_pk/4546

4] HP Impedance analyser 4192A description and datasheet,

http://www.testequipmentdepot.com/usedequipment/hewlettpackard/impedanceanalyzers/4194a.htm

5] Agilent Infiniium oscilloscope 54830B datasheet, http://www.datasheetcatalog.org/datasheet2/9/0o4ptsp0alkuqg2rh3tp0wy3expy.pdf

6] T.Zednicek, B.Vrana et col.,"Tantalum and Niobium Technology Roadmap", http://www.avx.com/docs/techinfo/tantniob.pdf

7] T.Zednicek, „Tantalum Polymer and Niobium Oxide capacitors“, http://www.avx.com/docs/techinfo/newtant.pdf