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Switched-Capacitor Converters—Is MLCC Lifetime A Concern?

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Analog Devices has released several switched-capacitor converter (SCC) controllers and has used this technology within several µModule devices. Within the switched-capacitor power conversion, the whole energy from input to output is transferred via the dielectric of the capacitor(s) rather than through the inductor—hence the name inductorless converters. This can challenge the capacitors with increased RMS currents.

In the SCC design, the so-called flying capacitors (C_{FLY}) are periodically switched between input and output capacitances, thus transferring the energy chunks from input to output in every switching cycle through them. These are the ones that are affected most by the RMS ripple load stress.

Electrical designers typically opt for multilayer ceramic capacitors (MLCCs) from various manufacturers due to their cost-effectiveness, compact size, and ability to handle higher switching frequencies. A valid concern is whether the increased RMS ripple current poses a design weakness, especially with the recent release of high-current SCC switchers like the LTC7825,[1] which can deliver output currents up to 12 A.

To assess the lifetime of MLCCs, it is essential to analyze their RMS currents and consider the expected ambient temperature of the system in which they're used. This article shows how to properly simulate the ripple current through the capacitors within the power converter design.

The formula for the estimated lifetime of capacitors is presented along with the calculation of the lifetime of the most stressed capacitors in the SCC design. Finally, the article discusses the differences between several capacitor types and gives recommendations for proper capacitor type selection with respect to improving their estimated lifetime.

Capacitors Within SCCs

Fig. 1 shows the typical schematic of the SCC design using the LTC7825 converter chip. Table 1 lists the capacitors used in the demo board implementation of this schematic.

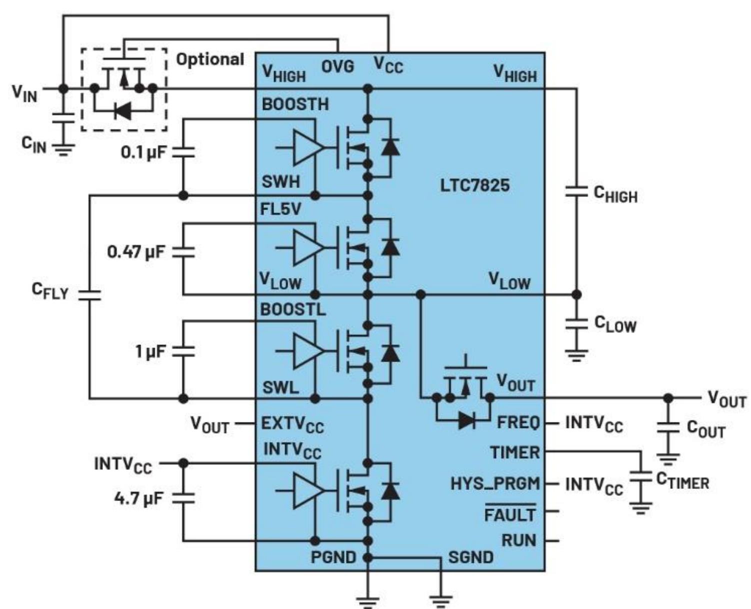

Fig. 1. Typical schematic of switched-capacitor 2:1 converter using the LTC7825.

Table 1. The main capacitors used in the DC2993A-A demonstration board.

Position	Ref	Qty	Part description	Manufacturer	Mfg pn	Note
C_{OUT}	C60 to C67	8	10 µF, X5R, 25 V, 20%, 0603	Murata	GRM188R61E106MA73D	No substitution allowed
C_{HIGH}	C24 to C31	8	10 µF, X5R, 25 V, 20%, 0603	Murata	GRM188R61E106MA73D	No substitution allowed
C_{LOW}	C33 to C40	8	10 µF, X5R, 25 V, 20%, 0603	Murata	GRM188R61E106MA73D	No substitution allowed
C_{FLY}	C41 to C56	16	10 µF, X5R, 25 V, 20%, 0603	Murata	GRM188R61E106MA73D	No substitution allowed
C_{IN}	C4 to C21, C129	19	2.2 µF, X5R, 50 V, 10%, 0603	Murata	GRM188R61H225KE11D	
				Taiyo Yuden	UMK107BBJ225KA-T	Substitution part
	C2, C3	2	68 µF, alum poly, 50 V, 20%, SMD 8.3 mm × 8.3 mm	Nichicon	GYA1H680MCQ1GS	

As can be seen, the main building blocks are the converter chip itself, and the C_{IN}, C_{OUT}, C_{HIGH}, C_{LOW}, and C_{FLY} capacitors. The rest of the capacitors (and other components) in the schematic are not directly involved in power conversion; they act only as supporting functions (for example, decoupling, timer, etc.).

Electrical Analysis Of Capacitors Within SCCs

This study will take the DC2933A-A[2] demonstration board design and operate it at the maximum input and output conditions: 24-V input voltage and 12-A output load current. The output voltage is unregulated at the $V_{IN}/2$ = 12 V, and the operating switching frequency is set to 400 kHz.

For this example calculation, assume the operating ambient temperature of the capacitors is 60°C. From the documentation files for the demonstration board, the capacitors shown in Table 1 are used for the main positions.

After the quick steady-state analysis of the SCC design, while neglecting the ripple and voltage drops on switching FETs, we can assess that the dc voltage across all but C_{IN} capacitors is $V_{IN}/2$, that is 12 V. This allows for the evaluation of the dc bias effects on these capacitors.

For all the power-related capacitor positions (C_{HIGH}, C_{LOW}, C_{FLY}, and C_{OUT}), the same 10-µF, 25-V part is used: manufacturer part number GRM188R61E106MA73D.

Using Murata's proprietary MLCC characteristics viewer SimSurfing, the characteristic graphs in Figs. 2 and 3 can be obtained for the main capacitors under investigation.[3]

For these graphs, the operating point settings are: 12-Vdc bias voltage and 50°C part temperature, 400-kHz frequency, and 0.2-Vrms ripple current.

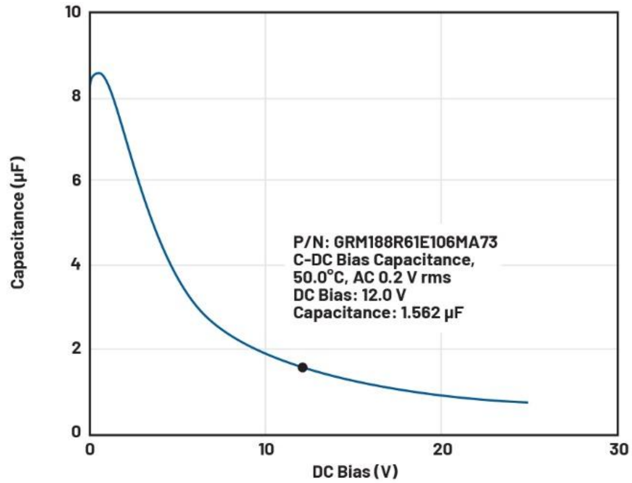

Fig. 2. Dc bias characteristic (10 µF, 20%, 25 V, 0603, X5R).

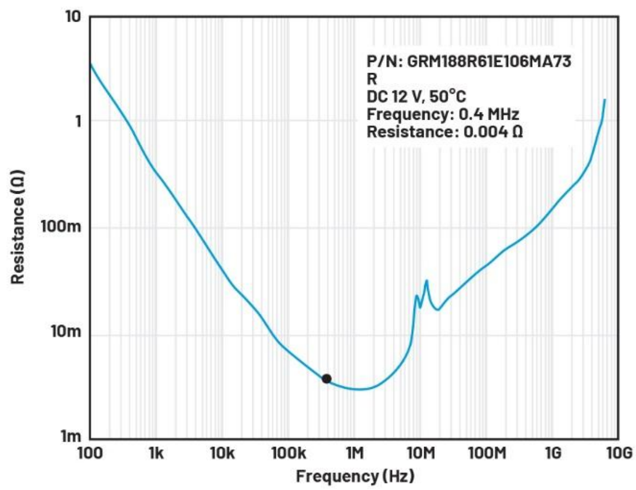

Fig. 3. ESR frequency characteristic (10 µF, 20%, 25 V, 0603, X5R).

Note 1: The C_{IN} capacitors will not be further investigated in this article; therefore, their characteristics are not shown here.

Note 2: The 0.2 Vrms was selected as a parameter for the characteristic as a compromise between two other possible values: 10 mVac and 1 Vac (which is unlikely to be seen on MLCCs at this power level).

Note 3: An attentive reader will surely notice that the article uses two different temperatures: +50°C to examine the capacitors' electrical parameters C_{EFF} and ESR, and +60°C to calculate the lifetime of the capacitors. This inconsistency in the temperature values is not intentional. Although this minor mistake is inconvenient, the overall results and article outcomes are not affected at all.

From the capacitor's characteristic graphs, the effective capacitance (C_{EFF}) is 1.562 µF and the equivalent serial resistance (ESR) is 4 mΩ.

These values are essential for simulating the SCC circuit and are used in the LTspice[4] simulation schematic to observe the ripple voltages and currents through the investigated main capacitors. See Fig. 4.

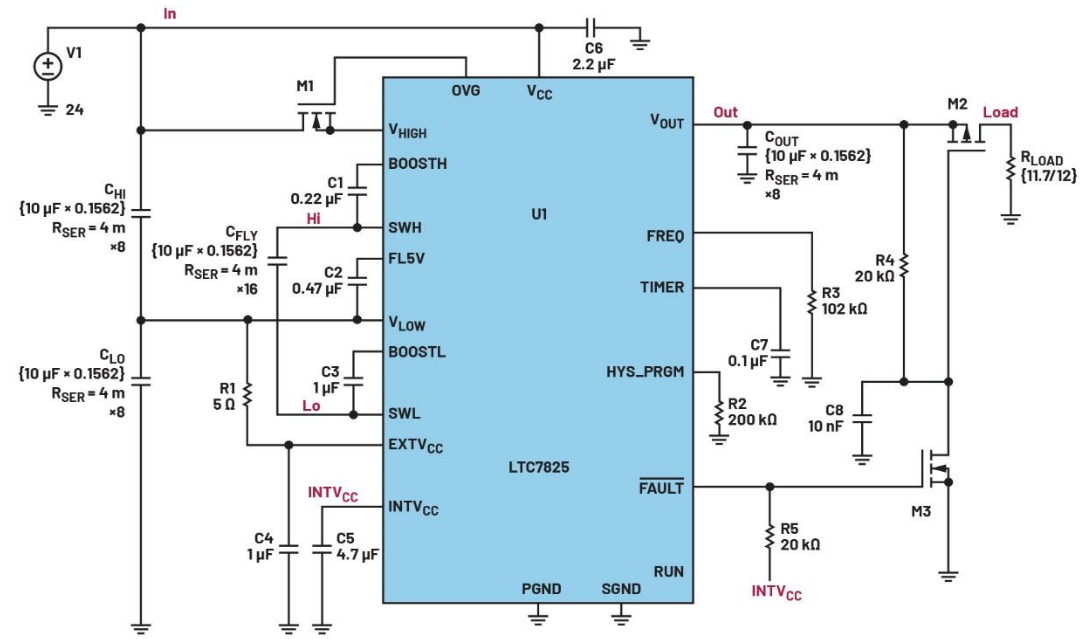

Fig. 4. The LTC7825 simulation schematic of SCC with capacitor parameters C_{EFF} and ESR.

Once the transient simulation reaches stable output conditions, plot the ripple voltages and currents of all investigated capacitors and measure their peak-to-peak and RMS values, using the LTspice waveform viewer's built-in measurement tool.[4]

The results from the simulation are shown in Fig. 5 and Table 2.

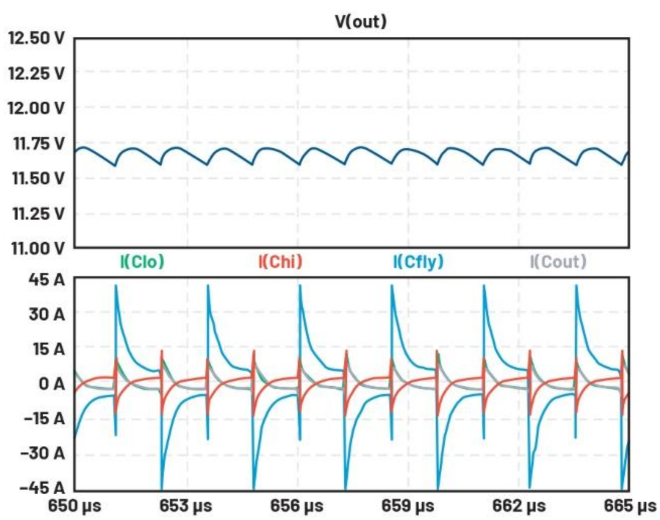

Fig. 5. The LTC7825 current ripple simulation waveforms.

Table 2. Voltage and current stresses for capacitors in SCC design.

Position	Qty	V_{RIPPLE}, peak-peak	Vrms	I_{RIPPLE}, rms	I_{RIPPLE}, rms per one capacitor
C_{OUT}	8	112 mV p-p	40 mV	2.85 A	0.35 A
C_{HIGH}	8	125 mV p-p	44 mV	3.14 A	0.39 A
C_{LOW}	8	125 mV p-p	44 mV	3.14 A	0.39 A
C_{FLY}	16	595 mV p-p	210 mV	14.98 A	0.94 A

From the waveforms and the summary table of capacitor ripple voltages and currents, the most stressed capacitor(s) are at the C_{FLY} position, where the expected RMS ripple current is 0.94 A per one capacitor. The other three capacitor positions have almost identical current and voltage stresses across them.

Note that for the C_{FLY} capacitor, the prior estimation of 0.2 Vrms was very close to the simulated result.

Now referring again to the manufacturers' MLCC capacitor characteristics viewer (the Sim-Surfing online tool), Fig. 6 shows the expected temperature rise due to RMS ripple current stress. This graph shows that the 0.94-A ripple current of 400-kHz frequency will increase the temperature of the capacitor by 2°C.

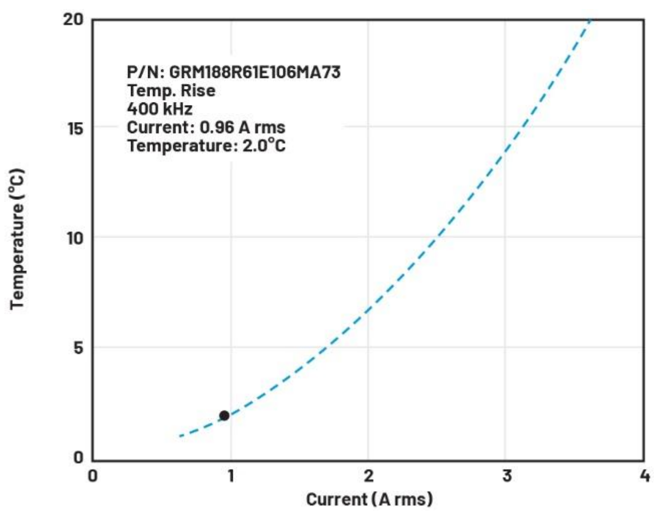

Fig. 6. Temperature rise vs. RMS current (10 µF, 20%, 25 V, 0603, X5R).

A summary of this design investigation, based on simulation results, is:

- The C_{FLY} capacitors are the most stressed capacitors in the SCC design.
- The C_{FLY} capacitors' voltage stress is half of the V_{IN} voltage, which is 12 Vdc superposed with 595-mV p-p ripple.
- The C_{FLY} capacitors are each stressed with 0.94-Arms current ripple with 400-kHz main harmonics frequency, causing the internal temperature to increase by 2°C above the ambient 60°C.

MLCC Lifetime Calculation

For ceramic capacitors, the lifetime equation conforms to the Eyring model, and it depends only on two design factors: applied voltage and temperature.[5,6] The temperature is a combination of system (ambient) temperature and temperature increase due to RMS ripple current.

The lifetime of the MLCC can only be estimated with the highly accelerated life testing (HALT) using excessive voltages and temperatures and measuring the mean time to failure (MTTF) parameter of the batch of samples. Based on these accelerated life tests, the voltage and temperature acceleration constants are calculated (or empirically estimated). As a final step, the lifetime of the capacitor operating at relaxed voltage and temperature conditions is calculated.

As per Murata's ceramic capacitors' FAQ note,[6] the simplified empirical formula for calculating the lifetime of MLCCs in the C_{FLY} position, where the expected RMS ripple current is 0.94 A per Table 2, is as follows:

$$L_N = L_A \left(\frac{V_A}{V_N}\right)^n 2^{\frac{T_A - T_N}{\theta}} \tag{1}$$

where L_A and L_N are lifetime in accelerated and nominal conditions, respectively; n is the voltage acceleration constant; T_A and T_N are temperature in accelerated and nominal conditions, respectively; V_A and V_N are applied voltages in accelerated and nominal conditions, respectively; and θ is the temperature acceleration constant.

For Class 2 MLCCs—and usually all power-related capacitors are this type—the acceleration constants are n = 3 and θ = 8.[6]

The investigated C_{FLY} capacitors belong to the "Consumer Electronic & Industrial Equipment MLCC" product category, which has the following accelerated test conditions (Durability Test Specification, section 16):[7]

- Test temperature (T_A)—maximum operating temperature ±3°C
- Test voltage (V_A)—150% of the rated voltage
- Test time (L_A)—1000 ±12 hours
- The capacitors under investigation are 25-V and 85°C rated.

Note that for a different capacitor part number or type, the accelerated test conditions may differ and need to be checked with the manufacturer.

The above information provides all the data for calculating the estimated lifetime under the operational conditions 12 V and 62°C:

$$L_N = L_A \left(\frac{V_A}{V_N}\right)^n 2^{\frac{T_A - T_N}{\theta}}$$

$$= 1000\left(\frac{25\,x\,1.5}{12}\right)^3 2^{\frac{85-62}{8}} = 223{,}877\ hrs \tag{2}$$

The estimated lifetime of the C_{FLY} ceramic capacitors, operated at 12 V and 60°C ambient temperature, is more than 223 thousands of hours, or 25.5 years.

MLCC Lifetime Discussion

The lifetime formula in equation 1 gives designers the clue that the proper derating of the MLCCs' operating conditions (voltage and temperature) is the key to their long life expectancy. The greater the derating, the longer the capacitor's lifespan.

Currently, the capacitors in question, C_{FLY}, are rated for 25 V and 85°C, using the X5R type Class 2 material.

Selecting a different type of dielectric material, for example, X6S (25-V and 105°C rated) or X7R (25-V and 125°C rated) will boost their estimated lifetime further due to the higher temperature derating factor. Note that rather than increasing the voltage rating, it is more practical to increase the temperature rating. For high life expectancy designs, this practice is highly recommended.

The life expectancy of MLCCs is shortened as the operating conditions get closer to the rated values. For example, the industry's expected lifetime is typically 10 years, which is approximately 87,800 hours of operation. For the X5R Class 2 MLCC this lifetime is achieved when the temperature reaches 73°C.

This is not an unrealistic temperature for the given design example, since the thermal measurements on the DC2933A-A show the temperature of the switcher IC peaking at 83.1°C, which will heat up the surrounding area by another ~10°C to 20°C above ambient. So the capacitors located nearby will be heated up as well. Therefore, it is advised to keep MLCCs away from the hot components to maintain their acceptable lifetime.

Do the real circuitry's thermal measurements and verify the real temperatures of capacitors. This will give you more precise estimation of their lifetime when entering the real temperatures into the formula in equation 2.

The MLCCs are self-heated due to the internal I^2R losses, where R is their internal ESR parameter. For the capacitors in this example, the ESR is 4 mΩ, which, for this small 0603 size, is a very respectable value.

For further life improvement, consider finding a part with an even smaller ESR, while keeping in mind that ESR needs to be examined at the switching frequency of the design. Note that usually the smaller ESR leads to a bigger package size.

Searching through the given manufacturer's MLCCs portfolio, it yields a 22-µF, 25-V, 0805, X5R capacitor, part number GRM21BR61E226ME44. This part has an ESR value of 2 mΩ at 400 kHz, which is half of the original value for 0603 capacitors.

Figs. 7 and 8 are gathered from the online MLCC tool Sim-Surfing, applied for the GRM21BR61E226ME44.

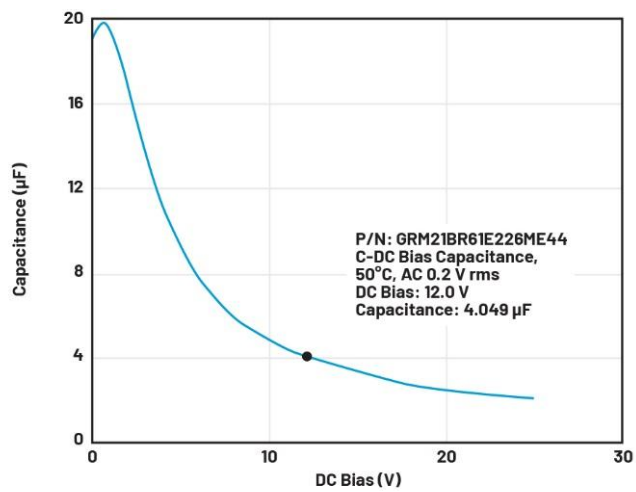

Fig. 7. Dc bias characteristic (22 µF, 20%, 25 V, 0805, X5R).

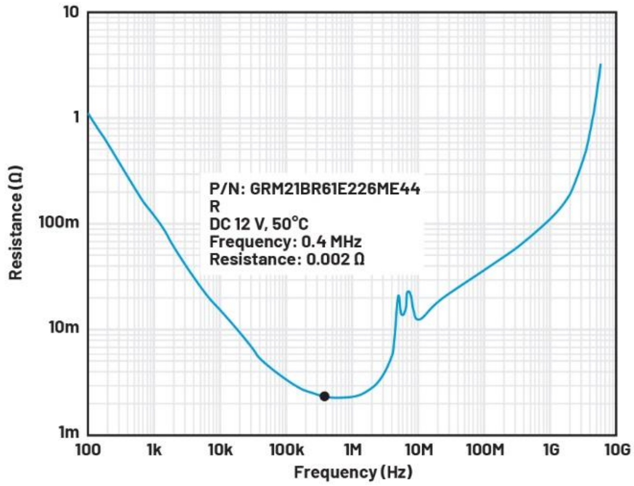

Fig. 8. ESR frequency characteristic (22 µF, 20%, 25 V, 0805, X5R).

The lower ESR allows the capacitor to better handle RMS ripple current, resulting in less temperature rise under the same ripple conditions. Furthermore, the bigger value and size also mean a smaller dc bias effect and a higher effective capacitance, C_{EFF}. As a result, instead of 16 parts with 0603 capacitors, only about six to eight parts are needed in the 0805 size.

The selection of the lowest-ESR high-quality capacitors will also directly affect the lifetime of the parts by lowering the temperature increase due to the RMS ripple current. The caveat is that this is true only if we keep RMS current per capacitor the same as before.

On the other hand, the drawback of using fewer capacitors in a bigger package is that their RMS current per part will be higher. This then results in an approximate factor of 2× for the I^2R power dissipated within the body of the MLCC (for approximately twice the I and half the R, in the discussed example). The higher dissipated power is then reflected into slightly higher MLCC temperatures, therefore (negatively) affecting the lifetime. In other words, changing the type and number of capacitors requires a new design analysis and recalculation of the lifetime value.

It is recommended that designers choose an MLCC manufacturer that supports their products with measured characterization graphs, preferably measured at (or close to) your specific operational values.

For power designers, here’s some guidance on maintaining a longer lifetime for MLCCs: limit the MLCC’s internal temperature rise to less than ~5°C above ambient.

Conclusion

In the calculations above, each parameter uses the typical values for each of the 16 parts of the C_{FLY} capacitor; that is, the calculation is for the ideal component. However, the reality is that each component in the design is unique and subject to its parameters’ tolerances.

Additionally, each part is located in a specific position on the PCB where the PCB itself has its own parasitic R, L, and C elements. All these factors cause the total RMS ripple current to not spread equally between each of the 16 C_{FLY} capacitors. Instead, the ripple current in each capacitor varies.

At this point, each designer can introduce their own experience-based worst-case multiplication coefficient for calculations to estimate the variations of the real part. In some specific industries (or companies), these worst-case multiplication factors are given within the internal design guidelines. This coefficient is usually in the range of 1.05 to 3.0, depending on the criticality level for the design.

For example, selecting a multiplication coefficient approximately in the middle at 2, the worst-case scenario for a single capacitor's C_{FLY} current ripple stress in our example would then be 2 × 0.94 A = ~2 Arms. This (only estimated) higher RMS ripple will then increase the internal temperature by approximately 7°C instead of 2°C (see Fig. 6), causing the estimated lifetime to drop to approximately 145,000 hours.

Also note that the highest RMS ripple current tends to flow through the parts closest to the switcher, due to usually the lowest parasitics of the PCB layout, resulting in the higher temperature rise inside these parts. In addition to the RMS ripple self-heating, the switcher IC itself is the great heat source. So the proximity to this heater will increase its temperature even further.

A careful layout is essential here to find a tradeoff between thermal and electrical performance. Ultimately, the final performance of the design should be evaluated on the prototype boards before implementing them into the final systems.

The importance of careful selection of the SCC's capacitors is also underlined by a small notice in the parts list in Table 1: No substitution allowed. This means that the selection of the proper part for these is not trivial. Designers must understand and meet specific requirements for these capacitors, and mainly understand the fact that not all 10-µF, 25-V capacitors in the market can meet these requirements.

References

1. LTC7825 product page.

2. Demonstration circuit DC2993A-A product page.

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7. Chip Multilayer Ceramic Capacitors for Consumer Electronics & Industrial Equipment, Murata reference sheet.

About The Author

Erich Horňan is a field applications engineer for power products at Analog Devices. Prior to joining the company, he worked as an electrical design engineer on various power design projects for companies in the aerospace, industrial, and medical industries. He holds a master of science degree in electrical engineering with a major in microelectronics from Slovak Technical University.

For more on capacitor selection in power supply design, see How2Power's Design Guide, locate the "Component" category and select "Capacitors".